

Nano 3D Fabrication of Devices by Expanding of LIFT Printing

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von
M.Sc. Stefan Lux
geb. in Reutlingen, Deutschland

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Hauptreferent:	Prof. Dr. Jan G. Korvink
Korreferent:	Prof. Dr. Frank Breitling

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To those who believe in me.

Abstract

The development of a novel material research strategy in the context of next-generation fuel cell development is the focus topic of the EU project Nanostacks. A central element of this strategy is a screening approach based on the fabrication of small arrays of stacked devices derived from OLED and solar cell architectures. These model systems allow the systematic investigation and optimization of material combinations for the development of functional fuel cell components.

Laser-Induced Forward Transfer (LIFT) was selected as the fabrication method because of its high flexibility regarding material classes and its capability to deposit functional materials with high spatial precision. In this process, a laser pulse is focused onto a donor substrate, initiating the transfer of material onto an acceptor substrate. Depending on the ink system, different transfer mechanisms are employed. In one configuration, a polyimide absorber layer converts the laser radiation into heat, initiating material transfer, while in another configuration the laser radiation is absorbed directly by the ink itself.

This work investigates the extension of the LIFT process toward the fabrication of electrical components in a dot-by-dot printing mode. Two demonstrator devices were selected that represent different dimensional regimes: an OLED with layer thicknesses in the nanometer range and a capacitor with structures in the micrometer range. It is demonstrated that LIFT can be used to fabricate electrical components with strongly differing thickness and material requirements within the same printing platform.

To achieve this goal, the material transfer process was systematically analyzed and optimized. A printing strategy based on overlapping individual transfer spots was developed, enabling a lateral resolution in the range of 50 μm to 100 μm . This allowed the fabrication of functional structures with dimensions of approximately 1 mm^2 . Process optimization promoted controlled merging of adjacent spots, resulting in smooth thin films with a surface roughness of $R_a = 2.78 \pm 0.25 \text{ nm}$. By adjusting process parameters and ink concentration, layer thickness could be tuned in the range of 20 nm to 140 nm, enabling the fabrication of closed OLED layers with thicknesses of approximately 20 nm.

Further improvements in lateral definition were achieved by implementing microstructured acceptor substrates. It was shown that pillar structures with heights of approximately 80 μm enable selective deposition on pillar tops, expanding the range of material options and allowing higher-density device arrays. In addition, the use of polyimide as an absorber layer was investigated in detail. Both commercial foils and ultrathin spin-coated polyimide layers were evaluated, revealing physical limits for efficient light-to-heat conversion for layers below 1 μm .

A major focus of this work was the development of inks tailored to the LIFT process. Organic small-molecule materials such as PEDOT:PSS, TCTA, Rubrene and

BPhen were successfully employed to fabricate OLED layers, while nanoparticle inks such as silver and titanium dioxide were used for conductive tracks and capacitor fabrication. Capacitors were realized by printing multilayer structures consisting of conductive and dielectric nanoparticle inks, whereas OLED layers were transferred in their dried state through local remelting in a contact-based configuration.

To support rapid material development, a dedicated LIFT test printer was designed and built in collaboration with TECNAN. This mobile system enables on-site ink qualification using a standardized testing routine in which defined droplets are transferred and evaluated optically. The system establishes a rapid feedback loop between ink formulation and process testing, significantly reducing ink development time.

The LIFT toolbox developed in this work consists of an optimized setup, tailored inks, customized substrates and adapted printing strategies. It enabled fabrication of different functional electronic devices with most diverse requirements and materials. Conductive tracks printed with silver ink reached resistivity values close to those specified by the manufacturer after thermal post-treatment. Parallel-plate capacitors fabricated from silver and titanium dioxide nanoparticle inks showed capacitance values in the pF range with a yield of 54 %. Due to the dot-by-dot fabrication principle, the capacitance can be tuned with a resolution of approximately 0.4 pF per printed dot.

Furthermore, different OLED architectures were successfully fabricated using the developed printing process. A hybrid OLED combining spin coating and LIFT printing exhibited electroluminescence and a fully printed multilayer OLED structure additionally showed significantly improved device stability and lifetime. Optical and electrical characterization as well as analytical methods confirmed light emission and verified the correct layer structure.

Overall, this work demonstrates that LIFT is highly suitable for the fabrication of complex electronic devices. The method enables the deposition of nanometer-scale organic layers as well as micrometer-scale nanoparticle structures within a single system. Beyond the demonstrated devices, the method shows strong potential for the fabrication of further functional structures such as solar cells or fuel cells, making it a promising technology for future material screening and device prototyping.

Kurzfassung

Im Zentrum des Nanostacks-Projekts steht die Entwicklung einer neuartigen materialwissenschaftlichen Strategie für die nächste Generation von Brennstoffzellen. Ein wesentlicher Bestandteil dieser Strategie ist ein Screening-Ansatz, der auf der Herstellung kompakter, regelmäßig angeordneter, gestapelter Bauelemente basiert, die vom Aufbau her von OLED- und Solarzellensystemen abgeleitet sind. Diese Modellsysteme ermöglichen die systematische Untersuchung und gezielte Optimierung von Materialkombinationen für funktionale Brennstoffzellenkomponenten.

Als Fertigungsmethode wurde das Laser-Induced Forward Transfer (LIFT)-Verfahren gewählt, da es eine hohe Flexibilität hinsichtlich unterschiedlicher Materialklassen bietet und zugleich einen präzisen, orts aufgelösten Transfer funktionaler Materialien ermöglicht. Dabei wird ein Laserstrahl auf ein Donorsubstrat fokussiert, wodurch der Materialtransfer auf ein Akzeptorsubstrat ausgelöst wird. Abhängig vom verwendeten Tintensystem kommen unterschiedliche Transfermechanismen zum Einsatz. In einer Variante wandelt eine Polyimid-Absorberschicht die Laserstrahlung in Wärme um und initiiert so den Materialtransfer, während in einer anderen Variante die Strahlung direkt vom Transfermaterial absorbiert wird und dadurch der Übertrag erfolgt.

In dieser Arbeit wird die Erweiterung des LIFT-Prozesses zur Herstellung elektrischer Bauelemente durch punkweisen Druck untersucht. Hierzu wurden zwei Demonstratoren ausgewählt, die unterschiedliche Dimensionierungen aufweisen: eine OLED mit Schichtdicken im Nanometerbereich sowie ein Kondensator mit Strukturendicken im Mikrometerbereich. Es wird gezeigt, dass sich mit LIFT elektrische Bauelemente mit stark unterschiedlichen Schichtdicken und Materialanforderungen innerhalb einer gemeinsamen Druckplattform realisieren lassen.

Zur Erreichung dieses Ziels wurde der Materialtransferprozess systematisch analysiert und optimiert. Es wurde eine Druckstrategie entwickelt, die auf der Überlappung einzelner Transferpunkte basiert und eine laterale Auflösung im Bereich von $50\text{ }\mu\text{m}$ bis $100\text{ }\mu\text{m}$ ermöglicht. Auf diese Weise konnten funktionale Bauelemente mit Abmessungen von etwa 1 mm^2 hergestellt werden. Die Prozessoptimierung führte zu einem kontrollierten Verschmelzen benachbarter Punkte und resultierte in glatten Dünnschichten mit einer Oberflächenrauheit von $R_a = 2.78 \pm 0.25\text{ nm}$. Durch die Anpassung von Prozessparametern und Tintenkonzentration ließ sich die Schichtdicke im Bereich von 20 nm bis 140 nm einstellen, sodass geschlossene OLED-Schichten mit Dicken von etwa 20 nm realisiert werden konnten.

Weitere Verbesserungen der lateralen Strukturauflösung wurden durch den Einsatz mikrostrukturierter Akzeptorsubstrate erzielt. Es konnte gezeigt werden, dass Säulenstrukturen mit Höhen von etwa $80\text{ }\mu\text{m}$ einen selektiven Materialübertrag auf den Säulenoberseiten ermöglichen. Dadurch erweitert sich das Spektrum einsetzbarer Materialien, und es lassen sich dichter gepackte Bauelementanordnungen realisieren.

Darüber hinaus wurde der Einsatz von Polyimid als Absorberschicht detailliert untersucht. Sowohl kommerzielle Folien als auch ultradünne, schleuderbeschichtete Polyimidschichten wurden analysiert. Dabei konnten physikalische Grenzen der Licht-zu-Wärme-Umwandlung für Schichtdicken unterhalb von 1 μm aufgezeigt werden.

Ein wesentlicher Schwerpunkt dieser Arbeit lag auf der Entwicklung von Tinten, die speziell auf den LIFT-Prozess abgestimmt sind. Organische niedermolekulare Verbindungen wie PEDOT:PSS, TCTA, Rubren und BPhen wurden erfolgreich eingesetzt und zur Herstellung von OLED-Schichten verwendet. Nanopartikeltinten auf Basis von Silber und Titandioxid kamen hingegen für leitfähige Strukturen und die Herstellung von Kondensatoren zum Einsatz. Kondensatoren wurden durch den Druck in mehrschichtiger Strukturen aus leitfähigen und dielektrischen Nanopartikeltinten realisiert, während OLED-Schichten im getrockneten Zustand durch lokales Wiederaufschmelzen in einem kontaktbasierten Prozess übertragen wurden.

Zur Unterstützung einer schnellen Materialentwicklung wurde in Zusammenarbeit mit TECNAN ein spezieller LIFT-Testdrucker entwickelt und aufgebaut. Dieses mobile System ermöglicht die Qualifizierung von Tinten direkt vor Ort anhand einer standardisierten Testprozedur, bei der definierte Tröpfchenmuster übertragen und optisch ausgewertet werden. Dadurch entsteht ein schneller Rückkopplungskreislauf zwischen Tintenformulierung und Prozessbewertung, was die Entwicklungszeit neuer Tinten deutlich verkürzt.

Das in dieser Arbeit entwickelte Konzept eines LIFT-Werkzeugkastens umfasst ein optimiertes Prozesssetup, angepasste Tinten, maßgeschneiderte Substrate sowie geeignete Druckstrategien. Damit konnten verschiedene funktionale elektronische Bauelemente mit unterschiedlichen Anforderungen und Materialien hergestellt werden. Gedruckte leitfähige Strukturen aus Silbertinte erreichten nach thermischer Nachbehandlung spezifische Widerstände nahe den Herstellerangaben. Plattenkondensatoren aus Silber- und Titandioxid-Nanopartikeltinten zeigten Kapazitätswerte im pF-Bereich bei einer Ausbeute von 54 %. Aufgrund des Punkt-für-Punkt-Druckprinzips lässt sich die Kapazität mit einer Auflösung von etwa 0.4 pF pro gedrucktem Punkt einstellen.

Darüber hinaus wurden verschiedene OLED-Architekturen erfolgreich mit dem entwickelten Druckprozess hergestellt. Für eine hybride OLED Variante, die Schleuderbeschichtung und LIFT-Druck kombiniert, wurde die Funktionalität durch den Nachweis der Elektrolumineszenz erbracht. Eine vollständig gedruckte mehrschichtige OLED-Struktur wies zusätzlich eine deutlich verbesserte Stabilität und Lebensdauer auf. Der korrekte Schichtaufbau wurde durch optische und elektrische Charakterisierungen sowie analytische Verfahren bestätigt.

Insgesamt zeigt diese Arbeit, dass sich das LIFT-Verfahren hervorragend zur Herstellung komplexer elektronischer Bauelemente eignet. Die Methode ermöglicht sowohl den Transfer organischer Schichten im Nanometerbereich als auch den Druck nanopartikelbasierter Strukturen im Mikrometerbereich innerhalb eines einzigen Systems. Über die demonstrierten Bauelemente hinaus besitzt das Verfahren großes Potenzial für die Herstellung weiterer funktionaler Strukturen wie Solarzellen oder Brennstoffzellen und stellt damit eine vielversprechende Technologie für zukünftiges Materials-Screening und die Prototypenentwicklung dar.

List of Publications

Published peer-reviewed articles

As first author

- [P1] **S. Lux**, C. Wu, C. Salazar, J. Crespo, A. Pérez, C. F. Acevedo, D. Mager, M. Stahlberger, D. Mattes, L. Weber, J. Schlindwein, C. Gedigk, M. B. A. Rosa, M. Amir, N. Kuznetsova, M. Kraft, F. Breitling, and J. G. Korvink “A Portable LIFT Printer to Enable the Fast On-Site Optimization of Inks Toward Special Customer Needs” *Nano Select* **6.4** (2025), e202400126. <https://doi.org/10.1002/nano.202400126>.
- [P2] **S. Lux**, N. Kuznetsova, A. R. Simha, D. Mager, F. Breitling, and J. G. Korvink “Dot-by-Dot Printing of Capacitors by LIFT” *Applied Research* **4.1** (2025), e202400266. <https://doi.org/10.1002/apxr.202400266>.
- [P3] **S. Lux**, J. Schlindwein, M. Plank, K.-M. Reichert, L. Koker, M. Rosa, M. Amir, B. Weber, E. Müller, A. Welle, N. Kuznetsova, M. Kraft, Y. M. Eggeler, L. K. Weber, D. Mattes, U. Gengenbach, M. Stahlberger, J. G. Korvink, F. Breitling, and D. Mager “Overlapping Nanostacks Enable Direct Printing of Organic LEDs” *Advanced Materials Interfaces* **n/a.n/a** (2025), e00501. <https://doi.org/10.1002/admi.202500501>.

Patents

Patent Pending

- [P4] Druckverfahren, Vorrichtung zur Durchführung eines entsprechenden Druckverfahrens sowie ein mittels eines entsprechenden Druckverfahrens hergestelltes nanoskaliges Funktionsmaterial, PEPperPRINT GmbH, AZ 10 2025 147 733.7

Conference contributions

Poster Presentations

- [P5] **S. Lux**, K. Reichert, M. Plank, D. Mattes, M. Stahlberger, D. Mager, J. Korvink, F. Breitling “Dot-by-dot Printing, a Novel Approach for OLED Fabrication by LIFT” *Nanotechnology, Thessaloniki* (2024)
- [P6] **S. Lux**, D. Mattes, M. Stahlberger, D. Mager, F. Breitling, J. Korvink “Dot-by-Dot Printing of Capacitors by LIFT” *Nanotechnology, Thessaloniki* (2024)

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Glossary

AFM atomic force microscopy

Alq₃ tris(8-hydroxyquinolin)aluminum

BA-LIFT blister-actuated LIFT

Bphen bathophenanthroline

CMC CMC Klebetechnik GmbH

CNC computerized numerical control

DAC digital-to-analog converter

DCM dichloromethane

DRL dynamic release layer

EML emissive layer

ETL electron transport layer

FIB focused ion beam

HEPA high-efficiency particulate air

HOMO highest occupied molecular orbital

HTL hole transport layer

ITO indium tin oxide

Kapton[®] Kapton, registered trade mark of DuPont, a polyimide variant

LIFT Laser-Induced Forward Transfer

LUMO lowest unoccupied molecular orbital

MATIS modular automated testing and inspection system

OLED organic light-emitting diode

PCB printed circuit board

PEDOT:PSS poly(3,4-ethylenedioxythiophene) polystyrene sulfonate

PS polystyrene

PVP polyvinylpyrrolidone

RT RegioTape

Rubrene 5,6,11,12-tetraphenylnaphthacene

S-LEC[®] styrene-acrylic copolymer S-LEC PLT 7552 (Sekisui, Japan), registered trade mark of Sekisui, a polymer related to polystyrene

SEM scanning electron microscopy

SMU source measure unit

TAPC 1,1-bis[(di-4-tolylamino) phenyl] cyclohexane

TCTA tris(4-carbazoyl-9-ylphenyl)amine

TiO₂ titanium dioxide

TOF SIMS time-of-flight secondary ion mass spectrometry

TPD N,N'-bis(3-methylphenyl)-N,N'-diphenylbenzidine

VSI vertical scanning interferometry

ZIF zero insertion force

1. Introduction

1.1 Motivation

The fabrication of modern electronic devices is dominated by conventional methods such as photolithography, deposition techniques, and etching. These approaches dominate due to their excellent scalability, low unit cost, high integration density and precision.

In contrast, a small fraction of electronics is produced using non-conventional methods such as additive manufacturing. These techniques complement conventional fabrication by offering high design freedom, suitability for low-volume production and the potential for functional integration. Modern electronic systems increasingly integrate multiple functionalities, such as sensing, communication, optics and mechanics, into a single device, as seen in everyday consumer products like smartphones. However, conventional fabrication relies on multi-step processes that become increasingly complex as additional functionalities are integrated. Furthermore, certain materials are difficult to integrate into wafer-based processes due to incompatibilities with thermal, chemical and environmental conditions, as exemplified by organic materials used in OLED fabrication.

Additive manufacturing is particularly suited for applications where conventional methods are either physically infeasible or economically impractical, for example when incorporating materials incompatible with standard processes or when only small production volumes are required.

While additive manufacturing expands material choices and reduces constraints on minimum batch sizes, no single technique can process all materials equally well. Instead, the field comprises a range of technologies, each defined by specific capabilities in terms of resolution, material compatibility and process conditions [1]. Inkjet printing, for example, is a well-established method for fabricating interconnects, sensors, actuators and microscale devices [2]. It is particularly effective for depositing nanoscale thin films, such as those used in organic solar cells [3]. However, its inherently low layer thickness limits its suitability for applications requiring highly conductive structures, as multiple deposition cycles are necessary to reach micrometer-scale thicknesses. In addition, the process relies on carefully engineered inks with tightly constrained rheological and interfacial properties

to ensure stable droplet formation and prevent nozzle clogging [4, 5]. These requirements restrict the range of compatible materials and can complicate process optimization.

Screen printing offers an alternative approach that supports higher-viscosity inks and is well suited for depositing nanoparticle-based materials such as silver inks [6]. This enables for example the fabrication of conductive tracks with thicknesses in the range of $5\mu\text{m}$ to $40\mu\text{m}$ [7, 8], making it attractive for applications requiring low-resistance structures. However, this comes at the cost of reduced flexibility and resolution. The need for custom masks limits rapid design iteration, while the achievable lateral resolution is typically restricted to approximately $20\mu\text{m}$ to $100\mu\text{m}$ [9]. These examples highlight a fundamental trade-off: inkjet printing provides high lateral resolution but produces thin layers with limited conductivity, whereas screen printing enables thicker, highly conductive structures at the expense of resolution and design flexibility. Consequently, there is a clear need for a deposition technique that overcomes the trade-off between resolution, layer thickness, and material compatibility that limits current additive manufacturing approaches.

Laser-Induced Forward Transfer (LIFT) represents a promising alternative or complement to existing additive manufacturing techniques. This laser-based process enables the contactless deposition of a wide range of materials onto various substrates. Depending on process conditions, LIFT can achieve vertical resolutions in the order of a few nanometers while also enabling the transfer of micrometer-thick layers [P2, P3]. This favors the usage as a fabrication device for thin film components.

Since its introduction in 1970 by Levene et al. as a laser-driven contactless technique for transfer and recording of material using the donor and acceptor principle [10]

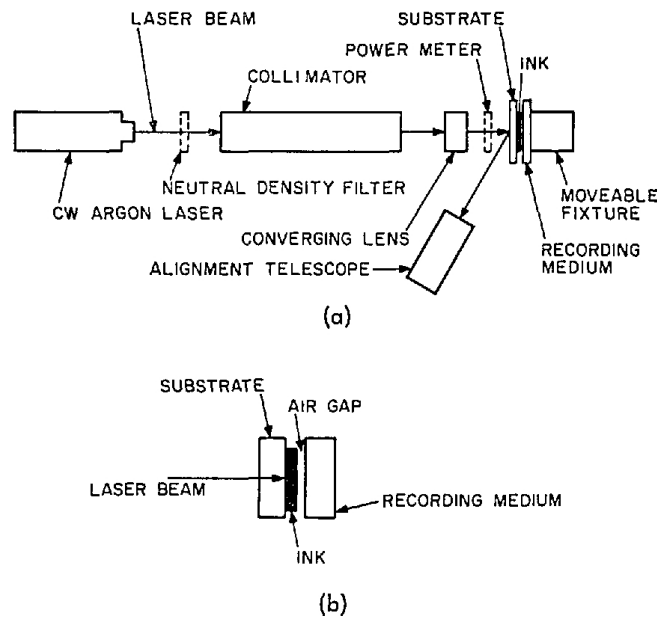


Figure 1.1: Early experimental layout from 1970 showing (a) the experimental apparatus of the LIFT predecessor (b) the recording material arrangement. Reprinted with permission from [10] © Optica Publishing Group

(see fig. 1.1), LIFT has evolved into a diverse set of process variants, differing primarily in laser configuration and material systems. Diode-based laser systems offer flexible adjustment of laser power and exposure time and suit especially well for the printing of material gradients or process adaptations.

A key advantage of LIFT is its broad material compatibility, including small molecules, polymers, nanoparticle inks and more. This versatility enables the integration of materials that are difficult or impossible to process using conventional techniques, potentially allowing new functionalities to be added to existing electronic systems and even fabrication of whole devices.

LIFT does not require fully planar substrates and is also capable of depositing materials onto non-planar substrates up to a certain degree due to its long flight distance [11], thereby allowing more freedom in device architectures and expanding the application side.

Furthermore, it allows the transfer of material systems that are otherwise restricted by processing constraints. For example, organic light-emitting diode (OLED) materials that are incompatible in solution due to mutual solubility can be deposited sequentially using LIFT without such limitations.

Another key advantage of this technology is building on the properties of LIFT such as printing flat structures with different materials and stacking them to enable functionality and fabrication of printed devices. The low material consumption and the lateral size of printed devices provide strong potential for using LIFT as a screening platform. Its maskless and digitally controlled deposition allows the rapid fabrication of large arrays of devices with systematically varied parameters on a single substrate. Combinatorial approaches are enabled in which material composition, layer thickness, concentration gradients or processing conditions are intentionally varied across the sample. A parallel, automated readout could provide fast response to many individual experimental configurations within a short time and with little material consumption.

This technology offers significant potential for the fabrication and high-throughput screening of solar cells, enabling optimization of absorber layer thickness, as well as for OLEDs to refine functional layer combinations and for fuel cells to identify organic alternatives to conventional catalysts.

Despite these advantages and possible applications, LIFT faces challenges in large-scale manufacturing. Some applications have reached commercial maturity, such as the printing of peptide chains [12] or the transfer of solder paste in microelectronics [13], but its serial processing nature enables only limited scaling.

The screening capabilities have not yet been fully utilized at the present time, and broader industrial applications require a deeper understanding of the underlying physical mechanisms. In particular, the general feasibility of printing adaptable components suitable for screening applications has to be established to enable further optimization. Therefore, this work aims to contribute to the understanding of the underlying processes and their applicability by investigating the printing of components.

The verification of component printing is carried out using passive components such as capacitors, as well as active, complex components with intricate chemistry. In this context, two manufacturing approaches are investigated: a hybrid process combining spin coating and LIFT printing, and a fully LIFT-based process. This study compares both approaches to evaluate their suitability for the reproducible fabrication of functional electronic components.

1.2 LIFT in Additive Manufacturing

Since its discovery Laser-Induced Forward Transfer (LIFT) has developed into several subbranches that are defined either by different transfer regimes, by the state of the transferred material or by the type of laser source. LIFT is a transfer method based on the donor and acceptor principle. The controlled and repetitive transfer is referred to as LIFT printing. A receiving substrate is called the *acceptor* and receives material from a donating slide called the *donor*. The donor slide is coated with transfer material (see Section 3.3) which is locally transferred by laser irradiation.

Its place in today's additive manufacturing environment lies between alternative technologies such as inkjet printing, screen printing and jet printing, to name only a few. Each technology has specific advantages and disadvantages. For example, inkjet printing offers high flexibility, low material consumption and the capability to deposit complex geometries without contact [2, 9]. However, challenges remain such as precisely matching ink parameters and ensuring ink substrate compatibility. Other techniques such as screen printing are widely used and offer high simplicity, good scalability and high material purity, which are relevant factors for the fabrication of printed electronics. Nevertheless, they lack resolution, which is in the range of 20 μm to 100 μm [9]. Inkjet printing also remains laterally restricted to the microscale, and printing structures with dimensions below 100 nm in thickness as required in high precision applications still is a significant challenge [2]. Only a few technologies in the field of additive manufacturing are capable of fabricating structures on the nanoscale due to the strict constraints on the printing system. Examples of such technologies include two photon polymerization (Nanoscribe) [14] and electrohydrodynamic jet printing [15]. While these methods offer high resolution, they face high equipment cost, low throughput and complex process conditions, which makes them less suitable for large scale industrial applications [16].

LIFT offers a potential solution or complement to existing additive manufacturing technologies. It enables fabrication of structures with a thickness down to the nanometer range while providing good scalability and low equipment cost. While the lateral resolution ranges from 10 μm to 200 μm depending on the specific setup and application it is applicable to print thin layers that are useful for thin film devices. Several LIFT subvariants have been developed that are specialized for the transfer of a wide range of materials such as solids [17, 18], liquids [P2], living cells [19] and more [20]. LIFT technology is currently in the process of becoming a useful tool across multiple disciplines [21, 22, 23] and also offers a promising platform for high throughput screening [24].

All LIFT variants share the same basic operating principle: A laser is directed onto a donor substrate coated with a transfer material. Parts of this material are then accelerated toward a receiving substrate. Among the most promising extensions of this technology are blister-actuated LIFT (BA-LIFT) and dynamic release layer (DRL) variants, which offer improved control over transfer accuracy [25]. While DRL-based methods improve accuracy, they can also cause unwanted effects when used for sensitive modules due to shockwave propagation [26]. Therefore this method is not suitable for the scope of this work. Additional variants exist and are listed in the review by Chen et al. [26], along with their respective advantages and disadvantages [27].

The improved conservation of sensitive materials make BA-LIFT a strong candidate for industrial scale applications which also benefits from its versatility. This underlines the choice to investigate the possibilities and limitations of this technique in the context of device fabrication. Two electrical components are chosen in this work, one in the micrometer range and one in the nanometer range, to display the capabilities of the LIFT technique. To date neither capacitor nor organic light-emitting diode (OLED) have been fabricated using this method by means of layer-by-layer or dot-by-dot printing. While for the fabrication of OLEDs the BA-LIFT is suited best, a modified version described as direct absorption LIFT [28] that transfers materials without absorption layer is used for the printing of capacitors using liquid pastes.

1.3 LIFT variants Based on Laser Absorption Mechanism

The transfer variants differ in the way the laser beam interacts with the substrate and the materials. This section is focused on the two different specific LIFT variants that are used in this work. They contrast in the way the laser light is absorbed in the donor material and how they are used for the transfer of different material classes. In the first variant, a layer of polyimide tape is used for absorption, while the second variant works without this layer and relies on direct absorption within the ink. The first variant with indirect absorption is known from literature as *BA-LIFT* [29, 30, 31, 20, 25], while the name of the direct absorption variant is not standardized and is therefore referred to in this work as direct absorption LIFT.

1.3.1 BA-LIFT

In BA-LIFT Kapton, registered trade mark of DuPont, a polyimide variant (Kapton®) adhesive tape is used for the absorption of the laser light. While it serves as the driving force behind the transfer, it is also useful in two other aspects. The absorption of the laser is independent of absorption within the transfer material and the layer helps shield sensitive materials from irradiation and temperature [32]. This method is especially favorable for polymers with T_g of 60 °C to 80 °C such as styrene-acrylic copolymer S-LEC PLT 7552 (Sekisui, Japan), registered trade mark of Sekisui, a polymer related to polystyrene (S-LEC®) [33] or small molecule materials, while a clear upper and lower limit for the T_g is not known.

BA-LIFT can be described in three steps, as shown in Figure 1.2. In the first step, the donor and acceptor slides are placed horizontally on top of each other. They are separated by a thin spacer with a typical thickness in the range of 10 µm to 100 µm. Donor and acceptor are both glass substrates, with the donor covered with polyimide tape and applied transfer material. In the second step the laser is turned on with varying laser power and laser duration, typically 10 ms. The laser energy is absorbed in the polyimide layer and converted into heat, resulting in thermal expansion of the polyimide and formation of a bubble that moves toward the acceptor. According to [29] the expansion takes 70 ms, which was observed with high speed cameras. During the expansion of the polyimide the transfer material, in this case polymer based, also heats up and can become viscous. When contact is made with

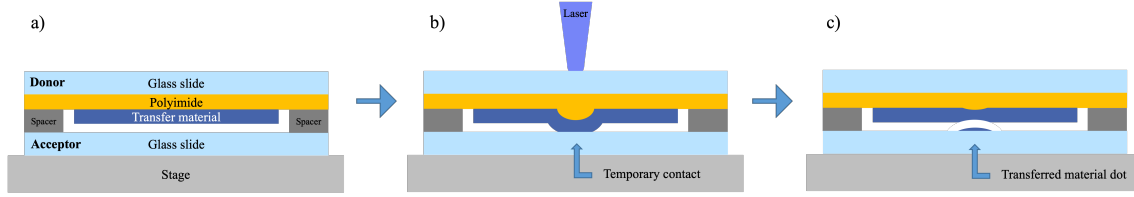


Figure 1.2: (a) Donor and acceptor slide horizontally arranged and separated by a thin spacer. (b) The laser is switched on and contact is formed between donor and acceptor. (c) Material is transferred at the irradiated location and the bubble from the donor retracts. Layer thicknesses not to scale. Source: Lux et al. [P1]

the acceptor substrate, some material adheres to the surface. In the third step the laser is turned off, the polyimide bubble retracts, and a small amount of material remains on the acceptor. By tuning the laser transfer parameters, the amount of transferred material can be controlled with nanometer precision, further described in Section 3.4.

1.3.2 Direct Absorption LIFT

BA-LIFT works mostly independently of the transfer material itself, because the driving mechanism lies within the polyimide layer. For materials that absorb the laser light, they can also be transferred without the use of an additional absorbing layer which is referred to as *direct absorption LIFT*. This approach works well for some liquid nanoparticle inks or pastes, and the laser-material interaction is presumably based on plasmonic effects. The mechanism differs from BA-LIFT and varies depending on the ink properties, such as absorption behavior, viscosity, surface tension, as well as experimental parameters including layer thickness, gap distance, and more. The actual transfer mechanism underlying this process is not known from direct measurements. However, its description can be based on documentation of similar experiments reported in the literature [34].

The transfer is based on the localized heating of the nanoparticle ink, which leads to evaporation of the organic solvent and bubble formation. The bubble expands in the z-direction and comes into contact with the acceptor slide. When the liquid material contacts the acceptor, it adheres to the surface, forming a material dot. Sometimes temporarily stable bridges of material form between the slides. Depending on the laser parameters, bubble formation can occur abruptly, like an explosion, leading to jet formation, or it can be slower and more controlled [20, 34]. The bubble is only temporarily stable and may rupture after a few milliseconds, sometimes after contact with the acceptor or even before contact is made, also depending on the gap between the slides.

There are multiple transfer regimes for liquids in LIFT, which are described in literature [35, 36]. For the printing of nanoparticle dots, the desired regime is referred to as "concrete dot transfer" because it produces symmetric, uniform material dots, useful for the printing of structures. According to literature, this regime occurs when the layer of transfer material is thick relative to the gap distance between donor and acceptor. The goal is to create a bubble that contacts the acceptor slide before it bursts, which avoids splashing and satellite droplets. The size of the dots can be controlled by adjusting the laser parameters. The smallest dot size reported in the literature with this method is 10 μm [37, 20].

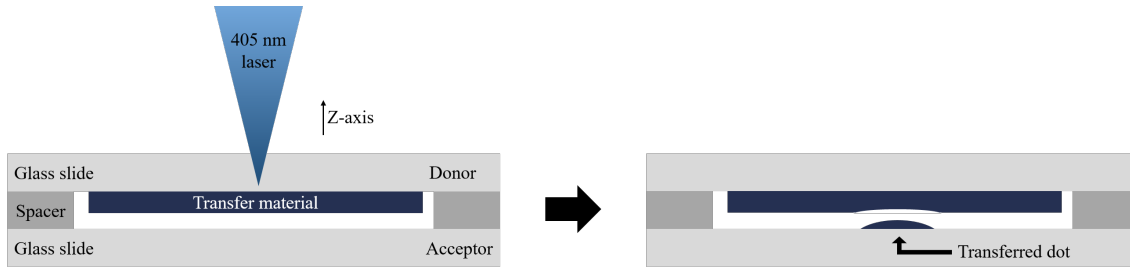


Figure 1.3: Schematic illustration of direct absorption LIFT. Liquid inks or pastes are transferred by direct laser absorption and bubble formation within the transfer material. Source: Lux et al. [P2]

Because many parameters influence the transfer, a systematic prediction of the transfer result based on experimental parameters is possible but requires complex models for each ink variant. Therefore, the approach for controlled transfer of liquids or pastes is to perform test prints with variation of a few parameters and select a suitable set of parameters based on the printing results. This is later referred to as a printing matrix. A schematic of the transfer mechanism and the arrangement of donor and acceptor slides is shown in Figure 1.3. The setup is similar to that of BA-LIFT, but without a polyimide layer between the glass slide and the transfer solution. Due to the sticking behavior of liquid inks or pastes, it is important to use a sufficiently thick spacer between the slides to ensure clean printing results without unwanted material transfer. Further details on the donor preparation with the usage of the spacer is described in Section 3.3. The following Section 1.4 outlines the scope of this work and how the potential of LIFT as a manufacturing technology can be utilized.

1.4 Scope and Key Objectives

The rapid development of additive manufacturing technologies has opened new pathways for the fabrication of electronic systems beyond conventional semiconductor processing. Among these technologies, LIFT has emerged as a promising approach due to its high flexibility, broad material compatibility and comparatively low entry barriers for precise material deposition. However, despite extensive research on the underlying transfer mechanisms, which vary between different LIFT configurations, the applicability of LIFT as a reliable and scalable fabrication method for functional electronic components remains to be thoroughly explored for practical and large-scale applications.

This work focuses on the evaluation of LIFT as an additive manufacturing technology for the fabrication of electrical and electronic components, with particular emphasis on process flexibility, geometrical reproducibility and material compatibility. The scope of the study is limited to the development of the printing process and the deposition of functional materials relevant for electronic applications, including the development and adaptation of conductive and polymer- or small molecule based inks, as well as to the investigation of their transfer behavior under different process conditions. Conventional semiconductor fabrication processes, high-volume industrial production, alternative additive manufacturing techniques or comprehensive comparison of different LIFT variants are beyond the scope of this work.

The primary objective of this study is to assess whether LIFT can bridge the gap

between highly optimized but inflexible semiconductor manufacturing and emerging demands for rapid prototyping, application-specific devices, small-scale production and screening applications. To this end, the following central research task is formulated:

Expand LIFT as a flexible rapid additive manufacturing method and investigate its suitability for the fabrication functional electronic components.

To address this overarching question, the study investigates the influence of process parameters and material properties on transfer stability, geometrical reproducibility and the functional performance of printed structures. The results are evaluated with respect to their suitability for the realization of functional printed electronic components and their potential application domains. This work is embedded in the EU project Nanostacks which utilizes specifically such technologies as a toolbox for finding solutions to fundamental questions in experimental material research.

1.5 Structure of the Thesis

The aim of this work is to explore a variant of LIFT printing as a potential solution to the demand for a rapid and flexible fabrication method for electronic components. The detailed objectives of this work, broken down into subfields and technical approaches to address the upcoming challenges, are presented in Chapter 2. These objectives can be understood as challenges that must be overcome to create a LIFT toolbox, to move from the simplified research question - *Can the following components be LIFT-printed and how?* - to their actual fabrication. This includes assessing whether the printing system meets the required specifications, identifying suitable inks and defining appropriate component dimensions.

The boundary condition of this research is the use of the existing production LIFT printer and the LIFT process developed with it as a starting point. The explanations in Chapter 3 are of fundamental importance for the subsequent chapters, as they describe the setup and its modifications, its capabilities and limitations, which form the basis for the experiments presented later. In addition, the preparation steps preceding the printing process and a brief overview of the basic printer functions are provided, with particular emphasis on the printing of fundamental structures.

For readers interested in reproducing the presented results, Chapter 4 provides a detailed description of all conducted experiments. This includes the design and fabrication of specialized substrates, the preparation of customized inks and a comprehensive documentation of all relevant material and process parameters. In addition, fabrication recipes for capacitors and OLEDs are presented which represent the main demonstrators of component fabrication within this work.

Chapter 5 focuses on the results of this work. Among the key outcomes, different printing modes are described in detail, including methods to achieve precise surface printing. This is especially important for the fabrication of OLEDs which rely on well-defined thin layers that do not mix at the interfaces between. Another highlight is the fabrication of printed capacitors, which are characterized optically, structurally and electrically. The development of suitable nanoparticle inks, which was enabled by the LIFT test device developed within the scope of this work, also plays a crucial role in these results.

Finally, Chapter 6 presents the conclusions drawn from the findings of this thesis and provides a summary. It presents the key findings of the printing process development, the result of the capacitor printing with liquid nanoparticle ink and the main outcome of the OLED printing which resulted in several OLED variants using LIFT technology.

In addition, possible applications of the fabrication of components are discussed and potential topics for future work are outlined in Chapter 7.

2. Objectives and Technical Approach

LIFT is a highly promising approach for the optimization of processes, manufacturing efficiency and the reduction of complexity. To demonstrate the feasibility of this printing technique for the fabrication of electrical components and to explore the limitations of the method, two representative components are investigated in this work. One component is fabricated in the microscale with $> 1\text{ }\mu\text{m}$ in thickness, while the other is fabricated in the nanoscale with a thickness $< 100\text{ nm}$. The printing of nanometric structures requires high precision and a high degree of process control with a low material deposition rate, while printing of micrometer-scale objects requires a higher deposition rate to achieve micrometer thick material layers. These fundamentally different requirements of the process cannot be met solely by one printing process, e.g. μm structures cannot be produced by repeated stacking of nanolayers because of process time and limited shelf life of inks. This requires the use of different inks together with an adaptation of the transfer process for optimum results. Only a limited number of machines and fabrication methods are capable of covering such a wide range of feature sizes without compromising fabrication speed or precision.

The successful fabrication of electrical components using this system is based on three main pillars, the equipment development, ink development and process development. The overarching objective of demonstrating the capability of LIFT printing for fabrication of functional electrical components is broken down into smaller tasks and technical approaches which are strongly interdependent. The flow chart in Figure 2.1 illustrates the relationship between the individual subtasks and the overall workflow of this study.

To achieve a high precision in combination with a sufficient printing speed requires careful printer and ink design but also a precise control over all aspects of the transfer process. The printer is adapted and developed to match the application specifications. New inks are developed and optimized for the printer and the desired applications. Further it is necessary to fabricate and test customized substrates for the printed components. For the printing of components new printing modes

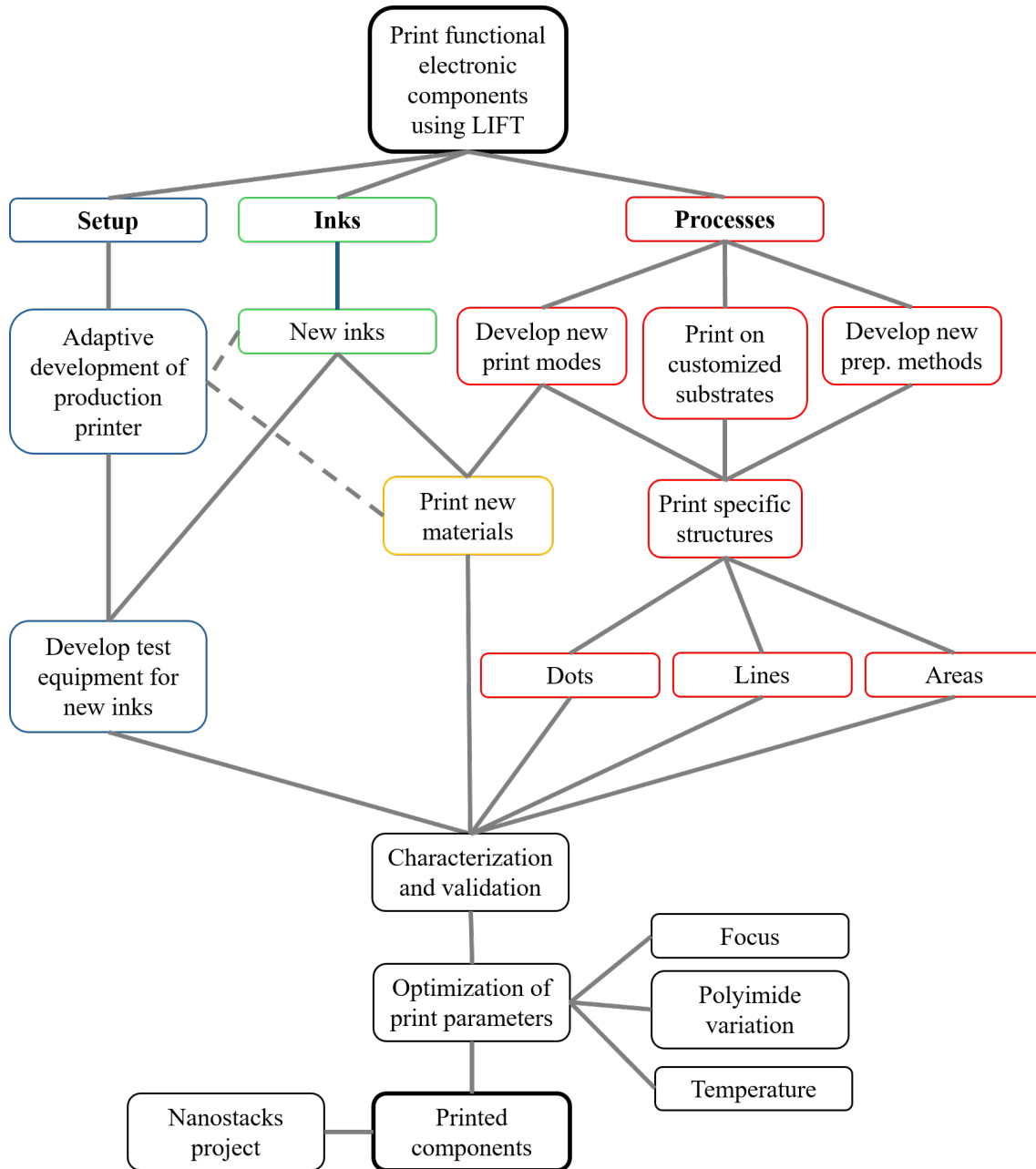


Figure 2.1: Flow chart illustrating the connections between the individual elements of this work, outlining the roadmap from the initial idea of printing functional electrical components to the successful fabrication of functional devices.

in coordination with new inks are developed to allow precise area printing. Every aspect of the printing system needs to be evaluated and considered including preparations methods, thermal conditions, laser alignment, donor-acceptor arrangement, feature morphology and reproducibility for precise and reliable printing of functional components. Together, these factors define the technical challenges that must be addressed to ensure stable and reliable LIFT printing across a broad range of feature sizes.

This work is embedded in the Nanostacks EU project. The objective of Nanostacks is to advance material research for novel fuel cell designs. This work contributes a printing process to manufacture nanometric components at a high density for the application of an efficient screening method for the identification of suitable or optimal functional material combinations. This is layed out in detail in Section 2.5.

2.1 Printer Development

The used printing system was originally developed based on the work of Stadler, Felgenhauer, Beyer, Fernandez, et al. [33] for the transfer of amino acids embedded in polymers as carrier materials. It was subsequently advanced by Loeffler, Foertsch, Popov, Mattes, et al. [30] for the transfer of thin material dots using the polymer material S-LEC[®]. Starting from the use of S-LEC[®] for dot transfer, as also applied by Stadler and Löffler, the printer is now further developed into a system capable of transferring structured features, including lines and surfaces, for the fabrication of functional electronic components.

To meet the specific requirements of electronic component fabrication and qualification of simple components such as capacitors and more complex devices such as OLEDs and to ensure compatibility with the materials used in this work, several modifications to the LIFT setup are required. These modifications are described in detail in Section 3.2.

In addition to this LIFT production printer a LIFT test printer was developed, a compact and portable version intended for rapid and easy on-site ink qualification by the developer compatible to the operating conditions of the more complex production LIFT printer. Since the use cases of these two printer variants differ they have distinct requirements which are described in the following sections.

2.1.1 Requirements on the Production System Printer

The fabrication of electronic components by additive manufacturing requires the precise positioning of different functional materials on a substrate in a well-defined geometry, thickness and stacking sequence. Functional devices are formed by arrangement of individual printed pixels into coherent structures. Depending on the ink chemistry and the printing process, adjacent pixels merge to form continuous layers or patterned geometries. Consequently, the requirements imposed on the printing system are directly derived from the requirements of the targeted, structures, components and the ink properties.

Geometric Precision and Lateral Accuracy

The precision of the printing system is a key requirement for the fabrication of functional electronic components. In this work, devices with lateral surface area in

the range of 0.01 mm^2 to 1 mm^2 are targeted. To achieve such geometries, a maximum pixel diameter of approximately $50\text{ }\mu\text{m}$ is required. The final device geometry is defined by the pixel size and by the degree of overlap between neighboring pixels. High lateral positioning accuracy is therefore essential. This accuracy is primarily determined by the laser scan head that positions the laser beam on the donor and by the reproducibility of the fixation of the acceptor substrate on the printer table. The latter is particularly relevant because substrates are repeatedly removed from the printer for inspection between printing steps and subsequently repositioned. Measurements show that the positioning accuracy of the laser scan head is negligible compared to the fixation tolerances of the substrate holder. The reproducibility of the fixation was determined to be $\pm 5\text{ }\mu\text{m}$, which is sufficient for the applications investigated in this work. The resulting lateral variance is considered in the three-dimensional design of the OLED layouts as described in Section 4.7.2.

The standard substrate format used in this work is a microscope glass slide with dimensions of $26\text{ mm} \times 76\text{ mm}$ which allows the fabrication of up to approximately 1000 individual millimeter-sized components including spacing. It is compatible with fluorescence scanners commonly used in biological research which enables highly sensitive quantification of nanometrically printed material dots.

Pixel-Based Component Printing

The geometrical structures for electronic components are fabricated by printing multiple adjacent pixels to form continuous lines and areas.

For capacitors, pasteable inks need to be used that inherently flow and merge, enabling the formation of continuous layers even with reduced pixel overlap. Different printing strategies are necessary because the requirement for the layer thickness, surface quality and thereby the ink preference is different for each application.

In the case of OLED fabrication, a printing strategy with significant pixel overlap is necessary to achieve homogeneous thin films. The pixel density to achieve the optimum results needs to be determined by printing tests.

The choice of component size represents a compromise between maximizing device density on a substrate and maintaining compatibility with standard laboratory characterization tools. A device area of approximately 1 mm^2 was identified as a suitable choice.

Depending on the printing mode, one OLED is fabricated from 100 to 15,000 individual material dots. Failures such as missing dots, height variations or roughness can lead to a malfunction of the whole device. Consequently, the failure probability per dot must be below approximately 0.1% in order to achieve a high yield of defect-free devices.

Printing Speed and Throughput

In addition to precision, printing speed is a critical requirement for efficient laboratory work and to avoid drying and ink degradation. The printing of a single substrate containing multiple devices should not exceed a few hours. Assuming that one device layer consists of approximately 15,000 dots and that 20 devices are printed per substrate, a total of approximately 300,000 dots must be transferred per layer. To achieve a minimum throughput of one device layer per hour, an average printing

time of approximately 10 ms per dot is required. This imposes strict requirements on the positioning system of the printer. Mechanical translation stages are limited by acceleration and settling times and are therefore unsuitable for this task. In contrast, the use of a laser scan head enables rapid repositioning of the laser beam and fulfills the throughput requirements.

Layer Stacking, Thickness Control and Surface Quality

OLED fabrication requires the successive printing of multiple functional layers, such as hole transport layer (HTL), emissive layer (EML) and electron transport layer (ETL). The successful operation of an OLED depends on the compatibility of stacked layer materials, precise thickness control and high layer uniformity. The typical OLED layer thickness ranges from 5 nm to 100 nm. Consequently, the printing system must be capable of transferring material with nanometer-scale thickness control, down to at least 1 nm.

In addition to thickness control, surface quality plays a crucial role in OLED fabrication. Layer roughness must be kept extremely low, ideally in the range of a few nanometers, to avoid electrical shorts, leakage currents or non-uniform emission. The printing system must therefore enable highly uniform material deposition with minimal surface roughness.

Capacitors impose different requirements. They are typically fabricated from inorganic materials and nanoparticle-based inks. To achieve high breakdown voltages, a minimum layer thickness is required and uniformity for the dielectric layer. Based on commercial ceramic capacitors a target thickness range of 0.5 μm to 5 μm was defined. This thickness range is almost an order of magnitude larger than the requirement for OLED layers. The design of the printing system must allow both, operation in the nano- and microscale regime.

If the thickness achieved in a single printing step is insufficient, multiple printing cycles can be used to build up the desired height. While this approach is useful to achieve for example 60 nm with an ink that only prints at a maximum height of 15 nm for each cycle it gets impractical with that ink if a height of a micrometer is desired. High number of repetitions increase the process time and can lead to degradation of ink. For requirements of thicknesses of several micrometers an ink specifically designed for such high thickness levels needs to be used. For the application of a printed capacitor multiple printing could reduce the risk of pinholes and defects. The printing system must therefore balance high vertical resolution at the nanometer scale with the ability to efficiently fabricate micrometer-thick structures.

Material Compatibility and Environmental Control

The printing system must support a wide range of materials, including organic OLED materials and inorganic nanoparticle inks. These materials exhibit different rheological properties and sensitivities. OLED materials are often sensitive to oxygen and humidity, while nanoparticle inks show temperature-dependent viscosity and solvent evaporation behavior. Therefore a humidity and oxygen protected printing environment is needed to allow the deposition of sensitive materials.

Stacked OLED layers are particularly sensitive to contamination. Dust particles can create defects, leading to device failure. Therefore, the printing process requires a controlled environment with minimized exposure to dust, oxygen and moisture.

To meet these requirements, the printer should operate in a closed and controlled environment. Atmospheric conditions need to be regulated, for example through gas flow systems or glovebox integration. Temperature control should be achievable either by stabilizing the laboratory environment or by integrating heating and cooling modules directly into the printer. A temperature-controlled transfer stage is desirable to provide greater flexibility than laboratory-wide temperature control. Dust exposure should be minimized by housing the setup and implementing appropriate air filtering measures.

2.1.2 Requirements on the Test Printer

The primary goal of the test printer is to enable rapid development of inks tailored to the LIFT production printer, allowing the fabrication of small electrical components without being limited to commercially available inks. The LIFT production printer requires inks with specific properties for precise dot deposition, so off-the-shelf inks are not broadly suitable. For the fabrication of customized inks, the exact required ink parameters would be needed, but these are unknown, making it difficult for developers to manufacture appropriate inks. Modification of existing, functioning ink formulations is not feasible, as their recipes are proprietary, and deep characterization is time-consuming, complex, and costly. Trial-and-error approaches to ink design without precise knowledge of process parameters are logistically inefficient. To address this, a test printer was developed as a platform for decentralized, rapid ink development for the LIFT production system. It provides a simplified, on-site LIFT testing capability for ink developers, enabling evaluation of novel inks before deployment to the production printer and thereby significantly reducing development cycle time. The requirements for the test printer differ from those of the production printer due to its intended purpose: while it must ensure functional reliability, compromises in printing speed and precision are acceptable. Assembly instructions for the test printer are provided in Section 4.2.3, while printing results are shown in Section 5.2.

Functional Requirements

The test printer must provide a reliable LIFT process that closely replicates the transfer behavior of the production printer. Therefore a nearly similar laser power density is required at a matching wavelength of 405 nm. To achieve a comparable power density the laser spot size in combination with the laser power has to be evaluated to replicate the laser source of the production printer with a power range of up to 300 mW.

To receive multiple dot transfers without moving the donor and acceptor, either a beam deflecting mechanism (as in the production printer) or a sample positioning system is necessary. While a mechanized stage may reduce printing speed compared to a deflecting mechanism, it allows systematic screening of laser transfer parameters while reducing the complexity and price of the test setup.

Mechanical Requirements

For the printing of a screening matrix using a mechanical sample positioning system the accuracy must match the printing resolution. Single dot transfers are expected to be around 100 μm , requiring positioning tolerances of a few micrometers. Stepper

motors can provide both the required accuracy and sufficient movement range to cover multi-dot patterns spanning a few centimeters.

Additionally, z-axis control of the laser diode for adjustment of the focal plane can also be implemented using a stepper motor.

Control and Electronics

The test device should operate independently of lab PCs, requiring centralized control. Microcontrollers are suitable for the management of the interaction between the mechanics and the laser source, as well as for running pre-programmed printing recipes.

The target users of the device are ink developers, who primarily focus on recipe optimization and ink chemistry. This requires a reliable and easy-to-operate system that provides direct feedback on the tested ink without requiring interaction at the programming level. Consequently, control can be simplified to a single switch or button to run the test program. For improved usability, an interface or indicator displaying the device status is also necessary.

Portability and Cost

The test printer was designed to match production printer specifications at the production site. High portability is important for the transfer to the ink manufacturers site. The device should be compact, lightweight and space-efficient. While cost is not critical, a simpler, lower-cost design that still meets all requirements increases accessibility and makes future modifications easier.

2.2 Ink Development

The underlying LIFT process of the production printer defines the fundamental requirements for printable inks. To extend the capabilities of the LIFT production printer toward new applications, new inks compatible with the system that operate reliably within these constraints need to be developed.

The printer was originally built and configured for the transfer of polymer inks containing S-LEC[®] with amino acids. In this work, its application is extended toward the processing of previously untested materials such as small molecule or nanoparticle inks. A central objective is therefore the evaluation of the compatibility of the printing system with novel ink formulations and the identification of any necessary adaptations to the printer.

This work aims to enable the transfer of both, organic material based inks and nanoparticle based inks, which is a requirement for the fabrication of functional electrical components. The ink development strategy differs between these two ink classes. Organic material based inks typically consist of a small number of components, whereas nanoparticle based inks involve multiple constituents, which significantly increases formulation complexity. This is necessary because the inks are transferred in the liquid state and therefore their rheology needs to be optimized. This differs from organic material inks which are transferred in a dried form.

The objective is to identify suitable compositions for both ink types that allow stable and reproducible transfer. For the nanoparticle inks, this increased complexity motivated the design of a dedicated LIFT test printer which was installed at the ink manufacturer's site.

2.2.1 Requirements for LIFT Printable Inks

A central objective of the ink development is the identification of material and formulation requirements that enable reliable material transfer in the employed LIFT setup. The transfer mechanism is based on a short and localized contact between donor and acceptor which requires sufficient adhesion of the transferred material upon contact. Consequently, inks must exhibit adhesive behavior either through thermal activation or through intrinsic wet adhesion.

Two principal ink classes are considered within this work: organic material based inks and nanoparticle based inks. Organic material based inks rely on a temporary decrease in viscosity during laser induced heating, which enables adhesion to the acceptor at contact. Nanoparticle based inks, in contrast, are transferred in a liquid state and adhere immediately upon contact with the substrate.

For organic material based inks, the objective is to formulate inks that can be applied to the donor substrate as thin films by coating techniques such as spin coating or doctor blading. This requires that the materials are either soluble in suitable solvents or can be dispersed in a stable manner. Both non-polar organic solvents, such as dichloromethane (DCM), chloroform or toluene and polar solvents, such as water or dimethyl sulfoxide (DMSO), are considered depending on material compatibility. A further requirement is that the material exhibits a melting temperature or glass transition temperature above ambient conditions and below the decomposition temperature of the polymer itself or the polyimide donor layer. Materials that tend to crystallize are considered less suitable due to the resulting inhomogeneous and poorly controllable transfer behavior.

Nanoparticle based inks are formulated as dispersions of nanoparticles in a solvent. For these inks, viscosity is a key governing parameter for successful transfer. The target viscosity range is defined between 3000 mPa s and 100 000 mPa s. Below this range, uncontrolled splashing and satellite formation are expected, whereas above this range, transfer is suppressed due to excessive cohesion within the ink.

Depending on the employed transfer configuration, two absorption mechanisms are considered. When a polyimide absorption layer is used, laser energy is primarily absorbed in the polyimide and the optical properties of the ink are of secondary importance. In configurations without an absorption layer, the ink itself must absorb the 405 nm laser radiation. Metallic nanoparticle inks are considered particularly suitable in this context due to plasmonic absorption effects [38].

The solvent selection represents another key factor in ink formulation. The solvent must ensure a stable nanoparticle dispersion while remaining compatible with both, the donor and acceptor substrates, as well as with the polyimide donor film [39]. Adequate wetting of the polyimide surface is required, which implies that the surface tension of the ink should be comparable to or lower than that of polyimide. As a consequence, purely water based inks are generally unsuitable unless surface active additives are employed to adjust the surface energy.

The drying behavior of the ink is considered at two stages of the process chain. Prior to transfer, inks are required to exhibit sufficient shelf life and process stability. A minimum shelf life of two to three weeks is targeted to meet logistical constraints. After deposition on the donor, the ink film should remain stable for at least 30 min to allow reproducible processing. This requirement favors solvents with high boiling points and low vapor pressure at room temperature.

After transfer, the objective is to obtain round and homogeneous printed features.

The suppression of inhomogeneous material redistribution, such as the coffee ring effect [40], is therefore a key requirement. This can be addressed by appropriate solvent selection or by the use of solvent mixtures with different vapor pressures or the addition of surfactants to induce compensating Marangoni flows [41, 42].

Finally, nanoparticle selection is guided by downstream processing requirements. Inks intended for conductive structures may require post processing by sintering. By selecting nanoparticles with suitable size and composition, melting point depression can be exploited to achieve reduced sintering temperatures, enabling compatibility with temperature sensitive substrates and additional manufacturing steps.

2.2.2 Ink Characterization and Qualification Objectives

A systematic characterization procedure is required, for the inks, whether commercially sourced or developed in-house and validated before use with the LIFT test printer. The qualification strategy focuses on experimental evaluation of printed structures rather than relying solely on analytical modeling or simulation of the transfer process with unknown parameters like substrate interaction. This approach allows a direct distinction between unsuitable and suitable ink formulations and also involves the usage of the developed test printer.

Since the targeted applications include electronic components such as capacitors and OLEDs, electrical properties are the primary qualification criteria. Conductive inks intended for electrodes or interconnects are evaluated based on their electrical conductivity, whereas dielectric and insulating inks are assessed based on their resistivity.

In order to measure the conductivity, standardized test structures are printed, in which a defined material line bridges conductive contact pads separated by a fixed distance. Insulating behavior is evaluated using structures with minimal gaps filled with printed insulating material to yield a measurable resistance. One suitable geometry consists of crossing conductive lines separated by a single printed insulating dot.

In addition to electrical characterization, printability itself is assessed by systematic variation of printing parameters. The primary parameters considered are laser power and exposure time. A parameter matrix consisting of single transfer dots arranged in rows and columns is printed, with each dot representing a distinct parameter combination. Optical microscopy is used to rapidly assess transfer quality, adherence to geometric dimensions and process stability. This procedure enables the efficient identification of suitable parameter windows and ink formulations for component printing.

2.3 Component Fabrication

In this section the versatility of LIFT printing is used and its potential as a manufacturing method is assessed for micro- and nanoscale devices. For this purpose, two representative components are fabricated using LIFT.

A capacitor is realized as an example of a microscale device, requiring the controlled deposition of conductive and insulating nanoparticle based materials. In addition, an organic light emitting diode is fabricated as a nano scale device composed of multiple organic layers with a thickness in the nanometer range. Together, these components are intended to demonstrate the capability of LIFT printing to process

different material classes and to realize functional devices across multiple dimensional ranges.

Following the successful transfer of simple structures such as dots, lines and surfaces, the fabrication of more complex structures, including stacked layers and printing on application specific substrates, is targeted. Component fabrication therefore represents a central objective of this work and is only possible with a robust and reproducible transfer process for both liquid nanoparticle inks and organic material based inks.

2.3.1 Printing of Capacitors

Capacitors are essential components in almost every electronic application. In certain use cases it is advantageous to tailor the capacitance to specific requirements, for example in resonant circuits. In addition, the use of standard surface-mounted device components or larger discrete capacitors may be limited by size constraints or experimental boundary conditions.

Printed capacitors offer a potential solution to these challenges as their capacitance can be adjusted through geometry by varying the printed area or layer thickness. Furthermore, printed capacitors can be realized with overall thicknesses of only a few micrometers, enabling integration in applications where conventional capacitors are unsuitable due to their form factor.

The objective of this work is therefore to explore the limits of LIFT printing for the fabrication of flat capacitors with adjustable capacitance and to evaluate the feasibility of producing such components using nanoparticle based inks.

2.3.2 OLED Printing and Readout

Organic light emitting diodes are widely used as light sources and in display technologies. They are thin film devices that require the deposition of multiple organic layers with nanometer scale thickness control. Conventionally, OLEDs are fabricated by thermal evaporation of organic materials in combination with shadow masks. While this approach allows large scale production, it is susceptible to defects arising from mask alignment and multilayer deposition. In high resolution displays containing millions of individual OLEDs, even small defect rates can result in significant yield losses and increased manufacturing costs.

An alternative fabrication method is based on coating techniques such as spin coating or blade coating. However, these methods require orthogonal processing, meaning that successive layers must be deposited from mutually incompatible solvents to avoid dissolution of previously deposited layers. This constraint significantly limits material selection and process flexibility.

A printing based fabrication approach avoids such limitations and allows more flexibility in material choice. The objective of this work is to demonstrate that OLEDs can be fabricated using LIFT printing without relying on orthogonal solvent systems or masking technologies. Successful realization of printed OLEDs would establish a basis for further investigations into the LIFT based fabrication of additional thin film devices, such as solar cells or the printing of cheap fuel cell variants.

2.4 Process Control

To enable the use of the LIFT production printer for the fabrication of electronic components, the transfer process must be investigated in greater detail based on

the existing knowledge described in Chapter 3. A systematic analysis of process-relevant parameters is required in order to identify, understand and control the factors influencing transfer quality, resolution and reproducibility.

Printing on Structured Substrates

A central objective of this work is the enhancement of print resolution and feature definition. To achieve a higher printing resolution a smaller laser spot would be required [22] which can be accomplished with additional optics. Since the LIFT production printer is a shared experimental platform used by multiple researchers, only moderate hardware modifications to the hardware may be implemented. A new strategy for the improvement of the printing resolution without a stronger intervention in the laser setup is by printing on customized non-flat substrates. This reduces the printed spot size by reduction of the contact area of donor and acceptor. Systematic experiments on these structured acceptor surfaces are conducted to quantitatively evaluate the influence of the substrate geometry on feature morphology and the achievable resolution.

Temperature Controlled Printing

In addition to surface structuring, thermal process control could be an important factor influencing transfer behavior. Variations in temperature during the LIFT process can affect material viscosity and expansion dynamics, which in turn impact the transfer, feature morphology and reproducibility. To achieve stable and consistent experimental results, precise control of the transfer stage temperature is therefore required.

Stage Control

To further improve process stability and reproducibility, precise control of the sample position in relation to the focal plane is required. Reliable adjustment of the donor-acceptor height relative to the laser focus is crucial, as small deviations significantly affect transfer quality and reproducibility. A precisely automated z-stage is therefore required to allow accurate and repeatable positioning of the system, particularly when processing large-area substrates or materials with narrow process windows, ensuring consistent transfer conditions across experiments.

Polyimide Investigation

Another important aspect of process control addressed in this work is the modification of the donor surface, with a particular focus on polyimide, commonly referred to as Kapton®. Polyimide serves as the laser-absorbing layer in the LIFT process, converting incident laser energy into thermal energy and inducing a rapid vertical expansion that drives the material transfer. As a result, the material properties of the polyimide have a decisive influence on the transfer dynamics.

Several research questions are investigated in this context. The influence of the adhesive layer used in commercial polyimide tapes is examined to determine whether it contributes to or interferes with the transfer process and whether LIFT can be performed without adhesives using spin-coated polyimide films. Furthermore, the

impact of the polyimide is analyzed to assess potential variations in material properties and to identify alternative sources with improved absorption or transfer characteristics.

Polyimide thickness is evaluated as a critical parameter for successful transfer. Lower and upper thickness limits are investigated and an optimal thickness range is identified based on transfer reliability, spot diameter and spot height. In addition, the optical absorption behavior of different Kapton® variants is analyzed to establish correlations between material properties and transfer outcomes. Finally, the influence of polyimide modifications on spot morphology is systematically studied to determine whether specific configurations enable the formation of smaller or higher transfer features, thereby improving the precision and applicability of the LIFT process.

2.5 Interrelation to the Nanostacks Project

The Nanostacks project aims at the fabrication of electronic components using LIFT in order to enable breakthroughs in experimental materials research. The central concept is the printing of a Twin Nanostack which consists of two nanomaterial stacks in close proximity that can be electrically connected and operate as a single functional unit. Due to their small separation, low loss interconnections are expected. This concept is illustrated in Figure 2.2.

One nanostack acts as a signal emitting component that can be detected by an external measurement system. The second stack is modular and can serve as a current or voltage generating device, such as a solar cell or a fuel cell. By electrically coupling both stacks, the properties of one component can be characterized through the signal generated by the other.

The readout can be realized using an imaging based screening approach. A fluorescence scanner is well suited for this purpose, as it can provide excitation light at a defined wavelength to activate a solar cell and simultaneously detect emission from a light emitting component at a different wavelength. This enables the parallel characterization of all printed Twin Nanostacks on a microscope slide within a short measurement time.

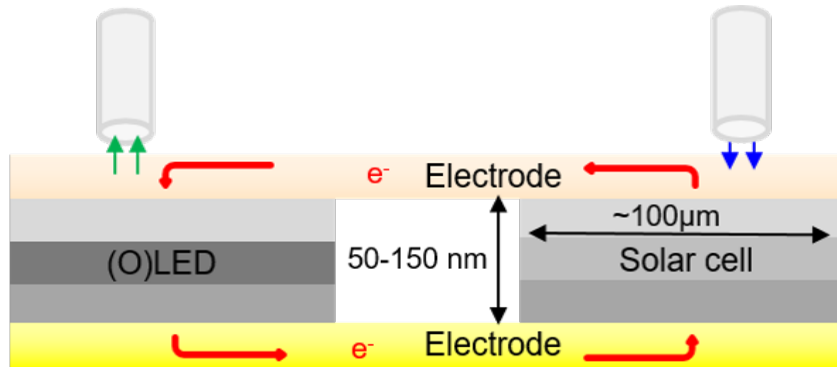


Figure 2.2: Schematic illustration of a Twin Nanostack with stimulation and optical readout. Since each nanostack is a stand-alone pair of supply and device-under-test, a minimum overhead for wiring is needed on the substrate. Source and copyright: Breitling [43], published with permission

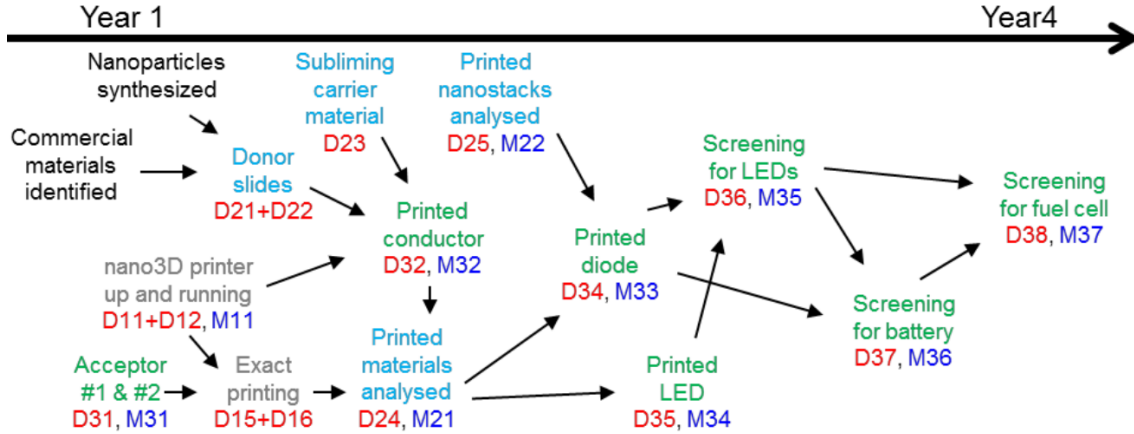


Figure 2.3: Interconnected work packages arranged over a four year timescale. The assignment to the individual work packages is color coded. Source and copy-right: Breitling [43], published with permission

With lateral dimensions of a few hundred micrometers, approximately 20.000 Twin Nanostacks can be printed on a single slide. Each stack can be fabricated individually with defined material combinations and layer thicknesses. This allows a large parameter space to be explored in a single experiment, which would be impractical using sequential fabrication and measurement approaches.

A combination of a solar cell and an OLED represents one possible implementation of the Twin Nanostack concept. However, the approach is not limited to this device pair. Other energy conversion devices, such as fuel cells, can also be considered. In this context, bio inspired concepts are of particular interest. Natural enzymes, such as hydrogenases, utilize redox gradients to guide electrons and protons toward a catalytic iron center while suppressing unwanted side reactions [44].

LIFT printing offers the possibility to fabricate artificial vertical nanometric gradients by multimaterial printing of ultrathin layers. Such structures could form defined pathways for charge carriers toward a catalytic center while blocking contaminants. Since the optimal device architectures and material combinations are not yet known, they must be identified through systematic variation and screening, which is enabled by the parallelized nature of the LIFT printing approach.

The Nanostacks project is organized into work packages, deliverables (D#) and milestones (M#), as shown in Figure 2.3. In the early stages, the LIFT printing process is systematically investigated and extended to new material classes suitable for electronic components. Subsequent work focuses on the printing of conductive and functional layers, progressing from simple interconnects toward complete devices such as diodes and OLEDs.

This work is embedded in the Nanostacks project and focuses on the component level, particularly on the printing of OLEDs, corresponding to Deliverable D35. This required the integration of new materials into the printing system and the development of controlled transfer processes. Printable conductors were realized using nanoparticle based pastes (D32), while printable insulators enabled the fabrication of capacitive structures (D33). Although not originally part of the project plan, these components represent useful building blocks for future device integration. The printing of diodes (D34) was accomplished through the successful fabrication of a functional OLED and the demonstration of its diode behavior.

The foundation for these developments is a fully functional LIFT printing system (D11 and D12), including all required modifications and process adaptations. The characterization of printed nanostacks is performed through detailed analysis of the transferred spots, corresponding to deliverable D25.

This work is essential for the success of the project by delivering the major milestones and elements such as the printing of devices. The printed OLED structures that were achieved provide a strong technological foundation for future projects focusing on the printing and screening of solar cells and fuel cells, with the long term goal of enabling scalable and efficient energy conversion.

3. Transfer Technology

In this chapter, the printing setup referred to as the production LIFT printer is described. Furthermore, the modifications to the setup required for improved process control and device fabrication are presented together with the corresponding preparation methods. Finally, the basic operating principle of the setup is demonstrated through the implementation of basic printing experiments.

3.1 The Printing Setup

For the protection of the operator, the printing setup is placed inside a laser tight enclosure whose doors are connected to an interlock mechanism (see Figure 3.1 (8)). The whole system is placed underneath a HEPA filter unit (6), which creates a slight overpressure of filtered air. This allows operation in a low dust environment in order to achieve reliable transfer results. The entire setup is operated from outside using a laboratory PC (9). A custom built interface allows control of the pneumatic systems, the robot, the laser, and the scan head.

The LIFT unit is located on the right side of the setup, while the left side is used for the pick and place robot arm (Fanuc 1 SR6IA-30P-C-CENR) (3), which automatically exchanges donor and acceptor slides. The slides can be picked up from the slide storage by using suction cups located at the back of the system (2).

A more detailed image of the LIFT unit is shown in Figure 3.2. The material transfer is based on the energy input of a 300 mW diode laser (8) with a wavelength of 405 nm (iBeam smart 405-S, TOPTICA Photonics AG, Munich, Germany). The laser beam is guided by mirrors (7) into the laser scan head (4) (intelliSCAN III 10, SCANLAB GmbH, Puchheim, Germany), which directs the laser beam by means of two movable mirrors onto the transfer stage. The scan head, in combination with the F-Theta lens (3) (JENar 170-355-140, JENOPTIK Optical Systems GmbH, Jena, Germany), allows the laser spot to be positioned at any location within a 6 cm × 6 cm square within microseconds (see Figure 3.2).

The transfer stage is a custom built table made of milled aluminum that holds the samples during transfer. A rectangular indentation (2) is used to fix the position of the transfer slides by pushing them into one corner using pneumatic stamps (5).

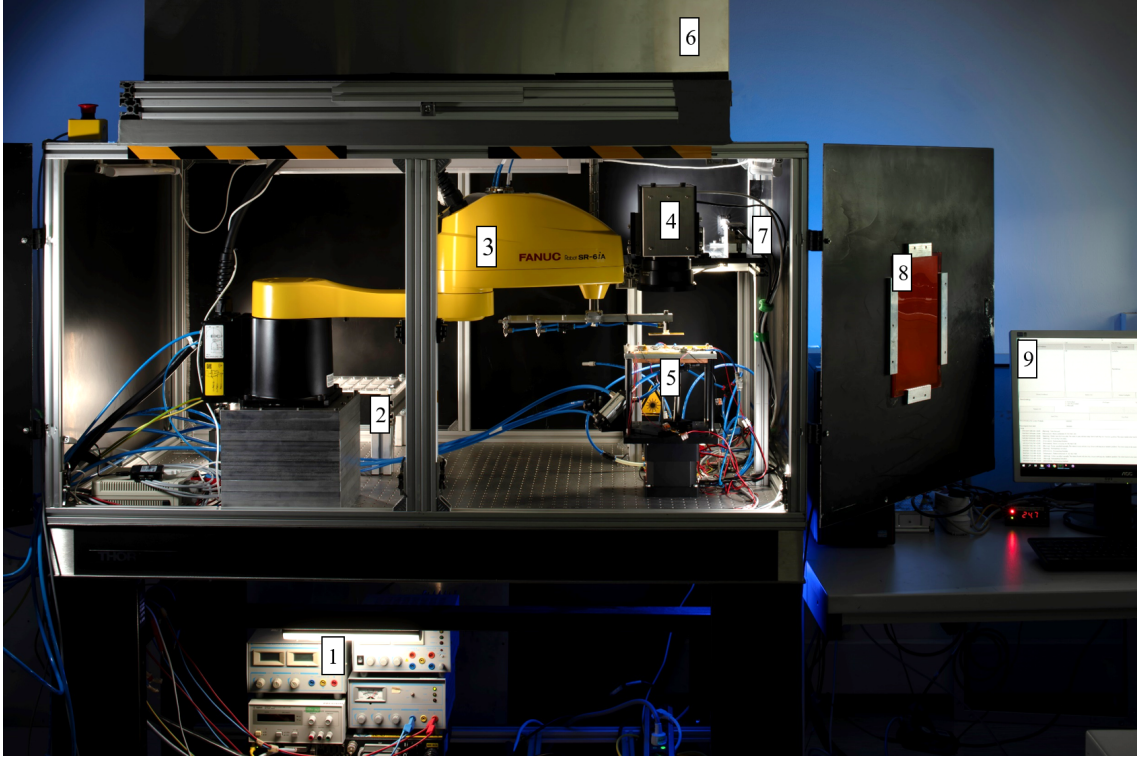


Figure 3.1: The LIFT printer setup. 1: Power supply 2: Slide storage 3: Pick-and-Place robot 4: Laser scanhead 5: Transfer stage 6: high-efficiency particulate air (HEPA) filter 7: Laser source 8: Laser-protected observation window 9: Control PC. Zoomed in image in Figure 3.2. For scale, the box is approximately 2 m wide. Source: Photograph by Markus Breig, published with permission

The slides for transfer are positioned horizontally on top of each other in close contact. This method has proven to be successful for repeatable and reliable positioning within a tolerance of $5\text{ }\mu\text{m}$. A vacuum suction system is implemented in the table to hold the bottom slide in position. Optional cameras positioned underneath the table can be used to control the slide position by observing the slide edges through observation holes in the table.

The table can be temperature controlled by the temperature control unit (1) (Figure 3.2) within a range of 0°C to 60°C . Electrical heating foils attached to the table and vortex tubes generating a cold air stream are used for this purpose. This system is described in more detail in Section 4.3.2. The transfer stage can be height adjusted using an automated z-stage (6) (Thorlabs Kinesis[®] Precision, Motorized Vertical Translation Stage KVS30).

3.2 Modification of the Printing Equipment

The printing setup was originally built for the transfer of amino acid building blocks in polymer material. For the fabrication of capacitors the usage of liquid nanoparticle inks is necessary which places different requirements on the printing system such as the implementation of spacers and temperature control. For the fabrication of OLEDs modifications to the setup were necessary to increase the repeatability of the experiments. These new goals created the demand for modifications which were implemented during the preparation of this work and are described below.

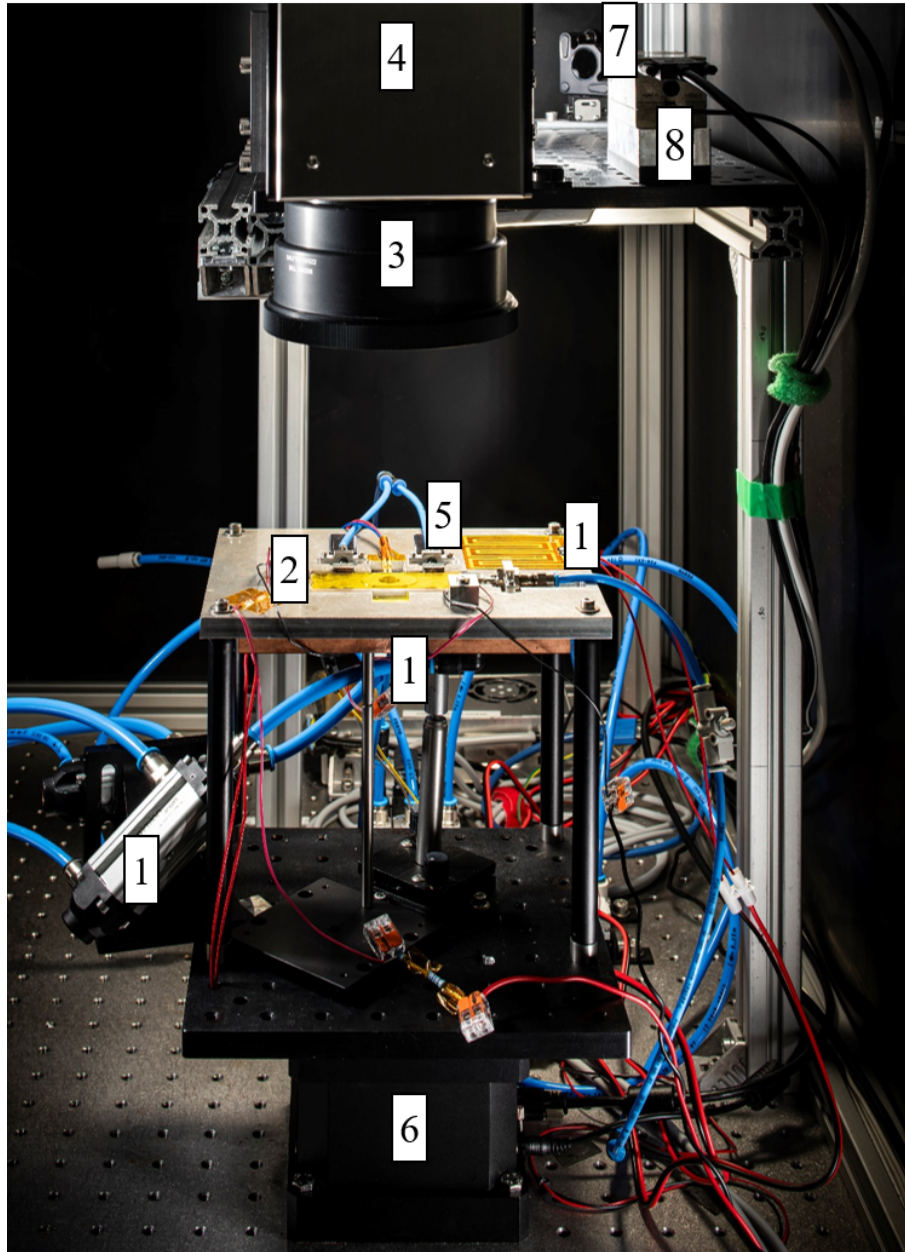


Figure 3.2: Detailed view of the LIFT setup: 1: Temperature control unit with cooling and heating 2: Donor and acceptor 3: F-Theta lens 4: Laser scan head 5: Pneumatic fixation 6: Z-stage 7: Laser-directing mirrors: 8: Diode laser source. For scale, the donor slide is 7.5 cm wide. Source: Lux et al.[P2]

The Transfer Stage

During the course of this work, the transfer stage was modified from a fixed stage to a height-adjustable stage. The Motorized Precision Vertical Translation Stage KINESIS® KVS30 by Thorlabs [45] was installed. This allows material transfers to be performed in the laser's focal plane. For applications that require a reduced energy density, out of focus transfers can be conducted. The motorized automated z-stage is controlled via an interface on the PC and moves to the desired position. The repeatability is better than 1 μm , which meets the requirements placed on the printing system. This enables the precise stacking of different materials in and out of focus.

The Printing Environment

The entire system is housed in a laser tight enclosure with an interlock system that immediately shuts down laser emission when the doors are opened. The selection of components to be printed imposes specific requirements on the atmospheric conditions within the laser setup. In particular, for the printing using LIFTs it is crucial to minimize dust particles and maintain low humidity levels.

To reduce dust particles within the setup, a HEPA filter was installed. This filter unit draws in ambient air, purifies it, and directs it from above through a small grid into the laser enclosure. This approach aims to create a low dust atmosphere comparable to that of a laminar flow box.

During the summer months, the laboratory air conditioning system is insufficient to regulate humidity levels. To ensure a consistently dry environment, a compressed air supply line was integrated into the setup. The compressed air is already dehumidified at the compressor stage, allowing to maintain a humidity level of approximately 20 %. While the enclosure is not perfectly sealed, the exchange of air with the surrounding atmosphere is limited and the overpressure allows specified atmospheric conditions to be maintained reliably.

The Temperature Control Unit

To reach and maintain the desired transfer temperatures, a temperature control unit was added to the printing setup. It allows temperature adjustment of the transfer stage within a range of 0 °C to 60 °C. The stage then exchanges heat with the sample placed in the indentation until both reach the same temperature. The system was designed to ensure stable transfer conditions throughout the year, even when the laboratory temperature varies between 15 °C to 30 °C.

Cooling is achieved by a cold air flow generated by vortex tubes, which has the advantage that waste heat is removed from the system. Heating is provided electrically by means of heating foils attached to the transfer stage. The implementation of the temperature control unit is described in more detail in Section 4.3.2.

Arrangement of Donor and Acceptor Slides

For the transfer of polymer materials, the acceptor and donor slides can be placed horizontally without using a spacer. Substrate surface roughness creates a natural gap below 10 μm between the two slides [29]. Polymers are transferred as solidified ink, with solvents evaporated prior to the transfer during donor preparation. For



Figure 3.3: Schematic display of the donor and acceptor arrangement for the transfer of liquid pastes.

the transfer of nanoparticle based inks as used for the printing of capacitors it is necessary to work with liquid inks or pastes. This novelty places new requirements on the arrangement of the donor and acceptor slides. To enable controlled printing and removal of the donor, it is necessary to introduce an artificial spacer between the slides.

For this purpose, Hasberg foils or Hasberg strips are used, which are made of rolled steel with a precisely defined thickness. They are placed at the sides of the donor and acceptor slides and act as modular spacers to avoid unwanted transfer of material (see Figure 3.3). The distance can be adjusted by selecting a foil thickness in the range of $10\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$. To enable a more reliable transfer by avoiding unwanted lifting of the upper slide and to ensure that the gap has the desired thickness, copper weights are placed on top of the steel spacers.

3.3 Preparation Work

The novel applications of the LIFT printer require new preparation techniques, which differ depending on the type of material being transferred and the LIFT variant used, BA-LIFT or direct absorption LIFT. Polymer solutions need to be processed differently compared to nanoparticle inks. This section describes the processes for donor fabrication, including the different coating variants.

3.3.1 Blank Donor Fabrication

The standard substrate size used in this work is microscope glass measuring $76\text{ mm} \times 26\text{ mm}$ with a thickness of 1 mm . This glass serves as the base for donor and acceptor slides, hereafter briefly referred to as donors and acceptors. The slides are fabricated from light-transparent soda-lime glass supplied by Paul Marienfeld GmbH & Co. KG, Lauda Königshofen, Germany [46]. With its low fabrication tolerance of $50\text{ }\mu\text{m}$ in thickness and low cost it is well suited as a key component of the production system. The glass is transparent to laser light of 405 nm .

Depending on the material to be printed, either BA-LIFT or direct absorption LIFT is used. Each method requires a different coating. BA-LIFT requires a layer of polyimide for laser absorption, while the direct absorption variant works without an additional layer. The substrates require special treatment before they can be coated with the transfer material.

The glass slides are cleaned in an ultrasonic bath with soap water, deionized water, isopropyl alcohol, and acetone, in that order, for one minute each to remove dust particles or residues. For BA-LIFT, the next step is coating with polyimide adhesive

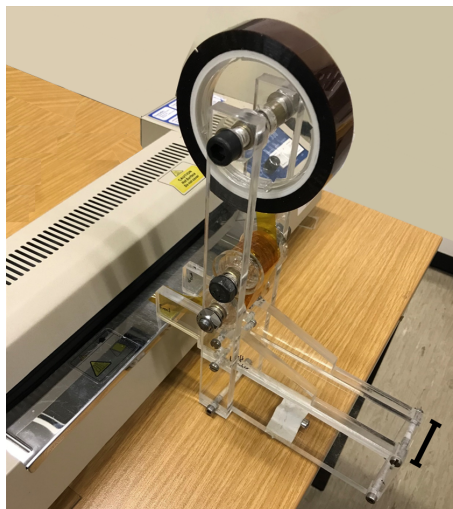


Figure 3.4: Custom built tape dispenser that guides the glass slides together with the tape to the laminator to cover them with adhesive polyimide film. Black scale bar = 5 cm in the plane of the dispenser.

tape from CMC Klebtechnik GmbH (CMC), Frankenthal, Germany, consisting of 25 μm polyimide and a 35 μm layer of polysiloxane glue. The adhesive tape is applied to the glass slides using a laminator. This process is delicate because air bubbles or scratches can negatively affect the transfer properties.

To ensure the fabrication of high-quality and reproducible donor slides, a customized tape dispenser was developed. This dispenser is compatible with the laminator (LM 330, Vogt Papiertechnik, Altdorf, Germany) and with the polyimide rolls from CMC (see Figure 3.4). The tape dispenser is made of acrylic glass pieces cut by a laser. It features a gliding path for the glass slides and deflection rollers for the polyimide tape. It is designed so that the sticky side of the tape only contacts the glass between the laminator rollers. The laminator pulls the tape and the adhering glass through the system, while the operator only needs to insert slides every few seconds and push them toward the laminator. Approximately 30 donor slides per minute can be prepared using this method. After lamination, the foil is cut to shape, and the slide surface is cleaned with acetone to remove any dust.

3.3.2 Coating of Donors

After preparing the blank donors with or without polyimide layer, they are coated with transfer material. Differences in the requirements for the film thickness and in the viscosity lead to process adaptations for different materials. These variants are described in the following paragraphs. All variants use a Film Applicator AB4120 by TQC Sheen that is operated with a speed setting of 10 mm/s (see Figure 3.5).

Variant for Polymer or Small Molecule Inks

Polymer or small molecule inks use organic solvents with low boiling points to enable fast drying after coating. A commonly used solvent for this process is DCM which has a boiling point of 40 $^{\circ}\text{C}$ [47]. Fast drying allows the fabrication of a homogeneous thin material film on the donor. For this method donors with a polyimide layer are required.

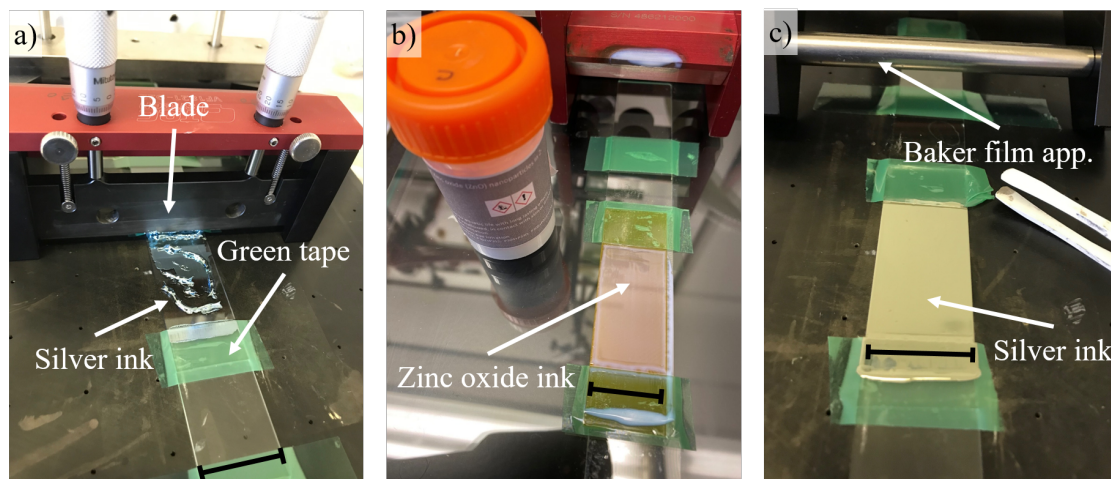


Figure 3.5: Blade coating of different types of inks. (a) High-viscosity silver ink XTPL CL85 before coating, spread with a spatula on a blank donor using a TQC Sheen blade. (b) Custom zinc oxide ink by TECNAN after coating using a polyimide donor using a Proceq ZUA 2000 blade. (c) Silver ink XTPL CL60 after coating with a Baker film applicator using a blank donor. Scale bars = 2.5 cm in the plane of the glass slides.

For the coating process, the donor slide is secured on the coating bed of the film applicator using green tape. The same tape is used as a cover in certain locations to prevent material deposition. The donor slide is cleaned with acetone to remove any dust or surface contamination. The blade of the Proceq ZUA 2000 is positioned directly above one end of the donor. Next, 60 μL of ink are dispensed from a pipette onto the sidewall of the blade, allowing it to flow down into the small gap between the donor and the blade. Initially, a small ink bridge forms, followed by a thin material film, assisted by capillary forces and gravity. This process is enabled by the very low viscosity of DCM of 0.437 mPa s [48].

As the blade moves along the donor, the material film is deposited, forming a thin coating that dries within seconds. The resulting dried film thickness is approximately 1 μm .

Variant for Nanoparticle-based Inks of Higher Viscosity

Nanoparticle inks are mixtures of nanoparticles in a liquid carrier consisting of organic solvents and additives to optimize ink properties. For coating, a donor without a polyimide layer is required, although a polyimide donor can also be used. For preparation, the donor slides are secured to the coating bed with green tape. Areas that should remain free of ink are protected with green tape. Typically, a 1 cm-wide stripe remains free of ink to place spacers that maintain separation between the donor and acceptor. Before coating, the donor slide is cleaned with acetone to remove dust and surface contaminants. The subsequent preparation method depends on the ink viscosity (see Figure 3.5).

High-Viscosity Inks ($\sim 100\,000$ mPa s) cannot be spread by moving the blade alone. They must be manually applied to the donor slide using a spatula. This initial application results in an uneven surface that is too rough for printing. To achieve a uniform layer, a blade or bar-shaped cylinder is dragged along the slide to

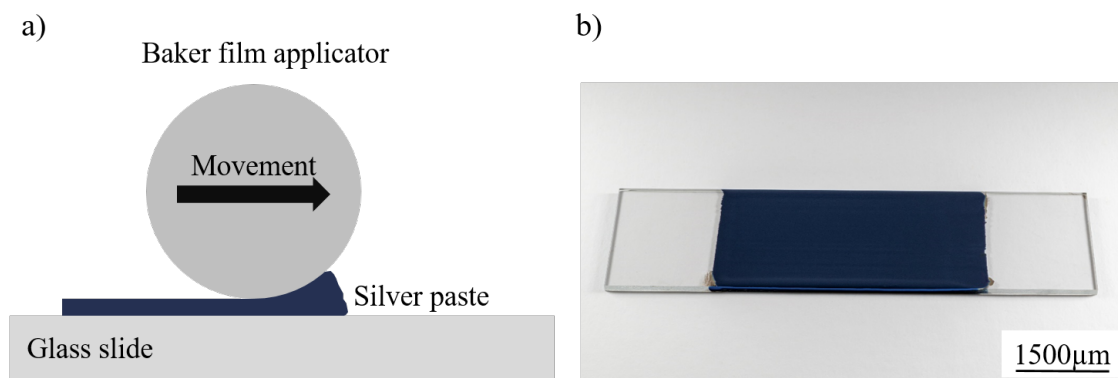


Figure 3.6: Blade coating of nanoparticle inks onto a donor slide without the use of Kapton[®] tape. (a) A Baker film applicator is drawn across the slide, leaving behind a thin and uniform ink layer. (b) Donor slide uniformly coated with silver ink XTPL CL60. The side regions are intentionally left blank to allow spacer placement, ensuring proper separation between donor and acceptor. Source: Lux et al. [P2]

smooth the surface and to produce a flat, thin layer of the desired thickness. This method is suitable for printing with silver ink XTPL CL85.

Low-Viscosity Inks ($<50\,000$ mPa s) are applied as a line along one short edge of the donor slide. The blade then moves along the slide, evenly distributing the material to achieve the desired thickness. This method is suitable for printing with silver ink XTPL CL60 and other inks with similar properties.

Blade Variants for Donor Coating

Depending on the coating material, the coating process must be adapted. For polymer or small molecule inks, which typically have low viscosity, the Proceq ZUA 2000 film applicator blade, a height-adjustable blade, is used. The set height for all transfers of small molecule or polymer inks with this blade is $440\,\mu\text{m}$ above the Kapton[®] layer. The transfer of pastes requires different parameters, with a typical height setting of $40\,\mu\text{m}$ above the substrate.

For nanoparticle-based inks with higher viscosity, a custom device was used: a 4-sided bar-shaped film applicator, type BAKER, with a width of $80\,\text{mm}$ (see Figure 3.6). This offers higher accuracy in the z-setting than the Proceq ZUA 2000. The gap between the bar and the substrate on each side is designed as $1010\,\mu\text{m}$, $1020\,\mu\text{m}$, $1030\,\mu\text{m}$, and $1040\,\mu\text{m}$, with an accuracy below $1\,\mu\text{m}$ according to the manufacturer Industrial Physics. While the nominal gaps between the donor slide and the film applicator are $10\,\mu\text{m}$, $20\,\mu\text{m}$, $30\,\mu\text{m}$, and $40\,\mu\text{m}$, the resulting film thickness is actually smaller.

3.4 Transfer Behavior

The LIFT printing process itself, as a method for the precise transfer of material dots, has been demonstrated by previous researchers and documented in the literature [20, 29, 30, 49, 34, 50]. A setup similar to the one used in this study has demonstrated printing with nanometric precision and serves as the basis for this work. The advances presented here were achieved by building upon this existing foundation of understanding. From this standpoint, further printing modes were developed and new materials were tested. To demonstrate the capability and functionality of the setup, transfer experiments with low complexity were conducted, such as printing of a laser parameter matrix, dot overlapping, stacking, and structure printing using the polymer material S-LEC[®] containing glycine (see Section 4.2.1). The experience gained from these experiments was subsequently used to develop fabrication recipes for the printing of thin film devices and are picked up again later in this work.

Laser Parameter Matrix for Dot Printing

The LIFT process is a thermally driven mechanism in which the outcome is determined not only by the total laser energy but also by how this energy is delivered to the donor layer through adjustments of the laser power and the exposure time. This input can be tuned either by varying the laser power, which ranges from 1 mW to 300 mW for the stationary printer and 1 mW to 500 mW for the test version, as defined by the laser sources, or by modifying the laser exposure time. The total laser energy E [J] is given by

$$E = P \cdot t \quad (3.1)$$

with P denoting the laser power and t the exposure time. While this relation describes the total energy, it does not capture the fact that power and exposure time influence the transfer in different ways. For example, the parameter sets 200 mW with 10 ms exposure time and 40 mW with 50 ms exposure time deliver the same total energy, yet result in different spot morphologies. While the transfer with the first set of parameters is shown in Figure 3.7 the second parameter does not even result in any measurable transfer. This demonstrates that the influence of laser power and exposure time is not symmetric. Higher peak power leads to steeper thermal gradients and different material responses compared to longer exposure at lower power.

Consequently, it is not sufficient to consider laser energy alone. The effects of laser power and exposure time must be treated separately. Since each material responds differently, the printing behavior must be mapped individually. Two strategies exist: either by predictive simulations, as presented by Paris et al. [29], which require detailed material parameters and computational effort, or by an empirical approach based on test prints. In the latter, the parameter space is systematically explored in a dot matrix, typically with power on the x-axis and exposure time on the y-axis, where each point corresponds to one printed spot. This straightforward method provides an experimental map of lateral size and height as a function of laser parameters. The resulting spot matrix, analyzed with VSI imaging, is shown in Figure 3.7a. A 3D representation is provided in Figure 3.7b, with the z-axis strongly magnified

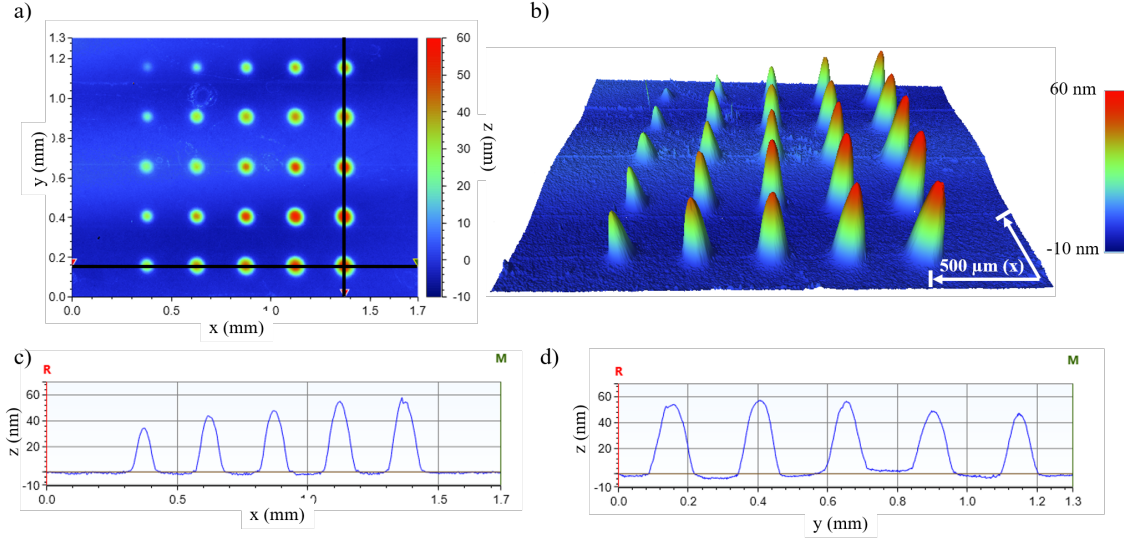


Figure 3.7: vertical scanning interferometry (VSI) analysis of a LIFT-printed S-LEC[®]-glycine dot matrix, where each dot corresponds to an individual set of laser parameters. The x-axis corresponds to laser power (160 mW to 200 mW), and the y-axis to laser exposure time (6 ms to 10 ms). (a) 2D topographic map of the dot matrix. (b) 3D visualization of the printed spots (Z axis not to scale). (c) Line profile of the spot height along the x axis taken along the line indicated in the topographic map. (d) Line profile of the spot height along the y axis taken along the line indicated in the topographic map.

($\times 10.000$) and not to scale. Figure 3.7c–d present the line profiles of the spot heights along the black line indicated in Figure 3.7a. The spot height increases with laser power in the range of 160 mW to 200 mW at 10 ms from approximately 35 nm to 55 nm, and with exposure time in the range of 6 ms to 10 ms at 200 mW from 45 nm to 55 nm. The lateral size also expands, from 100 μm to 130 μm with increasing power and from 110 μm to 130 μm with increasing exposure time. This demonstrates the different effect of laser power and pulse duration on the print result.

The smallest spot within this parameter range is obtained at the lowest energy input, measuring about 70 μm in width and 10 nm in height. At even lower energies, smaller features down to 1 nm in height are possible, though they become difficult to distinguish from substrate roughness. The maximum spot height for a single S-LEC[®]-glycine transfer reaches about 60 nm. Applying higher energies beyond this threshold leads to increased carbonization of the polyimide tape, which in turn causes unreliable transfer results such as missing dots.

Printing a spot matrix is a fast method to identify suitable laser parameters to produce a desired lateral spot size or height. Since different materials exhibit distinct transfer properties, this procedure must be applied individually for each material. The polymer S-LEC[®] can be considered a representative case. While other polymers behave differently in detail, possibly affected by different T_g , they generally follow the same overall trends.

Line Printing

A line can be fabricated by printing adjacent spots close enough to overlap, allowing them to merge into a connected structure. In this experiment, S-LEC[®]-glycine was

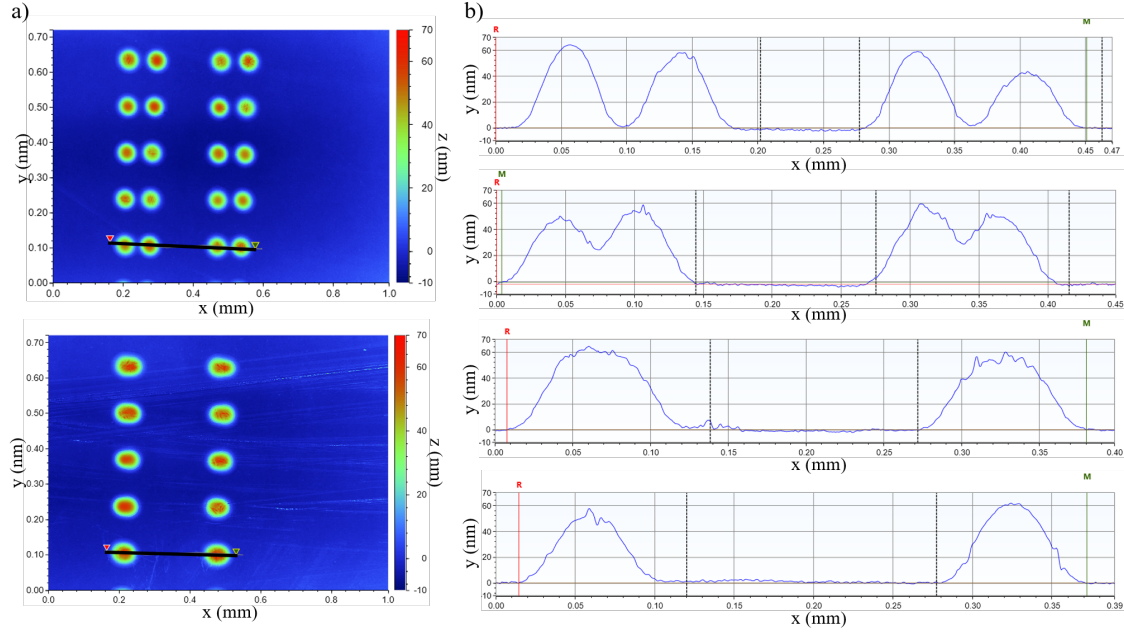


Figure 3.8: Multiple S-LEC[®]-glycine spots printed in close proximity with a pitch from 250 μm to 0 μm in steps of 5 μm . Not all images and line profiles for all pitch values are shown. (a) Topographic images obtained by VSI analysis, illustrating decreasing spot distance, overlap, and merging. (b) 2D line profiles of the spots shown in a.

transferred at 150 mW and 10 ms. To determine the optimal overlap, spot pairs were printed with a variable pitch, decreasing from 80 μm to 1 μm . The desired overlap for line printing corresponds to a connected structure with only minor deviations in height. The expected outcome of this experiment was an increase in spot height once dots began to merge and were deposited on top of each other. The printed spot pairs were analyzed by VSI imaging and are shown in Figure 3.8. From these images it can be observed that the spots begin to merge when printed sufficiently close together. The spot height, however, does not increase significantly upon merging. It depends on the printing mode whether the spot height is added up or remains at the same level under sufficient overlap. The spot height did not exceed 60 nm. This indicates that there is a limit for the spot height using this printing mode, which does not increase significantly when spots merge. The limit is likely caused by adhesion and cohesion of material, therefore a different constant is expected if other materials are used.

For printing continuous lines rather than single dot pairs, sequences of ten dots were printed with pitches of 40 μm , 60 μm , and 80 μm . The corresponding 3D visualizations and line profiles are shown in Figure 3.9. Printing order is up - down - left - right. For the smallest pitch of 40 μm the dots merged, but the line exhibited fluctuations in height along its path, possibly due to build-up of heat. At a pitch of 60 μm , this effect was still present. For the largest pitch of 80 μm , the height remained more stable along the line, although the first two dots were blended together and exhibited a slightly higher profile compared to the rest.

Line printing can thus be achieved if an appropriate pitch parameter is selected. If the pitch is too small, neighboring dots interfere with each other, leading to height

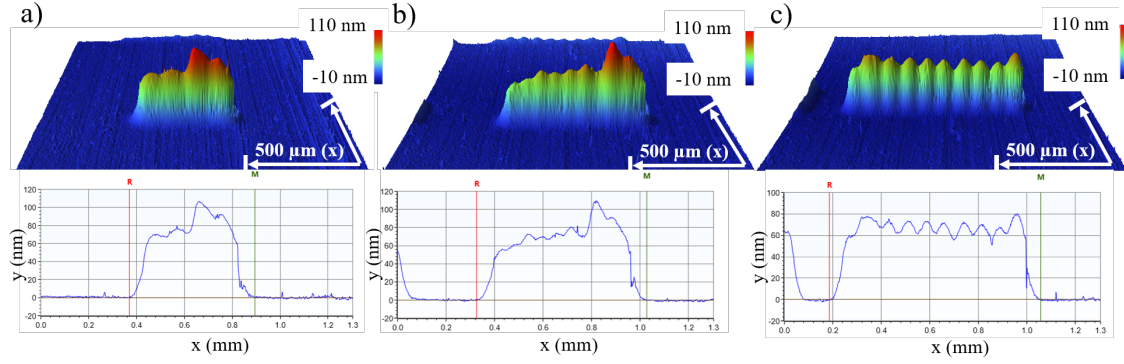


Figure 3.9: 3D visualization of topographic images of printed line structures and corresponding line profiles with a pitch of (a) 40 μm (b) 60 μm (c) 80 μm .

deviations. Since each set of laser parameters produces a characteristic spot morphology, line printing must be optimized individually for the chosen laser conditions. This optimization can be accomplished by printing test lines with varying pitches and analyzing the resulting structures using VSI.

Surface Printing

The fabrication of continuous surfaces can, in principle, be realized using the same method that was successfully applied for line printing. In this process, individual dots are deposited in close proximity until the printed material overlaps and merges into a continuous structure. The printing sequence proceeds column by column: the first dot is placed in the top-left corner, the second directly below in the y-direction, and so forth. Once a column is completed, the laser returns to the top and continues with the next column. Consequently, the waiting times between adjacent dots in the y-direction are short, while those in the x-direction are longer. This temporal difference depends on the aspect ratio of the printed surface and must be taken into account during surface fabrication. It should also be noted that, depending on the chosen pitch, height deviations and printing defects such as gaps or surface irregularities may occur. These defects arise because the deposition of a subsequent spot can spatially overlap with the expansion radius of a previously transferred spot, resulting in mutual interaction between adjacent transfers.

The temporal dynamics of the transfer process are also of importance. The laser exposure time typically amounts to 10 ms, while the expansion of the polyimide layer requires approximately 70 ms. A full relaxation of the Kapton[®] film occurs only after about 120 ms [29]. Consequently, if the pitch is chosen too small, depending on the applied laser parameters, overlapping transfer events are likely, which can lead to printing defects during surface formation.

An exemplary experiment with S-LEC[®]-glycine is shown in Figure 3.10. In Figure 3.10a, a pitch of 60 μm was applied, resulting in a surface layer of approximately 80 nm thickness. Both the line profile and the 3D visualization reveal a characteristic wave-like pattern, with wave crests propagating along the x-direction. Printing errors and irregularities are also evident in both representations. Increasing the pitch to 80 μm , as illustrated in Figure 3.10b, does not significantly improve the surface quality.

A clear improvement is achieved when temporal relaxation is explicitly taken into

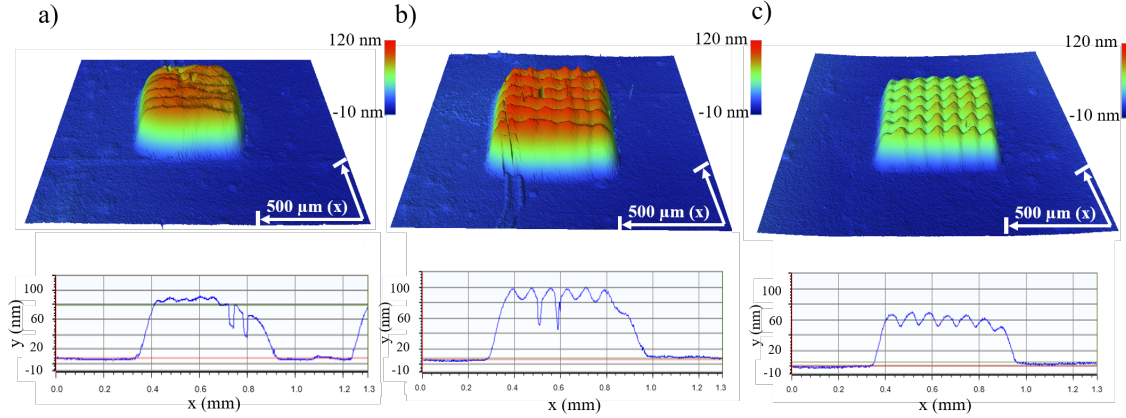


Figure 3.10: 3D visualization of topographic images of printed 7×7 dot surface structures with a pitch of (a) $60 \mu\text{m}$, (b) $80 \mu\text{m}$, and (c) $80 \mu\text{m}$, printed with a delay of 1000 ms between each dot.

account. By introducing a technically implemented delay of 1000 ms between successive single-dot transfers, the system is given sufficient time to return to equilibrium before the next spot is printed. Under these conditions, a much more uniform printing pattern is observed. As shown in Figure 3.10c, a surface thickness of about 60 nm could be obtained without visible printing defects. Nonetheless, a certain degree of surface roughness remains, with fluctuations in the order of 10 nm . It can therefore be concluded that this method enables the fabrication of comparatively homogeneous surfaces, although the realization of an entirely smooth and defect-free surface is not possible in this printing mode.

Material Stacking

To investigate the stacking behavior in LIFT printing, S-LEC[®]-glycine was transferred. In this study, it was further examined whether the stacking behavior depends on the type of printed structure. For this purpose, the height of the fabricated features was analyzed. Two cases were considered: stacks of individual spots and stacked lines consisting of 10 dots each. The pitch for the isolated spots was set to $500 \mu\text{m}$, while for line printing a pitch of $80 \mu\text{m}$ was chosen. To test the influence of the energy input, two laser parameter sets were applied: 150 mW , 10 ms and 150 mW , 7 ms .

Figure 3.11a shows the topographic image of stacked dots. On the left-hand side, a single transfer is displayed, while the right-hand side shows a double transfer. The donor film was exchanged between each transfer. It is evident that the double transfer results in approximately twice the height compared to the single transfer. This observation is confirmed by the x-line profile taken through the dot centers. The lateral dimensions, however, remain unchanged between single and double transfers. These results demonstrate that LIFT enables controlled and reproducible stacking of material, making it a suitable approach for tailoring the height of printed structures.

The graph in Figure 3.11b illustrates the relationship between the number of transfers at the same position and the corresponding structure height. For both energy levels the height increases linearly for that printing mode with the number of stacking steps, but with a lower slope for the reduced transfer energy of 150 mW , 7 ms .

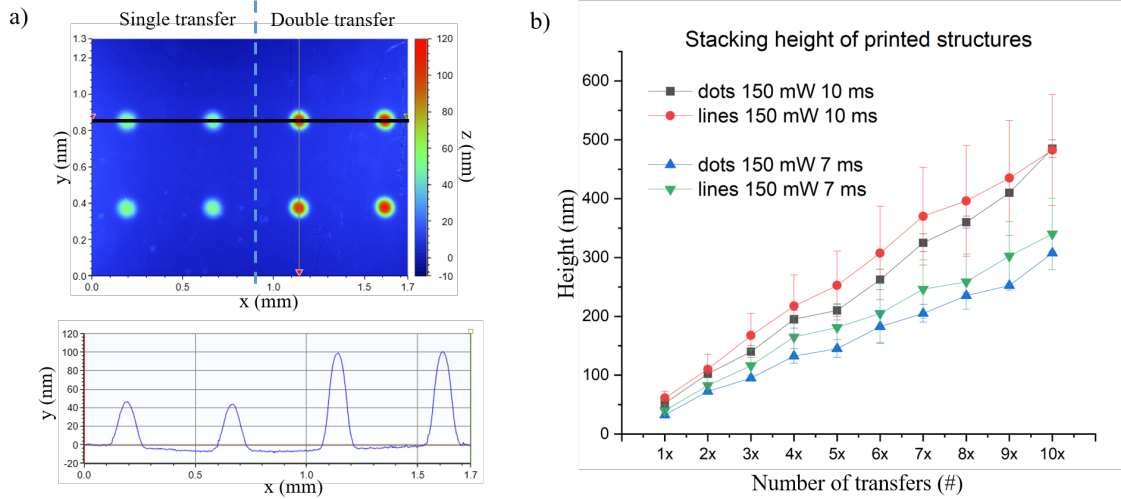


Figure 3.11: (a) Topographic image of stacked S-LEC[®]-glycine dots with corresponding x-line profile. (b) Correlation between the number of stacking steps and the resulting structure height.

This behavior is expected as a lower transfer energy results in smaller individual depositions. The type of structure, dot or line, did not alter the overall stacking behavior. However, the stacked lines consistently exhibited slightly higher values compared to stacked dots, which may be attributed to partial overlap of neighbor transferred spots.

Summary of Printing Behavior

In summary, the LIFT printing behavior of S-LEC[®]-glycine has been systematically characterized to demonstrate the capability of the LIFT printer. The dot parameter matrix revealed that both laser power and exposure time must be considered independently, since they influence the spot morphology in different ways. Line printing was shown to be feasible when an appropriate pitch is chosen. Extending this principle to surface fabrication demonstrated that uniform surfaces can be realized, when sufficient temporal relaxation is allowed between successive transfers. By using suitable transfer parameters, printing defects such as gaps or wave-like patterns can be minimized or avoided. Finally, the stacking experiments confirmed that LIFT enables controlled and reproducible adjustment of structure height, with a nearly linear dependence on the number of transfers. Altogether, these results establish the fundamental printing characteristics and limitations of S-LEC[®]-glycine, providing a reference framework for subsequent experiments with other materials and for the development of more complex printed architectures.

4. Experiments

This chapter describes the experiments performed in the scope of this study. Its main purpose is to document all relevant experimental parameters so that the experiments can be fully understood and reproduced. The work is structured into three main areas: the improvement of the printing system, the development of inks and the applications. The results in this work have mostly been published in peer reviewed articles in different Wiley journals [P1, P2, P3], whose experimental foundations are described in this chapter.

The first publication deals with the development of a LIFT test setup for liquid-ink optimization (see Section 4.2.3). The second publication focuses on the application of liquid inks for the printing of capacitors (see Section 4.8). The third publication addresses the advancement of the printing mode from dot printing to area printing for the fabrication of OLEDs (see Section 4.7).

In addition, this chapter includes experimental procedures for fabricating customized substrates to achieve specific printing outcomes or to build functional components. The influence and selection of the polyimide tape were also examined in detail. Furthermore, several smaller modifications to the printing setup are described, such as the implementation of a high-precision z-stage and the integration of a temperature-control unit to increase the reliability and reproducibility of the experiments.

4.1 Customized Acceptor Substrates

While the standard substrate material for test and characterization of material transfers is microscope glass, the fabrication of electrical components requires specific substrates with properties like conductivity for connection purposes or transparency to allow pass-through of optical emission. The requirements on material and substrate are discussed in this chapter. Other boundary conditions on acceptor substrates, like non-flat, pre-structured substrates, are discussed in Section 4.3.1.1.

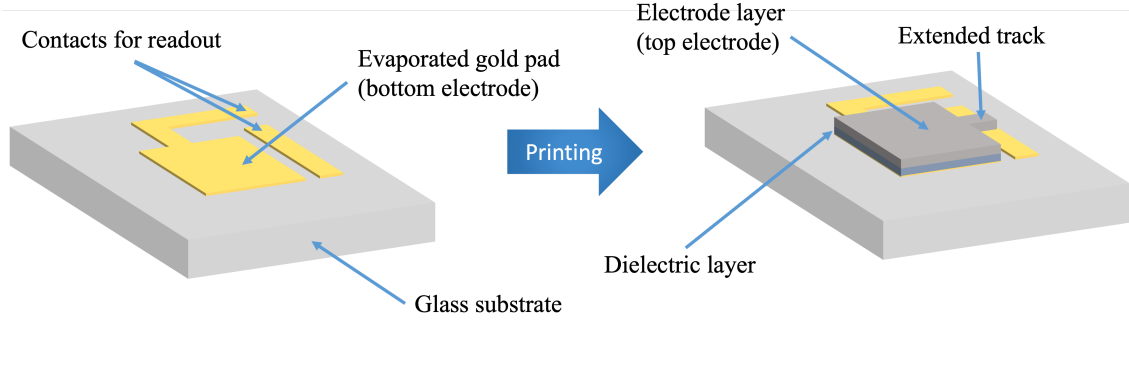


Figure 4.1: Substrate layout for printed plate capacitors.

4.1.1 Substrates for Capacitor Printing

Requirements on the Substrates for Printing of Capacitors

The choice and preparation of the substrate are critical for successful capacitor printing. Commercial glass slides are typically selected because they are readily available, chemically stable against nanoparticle inks and solvents, and thermally stable during thermal post-processing. This is essential since the printed silver electrodes must undergo heating up to approximately 260°C , where drying removes residual solvents and sintering enables nanoparticle coalescence into conductive pathways. Any alternative substrate must therefore tolerate both chemical exposure and this thermal budget without degradation.

Beyond selection of the substrate additional preparation steps are required to enable reproducible device readout. Gold layers are fabricated on the glass in a multi-step process to form contact pads and conductive tracks. These structures provide low-resistance electrical interfaces and mechanical durability during repeated probing. Importantly, the gold pads can serve as counter electrodes in the capacitor, providing flexibility in device configuration. The design (see Figure 4.1) also allows the top electrode to be printed with a small, extended portion that connects directly to the adjacent gold track, ensuring reliable electrical contact while maintaining the intended capacitor geometry. Their dimensions are defined by the measurement setup: electrical characterization is performed using a Cascade Microtech MPS150 probe station in combination with an Agilent E5061B network analyzer. The probe head requires a defined electrode spacing of $450\text{ }\mu\text{m}$, which directly sets the pad layout and track separation. The elastic design of the probe tips supports stable mechanical and electrical contact.

The combination of thermally stable glass slides, carefully fabricated gold contact structures, and a layout tailored to the probe station ensures robust and reliable electrical characterization of printed capacitors, while allowing the gold pads to function as counter electrodes and enabling convenient connection of the top electrode via the extended track segment.

Fabrication of Gold Pads for Characterization of Printed Capacitors

The layout for the gold pads is created using the software KLayout. The design is adopted to follow the outer dimensions of the glass substrate (see Figure 4.2). For alignment purposes, a frame was added to support the fabrication process. The

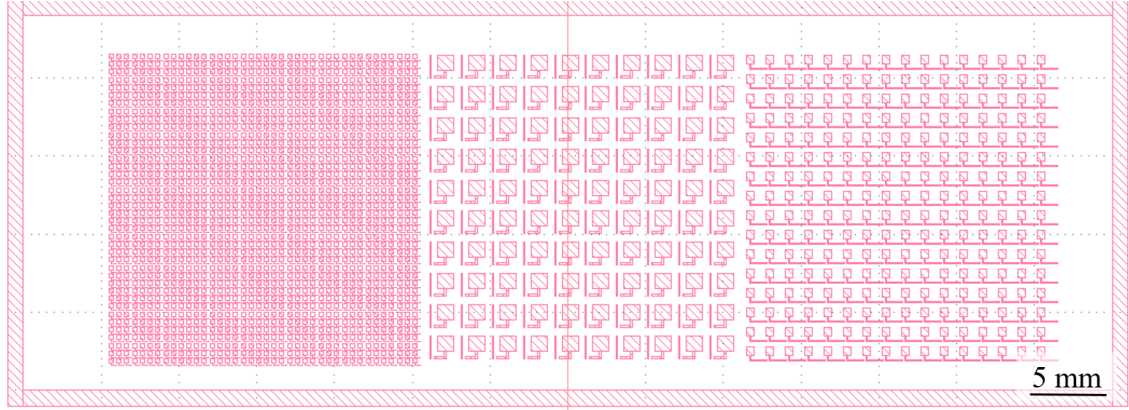


Figure 4.2: Layout for gold substrate fabrication for the printing and readout of capacitors, designed using the KLayout software

layout consists of multiple pads in various sizes ($100\text{ }\mu\text{m}$, $250\text{ }\mu\text{m}$, $1000\text{ }\mu\text{m}$) arranged in a grid architecture, each with $100\text{ }\mu\text{m}$ -wide legs for electrical readout. The legs feature a lateral gap that can be bridged by the probe head with defined spacing. The final substrate is shown in the cropped image in Figure 4.3. The fabrication of the gold pads uses the following process:

- Production of a film photomask at JD Photodata, Hitchin, UK, based on the layout designed in KLayout
- Cleaning of the glass substrates sequentially with isopropanol and acetone
- Application of the adhesion promoter hexamethyldisilazane (MicroChemicals) by vapor priming
- Spin-coating of the substrates with the negative photoresist MA-N 1440 at 3000 rpm for 30 s, followed by 1500 rpm for 30 s
- Soft-bake on a hotplate at 100°C for 180 s.
- Exposure with 365 nm filtered UV light at a dose of $550\text{ mJ}/\text{cm}^2$
- Development in the aqueous alkaline developer ma-D 533/S (containing surfactants) for 120 s
- Rinsing with distilled water
- Evaporation of 10 nm of chromium, followed by 40 nm of gold
- Lift off the remaining resist by gently shaking the sample in an acetone bath

4.1.2 Substrates for Material Characterization

For the intended application in electronic components as well as for the printing process itself, the inks must be electrically characterized. Therefore, dedicated characterization substrates are required to enable a standardized evaluation of both the electrical properties and the printability of the ink candidates.

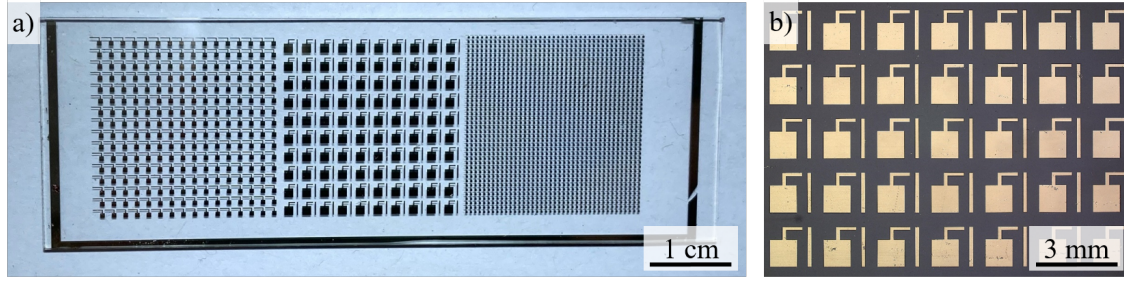


Figure 4.3: (a) Fabricated gold structures on glass substrates used for printing and readout of capacitors. (b) Gold pads, size 1 mm^2 , with contact structures

These substrates should be solid, stable at temperatures up to 300°C , and equipped with conductive pads or structures that allow manual measurement using a probe station. The electrical pads must be equally spaced and designed so they can be reliably bridged by printing.

The gold pads fabricated for the printing and readout of capacitors (see Section 4.1.1) also fulfill the requirements for material characterization experiments. Consequently, no additional layout is necessary.

4.1.3 Substrates for OLED Fabrication

Requirements on the Substrates for OLED Fabrication

OLED devices feature a more complex multilayer structure than printed capacitors, which imposes stricter requirements on the substrate and deposited layers. The substrate must be flat, chemically stable, and exhibit low surface roughness in order to prevent pinholes or defect sites in the nanometric OLED stack. Since OLEDs emit visible light, at least one electrode must be transparent to enable efficient light outcoupling.

indium tin oxide (ITO) is commonly used as the transparent anode because it combines high optical transparency in the visible range with good electrical conductivity ($\approx 20 \Omega/\square$ at 100 nm thickness) and a work function compatible with typical OLED architectures. However, direct printing of ITO onto the substrate is challenging due to strict process requirements regarding temperature, contamination and layer uniformity. Therefore, ITO is typically pre-deposited onto the substrate before OLED fabrication, providing a robust, conductive and transparent bottom electrode while allowing the sensitive organic layers to be deposited under controlled conditions.

Compared to capacitors, OLEDs are far more sensitive to substrate imperfections, which explains the higher demands on surface quality, material compatibility and processing conditions [51]. In addition, printing, operation, and readout places further constraints on the design of the ITO structure, illustrated in Figure 4.4. The size of each OLED, defined by the ITO anode area, must balance several factors. It should be large enough to allow manual removal of deposited layers for separation of spin-coated OLED films, which requires a lateral structure size of roughly 1 mm minimum. A larger area reduces the relative influence of edge effects, but printing larger structures requires a more robust process to achieve defect-free devices and ensure functionality. Smaller devices, on the other hand, allow more devices to be printed on a single slide. The device's compatibility with the optical

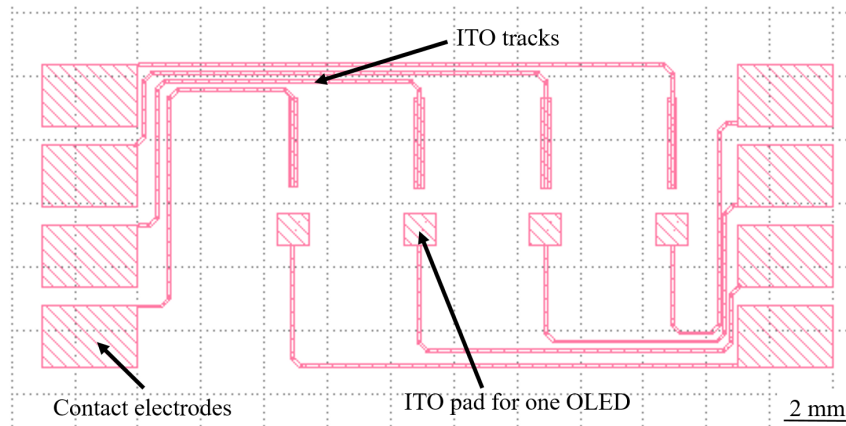


Figure 4.4: Layout for 4 OLEDs on ITO substrate for device printing and operation, designed using the software KLayout. This unit is replicated 5 times on each acceptor slide.

readout and possible lower detection threshold also needs to be considered. For these reasons, an anode size of 1 mm^2 is chosen.

For operation and readout, external electrodes must be attached. While contacting with a manual probe station would be possible, it is impractical for routine measurements. Instead, connection legs by Ossila were used to be attached to the edge of the glass substrate, which can be contacted easily. To ensure robust handling, these pads are at least 2 mm in size. A pitch of 2.54 mm was selected to make the design compatible with standard breadboard connectors, allowing a maximum of 20 electrode pads per side of the substrate. One side hosts the anode connectors and the other the cathode, allowing individual addressing and testing of each OLED.

The electrical tracks connecting anode pads to electrode pads are $100\text{ }\mu\text{m}$ wide and designed with a maximum corner angle of 45° to facilitate efficient charge transport. On the cathode side, the connection path is widened to $300\text{ }\mu\text{m}$ and further enlarged at the contact area to relax alignment tolerances during cathode deposition. A complementary shadow mask is used to locally define the cathode by evaporating the metal only in the desired regions above the printed ITO structure.

Fabrication of ITO Slides for Operation and Characterization of OLEDs

For the fabrication of structured ITO-coated glass slides, unpatterned ITO-coated glass slides from Ossila were used. The size of the ITO slides is $25\text{ mm} \times 75\text{ mm}$. The substrate is polished soda lime float glass with a thickness of 1.1 mm. The resistance of the ITO coating is $20\text{ }\Omega/\square$ with a thickness of 100 nm [52]. The relative transmittance of the ITO is approximately 0.92 in the emission window 400 nm to 750 nm. The roughness of the ITO is only 1.8 nm Root Mean Square (RMS) roughness, which makes this choice of ITO glass well-suited for this purpose. The selective patterning of the ITO layer is carried out according to the following process:

- Spin-coating of the slides with the positive photoresist ma-N 1420 (Micro Resist Technology GmbH, Berlin) at 3000 rpm for 60 s to form a uniform thin film

- Pre-exposure bake on a hotplate at 110 °C for 2 min to improve adhesion by evaporating residual solvents
- Alignment the slides with a photomask in a mask aligner and exposing to 135 mJ/cm² of ultraviolet light
- Development of the exposed slides in ma-D 5335 developer (Micro Resist Technology GmbH, Berlin) for 4.5 min to dissolve the unwanted photoresist and reveal the underlying ITO structures
- Inspection of the developed structures under a light microscope to confirm successful patterning
- Etching of the unprotected ITO areas by immersing the slides in a 4.0 mol/L Hydrochloric acid (HCL) solution at 30 °C for 50 min, with the solution temperature maintained in a water bath
- Monitoring of the etching process by measuring the surface resistance to ensure complete removal of excess ITO
- Removal of the remaining photoresist by sequentially immersing the slides in acetone and isopropyl alcohol, followed by rinsing with deionized water

4.2 Composition of Inks for LIFT Printing

This chapter provides an overview of the inks used in this work and describes the corresponding fabrication steps. Depending on the targeted application and transfer mechanism, two fundamentally different ink concepts are employed: solubilized inks for organic electronic materials and nanoparticle-based inks for metallic and dielectric layers.

Solubilized inks are used primarily for OLED fabrication and printing process development. In these systems, the functional materials are dissolved in suitable organic solvents, enabling the preparation of smooth donor films that are dried prior to transfer. Nanoparticle-based inks consist of solid particles dispersed in a carrier liquid and are transferred in the liquid state, which introduces additional requirements regarding stability, viscosity and handling.

Section 4.2.1 summarizes the solubilized ink formulations used in this work while Section 4.2.2 addresses nanoparticle-based inks and their specific fabrication and handling protocols. In addition, Section 4.2.3 describes a custom-built LIFT test setup that serves as a guideline for the construction and use as a on-site validation platform for newly developed nanoparticle inks.

4.2.1 Solubilized Ink Formulations

The fabrication of OLEDs using LIFT printing requires solubilized inks to allow the fabrication of smooth donors. These inks are first coated onto donor slides and subsequently dried prior to transfer. The ink formulations, including materials and corresponding solvents, are summarized in Table 4.1.

The organic solvents are selected to ensure high solubility of the target materials and to provide a relatively low boiling point suitable for the coating process. For

ink preparation, the respective materials are dissolved in its solvent. For all materials except tris(4-carbazoyl-9-ylphenyl)amine (TCTA), DCM can be used as an alternative to chloroform without any observable deviation in printing behavior or film quality.

A production-ready poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) ink (type F HC Solar, Ossila M126) is used without further modification in one OLED variant for spin coating of the first OLED layer.

Material	Ink Type	Concentration [mg/mL]	Solvent
PEDOT:PSS	HTL ink	1.0 to 1.5 wt. %	Water, DMSO
TCTA	HTL ink	30.0	Chloroform
TPD	HTL ink	30.0	Chloroform
TAPC	HTL ink	30.0	Chloroform
Rubrene	EML ink	8.0	Chloroform
Alq ₃	EML ink	15.0	Chloroform
Bphen	ETL ink	4.0	Chloroform

List of abbreviations:

HTL	Hole transport layer
ETL	Electron transport layer
EML	Emissive layer
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate
TCTA	Tris(4-carbazoyl-9-ylphenyl)amine
TPD	N,N'-Bis(3-methylphenyl)-N,N'-diphenylbenzidine
TAPC	1,1-Bis[(di-4-tolylamino)phenyl]cyclohexane
Rubrene	5,6,11,12-tetraphenylnaphthacene
Alq ₃	Tris-(8-hydroxyquinolin)aluminum
Bphen	Bathophenanthroline

Table 4.1: Overview of different ink formulations with respective materials, concentrations and solvents

Polymer Inks for Printing Process Development

A range of materials is selected to cover a broad spectrum of properties relevant for the development and optimization of the printing process. As a reference material, S-LEC[®] is chosen due to its well-established transfer characteristics, which are extensively documented in the literature [31, 29]. The printer optimized and further developed in this work was originally designed for the transfer of S-LEC[®] and later adapted for the transfer of additional materials. S-LEC[®] is a styrene-acrylic copolymer, chemically related to polystyrene, and is commonly used as a carrier material for the printing of amino acid building blocks. Its glass transition temperature is in the range of 60 °C to 80 °C [33].

A standard formulation of S-LEC[®] ink consists of 67.5 mg S-LEC[®] powder, 7.5 mg glycine, and 500 µL DCM. Other non-polar solvents such as toluene or chloroform

Ink Type	S-LEC [®] [mg]	Ingredient	Amount [mg]	Solvent	Volume [μ L]
Polystyrene ink		Polystyrene	75.00	DCM	500
10% Glycine ink	67.50	Glycine	7.50	DCM	500
1% Rhodamine ink	74.25	Rhodamine	0.75	DCM	500
3% Rhodamine ink	72.75	Rhodamine	2.25	DCM	500
10% Rhodamine ink	67.50	Rhodamine	7.50	DCM	500
1% Coumarin ink	74.25	Coumarin	0.75	DCM	500
3% Coumarin ink	72.75	Coumarin	2.25	DCM	500
10% Coumarin ink	67.50	Coumarin	7.50	DCM	500

Table 4.2: Composition of inks especially based on S-LEC[®] with different dye or additive concentrations

may be used as alternatives, and solubility can be improved by gentle heating or shaking. Empirically, the addition of glycine is found to enhance the transfer process significantly, resulting in approximately tripled height of transferred spots. Therefore it is used for experiments on the printing process development.

Dyed S-LEC[®] inks are also prepared by incorporating different concentrations of fluorescent dyes. These formulations are particularly employed in experiments with pre-structured acceptors. The compositions of the various ink formulations are summarized in Table 4.2.

For comparison, polystyrene inks are prepared analogously by dissolving 75 mg of polystyrene powder in 500 μ L DCM.

4.2.2 Nanoparticle-Based Inks

Metallic or oxidic materials such as silver, titanium dioxide, zinc oxide, and silicon dioxide are transferred in the form of nanoparticle-based inks. These inks consist of nanoparticles dispersed in organic solvents and, unlike polymer or small molecule based inks, they are transferred in the liquid state after being coated onto donor slides in preparation for the transfer.

Using liquid inks introduces several challenges to the LIFT printing process which are discussed in Section 2.2.1. The donor and acceptor substrates must be kept at a defined distance, typically by a spacer, to avoid unintended material transfer. Moreover, because the inks remain in the liquid phase, their transfer behavior is sensitive to subtle variations in their physical properties. Over time, volatile solvent components may evaporate, leading to concentration changes. Additionally, inks can phase-separate or agglomerate and must therefore be stored below certain temperatures. The inks also begin to dry on the donor slide depending on the ambient temperature and humidity, which limits the allowable time between donor preparation and printing.

The ink properties are strongly temperature-dependent, especially regarding viscosity, which is a crucial parameter for transfer quality. To mitigate these issues, several routines are implemented: inks are monitored for aging effects, stored in a refrigerator, and shaken before coating to ensure homogeneity. Donor preparation is carried out immediately before transfer, and the donor stage is kept at consistent temperature. These measures help minimize deviations and ensure reproducibility. Silver inks are employed for printing of conductive tracks or electrodes, whereas

titanium dioxide inks are used for dielectric layers. Both materials are commercially available. These off-the-shelf inks are tested under specific LIFT conditions, and some are successfully qualified for component fabrication. The key ink characteristics according to manufacturer specifications are summarized in Table 4.3.

Several commercial silver inks are explicitly designated as LIFT-compatible by their manufacturers. Among the inks tested with the production setup, XTPL CL60 showed the most robust and consistent printing performance. Consequently, it is selected for subsequent experiments, including the fabrication of capacitors. Further investigations also included conductivity measurements of XTPL CL60 under specific printing conditions as described in Section 4.8.1.

Ink Type	NP wt%	Viscosity [Pa·s]	Solvent(s)
XTPL Ag ink CL60	58.0 ± 2.0	30 to 50 (SR = 0.2 s ⁻¹)	Glycol(s)
XTPL Ag ink CL85	82.0 ± 2.0	1 000 000 (SR = 0.2 s ⁻¹)	Glycol(s)
SA Titania paste 791547	19.0	40 to 55 (SR = 40 s ⁻¹)	-
SA Ag ink 907669	75.0	50 to 100 (SR = 1 s ⁻¹)	DGBE
PV N. Ag ink Sycris p75db-1	75.0	approx. 10 to 50 (SR = 0.2 s ⁻¹) -	DGBE

List of abbreviations:

DGBE	Diethylene Glycol Mono Butyl Ether
SA	Sigma-Aldrich
PV N.	PV Nanocell

Table 4.3: Comparison of commercially available LIFT inks tested for compatibility with the setup.

Further ZnO nanoparticle-based inks were fabricated by the project partner TECNAN (Los Arcos, Spain) as a result of the on-site optimization using the portable LIFT printer described in Section 4.2.3. The general procedure for the fabrication of the nanoparticle inks is described below while the specific quantities are omitted in order to protect the proprietary manufacturing process of the project partner.

- Dissolving of 100 mg/mL to 200 mg/mL of polyvinylpyrrolidone (PVP) in the organic solvent 2-butoxyethanol, or alternatives such as glycol or ethanol, followed by sonication for 5 min to promote complete dissolution
- Addition of nanoparticles according to Table 4.4 to obtain good homogeneity and the desired printing height
- Sonication of the ink for 15 min to 30 min to improve the dispersibility of the inorganic materials
- Pre-dissolving of ethyl cellulose in the selected solvent by magnetic stirring at 70 °C in a hot oil bath to prepare the thickener solution for viscosity adjustment
- Heating of both the nanoparticle dispersion and the ethyl cellulose solution in the oil bath and mixing under magnetic stirring

Ink Type	Np. Content [mg/mL]	Viscosity [mPa·s]	Solvent
ZnO Ink type A	8	2900	2-butoxyethanol
ZnO Ink type B	30	3800	2-butoxyethanol
ZnO Ink type C	170	6100	2-butoxyethanol
ZnO Ink type D	170		DEGMME

List of abbreviations:

DEGMME Diethylene Glycol Monoethyl Ether

Table 4.4: Custom-made LIFT inks with varying viscosity, nanoparticle content and solvent composition

4.2.3 Fabrication and Usage of the LIFT Test Printer for Ink Development

This subsection provides a detailed guide for the fabrication of the LIFT test printer intended for on-site ink development. In addition, its operation and usage, including the applied process parameters, are described.

Fabrication of the Test Printer

The custom-built device for ink development is a compact, mobile version of the production LIFT printer located at KIT, designed for on-site use at the nanoparticle and ink manufacturer TECNAN in Los Arcos, Spain. The purpose of this setup is to establish a standardized test procedure for new ink candidates that can be applied directly by the manufacturer, thereby avoiding time-consuming logistics for shipment of test batches to KIT. The target and use case of this test system are described in more detail in Section 2.1.2.

The construction and setup of the mobile LIFT printer are described in the following section, while the results obtained with the system are presented in Section 5.2. The successful implementation and use of the mobile LIFT printer were published by the author during the preparation of this work, and parts of the description and construction plan are adapted from Lux, Schlindwein, Plank, Reichert, et al. [P3].

The system enables fast on-site testing of the printability of newly developed LIFT inks and serves as a valuable tool for the rapid development and evaluation of customized ink formulations. It is particularly advantageous in international research collaborations where standardized testing conditions are essential. Acting as a reference platform, it allows reproducible and comparable qualification of inks developed at different locations. Consequently, ink formulation and optimization can be carried out remotely, while printability and performance are assessed under consistent conditions at a centralized or partner facility. This flexibility significantly accelerates the development cycle and enhances the efficiency of collaborative projects.

To achieve portability and cost-efficiency, the printer was designed as a simplified version of the main production system, retaining only its core functions, while being affordable for a few hundred Euros. It features controlled laser emission focused on a receiving substrate and incorporates an x-y positioning system to

enable precise transfer at various substrate locations. The compact design utilizes widely accessible components, facilitating easy replication and customization. This approach ensures compatibility not only with the specific ink requirements of the production printer but also allows adaptation for other LIFT systems within this research field.

The machine consists of three main components working together to form the portable LIFT printer: the mechanical stage, the laser source, and the LIFT control unit. The electronic circuit diagram illustrates the interaction of these components on the electrical level (see Figure A.13). The micro controller code that controls the components is provided in Appendix A.7.

The mechanical unit is based on a Sainsmart computerized numerical control (CNC) milling machine [53]. It serves as a mechanical platform allowing relative movement of a device or in this case, a laser diode, across an area of 300 mm $\times$ 180 mm. A laser diode directed at the sample replaces the original device. The choice of a CNC machine allows for flexible replacement of the device with various types of lasers, depending on the intended setup. Its open design provides easy access to components and simplifies modifications.

Motion along the x- and y-axes is driven by two stepper motors, each providing 0.25 N m of torque, more than sufficient for laser positioning tasks. The positioning resolution is approximately 2.5 μ m, calculated based on the microstep movement translated through a threaded rod into lateral displacement. Mechanical tolerances, estimated at 3 μ m to 5 μ m, contribute additional variability to this value.

Z-axis movement of the laser diode is controlled by a third stepper motor. This motor enables precise alignment of the laser's focal plane with the substrate using the collimator lens, by adjusting the laser diode's height in increments as small as 0.1 mm. To maintain a simple design, the original control unit and user interface of the CNC machine are retained for z-axis control. This user-friendly interface is helpful in the rare cases where the focal plane needs to be adjusted, e.g. when using non-standard substrates.

The second main component is the laser system. It includes a diode laser mounted in a custom holder and a driver unit that regulates its operation. The laser diode is sourced from Lasertack GmbH, 34277 Fuldabrück, Germany. It was selected for its compact size, easy emission control, and cost-effectiveness. This modular choice also allows for quick replacement if a different laser is needed for other setups. Images of the setup are shown in Figure 4.5.

In the current configuration, a 405 nm multimode diode laser with an output power of 500 mW is used to closely replicate the wavelength and power of the production LIFT printer (see Section 3.1). According to the manufacturer, the emission wavelength ranges from 398 nm to 410 nm [54]. As the primary function of the laser is to provide thermal energy for ink heating and material deposition, small deviations from the exact wavelength are not critical for the transfer process.

The laser's focal plane is initially coarsely adjusted using the integrated collimator lens which is set to a working distance of 81 mm. The collimator lens must remain fixed during operation, as any movement would affect the laser's output power and require recalibration. Fine alignment of the focal plane to the substrate surface is achieved using the z-axis control of the laser module.

Optimal focus is determined experimentally by inspecting carbonization marks

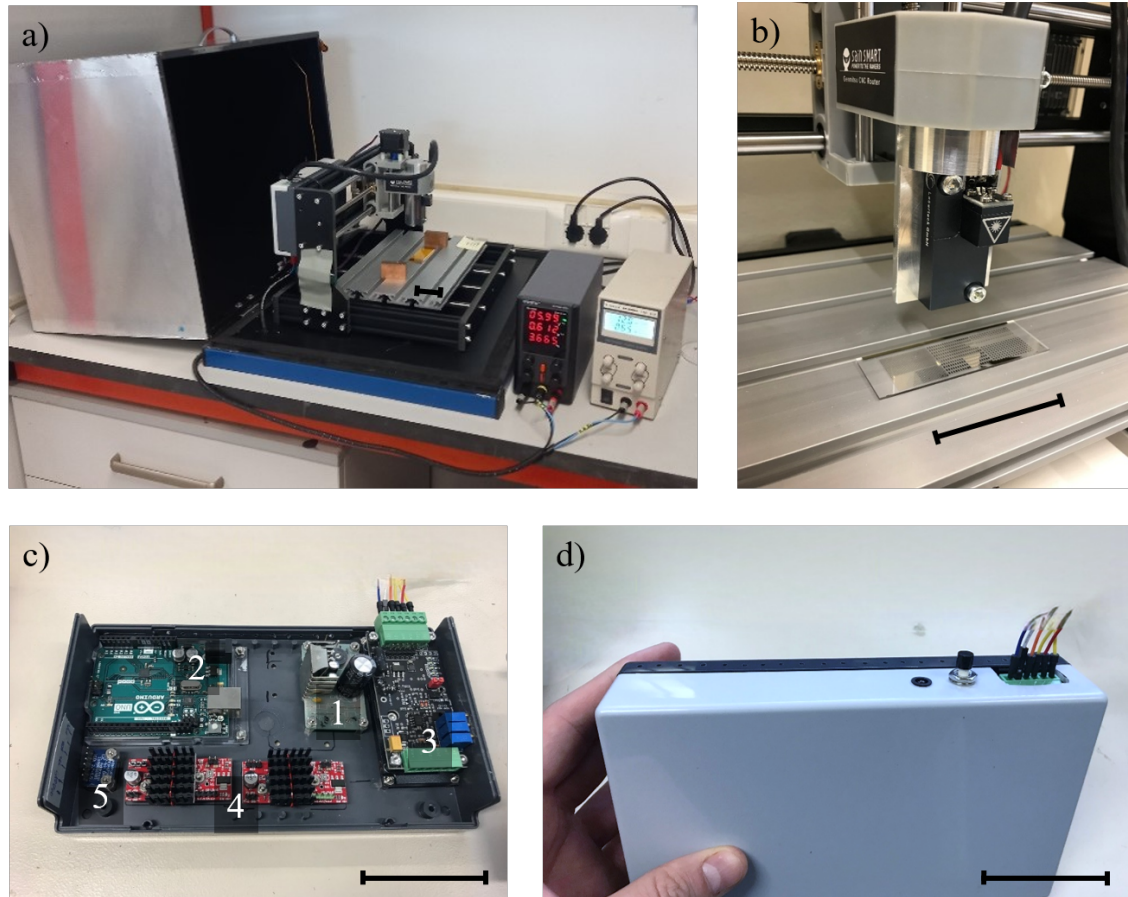


Figure 4.5: LIFT test setup, a compact version used to identify suitable nanoparticle ink compositions for LIFT printing. (a) Test printer with laser-tight enclosure and power supply (b) Laser diode mounted on a stepper-motor-controlled movable platform (c) Individual modules, including voltage controller (1), micro controller (2), laser driver (3), stepper motor drivers (4) and DAC (5) arranged in a box prior to electrical wiring (d) Simplified control interface with a single button to initiate the test print after a short delay, allowing time to close the lid. Black scale bar is 5 cm. Source: Lux et al. [P1].

left on the polyimide layer of donor slides. By varying the laser module's height, the size of the carbonized spot changes. The smallest possible mark indicates the correct focal position. The resulting laser spot diameter of this mobile setup is approximately 80 μm .

The emission of the laser diode is regulated via the applied drive voltage, which is linearly converted into optical output power by the laser driver unit. The laser diode was delivered pre-calibrated by the manufacturer. This calibration was independently verified using a Thorlabs Thermal Power Sensor (see Appendix A.1.3). The measurement confirmed that the diode's output power accurately matched the specified range of 0 mW to 500 mW.

The third main component is the LIFT control unit with all electronics, the laser driver, the x-y-motor drivers, the voltage controller, the digital-to-analog converter (DAC) and the micro controller in one compact housing. A programmed micro controller type Arduino Uno is the heart of the machine and is used to control the interaction of all separate units. The control unit is equipped with a button to start the machine and an indicator LED to show that the program is running. The micro controller is pre-programmed and runs a code after the start signal is given by pressing the button. The micro controller will communicate with the driver motors and move the stage in the predefined positions. For the laser emission the laser driver is reading an analog signal coming from an additional DAC type MCP 4725 connected to the micro controller. Over the SDA-SCL output port it will transform the digital signal of the micro controller into a true analog signal required for the laser driver. For the printing of a single dot, the laser is moved into position before the laser is turned on for a short time. The switching behavior of the DAC is monitored by an oscilloscope which confirmed a nearly ideal step function, suited for fast switching.

To ensure compatibility with the production printer, the printing procedure is designed to closely replicate its key parameters, including laser power, exposure time and positioning. The production printer operates with a maximum output power of 300 mW and the mobile LIFT printer is therefore set to operate within a similar energy range to maintain comparable processing conditions.

Operation of the Test Printer

For the qualification of paste candidates, a systematic screening was performed across a defined energy window to evaluate transfer performance. Paste samples were tested using a laser power ranging from 160 mW to 280 mW in increments of 20 mW, with a fixed pulse duration of 10 ms, which corresponds to typical settings of the production printer at the KIT. At each energy level, 16 identical dots are printed for statistical purposes, resulting in a total of 96 dots per test. The 260 mW setting was omitted due to limited substrate space. This approach allows for the assessment of each material's transferability within the tested energy range and the determination of the lower transfer energy threshold and overall reliability. Each test cycle requires approximately 3 min, corresponding to roughly 2 s per material dot. For reasons of workplace safety a laser tight cover box with an interlock system is installed, allowing operation only when closed. The results of the paste evaluations conducted with the test setup are presented in Section 5.2.

4.3 Optimization of the LIFT Transfer

In order to improve the performance and applicability of the LIFT process, several technical and material-related optimizations are implemented and evaluated in this work. These measures aim to enhance print resolution, improve transfer reliability, and enable the printing of more complex structures and devices. One key area of focus is the improvement of print resolution (see Section 4.3.1). To achieve more defined and localized transfers, artificial pillar structures are fabricated on the acceptor substrates. These microstructures serve to reduce material spreading on the acceptor and increase the precision of material placement (see Section 1.3). Subsequent printing experiments on the modified surfaces allow for a systematic evaluation of their impact on feature quality and resolution. To better control the thermal conditions during the transfer process, a temperature control unit is integrated into the LIFT setup (see Section 4.3.2). This enables the investigation of temperature-dependent effects on different material types, including both paste-based and polymeric donor materials. The findings provide insights into thermal influences on transfer efficiency, feature morphology and material integrity. Furthermore, an automated Z-stage is introduced to allow for precise and reproducible adjustment of the focal plane. This addition reduces alignment errors and ensures consistent transfer conditions which is particularly important when processing large sample areas or sensitive materials. Surface properties of the donor films are also systematically studied. In particular, different polyimide configurations are applied to the donor substrates, including variations in adhesive tapes and spin-coated layers. The influence of these modifications on adhesion, energy absorption, and overall transfer behavior is analyzed (see Section 4.3.3.2). The cumulative results from these optimization steps lay the foundation for more advanced applications of the LIFT process. This includes the printing of continuous structures such as lines and complex shapes, as well as the fabrication of functional devices such as capacitors and organic light-emitting diodes (OLEDs). For the latter, additional parameters including acceptor slide customization, material selection, and device layout are considered, alongside appropriate characterization strategies.

4.3.1 Improvement of Print Resolution

The print resolution is determined by the size of the transferred material dots and their spacing. A higher print resolution allows the production of finer structures. In the case of printed electronic components and sensors this means higher packing density and more functionality in a given space and therefore improved cost performance.

Special techniques for the improvement of printing resolution could also help to reduce variations in layer thickness. This would make it possible to realize smaller, more uniform and thinner layers.

One promising idea is the use of raised structures on the acceptor that dimensionally limit the printing area. This elevation artificially reduces the contact area during printing, as only the hills and not the valleys come into contact with the expanded donor (see Figure 4.6). This strategy is promising because the improvement is not depended on modifications of the LIFT process and it could have two positive effects.

- Increase of the printing resolution: it could be possible to reduce the spot diameter by specifically selecting the plateau diameter. In combination with

an optimized distance between the plateaus an increase in resolution will be achieved.

- More homogeneous material distribution: According to the VSI analysis in Section 3.4, the material thickness distribution of a single spot resembles approximately a normal distribution curve, with very thin edge areas and a thicker center [29]. By limiting the print area, the thinner edge regions would be excluded, leaving only the more homogeneous central section in terms of thickness.

The depth of these elevations to enable exclusive transfer on the elevated regions and their optimal spacing is determined experimentally. The experiments were conducted using the material S-LEC[®], to which the dyes coumarin and rhodamine were added at varying concentrations for fluorescence signal detection (see Section 4.2.1), with the aim of determining a suitable geometry for the elevated printing area and an appropriate spacing. For this purpose, dye concentrations and other experimental parameters were systematically varied within defined limits to identify optimal process conditions. The results are presented in Section 5.1.1.

4.3.1.1 Fabrication of Artificial Pillar Structures on Acceptors

A modular system is developed to allow efficient production of these structures and use in the LIFT printer. It consists of a holder adapted to the printing system and a modular tile. The tiles are produced lithographically and can be exchanged quickly. The print is characterized using a fluorescence scanner which precisely determines the amount of dye transferred. A sketch of the tile and the holder is shown in Figure 4.7. The tiles are fabricated out of silicon which can be processed by etching to receive the desired structures. This is expected to behave similar to a glass surface due to the oxidic layer while being easier processable than glass. The size of the tiles is 10 mm × 15 mm with 500 µm in thickness. They fit into the indentation of the 75 mm × 26 mm steel holder. The modules are fabricated in a cleanroom using lithography steps. A 500 µm, 6-inch silicon wafer is used as the base material, in which recesses are etched, leaving raised structures. The design of a high number of square shaped columns is created using the software KLayout.

The parameter settings for the pillar height, diameter, and pitch are unique for each

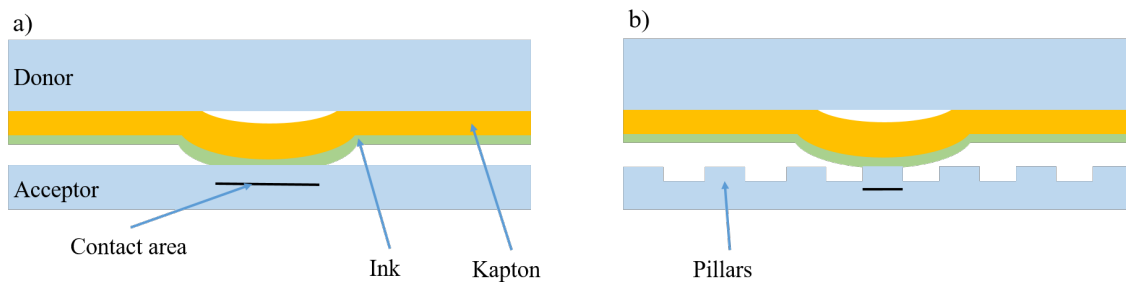


Figure 4.6: Schematic display of a donor-acceptor configuration during the transfer with the contact area marked as black line using (a) a flat acceptor (b) a pillar shaped acceptor.

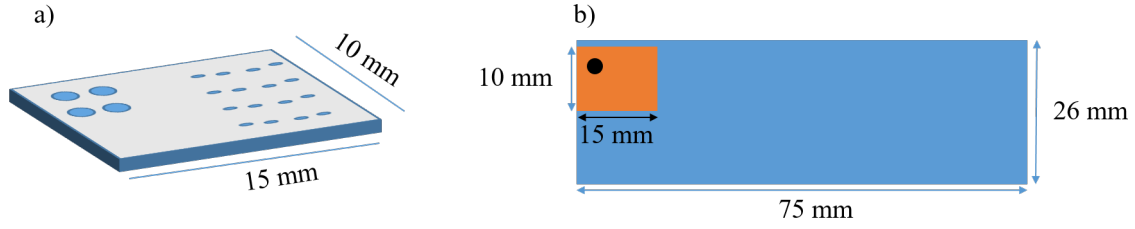


Figure 4.7: (a) Exchangable modular tiles, fabricated with raised substructures (b) which can be inserted in a holder for the LIFT printer

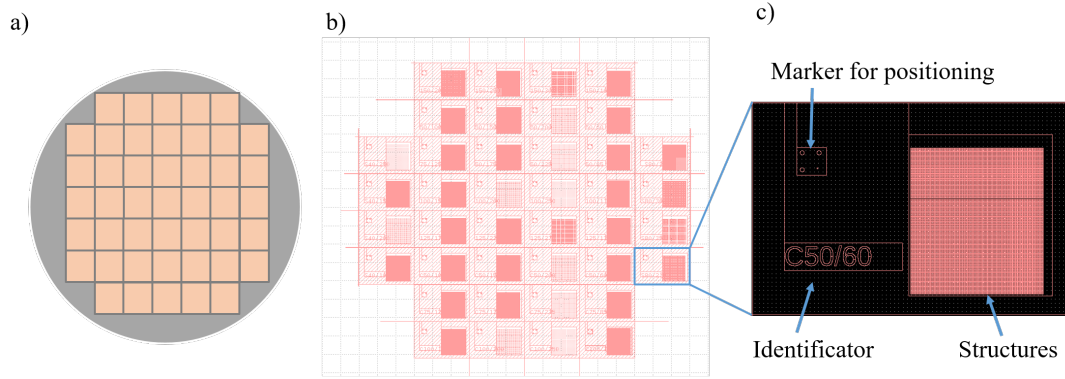


Figure 4.8: (a-b) Arrangement of tiles on the production wafer. Tiles have a unique combination of pillars with different diameter and pitch. (c) One tile consist of the structure (right) and area that is used for labeling each unique tile (left).

tile and are determined experimentally. The etching depths are identical across a single wafer due to the processing method. The parameters are summarized in Table 4.5. The tiles are arranged on the wafer in the pattern shown in Figure 4.8. After processing, the wafer is diced using a laser cutter to obtain the individual tiles.

The detailed recipe for the fabrication of the silicon structures is developed and provided by the project partner KU LEUVEN.

Mask Design and Patterning Steps

- Design of mask using KLayout
- Cleaning of the glass plate photomask, composed of an anti-reflective and a chromium layer, in a concentrated photoresist developer for 20 s. Rinsing of the plate in DI-water and drying with N gas gun.
- Coating of the glass plate with an adhesion promoter, followed by a spin-coating process with AZ 1518 photoresist.
- Baking of the photomask on a hot plate for 5 min at a temperature of 105 °C.
- Patterning of the plate with the LaserWriter LW405D with 4 μm (or less), corresponding to an L3 lens (or other). In this stage, the table should move following a D8 value, with a 30% transmission of light through the filter, and a gain of 20.

- After approximately 1 h, developing of the mask in a solution of 400 mL DI-water and 100 mL developer for 1 min, followed by a rinse in DI-water.
- Etching of the chromium with a solution of CR-14 until the pattern becomes transparent, followed by a rinse in DI-water.

Photolithographic Process of the Silicon Wafer

- Start with a prime silicon wafer and clean it by immersing it in acetone for 2 min, followed by 2 min in isopropyl alcohol (IPA). Rinse it in DI water.
- Place the wafer on a hot plate at 120 °C for 3 min to remove any residual solvents.
- Spin coat AZ125 NXT-10 A at 2000 rpm for 1 min. The resulting photoresist thickness is around 21 μm to 25 μm .
- Soft bake the wafer on a hot plate at 135 °C for 25 min, then let it cool for 5 min.
- Expose the wafer using the mask with a dose of 1000 mJ/cm².
- Develop the wafer in MIF726 for approximately 1 min or until the pattern becomes visible.
- Inspect the developed pattern under an optical microscope.
- To form the pillars, perform deep reactive ion etching (DRIE), adjusting the number of cycles as needed to achieve the desired pillar height.

4.3.1.2 Printing on Artificial Pillars

To print on the artificial pillar structures, the silicon tiles are inserted into a custom acceptor holder. Donor substrates are prepared using S-LEC[®] ink with different rhodamine dye concentrations (1% and 10%). The objective of these experiments is to investigate whether material can be selectively deposited onto the tops of the pillars while avoiding transfer into the valleys between them.

A grid of material dots is printed onto the pillar structures, with careful alignment necessary between the laser spot positions and the pillar array. Since the laser system lacks absolute positioning, the laser pitch is intentionally chosen to differ slightly from the pillar pitch. This mismatch ensures that at least some pillars are hit precisely. For example, a pitch deviation of approximately 10% produces a periodic alignment pattern that repeats after every tenth pillar. Between these exact matches, intermediate positions occur in which the laser spot and the pillar array are nearly aligned.

Printing is performed on pillar structures with different geometrical parameters to investigate selective material transfer onto the pillar tops. Pillars with a height of 78 μm , a diameter of 90 μm , and a pitch of 200 μm are printed using a S-LEC[®] ink containing 10% rhodamine dye. The laser parameters are a laser power of 200 mW and an exposure time of 10 ms.

For comparison, additional experiments are conducted on pillar structures with a

Wafer	Etching Depth [μm]	Pillar Diameter [μm]	Pitch [μm]
Wafer 1	8	50	50
	8	70	70
	8	100	100
	8	250	150
Wafer 2	18	50	50
	18	70	70
	18	100	100
	18	250	150
Wafer 3	36	50	50
	36	70	70
	36	100	100
	36	250	150
Wafer 4	78	50	50
	78	70	70
	78	100	100
	78	250	150

Table 4.5: Parameter settings for the substructures of each wafer and the corresponding etching depths

height of $18\mu\text{m}$. In these experiments, a S-LEC[®] ink containing 1% rhodamine dye is used while the alignment strategy remains unchanged.

To further investigate the influence of laser parameters and pitch mismatch, additional experiments are performed using a reduced laser power of 170 mW , an exposure time of 10 ms , and a laser pitch of $60\mu\text{m}$, while the pillar structures have a pitch of $250\mu\text{m}$ and a diameter of $90\mu\text{m}$. All printed samples are analyzed using a fluorescence scanner (see Appendix A.1.4). The corresponding results are presented in Section 5.1.1.

4.3.2 Addition of a Temperature Control Unit to the LIFT Setup

To improve the stability of the printing process and to avoid fluctuations of the temperature during the transfer and in between transfers a heating and cooling system was installed. This temperature control system can be used to counteract the changes in ambient temperature and to test the behavior of the transfer at different temperature settings. Since the transfer process induced by the laser is heat-driven, the influence of the ambient temperature needs to be investigated.

Controlling the temperature can be split into two modes: Heating and Cooling. The heating of the donor-acceptor stack was done by installing electrical heating foils on the top and bottom of the transfer stage. A thermal sensor was installed near the center of the transfer stage that monitors the actual temperature. A thermostat

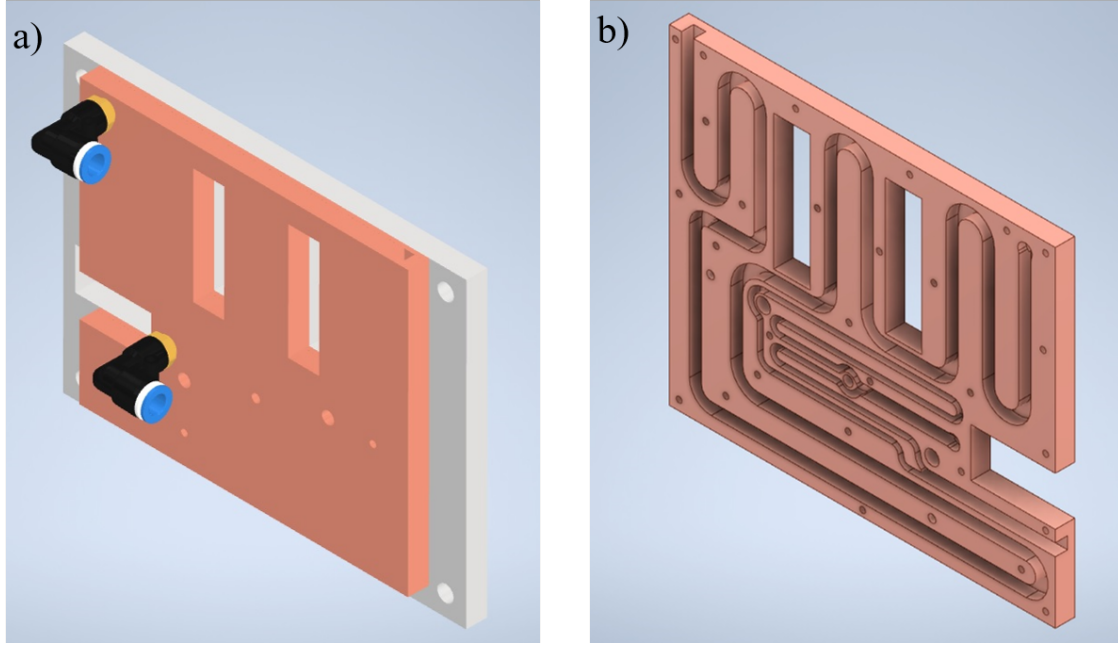


Figure 4.9: Heat coupling unit for enhanced cooling of the transfer stage. (a) CAD model of the unit mounted on the transfer stage of the LIFT printer. Two 8 mm tubes can be connected to introduce a cold air stream. (b) Channels milled into the copper block guide the cold air stream and increase the effective surface area. The copper component is attached and sealed directly to the transfer stage.

controls the current through the heating foils with the measured temperature as reference. This allows temperature control of the whole transfer stage from 21 °C up to 60 °C. While in theory higher temperatures would be feasible, some elements of the transfer stage are not resistant to temperatures above that limit. For purposes that require a higher temperature a modular insertable heating unit can be used. For the cooling unit several options are considered. The challenge is to move the heat outside of the system, without inserting more heat with the cooling setup into it which would limit its efficiency. The choice is made for vortex tubes which have the benefit of creating no extra heat inside the setup to remove heat from the system. Vortex tubes are passive elements which work by applying pressurized air of 2 bar to 7 bar. By rotating the air in a vortex inside the device it creates a cold and a warm airstream. Here the cold air is up to 31 K colder than the initial temperature of the pressured air depending on the initial pressure [55]. The higher the pressure, the greater is the temperature difference. The heat generating work that comes with every work-performing system is being performed by a compressor located outside of the building. Hereby heat input into the experimental setup is reduced. The warm air stream that comes from the vortex tube is directed away from the setup by tubes.

A custom designed channel system is designed to increase the cooling surface contact area for better cooling of the substrate. This channel system was fabricated by milling trenches inside a copper plate. The channels are then sealed with a metal sheet of copper and screwed together (see Figure 4.9). Thermal paste was used to seal the gap in between the two copper pieces. The high thermal conductivity of the copper creates a low thermal gradient in the cooling unit. The cooling unit is then

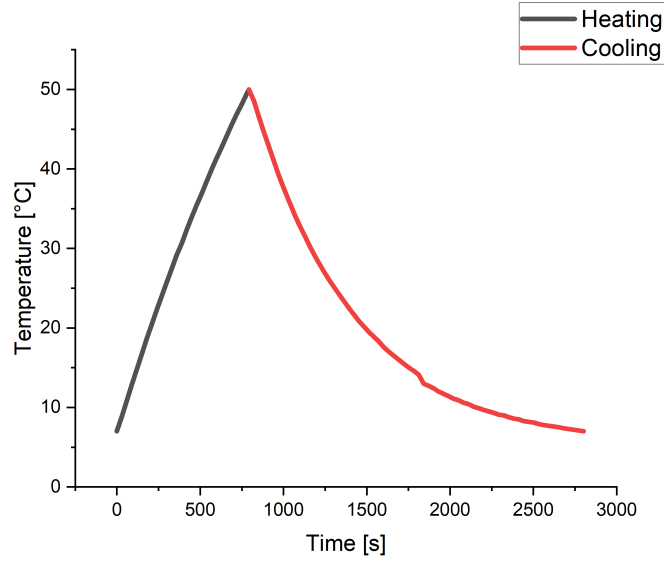


Figure 4.10: Temperature of the transfer stage when heated to 50 °C, then cooled down to 7 °C

attached to the transfer stage from below. Two vortex tubes are then connected with the quick connectors to the bottom side. The heating and cooling was tested and the temperature over time is shown in Figure 4.10. Heating from 7 °C to 50 °C takes approx. 13 min and cooling back down to 7 °C takes approx. 30 min. This temperature control method and temperature adjustment times are sufficient for the process.

4.3.3 Influence of Polyimide Modifications on the Transfer

Polyimide, also commonly referred to as Kapton[®], plays a crucial role in LIFT printing. Its primary function is to absorb the incident laser light, thereby generating sufficient thermal energy to induce vertical expansion of the polyimide layer. This functionality strongly depends on the material properties of the polyimide.

Several polyimide variants are systematically investigated with respect to their printing behavior. These include the orange adhesive tape from CMC, type 70110, with a thickness of 25 μm . Furthermore, adhesive tape variants from RegioTape (RT) in orange to red are examined, with thicknesses of 20 μm , 25 μm , and 100 μm . In addition, black adhesive Kapton[®] tape of the type Flexiso PI FI 16125 from Müller-Ahlhorn is studied. As a reference, in-house fabricated polyimide films prepared by spin coating are employed, which allow systematic variation of the film thickness without the presence of adhesives. The corresponding experiments on these polyimide variants are presented in the following section and the results are discussed in Chapter 5.

Manufacturer	Product	Color	Adhesive [μm]	Thickness [μm]
CMC Klebetechnik	70110	Orange	Polysiloxane 35	25
Regiotape	Polyimide	Yellow	Acrylate 15	20
Regiotape	Polyimide	Orange	Acrylate 15	25
Regiotape	DuPont Kapton [®]	Red	Acrylate 50	100
Müller-Ahlhorn	Flexiso [®] PI FI 16125	Black	Acrylate 30 to 40	25
KU Leuven	Spin coated film	various	-	0.35 to 25.2

Table 4.6: Overview of investigated polyimide/Kapton[®] variants and their properties

4.3.3.1 Variation of Adhesive Tape

In order to evaluate the transfer behavior of different polyimide adhesive tapes, several commercially available variants were investigated. An overview of the investigated materials is provided in Table 4.6.

For the preparation of the donor films, 15 mg glycine is dissolved in 1 mL DCM and subsequently mixed with 135 mg S-LEC[®]. A volume of 60 μL of the resulting ink is applied to the respective polyimide substrates using a doctor blade with a gap height of 1500 μm at a blade speed of 10 mm/s. (More details on the fabrication of inks and donors are found in Section 4.2.1 and Section 3.3.1.)

To assess the transfer properties under comparable conditions, identical laser parameter configurations are used for all tape variants. For each material a screening matrix is printed covering a laser power range from 120 mW to 160 mW and a pulse duration range from 6 ms to 10 ms. Based on previous studies with S-LEC[®] described in Section 3.4, these parameter ranges were found to allow reliable material transfer in the investigated energy and pulse duration window. Each matrix is printed four times under identical conditions in order to determine mean values and standard deviations for the respective parameter sets.

The complete measurement series is also conducted using various amino acid additives (glycine, cysteine, histidine, and lysine). However, these variations are not analyzed in detail in this section as they do not provide additional insight into the suitability of the polyimide substrate materials. Results of this study are presented in Section 5.1.2.

4.3.3.2 Spin Coated Polyimide

The experimental work described in this chapter is supported through a collaboration with KU LEUVEN (Belgium), which supplied the spin-coated polyimide layers and developed the fabrication process. The transfer with the customized polyimide covered glasses and the characterization measurements were carried out by the author of this work at the KIT.

In this section, the influence of the thickness of the polyimide layer on top of the donor slide on the transfer of polymers with the LIFT process is examined. For that purpose customized donor glasses are fabricated with spin coated polyimide of variable thickness. The fabrication of the polyimide slides is done by Maria Rosa and Momina Amir (KU LEUVEN, Belgium) according to the following procedure based on lab experience and input by the handbook of the manufacturer of the polyimide precursor [56, 57].

Fabrication of Spin Coated Polyimide Slides

The deposition of polyimide layers on glass substrates requires meticulous surface preparation and thermal treatment to ensure optimal adhesion and mechanical integrity. The process addresses interfacial stresses caused by mismatched thermal expansion coefficients between inorganic glass and organic polymers, utilizing silane coupling agents to promote adhesion and durability.

The materials for this recipe include soda-lime glass slides as substrates, VM651 or APTES as silane coupling agents (0.1% aqueous solution), and PI-2611 precursor from HD Microsystems as the polyimide. The equipment consists of a Headway spinner for drying, a POLOS spin-coater for polyimide deposition, a hot plate for soft baking and a programmable oven for final curing.

To prepare the surface, each glass slide is dip-coated in a 0.1% aqueous solution of VM651 or APTES for 20 s. The slides are then spin-dried using a Headway spinner and subsequently baked at 110 °C for 60 s to fix the silane layer. This treatment improves surface energy and promotes strong bonding between the glass and the polyimide layer [57].

For the polyimide coating, PI-2611 is dispensed at room temperature directly in the center of the slide, avoiding air entrapment. A short delay of a few seconds is allowed for the polyimide to flow and relax before spinning. The spin coating is performed using a POLOS coater with the following parameters (see Table 4.7):

Thickness [μm]	Spin Speed [rpm]	Time [s]
2	8000	60
5	5000	90
7	4000	90
9	3000	90
13	2000	90

Table 4.7: Spin-coating parameters for different film thicknesses

During spinning, the acceleration to the final speed should be as slow as possible to allow even coating. After spin coating, the slides undergo a soft bake on a hot plate at temperatures between 90 °C to 150 °C for 90 s. Final curing is performed in a programmable oven at 350 °C for approximately 30 minutes to complete imidization of the polyimide.

Using this procedure, donor slides with different thickness parameters are fabricated. In the first batch, donor slides with thickness parameters of 3.3 μm , 4.1 μm , 7.5 μm , 8.0 μm , 15.6 μm , 19.1 μm , and 25.2 μm are fabricated. The second batch consists of thinner layers with polyimide thicknesses of 0.83 μm , 0.5 μm , 0.43 μm , and 0.35 μm (see Table 5.1).

Experiments Using Spin Coated Polyimide Donors

These customized slides are blade coated using S-LEC[®] and polystyrene (PS) ink (see Section 4.2.1) as preparation for the LIFT transfer.

Two types of experiments are conducted: Printing of a spot scan matrix to determine the influence of a variation of laser parameters in combination with different polyimide thicknesses and printing of a fixed parameter matrix.

For the scan matrix the range of tested laser powers extends from 20 mW to 300 mW in increments of 20 mW, and the exposure times vary from 2 ms to 20 ms in steps of 2 ms. Donor films with varying polyimide layer thicknesses are prepared and the printing results are compared across these variations.

For the fixed parameter matrix a parameter set of 150 mW laser power and 15 ms exposure time is selected based on preliminary test prints and results from the scan matrix tests. This setting is chosen for its consistent transfer behavior across almost all polyimide thicknesses tested in batch 1. For statistical evaluation, 25 spots are printed with these fixed parameters. Quantitative analyses of the spot radii, spot heights and transferred volumes are performed to assess the reproducibility and stability of the transfer process.

Samples from batch 1 are exclusively printed using the transfer material S-LEC[®]. In contrast, batch 2, with its thinner polyimide layers, is tested with both S-LEC[®] and PS as transfer materials. The latter exhibits a slightly enhanced transfer behavior compared to S-LEC[®] under comparable laser settings.

A separate set of laser parameters, 300 mW and 20 ms, derived from batch 2 optimization trials, is applied to this batch and evaluated across the range of polyimide layer thicknesses. Results of these experiments are found in Section 5.1.3.

4.4 Suitable Laser Parameters for Line and Area Printing

The LIFT printer allows the deposition of individual material spots as well as continuous surfaces or layered material stacks. By combining different materials in various geometries, the fabrication of functional stacks and components becomes feasible. However, each new material exhibits a distinct printing behavior and must therefore be characterized before it can be used for the fabrication of structures and components. The standard approach for polymer-based materials is described in Section 3.4, using S-LEC[®] as a representative for most polymeric and small-molecule materials. S-LEC[®] holds a particular relevance in this context as the LIFT printer was originally developed and optimized for transfers with this material. Consequently, the fundamental process mechanisms in this work are studied primarily using S-LEC[®], since it provides the most reliable and reproducible transfer results. In this chapter, additional strategies for printing smooth surfaces, which are relevant for OLED fabrication, are presented. Furthermore, the standard approach applied to liquid nanoparticle inks is introduced.

Approach for Nanoparticle Inks

To identify suitable laser parameters for the transfer of nanoparticle inks, a dot scan matrix is printed in which laser power (120 mW to 300 mW) and exposure time (2 ms to 10 ms) are systematically varied, with each combination producing a single dot. The resulting matrix is analyzed under an optical microscope to determine the optimal parameter set based on transfer quality which is assessed by evaluating the shape, size and uniformity of the printed dots. An example of such a parameter

matrix is shown in Figure 5.21.

Each region of the matrix corresponds to a distinct combination of laser power and exposure time, allowing the identification of trends in spot morphology and systematic selection of suitable parameters. In a subsequent step, a specific parameter set is chosen according to criteria that favor the desired structure. For instance, larger lateral spots are preferred for continuous area printing to improve coverage, whereas smaller spots are advantageous for fine line definition. After parameter selection, printing tests are conducted with variations in the pitch. Depending on the lateral spot diameter, pitch values between 50% and 150% of the diameter have proven effective for connected structures. The resulting structures are examined under a light microscope and the optimal parameters are determined based on printing reliability, material spreading and the occurrence of satellite droplets to ensure high-quality printed structures.

Approach for Polymer or Small Molecule Inks to Fabricate Smooth Surfaces

In Section 3.4 the groundwork of area printing is demonstrated in which the pitch was reduced to create a slight overlap, thereby enabling the fabrication of continuous patterns. This method, however, has two disadvantages. First, the surface does not appear smooth on the nanometric scale, as well as occasional printing defects such as holes. Second, while introducing a delay of 1000 ms helps to mitigate such defects, it significantly increases the printing time and still results in height variations of approximately 10 nm. To achieve an even smoother surface, which is advantageous for the fabrication of OLEDs and other electronic components, a new printing strategy is developed.

In this approach, S-LEC[®]-glycine is used as the transfer material, combined with Kapton[®] adhesive tape and glass as receiving substrate. Donors are fabricated by blade coating 60 μ L of ink at a coating speed of 10 mm/s and a blade height of 1500 μ m. Instead of printing with a moderate overlap at a pitch of 80 μ m, the pitch is reduced to 8 μ m, corresponding to a theoretical overlap of more than 90%. The laser energy is 70 mW with an exposure time of 1 ms. It should be noted, however, that other materials may require different optimal parameter sets. The results of these experiments are shown in Section 5.3.

4.5 Area Printing with Tunable Feature Height

The fabrication of functional components requires both area printing and thickness adjustment of the deposited layers. The latter can be achieved by two approaches: (i) variation of the ink concentration on the donor substrate and (ii) adjustment of the laser parameters during transfer. The strategy of modifying the donor ink concentration to control the resulting feature height is applicable to a wide range of polymeric and small-molecule materials. This approach is demonstrated here using bathophenanthroline (Bphen), an ETL material commonly employed in OLED fabrication. Additional examples include TCTA, N,N'-bis(3-methylphenyl)-N,N'-diphenylbenzidine (TPD), 5,6,11,12-tetraphenylnaphthacene (Rubrene), tris(8-hydroxyquinolin)aluminum (Alq₃), and S-LEC[®]. The corresponding ink formulations are described in Section 4.2.1.

For the thickness variation experiments, different ink concentrations in chloroform

are employed: 4 mg/mL, 8 mg/mL, 12 mg/mL, and 30 mg/mL. Donor substrates are prepared using orange polyimide tape (CMC Klebetechnik, 70110 brown, thickness 25 μm). For TCTA and Alq₃, the alternative black polyimide tape (Dr. Dietrich Müller GmbH, Flexiso PI FI 16125 black, thickness 25 μm) is required. Donors are fabricated by blade coating 60 μL of ink at a coating speed of 10 mm/s and a blade height of 1500 μm . The coating process parameters are individually optimized for each material. For the model substance BPhen, the laser transfer parameters were set to 70 mW, 2 ms pulse duration, and a pitch of 8 μm . The resulting printed area consisted of 145 dots per column (1160 μm in width) and 190 dots per row (1520 μm in length). The results are shown in Section 5.3.1. In total, 11 printed surfaces were analyzed to obtain the values of the topography analysis.

The second approach to control the printed layer thickness is the adjustment of laser parameters. The laser power is varied starting from a baseline of 70 mW, 2 ms, and a pitch of 8 μm . The material properties and transfer conditions are kept identical to those described above. Two variations were tested: (i) increasing the laser power to 80 mW while keeping the exposure time constant, and (ii) increasing the exposure time to 3 ms while maintaining the laser power. The concentration of the ink on the donor is 12 mg/mL. The corresponding results are presented in Section 5.3.1 and Section 5.3.2.

4.6 Control of Surface Roughness for Area Printing

Controlling surface roughness is an important factor for the printing of material layers and potential components. The material BPhen is printed under conditions described in Section 4.5. Donors prepared with orange Kapton (CMC Klebetechnik) are fabricated by blade coating 60 μL of a 12 mg/mL solution of BPhen in chloroform. The surface roughness is tuned by varying the laser parameters for area printing between 70 mW, 2 ms; 70 mW, 3 ms; and 80 mW, 2 ms. Surface morphology was characterized using VSI and analyzed with the *Vision64* software (Bruker, Germany). Four surfaces were analyzed per laser parameter setting to determine the R_a values.

The corresponding results are presented in Section 5.3.2. Additionally, the dependence of surface roughness on the donor material concentration is investigated. Printing is carried out using the empirically determined optimum laser parameters of 70 mW, 2 ms with donor concentrations of 4 mg/mL, 8 mg/mL, 12 mg/mL, and 30 mg/mL. Surface morphology is analyzed using VSI and *Vision64*. The corresponding results are shown in Section 5.3.2.

4.7 Fabrication of OLEDs

This section presents the application of knowledge gained from previous experiments to the printing of OLEDs. OLEDs are multi-material, multilayer components with a flat architecture that require nanometric precision in fabrication to function properly. The ITO substrates fabricated in Section 4.1.3 are used for the operation and characterization of the OLEDs. The inks described in Section 4.2.1 serve as the donor materials for printing. The printing techniques and methods outlined in Section 4.4 are applied for area printing and thin-layer deposition. Strategies from

Section 4.5 are employed to adjust layer thickness, while Section 4.6 provides approaches to achieve smooth surfaces. For operation and characterization, the MATIS setup described in Appendix A.1.9 is used.

4.7.1 Materials for OLED Fabrication

Material selection is a key determinant for successful OLED fabrication, particularly when using LIFT under ambient conditions. Since both the LIFT setup and the donor preparation process operate without inert gas protection, only materials that exhibit sufficient stability toward oxygen and humidity can be employed. The chosen organic and electrode materials therefore combine reasonable environmental stability with suitable electronic properties for charge injection, transport and recombination.

ITO-coated glass is used as the substrate material for OLED fabrication. Both glass and ITO are transparent in the visible spectral range and show good stability under air exposure. The work function of ITO is reported in the literature as 4.6 eV to 4.75 eV [58, 59, 60], although it can vary depending on surface treatments and cleaning procedures. The work function represents the minimum energy required to remove an electron from the material's surface and is therefore crucial for assessing the compatibility of different materials in electronic devices.

Two fabrication approaches were employed to produce three-layer OLEDs (excluding electrodes): (i) a hybrid OLED, which combines the well-established processes of OLED fabrication with the patterning flexibility provided by LIFT printing. This approach allows individual LIFT-printed layers to be studied before proceeding to fully multilayer LIFT-printed devices, and (ii) a fully LIFT-printed OLED, composed entirely of printed organic layers. This approach demonstrates a fully additive, maskless fabrication route that is compatible with flexible patterning.

The key distinction between both device types lies in the number of layers deposited via LIFT.

The materials used are listed together with their work function and highest occupied molecular orbital (HOMO)-lowest unoccupied molecular orbital (LUMO) level because those numbers are relevant for their functionality. For the hybrid OLED, a PEDOT:PSS ink from Ossila (Clevios™ F HC Solar Solvent) is first spin-coated to form the HTL. This material is selected for its high conductivity (100 to 1000 $\Omega/\square$) and excellent wetting behavior on glass substrates [61]. Its reported work function of 4.8 eV to 5.0 eV. For clarity, the material parameters are shown in Table 4.8.

Subsequent organic layers were deposited by LIFT, comprising Rubrene as the EML and Bphen as the ETL. Rubrene exhibits a work function of 4.2 eV [62], a HOMO level of 5.4 eV, and a LUMO level of 3.2 eV [63]. Bphen has a reported work function of 4.7 eV [64], a HOMO of 6.4 eV, and a LUMO of 3.0 eV [65]. These energy levels enable efficient charge confinement within the emissive Rubrene layer, because the adjacent HTL is energetically more negative and the adjacent ETL is energetically more positive and therefore enables the natural charge transport into the EML [66]. Finally, an aluminum cathode (work function of 4.3 eV to 4.4 eV [67]) is thermally evaporated.

The fully printed OLEDs are fabricated exclusively by LIFT deposition of all organic layers. Several material combinations are investigated, employing TCTA, TPD, 1,1-bis[(di-4-tolylamino) phenyl] cyclohexane (TAPC), Rubrene, Alq₃, and Bphen. TCTA exhibits a HOMO level of approximately 5.7 eV and a LUMO level

of 2.4 eV [68], while TPD possesses a HOMO level of 5.5 eV and a LUMO level of 2.3 eV [69] and TAPC possesses a LUMO of 2.0 eV and a HOMO level of 5.5 eV [70]. For clarity, the material parameters are shown in Table 4.8. These properties make TCTA and TPD suitable as hole-transport or exciton-blocking layers. TAPC is investigated for printing but not used as material in a final OLED stack configuration. Alq₃ has a HOMO level of 5.62 eV and a LUMO level of 2.85 eV [71], providing balanced electron transport and emissive characteristics. Bphen serves as the ETL, analogous to its role in the hybrid structure. Finally, an aluminum layer is thermally evaporated to form the cathode. The structural formula of the OLED materials is shown in Figure A.9.

For the selection of materials, resistance to oxidation and humidity as well as availability is taken into account. To achieve a functional OLED, basic design rules should be followed as closely as possible. For efficient hole injection, the HOMO level of the HTL should be close to the work function of the anode [66]. In the configurations ITO–TPD and ITO–TCTA, the HOMO–anode differences are 0.8 eV and 1.0 eV respectively which are considered sufficiently small for efficient injection. For efficient electron injection, the LUMO level of the ETL should be close to the work function of the cathode [66]. In this case the difference between aluminum and Bphen is 1.3 eV to 1.4 eV which is not insignificant. This will create an injection barrier which has to be overcome by electrons, raising the overall voltage necessary to operate the OLED. Aluminum was selected because, although it readily oxidizes, it forms a thin, dense, and self-limiting oxide layer that passivates the surface and thereby slows further oxidation compared to other metals such as silver. Although materials like LiF, Ba, or Ca are often used as interlayers to reduce the injection barrier, they are not used here due to their instability in the presence of oxygen. Other candidates such as ZnO lack availability.

For efficient charge transport in between the layers HTL, EML, ETL the energy levels should be aligned such that:

- The HOMO of the EML is slightly lower than the HOMO of the HTL, facilitating hole transport into the EML.
- The LUMO of the EML is slightly higher than the LUMO of the ETL, facilitating electron transport into the EML.

This will lead to recombination of electrons and holes in the EML which produces excitons. Maintaining a small HOMO–LUMO offset at the EML interfaces additionally helps to confine excitons within the EML, enhancing emission efficiency. Therefore, small energy offsets at the interfaces are desirable.

The selected material combinations ensure favorable energy-level alignment across all interfaces, promoting charge injection and recombination within the emissive region while maintaining sufficient stability for LIFT processing under ambient laboratory conditions which includes the exposure to oxygen and humidity.

4.7.2 3D Layout

The 3D layout of OLEDs plays a crucial role in determining their electrical and optical performance. This section describes the spatial arrangement of the printed OLED layers, as well as the supporting structures and materials used for device fabrication. The base substrate is a customized ITO-coated glass slide, fabricated using

Material	Type / Role	Work Function [eV]	HOMO [eV]	LUMO [eV]
ITO	Anode	4.6–4.8	-	-
PEDOT:PSS	HTL	4.8–5.0	-	-
TCTA	HTL / EBL	-	5.7	2.4
TPD	HTL / EBL	-	5.5	2.3
TAPC	HTL / EBL	-	5.5	2.0
Rubrene	EML	4.2	5.4	3.2
Alq ₃	EML / ETL	-	5.6	2.9
BPhen	ETL	4.7	6.4	3.0
Al	Cathode	4.3–4.4	-	-

Table 4.8: Electronic properties and functional roles of materials used for OLED fabrication. Sources cited in the text.

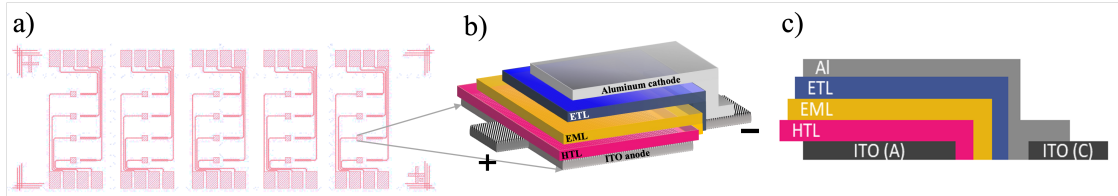


Figure 4.11: (a) Layout of the ITO substrate used for OLED fabrication, featuring 20 pads serving as printing centers for the OLEDs. (b) 3D schematic of the printed OLED stack, showing the ITO, HTL, EML, ETL, and Al layers. (c) 2D projection of the same printed OLED layer geometry. Source: Lux et al. [P3]

cleanroom processes as described in Section 4.1.3. The ITO layer forms a pad with a size of 1 mm^2 serving as the OLED anode. Layer by layer, the OLED is successively fabricated on top of this pad. The cathode material is subsequently evaporated and must be electrically connected to the counter electrode located adjacent to the ITO pad, separated by a non-conductive glass gap. The layout of the ITO substrate and schematic representations of the OLED structure are shown in Figure 4.11.

The hybrid OLED and the fully printed OLED share the same basic layout, differing only in the HTL. In principle, an OLED could be realized as a simple vertical stack of layers with identical lateral dimensions. However, this configuration complicates electrical contacting of the cathode, which is located at the top of the stack. Direct top-probing of the cathode with a probe station can lead to mechanical damage if excessive force is applied, or to an unstable electrical contact if the applied pressure is insufficient.

To ensure reliable electrical connection without damaging the device, the cathode is laterally elongated and connected to predefined conductive paths on the substrate. These paths lead to contact pads positioned at the substrate edge. Among possible designs, the bridging approach where the cathode is extended to meet the external contact path is selected for all OLED variants.

For controlled charge transport and electrical isolation between layers, the OLED stack was designed in a pyramid-like geometry. Each subsequent layer is printed

slightly smaller than the one below, preventing undesired vertical bridging or short circuits. To further minimize the risk of overlap between the cathode and underlying layers, the pyramid was tilted into a staggered layout aligned along the ITO track direction.

The first HTL layer consists of a rectangular array of 165 by 190 printed pixels with an $8\text{ }\mu\text{m}$ pitch, yielding an active area of $1320\text{ }\mu\text{m} \times 1520\text{ }\mu\text{m}$. The second layer is printed $40\text{ }\mu\text{m}$ smaller on each side, except on the side aligned with the ITO track, where it is extended by $40\text{ }\mu\text{m}$. The third layer follows the same principle, being $40\text{ }\mu\text{m}$ shorter on the other sides and equally elongated along the ITO direction.

The cathode is deposited through a shadow mask fabricated by laser cutting of a thin steel foil. Each cathode opening formed a $1000\text{ }\mu\text{m} \times 1000\text{ }\mu\text{m}$ square, extended by a rectangular bridge measuring $1100\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$, (shown in Figure A.10) which connects the cathode to the electrical path on the substrate. This design is consistently applied to all OLED variants, including the hybrid OLED with a spin-coated HTL.

4.7.3 Fabrication Recipe

This chapter describes the fabrication recipes for different OLED variants. Two main device types are produced: a hybrid OLED, where one layer is deposited by spin coating with the remaining layers printed via LIFT, and a fully printed OLED with several sub-variants. To maintain a clear focus and a manageable experimental scope, only representative material systems are selected for actual device fabrication, while additional materials are investigated primarily for comparative purposes or to show alternatives.

Hybrid OLED

The complete fabrication process for the hybrid OLED comprises substrate preparation, manual processing steps, and subsequent spin coating and printing. The ITO substrates are prepared according to the procedure described in Section 4.1.3. For some printed OLEDs, commercially obtained custom ITO-coated glass slides are used, identical in all relevant specifications to the manually fabricated substrates. These ITO glasses were custom-manufactured by VisionTek Systems Ltd, Cheshire, UK, based on a layout provided by the author. Details of the manufacturing process are not disclosed.

Although all ITO substrates are nominally identical, manufacturing-related deviations in the positioning of the structures on the slides can occur. These deviations may arise because the cut edges of the glass slides are always slightly misaligned by a few micrometers with respect to each other. To ensure proper positioning of the printed structures on the substrate, manual alignment using test prints and subsequent corrections is necessary. After test printing, the printed layers are removed again using acetone to prepare the slide for the actual OLED fabrication.

Prior to further processing, the substrates are cleaned with acetone and subsequently plasma cleaned as described in Appendix A.1.2. The plasma treatment is performed using oxygen from ambient laboratory air at a power of 65 W for 5 min. Immediately after plasma cleaning, the substrate is spin coated with PEDOT:PSS ink as described in Section 4.2.1. Approximately 1 mL of the ink, is necessary to fully cover the substrate. The spin coater is operated at 50 rps for 40 s, with an acceleration

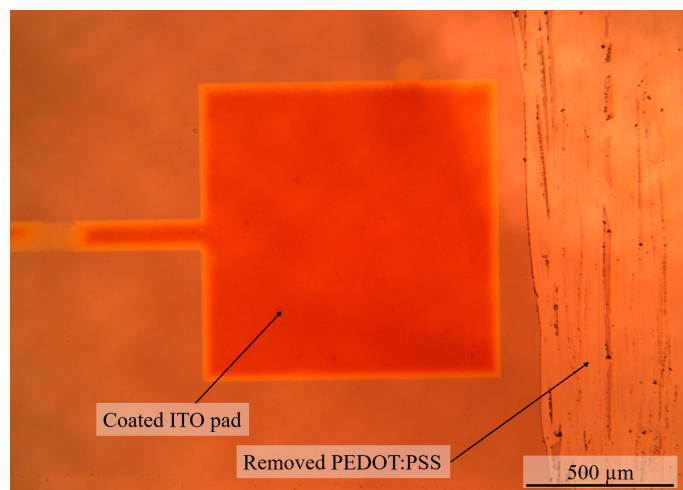


Figure 4.12: PEDOT:PSS spin-coated onto an ITO pad for OLED fabrication. The selectively removed area, created using a cotton swab and a scalpel, is visible on the right side. The ITO track towards the anode is seen at the left side.

phase of 5 s, followed by 30 rps for 1 s. The coated substrate is then dried in an oven at 100 °C for 10 min to remove residual water and DMSO.

Spin coating is a non-selective process that covers the entire substrate. Since PEDOT:PSS is conductive, selective removal is required to prevent unwanted electrical contact between adjacent OLEDs. The PEDOT:PSS layer is manually removed using a cotton swab or scalpel around the OLED area and most importantly, between the ITO pad (anode) and the conductive track of the cathode (see Figure 4.12).

In some cases, deionized water is used to assist the selective removal of PEDOT:PSS. When this approach is applied, the substrates are dried again in the oven to remove any remaining moisture.

Subsequently, the OLED fabrication continues with the LIFT printing of Rubrene and Bphen. To minimize exposure to humidity, the laser setup is flooded with dehumidified air to maintain a relative humidity of approximately 20%. Rubrene is transferred using a laser power of 70 mW and an exposure time of 2 ms, with a lateral pitch of 8 μm. The donor substrates are prepared using 60 μL of 8 mg/mL Rubrene ink dissolved in chloroform (see Section 4.2.1 for ink preparation), applied onto CMC Kapton® tape (see Section 4.3.3.1 for Kapton® variants). The area printing pattern described in Section 4.7.2 is used.

Following the Rubrene deposition, a second layer consisting of Bphen is added. This layer is transferred using CMC Kapton® tape coated with 60 μL of 15 mg/mL Bphen ink in chloroform. The laser parameters are identical to those used for Rubrene transfer, except for the lateral dimension (Section 4.7.2). The printing pattern described in Section 4.7.2 is applied. The process parameters are summarized in Table 4.9.

The printing of the layers is followed by the fabrication of the cathode. A customized shadow mask is applied to the sample, as shown in Figure A.10. To prevent scratching or damaging the printed structures, thin strips of polyimide tape are carefully adhered between the OLED columns. These tape pieces create a small artificial gap that prevents direct contact between the mask and the sample. The shadow mask is manually positioned and fixed above the sample using a light microscope.

Material	Conc. [mg/mL]	Laser power [mW]	Exposure [ms]	Prints	Type of Polyimide
TCTA	30	70	3	2	Flexiso PI FI 16125
TPD	30	70	2	1	Flexiso PI FI 16125
Rubrene	8	70	2	1	CMC Klebetechnik 70110
Alq ₃	15	70	2	1	Flexiso PI FI 16125
Bphen	4	70	2	1	CMC Klebetechnik 70110

Table 4.9: Transfer parameters of each material used for the fully printed OLEDs.

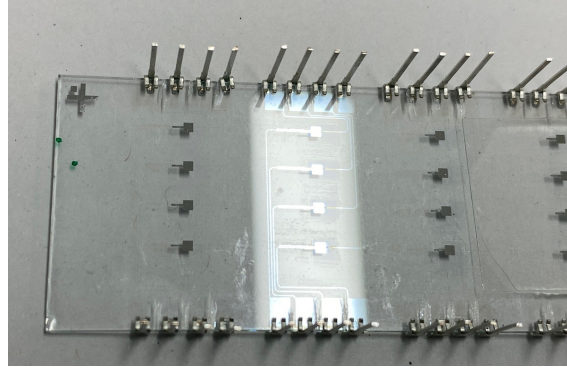


Figure 4.13: Image of a hybrid OLED sample after aluminum evaporation, with connection legs attached to the edge of the glass slide, ready for characterization. The light reflection makes the ITO tracks and the scratched PEDOT:PSS layer visible. One slide consists of 5 of these highlighted units.

Aluminum with a thickness of approximately 100 nm is deposited by thermal evaporation using an evaporator (UNIVEX 400, Leybold). The deposition rate is set to 0.1 nm/s, with no tilt, and the sample is rotated at 10 rpm. During evaporation, the sample temperature is maintained at 20 °C and the chamber pressure at 8.0×10^{-6} bar. After evaporation, the sample is inspected and tested for electroluminescence. During transport and waiting phases, which are kept as short as possible, the sample is stored under laboratory atmosphere with desiccant to minimize humidity exposure. An image of the sample ready for the characterization is shown in Figure 4.13.

Fully Printed OLED

The fully printed OLED represents a further development beyond the hybrid OLED. Instead of combining two fabrication methods, spin coating and printing, the organic layers are fabricated exclusively by LIFT printing, and the PEDOT:PSS layer is replaced by a LIFT-printable HTL. An advantage of this approach is that manual process steps, such as the selective removal of PEDOT:PSS, are no longer required. This reduces potential sources of variation in the fabrication process and makes the overall procedure more robust. Furthermore, an increased robustness against humidity exposure is observed, since PEDOT:PSS is known to be sensitive to water exposure.

The substrates used here are identical to those employed for the hybrid OLEDs as described in Section 4.1.3. For some printed OLEDs, commercially obtained custom ITO-coated glass slides were used, which were identical in all relevant specifications to the manually fabricated substrates. These ITO glasses are custom-manufactured

by VisionTek Systems Ltd, Cheshire, UK and were not available for all experiments. For the preparation of the donor films, different Kapton[®] variants and inks are utilized (see Section 4.3.3.1 for Kapton[®] variants and Section 4.2.1 for ink formulations). The materials TCTA, TPD, and Alq₃ are tested with various Kapton[®] types, and Flexiso PI FI 16125 is found to perform best for these materials.

Prior to printing, the substrates are cleaned with acetone to remove dust or other contaminants. To minimize exposure to humidity, the laser setup was flooded with dehumidified air, maintaining a relative humidity of approximately 20%.

The printing layout described in Section 4.7.2 is applied. Accordingly, three-layer OLED stacks are printed using combinations of HTL materials (TCTA, TPD), EML materials (Rubrene and Alq₃), and the ETL material Bphen. The corresponding transfer parameters used for printing are listed in Table 4.9.

The LIFT printing is followed by the deposition of 100 nm of aluminum by thermal evaporation under conditions similar to those described in the section on the hybrid OLED.

Additionally, the material TAPC, a potential replacement for the HTL, is tested for its printability. The transfer and layer printing using LIFT are found to be feasible. Therefore, TAPC is included among the OLED materials investigated in this work. However, its printing parameters are neither fully optimized for OLED layer transfer, nor is it integrated into an actual OLED stack, as this was beyond the main focus of the present study.

The results of the OLED printing experiments are presented in Section 5.4, while the corresponding characterization methods are described in Section 4.7.4.

4.7.4 Characterization Strategy

In the previous steps it is demonstrated how OLEDs can be printed on customized ITO substrates. These samples are now tested to evaluate their operation and performance. Since the sample slides are custom-fabricated, a tailored measurement setup is required to operate the OLEDs reliably during testing. This requirement is met by the modular automated testing and inspection system (MATIS) setup, which is described in more detail in Appendix A.1.9. In brief, the setup provides the necessary electronics for OLED operation using a source measure unit (SMU), which simultaneously applies and records voltage and current. The setup also integrates a spectrometer that detects the optical emission guided to it via an optical fiber. With this configuration it is possible to determine whether light emission occurs to compare emission spectra between different OLEDs to and analyze the voltage and current conditions under which the devices operate.

Since the lifetime behavior of the OLEDs is of particular interest, emission spectra are recorded over various measurement times by integrating the spectrometer signal over the measurement period. Prior to the acquisition of the OLED emission, the MATIS software records three dark spectra with an integration time similar to that of one measurement cycle. During data processing the cycles are averaged and the dark spectra are subtracted from the measurement signal to eliminate the influence of background light. The SMU operated the OLEDs with a maximum current of 1 mA or 10 mA and a maximum voltage of 20 V. The devices are operated in "source with compliance" mode, which limits either the voltage or the current if one of the parameters would exceed the set limits. This mode protects the OLEDs from rapid degradation due to high voltage or from burnout caused by excessive current. The following characterization measurements are performed using the MATIS setup:



Figure 4.14: Image of an OLED sample being characterized using the MATIS setup. The lens is positioned directly above the sample to capture the emission signal, which is then guided to the spectrometer via an optical fiber. The small yellow dots are emitting OLEDs during measurement. White scale bar = 2.5 cm.

- Current-Voltage (IV)-curve measurement under emission to determine the turn-on voltage
- Short-term lifetime measurements with acquisition cycles of 0.5 s
- Mid-term lifetime measurements with acquisition cycles of 5 s, 10 s, and 20 s
- Long-term lifetime measurements under continuous operation with acquisition cycles of 20 min
- Long-term lifetime measurements with intermediate testing at acquisition cycles of 10 s
- Time-resolved current and voltage monitoring

An image of a sample being analyzed using the MATIS setup is shown in Figure 4.14. Optical images of the measured devices can also be acquired using an integrated camera.

Selected OLED samples are further examined by focused ion beam (FIB)-scanning electron microscopy (SEM) tomography (see Appendix A.1.8) to obtain information about their three-dimensional structure. The SEM analysis additionally provided cross-sectional images, allowing the determination of printed layer thickness.

Moreover, some samples are analyzed using time-of-flight secondary ion mass spectrometry (TOF SIMS) to gain insights into the molecular composition of the printed structures. This method offers detailed mass spectrometric information

about the chemical makeup but does not provide data on layer thickness (see Appendix A.1.11). By combining FIB-SEM analysis and TOF SIMS, it is possible to determine the thickness of the printed layers as well as to verify the transferred material and the printing sequence. The results of the OLED printing experiments, characterized using the methods described in this chapter, are presented in Section 5.4.

4.8 Fabrication of Capacitors

To demonstrate the feasibility of LIFT for the fabrication of functional electronic components, parallel-plate capacitors are realized with dot-by-dot printing of nanoparticle inks. The devices are printed onto a bottom gold electrode by dot-by-dot printing of a titanium dioxide ink as the dielectric layer and a silver ink as the top electrode. More detailed information on the ink formulations is provided in Section 4.2.2.

For the electrical characterization of the printed capacitors, a custom-fabricated base substrate is required to ensure a low-resistance contact to the network analyzer. The fabrication of these custom-made substrates is described in Section 4.1.2.

The dot-by-dot LIFT printing of capacitors is published by the author in Wiley Applied Research (2024) [P2]. Parts of the fabrication description and selected images in this section are reproduced from that publication.

4.8.1 Material Selection and Conductivity Measurements

For the printing of capacitors, conductive and electrically insulating materials are required that are compatible with the LIFT printing process. In this work, nanoparticle inks that are non-transparent to laser light were used, allowing them to act both as the functional material and as the laser-absorbing layer, replacing the previously applied Kapton[®] tape. The corresponding coating process is described in Section 3.3.2. Since the inks must simultaneously absorb laser energy and form stable printed features, their rheological and optical properties are crucial for reproducible transfer.

Successful LIFT printing requires inks with sufficiently high viscosity to maintain coating stability on the donor slide and to enable uniform droplet transfer without splashing. While no strict lower viscosity limit is identified, stable printing is achieved for inks with viscosities between 30 Pa s to 50 Pa s and up to approximately 1×10^6 Pa s (see Table 4.3). The upper viscosity limit is governed by the energy required for the laser to generate a bubble or to propel the ink onto the acceptor. However, inks at the upper end of this range are generally not recommended, as their high viscosity prevents sufficient flow before drying occurs. To achieve smooth and homogeneous layers, inks must remain fluid enough for the droplets to coalesce and, driven by surface tension, form a uniform surface.

Furthermore, the inks must withstand direct laser irradiation and convert the absorbed energy into localized heat that drives bubble formation and material ejection. To ensure proper wetting on both donor and receiver substrates, surface energies are adjusted by plasma treatment where necessary.

Silver and titanium dioxide nanoparticle inks are selected as electrode and dielectric materials, respectively, based on their electrical and thermal properties. The detailed compositions and key parameters of both inks are summarized below.

Silver Ink XTPL CL60

Silver is chosen as the conductive electrode material due to its low electrical resistivity and established use in printed electronics. Gold inks would be an alternative but are cost-prohibitive and less available. The resistivity of bulk silver is $1.47 \times 10^{-8} \Omega \text{ m}$ [72], while that of printed XTPL CL60 silver is reported as $5.1 \times 10^{-8} \Omega \text{ m}$ [73]. The ink contains 54 wt % to 63 wt % silver nanoparticles with diameters between 35 nm to 50 nm, dispersed in a glycol-based solvent. With a viscosity of 30 Pa s to 55 Pa s at 25 °C (shear rate = 0.2/s) it spreads uniformly and remains stable after transfer. Post-printing, thermal sintering enhances particle interconnection and removes organics, thereby reducing resistance. Compared to copper, silver is chemically stable and does not form surface oxides.

Titanium Dioxide Ink Sigma-Aldrich 91547

titanium dioxide (TiO_2) is selected as the dielectric material due to its high permittivity and thermal stability. The dielectric constant ϵ_r of TiO_2 is reported to lie between 173 to 211 depending on crystal structure and temperature [74], while a value of $\epsilon_r = 18.9$ is reported for anatase [75]. The crystalline phase present in the used ink is not specified by the manufacturer. The Sigma-Aldrich 91547 ink contains 17.8 wt% to 20.2 wt% TiO_2 nanoparticles (diameter ≈ 20 nm) dispersed in an organic medium with a viscosity of 40 Pa s to 55 Pa s [76]. Although its effective permittivity is expected to be lower than that of bulk TiO_2 , it remains suitable for compact capacitor structures. The ink exhibits high thermal stability during LIFT printing and subsequent sintering, enabling reproducible dielectric layers with minimal organic residue.

Both inks are evaluated with respect to transfer stability, layer uniformity, and electrical performance to ensure reliable capacitor fabrication. Their respective functional roles within the capacitor stack are described in Section 4.8.2.

Resistivity Measurements

Since the electrical performance of nanoparticle-based materials can differ significantly from that of bulk materials and may strongly depend on the specific printing or deposition process, resistivity measurements are performed. For this purpose, conductive silver tracks are printed and evaluated with respect to the bridged length, the number of printed layers and the effect of sintering. The substrate preparation and printing are carried out at KIT, while the resistivity measurements are performed by the project partner KU Leuven, Belgium (see Appendix A.1.6). To ensure a low-ohmic contact between the printed structure and the measurement setup, a suitable substrate is required. Gold-plated glass slides are therefore selected, as they provide a conductive interface and are also used for capacitor fabrication (see Section 4.1.2 and Figure 4.15a).

The conductive tracks are printed to bridge the insulating glass gap between two gold pads, with gap lengths of either 500 μm or 1000 μm . The resistivity is determined using a four-point probe connected to a Keithley 2450 SMU, as illustrated in Figure 4.15b. The resistance is measured by applying a DC current through the outer probes while recording the voltage drop across the inner probes. The geometrical dimensions of the printed structures are measured and used to calculate the material resistivity.

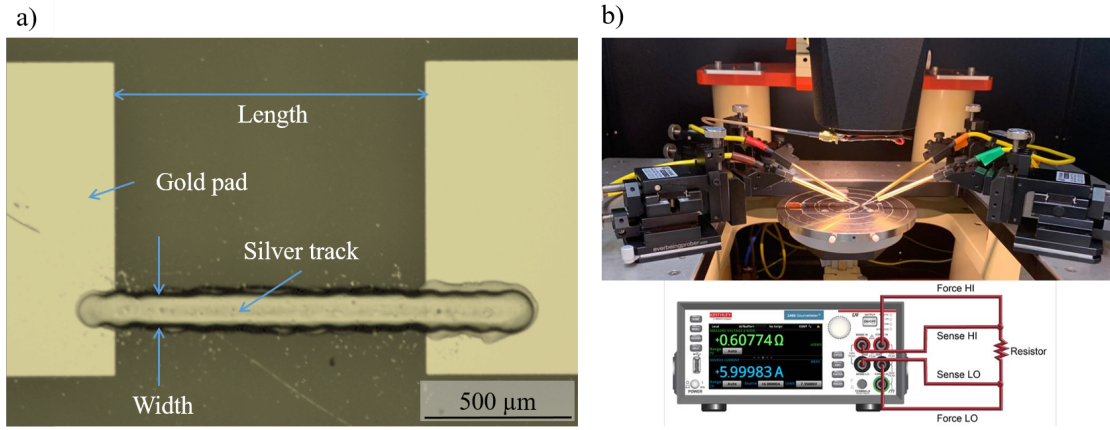


Figure 4.15: (a) Conductive tracks printed from silver ink bridging two adjacent gold pads. (b) Four-point probe setup connected to a SMU for measuring the conductivity of the printed tracks. Source: Lux et al. [P2]

The printing parameters are optimized to achieve uniform and continuous line structures. The selected parameters are a laser power of 220 mW, a pulse duration of 4 ms, a pitch of 90 μm , a spacer distance between donor and acceptor of 70 μm , and a blading gap of 20 μm for donor preparation. The transfer process is performed by printing 8 or 16 dots in a horizontal line between two adjacent pads at a stage temperature of 25 $^{\circ}\text{C}$ (see Figure 4.15a). The samples are electrically measured before the sintering step.

The sintering process consists of two stages. The temperature is increased at a rate of 4 $^{\circ}\text{C}/\text{min}$ up to a plateau at 100 $^{\circ}\text{C}$, which is maintained for 5 min. It is then further raised at 2.5 $^{\circ}\text{C}/\text{min}$ to reach 250 $^{\circ}\text{C}$, held for 30 min, and subsequently cooled down gradually to room temperature. After sintering, the resistivity measurements are repeated. The results of this study are presented in Section 5.5.1.

4.8.2 3D Layout

The 3D layout of the printed capacitors is defined by the vertical stacking of functional layers, each serving a distinct electrical role. The capacitor architecture consists of two conductive silver electrodes separated by a TiO_2 dielectric layer (see Figure 4.1). Silver provides low resistivity for efficient charge transport, while TiO_2 ensures high charge storage capacity due to its relatively high dielectric constant. The layer sequence and material selection are discussed in Section 4.8.1.

For accurate and reproducible electrical characterization all capacitors are printed on custom-fabricated gold base substrates. Gold offers high conductivity and ensures low-ohmic contact with the measurement probes due to its softness, minimizing contact resistance. The fabrication of these base substrates is detailed in Section 4.1.2 and the layout is shown in Figure 4.3. The probe head used for characterization requires contact pads at a fixed spacing of 450 μm , which defines the geometry of the extended contact arms adjacent to each capacitor pad.

The first electrode consists of a 40 nm vapor-deposited gold layer that serves as the foundation for the printed layers. Each capacitor unit is designed as a square with an active electrode area of 1 mm^2 . The extended contact arms enable precise probe placement for electrical testing without damaging the printed stack. The subse-

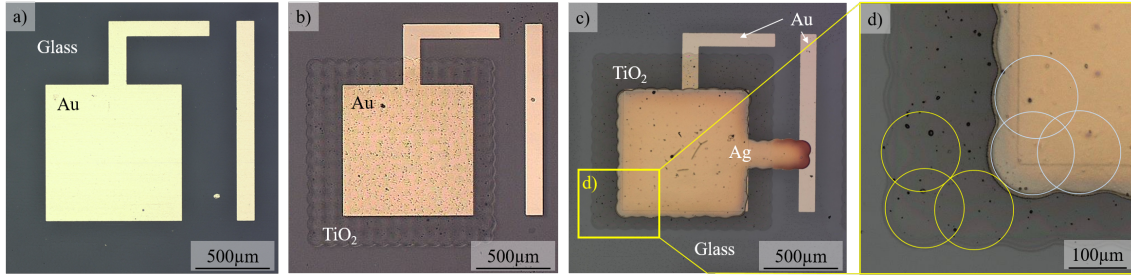


Figure 4.16: Capacitor fabrication shown layer by layer after drying. (a) Bottom gold electrode deposited on a glass substrate. (b) Dielectric TiO_2 layer printed on top of the gold electrode with defined overlap. (c) Top electrode printed using silver nanoparticle ink, including a conductive track for electrical connection. (d) Detailed microscopic image of a completed capacitor. Individual printed dots are still faintly visible and highlighted in yellow and white. Source: Lux et al. [P2].

quently printed silver and TiO_2 layers form the complete capacitor structure, as illustrated in Figure 4.16.

The second layer consists of printed titanium dioxide ink, forming the dielectric layer. It covers an area slightly larger than the 1 mm^2 bottom electrode to prevent short circuits along the edges. The individual droplets are deposited with partial overlap, as shown in Figure 4.16d. The layer thickness is on the order of a few micrometers but is not measured in the liquid state. Upon sintering, the layer shrinks and is characterized in its solidified form (see Section 4.8.4).

The third layer serves as the top electrode and consists of printed silver. It covers an area identical to that of the bottom electrode (1 mm^2), completing the parallel-plate capacitor layout. A narrow silver track connects the capacitor to the underlying gold structure, enabling electrical readout using the probe station.

4.8.3 Fabrication Recipe

As described in Section 4.8.1 Section 4.8.2, the fabrication of the printed capacitors involves three functional layers: the bottom electrode, the dielectric, and the top electrode. Customized gold substrates, TiO_2 ink, and silver ink are used to form these vertically stacked layers. Since the inks are transferred in a liquid state, drying between consecutive printing steps is necessary to ensure layer integrity. To further improve the electrical performance of the capacitors, a sintering process is applied after each printing step.

The first printing step involves the deposition of the TiO_2 dielectric layer in a dot-by-dot manner using a laser power of 200 mW and a pulse duration of 2 ms, with a pitch of $100\text{ }\mu\text{m}$. This results in overlapping TiO_2 ink spots (see Figure 4.16b), forming a continuous film. A total of 14×14 dots are printed in a square arrangement, slightly larger than the bottom electrode to ensure full coverage. To guarantee good layer separation and solvent removal, the printed structures are treated in a vacuum oven at 260°C for 180 min. The vacuum environment aids solvent evaporation before heating and prevents oxidation during thermal treatment.

In the subsequent step, the silver top electrode is printed using a laser power of 120 mW and a pulse duration of 4 ms, maintaining the same pitch of $100\text{ }\mu\text{m}$. Dots are printed in a square pattern of 10×10 overlapping dots, forming a continuous

layer. Additionally, a narrow conductive track is printed under identical conditions to connect the top electrode to the gold base contact. Finally, the printed capacitors are sintered again in the vacuum oven at 260 °C for 180 min, which significantly improves the conductivity of the silver electrode. To adjust the capacitance of the printed capacitors the coverage area of the top electrode can be reduced by printing fewer than the full array of 100 dots, with each omitted dot proportionally decreasing the overall capacitance.

4.8.4 Characterization Strategy

To evaluate the functionality and performance of the printed capacitors, two main characterization techniques are employed: electrical analysis using a manual probe station connected to a network analyzer, and structural analysis using a FIB-SEM system to assess the layer integrity of the devices.

Electrical measurements are conducted using an Agilent E5061B network analyzer, which provides frequency-dependent parameters for evaluating device performance, such as the capacitance (see Appendix A.1.5). In addition to numerical parameter extraction the device functionality is verified by analyzing the impedance response displayed in a Smith chart. The Smith chart represents the complex impedance as a function of frequency, plotted over the real component of resistance.

The impedance of a capacitor in an AC circuit is described as

$$Z_C = \frac{u(\omega)}{i(\omega)} = \frac{U_0 e^{j\omega t}}{CU_0 j\omega e^{j\omega t}} = \frac{-j}{\omega C}, \quad (4.1)$$

where $u(\omega)$ and $i(\omega)$ are the alternating voltage and current, respectively, and ω is the angular frequency. Consequently, an ideal capacitor appears in the lower hemisphere of the Smith chart, moving clockwise with increasing frequency. A perfect, lossless capacitor traces a radial line, while a capacitor exhibiting dielectric or resistive losses produces a spiral trajectory toward the chart center. These signatures are used to verify the capacitive behavior and to detect possible defects such as short circuits. For the analysis and visualization of the data, the software tool *ZPlots* by Agilent Technologies is used.

The structural and morphological characterization is performed using a FIB-SEM system, specifically an FEI DualBeam Helios G4 FX (Thermo Fisher Scientific) (see Appendix A.1.8). A FIB is used to mill a trench into the capacitor, enabling cross-sectional imaging at a tilt angle. After applying tilt correction, the thicknesses of the individual printed layers can be measured accurately. The chosen materials are expected to exhibit high material contrast as well as distinct topographical features due to their nanoparticle-based microstructure. Results of the capacitor printing and characterization are shown in Section 5.5.

5. Results and Discussion

This chapter presents the results of investigations into the fabrication and optimization of structures based on nanoparticles and organic materials using LIFT. Building on the methodology described in Chapter 4, the work demonstrates that nanoscale structures can be reproducibly printed using LIFT and that key process and material parameters, such as laser parameters, number of printed layers, substrate and ink selection can be systematically identified and optimized. The optimization of these parameters is essential for achieving uniform, defect-free structures suitable for electronic device applications.

The results are structured to first address the optimization of LIFT parameters (see Section 5.1.1), including the use of microstructured acceptors, variations of adhesive and spin-coated polyimide films, and on-site ink optimization (see Section 5.2). This includes the assessment of ink quality, viscosity, nanoparticle concentration and solvent effects as well as the validation of customized ink formulations. Together, these investigations establish the conditions necessary for high-quality, reproducible nanoparticle ink printing.

Following the optimization studies, the chapter presents the realization of functional devices. This includes line and area printing (see Section 5.3), where control over layer thickness and surface roughness is demonstrated as well as the fabrication of printed OLEDs and capacitors.

Two fabricated OLED devices are discussed here, one combining conventional spin coating with LIFT and the other being a fully LIFT-printed multilayer device, highlighting the flexibility and potential of the LIFT approach for complex device architectures (see Section 5.4).

Capacitor fabrication is presented as a further demonstration of the process versatility, including electrical characterization and evaluation of electrical material resistivity (see Section 5.5). These examples show that LIFT can be applied across a range of device types, confirming the feasibility of additive, high-resolution patterning of functional nanostructures.

5.1 LIFT Parameter Optimization

5.1.1 Printing on Microstructured Acceptors

Small silicon tiles are fabricated and used as insertable modules in a customized acceptor holder, as described in Section 4.3.1. These tiles feature pillars of varying heights, diameters, and pitches (see Table 4.5). Technical limitations do not allow a perfect alignment of substructures on the sample with the laser beam due to positioning difficulties. Therefore to perform these experiments a dot matrix is printed with a pitch slightly deviating from the pitch of the pillar structures. The expected outcome of this experiment is a Moiré pattern with dots fully, partially or not hitting a pillar which is illustrated in Figure 5.1. This allows to proof the printing on elevated structures for varying geometrical coverage and determine the necessary pillar height to only deposit on the pillar tops while avoiding the valleys.

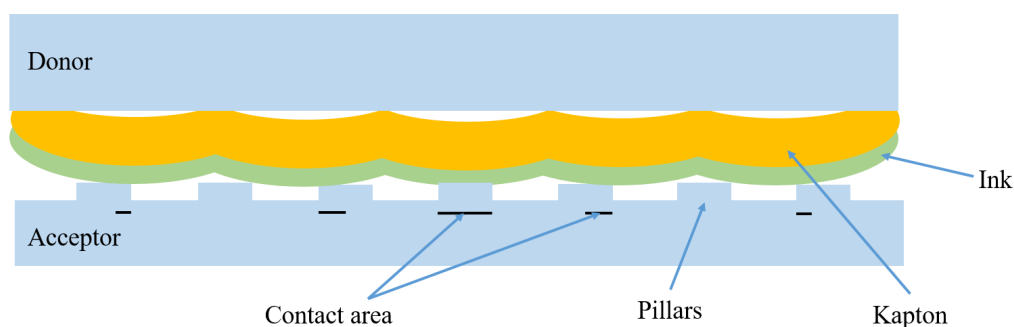


Figure 5.1: Sketch of dot matrix printing on non flat substrate with pillars. Pitch of dots and pillars are defines slightly different, some dot transfers hit the pillars fully, partially or not at all. A Moiré pattern is expected.

The printing results are analyzed using a fluorescence scanner (see Appendix A.1.4) which scans over the sample surface and creates a fluorescence signal map of the sample. This allows to determine the location of deposited fluorescent ink and conclusions can be drawn about the relative ink amount. The fluorescence scanner provides images with limited depth of field. Therefore two images are necessary, one focused on the pillar tops and the other focused on the valleys to show the potential deposition of material. The fluorescence scanner is operated with the Cy3 555 nm channel, so the excitation wavelength is 555 nm. The ink used for these experiments is rhodamine ink in various concentration (see Section 4.2.1).

Figure 5.2a shows a fluorescence image with the bottom level in focus with no printed dot matrix visible, only few ink fragments are visible which might indicate local defects in the donor coating. Figure 5.2b shows a fluorescence signal image with the pillar level in focus and demonstrates by absence of fluorescence in the valleys that material is transferred exclusively to the tops of the pillars. The pillar grid and the dot matrix are drawn in the figure for better visualization. In this case, the pillars are 78 μm high, with a diameter of 90 μm and a pitch of 200 μm .

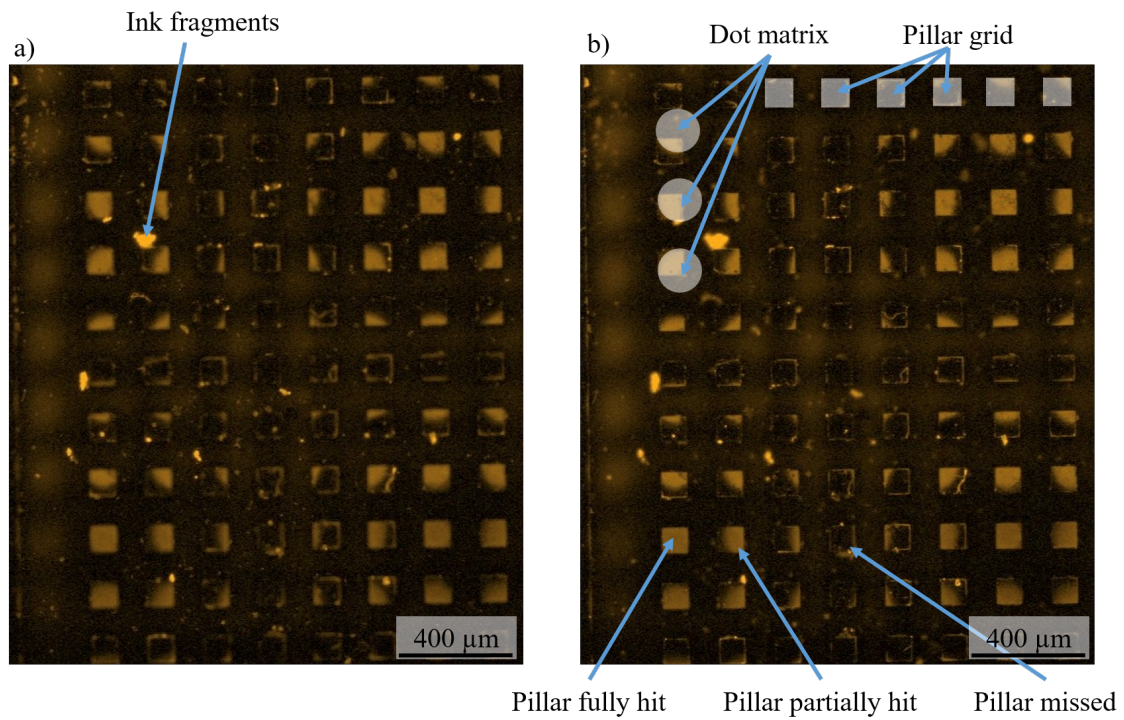


Figure 5.2: Transfer of S-LEC[®] containing 10% rhodamine dye onto pillar structures by printing a dot matrix with a mismatch to the pillar grid. The pillars have a diameter of 90 μm and a pitch of 200 μm . Images acquired using a fluorescence scanner with the Cy3 555 nm channel and 5x magnification. (a) Focus at the bottom substrate. (b) Focus at the pillar level.

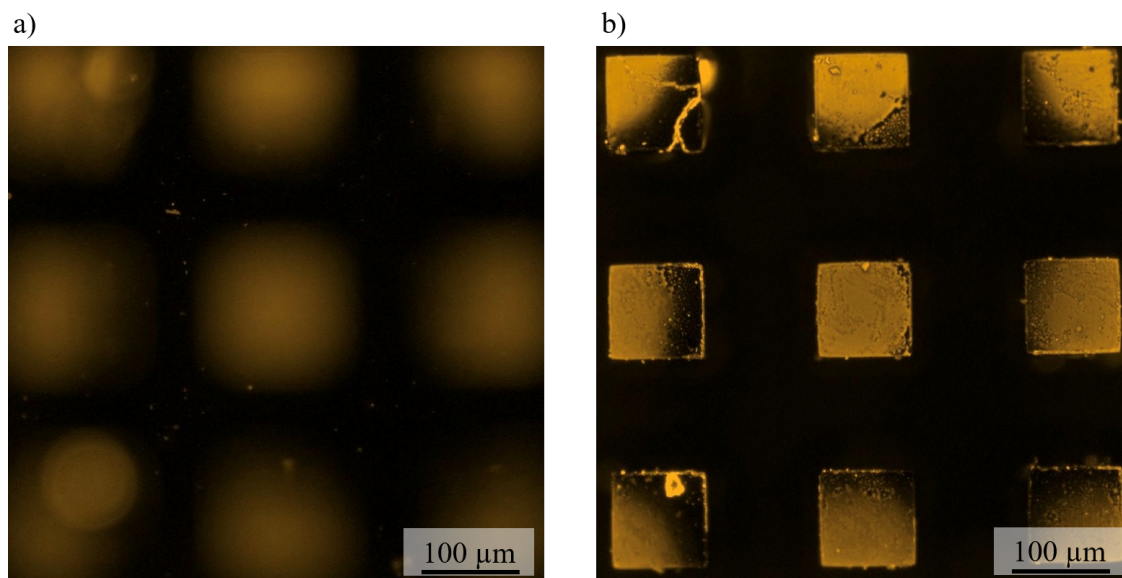


Figure 5.3: Transfer of S-LEC[®] containing 10 % rhodamine dye onto pillar structures. The pillars have a diameter of 90 μm and a pitch of 200 μm . Images acquired using a fluorescence scanner with the Cy3 555 nm channel and 20x magnification. (a) Focus at the bottom substrate. (b) Focus at the pillar level.

The printing is performed in dot matrix mode with a pitch closely matching that of the pillars. This results in a Moiré pattern where some pillars are hit directly, some partially, and others not at all. These observations highlight the necessity of precise positioning in order to achieve a matching pillar and dot matrix.

Figure 5.3 presents the same pillars at a higher magnification. Figure 5.3a is focused on the bottom level, while Figure 5.3b is focused on the tops of the pillars. No material is detected in the valleys between the pillars. However, the ink distribution on the pillar tops is not entirely uniform, as seen in the image. Some pillars are only partially covered, while the central pillar is hit directly. For the central pillar, the ink distribution appears largely homogeneous within the pillar top while the other pillars are fading to the side, indicating a thinning printing thickness. However, the actual printed amount and thickness distribution must be determined using other measurement techniques.

Additional tests were conducted using pillars with a larger pitch of 250 μm and a pillar diameter of 90 μm . Printing was performed with a laser pitch of 60 μm , which is significantly offset from the pillar grid. The laser power was set to 170 mW with an exposure time of 10 ms. The result is shown in Figure 5.4a. The fluorescence image, focused at the pillar top, shows ink deposited on top of the pillars as well as in the valleys. Slightly less ink is observed in the valleys directly adjacent to the pillar walls. This observation is consistent with the proposed transfer mechanism involving an expanding bubble that is partially shielded by the pillar and therefore does not fully contact the bottom substrate. The results further indicate that a pillar pitch of 250 μm or the mismatch is too large to achieve selective printing exclusively on top of the pillars.

Further printing experiments were performed on 18 μm high pillars with a diameter of 50 μm and a pitch of 200 μm . A 1 % rhodamine S-LEC[®] ink was used together

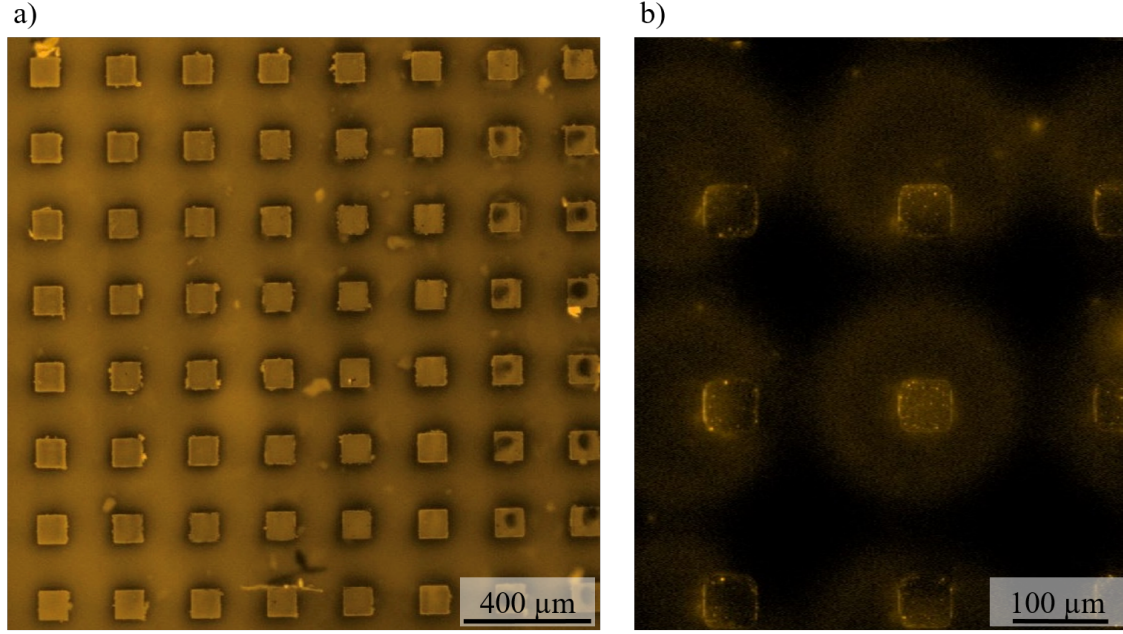


Figure 5.4: Fluorescence images of S-LEC[®] transfer on pillar structures using rhodamine dye. Images acquired using a fluorescence scanner with the Cy3 555 nm channel with 5x and 20x magnification. (a) Pillars with a diameter of 90 μm , pitch of 250 μm , using a laser parameters of 170 mW, 10 ms, and a laser pitch of 60 μm . (b) Pillars with a diameter of 50 μm , pitch of 200 μm , using laser parameters of 200 mW, 10 ms, and a laser pitch of 250 μm .

with a laser pitch of 250 μm . The results are shown in Figure 5.4b and demonstrate a weaker fluorescence signal, which is consistent with the lower dye concentration. The focus level is set to the pillar top, and the depth of field is sufficiently large to confirm that material was deposited not only on top of the pillars but also in the valleys, where it appears as a round dot. Therefore 18 μm pillar height is not sufficient for exclusive printing on the pillar tops.

The experiments were also conducted using Coumarin ink, which showed results similar to those obtained with the rhodamine ink.

Conclusion

The presented results demonstrate that the LIFT technique enables selective printing on microstructured acceptors, in particular on the tops of silicon pillars, while suppressing material deposition in the valleys. For sufficiently high pillars and appropriate pillar pitches, fluorescence imaging confirms that the transferred material is deposited exclusively on the elevated structures. The use of a dot matrix with a slight pitch mismatch to the pillar grid successfully reveals the interaction between the transfer process and the microstructured topography, allowing selective pillar printing to be evaluated without precise alignment.

The experiments further show that pillar geometry plays a crucial role to achieve selective deposition. High pillars with a pitch of 200 μm enable printing solely on the pillar tops, with a small dot matrix mismatch of 250 μm . Larger pillar pitches of 250 μm in combination with smaller laser pitch of 60 μm or reduced pillar heights of 18 μm result in additional material transfer into the valleys. These observations are

consistent with the proposed transfer mechanism involving an expanding bubble, which can be partially shielded by sufficiently tall pillars but reaches the bottom substrate when the pillar height or pitch is insufficient.

Variations in fluorescence intensity on top of the pillars across individual pillars indicate that precise positioning remains important for achieving uniform coverage. Partial hits lead to inhomogeneous ink distributions, while direct hits result in more homogeneous deposits on the pillar tops. Although selective printing was successfully demonstrated, the observed nonuniformities suggest that further optimization of laser parameters, ink properties and pillar geometry is required to achieve reproducible and spatially uniform deposition. Additionally the availability of an absolute positioning unit for substrates would enable reliable printing on designated material pillars without any mismatch.

Overall, these findings highlight the potential of LIFT printing for structured acceptor surfaces. In addition to enabling selective deposition on elevated features, this approach allows for increased effective array densities compared to flat substrates, as overlap between printed spots is suppressed by the microstructure. Furthermore, the interaction between the transfer process and the pillar geometry opens possibilities for shaping transferred dots toward tailored geometries. While conventional LIFT on flat substrates typically produces round deposits, controlled trimming of the deposit edges on microstructured surfaces may enable a more uniform thickness distribution, compensating for the bell shaped height profile commonly observed in printed dots.

These findings could play a role in the further development of components or twin nanostacks, which are based on the parallel layer-by-layer stacking of individual layers. The thinning at the edges of the components could be improved by printing on artificially structured substrates. At the same time, new shapes and sizes could be achieved that would normally require the combination of multiple dots. Due to technical limitations in absolute positioning of laser to structures on the substrate no components are fabricated on structured acceptors in this work.

5.1.2 Variation of Adhesive Polyimide Film

Variants of adhesive polyimide tape are tested as described in Section 4.3.3.1. The experiments are focused on the printing behavior of the polymer S-LEC[®] and are characterized using VSI to determine spot heights and diameters. In addition, the donor and acceptor surfaces were examined by optical microscopy to obtain further qualitative information on the transfer behavior. Moreover, fluorescence scanning was performed to enable an optical comparison of the transferred material amount. The VSI data shown in Figure 5.5 illustrate the transfer of S-LEC[®] for different polyimide tape variants. Only the 20 μm RT and 25 μm CMC samples are displayed. For the 25 μm and 100 μm RT variants there was no signal detected using VSI.

Comparison of the topographic maps indicates that both polyimide variants affect the spot diameter, with a more pronounced gradient observed for the CMC tape. The 3D visualizations reveal differences in spot morphology between the tape variants: spots in Figure 5.5c appear wider and less sharp than those in Figure 5.5d. It should be noted, however, that the 3D representation is highly distorted due to the combination of millimeter-scale lateral dimensions and nanometer-scale vertical dimensions, so interpretations regarding spot sharpness should be made with caution.

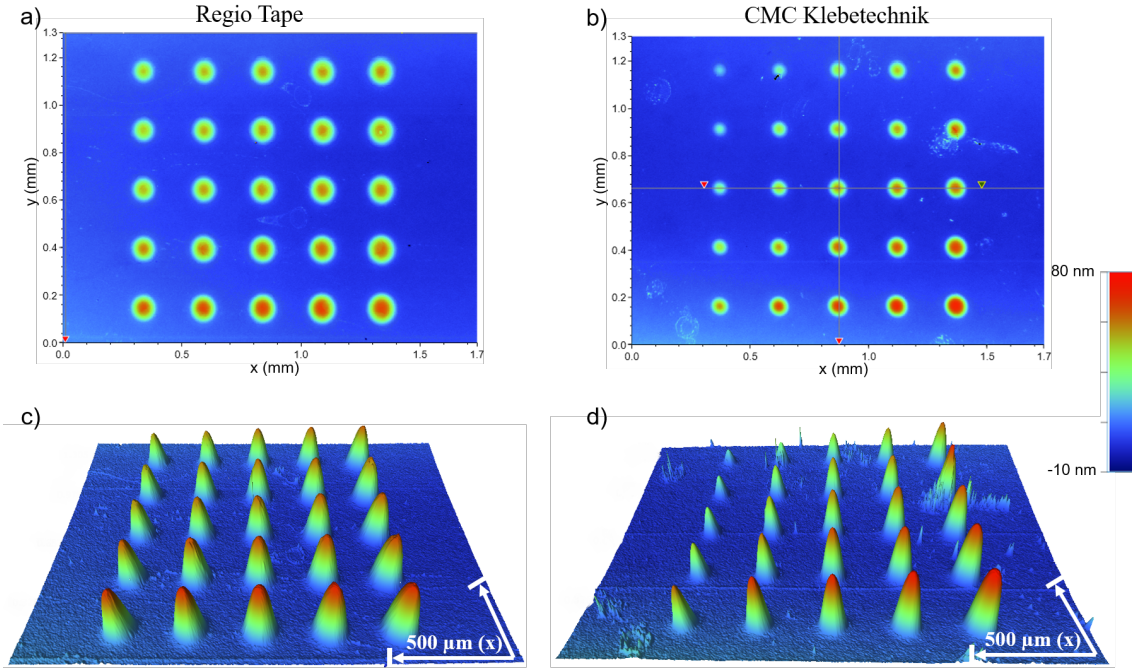


Figure 5.5: VSI measurements of transferred material dots from a laser scan matrix with laser powers ranging from 120 mW to 160 mW along the x-direction and pulse durations from 6 ms to 10 ms along the y-direction for S-LEC[®] glycine transfer using polyimide adhesive tapes of varying thicknesses. The highest laser energy corresponds to the bottom-right corner of the matrix.

(a) and (b) 2D topography maps of transferred spots on 20 μm RT (a) and 25 μm CMC tape (b).

(c) and (d) Corresponding 3D topography maps for the same samples (c): RT, (d): CMC. Vertical dimensions are not to scale relative to lateral dimensions.

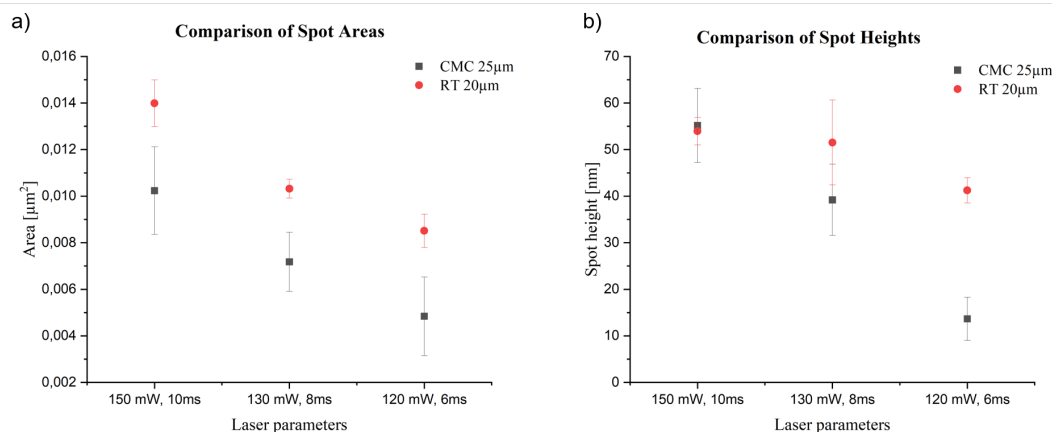


Figure 5.6: (a) Measured spot area and (b) measured spot height for different adhesive polyimide tape variants of the manufacturer CMC with the thickness 25 μm and RT with the thickness 20 μm . Comparison of three laser parameter settings, high (150 mW, 10 ms), medium (130 mW, 8 ms) and low (120 mW, 6 ms). Mean and standard deviation displayed (n=4)

To quantify these observations, three laser parameter sets within the screening range were selected for comparison (150 mW 10 ms, 130 mW 8 ms and 120 mW 6 ms). Spot area and height were extracted using the analysis tools of Vision64 (Bruker, Ettlingen, Germany). The resulting graphs are shown in Figure 5.6.

The data confirm the previous observations: spots transferred with CMC tape exhibit a steep decrease in height with decreasing laser energy, whereas RT shows a comparatively shallower decline. In terms of spot area, CMC-transferred spots are significantly smaller than those obtained with RT. The laser-energy-dependent decrease in area at lower transfer energies is comparable for both tape variants. The exact formulations of the polyimide tapes and the associated physical parameters provided are not known and not provided by the manufacturers. Therefore, no direct systematic relationship for the observed behavior can be derived. One possible speculative hypothesis to explain the observed behavior is that the reduced layer thickness results in an improved heat conduction from the Kapton[®] into the transfer layer. This could lead to an increased transfer temperature, which in turn lowers the viscosity and enhances the adhesion behavior, resulting in larger and higher transferred spots.

The fluorescence analysis serves as an additional tool that provides more sensitive information about the transfer of spots. The fluorescence scanner can detect traces of material even where VSI no longer reveals any spots. It provides relative information about the amount of transferred material, since every molecule contributes to amplifying the fluorescence signal. However, it cannot be used to derive information about the transferred spot height.

In Figure 5.7, the fluorescence signal of the parameter screening for different tape variants is shown. At lower transfer energies (top left corner), the spots appear laterally smaller compared to higher transfer energies (bottom right). The variation in spot size is greater for RT, which is consistent with the data obtained from VSI. For RT with 25 μm of thickness, a fluorescence signal is detected even though no transfer is observed with VSI. This indicates that a small number of molecules

is transferred below the VSI detection limit. Here as well, the spots increase in lateral size with higher transfer energies. Increasing the transfer energy to receive higher spots entails enhanced thermal degradation of the polyimide, which in turn negatively affects the transfer. For RT with 100 μm of thickness, no signal is detected by the fluorescence scanner.

Furthermore, the donor slides are analyzed using light microscopy to check for burn marks and bubble formation as indicators of transfer reliability. Burn marks in the polyimide film are observed for all donor types. Bubbles form due to degradation and outgassing of either the polyimide or the adhesive and are interpreted as indicators of excessively high transfer parameters. Bubbles are visible in Figure 5.7c and Figure 5.7d, which also show poor transfer results in terms of spot height and diameter.

In summary, adhesive polyimide tapes are evaluated for S-LEC[®] laser transfer using VSI, fluorescence and light microscopy. Only RT with thickness of 20 μm and CMC with a thickness of 25 μm produced measurable spots. CMC spots were wider, less defined, and exhibited a steeper height decrease at lower laser energies, whereas RT spots were larger with a gentler height decline. Fluorescence confirmed material transfer even below VSI detection limits. Light microscopy revealed burn marks on all donors and bubbles in CMC and RT with 25 μm of thickness, which could be associated with observed reduced spot height and diameter.

The conclusion is that two of the tested tapes were unsuitable for S-LEC[®] printing, as no sufficient transfer could be measured. As a possible alternative to the standard CMC tape, the 20 μm RT shows similarly good transfer properties. Interestingly, this occurs with a significantly thinner, different adhesive layer, which could be advantageous due to potentially reduced bubble formation. It was also found that neither the type of adhesive nor the manufacturer has a significant impact on successful transfer. The smaller lateral spot size is beneficial, as it can increase resolution, and the steeper spot height gradient is advantageous because it allows easier adjustment of spot height to requirements. Overall, the measurements confirm that CMC as supplier for polyimide tape is a validated choice.

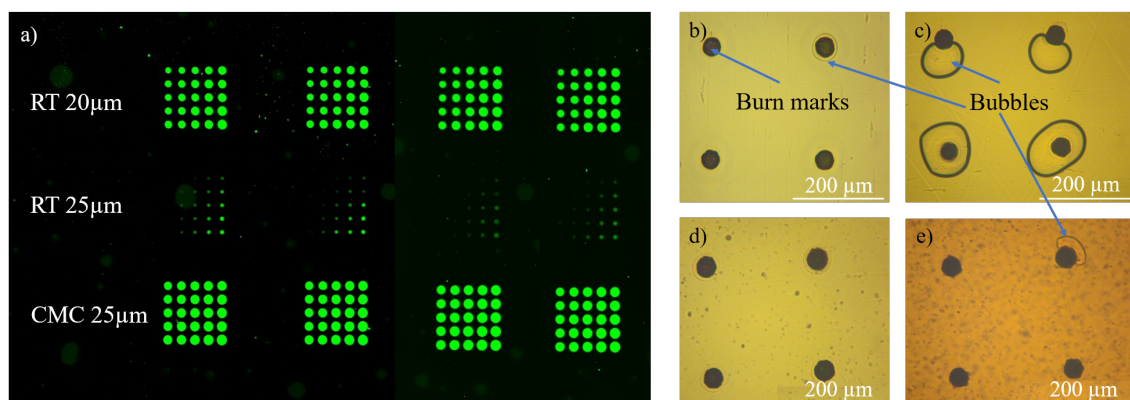


Figure 5.7: (a) Fluorescence images of transferred spots obtained with different adhesive polyimide tape variants (RT 20 μm , RT 25 μm , and CMC 25 μm) using laser transfer parameters of 130 mW and 8 ms. b–e) Light microscopic inspection of the donor slides after spot transfer, showing burn marks and bubble formation for (b) RT 20 μm , (c) RT 25 μm , (d) CMC 25 μm , and (e) RT 100 μm .

5.1.3 Variation of Spin Coated Polyimide

Different variants of polyimide are fabricated (see Section 4.3.3.2) to investigate the influence of layer thickness on the morphology of the printed features. For details on the fabrication of the polyimide layers, see Section 4.3.3. Two batches of samples with different layer thicknesses are fabricated. Batch 1 comprises samples with thickness of 3.3 μm and above, while batch 2 includes samples with thickness between 0.35 μm and 0.83 μm . The batches are produced using different fabrication processes and are analyzed using laser parameters specifically tailored to the respective layer thickness. The evaluation of the LIFT process is carried out by characterization of the printed structures, specifically the spot diameter and spot height. These values are extracted using VSI (see Appendix A.1.7), which also provides visualized 3D images of the printed spots.

Batch		Film thickness [μm]					
Batch 1	3.30	4.10	7.50	8.00	15.60	19.10	25.20
Batch 2	0.83	0.50	0.43	0.35			

Table 5.1: Measured film thicknesses of spin-coated polyimide layers for batch 1 and batch 2.

Influence of Polyimide Thickness - Batch 1

In batch 1, the influence of polyimide layer thickness on the transfer process is investigated for thickness ranging from 3.3 μm to 25.2 μm (see Table 5.1). Two experimental approaches are used:

- A parameter screening by variation of the laser power from 40 mW to 180 mW and the exposure time from 10 ms to 28 ms, followed by analysis of the resulting transfers
- The application of fixed laser parameters (150 mW power and 15 ms exposure time) to allow direct comparison between the different layer thicknesses.

The effects of the parameter screening on the transferred layer morphology are shown in Figure 5.8, which presents representative 3D visualizations of topographic images. From the 3D images it is observed that the spot height reaches its maximum for a polyimide thickness near 7.5 μm and 8.0 μm . For thicker films beyond this range, the spot height decreases progressively. In this regime, the highest laser powers also correlate with the highest spot heights, as is expected from the experiments in Section 3.4, with only a few exceptions that could be related to degradation of the polyimide layer due to excessive energy input.

Moreover, the transfer window, defined as the range of laser parameters that result in successful material transfer, narrows with increasing film thickness. For instance, the 25.2 μm film only allows transfers at high laser power, indicating a reduced transfer window. In addition, the average spot height declines with increasing layer thickness.

A quantitative analysis of the spot morphology is presented in Figure 5.9 and Table 5.2, as visual inspection alone is insufficient to adequately assess the morphological differences. To ensure comparability of the spots across different values of polyimide thickness, identical laser parameters are applied to all layers. These parameters are selected because they produce detectable features for nearly all tested thickness values. However, for the $25.2\mu\text{m}$ layer, material transfer does not occur under the chosen conditions; therefore, this data point is excluded from the comparative analysis.

All transfers in this batch are performed using S-LEC[®] as the ink material.

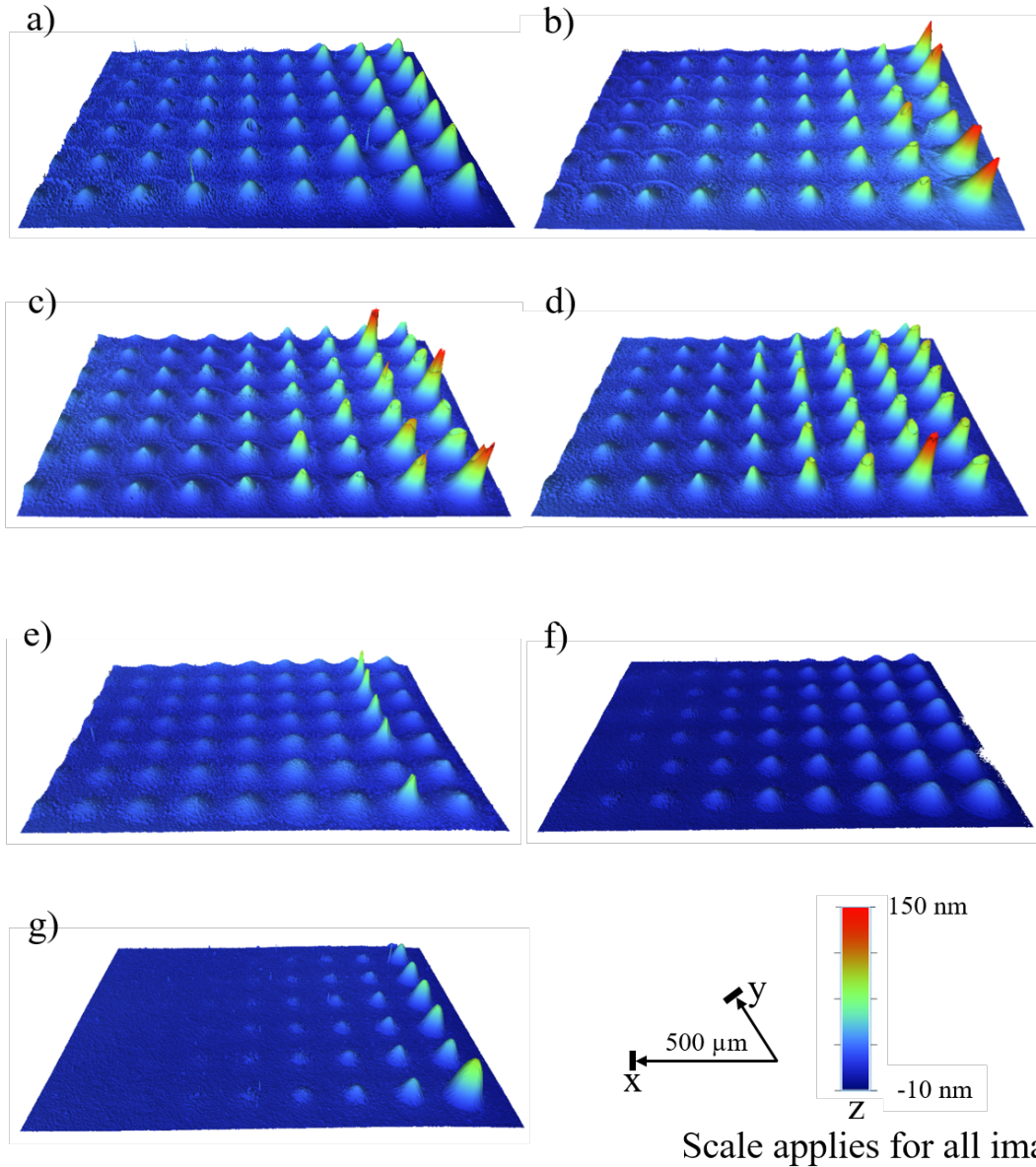


Figure 5.8: Laser parameter screening in dependence of layer thickness. 3D visualization of printed dot features. Laser parameters ranging from 40 mW to 180 mW on the x-axis and 10 ms to 28 ms on the y-axis with variable polyimide thickness of (a) $3.3\mu\text{m}$ (b) $4.1\mu\text{m}$ (c) $7.5\mu\text{m}$ (d) $8.0\mu\text{m}$ (e) $15.6\mu\text{m}$ (f) $19.1\mu\text{m}$ (g) $25.2\mu\text{m}$. Highest laser energy (power and duration) is in the bottom right corner.

Donor type	Film Thickness [μm]	Diameter [μm]	Height [nm]
S-LEC [®]	3.3	111.2 $\pm$ 6.3	11.3 $\pm$ 0.3
S-LEC [®]	4.1	105.1 $\pm$ 6.0	12.3 $\pm$ 0.8
S-LEC [®]	7.5	112.3 $\pm$ 6.6	13.7 $\pm$ 0.5
S-LEC [®]	8.0	122.5 $\pm$ 7.3	17.1 $\pm$ 1.4
S-LEC [®]	15.6	138.0 $\pm$ 6.5	4.7 $\pm$ 0.1
S-LEC [®]	19.1	78.3 $\pm$ 7.6	3.5 $\pm$ 0.5

Table 5.2: Extracted values from batch 1 at laser parameters of 150 mW and 15 ms showing the diameter and height of transferred spots. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 printed dots each.

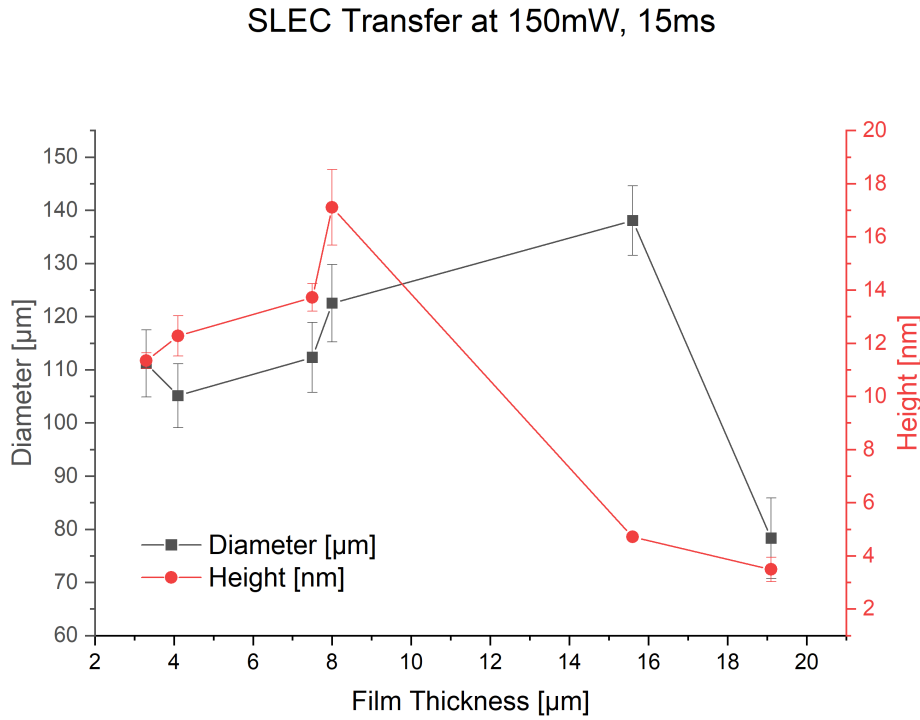


Figure 5.9: Morphology of printed S-LEC[®] spots of Batch 1 for different polyimide thicknesses quantified by measured diameter and height. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 spots each.

Influence of Polyimide Thickness - Batch 2

In batch 2, the influence of varying polyimide layer thicknesses below 1 μm , ranging from 0.35 μm to 0.83 μm (see Table 5.1), is analyzed. Transfers are performed using the materials S-LEC[®] and PS with two laser settings: 20 ms at 300 mW and 10 ms at

250 mW. Identical laser parameters were applied across different layer thicknesses to allow a meaningful comparison of the influence of thickness on spot transfer. These settings were selected to represent high and medium laser energy conditions.

However, the chosen parameters do not always yield consistent transfer quality across all tested film thicknesses that enable a comparative measurement. In some cases no spots are detected at all. A possible explanation is contamination on the samples that leads to a change in the wideness of the gap in between donor and acceptor which is an important factor for the amount of material transferred according to Paris, Klinkusch, Heidepriem, Tsouka, et al. [29]. As a result, conditions that did not show reliable transfers were excluded from the analysis.

Representative 3D topographic visualizations are shown in Figure 5.10, illustrating morphological changes in the printed features. For S-LEC[®] (Figure 5.10a-c), a clear increase in spot height with increasing polyimide thickness is observed. Compared to the PS structures (Figure 5.10 d-f), the S-LEC[®] spots appear sharper and exhibit smaller diameters. An increase in spot height with increasing polyimide thickness is also evident in the PS structures. The observed curvature of the substrate is a measurement artifact and is not related to the transfer itself.

Quantitative data for spot diameter and height, extracted using Bruker's Vision64 software, are presented in Table 5.3 for the higher transfer energy and in Table 5.4 for the intermediate transfer energy. The corresponding visualizations are provided in Figure 5.11 for S-LEC[®] at high energy, Figure 5.12 for PS at high energy, Figure 5.13 for S-LEC[®] at medium energy and Figure 5.14 for PS at medium energy.

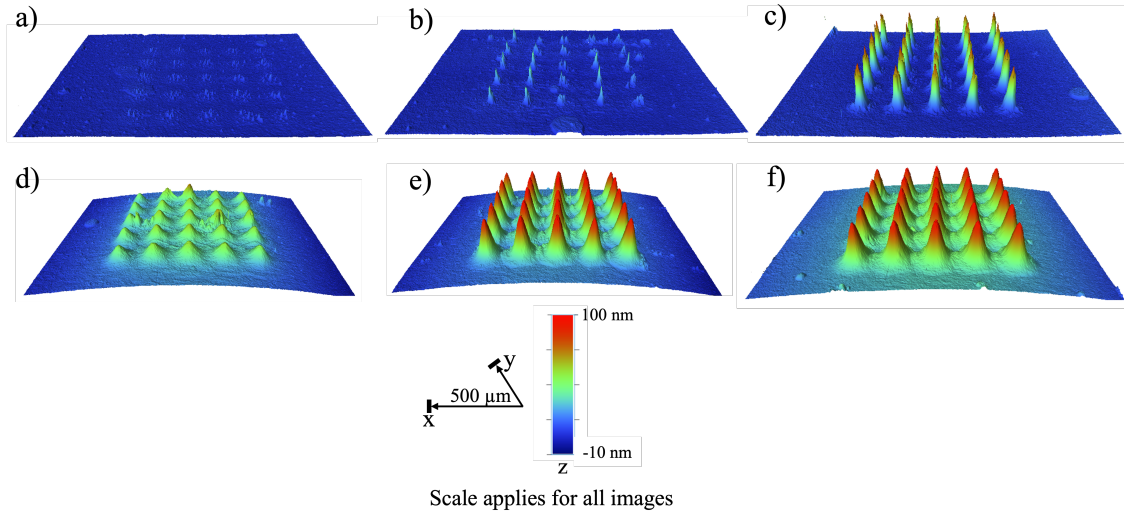


Figure 5.10: 5x5 printed material spots to evaluate the spot morphology over the layer thickness. 3D visualization of printed dot features for different polyimide layer thicknesses obtained by VSI measurements. All samples are processed with identical laser parameters (300 mW, 20 ms). Variants differ in polyimide thickness and material:

a–c) S-LEC[®] with 0.35 μm , 0.43 μm , and 0.83 μm , respectively;

d–f) PS with 0.35 μm , 0.5 μm , and 0.83 μm , respectively.

Donor Type	Film Thickness [μm]	Diameter [μm]	Height [nm]
S-LEC [®]	0.83	68.2 $\pm$ 1.8	32.2 $\pm$ 1.3
S-LEC [®]	0.43	67.2 $\pm$ 7.0	5.9 $\pm$ 0.7
S-LEC [®]	0.35	118.0 $\pm$ 23.9	0.9 $\pm$ 0.1
PS	0.83	107.4 $\pm$ 5.8	45.7 $\pm$ 0.3
PS	0.50	111.6 $\pm$ 5.4	39.1 $\pm$ 0.6
PS	0.35	109.6 $\pm$ 6.4	15.7 $\pm$ 1.0

Table 5.3: Extracted values from batch 2 at laser parameters of 300 mW and 20 ms showing the diameter and height of transferred spots. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 spots each.

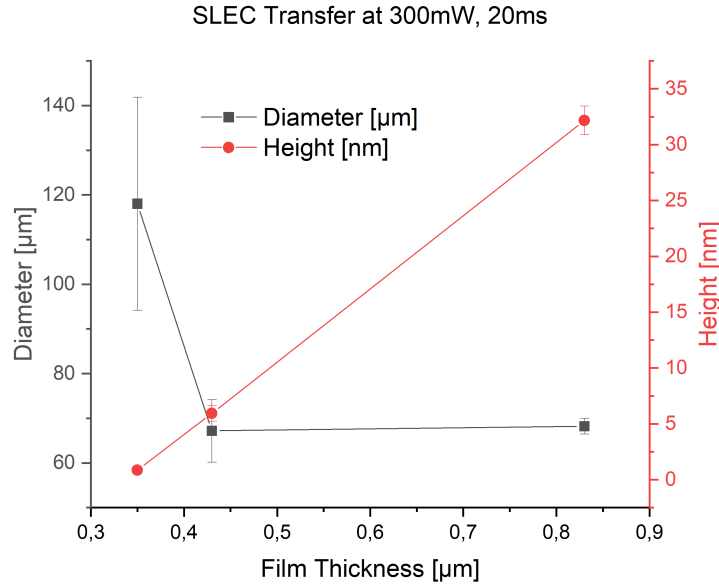


Figure 5.11: Morphology of printed S-LEC[®] spots of batch 2 at laser parameters of 300 mW and 20 ms for different polyimide thicknesses quantified by measured diameter and height. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 spots each.

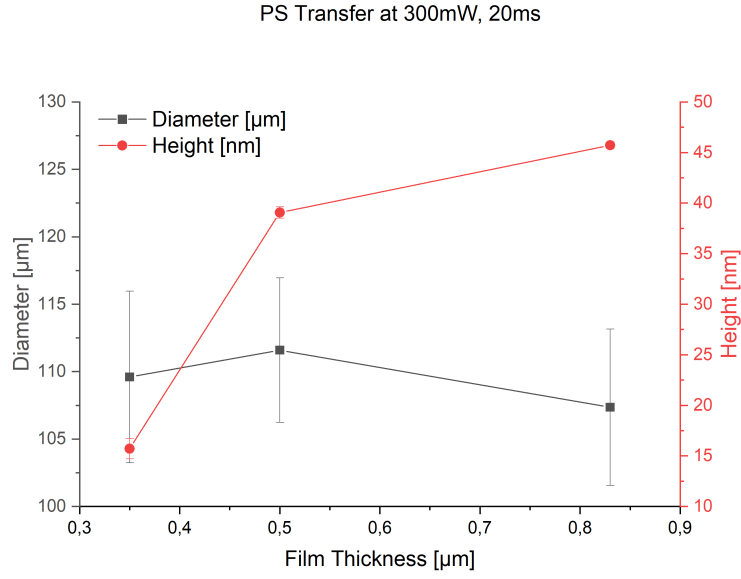


Figure 5.12: Morphology of printed PS spots of batch 2 at laser parameters of 300 mW and 20 ms for different polyimide thicknesses quantified by measured diameter and height. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 spots each

Donor Type	Film Thickness [μm]	Diameter [μm]	Height [nm]
S-LEC [®]	0.83	62.5 ± 1.8	29.2 ± 0.4
S-LEC [®]	0.43	46.3 ± 8.0	1.7 ± 0.6
PS	0.83	99.5 ± 3.2	33.8 ± 0.4
PS	0.50	100.3 ± 4.1	26.0 ± 0.7
PS	0.35	86.6 ± 7.5	4.4 ± 0.4

Table 5.4: Extracted values from batch 2 at laser parameters of 250 mW and 10 ms showing the diameter and height of transferred spots. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 spots each.

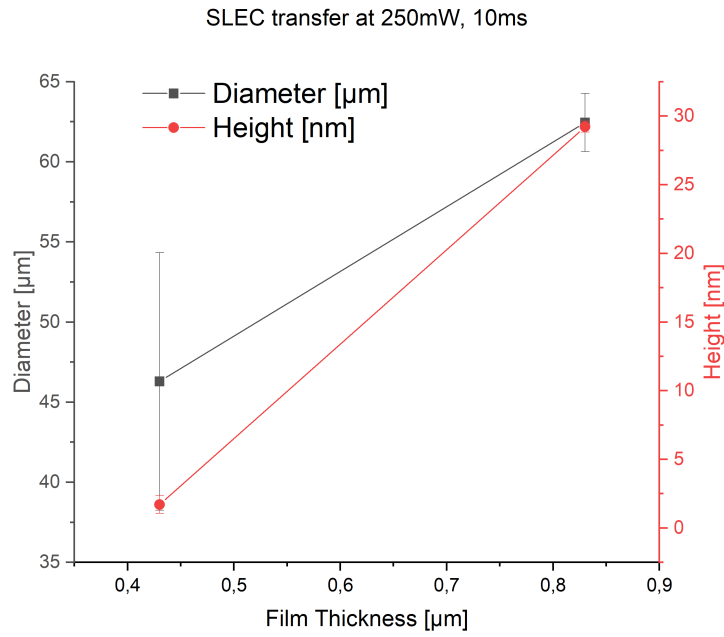


Figure 5.13: Morphology of printed S-LEC[®] spots of batch 2 at laser parameters of 250 mW and 10 ms for different polyimide thicknesses quantified by measured diameter and height. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 spots each.

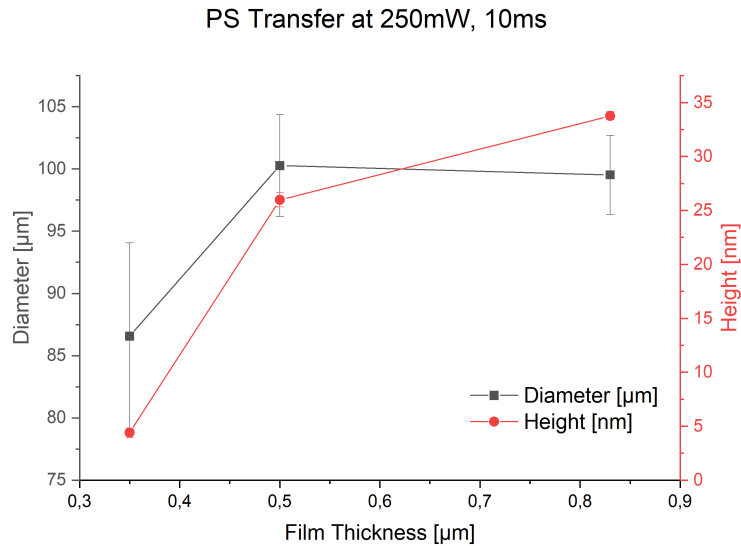


Figure 5.14: Morphology of printed PS spots of batch 2 at laser parameters of 250 mW and 10 ms for different polyimide thicknesses quantified by measured diameter and height. Measurements were performed using Vision64 software by Bruker. Uncertainties represent standard deviations based on the analysis of 25 spots each.

Discussion

Transfer with Thick Polyimide Layers (Batch 1)

In batch 1, spin-coated polyimide layers with a thickness above 1 μm are evaluated for their usability in LIFT using S-LEC[®] and PS. Topographic measurements reveal that material transfer is generally successful for these thicker layers. However, the screening shows that with increasing polyimide thickness the printing window narrows significantly. At a layer thickness of 25.2 μm , only the highest available laser energies result in material transfer. A possible explanation for this effect is that thicker layers require a higher laser energy input to induce the deformation that leads to transfer.

The spot height reaches a maximum at a layer thickness of 8.0 μm , as confirmed by measurements conducted at constant laser settings of 150 mW and 15 ms. The spot diameter also peaks at 8.0 μm , although it remains relatively consistent across all tested thicknesses with no clear dependence on the layer thickness. The analysis reveals that spot diameter and height are generally correlated and follow the same overall trends. This observation is consistent with the assumption that the fundamental spot morphology remains unchanged while the spot size varies.

However, at a layer thickness of 15.6 μm , an anomaly is observed. The spot diameter and height show opposite tendencies and unusually flat spots. This data point is therefore regarded as an outlier. It should also be noted that for very small measured spot heights, the quantitative determination of spot parameters is particularly sensitive to measurement uncertainties. Even minor surface contamination or slight variations in the substrate height can significantly affect the reliable detection of the spot boundaries. Overall, the spot morphology is comparable to that observed in prior measurements using Kapton[®] adhesive tape.

Transfer with Thin Polyimide Layers (Batch 2)

Batch 2 focuses on polyimide layers with sub-micrometer thickness, ranging from 0.35 μm to 0.83 μm . Experiments are conducted for both S-LEC[®] and PS using high and medium laser energies (300 mW, 20 ms and 250 mW, 10 ms). For S-LEC[®], reliable material transfer is only observed for the 0.83 μm layer. At 0.50 μm , no transfer is detected. Minimal and very thin spots appear at 0.43 μm , and only trace amounts of material below 1 nm in height are identified at 0.35 μm . In contrast, PS exhibits more robust transfer behavior. Spots are detected for all tested thicknesses except 0.43 μm , where no transferred material is observed. For the thinnest layers, higher laser energy is required to achieve any material transfer. The 3D topographic analysis confirms these observations. Spot height increases with increasing polyimide layer thickness for both energy levels and both materials. While spot diameter is also influenced by thickness, the trend is less consistent. Notably, a large statistical deviation is observed for S-LEC[®] at 0.34 μm and high energy, likely due to the extremely low spot height approaching the detection limit of the VSI. This effect can lead to inaccurate border recognition and increased uncertainty. In general, PS spots are larger than S-LEC[®] spots, exhibiting greater height and diameter and therefore higher volumes.

Transfer Optimization and Suitability

The optimum transfer condition depends strongly on the target application. For applications requiring small-diameter spots, polyimide layers close to 1 μm using

S-LEC[®] appear most suitable. For enhanced reproducibility, a layer thickness of around 8.0 μm offers a good compromise between spot quality and process reliability. The ultra-thin layers in batch 2 are more fragile and prone to transfer failures. While PS may offer higher transfer volumes at sub-micron polyimide thickness, similar results can be obtained with S-LEC[®] using thicker layers from batch 1.

Influence of Optical Absorption

One explanation for the behavior of ultra-thin polyimide layers can be derived from their optical absorption characteristics. UV-VIS spectroscopy data provided by the Max Planck Institute of Colloids and Interfaces (Figure 5.15) shows that absorption of 405 nm light, the wavelength used in the LIFT printer, is significantly lower for thin polyimide films compared to Kapton[®] adhesive tape. This suggests that much of the laser energy is transmitted rather than absorbed in the polyimide, necessitating higher laser energies to achieve material transfer. The transmitted fraction of the laser beam, which is largely suppressed when using Kapton[®] tape, may in principle also impinge on the transferred spots. However, no influence on the outcome is expected, since both the acceptor substrate and the donor substrate are made of soda-lime glass, transparent to the applied laser wavelength, and the transfer material likewise exhibits high transmission in the visible spectral range. Any absorbed fraction of the laser radiation can therefore be neglected.

Donor Surface Observations

Post-transfer inspection of the donor substrates further supports this explanation. As shown in Figure 5.16, visible craters appear at the laser impact sites where absorption occurred. These craters are likely formed as a result of localized polymer melting and subsequent physical deformation. During contact with the acceptor, the molten material is displaced, leaving behind a thin residual layer of transferred material. The thinner the polyimide layer, the shallower the resulting crater. Additionally, crater size increases with higher laser energy as can be observed. A control donor slide without S-LEC[®] material showed only burn marks and no crater formation, indicating that the craters are indeed formed from S-LEC[®] material rather than deformed polyimide alone.

Outlook and Method Evaluation

The use of spin-coated polyimide layers as dynamic release layers in LIFT offers unique potential for tailoring the morphology of printed spots. In particular, both spot height and diameter can be influenced through precise control of the polyimide layer thickness. Although only minor improvements are observed in terms of transfer height and diameter compared to adhesive tape transfers, optimized spin-coated layers enable the formation of thinner spot features that cannot be achieved using Kapton[®]. However, this approach is more error-prone and less reproducible due to the additional fabrication steps involved. Furthermore, the LIFT system must be individually tuned for each donor to compensate for inherent small variations in layer thickness.

In contrast, adhesive tape provides reliable and consistent performance and is readily available in large quantities, making it a practical choice for large-scale and routine applications. While spin-coated polyimide layers offer distinct opportunities for

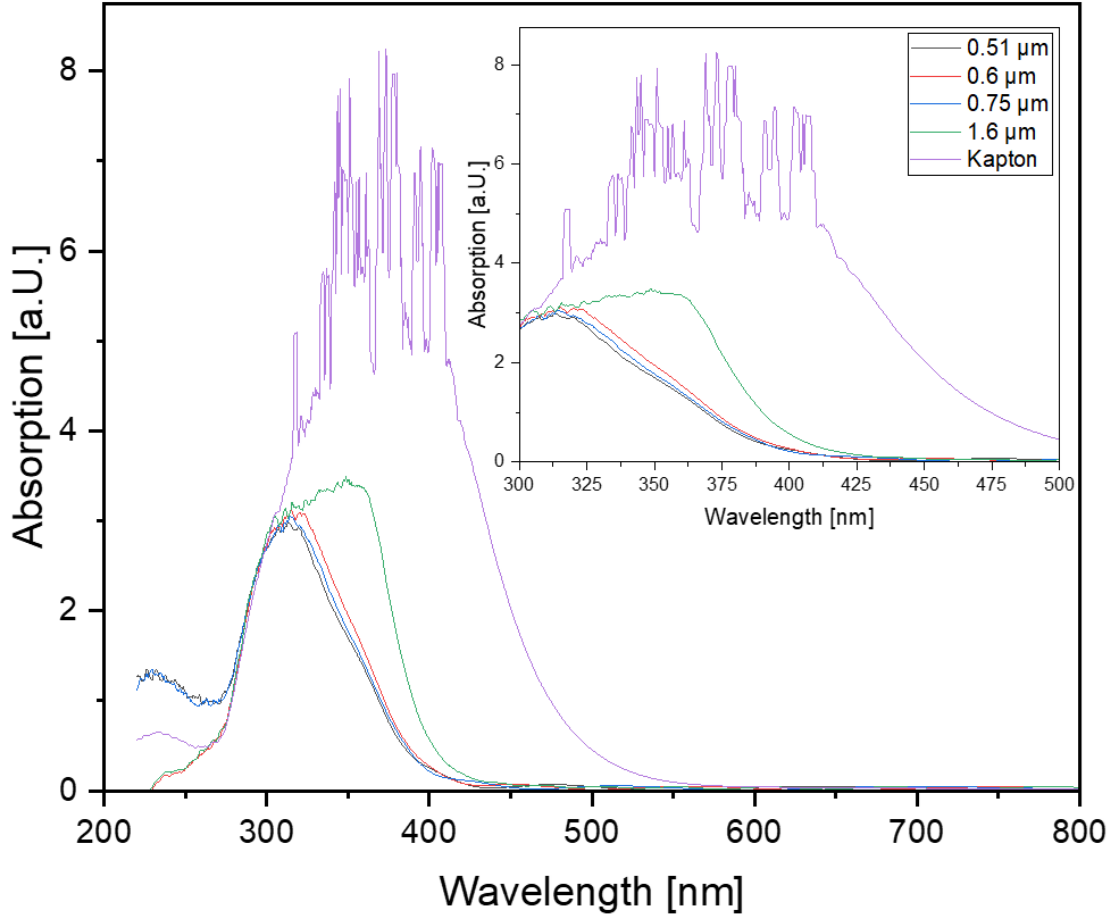


Figure 5.15: Absorption of light for different wavelengths in thin layers of polyimide and Kapton[®] adhesive tape obtained by Ultraviolet - Visible (UV-VIS) spectroscopy. Data and figure provided by the Max Planck Institute of Colloids and Interfaces. © Max Planck Institute of Colloids and Interfaces.

precise control of the transfer process and enable the printing of small components with improved resolution, this level of resolution is not required for the components fabricated in this work. Therefore, due to its high availability, low defect sensitivity, and robust process stability, adhesive Kapton[®] tape is used in the subsequent experiments.

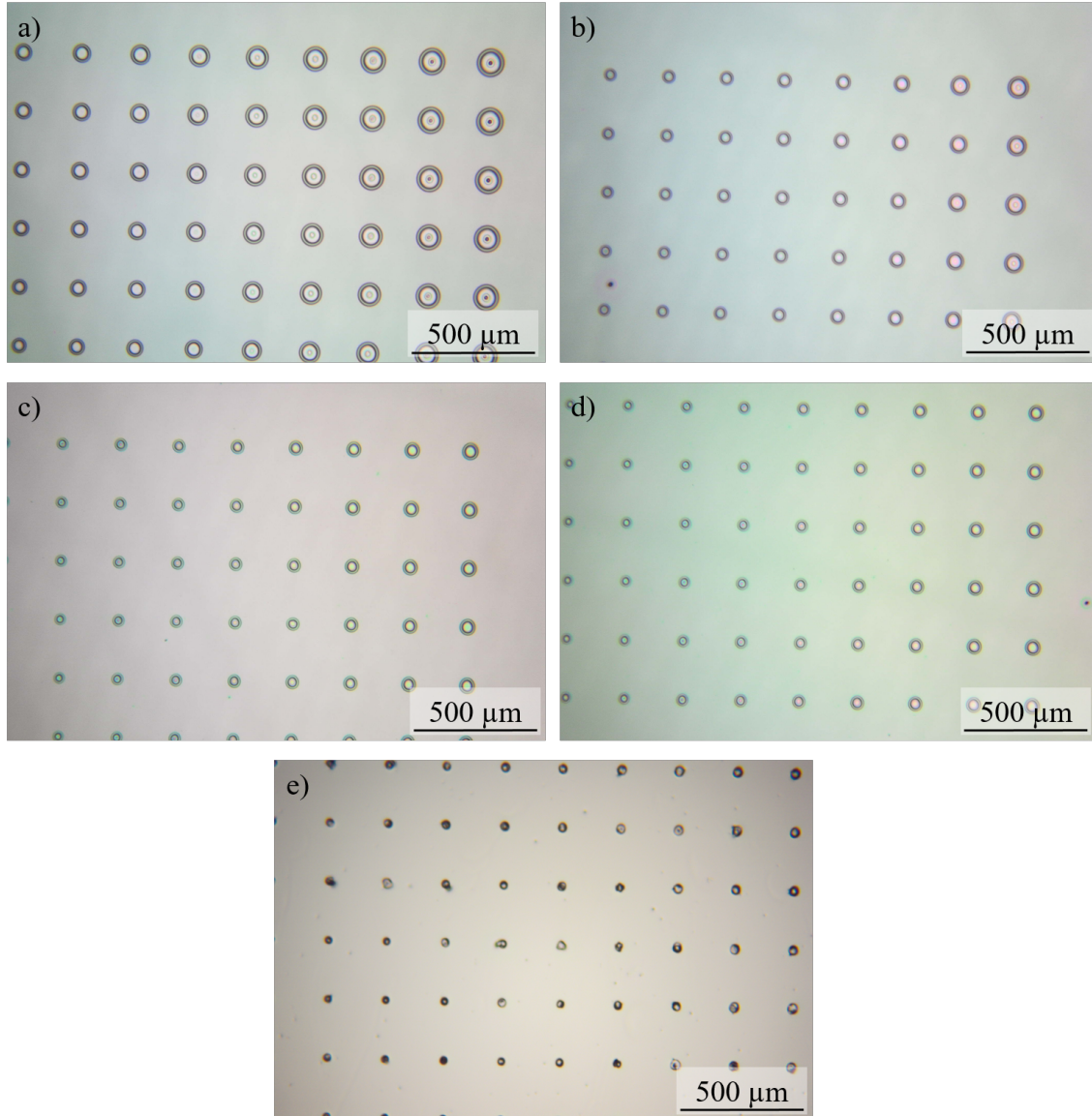


Figure 5.16: Light microscope images of donor slides coated with S-LEC[®] after laser exposure and material transfer. Different polyimide layer thicknesses are shown: (a) 0.83 μm , (b) 0.50 μm , (c) 0.43 μm , (d) 0.35 μm . (e) Donor slide with 0.83 μm polyimide thickness without transfer material (pure polyimide).

5.2 On Site Ink Optimization

To enable a fast test cycle for the development of customized inks for LIFT printing, a small portable test setup is designed and built for operators not specifically trained in LIFT printing. This setup matches the transfer conditions of the stationary production printer located at KIT and uses a compatible laser wavelength and power range to achieve comparable results. Simplification is achieved by replacing the laser scanhead with motorized stages and using less advanced focusing optics. Consequently, the setup can be built at extremely low cost, as described in more detail in Section 4.2.3. By eliminating the logistical delay of shipping samples across Europe, a tighter feedback loop for the iterative steps of ink adjustment is achieved. The setup and its results are published by the author in the journal *Wiley Nano Select* (2025). Parts of this description are adapted from Lux, Wu, Salazar, Crespo, et al. [P1].

The LIFT test setup is devised to eliminate logistical delays by enabling ink optimization directly at remote locations, mainly on site or near nanoparticle fabrication facilities. It is designed to be compact, lightweight, and easily transportable, occupying only about half of an office desk's space. The system is based on a commercially available low cost CNC machine, whose milling head is replaced by a laser source. This provides an x and y platform capable of positioning the laser beam over desired locations on the substrate. The optical pathway remains straightforward: the laser beam is directed through a collimator lens onto the donor substrate. While this simplicity limits the minimum achievable laser spot size and affects its energy distribution, it does not compromise the effectiveness of the setup for characterizing inks.

The controller electronics are housed in a protective enclosure that typically requires no access, as the transfer protocol is pre programmed and can be initiated with a single button press. After a short countdown, the transfer starts automatically, making the setup user friendly even for operators without programming or electronics experience.

The development and testing of inks are carried out by TECNAN in Los Arcos, Spain, a project partner in the Nanostacks consortium and manufacturer of nanoparticle based inks. Various nanoparticle materials for ink formulation are evaluated. In this study, zinc oxide nanoparticle inks are investigated in greater detail. Such inks hold potential for use as functional materials in printed diodes, light emitting diodes (LEDs), or as sensing layers in gas sensors. Ink optimization for LIFT printing focuses on tuning viscosity, particle concentration, and solvent composition as the main parameters influencing the transfer process, but other determining factors such as surface tension, ink stability or compatibility with other ink systems also need to be considered. The portable setup enables rapid iteration and testing within a range of laser powers and exposure times, replacing lengthy cross laboratory testing cycles. Once a promising ink candidate is identified, it is shipped to the production printer site, where its printability is verified and confirmed.

5.2.1 Assessment of Developed Inks

The developed inks are evaluated both at the manufacturer's site using the test printer and later validated at the production site with the LIFT production printer. Since the laboratory equipment, laser sources and optical components of the two LIFT systems are not perfectly identical, fine-tuning of the process parameters is

often required to identify the optimal transfer conditions. The quality of an ink is determined by its processing properties, long-term stability and printing performance.

Testing of the ink candidates includes analysis of their spreading behavior by blade coating on the donor substrate and determination of the blade-gap parameter that results in the best printing performance. Ink stability is assessed by evaluating the behavior of the coated thin film on the donor. The ink must remain stable for several minutes, long enough to complete the LIFT printing process. Shelf-life stability is also considered, with a target duration of at least several weeks to allow for logistics and a sufficient number of experiments. Optimal printing properties are established by printing with systematically varied laser parameters and analyzing the resulting transfer quality.

Characterization methods include rheological measurements, optical microscopy, and VSI. Parameters such as viscosity, nanoparticle concentration and solvent composition are systematically investigated during on-site testing.

Printing quality is assessed based on spot roundness (defined as the deviation between the x- and y-diameter), occurrence of spattering, spot height, coverage and the homogeneity of material distribution within the spot. By correlating ink properties, such as viscosity, with the observed printing behavior, relationships between material characteristics and printing performance are identified.

5.2.2 Influence of Viscosity

In addition to nanoparticles and a solvent, serving as a dispersion medium, nanoparticle inks contain additional ingredients required to tailor the ink properties according to specific printing needs, such as an adjusted viscosity. A more detailed description of the ink fabrication process is provided in Section 4.2.2, and a list of potential ink candidates is shown in Table 4.4.

For the preparation of zinc oxide (ZnO) inks and the modification of their viscosity, the ZnO nanoparticles are first dispersed in a solution containing PVP and 2-butoxyethanol. In a subsequent step, ethyl cellulose is added. PVP and ethyl cellulose act as dispersing agents by adsorbing onto the nanoparticle surfaces and forming an organic shell. This steric stabilization causes mutual repulsion between particles and serves as a barrier that prevents agglomeration caused by van der Waals forces or electrostatic interactions. The result is a well-dispersed and stable ink. PVP is soluble in both polar organic and aqueous solvents, while ethyl cellulose is soluble primarily in organic solvents.

The viscosity of the ink is mainly determined by the concentration of particles and polymeric binder relative to the solvent content. Increasing the concentration of solids and binders leads to higher viscosity, while dilution results in lower viscosity. Viscosity control is important to regulate the spreading behavior of the ink on the receiving substrate and its transfer properties. In this study, the ethyl cellulose content is adjusted in the range of 1 % to 3 %. The influence of this adjustment is illustrated in Figure 5.17. Different ink formulations lead to spots that vary in appearance and lateral dimensions. However, variations in color cannot be attributed solely to the ink formulations, as they may also arise from differing illumination conditions.

The inks with modified viscosity are tested using the portable LIFT setup. The

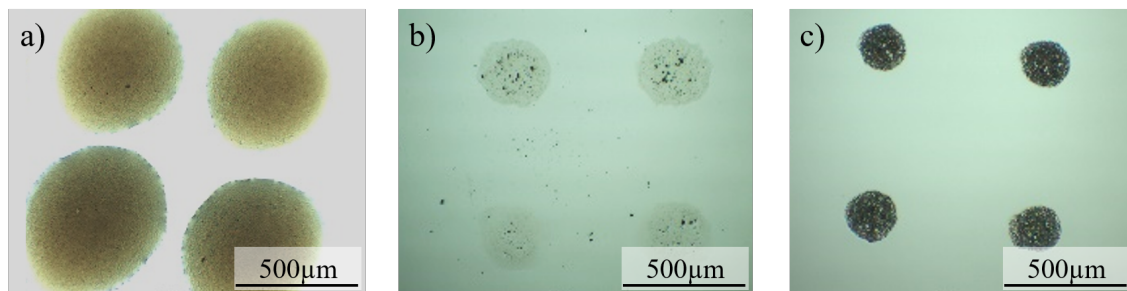


Figure 5.17: Exemplary spots printed with the LIFT test setup using ink samples of different viscosities, characterized on-site using light microscopy. Laser parameters are 220 mW and 10 ms. (a) 1% ethyl cellulose content, (b) 2% ethyl cellulose content, (c) 3% ethyl cellulose content. Source: Lux et al. [P1]

printed spots are analyzed by optical microscopy and their diameters measured. The relationship between viscosity and spot diameter is shown in Figure 5.18b. The mean spot diameter with its standard deviation is plotted against the ethyl cellulose content and the corresponding measured viscosity with its standard deviation. From this graph it can be derived that a lower viscosity corresponds to a lower ethyl cellulose content which leads to larger spots, while a higher viscosity results in smaller lateral spot sizes.

The underlying mechanism behind this trend cannot be derived from these data alone. It may be related to ink spreading on the substrate or to processes occurring during the ink transfer itself. Identifying the specific cause requires additional information, for example measurements of deposited ink volume or contact angle. A detailed investigation of these aspects is outside the scope of this work and is therefore not pursued. Nevertheless, future studies could address these open points more comprehensively, since a clearer understanding of the mechanism may help to further optimize ink formulation and transfer behavior.

Further observations within this study reveal a lower viscosity limit of approximately 100 cPs (100 mPa s), below which no material transfer is observed. Within the range of 100 cPs to 3000 cPs (100 mPa s to 3000 mPa s), transfer is possible but exhibits significant spot variability, indicating unreliable printing behavior. An upper limit is also identified at 3000 cPs, above which no transfer occurs.

Since the portable LIFT test printer shares nearly identical transfer characteristics with the main production LIFT system, these findings apply to both setups.

5.2.3 Influence of Nanoparticle Concentration

The nanoparticle content is a key parameter in ink formulation, as it determines both the rheological properties and the elemental composition in the printed features. Increasing the nanoparticle weight fraction raises the ratio of solids to solvent, thereby increasing viscosity and influencing the size and morphology of the printed spots. A low ZnO concentration may require post-processing, such as heat treatment, to remove remaining organic compounds, whereas a higher concentration can yield purer structures. The favored variant is depending on the intended application.

The nanoparticle concentration must be aligned with the desired outcome and application. In certain cases, a lower particle content may be advantageous particularly

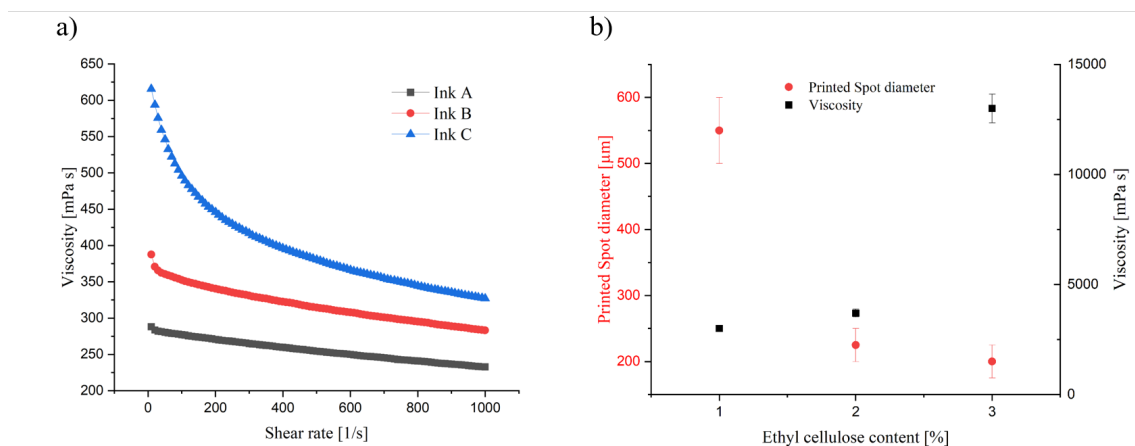


Figure 5.18: Testing of ink candidates A, B, C at the production printer which are previously iteratively adjusted and tested with the small test printer on-site. (a) Viscosity measurements of three zinc oxide (ZnO) pastes containing different concentrations of ethyl cellulose across a shear range of 0 L/s to 1000 L/s using a parallel plate geometry. b) Elevating the ethyl cellulose content leads to an increase in viscosity and an observed decrease in spot diameter. Source: Lux et al. [P1]

when porous structures are required after sintering. For instance, in gas sensor applications, enhanced porosity improves sensitivity and overall performance [77]. In other cases, a denser or bulkier structure is beneficial, e.g. to achieve high electrical conductivity [78].

Based on the viscosity adjustment and nanoparticle concentration studies, three ink formulations are selected that exhibit good printing performance in the form of circular spots with uniform ink distribution and high repeatability using the test setup. These candidates are referred to as Ink A, Ink B and Ink C, each representing a different nanoparticle concentration. Ink A contains 8 mg/mL ZnO, Ink B 30 mg/mL, and Ink C 170 mg/mL.

The inks are subsequently evaluated for printability using the production LIFT printer. Additionally, their viscosities are analyzed rheologically with a Haake Rheostress 300 rheometer. The viscosity as a function of shear rate is shown in Figure 5.18a. As expected, ink C exhibits the highest viscosity and solid content, while ink A shows the lowest viscosity and nanoparticle concentration. Each ink also displays a varying degree of shear-thinning behavior, with ink C demonstrating the most pronounced effect and Ink A the least. This phenomenon can be attributed to the lower presence of ethyl cellulose polymer chains in Ink A, resulting in reduced resistance to flow under shear stress and, consequently, a weaker shear-thinning response.

5.2.4 Influence of Particle Size and Solvent

Further studies investigate the influence of nanoparticle size and solvent type on the transfer behavior of the inks. Tests performed with the test LIFT setup show that inks containing smaller nanoparticles (< 77 nm) do not exhibit any successful material transfer. In contrast, inks with larger particle sizes (> 191 nm) demonstrate improved transfer behavior. Although nanoparticle inks with smaller particle sizes generally exist and are used in other printing applications, this result is unexpected.

Further investigation of the underlying physical processes is beyond the scope of this work. Consequently, inks containing smaller particles are excluded from further testing.

The solvent influence is studied by comparing inks based on 2-butoxyethanol and diethylene glycol monoethyl ether (DEGMME). Interestingly, inks using 2-butoxyethanol can be transferred without visible agglomerations (see Figure 5.19a-c), whereas inks formulated with DEGMME show transferred dot patterns that exhibit clear agglomeration effects (see Figure 5.19d) (Ink D). These agglomerations may result from an improper ratio of nanoparticles to dispersing agents or from effects occurring during the LIFT transfer, where laser-induced heating could alter the ink's properties. These findings show that both particle size and solvent composition critically influence LIFT transfer quality, emphasizing the importance of tailoring ink formulations for successful printing.

5.2.5 Validation of Customized Ink Candidates

Different ink formulations are tested on-site for their printability using the LIFT test printer. Promising ink candidates are selected based on three key criteria: the roundness of the printed spots, the uniformity of ink distribution within the spots and the repeatability of the transfer. The resulting inks are labeled as A, B, C and D (A,B,C identical to Figure 5.18), differing in nanoparticle content and solvent composition. Their specifications are listed in Table 4.4, while the detailed fabrication recipes are described in Section 4.2.2.

The viscosity of inks from A to C is analyzed using rheological measurements, as shown in Figure 5.18a. Ink D is not stable enough and shows agglomerations. Blading tests are also performed to evaluate the coating behavior of the inks on the donor substrate (see Figure A.11). The inks can be evenly distributed using a blade gap of 20 μm . Over time, surface-tension-driven effects can alter the coated film and affect the transfer behavior. To ensure reproducible and reliable spot formation, all transfer tests are therefore performed within a few minutes after coating.

For validation measurements with the production LIFT printer, a spacer of 70 μm is placed between the donor and receiver substrates. The test setup is configured to use the same spacing. A screening of suitable laser parameters is conducted with a representative subset shown in Figure 5.19, using laser powers from 220 mW to 300 mW and pulse durations from 6 ms to 10 ms. All inks from A to D are successfully transferred with the production printer, confirming that the mobile test device provides reliable on-site validation of ink performance.

Ink C shows the best overall performance, providing the most reliable transfer behavior, high spot symmetry, and homogeneous particle distribution. Laser parameters of 300 mW and 10 ms (highlighted in the yellow box) yield nearly circular 200 μm spots with optically uniform particle distribution and no visible spilling.

Ink A exhibits clear limitations due to its low viscosity and nanoparticle content, resulting in irregular spot shapes, darker edge rings and, for some parameter combinations, no transfer at all.

Ink B performs better than Ink A, with improved roundness and uniformity, but still shows minor deviations compared to Ink C.

Ink D shows the strongest drawbacks, producing laterally large spots with visible agglomerations that indicate inhomogeneous particle distribution, making it less suitable for structure fabrication.

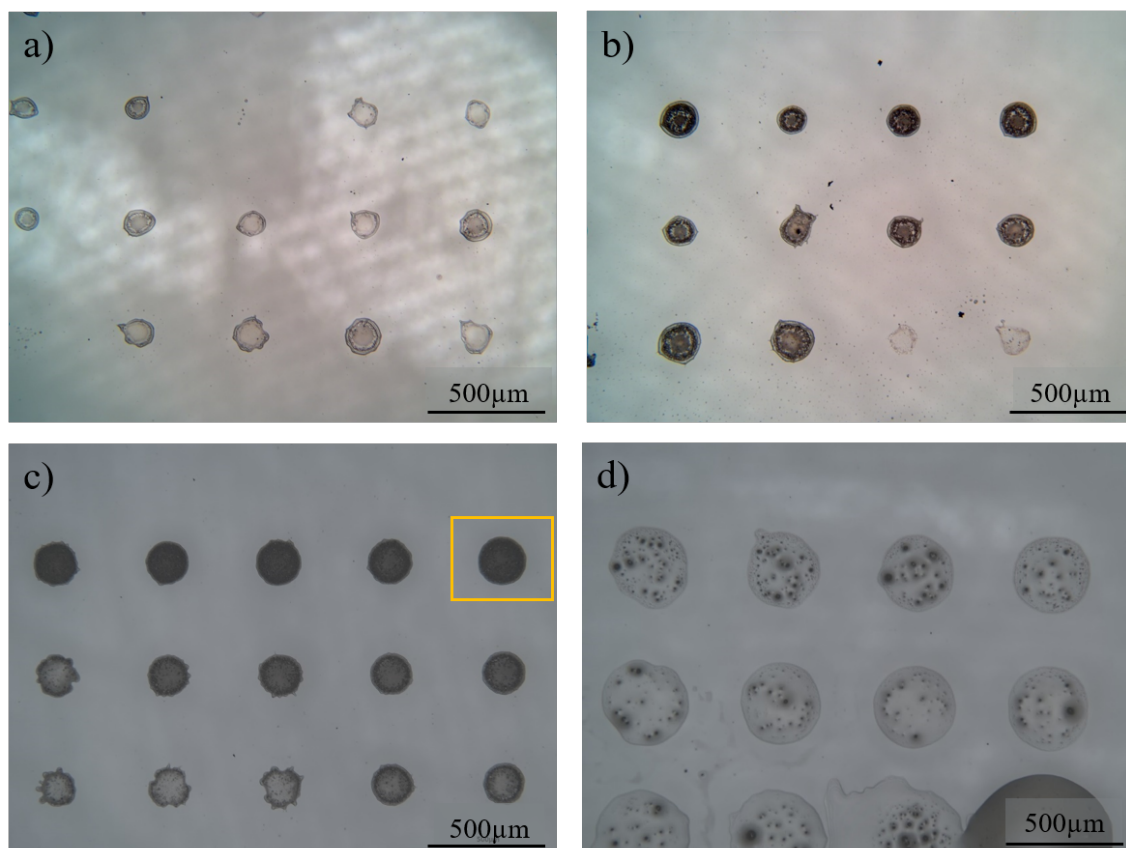


Figure 5.19: Ink candidates iteratively optimized for printability were tested with the production LIFT printer. Each horizontal row of five spots represents increasing laser power in 20 mW steps from 220 mW to 300 mW left to right, while vertically spaced rows correspond to increasing laser durations in 2 ms steps from 6 ms to 10 ms down to up. (a) Ink A with the lowest viscosity (2900 mPa s); (b) Ink B with medium viscosity (3800 mPa s); (c) Ink C with the highest viscosity (6100 mPa s); (d) Ink D showing inhomogeneous particle distribution and visible agglomerations, resulting in larger and more widely spread spots on the receiving substrate. Source: Lux et al. [P1]

Further optimization of ink performance can be achieved by modifying the surface energy of the receiving substrate, making it more repellent and thereby improving spot circularity. Surface energy can, for example, be adjusted through silanization or plasma treatment. Disproportionally shaped spots or spilling occur when the transferred ink volume exceeds the local surface capacity, causing material to overflow toward one side. Reducing the surface energy mitigates this effect, and using inks with higher viscosity likewise limits excessive spreading and promotes faster drying, helping the deposited material maintain its intended position.

Another observed phenomenon is the coffee-ring effect [79]. This behavior arises from the surface-dependent evaporation of the solvent. As solvent evaporation proceeds, the total spot volume decreases, which would theoretically reduce spot diameter because the contact angle stays the same [80]. However, since the edges of the spots are pinned to the substrate, the spot flattens instead of shrinking. Continuous evaporation drives material flow toward the perimeter, where it accumulates and forms a crater-like rim. This effect is observed for all printed ink materials but is more pronounced in inks A and B due to their lower viscosities which allow increased internal material flow. In contrast, higher viscosity inks such as C limit this flow and thus suppress the formation of pronounced coffee rings. Implementing temperature control in the test LIFT setup could further mitigate this effect by reducing the evaporation rate and promoting more uniform drying.

To analyze the ink distribution in greater detail, VSI measurements are performed for inks A, B and C. This method provides quantitative information about the spot morphology and the thickness variation of the printed features. The corresponding height maps are shown in Figure 5.20. The results reveal that nanoparticles tend to migrate toward the spot edges where they accumulate depending on the ink viscosity as the solvent evaporates. The average height along the line profiles of the printed spots ranges from 200 nm to 260 nm, with significant fluctuations across the spot area. After sintering, the remaining average height is approximately 70 nm.

5.2.6 Further Optimization Perspectives

When printing structures with nanoparticle inks it is desirable to achieve highly circular spots with a uniform particle distribution to allow the fabrication of flat and homogeneous layers. Therefore, strategies are needed to minimize the coffee-ring effect and further improve printing quality. Several established approaches can reduce this phenomenon, such as increasing the viscosity to suppress fluid flow, adding surfactants or using a mixture of high- and low-boiling-point solvents during ink formulation [40, 41, 42].

These optimization strategies, which involve substrate properties, must be integrated into the ink manufacturer's development process. Effective implementation requires analyzing the ink's surface tension and adjusting it via surfactants, while simultaneously tuning the surface energy of the receiving substrate for better compatibility. While increasing the ink viscosity is often the simplest approach, however it is limited by the point at which the ink becomes too thick for reliable transfer and the energy input is no longer sufficient for a bubble formation. Using a combination of solvents with different boiling points may provide a more balanced solution.

The effectiveness of the current approach is constrained by the testing capabilities available to the ink developer. With further studies and analysis of the internal ink

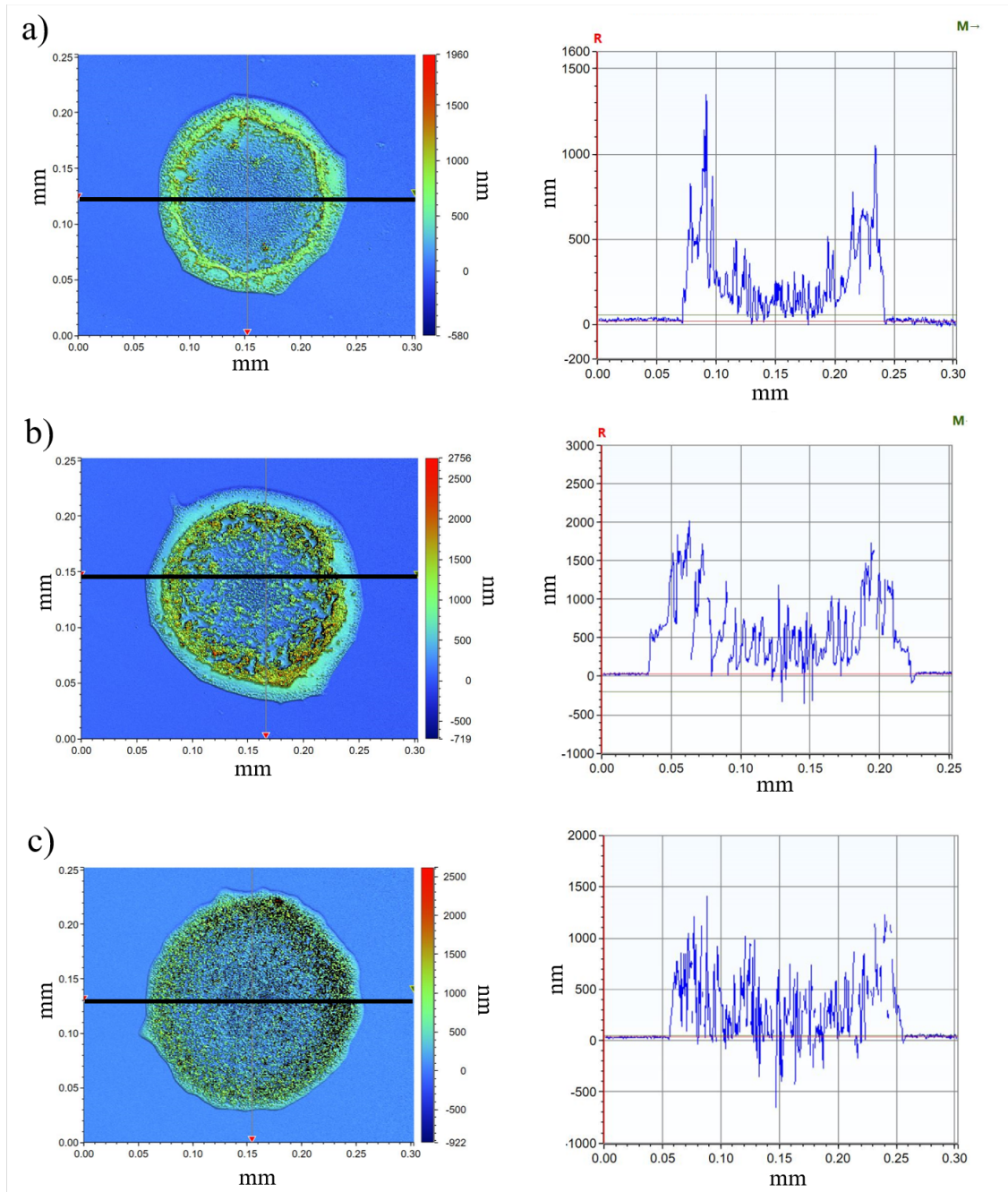


Figure 5.20: VSI analysis of ZnO spots printed with the production LIFT printer, optimized through preliminary testing with the portable LIFT setup. The topographic images show height variations within each spot along with corresponding line profiles (black line). The coffee-ring effect causes material accumulation at the edges of the spots, with its intensity depending on the ink viscosity. (a) Ink A, 280 mW, 20 ms: average height over the x-profile 250 nm, pronounced coffee-ring effect visible. (b) Ink B, 280 mW, 6 ms: average height 200 nm, slightly less pronounced coffee-ring effect. (c) Ink C, 280 mW, 6 ms: average height 260 nm, coffee-ring effect weakest among the three samples and best particle distribution. Source: Lux et al. [P1]

distribution within printed spots, potentially via light absorption measurements or advanced surface characterization techniques such as VSI, SEM or atomic force microscopy (AFM) more precisely tailored inks could be achieved.

Given the current goal of providing a low-cost, rapid on-site testing workflow, these advanced instruments may exceed practical limits. A more feasible alternative could involve controlling the drying behavior of printed spots by adjusting the substrate temperature, thereby influencing solvent evaporation dynamics without requiring complex equipment.

In this study, the effectiveness of a small test LIFT device for rapid on-site ink testing and optimization is demonstrated. Numerous inks are fabricated and tested directly at the development site, far more efficiently than is possible through conventional sample shipping, testing, feedback and reformulation cycles. Promising ink candidates are subsequently transferred to the production LIFT facility, and four representative formulations are analyzed in detail. The parameters investigated include particle size, viscosity, solvent selection and nanoparticle concentration, leading to the identification of well-performing inks.

Ink type C is among the shipped inks the most suitable candidate for LIFT printing. It is further analyzed by printing ZnO-based silver structures for conductivity measurements which are presented in Appendix A.5. The test LIFT setup is developed as a targeted solution for decentralized research projects. Although designed for a specific application, its modular design makes it highly adaptable to other LIFT printing setups outside of this research group. The laser diode can be easily exchanged to adjust the wavelength to different LIFT configurations, and the system can also be extended to pulsed laser sources. This demonstrates the versatility of the device and shows that it provides a solution to a problem that arises from decentralization and logistics, a challenge encountered by many research groups in academia and also in industry related projects.

5.3 Line and Area Printing

Since the printing with nanoparticle inks compared to small molecule and polymer materials differs from the transfer mechanism and the deposition rate, the approach for line and area printing is also different. Therefore the approaches are described separately in this section. The printing with small molecule and polymer materials is then further expanded in Section 5.3.1.

Approach for Nanoparticle Inks

The approach for identifying suitable laser parameters for line and area printing is described in Section 4.4, and the results of this study are presented in this chapter. To determine the optimal parameters for the silver ink XTPL CL60, a dot matrix is printed in which laser power and exposure time are systematically varied, with each combination producing a single dot. The resulting matrix is analyzed under an optical microscope to identify trends in dot formation and transfer behavior. An example of such a parameter matrix is shown in Figure 5.21. All printable dots are displayed. 120 mW represents the power threshold below which no material transfer occurs.

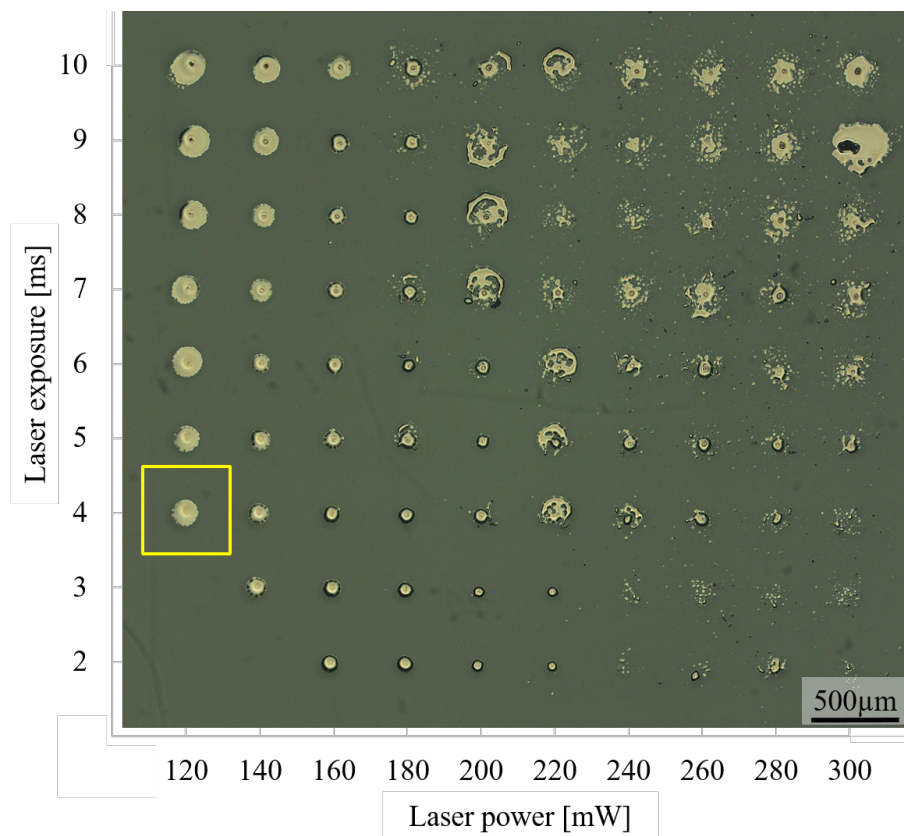


Figure 5.21: Screening for suitable printing parameters of silver ink XTPL CL60 by varying laser power and exposure time. The yellow-marked dot indicates the parameter set selected for area printing. Obtained by light microscopy. Source: Lux et al. [P2]

Within this matrix the shape and size of the printed dots vary significantly. The top-right corner corresponds to the highest laser energy and shows large dots accompanied by splashes and satellite droplets. The bottom-right corner shows no main dots but scattered satellite droplets. The top-left corner features large dots, while the bottom-left corner exhibits no material transfer. In the central region between these extremes, small and well-defined dots mark a transitional zone.

A clear trend can be observed. Near the transfer threshold of approximately 120 mW, the transferred dots exhibit the largest diameters. As the laser power increases to around 160 mW to 200 mW, the dot size decreases and small compact structures are formed. At even higher laser powers, satellite droplets appear around the main dot, indicating that the solvent evaporates too rapidly and explosively, propelling small amounts of material outward. Between the regimes of small dots and those with satellite droplets, ring-shaped structures are occasionally observed. These are likely caused by transient ink bubbles that form and burst during the transfer, resulting in a ring-like deposition pattern that reflects the bubble geometry [35].

Laser power alone cannot fully describe this behavior. The transfer dynamics are determined by the combined influence of laser power and exposure time, which together define the total energy input. In the present case, the minimum transfer threshold can be estimated as approximately 120 mW for 4 ms, 140 mW for 3 ms, or 160 mW for 2 ms.

To verify these interpretations, detailed numerical simulations of the laser-material interaction or high-speed imaging of the actual transfer dynamics would be required which are out of the scope of this work. Such analyses could reveal transient effects such as bubble formation, solvent evaporation, and pressure evolution within the ink layer, which are not directly accessible from static imaging.

For the printing of functional structures, round and uniform dots without splashes or satellite droplets are preferred. Although smaller dots generally enable higher resolution, this advantage does not apply here. Printing smaller dots requires a reduced pitch for area coverage, which can lead to unreliable results when using liquid inks. The heat-affected zone from the laser may alter the ink properties of adjacent spots, causing premature drying or viscosity changes that can inhibit proper material transfer. Literature also reports that pressure buildup can escape into nearby cavities formed by previous transfers [81].

Therefore, a compromise must be made between smaller dots, which offer higher resolution, and larger dots, which provide improved reliability and faster printing. It should be noted that the selected printing parameter lies close to the transfer threshold, which is generally considered disadvantageous, as small fluctuations in laser power or layer properties may lead to missing transfers. However, empirical studies have shown that reliable material transfer is still achievable under these conditions.

In this context, the yellow-marked dot (see Figure 5.22) at 120 mW and 4 ms is selected for printing the capacitor electrodes. It is round, uniform, and relatively large, which is advantageous for printing speed and reliability. Additionally, no satellite droplets are observed around the dot, as is typically the case at higher laser transfer energies.

After selecting laser parameters of 120 mW and 4 ms, which produce dots with an average diameter of approximately 170 μm , different pitch values are tested for line and area printing. Under these conditions, a pitch of 100 μm is found to be optimal for area printing, as it enabled the deposition of a continuous ink film without

holes while preventing the spilling that occurs when excessive ink is deposited. The corresponding printing result is shown in Figure 5.22. To further demonstrate the versatility of the printing process, the KIT logo is also fabricated with the same ink, without detailed specification of the transfer parameters. A more detailed investigation of line printing using the silver ink XTPL CL60, including conductivity measurements under specific printing modes, is presented in Section 5.5.1.



Figure 5.22: Light microscopic images of (a) KIT logo printed with XTPL CL60 silver ink and (b) a continuous area of the same ink printed with a pitch of 100 μm . Color appears different due to different illumination settings.

Approach for Polymer or Small Molecule Inks

As described in Section 4.4, S-LEC[®]-glycine is transferred with a pitch of 8 μm to achieve smooth S-LEC[®] surfaces. This differs from the 80 μm pitch obtained in Section 3.4, which uses a pitch of 80 μm . To compare the different area printing approaches, various printing modes are illustrated in Figure 5.23.

Figure 5.23a shows printing with a larger pitch of 80 μm , where the deposited dots begin to fuse but the resulting layer remains discontinuous. Reducing the pitch to 60 μm (Figure 5.23b) initiates area coverage, although small gaps and missing dots are still present due to insufficient overlap. A further reduction to 8 μm , corresponding to approximately 90% overlap, leads to the transition from isolated dot structures to continuous film formation. Under these conditions, smooth surfaces with a height of about 80 μm are obtained. The high degree of overlap requires adjustment of process parameters to avoid excessive energy input. Therefore, the laser power is reduced to 70 mW and the exposure time to 1 ms, yielding stable and reproducible printing while preventing heating or carbonization of the Kapton[®].

These printing conditions primarily enlarge the printed area rather than increase its height, resulting in a small, homogeneous surface. This behavior is consistent with observations from Section 3.4, where closely spaced dots exhibit fusion, a mechanism deliberately exploited for area printing.

The identified parameters are optimal for smooth S-LEC[®]-glycine transfer based on VSI analysis. However, other materials may require different optimal parameter sets.

5.3.1 Area Printing with Adjustable Layer Thickness

Bphen layers are transferred using different ink concentrations on the donor substrate. The detailed transfer parameters are provided in Section 4.5. As shown in Figure 5.24b, the layer thickness increases with concentration. For concentrations

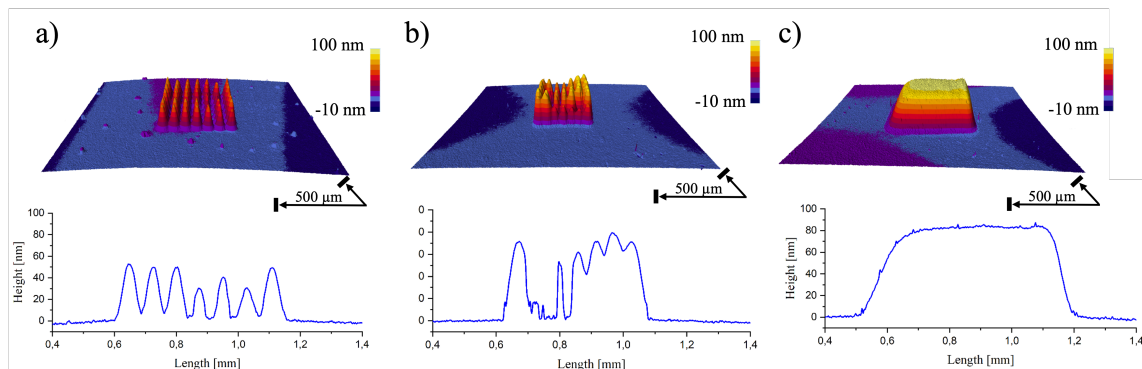


Figure 5.23: Printing with different pitches with S-LEC[®] material results in (a) dots beginning to overlap (80 μm , 150 mW, 10 ms) (b) fused dots forming a polymer layer which is not planar (60 μm , 150 mW, 7 ms) (c) fused dots with homogeneous height forming a plane layer (8 μm , 70 mW, 1 ms). Source: Lux et al. [P3]

up to 12 mg/mL, the behavior is approximately linear. At the highest concentration of 30 mg/mL, a saturation effect becomes evident, as the resulting thickness falls below the observed linear trend. Overall, the layer thickness varies from 20 nm at the lowest concentration to about 140 nm at the highest concentration.

The observed deviation from linearity at high concentration may be attributed to increased absorption of laser-induced kinetic energy within the more viscous donor layer, leading to a reduced effective transfer of material. Figure 5.24a presents a representative topographic image of a printed Bphen structure acquired by VSI. The visualization appears distorted because the lateral and vertical z-scales differ. The overall structure is relatively flat, with minor height variations that could originate from technical aspects of the printing process, residual impurities in the ink, surface roughness of the acceptor, or contamination. Adjusting the concentration of the donor solution allows control over the thickness of the printed layers and can therefore serve as a helpful tool for device fabrication.

The second method of adjusting the printed layer thickness is the change of laser parameters for the transfer. Two more laser settings are tested in addition to the empirically found optimum 70 mW, 2 ms: 80 mW, 2 ms and 70 ms, 3 ms with a pitch of 8 μm and a constant concentration of 12 mg/mL. The increase in laser energy by raising the laser power or exposure time leads to an increase of layer thickness from initially approx. 100 nm to 120 nm. The topographic images and corresponding line profiles are shown in Figure 5.25.

5.3.2 Control of Surface Roughness for Area Printing

The control of surface roughness is an important factor in the printing of material layers for potential applications. Depending on the application, either a rough or a smooth surface may be desirable. For instance, sensors or solar cells with bulk heterojunction architectures can benefit from increased surface roughness due to the larger interfacial area, while devices such as OLEDs require a flat surface for optimal performance due to more efficient charge transport. In the present work, the objective is to optimize the printing process toward the fabrication of printed OLEDs, where minimized surface roughness is essential.

Experimental details are described in Section 4.6. The results demonstrate that the

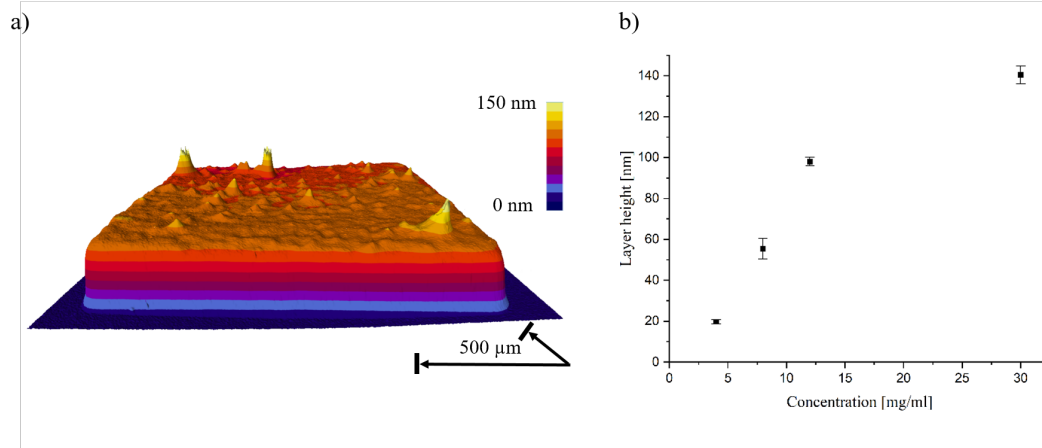


Figure 5.24: (a) Exemplary white-light interferometry measurement of a transferred Bphen layer prepared from a donor ink concentration of 12 mg/mL, transferred using a laser power of 70 mW and an exposure time of 2 ms. b) Height distribution of printed Bphen layers as a function of material concentration. Error bars represent the standard deviation. Source: Lux et al. [P3]

adjustment of laser parameters is an effective method to tune the surface roughness. Different parameter sets are tested around the empirically identified optimum of 70 mW, 2 ms. The resulting surfaces are analyzed with VSI, and both the topography maps and corresponding line profiles are shown in Figure 5.25. Data visualization and roughness evaluation are performed using the software *Vision64* (Bruker, Germany), which outputs the arithmetic mean roughness value R_a from surface line profiles.

The lowest surface roughness in this experiment, conducted with a fixed donor concentration of 12 mg/mL, is obtained using laser parameters of 70 mW and 2 ms, yielding an R_a value of $2.78 \text{ nm} \pm 0.25 \text{ nm}$ standard deviation. Increasing the exposure time to 3 ms led to a moderate rise in roughness ($R_a = 3.29 \text{ nm} \pm 0.27 \text{ nm}$ standard deviation), whereas raising the laser power to 80 mW resulted in a pronounced increase ($R_a = 6.08 \text{ nm} \pm 1.24 \text{ nm}$ standard deviation), as also reflected in the corresponding surface topography. In total, line profiles of twelve printed surfaces are analyzed to determine these R_a values. The increase in roughness at higher laser energy may be explained by stronger thermal gradients in the material induced by the higher energy input.

Additionally, roughness is measured for material concentrations ranging from 4 mg/mL to 30 mg/mL, with the corresponding R_a values listed in Table 5.5. The results show that R_a increases with increasing concentration. Comparing this trend with the measured layer heights shown in Figure 5.24 suggests a correlation between layer thickness and surface roughness. A possible explanation is that higher concentrations transfer more material which remains in a heated, viscous state for longer. Instead of cooling almost instantly at the surface, some material may still be viscous and pulled back from the acceptor by the receding donor, forming protrusions of a few nanometers in height.

For printing smooth, thin layers, this implies that the material can first be optimized for minimal roughness by adjusting the laser parameters. The height of the printed layers can then be controlled by varying the material concentration on the

donor without affecting the achieved smoothness, which primarily scales with layer thickness. A data set is available in the appendix in Table A.2 and Table A.3.

Concentration [mg/mL]	R_a [nm]	SD [nm]
4	1.44	0.03
8	1.74	0.33
12	2.78	0.26
30	4.05	1.22

Table 5.5: Measured surface roughness values R_a and their corresponding standard deviations at varying concentrations, obtained with laser transfer parameters of 70 mW and 2 ms for the material Bphen. Roughness values were derived from eleven analyzed surfaces. SD represents the standard deviation.

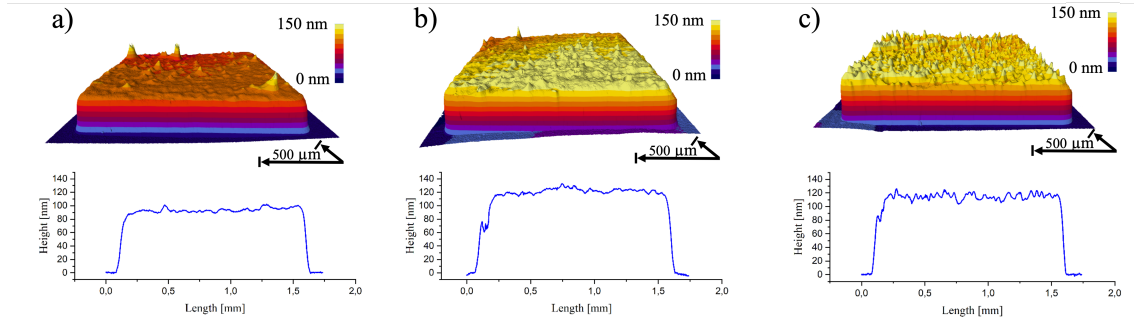


Figure 5.25: Transfer of Bphen under different laser conditions investigated while keeping the concentration of the donor material constant at 12 mg/mL. Topographic images display the surface features, while line profiles indicate thickness variations for laser powers and exposure times of (a) 70 mW, 2 ms (b) 70 mW, 3 ms and (c) 80 mW, 2 ms. Source: Lux et al. [P3]

5.4 Realization of Printed OLEDs

The successful fabrication of OLEDs in this work using LIFT printing is an important achievement showing that LIFT printing is capable to produce complex devices consisting of organic layers. It is shown that the method can flexibly and reliably use different material combinations. The printing process of these OLEDs is described in detail in Section 4.7. Thus, in general, the capability of LIFT printing for the fabrication of demanding multilayer systems seems a promising outlook to be further investigated. However, in this work OLEDs are chosen as an example to illustrate the method's capability to meet the high requirements on layer uniformity, thickness control and lateral precision.

Two types of OLEDs are fabricated, a *hybrid OLED*, in which the organic layers are deposited by a combination of spin coating and LIFT printing and a *fully printed OLED*, in which all organic layers are deposited by LIFT printing. Both device types are subsequently completed using the same fabrication steps for the anode and cathode.

5.4.1 Hybrid OLED

The hybrid OLED is fabricated by combining spin coating and LIFT printing on customized substrates. The fabrication procedure is described in Section 4.7.3. In this section, the results and characterization of the hybrid OLEDs are presented. A hybrid OLED is shown in Figure 5.26a. The selectively removed PEDOT:PSS layer, the printed organic layers, and the evaporated cathode bridging the gap to the ITO track are clearly visible. The OLEDs are operated and characterized using the MATIS setup (see Appendix A.1.9).

Yield and Emission

Within a single batch of 20 devices, an average yield of approximately 50% is achieved under laboratory conditions of 25 °C and 44 % relative humidity. Strong indications on the dependence of device yield and lifetime on ambient humidity is observed, indicating that moisture strongly interacts with the printed organic layers which is consistent with literature [82, 83]. The exposure to humidity is reduced by the use of desiccants and improved process control, which resulted in a noticeable increase in device yield and operational stability, with continuous operation times of up to about 30 s.

The optical emission spectra of the printed OLEDs are shown in Figure 5.26b. Since the setup is not calibrated for absolute intensity, the relative intensity is given in arbitrary units. The spectra are acquired by integrating the signal over measurement cycles of 0.5 s. The short integration time is chosen because the OLED lifetime was limited to a few seconds up to about one minute. The data shown represent averaged spectra for each OLED over ten consecutive measurement cycles of 0.5 s each. The background signal obtained from dark measurements is subtracted (see Section 4.7.4), and the resulting spectra are smoothed using a low-pass filter with a cutoff frequency of 0.02 Hz.

The emission peak occurs at 570 nm, corresponding to the yellow-green spectral region. The OLEDs show variation in emission intensity, which may be attributed to partial failure or malfunction, but only small variations in the peak wavelength. The averaged emission spectrum of one batch of ten functional OLEDs is shown in Figure 5.27. Data were processed the same way as for Figure 5.26b. A smaller shoulder at approximately 620 nm is visible. According to literature [84], this double-peak indicates the presence of two distinct transitions from the excited state of Rubrene molecules. The first peak corresponds to a direct electronic transition from the excited state to the ground state, whereas the smaller secondary peak is attributed to a vibronic transition, in which part of the energy is transferred into a vibrational energy level. This vibrational excitation subsequently relaxes through phonon coupling, releasing energy as heat and leading to a redshift of the emitted light.

Electrical Performance

The electrical performance of the hybrid OLEDs is investigated by measuring their voltage–current behavior under controlled operation. The primary objective of these measurements is to evaluate the electrical stability of the printed OLEDs during continuous operation while preventing device damage caused by overcurrent or thermal degradation. For this purpose, the SMU is operated in a protective source mode,

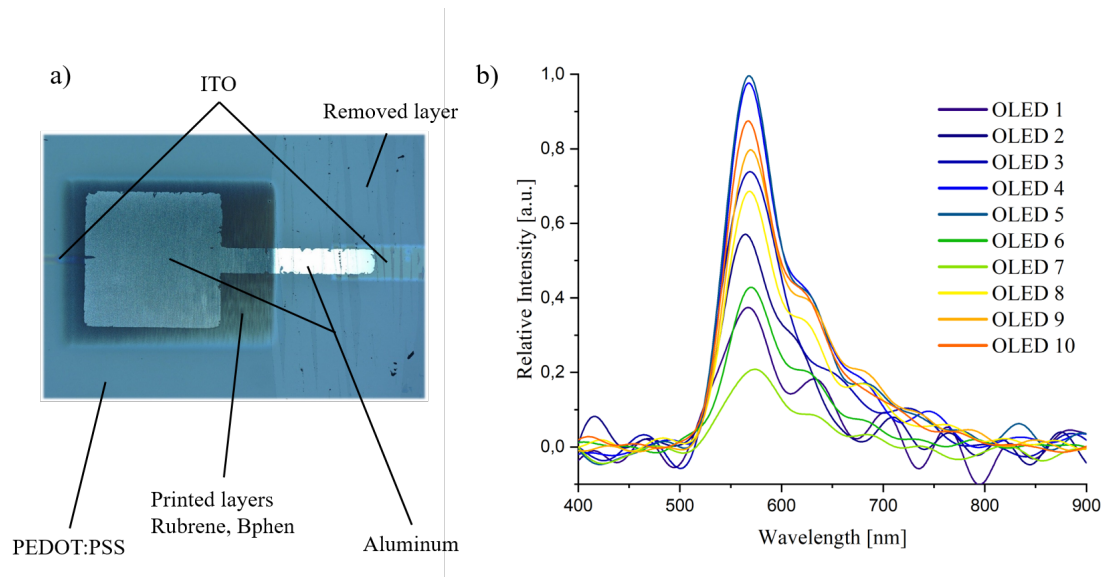


Figure 5.26: (a) Optical microscope image of a hybrid OLED prior to operation and testing. (b) Emission spectra of fabricated hybrid OLEDs. PEDOT:PSS was spin-coated, while Rubrene and Bphen were deposited via LIFT printing. Each color represents the spectrum of one OLED, obtained by averaging 10 measurement cycles with an integration time of 0.5 s. The intensity of the brightest OLED was normalized to 1, and all other OLEDs are shown with their relative intensities. Source: Lux et al. [P3]

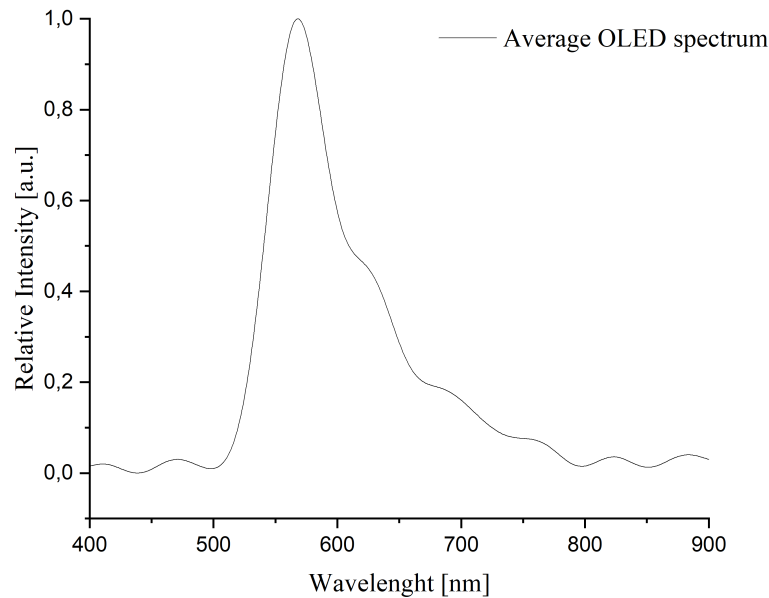


Figure 5.27: Normalized and averaged emission spectrum of fabricated hybrid OLEDs in Figure 5.26. PEDOT:PSS was spin-coated, and Rubrene as well as Bphen were deposited by LIFT printing. Data were obtained by averaging the emission signal of ten OLEDs with ten measurement cycles each of about 0.5 s.

which limits the current and voltage to a predefined maximum value. This safety feature prevents excessive current flow that could otherwise lead to localized breakdown and burning of the organic layers or accelerate degradation through high operating voltages.

The OLEDs begin to emit light at voltages as low as 5 V. The devices are operated at currents of up to 1 mA with a variable voltage limit of 20 V. During a measurement period of 5 s, divided into ten cycles of 0.5 s, a gradual increase in the required operating voltage is observed, as shown in Figure 5.28a. This trend is consistent across all tested OLEDs. Devices that emitted only at voltages near the 20 V limit are excluded, as their current dropped below 1 mA, due to the SMU constraints, making them not directly comparable.

The variation in operating voltage between devices is likely due to partial device failure. A higher or lower operating voltage indicates an increased or decreased internal resistance, suggesting structural or morphological variations introduced during fabrication or operation. The mean supply voltage, averaged over time for all hybrid OLEDs, is shown in Figure 5.28b together with its standard error of the mean, with an average value of approximately 18.5 V. The two significantly lower voltage curves are clearly outside the characteristic distribution and are therefore excluded from the average calculation. A possible cause may be pinhole-induced short circuits, although none are observed, or thickness variations in the spin-coated PEDOT:PSS layer.

From these measurements, a mean internal resistance of approximately 17 k Ω is calculated. Considering an OLED pixel size of 1 mm², this corresponds to an average current density of about 100 mA/cm².

The observed variations in electrical characteristics most likely originate from the fabrication process. Since the HTL is applied by spin coating, OLEDs positioned closer to the rotational center of the substrate may exhibit thicker PEDOT:PSS layers than those located near the edge. Such thickness variations can influence the series resistance and charge injection properties, leading to differences in operating voltage and stability. The thickness distribution of the HTL across the substrate was not investigated further.

Lifetime and Degradation

The operational lifetime of the OLEDs ranges from a few seconds to about one minute. Standardized lifetime measurements are not performed, as they are beyond the scope of this study. Based on repeated experiments, a strong correlation between humidity and both yield and lifetime is observed. Humidity is known to accelerate OLED degradation, and PEDOT:PSS is well known for its hygroscopic nature [85, 83]. Optical inspection of the devices before and after operation reveals visible surface changes, confirming rapid degradation during operation. Figure 5.29 shows the degradation process over several seconds. The initially shiny surface becomes matte, particularly at the outer regions, while the center remains reflective. Small bubbles appear and grow over time, especially near the edges and along the Al track (with PEDOT:PSS underneath), indicating that degradation occurs where current flows. Eventually, the central area remains bubble-free. The bubble distribution suggests that the failure mechanism may be driven by oxygen or moisture diffusion into the device. Since the aluminum cathode and the glass substrate act as barriers, only the outer areas are affected. Delamination of the cathode caused by outgassing of water

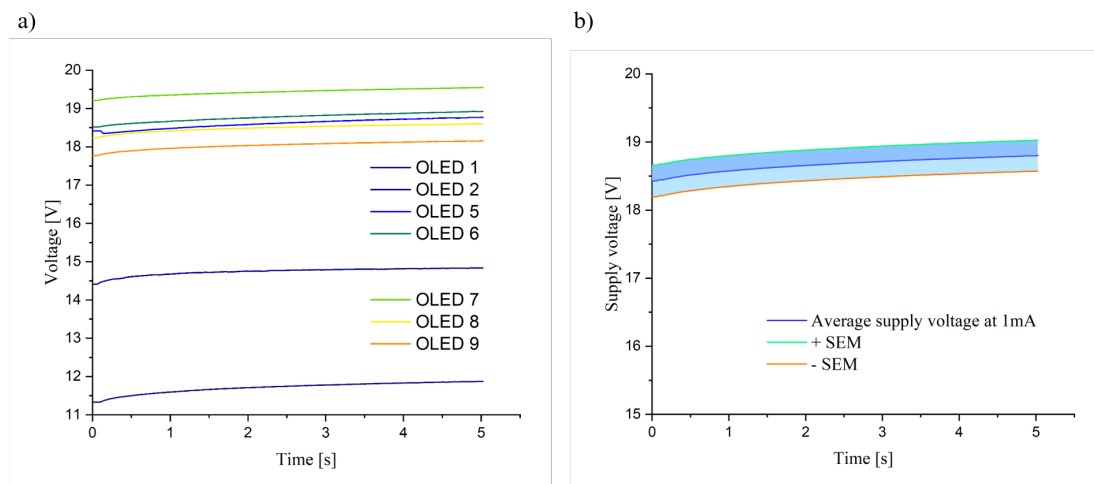


Figure 5.28: OLED supply voltage over time for ten measurement cycles of 0.5 s each under a constant current of 1 mA. (a) Supply voltage of multiple OLEDs, showing a slow increase over time, indicating a change in internal resistance. (b) Average supply voltage over time, obtained by averaging the signals of seven OLEDs operated at 1 mA. The colored area indicates the standard error of the mean (SEM).

during operation from the OLED layers is the most probable failure cause. To reduce oxygen and humidity exposure, samples are operated under an argon gas flow, which improves stability during operation but cannot undo diffusion that has already occurred during sample preparation under ambient conditions. After analyzing these OLED samples and observing fast degradation, measures were taken to reduce exposure to humidity, such as printing under reduced-humidity atmosphere or using desiccants during transfer and storage. After applying these methods, degradation is observed to be slower and the lifetime of the OLEDs increases. Quantitative measurements are not taken because the OLED fabrication takes place over several days in different labs, which does not allow the definition of a standardized humidity parameter connected to a defined result.

Failed OLEDs are analyzed using FIB-SEM, as shown in Figure 5.30, revealing detailed microstructural information. The FIB is used to cut a trench into the OLED sample, which is then tilted to obtain a cross-sectional view. In (a), the surface shows pores and protrusions around 1 μm in size. These likely originate from outgassing of humidity or solvents trapped in the OLED layers, probably in the PEDOT:PSS layer, which is known for its hygroscopic properties [85]. In this analysis the OLED is positioned about one centimeter away from the rotational center of the substrate, which may result in a thinner PEDOT:PSS layer and lower moisture absorption. In (b), raised aluminum structures forming bubbles and hollow sections are visible, with a FIB trench in the middle. This OLED originates from a region closer to the rotational center, where a thicker PEDOT:PSS layer is expected. Image (c) shows a detailed view of the raised aluminum layer, likely lifted by internal pressure during operation. Image (d) shows a cross section of the OLED with visible material contrast, allowing the identification and thickness measurement of individual layers. From bottom to top, the black region represents the glass substrate, the white layer is ITO with a thickness of 100 nm, followed by the spin-coated PEDOT:PSS layer with a thickness of 71 nm. Above this is the LIFT-printed Rubrene layer (21 nm),

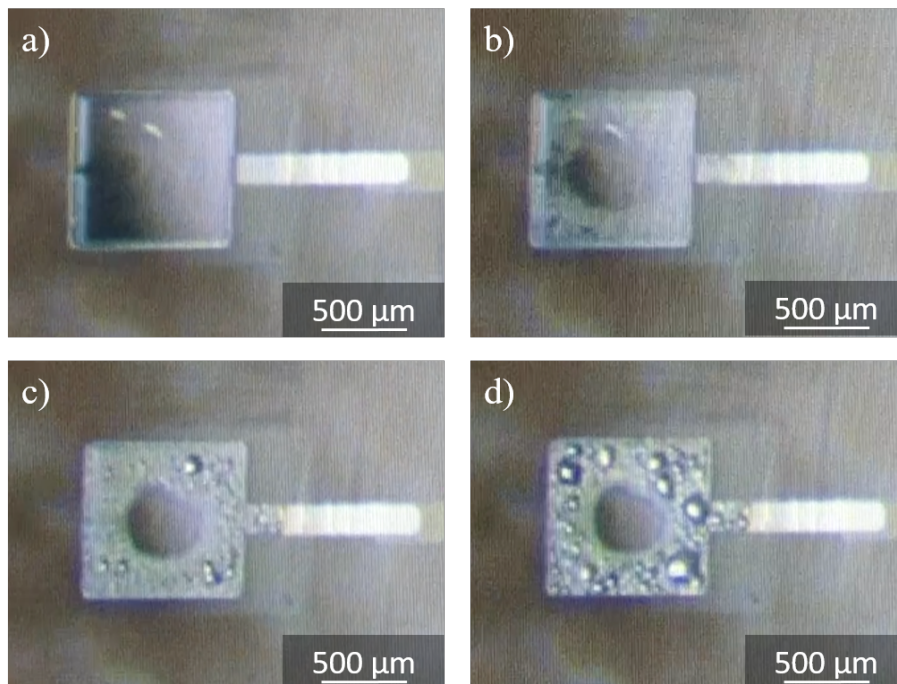


Figure 5.29: Light microscopic images of a single hybrid OLED during operation, showing degradation over a period of a few seconds. Bubbles form progressively over time, except in a small region at the center.

then a Bphen layer (104 nm) and finally the aluminum cathode (152 nm). These SEM results indicate that internal pressure, likely caused by humidity diffusing into the PEDOT:PSS layer and vaporizing during operation, causes the aluminum layer to lift. These findings highlight the importance of minimizing humidity exposure during OLED fabrication and operation. Furthermore, the Bphen layer is probably too thick to ensure efficient device performance. The primary function of this layer is to facilitate electron transport and injection into the Rubrene layer, which can be achieved with thinner films. Reducing the Bphen thickness offers the additional benefit of lowering the series resistance and the operating voltage. These experiments highlight the potential of LIFT printing for OLED fabrication, which motivates the fabrication of a fully printed OLED presented in the following section. Subsequent OLED designs therefore use lower Bphen concentrations to achieve thinner layers with improved electrical performance while also avoiding thickness variations associated with spin-coated layers.

Summary

The hybrid OLED concept, combining spin coating and LIFT printing, is successfully demonstrated, resulting in functional devices that are electrically and optically characterized. Within a single batch of 20 devices, a yield of 50% is achieved under laboratory conditions. Further enhancement of device stability and yield is expected through improved encapsulation of the OLEDs and humidity control of the experimental setup. However, such optimization is beyond the scope of this work. The primary objective here is to demonstrate the feasibility of LIFT-printed OLED fabrication and to achieve operational lifetimes sufficient for reliable optical and electrical characterization.

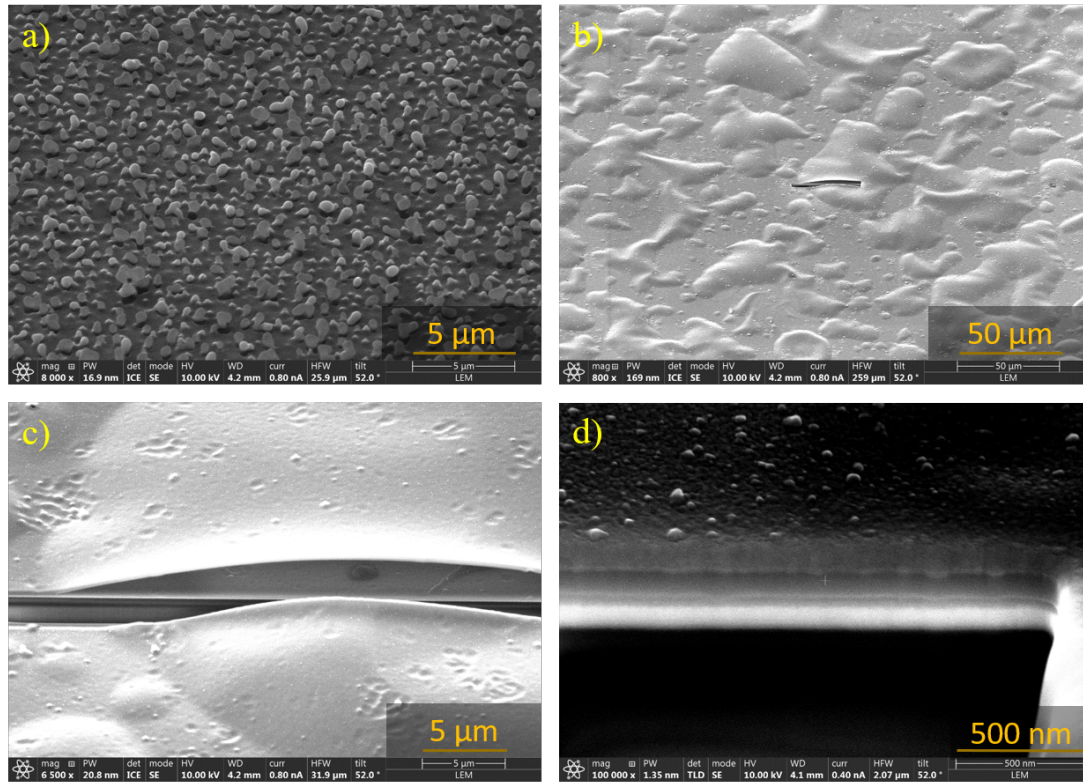


Figure 5.30: FIB-SEM analysis of degraded hybrid OLEDs after operation.

- (a) Surface morphology showing pores and protrusions of approximately 1 μm , likely caused by outgassing of humidity trapped in the hygroscopic PEDOT:PSS layer.
- (b) Raised aluminum structures and hollow regions are visible, with an FIB trench in the center.
- (c) Close-up of the lifted aluminum layer, presumably displaced by internal pressure during operation.
- (d) Cross-sectional view revealing individual OLED layers: glass substrate (black), ITO (100 nm), PEDOT:PSS (71 nm), Rubrene (21 nm), Bphen (104 nm), and aluminum cathode (152 nm).

The hybrid OLEDs exhibit electroluminescent emission with a peak at 570 nm, corresponding to the yellow-green spectral region, and an average operating current density of 100 mA/cm². The mean supply voltage during operation is approximately 17 V, yielding an estimated mean internal resistance of 17 k Ω which is comparable to other devices[86].

Operational lifetimes are limited to a few seconds up to about one minute and show strong variation between batches. Repeated experiments and post-mortem FIB-SEM analyses reveal that humidity ingress and subsequent outgassing, most likely originating from the hygroscopic PEDOT:PSS or other organic layers, represent the dominant failure mechanism. Degradation manifests in the form of bubble formation, aluminum delamination and surface pores, particularly in outer regions where diffusion pathways and mechanical stress are more pronounced.

Improvements in yield and stability are achieved by using desiccants and optimizing handling procedures. However, a quantitative evaluation is not possible because fabrication and testing occur over several days in different laboratories under varying humidity conditions. In addition to humidity-related degradation, process-related inhomogeneities such as non-uniform HTL thickness from spin coating likely contribute to device variability.

Overall, these results demonstrate the feasibility of OLED fabrication using LIFT and enable the production of operational devices with characteristic electroluminescent behavior. Although hybrid OLEDs exhibit limited stability and are therefore not studied as extensively as the following variants, they provide a solid foundation for subsequent optimization and for the development of fully printed OLED architectures with improved performance and reproducibility.

5.4.2 Fully Printed OLED

The preceding studies on the hybrid variant demonstrate the performance of LIFT for the fabrication of adjustable thin films for use in optoelectronic devices. In the next step, an OLED is to be developed on this basis, whose active structure is entirely fabricated by LIFT printing. All three layers of these fully printed OLEDs consist of selected organic materials printed onto a customized ITO substrate. In the final fabrication step, an aluminum cathode is deposited by thermal evaporation. This chapter presents the results of the OLED characterization for the detailed fabrication procedure of the fully printed OLEDs refer to Section 4.7.3.

The realization of LIFT-printed OLEDs represents a novel achievement and is published in the journal Wiley Advanced Material Interfaces (2025) by the author [P3].

Several OLED variants are printed using different combinations of the materials TCTA, TPD, Rubrene, Alq₃ and Bphen. Among these, the stack configuration ITO–TCTA–Rubrene–Bphen–Al is investigated in greater detail, while other layer combinations are tested primarily to demonstrate feasibility.

For standard operation and testing, rectangular TCTA–Rubrene–Bphen OLEDs are printed, as described in Section 4.7.2. The devices are characterized using the MATIS setup, which operates the OLEDs via an SMU and records their emission with a spectrometer. The OLEDs are driven within the upper limits of 10 mA and 20 V using the compliance mode, which limits either the voltage or the current if one of the parameters would exceed the set limits. A supply voltage of 20 V is

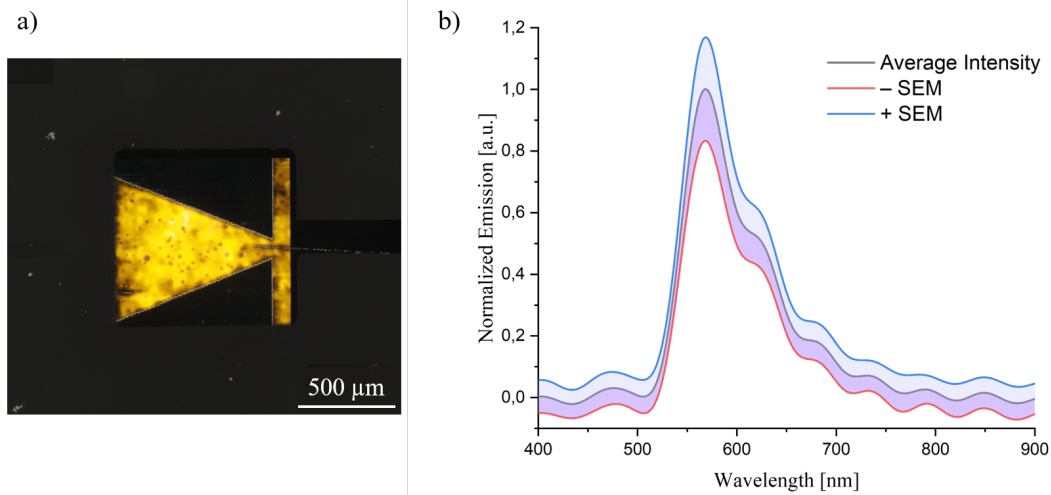


Figure 5.31: (a) Light microscopic image of the bottom side of a single OLED during operation, showing light emission. The OLED is printed on a specially designed ITO pattern in the shape of a diode symbol. (b) Normalized and averaged emission spectrum of printed TCTA–Rubrene–Bphen OLEDs. The shaded area represents the standard error of the mean (SEM). Source: Lux et al. [P3]

applied and the actual current decreases to a fraction of the set limit. The current and emission are detected simultaneously.

LIFT printing of OLEDs offers a high degree of freedom in pixel layout and design. In principle, various shapes and colors can be realized by printing different combinations of emissive and transport materials. This enables customizable and adaptable OLED designs that are difficult to achieve using conventional fabrication methods based on evaporation through shadow masks. To demonstrate the versatility of this approach, an TCTA-Rubrene-Bphen OLED in the shape of a diode symbol is fabricated on a custom-shaped ITO substrate, as shown in Figure 5.31a. The image shows the device under operation, obtained with an optical microscope. The observed color corresponds to the electroluminescent emission of the OLED. Local intensity variations indicate internal inhomogeneities, which may originate from thickness variations or non-uniform material distribution within the printed layers.

Emission and Long Term Behavior

The emission spectra are analyzed and are shown in Figure 5.31b. Each spectrum is accumulated over a measurement interval of 0.5 s, and dark spectra are subtracted to minimize the influence of background light which is already kept as low as possible. For each OLED, ten consecutive measurements are averaged, and the resulting spectra are further averaged over eight OLEDs of the same type. To reduce noise, the data are smoothed using a low-pass filter with a cutoff frequency of 0.02 Hz. The mean spectrum is normalized and displayed together with the standard error of the mean of the spectra since an absolute calibration is not available. The spectrum shows a dominant emission peak at 570 nm and a smaller

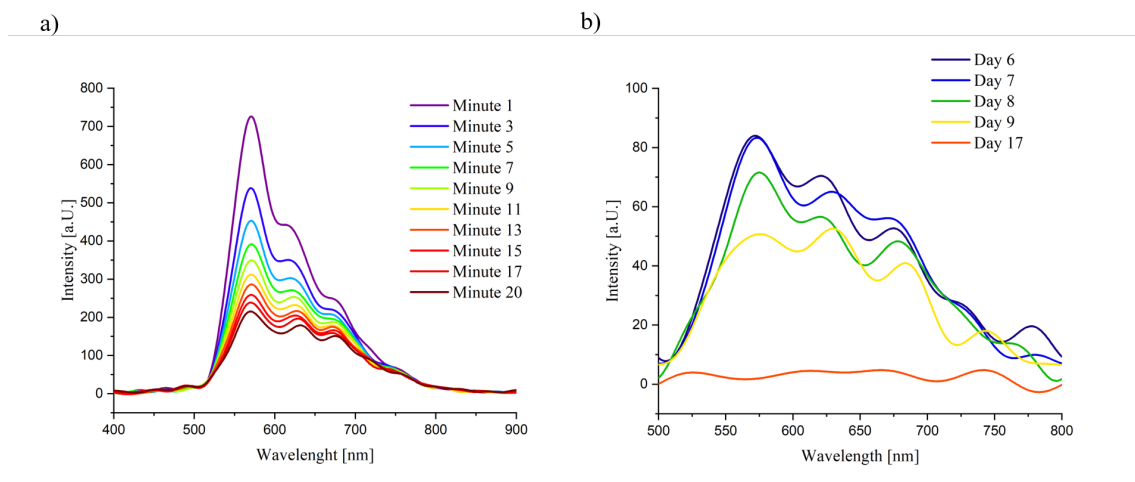


Figure 5.32: (a) Emission of a TCTA–Rubrene–Bphen OLED during continuous operation under argon flow for 20 min, showing degradation over time. (b) Intermittent testing of a TCTA–Rubrene–Bphen OLED over 17 days, operated under argon and stored under ambient laboratory conditions between measurements. Data from day 1 are not shown due to differing test conditions. Source: Lux et al. [P3]

secondary peak at 620 nm. This observation is consistent with literature [87].

The best yield of functional devices with detectable emission within a single batch of 20 OLEDs is approximately 60%. The majority of device failures are attributed to open-circuit behavior. The laboratory conditions during operation are 21 °C and 54% relative humidity. As no encapsulation is applied, the performance and lifetime of the OLEDs are likely influenced by ambient humidity and oxygen exposure in addition to fabrication-related factors.

Compared to the hybrid OLEDs, the lifetime and robustness of the fully printed OLEDs are significantly improved. The fabrication process requires fewer steps and less manual handling. Notably, the spin-coating process and the subsequent selective removal of PEDOT:PSS, both potential sources of quality variations, are eliminated by replacing it with other printable HTLs. The resulting devices exhibit substantially longer lifetimes, due to the absence of PEDOT:PSS, which allows for extended characterization. OLEDs are tested for their lifetime under different operation scenarios, continuous operation and intermittent operation. The TCTA–Rubrene–Bphen OLED is operated at 1.6 mA and 14.8 V for a total time of 20 min, consisting of 20 measurement cycles of 1 min each. The emission spectra for each minute of operation are shown in Figure 5.32a. It can be seen that the intensity does not remain constant but decreases with each minute of operation. The rate of decline slows down at longer operation times.

Figure 5.32b shows the spectra recorded during intermittent operation over a period of 17 days. The OLED is operated for 10 s under argon atmosphere and stored under ambient laboratory conditions between measurements. Data from day one are omitted due to differing measurement conditions. From day six onward, a daily decrease in intensity is observed. After 17 days, no emission signal is detectable. Data smoothing is applied to both plots using a low-pass filter with a cutoff frequency of 0.02 Hz.

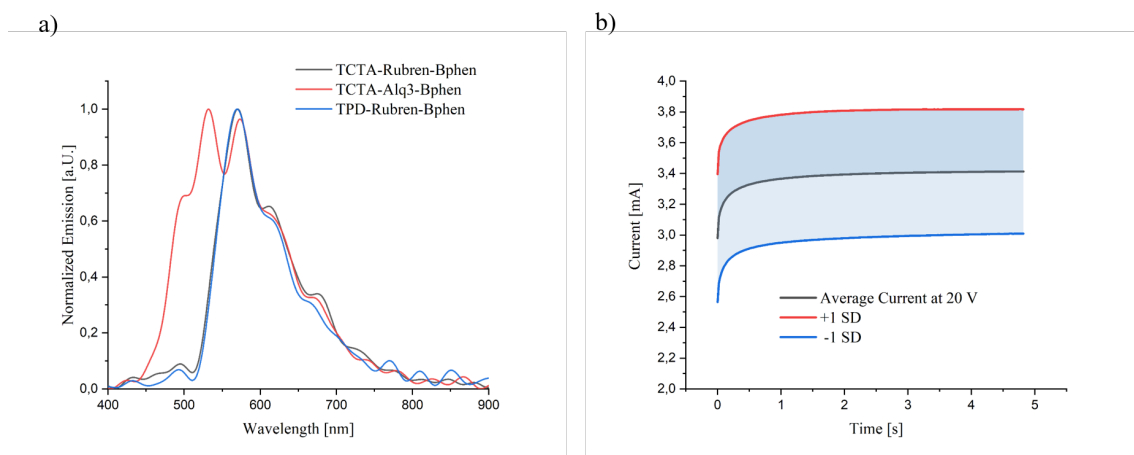


Figure 5.33: (a) Normalized emission spectra of different OLED configurations. (b) Average supply current of TCTA–Rubrene–Bphen OLEDs with corresponding standard deviation (SD). Source: Lux et al. [P3]

Other OLED Variants

Additionally, further OLED material combinations are tested for their suitability in printed OLEDs. In one variant, the emissive layer is replaced with Alq₃ instead of Rubrene, resulting in the stack ITO–TCTA–Alq₃–Bphen–Al. In another variant, the HTL is exchanged from TCTA to TPD, yielding the stack ITO–TPD–Rubrene–Bphen–Al. The fabrication of these OLEDs variants is described in greater detail in Section 4.7.3, and the corresponding transfer parameters are listed in Table 4.9.

These variants are operated under the same test conditions as the standard stack ITO–TCTA–Rubrene–Bphen–Al, with operation times between 5 s to 10 s. The emitted light is recorded, and the normalized emission spectra are shown in Figure 5.33a. Data smoothing is performed by applying a low-pass filter with a cutoff frequency of 0.02 Hz.

The exchange of the HTL from TCTA to TPD does not cause a significant change in the emission spectrum. In contrast, replacing Rubrene with Alq₃ shifts the main emission peak towards shorter wavelengths, changing the color from yellow to yellow-green. This observation is expected, as the emissive wavelength is primarily determined by the molecules in the emissive layer. Moreover, the Alq₃-based OLED exhibits a double emission peak at 530 nm and 580 nm. Tang, Liao, Xu, Zhou, and Zhu [88] attributes this double peak to recombination involving triplet excitons or the presence of defect states, and reports that its occurrence depends on the chosen HTL material.

Electrical Performance

The TCTA–Rubrene–Bphen OLEDs are evaluated with respect to their electrical performance. They are operated in compliance mode with a voltage limit of 20 V and a current limit of 10 mA. Voltage and current depend on the internal resistance of the OLED. When the current limit is reached, the applied voltage decreases; conversely, when the voltage limit is reached, the current decreases.

The measured operational voltage of the OLEDs is 20 V, and the current is recorded

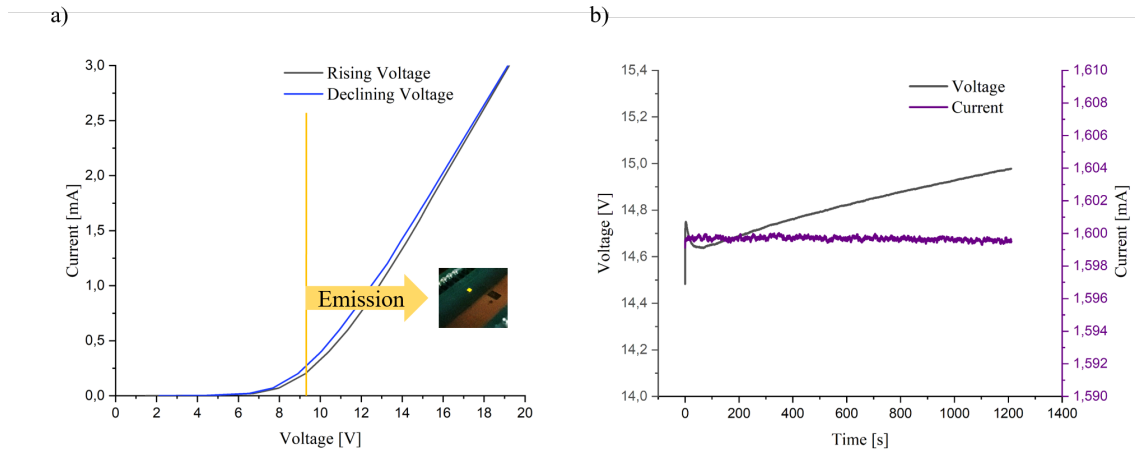


Figure 5.34: (a) Current-voltage (I-V) curve of an ITO-TCTA-Rubrene-Bphen-Aluminum OLED, measured during both increasing and decreasing voltage sweeps. Emission was observed at 9 V and above (b) Voltage and current behavior of a printed OLED permanently operated for 20 min. SMU in compliance mode with current limit at 1.6 mA. Source: Lux et al. [P3].

over time. Each device undergoes ten measurement cycles, each lasting 0.5 s. The mean current of seven OLEDs, along with the corresponding standard deviation, is shown in Figure 5.33b. Initially, the current starts at approximately 3.0 mA and increases by about 10% to 3.3 mA, where it stabilizes over the measurement period of 5 s. The standard deviation between the devices is approximately $\pm 12\%$, represented by the shaded area in the plot. From these measurements the mean current density is calculated to be 33 A/cm^2 and the internal resistance is determined as $6.06 \text{ k}\Omega$. Compared to the hybrid OLED the current is significantly higher and the internal resistance lower, which could be attributed to the thinner Bphen layers and the newly printed HTL material.

A varying current indicates internal processes within the OLED materials, potentially related to temperature adaptation or material degradation. Overall, the observed current stability demonstrates reliable operation of the printed OLEDs during the measurement period.

Longer achieved OLED lifetime achieved by switching to other HTL materials allows a more detailed analysis including long term emission measurements and obtaining a current-voltage-curve (I-V diagram) displayed in Figure 5.34a. The voltage is slowly raised in steps from 0 V to 20 V and the current and emission are monitored. For one data point the average parameters during one measurement cycle of 0.5 s are used. The current stays near zero until 7 V where it starts to increase. At 9 V and above there is emission visible and the current rises linearly. The voltage is raised to the maximum and reduced subsequently back to zero. Only a small deviation between rising and falling voltage is observed. The behavior appears similar to that of a conventional electrical diode [89]. The small deviation in raising and falling voltage could be related to aging of the OLED during operation.

The current and voltage are also monitored during long-term measurements to evaluate the effects of aging under continuous operation for 20 min. The evolution

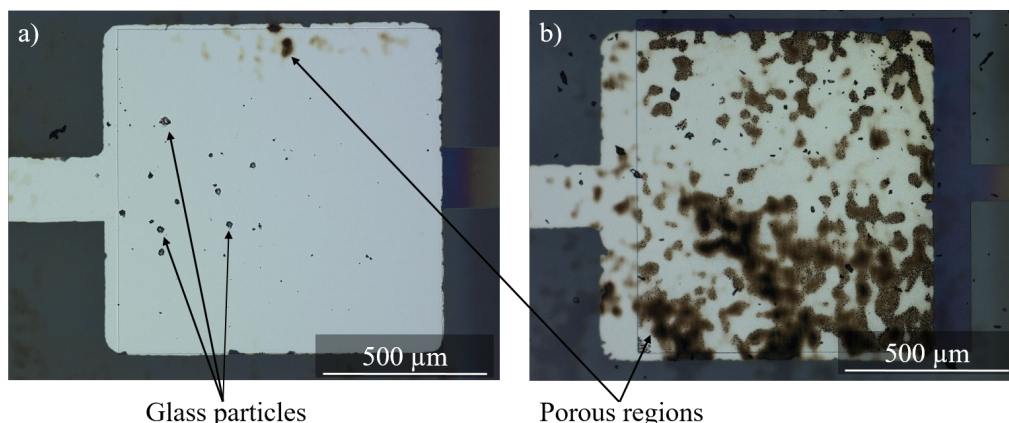


Figure 5.35: Comparison of two OLEDs fabricated with the same recipe and similar process parameters. The two contrasting examples illustrate fluctuations in printing results that can arise from variations in donor quality. Dark exposed areas indicate porosity and correspond to regions within the OLED pixel that show no emission. Source: Lux et al. [P3]

of voltage and current over time is shown in Figure 5.34b. The current is fixed by the SMU at 1.6 mA and fluctuates within the μA range. These fluctuations could originate either from abrupt internal changes within the OLED, from external disturbances picked up by unshielded cables in the surrounding environment, or from the control tolerance of the SMU. During the initial few seconds, the voltage drops by approximately 1% before it begins to increase slowly but steadily. The initial quick drop can be attributed to thermal effects, whereas the subsequent slow voltage increase of 2.7% over 20 min is likely related to internal resistance changes and material degradation.

OLED Degradation

To further analyze the degradation mechanism, light microscopy images of the OLEDs are obtained. Figure 5.35 shows the top view of two OLEDs for comparison. Both are fabricated under identical conditions and show emission in the measurement data. While the left OLED appears almost flawless, the right OLED exhibits distinct dark regions. Images taken during operation confirm that these dark areas correspond to regions without emission, resulting in a reduced overall brightness of the device. Such dark regions appear occasionally and could originate from irregularities in the printing or fabrication process, potentially caused by an inhomogeneous ink distribution on the donor, leading to imperfect material transfer. These irregularities are more frequently observed on one side of the donor sample, suggesting a connection to the donor coating step, where manual preparation introduces process variability. Misalignment of the laser beam in combination with the f -Theta lens might also contribute, as these dark regions tend to occur more often toward the outer areas of the substrate, which is positioned centrally beneath the lens and scan head. Humidity or residues of solvents might also contribute to the OLED failures.

For a more detailed analysis of the internal structure, a FIB-SEM investigation is carried out. Regions on the OLED exhibiting partial emission are analyzed, with particular attention given to the dark (non-emitting) regions. Light and dark appearance can have multiple causes, light emission, light absorption, reflection, interference, which needs a more detailed analysis. In addition to visual inspection, SEM imaging allows determination of the thickness of printed layers and evaluation of the overall material distribution within the OLED stack.

Figure 5.36 shows SEM images of an OLED containing both emissive and non-emissive regions. Figure 5.36a provides an overview image of the OLED, showing the top aluminum layer. The dark regions from Figure 5.35 appear bright here, due to differences in SEM image contrast processing. A notable number of micrometer-sized particles can be seen on the OLED surface. These particles originate from sample preparation, as the glass-ITO substrate has to be cut into smaller pieces to fit into the SEM chamber. The cutting process with a ceramic knife generates such particles, which then spread across the sample surface.

Figure 5.36b presents a detailed view of both bright and dark gray regions on the OLED. The bright regions show protrusions of the aluminum layer with small visible pores. Figure 5.36c shows an enlarged view of a porous area on the side, where the protrusions exhibit pronounced topographical contrast. The pores are smaller than $1\text{ }\mu\text{m}$ in diameter. Figure 5.36d displays a cross-sectional view of the porous region, created by milling a trench with the FIB. The layers appear non-parallel and exhibit voids, suggesting that the top aluminum layer has lifted in certain areas.

Layer thicknesses are also measured for several materials, yielding approximate values of typically 130 nm for ITO, 45 nm for TCTA, and 80 nm for aluminum. The layers are uneven as can be seen in the images and their thickness varies along the examined cross-section.

The FIB-SEM analysis reveals significant structural irregularities in the non-emissive areas of the OLEDs. The cross-sectional images indicate that the layer stack is not well-defined, exhibiting non-parallel interfaces, cavities, and partial delamination of the top aluminum electrode. These findings suggest possible damage or deformation during fabrication or operation. The observed porosity and uneven layer thickness likely disturb charge transport and recombination, causing the absence of light emission in the affected regions.

Light and dark regions are observed in some of the printed OLEDs even before operation, indicating that these inhomogeneities originate from the manufacturing process itself. This points to an uneven transfer of material during OLED fabrication. The evaporated aluminum layer appears to follow the topography of the underlying substrate. The presence of pores may therefore be related to the outgassing of residual solvents during or after material transfer. Although the FIB-SEM data do not directly prove that aluminum delamination results from uneven printing, it is likely that the existing inhomogeneities cause localized increases in electrical resistance. This, in turn, may lead to a temperature rise within the layer stack, promoting material degradation and pressure buildup that lifts the aluminum layer and creates cavities.

Overall, the results highlight the need for even increased control of layer uniformity and process parameters during deposition to ensure stable and reliable device performance.

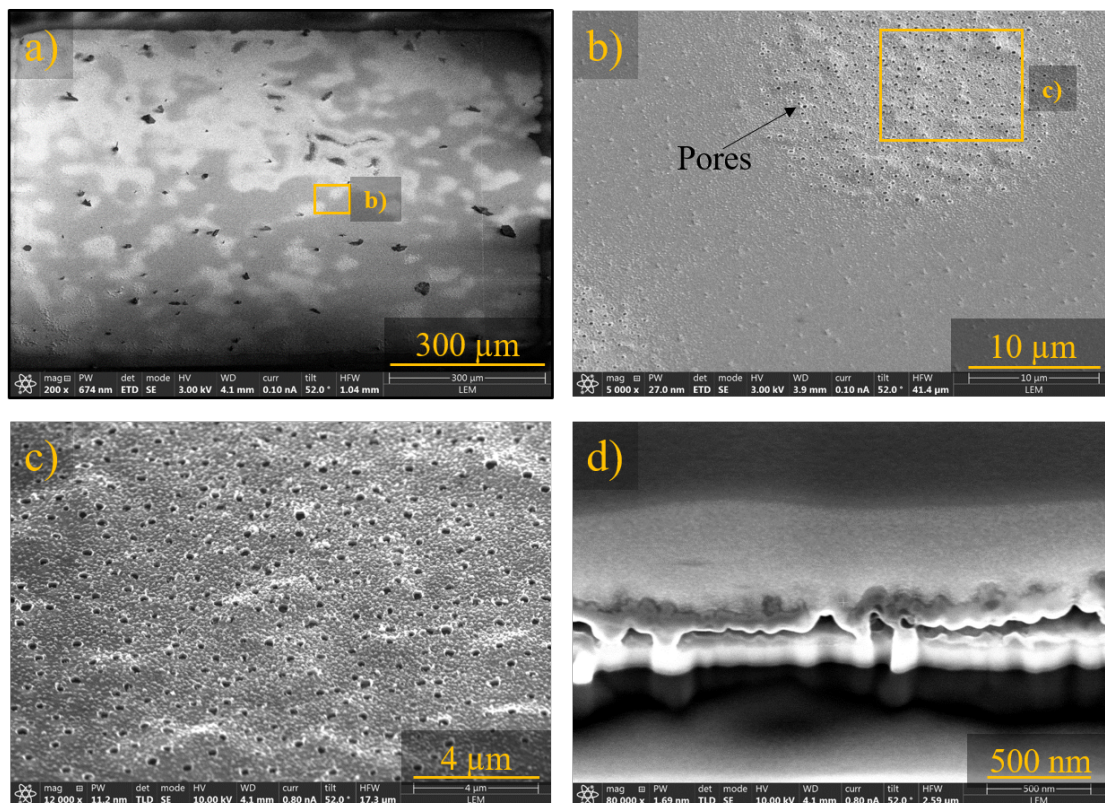


Figure 5.36: SEM images showing top and cross-sectional views of an OLED with non-emissive areas. (a) Tilted overview of the OLED: the bright regions in the SEM image correspond to the dark regions observed under the optical microscope. (b) The bright regions exhibit protrusions and small pores. (c) Detailed view of the pores, which are fractions of a micrometer in size. The topography contrast reveals that the OLED surface is wavy. (d) Cross-sectional image of a non-emissive porous region, where the layers are non-parallel and contain cavities in between. Intact layers are displayed in Figure 5.37

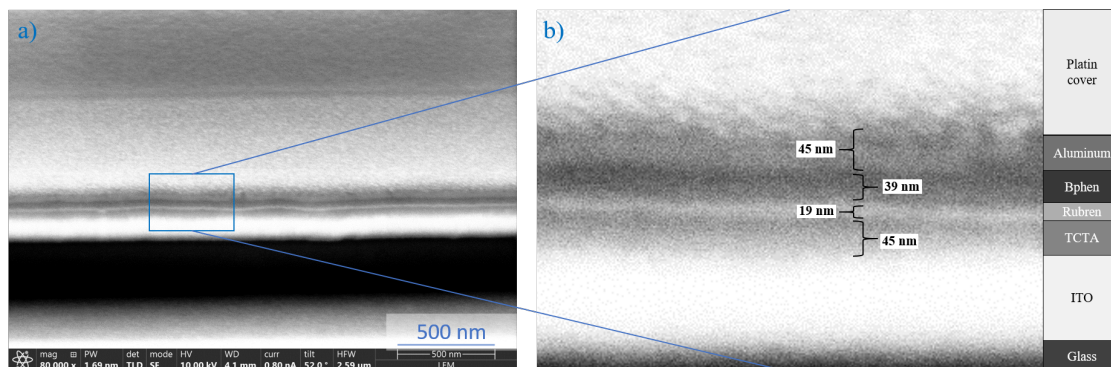


Figure 5.37: SEM images showing the cross-sectional view of an OLED with emission. (a) Flat, parallel printed layers of material can be distinguished by material contrast. (b) A detailed view of the material stack reveals separated printed layers, allowing for thickness measurements of the individual materials: 45 nm of TCTA, 19 nm of Rubrene, and 39 nm of Bphen. Source: Lux et al. [P3].

To compare the non-emissive regions of the OLEDs with areas exhibiting emission, another FIB-SEM analysis is performed. Figure 5.37a shows the cross-sectional view of an OLED with emission. The surface of the top aluminum layer appears flat, and no pores are visible. The printed layers are mostly parallel, a slight curvature can be observed. Across the examined cross-section, the layer thickness is uniform with minor deviations. Three printed layers are visible between the electrodes, ITO and aluminum, along with a protective platinum coating applied to facilitate FIB trenching.

Figure 5.37b presents a magnified view of Figure 5.37a, highlighting the layer structure in more detail and presenting the corresponding thickness measurements. From bottom to top, the layers are as follows: the glass substrate (black), 133 nm of ITO (white), 45 nm of TCTA (dark gray), 19 nm of Rubrene (light gray), 39 nm of Bphen (dark gray) and 45 nm of aluminum. A clear distinction between the aluminum layer and the platinum protective coating is not possible.

In comparison to the devices showing no emission, it becomes evident that the quality of the printed OLED layers determines whether a device emits light or fails. This highlights the importance of achieving thin, uniform, and parallel layers. The origin of the pores observed in the non-emissive devices remains unclear; however, uniformly printed layers show no signs of such defects. Therefore, the issue likely arises from deficiencies in the material transfer conditions during printing.

Summarized it can be conducted that the potential and capabilities of LIFT printing, have successfully been demonstrated to produce thin and uniform layers in the nanometer range.

Structural Analysis using TOF SIMS

While the SEM analysis provides valuable information on the structural quality of the layers, it does not offer insight into the chemical composition of the transferred material or possible intermixing between layers during the printing process. To gain further information about the material properties and to confirm the device architecture, a TOF SIMS analysis is performed on a printed OLED of the standard

type ITO–TCTA–Rubrene–Bphen. The TOF SIMS technique employs Ar^+ ions to gradually erode the sample layer by layer from the top. Erosion of the aluminum layer requires a higher ion beam energy compared to the underlying organic layers. However, a lower beam energy is necessary to achieve a high-resolution depth profile. Therefore, no aluminum cathode is applied in this measurement. For more technical details on the TOF SIMS procedure, see Appendix A.1.11.

Figure 5.38 shows an in-depth profile of the OLED stack (ITO–TCTA–Rubrene–Bphen), representing an area of $300 \times 300 \mu\text{m}^2$, measured in positive ion mode. In this mode, intact molecular peaks for each layer are detectable, indicating the excellent stability of the OLED materials during the transfer process. The normalized intensity of the detected ions depending on the depth is shown in Figure 5.38a.

The profile reveals that the first detected material corresponds to the ion peak of Bphen ($\text{C}_{24}\text{H}_{17}\text{N}_2^+$, blue), located at the surface. As the Bphen signal declines, a signal for Rubrene ($\text{C}_{42}\text{H}_{28}^+$, yellow) becomes more pronounced. The graphs of Bphen and Rubrene show the correct sequence of the deposited layers but no distinct interface between them. At greater depths, indicated by higher fluence, TCTA ($\text{C}_{54}\text{H}_{36}\text{N}_4^+$, pink) is detected, showing a distinct interface characterized by a clear increase in intensity of the related ion peaks, followed by a plateau in intensity while the other ion peaks vanish. The intensity plateau of TCTA is followed by a second increase in signal, resulting from an interface effect near the ITO (In_3O_2^+ , gray) layer, which causes an elevated ion count.

For better visualization, the depth profile is depicted as a 3D reconstruction of the measured sample in Figure 5.38b, showing the desired layer-by-layer (LbL) structure from bottom to top. Also visible is an apparent intermixing effect between Bphen and Rubrene, which cannot be clearly assigned to the printing method but is likely an artifact of the sputter erosion process during SIMS data acquisition. Since the signal is integrated across a $300 \mu\text{m} \times 300 \mu\text{m}$ field of view, any local variation in layer thickness within this area contributes to reduced interface fidelity. An undulated or slightly skewed interface, as well as a non-planar erosion front, although barely noticeable in SEM, can reduce the apparent depth resolution in the resulting TOF SIMS profile. Figure and TOF SIMS analysis from publication Lux, Schlindwein, Plank, Reichert, et al. [P3].

Summary

In this work, for the first time, OLEDs printed dot-by-dot using LIFT are successfully demonstrated, as published by the author in Lux, Schlindwein, Plank, Reichert, et al. [P3]. The printing of OLEDs is achieved by LIFT of organic material layers. Two device architectures are realized: a hybrid OLED combining spin coating and LIFT printing, and a fully printed OLED where all organic layers are deposited by LIFT. Both device types exhibit characteristic electroluminescence in the yellow-green spectral region with a dominant emission peak at 570 nm and a smaller secondary peak near 620 nm, corresponding to vibronic transitions of Rubrene molecules.

The fully printed OLEDs exhibit improved robustness and longer operational stability compared to the hybrid OLED, with continuous emission for up to 20 min and a shelf lifetime of up to 9 days. Comparable experimental devices show a lifetime of a few hours without encapsulation which can be significantly increased by the usage of encapsulation methods [90]. Eliminating the PEDOT:PSS layer and

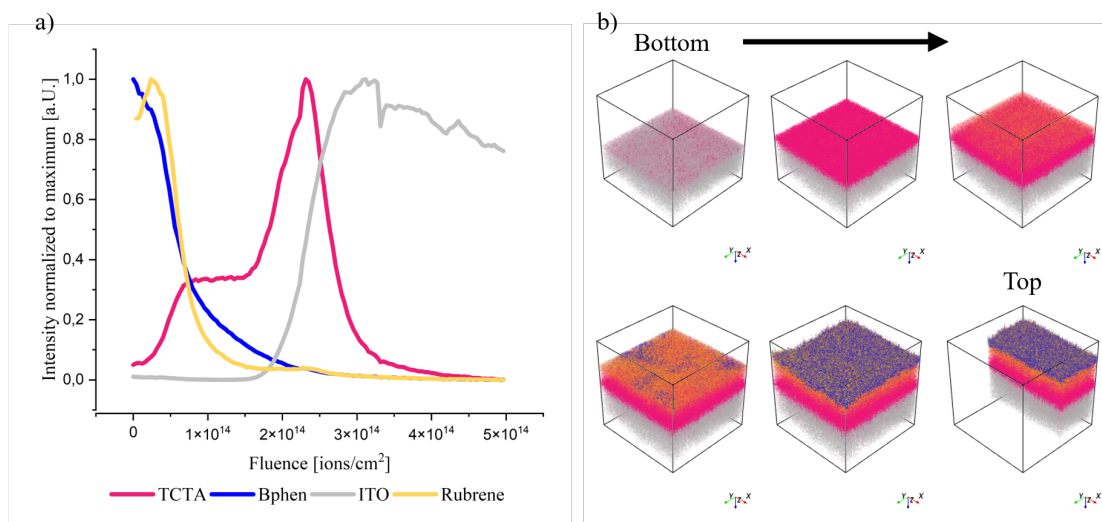


Figure 5.38: (a) TOF SIMS depth profile of the different molecule ion peaks illustrating the layer sequence of the OLED structure. (b) 3D reconstruction of the depth profile obtained by TOF SIMS of a representative OLED (Signals integrated from a field of view of $300\text{ }\mu\text{m} \times 300\text{ }\mu\text{m}$ in x and y, z not to scale.) Source: Lux et al. [P3]

reducing manual processing steps leads to higher reproducibility, with a best yield of 60%. Electrical characterization indicates a mean internal resistance of $6.06\text{ k}\Omega$ and a current density of 33 A/cm^2 , showing a more efficient charge transport compared to hybrid OLEDs. Improvements of the setup, based on the experience gained from the characterization of the hybrid OLED, lead to increased intensity measurements. Therefore the emission intensity cannot be compared directly between the two OLED types. The degradation during operation correlates with increase in electrical resistance and operating voltage over time.

FIB-SEM and TOF SIMS analyses provide detailed insight into the layer morphology and chemical composition. Devices showing uniform and well-aligned layers correlate with stable light emission, while non-emissive regions are associated with voids, non-parallel interfaces, and aluminum delamination. TOF SIMS confirms the layer sequence and chemical integrity of the transferred materials, while apparent intermixing between layers is primarily attributed to sputter-induced artifacts.

The results confirm that LIFT enables precise and reproducible deposition of thin organic films while maintaining material integrity. Overall, this work demonstrates the feasibility of fabricating functional OLEDs entirely by LIFT printing. Further optimization of the layer thickness, printing parameters and environmental control is expected to enhance device yield, stability and lifetime, thereby advancing the realization of scalable, fully printed OLED technology.

5.5 Realization of Printed Capacitors

In this work, capacitors fabricated using the LIFT process demonstrate the feasibility of additive manufacturing for functional electronic components in the μm range. It is the first time that dot-by-dot printed capacitors are reported and the author publishes this work as a journal paper in the Wiley Applied Research in 2024 [P2]. Parts of the descriptions in this chapter and selected images are reproduced from

that publication. The objective is to realize planar capacitors using sequential dot-by-dot printing of dielectric and conductive layers on predefined electrode areas. The layer composition, homogeneity, and electrical performance are analyzed to confirm the successful transfer and functionality of the printed structures.

The printing process involves the transfer of titanium dioxide ink as the dielectric material and silver paste as the top electrode. Optimal transfer parameters are determined experimentally to achieve round, defect-free dots with uniform coverage. The capacitors are printed on lithographically prepared gold electrodes and subsequently sintered to remove residual solvents and improve conductivity.

Additionally, printed silver ink structures are analyzed electrically to evaluate the resistivity as a function of printing parameters and to assess the effect of sintering. The fabricated capacitors are characterized by impedance measurements using a network analyzer, while structural analysis is conducted using FIB-SEM.

5.5.1 Measurements of Silver Ink

To evaluate the electrical performance of the printed silver structures, conductive tracks are fabricated between adjacent gold pads, as described in Section 4.8.1. The resistivity of these tracks is measured using a SMU under varying conditions, including single layer and double layer printing (1x and 2x), different bridging lengths and pre and post sintering. Geometrical properties of the printed lines are also considered during the analysis. The results including the mean resistivity and standard deviation for 16 identically printed structures are summarized in Table 5.6.

Length [μm]	Layers	Height [μm]	Width [μm]	ρ_{mean} [Ωm] B.S.	SD [Ωm]	ρ_{mean} [Ωm] A.S.	SD [Ωm]
1000	1x	2.8	130	1.10×10^{-2}	1.39×10^{-2}	2.15×10^{-7}	7.47×10^{-8}
1000	2x	4.2	130	4.99×10^{-6}	5.38×10^{-7}	1.05×10^{-7}	5.73×10^{-9}
500	1x	1.2	130	3.31×10^{-4}	2.71×10^{-4}	1.33×10^{-7}	3.52×10^{-8}
500	2x	1.6	130	2.31×10^{-5}	3.53×10^{-5}	1.25×10^{-7}	1.78×10^{-8}

Table 5.6: Comparison of geometrical parameters and electrical resistivity of silver lines printed by LIFT before sintering (B.S.) and after sintering (A.S.), SD indicates the standard deviation. Source: Lux et al. [P2]

As shown in Table 5.6, sintering significantly improves the conductivity of all printed structures, reducing the mean resistivity to approximately $1 \times 10^{-7} \Omega\text{m}$. Double-printed lines exhibited lower resistivity than single-printed ones, reflecting the beneficial effect of increased material volume and improved interparticle connectivity. Shorter tracks generally showed slightly lower resistivity than longer ones, which may be attributed to reduced defect probability and lower cumulative resistance.

These findings highlight the advantages of double printing, which not only enhances conductivity but also reduces the likelihood of open circuits due to incomplete material transfer. Furthermore, sintering substantially decreased the variability in resistivity among identically printed samples. The printing quality is considered good, as no discontinuities or open circuits are observed that could lead to device failure. The measured resistivity values are compared to that of bulk silver ($1.47 \times 10^{-8} \Omega\text{m}$) [72] and to the XTPL CL60 datasheet value ($5.1 \times 10^{-8} \Omega\text{m}$) [73]. The average resistivity obtained after sintering is $1.25 \times 10^{-7} \Omega\text{m}$, which is approximately $8.5 \times$ higher than bulk silver and in reasonable agreement with the manufacturer's data. This deviation is expected, as printed nanoparticle-based structures typically

exhibit porosity and contain organic residues, both of which increase resistivity. Sintering enhances conductivity by promoting nanoparticle coalescence and removing organic stabilizers. The high post-sintering conductivity confirms the suitability of this ink for LIFT printing of capacitors and other electronic devices.

5.5.2 Characterization of Capacitors

In this section, the results of the capacitor characterization using the network analyzer (see Appendix A.1.5) and FIB-SEM (see Appendix A.1.8) are presented. The fabrication process of the devices is described in Section 4.8. Electrical measurements are performed with a network analyzer by contacting the gold tracks over a frequency range of 1 MHz to 1000 MHz (see Section 4.8.4).

Yield and Functional Classification

Capacitors are printed with identical laser parameters and showed some fluctuation in their performance. The overall yield can be categorized as follows based on $N = 100$ measured devices:

- **26%** of the devices show **visible printing defects**, such as missing dots in the electrode, but still behaved as capacitors. This is possible when the electrode remains electrically continuous despite local voids.
- **30%** of the devices show **no visible defects** and behaved as fully functional capacitors.
- The remaining **44%** do **not** behave capacitively but exhibited an **inductive** response. This behavior is interpreted as an electrical short circuit between the electrodes, effectively forming a single-turn coil.

A structure is classified as a capacitor if its S-parameter trajectory appeared in the lower hemisphere of the Smith chart.

Capacitance Results

For the 30% defect-free devices, the mean capacitance and standard deviation at 100 MHz were $C = 40.1 \text{ pF} \pm 2.2 \text{ pF}$. The much smaller variation reflects the consistent electrode geometry of these structures.

For the capacitance measurements $N=70$ devices are measured. For the 26% defective-but-functional devices, the mean capacitance and standard deviation at 100 MHz were $C = 36.0 \text{ pF} \pm 10.3 \text{ pF}$ with $N=70$, total number of devices. This trend is expected: missing dots reduce the effective electrode area, resulting in lower capacitance and larger variation.

Furthermore, to adjust the capacitance of the printed capacitors, the effective electrode area is varied. This is achieved by reducing the number of printed dots that form the top electrode. For example, to obtain an estimated electrode coverage of 30 %, the number of printed dots is reduced from 100 to 30. This approach allows tuning the capacitance of the device to specific requirements. The results of this

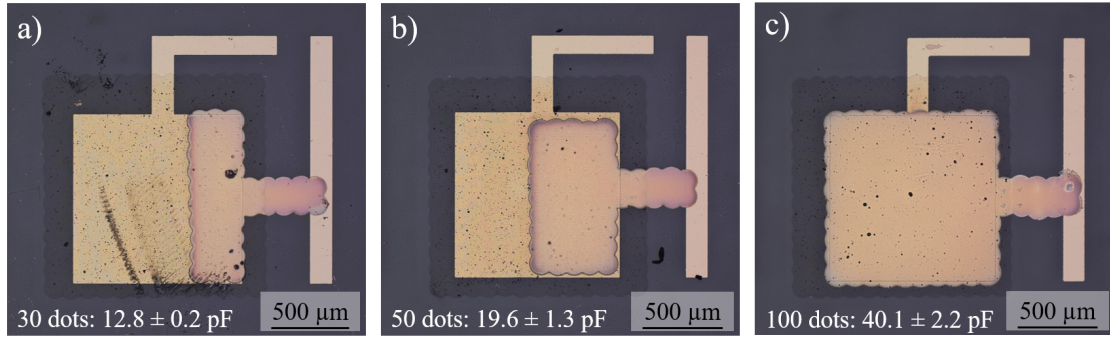


Figure 5.39: Partial coverage of printed top electrodes out of silver with a coverage of (a) 30% (b) 50% (c) 100%. Source: Lux et al. [P2]

electrode size variation are shown in Figure 5.39a–c.

For an estimated 30 % area coverage, an average capacitance of 12.8 pF with a standard deviation of 0.2 pF with $N = 5$ is measured. For an estimated 50 % coverage, the resulting mean capacitance is 19.6 pF with a standard deviation of 1.3 pF and $N = 5$. These values are close to the expected trend, since the capacitance of a parallel plate capacitor is given by

$$C = \epsilon_0 \epsilon_r \frac{A}{d}, \quad (5.1)$$

where A is the electrode area and d is the separation between the two electrodes. A linear relationship between electrode area and capacitance is therefore expected. Small deviations from linearity can be attributed to edge effects, where the electric field lines are no longer parallel between the plates, or to alignment inaccuracies. Misalignment occurs when the printed top electrode does not perfectly overlap with the bottom electrode or when slight overhang appears due to ink flow or the limits of the printing resolution. The results show that the top electrode can be printed with the smallest step size of a single dot, which corresponds to a capacitance adjustment in steps of 0.4 pF. Furthermore, the larger the electrode area, the smaller the deviation from an ideal linear behavior becomes, which allows for a precise adjustment of the capacitance.

Frequency Behavior

Capacitors are analyzed for their frequency response to evaluate potential applications. The Smith chart is a valuable tool to visualize the frequency-dependent complex impedance of measured devices. Inductive components appear as half-circles in the upper hemisphere, while capacitive components appear in the lower hemisphere (see Section 4.8.4).

Figure 5.40a shows the Smith chart of a representative LIFT-printed capacitor. The curve starts at the open-circuit point on the right and follows a spiral trajectory in the lower hemisphere, indicating dielectric or resistive losses. The curve crosses the horizontal axis at 35 Ω at 744 MHz, which corresponds to the resonance frequency. Beyond this frequency, the device exhibits inductive behavior. The average resonance frequency of devices without visual defects and its standard deviation is 739 MHz ± 67 MHz.

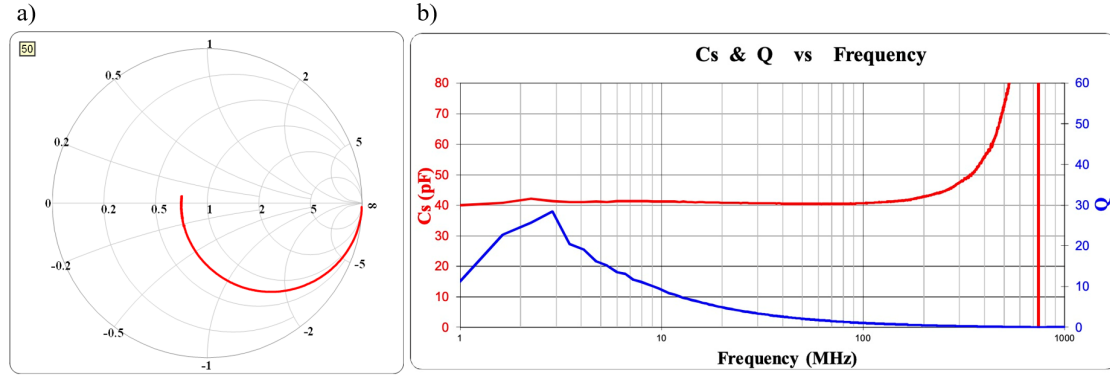


Figure 5.40: Frequency behavior of LIFT-printed capacitors visualized using ZPlots by Agilent Technologies. (a) Smith chart with 50 Ω in the center, showing the complex impedance of a representative LIFT-printed capacitor over frequency. The resonance frequency of 744 MHz is observed when the curve crosses the horizontal axis separating the capacitive (lower hemisphere) and inductive (upper hemisphere) regions. (b) Series resistance (red) and Q-factor (blue) obtained over a logarithmically scaled frequency range.

Figure 5.40b shows the series capacitance and Q-factor as a function of frequency over the range 1 MHz to 1000 MHz, with the frequency axis displayed logarithmically to capture the full range of behavior. The capacitance remains approximately constant from 0 MHz to 100 MHz and increases above 100 MHz until the resonance frequency is reached. Beyond the resonance, non-physical results such as negative capacitance are observed, consistent with the inductive behavior in the Smith chart. The Q-factor, defined as

$$Q = \frac{1}{\omega C R_{\text{ESR}}}, \quad (5.2)$$

with ω the angular frequency, C the capacitance, and R_{ESR} the series resistance, quantifies losses in the resonant circuit. A high Q-factor indicates low energy losses, whereas a low Q-factor corresponds to high losses or damping. In this study, the Q-factor increases to a maximum value of 38 at 2 Hz before decreasing at higher frequencies. The reduction at higher frequencies is attributed to the rising effective series resistance of the system, which includes contributions from the printed silver bridge and the gold connectors.

Structural Analysis

The structural analysis of the printed capacitors is performed using a FIB-SEM system (see Appendix A.1.8). A protective platinum layer is first deposited to shield the sample from ion-beam damage. Subsequently, a trench is milled into the capacitor using the FIB, and the sample is tilted to obtain a cross-sectional image. Figure 5.41 shows the distinct layers of the printed capacitor, which can be differentiated by their material contrast. From bottom to top, the layers consist of the glass substrate, an evaporated 40 nm gold layer, a printed TiO₂ layer of 1.5 μm, a printed Ag layer of 1.4 μm, and the protective platinum coating. This analysis is performed after the sintering step.

The grain size in the silver layer ranges from 50 nm to 110 nm, with an estimated porosity of approximately 20 %. The TiO₂ layer also exhibits porosity, although

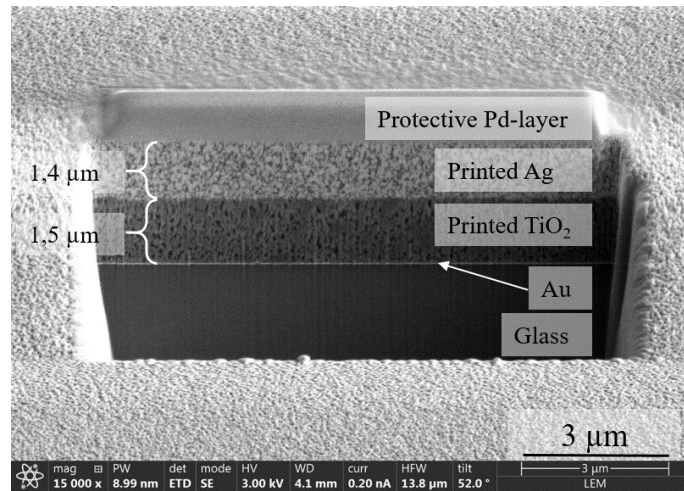


Figure 5.41: Structural analysis of a representative LIFT-printed capacitor using a FIB-SEM. The layers can be distinguished by material contrast and consist of: glass base substrate, 40 nm gold layer, printed TiO_2 , printed Ag, and a protective platinum layer. Porosity is visible in the printed layers. Source: Lux et al. [P2]

the pores are smaller than those observed in the silver layer. Using Equation (5.1), together with the printed geometry and the measured dielectric-layer thickness, the effective permittivity ϵ_r of the TiO_2 layer is calculated to be $\epsilon_r = 6.8$. Considering that only about 20 % of the ink consists of TiO_2 nanoparticles and that the printed layer exhibits noticeable porosity, this value lies within the expected range. It is significantly lower than the permittivity of bulk TiO_2 (depending on the crystalline forms rutile: $\epsilon_r \approx 173$ to 211 [74], anatase: $\epsilon_r \approx 18.9$ [75]), as expected for a porous nanoparticle-based composite.

Summary

This work demonstrates the successful LIFT fabrication of planar plate capacitors using dot-by-dot printing. The devices consist of an evaporated gold bottom electrode, a printed TiO_2 dielectric layer, and a printed silver top electrode. TiO_2 is selected for its expected high permittivity and suitable ink viscosity, while silver is chosen for its high conductivity. The silver ink is further characterized by printing conductive tracks and measuring their resistivity, which shows good agreement with manufacturer specifications. Sintering substantially reduces the resistivity, confirming the suitability of the printed silver for functional electronic devices. The capacitors are fabricated dot-by-dot and layer-by-layer following a dedicated printing and sintering workflow, marking the first demonstration of capacitors produced using this method, as published in Wiley Applied Research (2024) by Lux, Kuznetsova, Simha, Mager, et al. [P2].

Capacitor arrays are printed and electrically characterized using a manual probe station and a network analyzer. The overall yield is 54%, with the remaining devices damaged during printing or thermal processing. Achieving higher yields requires further optimization of laser pulse energy, focus conditions, droplet behavior and substrate interaction. Long-term stability and process repeatability also warrant further investigation.

Capacitance can be tuned by adjusting the area of the top electrode, enabling fine

control. For example, a 40 pF capacitor can be varied in steps of approximately 0.4 pF. Frequency-dependent measurements show stable capacitance up to 100 MHz. The typical resonance frequency of the printed capacitors is around 800 MHz, thus effective operation requires frequencies below roughly 100 MHz. For lower frequencies, the Q-factor is higher, which allows a more effective operation of possible circuits. Structural analysis using FIB-SEM confirms well-defined multilayer architectures consisting of the glass substrate, gold electrode, TiO₂ dielectric and silver top electrode. Both printed layers exhibit porosity, with grain sizes in the silver layer ranging from 50 nm to 110 nm. Layer thicknesses between 1 μ m to 2 μ m are observed, and the structural integrity of the capacitor stack is verified through cross-sectional SEM imaging. The flat geometry makes these capacitors promising for use in flexible electronics.

The printed capacitors fabricated in this work cover a range from 4 pF to several hundred picofarads, with precise control enabled by the dot-by-dot approach. For example, a 40 pF device composed of 100 dots can be adjusted in single-dot increments. The printed capacitance values show an estimated precision of approximately 5.5%, highlighting the accuracy and reproducibility of the method.

The 50 μ m dot resolution demonstrated here offers significantly greater design flexibility than earlier LIFT-based approaches, which transfer pre-stacked dielectric-electrode double layers in fixed square geometries [91, 92, 93].

LIFT printing offers substantial versatility for the design and integration of capacitors directly into printed circuits. Beyond conventional layouts, custom geometries such as interdigitated structures can also be realized without lithography, enabling rapid prototyping and frequency tuning by simply adding or removing printed dots. This provides a compelling alternative to traditional capacitor design workflows that typically rely on complex simulations and costly cleanroom processes.

The electrical and structural characteristics have a direct influence on the suitability for possible applications. With the ability to adjust the capacitance in small steps it provides an advantage for applications that require iterative electrical optimization, such as impedance matching networks and resonant circuits. Its stable operation up to 100 MHz with its higher Q factor indicate the suitability for low- and mid radio frequency electronic systems. The resonance frequency imposes an operational limit for the usage in microwave frequency applications.

One notable domain that can benefit from such flexibility is Magic Angle Spinning Nuclear Magnetic Resonance (MAS NMR), where precise tuning and matching of microcoil resonance frequencies is essential [94, 95, 96, 97, 98]. The ability to quickly adjust capacitance through LIFT-printed structures can significantly simplify and accelerate the design of tuning and matching circuits in these experiments.

Looking ahead, the LIFT process opens broad opportunities for advancing capacitor technology across multiple industries. Customizable printed capacitors are particularly attractive for high-frequency circuits, flexible and wearable electronics, advanced medical devices, environmental sensors, RFID and NFC components, and rapid prototyping of hybrid electronic systems.

Overall, the successful fabrication of printed capacitors presented in this work is an important step toward fully printed electronics based on LIFT, enabling precise, adaptable, and lithography-free production of capacitive components.

6. Summary and Conclusion

Laser-induced Forward Transfer is an emerging technology that is already established in certain fields, for example in bioprinting applications. In other areas such as micro-additive manufacturing, the method is still at an early stage but remains subject to ongoing research. LIFT is characterized by its broad range of application possibilities and its high tolerance towards different material classes such as the printing of solid and liquid materials. Depending on the configuration of the transfer system, the method can be specifically tailored to a given application and can be used for the highly precise transfer of nanometer-thin material layers. At the same time, the process parameters can be adjusted to allow the transfer of liquid ink systems in thickness ranges of a few micrometers.

The high adaptability to different materials and the capability for precise nanolayer transfer make the method particularly suitable for the fabrication of nanoscale devices such as OLEDs whose architecture is based on nanometer-thin layers of different functional materials. Furthermore, the possibility to transfer liquid materials in the form of nanoparticle inks enables the fabrication of conductive tracks and electronic components requiring insulating, conductive or semiconducting materials, which can be defined by the choice of ink.

In the present work it was successfully demonstrated that electrical components such as capacitors and conductive tracks, as well as more complex electronic devices such as OLEDs can be fabricated using this method. Printing processes were developed for the transfer of the materials required for device fabrication and the optimization of these processes towards thin and smooth nanometer-scale structures. Dedicated inks tailored for use with the LIFT printer were developed and a qualification method for newly developed inks at the manufacturer for specific application cases was established. This included the development of a mobile and user-friendly LIFT test printer for on-site ink qualification.

During process development, a printing strategy was established and continuously optimized in order to achieve a lateral resolution in the range of 50 μm to 100 μm . This resolution is required to fabricate components with an area of approximately 1 mm^2 by overlapping individual printed spots. In addition, the process was optimized systematically to promote partial merging of adjacent spots, resulting in

a low surface roughness of $R_a = 2.78 \pm 0.25$ nm. By adjusting printing parameters and ink concentration, layer thickness could be precisely controlled in the range of 20 nm to 140 nm, enabling the realization of closed, very thin OLED layers with a thickness of approx. 20 nm.

To further improve printing resolution and material distribution, the feasibility of microstructured acceptor substrates was investigated. While the initial process optimization focused on the transfer dynamics, subsequent work addressed potential improvements through substrate modification. It was demonstrated that pillar structures with heights of approximately 80 μ m are required to achieve selective deposition exclusively on the pillar tops. This approach enables the fabrication of higher-density arrays and significantly enhances lateral resolution. In addition, the confinement of the deposited material to the pillar tops prevents material fading and thinning at the spot edges, resulting in improved homogeneity.

A different key aspect of process optimization was the investigation of polyimide foil as absorber material. Commercial foils with different thicknesses as well as self-fabricated, ultrathin spin coated polyimide layers were examined as functional components within the LIFT setup. Thereby, the physically applicable limit of light-to-heat conversion for material deposition was identified for layers below 1 μ m in thickness. Investigating these limits represents an important step toward achieving full control over the transfer process.

New materials were evaluated with respect to their suitability and compatibility with the LIFT process and were subsequently used for device fabrication. Nanoparticle inks such as TiO_2 and silver ink were applied for capacitor fabrication, while small-molecule materials were transferred in thin layers comparable to polymer inks. It was demonstrated that PEDOT:PSS, TCTA, Rubrene and Bphen can be used to fabricate functional OLEDs by LIFT printing. Capacitors were realized by printing liquid inks, whereas OLED layers were transferred in their dried state by local remelting in a contact-based configuration.

Modifications to the printer setup were implemented to meet the respective process requirements. In addition to high lateral resolution, a high vertical precision was required and achieved by integrating an automated Z-stage. To ensure reproducibility, a heating and cooling unit was installed to maintain a defined substrate temperature. Process stability was further improved by integrating a HEPA filter and a compressed air supply system, reducing the relative humidity to approximately 20 %. For the transfer of liquid materials, spacers were introduced to maintain a defined gap between donor and acceptor, thereby ensuring stable and reproducible transfer conditions for Direct Absorption LIFT.

Due to the limited availability, proprietary inks were developed in specialized laboratories in cooperation with TECNAN (Los Arcos, Spain). To qualify these inks it was necessary to develop a test printer in which the inks could be evaluated on-site under the intended processing conditions. A feedback loop enabled rapid on-site testing and iterative optimization of ink formulations, significantly reducing development time by eliminating logistical delays between ink production and process evaluation.

A standardized qualification procedure was established along with the implementation of the test system. A preprogrammed routine was used to transfer defined droplets onto a receiver substrate. Transfer quality could be assessed either by

visual inspection or by detailed optical microscopy directly on site. Ink candidates that successfully passed this qualification were subsequently transferred to the production system at KIT and tested under real process conditions, confirming the qualification capability of the test system.

Based on the optimized process, tailored inks and adapted functional setup, devices were fabricated using the LIFT process. Conductive tracks were printed using silver ink and their electrical conductivity was characterized under different transfer conditions as well as thermal post treatment. It was possible to optimize the LIFT process in such a way that the resistivity values close to those specified by the manufacturer for the commercial inks were achieved. Furthermore, the results showed that thermal treatment is essential to achieve low-resistivity conductive lines.

Parallel-plated capacitors were fabricated by combining silver ink with TiO_2 ink on customized gold pad substrates. The internal structure was analyzed by means of FIB and SEM to correlate structural properties with fabrication parameters. The capacitors were electrically characterized using a network analyzer by evaluating the obtained S-parameters. A yield of 54% functional devices was reached with capacitance values in the pF range. The dot-by-dot printing mode provides high flexibility in capacitor design, allowing capacitance tuning by adjustment of the size and shape of dielectric and electrode layers. With a minimum resolution corresponding to approximately 0.4 pF per printed dot, this approach allows precise capacitance tuning, which is particularly relevant for applications where accurately defined capacitances are essential.

Furthermore, several OLED architectures were fabricated based on the developed process for smooth and thickness-controlled thin films. Initially, a hybrid OLED combining spin coating and LIFT printing was realized, which showed emission but had a limited lifetime due to the usage of PEDOT:PSS whose hygroscopic properties lead to device failure at exposure to ambient conditions. Subsequently, a fully printed three-layer OLED structure was fabricated, replacing the spin-coated layer and achieving a significantly improved lifetime. More OLED variants were demonstrated by testing alternative EML and HTL materials. Electrical and optical characterization was performed using the MATIS setup, successfully confirming light emission. Cross-sectional analysis via FIB-SEM verified layer sequence and thickness and showed a correlation between the internal structure and emissive or non-emissive regions.

Overall, it was successfully demonstrated that the LIFT method is suitable for the fabrication of complex electronic devices and structures, as proven by the realization of capacitors and OLEDs. The process was designed to enable both nanometer-scale layer deposition using small-molecule materials and micrometer-scale structures using liquid nanoparticle inks within the same system.

The fabricated devices were confirmed to be functional. In the future, further improvements will allow higher yield and process stability. The use of polyimide as absorber layer makes the method particularly suitable for temperature-sensitive materials such as OLED compounds, since the polyimide layer protects the functional material during transfer. Moreover, polyimide enables a largely material-independent process that requires only parameter adjustment for optimization.

Compared to alternative fabrication techniques such as spin coating, which is limited by orthogonal solvent processing, LIFT provides a more flexible transfer approach. This opens new perspectives for OLED fabrication without the need for shadow masks or vacuum deposition, potentially reducing fabrication costs and material consumption. The method is therefore also well suited for the development of functional structures within the EU project Nanostacks.

In summary, the range of fabrication technologies for electrical and electronic components has been extended by a method that enables the deposition of functional materials in larger quantities onto a substrate, offers high design flexibility, allows rapid adaptation to specific requirements, is suitable for small series and prototyping and is subject to fewer process-related limitations compared to inkjet printing or spin coating.

7. Outlook

This work successfully demonstrates the capability of LIFT printing for micro- and nanoscale electronic components and indicated that expansion to other complex components and structures is possible. The level of process control achieved allowed the manufacturing of complex geometrical structures with low surface roughness that are essential to such components. The electrical functionality of both, capacitors and OLEDs, was characterized and encourages further in-depth work on other devices such as solar cells or fuel cells. The LIFT process offers multiple advantages over other technologies, including a high degree of flexibility in component design and material choices. As for most additive manufacturing technologies the shape and size of components can be chosen freely and allows the printing of new geometries. The printer can be adapted for the fabrication of individual components and can also be used for systematic optimization routines by applying intrinsic material parameter gradients or thickness gradients across multiple samples to identify optimized performance metrics. In terms of material restrictions LIFT offers a broader spectrum than most technologies, ranging from solids, to liquids and even includes transferable multilayer stacks. Switching materials within a production process is achieved by exchanging the donor, which carries the transfer material and adapting the process parameters. The multi material printing give this technology an advantage over other technologies and opens up new opportunities in component design, which were previously difficult to realize due to material restrictions or process limitations. Compared to established techniques such as lithography, the equipment costs are low and comparable to those of other additive manufacturing technologies such as inkjet printing. Therefore, the technology is highly accessible for small companies and research laboratories.

Due to its advantages over other technologies including the flexibility in the fabrication, it is particularly well suited for small series production where other processes cannot work efficiently for low production quantities. Other possible applications are the integration of LIFT into other manufacturing technologies, to handle materials that cannot be processed efficiently with existing methods. It could serve the role as an integration device which could enhance an existing circuit or chip by adding materials for sensor applications or components for functional

integration.

The usage as an industrial fabrication or integration device places the demand of speed and efficiency on the printer, whose full potential is not yet exhausted with the current setup. Process scaling could be enhanced by multiplying parts of the machines such as the laser or by the introduction of beam splitters to allow parallel processing. Efficient multi material printing without waiting time for the donor exchange could be accomplished by the use of a pick-and-place robot for donor exchange. Thermal treatment of printed structures with nanoparticle inks could be done in the same device with adjusted laser settings. Such developments could facilitate the transition from a laboratory setup to a pilot production line for future component manufacturing.

Printed capacitors fabricated by LIFT enable application specific capacitance tuning through direct, dot by dot control of the electrode geometry. Beyond geometric flexibility, a key advantage of the process is the wide range of compatible materials. Since LIFT operates without high temperature sintering or firing steps, temperature sensitive materials can be integrated, enabling combinations that are difficult or impossible with conventional fabrication techniques. This includes polymer based dielectric layers, functional membranes and ultra thin dielectric films, which expands process boundaries for capacitive components.

The absence of structured screens, as required in screen printing for example in ceramic capacitor fabrication, allows rapid and flexible adjustment of component geometry during processing. As a result, capacitor properties can be adapted directly through process control rather than through dedicated tooling. This tool free fabrication approach supports fast design iteration and integration into existing electronic layouts.

Furthermore, the capability to deposit material across nano- and microscale regimes enables the direct fabrication of both functional elements and interconnect structures within a unified process. This reduces process complexity and broadens the range of realizable device architectures while maintaining compatibility with temperature sensitive substrates and material systems.

Other components could also benefit from advances in LIFT technology. It was shown that conductive tracks with high conductivity can be printed from silver nanoparticle ink. Such tracks could be implemented in solar cell technology as thin wiring of individual cells while minimizing optical shading losses [28]. In addition, the fabrication of thin film solar cells using LIFT printing appears feasible. Bulk hetero junction solar cells from organic polymers suffer from a low carrier mobility paired with a low exciton diffusion wavelength within the range of a few nanometers. This requires a careful precise fabrication process, that can arrange the materials in the nanoscale. Thin layers are required to allow a sufficient power conversion and to reduce losses. A challenge which LIFT printing would be well suited for. Solar cells with higher efficiency and low device fabrication cost could play a huge role in the development of renewable technologies. Other advantages of thin printed solar cells are they printability on flexible curved substrates which could innovate the market of wearables, where devices are integrated into every day goods. With the ability to print solar cells, LIFT printing could unlock significant potential as a key tool for materials research. By exploiting the capability to print large

numbers of individual devices or material gradients with high spatial density, LIFT could be used for high throughput material screening. Thousands of small devices printed on a single substrate could each function as an individual experimental unit for performance evaluation.

This concrete application is being implemented in the EU project Nanostacks in which this work is embedded in combination with the OLEDs presented in this work. These were printed on prestructured ITO substrates that served both as transparent electrodes and as electrical wiring for device connection and readout. However, this fabrication approach limits device density because conductive tracks, even with widths of 100 μm , occupy significant space and complicate individual addressing. This limitation can be overcome by integrating solar cells directly adjacent to the OLEDs. A so called Twin Nanostack consists of a connected pair of a miniature solar cell and a miniature OLED, each with a diameter of approximately 100 μm , operating together as a self powered unit without external wiring. Illumination at wavelength A would generate charge carriers in the solar cell, which would recombine in the OLED to produce emission at wavelength B. Eliminating external wiring would allow significantly higher device densities than demonstrated in this work and would enable systematic screening of optimized device architectures. By printing thickness or material gradients, either the energy generating or the energy consuming component could be optimized while keeping the other component constant. Device characterization can be performed using fluorescence scanners, which provide excitation at a defined wavelength and detect emission at another wavelength using optical filtering. These systems can generate emission maps while excitation of a substrate within minutes, enabling efficient identification of optimal device architectures for OLEDs or solar cells. Optimized designs could then be fabricated at larger scale using LIFT or other manufacturing technologies.

The long term goals of the Nanostacks project go even beyond that stage and cover a broader perspective. After optimization of the Twin Nanostack architecture, the energy producing component is intended to be replaced by an artificial printable fuel cell, which is developed in the scope of this project. Currently, proton exchange membrane fuel cells are costly due to the use of noble metal catalysts and exhibit limited efficiency because of parasitic reactions. Using LIFT printing, a new fuel cell design could be realized that employs iron based catalytic centers inspired by the enzyme hydrogenase. These centers could be embedded within selective barrier materials that allow reactant transport while excluding catalytic poisons. Nanometric thin layers with gradually varying redox potentials could guide reactants toward the catalytic center. Here LIFT key properties can be used for the fabrication by precisely printing nanometric thin multi-material layers. The long term vision is to fabricate such fuel cell stacks, integrate them into the modular Twin Nanostack architecture, and utilize high throughput screening for performance optimization. Insights gained from screening could then support industrial scale production of cost effective and efficient fuel cells capable of buffering fluctuations in renewable energy generation within the electrical grid.

Overall, the results of this work provide a robust foundation for both scientific and industrial advancement by demonstrating the capability of fabricating functional electronic components by LIFT printing, while using its key properties, multi material printing in combination with nanometric precision. Future research should focus on expanding device spectrum, material combinations, improving process stability, and advancing automation to fully exploit the potential of this versatile printing technology.

A. Appendix

A.1 Methods and Devices

A.1.1 Spin Coating

Spin coating was used as an alternative method for the preparation of thin films on donor and acceptor slides, following the recommendations of the respective ink manufacturers. The final film thickness depends on multiple parameters and can be precisely tuned by adjusting the spin speed and duration. A K+L spin coater type SCC-200 was used for all spin coating processes (see Figure A.1). Spin coating is a non-selective deposition method resulting in a uniform coating sometimes exhibiting a process-related radial gradient.

In this work, spin coating was used for the preparation of acceptor slides to build the first functional layer of an OLED, since PEDOT:PSS cannot be transferred by printing. It also served as a feasible method for distributing small-molecule or polymer solutions onto donor slides.

For the spin coating process, the substrate was first placed in a customized holder designed for rectangular substrates. A defined volume of ink, typically 1 mL was dispensed onto the substrate completely covering the surface. The spin parameters speed and duration were set to reach the desired film thickness and to achieve a dried and even surface.



Figure A.1: Spin coater used for the deposition of thin films on microscope slides

A.1.2 Plasma Cleaning

Plasma cleaning removes organic contamination and ensures more hydrophilic substrate surfaces in order to match the surface energy of inks. In this work, a Zepto 111511 low-pressure plasma cleaner by Diener electronic GmbH & Co. KG, Ebhausen, Germany was used. This process improves the homogeneous distribution of inks in a uniform film, which is especially important in the case of PEDOT:PSS for OLED manufacturing.

Before plasma cleaning, the substrates were cleaned with acetone to remove any contamination or dust. The plasma cleaning process was performed under air atmosphere for 5 min at 65 W.

A.1.3 Laser Calibration

The Thorlabs Thermal Power Sensor Head S401C [99] is a thermopile-based sensor designed for measuring optical power from 10 μ W to 1 W across a broad spectral range of 190 nm to 20 000 nm wavelength. It features a 10 mm $\times$ 10 mm active area and provides accurate power readings with a resolution of 1 μ W. In this work, the powermeter S401C was used to calibrate the output power of the 405 nm diode lasers, the stationary laser of the LIFT production printer with a maximum output of 300 mW and the mobile LIFT printer with up to 500 mW of output power. For the mobile LIFT printer it was used to confirm the calibration of the manufacturer and the linear behavior of the control voltage and the output power. For the stationary LIFT printer it was used to measure the laser power onto the target substrate after losses through mirrors and lenses in the optical path. The sensor was placed after the two deflecting mirrors, the laser scan head, and the f-theta lens, when viewed from the laser source, just in front of the sample position. The calibration Table A.1 and graph can be found in Appendix A.2. In this work the given values for the laser power always refer to the output power of the laser, not the input power at the sample. For comparison purposes with other devices the power values should therefore be corrected by a factor of 0.65, which is derived from a linear regression of the graph in Figure A.8.

A.1.4 Fluorescence Scanner

To characterize the transfer of fluorescent molecules with high sensitivity, two fluorescence imaging systems were employed. Although these devices do not provide information about the topographical height of transferred material, the relative fluorescence intensities can be used to reliably assess whether a transfer has occurred. The InnoScan 1100-AL fluorescence microscope (INNOPSYS, Carbonne, France) was used to detect the transfer of Super yellow light-emitting PPV copolymer, with particular focus on the temperature-dependent increase in fluorescence intensity (see Figure A.2) This device operated in simultaneous scan mode with excitation wavelengths of 488 nm, 532 nm, and 635 nm, and a scan resolution of 5 μ m. Image analysis was performed using Mapix software, with subsequent contrast and brightness adjustments made in ImageJ. The AxioScan.Z7 fluorescence scanner (Carl Zeiss AG) was used to examine the transfer of S-LEC[®] labeled with fluorescent markers onto modified acceptor slides featuring a columnar surface structure. This system offers an excitation range from 385 nm to 735 nm, and image analysis, including contrast and brightness adjustments, was conducted using ZEN software.



Figure A.2: Fluorescence scanner used for the analysis of printed nanoscale structure: Innopsys

A.1.5 Capacitor Characterization with Network Analyzer

A network analyzer (Agilent E5061B) in combination with a probe station (Cascade Microtech MPS150) (see Figure A.3) equipped with a Z-probe (Z0-20-K3N-GS-500, Cascade Microtech GmbH) is used to characterize electronic components in the frequency domain. Prior to measurements, a calibration procedure is performed to ensure accurate impedance readings. This involves using the Z-probe to perform open, short, and load (typically 50Ω) measurements on an impedance standard substrate. Once calibrated, the probe is used to contact designated metal tracks or contact pads on the device under test. This setup enables precise high-frequency characterization of microscale components and structures.

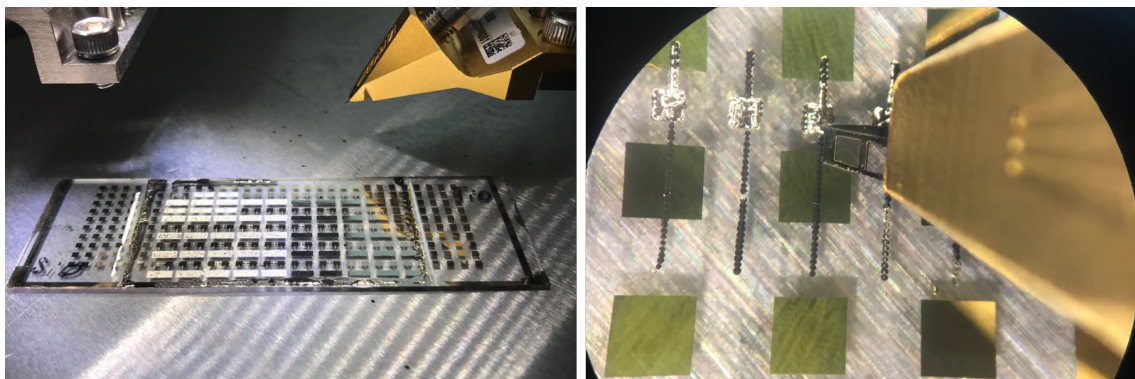


Figure A.3: Probe head of the manual probe station used for contacting components printed on the carrier substrate. The probe head is connected to a network analyzer for electrical characterization.

A.1.6 Resistance Measurement of Printed Tracks with an SMU

A four-point probe setup, connected to a Keithley 2450 SMU, is commonly used to accurately determine the electrical resistivity of printed conductive materials. This method minimizes the influence of contact resistance by applying a current through

the outer probes while measuring the voltage drop across the inner probes. Conductive paths are typically printed between predefined contact pads, and the geometry of these paths is carefully considered to enable precise resistivity calculation. Prior to measurement, printing parameters such as pitch, laser power, and exposure time are optimized for uniform material deposition. To further improve conductivity, sintering processes are applied, often in multiple thermal steps that raise and hold the sample at elevated temperatures, followed by controlled cooling. The four-point measurement is performed both before and after such thermal treatments to assess changes in conductivity. This setup allows for the evaluation of material performance in applications requiring high-conductivity printed structures, such as interconnects or capacitor electrodes.

A.1.7 Topographic Measurements with a Vertical Scanning Interferometer

White light interferometry, also referred to as VSI, is an exceptionally accurate optical measurement method used for non-contact and non-destructive examination of surface structures at the nanometer level. This technique relies on the principle of interference, employing coherent white light, which includes a wide spectrum of wavelengths, directed at a sample to create three-dimensional surface profiles. A white light source emits a beam that is split into a measurement beam and a reference beam. The reference beam is directed towards a mirror and reflected back, while the measurement beam reflects off the sample's surface. The surface topography of the sample causes a path length difference between the measurement and reference beams. When these beams are recombined, they produce an interference pattern (fringes), which is detected and analyzed using specialized software. This process results in a high-resolution height profile of the surface being examined. Figure A.4 illustrates a schematic diagram of a white light interferometer. In this study, a VSI Contour GT-KOX-14-157 system from Bruker (Ettlingen, Germany) was used for optical and topographical characterization. This system facilitates non-contact, high-resolution surface profiling by capturing three-dimensional topographical data with nanometer accuracy. Unless specified otherwise, measurements were generally conducted using a $2.5\times$ magnification objective, and the data were processed using Bruker's Vision64 software. Compared to other topographical characterization methods VSI offers fast measurements and is particularly advantageous for analyzing larger surface areas. This makes it a favored technique in materials science and microfabrication. However, certain technical difficulties may occur when examining highly reflective or rough surfaces with very steep slope angles, as these can disrupt fringe formation and thus diminish measurement accuracy. VSI is a valuable tool for the detailed assessment of print quality in nano-3D printing. It enables precise characterization of surface structures and geometrical parameters such as layer thickness, surface roughness, and microstructural features at the micro- and nanometer scale. As a result, it is a crucial instrument for optimizing printing parameters and advancing fabrication processes.

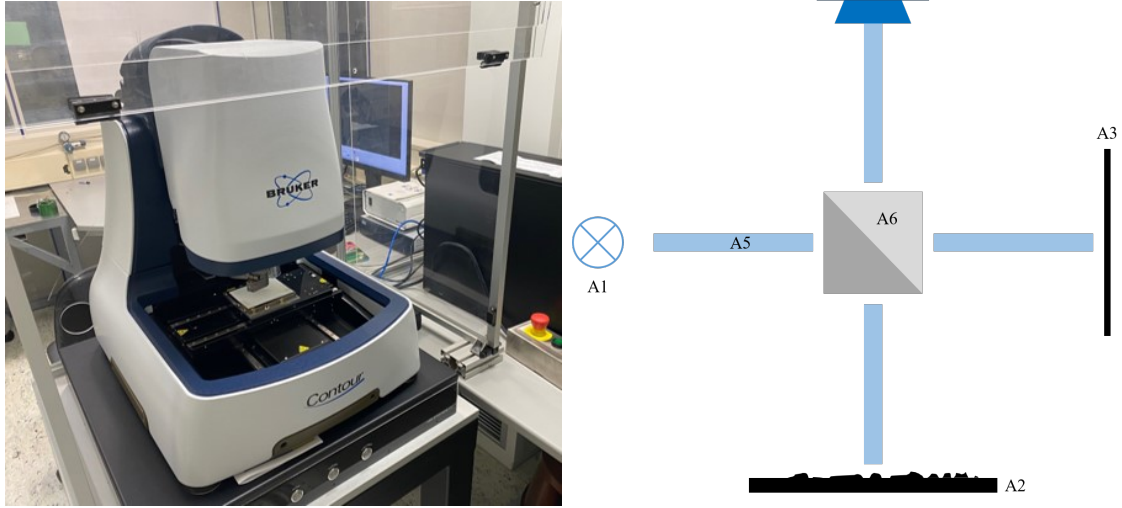


Figure A.4: Image of the Bruker VSI setup and sketch of a light interferometer. A1: Light source A2: Sample A3: Mirror A4: Camera A5: Light beam A6: Beam splitter

A.1.8 Tomographic Analysis with Scanning Electron Microscope

Cross-sectional imaging was performed using a focused ion beam scanning electron microscope (FIB-SEM, FEI DualBeam Helios G4 FX, Thermo Fisher Scientific), allowing simultaneous ion milling and high-resolution electron imaging. OLED or capacitor samples were mounted following standard procedures and milled with a gallium ion source to expose the internal structure. Prior to milling, a protective platinum layer was deposited in situ via gas injection to minimize beam-induced damage and ensure clean trench formation. The sample stage was tilted by 52° to acquire high-contrast cross-sectional images using the integrated secondary electron detector.

A.1.9 OLED Operation and Testing with the MATIS Setup

The following description of the MATIS setup is cited from the work of Liane Koker that was prepared for a collective publication [P3]. For optical and electrical characterization of the OLEDs a MATIS is applied [100].

The measurement setup is shown in Figure A.5. The four-axis platform consists of an xy-stage with a vacuum chuck (6), on which a carrier (4) is clamped to host the sample to be tested. A microscope optics (1) for optical inspection of the sample and fiducial detection as well as a z-axis and a rotation axis that carries the probe head are mounted to a gantry above the xy-stage. The probe head can be adapted to the probing task by means of a Schunk MWS 30 tool change interface (3). For the OLED characterization an optical probe head is required. Hence, for this purpose an adapted tool plate was mounted to the tool change interface carrying a Thorlabs F950SMA-A lens to maximize light input from the sample. This lens is connected to an Ocean Optics Red Tide USB650 Fiber Optic Spectrometer via a 2 m UV-VIS glass fiber with a core diameter of $400\mu\text{m}$ (2).

Up to 20 OLEDs (13) can be fabricated on each glass substrate (8), where they are

electrically connected using laser-structured ITO tracks (14). Ossila connection legs (10) are used to establish electrical contact with the ITO pads located at the edges of the substrate. To protect the devices, some of the OLEDs are encapsulated with epoxy resin and a cover glass (11).

The sample carrier consists of a printed circuit board (PCB), on which two lever operated zero insertion force (ZIF) sockets (12) are mounted parallel to each other to mate with the connection legs. The sockets are connected to 24 Meder SIL05-1A72-BV669 relays (7) and a multiplexer unit mounted on the same PCB for individual supply of each OLED. A Keithley 2612b SMU is used for power supply ($I_{max} = 10\text{ mA}$, $V_{max} = 20\text{ V}$) and the measurement of OLED power consumption.

In this setup, the glass substrate with the printed OLEDs is facing downwards, while the light is emitted upwards through the glass and collected by the optical probe head positioned above. A sealed chamber formed by the glass substrate, the ZIF sockets, sidewalls and the PCB below is flooded with Ar gas via an inlet (9) to protect the unencapsulated OLEDs from ambient oxygen and humidity during the measurement. The setup is protected against scattered light by an enclosure (5) and shielding of any additional light sources within the platform like displays. To evaluate the acquired spectrum, the dark current is subtracted from the measurement data.

The spectrum of each OLED can be acquired individually by manual alignment of the microscope optics for the measurement. Another option is a teach-in mode, where each OLED position is manually stored, allowing an automated measurement procedure. Perspectively, a fully automated characterization would be also feasible. In this case, the layout of an entire substrate with multiple devices would be imported into the machine control, and the clamped substrate automatically scanned to detect the fiducials. Based on these fiducials, the transformation from machine to substrate coordinate system is calculated and ultimately the OLED positions derived from the substrate layout to calculate the motion paths.

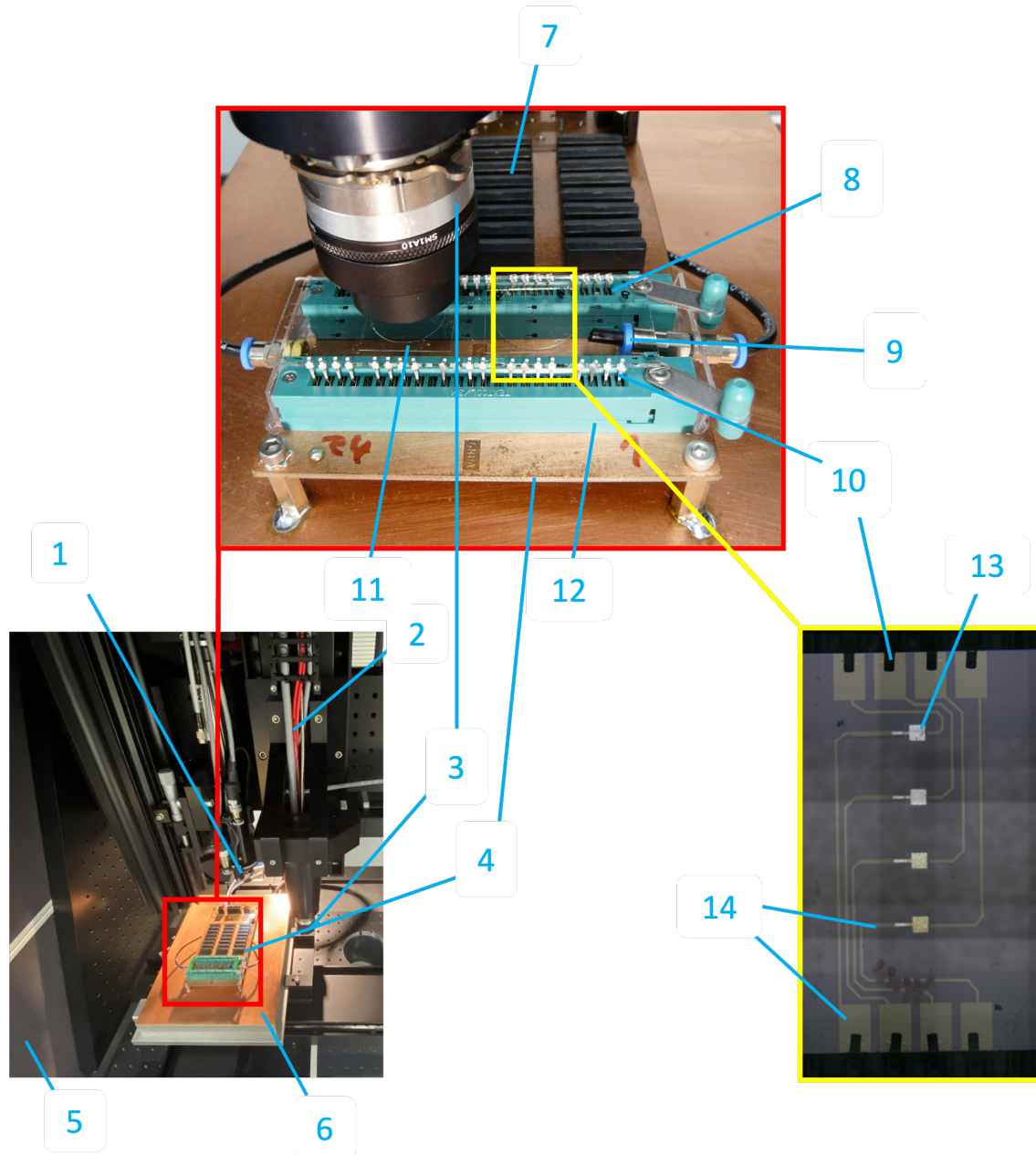


Figure A.5: OLED characterization setup with a view of the entire platform (left), the carrier hosting a glass substrate with printed OLEDs (middle) and a microscope image of a section comprising four OLEDs (right). The setup consists of microscope optics (1), glass fiber (2) leading to spectrometer, tool change interface (3), carrier to host the samples (4), enclosure against scattered light (5), vacuum chuck (6), relays (7), glass substrate with printed OLEDs (8), argon inlet (9), connection legs (10), OLED encapsulation (11), ZIF sockets (12), printed OLED (13), structured ITO (14). *Images and description provided by Liane Koker*

A.1.10 Light Microscopes

The optical analysis of printed microstructures, such as printed capacitors and test structures for material research, was carried out using a Leitz Ergolux 200 optical microscope (see Figure A.6). The microscope was employed to inspect the printed structures for defects in printing as well as to verify the positioning of the printed

features on the substrate.

The system is equipped with multiple objective lenses ($5\times$, $20\times$, and $50\times$), providing total magnifications of $50\times$, $200\times$, and $500\times$, respectively. In addition, the microscope is fitted with an Olympus EP50 digital camera, enabling image acquisition via a dual-mode beamsplitter configuration.

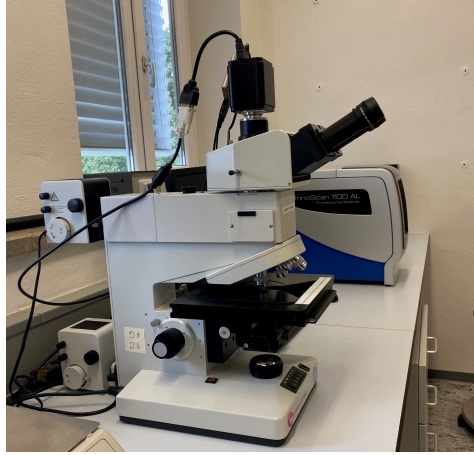


Figure A.6: Light microscopes used for characterization of printed microstructures. Left: Leitz Ergolux 200

A.1.11 Structural Analysis using TOF-SIMS

TOF SIMS is a highly sensitive surface analysis technique used to investigate the chemical composition and molecular structure of the outermost layers of solid materials. The method is based on the sputtering of secondary ions from the sample surface by means of a focused primary ion beam, typically consisting of monoatomic ions (e.g., Ar^+ , Bi^+) or cluster ions (see Figure A.7). When the high-energy primary ion beam impacts the sample surface, it transfers energy to atoms in the topmost atomic layers, initiating a collision cascade. If the transferred energy is sufficient to overcome the binding energies of surface atoms, covalent bonds are broken and a variety of species, including neutral atoms, electrons, and secondary ions, are emitted. Only the ionized species are accelerated into a time-of-flight (ToF) mass analyzer, where they are separated according to their mass-to-charge ratio. The flight time of the ions depends on both their mass and charge, allowing for high-resolution mass spectrometric detection. The resulting spectra typically contain a vast number of peaks, reflecting the complex chemical composition of the surface. Importantly, TOF SIMS combines both spectral and spatial information, enabling the generation of chemical maps and three-dimensional reconstructions.

In the present work, TOF SIMS analyses were conducted using a TOF.SIMS5 instrument (ION-TOF GmbH, Münster, Germany), equipped with a bismuth liquid metal cluster ion source and a reflectron-type ToF analyzer. The measurements were performed under ultra-high vacuum (UHV) conditions, with a base pressure below 5×10^{-8} m bar. For high mass resolution, the primary ion source was operated in "high current bunched mode", generating Bi_3^+ pulses with a duration of 1.24 ns at 25 keV kinetic energy. This setup yielded a lateral resolution of approximately $4 \mu\text{m}$, with a primary ion current of 0.35 pA and a cycle time of 100 μs . The primary ion beam was raster-scanned across a $300 \times 300 \mu\text{m}^2$ field of view, and 128×128 pixels

were recorded per measurement. Mass calibration was carried out using common reference peaks such as C^+ , CH^+ , CH_2^+ , and C_2H_2^+ , Sn^+ and InO_3^+ .

ToF-SIMS can be operated in two distinct modes: static and dynamic. In static mode, the ion dose is kept below $1 \times 10^{13}/\text{cm}^2$, ensuring that only a negligible fraction of the surface is sputtered. This allows for virtually non-destructive analysis of the outermost monolayers and is particularly suitable for high-resolution chemical imaging. In contrast, dynamic mode employs significantly higher ion doses ($>1 \times 10^{17}/\text{cm}^2$), resulting in substantial material removal. This enables the generation of depth profiles, which provide insight into the chemical composition of deeper layers.

Depth profiling in this work was performed in dual-beam, non-interlaced mode, utilizing an Ar_{1300}^+ sputter beam operated at 2.5 keV. This beam was rastered across a $750 \times 750 \mu\text{m}^2$ area with a target current of 0.62 nA. The analysis beam Bi_3^+ was centered within the sputter crater and scanned over a $300 \times 300 \mu\text{m}^2$ region, recording 125×125 data points per layer with primary ion currents ranging from 0.28 pA to 0.35 pA at a cycle time of 100 μs . To account for calibration shifts caused by differential charging during depth profiling, the instrument's onboard Advanced ToF Correction (Depth) software module was used.

Although depth profiling provides detailed information on the vertical distribution of chemical species, it does not allow direct determination of absolute layer thicknesses, as sputter rates vary depending on the material. However, approximate thickness data can be inferred by calibrating sputter rates using reference materials or through simulation.

A key advantage of TOF SIMS lies in its exceptionally high sensitivity, with detection limits in the femto- to attomole range. However, this sensitivity also results in highly complex spectra, often containing thousands of peaks. The interpretation of such rich datasets requires advanced data analysis techniques. To extract meaningful chemical information and identify patterns, multivariate statistical methods, such as Principal Component Analysis (PCA), are frequently employed. These techniques reduce the dimensionality of the data and facilitate the recognition of characteristic fragment distributions and material interfaces.

In summary, TOF SIMS offers a powerful platform for surface and depth-resolved chemical analysis with high mass resolution, excellent spatial resolution, and extreme sensitivity. It is particularly well-suited for the study of multi-layered materials and printed thin-film stacks, enabling both qualitative and semi-quantitative evaluation of material composition and distribution.

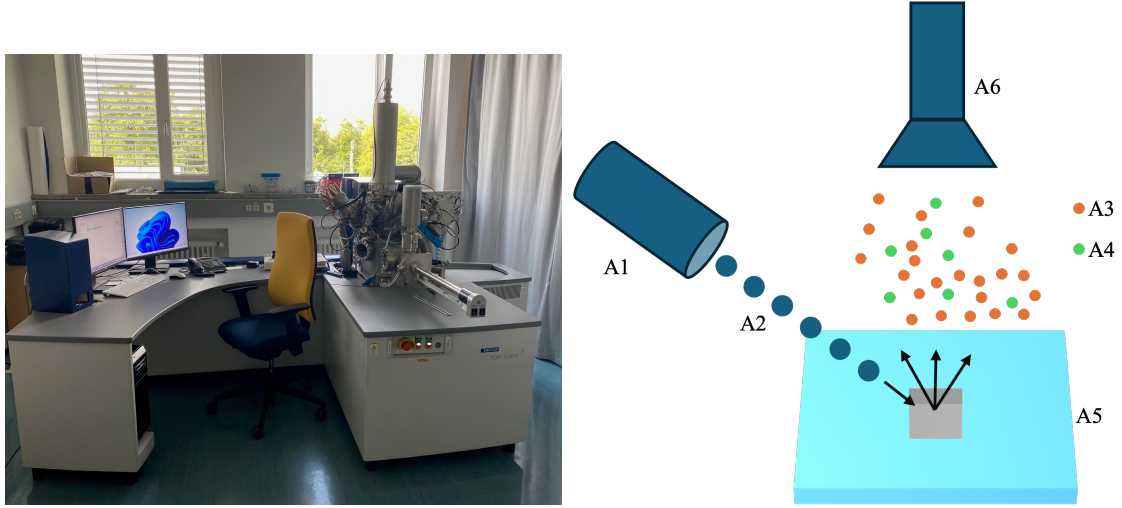


Figure A.7: Image of the TOF-SIMS setup and sketch of a ToF-SIMS device. A1: Primary ion source A2: Primary ion beam A3: Secondary neutrals A4: Secondary ions A5: Sample substrate A6: ToF analyzer

A.2 Laser calibration

The laser sources were calibrated using the Thorlabs power meter described in Appendix A.1.3. For this purpose, the sensor head was positioned at the intended sample location. This setup allowed measurement of the laser power incident on the sample, accounting for all losses introduced by the optical components. To evaluate the linear response of the system, the laser output was incrementally increased in steps of 10 mW, starting from the minimum power level up to a maximum of 300 mW. The measured power values at the sample position are shown in Figure A.8, along with the corresponding values in Table A.1. While the laser power at sample position exhibits linear behavior with the set power level, significant losses of approximately 35% occur due to the optical elements in the path.

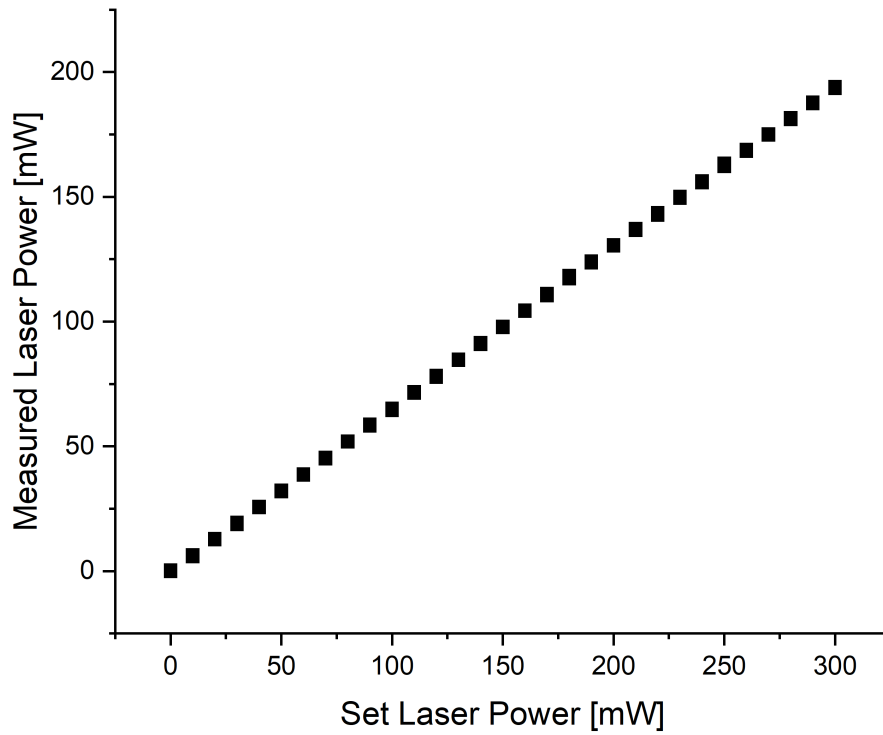


Figure A.8: Measured power at the sample position after losses in comparison to set laser power

In contrast, the mobile LIFT setup contains no intermediate optical elements in the laser beam path, apart from the diode's collimating lens. The system was pre-calibrated by the manufacturer and the power meter was used for verification. The measurement confirmed that the emitted power precisely matched the specified nominal value as specified by the manufacturer.

Set Power [mW]	Measured [mW]	Set Power [mW]	Measured [mW]
10	6	160	104
20	13	170	111
30	19	180	118
40	26	190	124
50	32	200	130
60	39	210	137
70	45	220	143
80	52	230	150
90	59	240	156
100	65	250	163
110	72	260	169
120	78	270	175
130	85	280	181
140	91	290	188
150	98	300	194

Table A.1: Comparison of set laser power and measured laser power at the sample position

A.3 Area Printing - Height and Roughness Variation Data

Conc. [mg/mL]	Step height 1 [nm]	Step height 2 [nm]	Mean step height [nm]	R_a [nm]
4	20.6	20.7	20.7	1.41
4	17.95	19.5	18.7	1.46
8	54.9	62.5	58.7	1.41
8	48.1	48.4	48.3	2.19
8	56.9	61.4	59.2	1.63
12	95.4	99.8	97.6	2.58
12	99.2	101.0	100.1	2.48
12	96.5	102.7	99.6	3.08
12	91.9	97.4	94.7	2.99
30	135.0	137.2	136.1	5.26
30	142.1	147.2	144.7	2.83

Table A.2: Measured step heights and surface roughness R_a values for Bphen samples at varying concentrations using laser parameters of 70 mW and 2 ms. Step height values correspond to the measured edge height of transferred features.

Conc. [mg/mL]	Laser parameters	Step height 1 [nm]	Step height 2 [nm]	Mean step height [nm]	R_a [nm]
12	70 mW, 2 ms	95.4	99.8	97.6	2.58
12	70 mW, 2 ms	99.2	101.0	100.1	2.48
12	70 mW, 2 ms	96.5	102.7	99.6	3.08
12	70 mW, 2 ms	91.9	97.4	94.7	2.99
12	70 mW, 3 ms	117.6	117.8	117.7	3.61
12	70 mW, 3 ms	120.4	123.1	121.8	2.98
12	70 mW, 3 ms	118.6	118.4	118.5	3.50
12	70 mW, 3 ms	105.6	113.6	109.6	3.08
12	80 mW, 2 ms	107.7	106.9	107.3	7.61
12	80 mW, 2 ms	114.1	114.0	114.1	5.89
12	80 mW, 2 ms	134.4	135.0	134.7	6.60
12	80 mW, 2 ms	98.1	83.7	90.9	4.20

Table A.3: Measured step heights and surface roughness R_a values for Bphen samples with a concentration kept at 12 mg/mL under varying laser powers and pulse durations. Step heights correspond to the measured edge height of transferred features.

A.4 OLED Fabrication - Additional Images

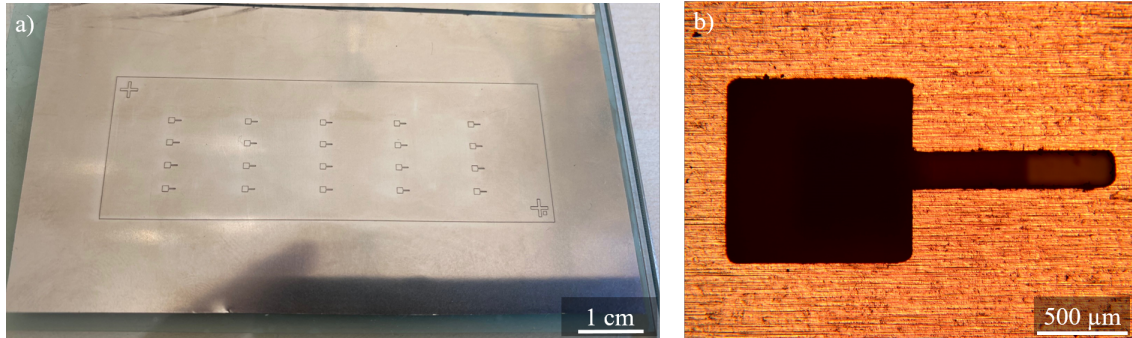


Figure A.10: Shadow mask used for the selective deposition of aluminum onto the OLED sample. The square-shaped electrode extends along the direction of the conductive track which is visible on the right side, but not in focus. Alignment was performed manually under a microscope using alignment markers on both the glass slide and the mask.

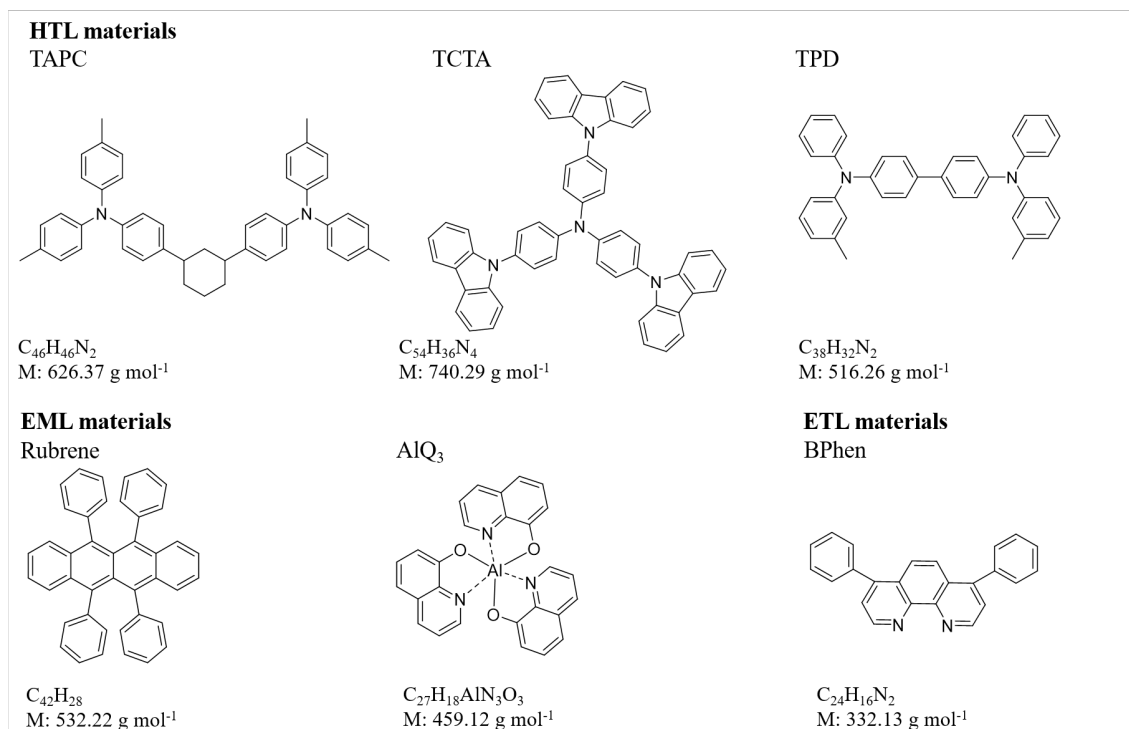


Figure A.9: Chemical structures of the materials used for OLED fabrication by LIFT printing. Source: Lux et al. [P3]

A.5 Characterization of Customized Inks

A.5.1 Ink Distribution

The customized inks were tested for their spreading behavior on the donor slide. Kapton[®] is a non-polar substrate, and therefore non-polar inks spread well on its surface. However, if the surface energy of the ink and substrate do not match—such as when using a polar, water-based ink—the surface properties must be modified. In such cases, plasma cleaning can be applied to increase the surface energy by introducing O–H groups, thereby enabling a more homogeneous ink distribution. Blade coating was performed with a gap of 20 μm in between the blade and the donor substrate. For the ink type C provided by the project partner TECNAN, a slight mismatch in surface energy was observed. As a result, the ink retracts due to surface tension effects. Consequently, the donor slides must be used in the LIFT printer immediately after preparation, as the ink layer becomes unstable within a few minutes.

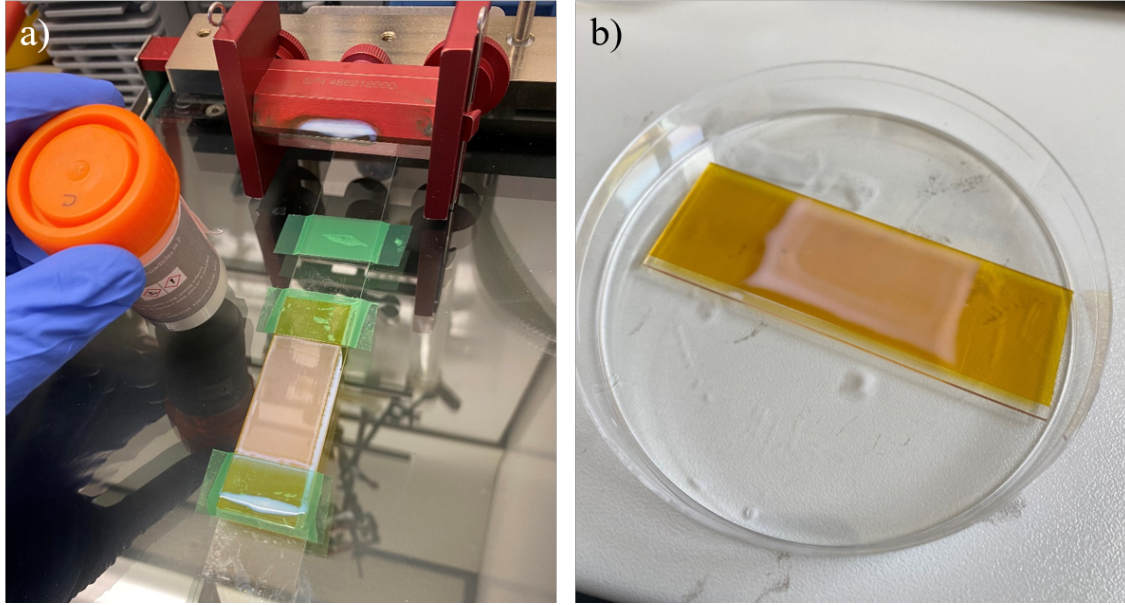


Figure A.11: (a) Distribution of test ink type C on the donor slide showing homogeneous spreading with a slightly milky appearance. (b) After 15 min, surface tension causes the ink to retract and form thicker regions. Therefore, either immediate use after donor preparation is recommended, or surface treatment is required to ensure longer stability.

A.5.2 Electrical Characterization of Custom-Fabricated ZnO Ink

To evaluate the electrical conductivity of structures printed with the custom-fabricated ZnO ink type C, two types of test patterns were prepared. The first pattern consisted of a crossing structure, where a base line of XTPL silver ink (CL60) was printed and dried prior to the deposition of a single centered ZnO dot. Afterward, a second silver line was printed perpendicular to the first, forming a cross with the ZnO dot at the intersection. The total length of each line was approximately 1 mm. The second structure comprised a line of overlapping ZnO dots printed in series, forming a continuous ZnO trace of approximately 2 mm in length. After printing, all samples were subjected to a post-processing step in a vacuum oven at 400 °C for 60 min to remove residual organic components and improve conductivity. Electrical characterization was performed by measuring the resistance across the printed features using a probe station. A grid of 7×8 crossing structures was measured, with each intersection contacted individually. The results, shown in Figure A.12, indicate that the measured resistance of the crossings was either very low (a few Ω) or relatively high (in the range of 10–100 k Ω). This variation suggests an inconsistent electrical contact through the ZnO layer, possibly due to variations in layer thickness or incomplete sintering.

For the printed ZnO line structures (3×8 grid), an open-circuit behavior was observed, with resistances exceeding the measurable range over a distance of 2 mm. This indicates that the ZnO material behaves predominantly as an electrical insulator under the tested conditions.

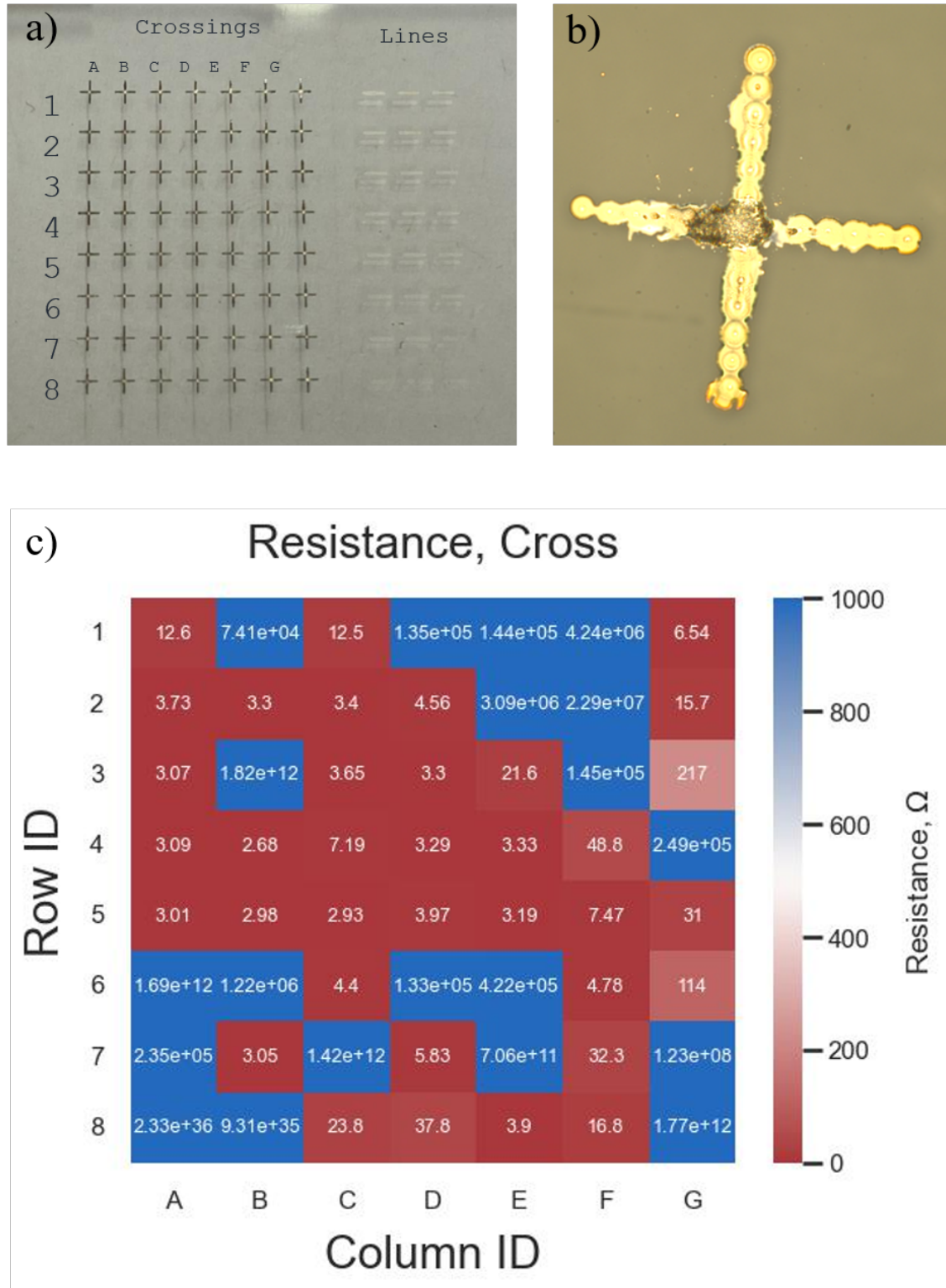


Figure A.12: (a) Silver–ZnO crossing structures used to measure the electrical conductivity of printed ZnO ink type C. (b) Magnified image of a single crossing showing slight misalignment and non-uniform material deposition. (c) Heat map of the measured resistances for the array of crossing structures. Source: Kuznetsova, Personal Communication[101]

A.6 Datasheet Polyimide Tape

Source: CMC Klebetechnik [102]



CMC Klebetechnik

Beschichten - Stanzen - Schneiden

Technisches Datenblatt

CMC Klebetechnik GmbH Rudolf-Diesel-Straße 4 Germany - 67227 Frankenthal 0049 (0)6233/872-300

DATENBLATT

CMC TYP	70110  E93622 (M)
Trägermaterial	Kapton® (Polyimid)
Farbe	braun
Trägerstärke in mm	0,025 ± 17%
Gesamtstärke in mm	0,060 ± 10%
Klebereigenschaften	
Kleberart	Polysiloxan
Klebkraft in N/cm nach interner Prüfvorschrift PV 1006-32 (180°-Abzug von Stahl)	≥ 2
Thermische Eigenschaften	
Dauergebrauchstemperatur (maximal) in °C	180
Kurzzeitbelastung (ca. 1 h) in °C	350
Anwendungstemperaturbereich	- 80°C bis + 350°C
Flammprüfung nach UL 510A	schwer entflammbar
Isolierstoffklasse nach DIN EN 60085	H
Elektrische Eigenschaften	
Durchschlagsspannung in Anlehnung an DIN EN 60243-1 in V _{eff.}	≥ 6'000
Mechanische Eigenschaften	
Reißkraft in N/cm	≥ 40
Reißdehnung in %	≥ 40
Sonstige Merkmale	RoHS konform ✓ REACH konform ✓
®Eingetragenes Warenzeichen DuPont de Nemours	

Die technischen Daten sind Mittelwerte und entbinden nicht von eigenen Prüfungen.
 Lagerung der Bänder: Kühl und trocken (15 - 25°C, < 65% rel. Luftfeuchtigkeit)
 Qualitätsgewährleistung: 12 Monate
 Technische Änderungen vorbehalten.

03/18

A.7 Arduino Code and Electric Circuit Diagramm for the LIFT Test Printer

Source: Lux et al. [P1].

Arduino code

```
#include <Adafruit_MCP4725.h>
#include <Wire.h>

//Steppermotor 1mm=400steps=90deg oder 4mm = 360deg = 1600steps

#define Taster 2 // lever on Pin 2

Adafruit_MCP4725 dac; // dac now at serial port

void Laser(int laserpower, int exposure){
  int Bitspower = Laserpower2Bits(laserpower);
  digitalWrite(7, HIGH); // Status LED on
  dac.setVoltage(Bitspower, false); //laser on
  delay(exposure); //exposure duration
  dac.setVoltage(0, false); // laser off
  digitalWrite(7, LOW); // Status LED off
}

int Laserpower2Bits(float laserpower){
  int Bitspower;
  int LaserMaxOut = 500; //Laser maximum power is 500mW
  if (laserpower > 500){
    laserpower = 500;
  }
  if (laserpower < 0) {
    laserpower = 0;
  }
  Bitspower = 4095 * (laserpower/LaserMaxOut); //4095 is the maximum number of bits
  return Bitspower;
}

void MoveX(float mm){
  digitalWrite(3, LOW);
  if (mm <= 0){
    digitalWrite(2, LOW); // The signal for the rotation direction will be set at LOW. If direction is not right,
    set as HIGH.
  }
  if (mm > 0){
    digitalWrite(2, HIGH); // The signal for the rotation direction will be set at LOW. If direction is not right,
    set as HIGH.
  }
  for (int i = 0; i < abs(int(400*mm)); i++){
    digitalWrite(3, HIGH);
    delay(1);
    digitalWrite(3, LOW);
    delay(1);
  }
}

void MoveY(float mm){
  digitalWrite(5, LOW);
  if (mm <= 0){
    digitalWrite(4, LOW); // The signal for the rotation direction will be set at LOW. If direction is not right,
    set as HIGH.
  }
  if (mm > 0){
```

```
    digitalWrite(4, HIGH); // The signal for the rotation direction will be set at LOW. If direction is not right,
    set as HIGH.
```

```
    }
    for (int i = 0; i < abs(int(400*mm)); i++){
        digitalWrite(5, HIGH);
        delay(1);
        digitalWrite(5, LOW);
        delay(1);
    }
}
```

```
void setup() {
    Serial.begin(9600); // open the serial port with transferspeed of 9600
    pinMode(2, OUTPUT); // Pin2 must be an Output to send a signal
    pinMode(3, OUTPUT); // Pin3 must be an Output to send a signal
    pinMode(4, OUTPUT); // Pin4 must be an Output to send a signal
    pinMode(5, OUTPUT); // Pin5 must be an Output to send a signal
    pinMode(6, OUTPUT); // Pin6 must be an Output to send a signal
    pinMode(7, OUTPUT); // Pin7 must be an Output to send a signal
    pinMode(8, INPUT); // Pin2 must be an Input to detect a signal
    digitalWrite(8, HIGH);
    //digitalWrite(6, HIGH); // enables microsteps
```

```
    dac.begin(0x62); // adressng of dac 0x62 or 0x63
    dac.setVoltage(0, false); //laser off
```

```
    pinMode(13, OUTPUT);
    //Laser signal low
}
```

```
void loop() {
    if (digitalRead(8)==LOW){
        digitalWrite(7, HIGH);
        delay(2000);
        digitalWrite(7, LOW);
        delay(10000); // Time to close the lid
```

```
//-----START first laser pattern-----
```

```
    int DotsPerRow =4;
    float pitch = 0.8;
    int LaserP = 160;
    int LaserD = 10;
    for (int i = 0; i < DotsPerRow; i++) { // y-Movement
        for (int j = 0; j < DotsPerRow; j++){ // x-Movement
            Laser(LaserP,LaserD); //Laser on-off
            MoveX(pitch); //Movement in X for one step
            delay(1);
        }
        MoveX(DotsPerRow*-pitch); //Back to the beginning of the row
        delay(1);
        MoveY(pitch); //Movement in Y for one step
        delay(1);
    }
```

```
    MoveY(DotsPerRow*-pitch); //go back to START position
```

```
//-----END first laser pattern -----
```

```
//-----START second laser pattern-----
```

```
    DotsPerRow =4;
    pitch = 0.8;
```



```

LaserP = 180;
LaserD = 10;
MoveX(5);
for (int i = 0; i < DotsPerRow; i++) { // y-movement
    for (int j = 0; j < DotsPerRow; j++) { // x-movement
        Laser(LaserP,LaserD); //Laser on-off
        MoveX(pitch); // Movement in X for one step
        delay(1);
    }
    MoveX(DotsPerRow*-pitch); // Back to the beginning of the row
    delay(1);
    MoveY(pitch); // Movement in Y for one step
    delay(1);
}
MoveY(DotsPerRow*-pitch); // go back to START position
//-----END secondlaser pattern -----

//-----START third laser pattern-----
DotsPerRow =4;
pitch = 0.8;
LaserP = 200;
LaserD = 10;
MoveX(5);
for (int i = 0; i < DotsPerRow; i++) { // y-Bewegung
    for (int j = 0; j < DotsPerRow; j++) { // x Bewegung
        Laser(LaserP,LaserD); //Laser an-aus
        MoveX(pitch); //Bewegung in X um je 1 Schritt
        delay(1);
    }
    MoveX(DotsPerRow*-pitch); //Zurück an den Anfang der Zeile
    delay(1);
    MoveY(pitch); //Bewegung in Y um je 1 Schritt
    delay(1);
}
MoveY(DotsPerRow*-pitch); //in die Ausgangsposition fahren
//-----END thirdlaser pattern -----

//-----START fourth laser pattern-----
DotsPerRow =4;
pitch = 0.8;
LaserP = 220;
LaserD = 10;
MoveX(5);
for (int i = 0; i < DotsPerRow; i++) { // y-Bewegung
    for (int j = 0; j < DotsPerRow; j++) { // x Bewegung
        Laser(LaserP,LaserD); //Laser an-aus
        MoveX(pitch); //Bewegung in X um je 1 Schritt
        delay(1);
    }
    MoveX(DotsPerRow*-pitch); //Zurück an den Anfang der Zeile
    delay(1);
    MoveY(pitch); //Bewegung in Y um je 1 Schritt
    delay(1);
}
MoveY(DotsPerRow*-pitch); //in die Ausgangsposition fahren
//-----END fourth laser pattern -----

//-----START fifth laser pattern-----
DotsPerRow =4;

```

```

pitch = 0.8;
LaserP = 240;
LaserD = 10;
MoveX(5);
for (int i = 0; i < DotsPerRow; i++) { // y-Bewegung
    for (int j = 0; j < DotsPerRow; j++) { // x Bewegung
        Laser(LaserP,LaserD); //Laser an-aus
        MoveX(pitch); //Bewegung in X um je 1 Schritt
        delay(1);
    }
    MoveX(DotsPerRow*-pitch); //Zurück an den Anfang der Zeile
    delay(1);
    MoveY(pitch); //Bewegung in Y um je 1 Schritt
    delay(1);
}
MoveY(DotsPerRow*-pitch); //in die Ausgangsposition fahren Y
//-----END fifth laser pattern -----

//-----START sixth laser pattern-----
DotsPerRow = 4;
pitch = 0.8;
LaserP = 280;
LaserD = 10;
MoveX(5);
for (int i = 0; i < DotsPerRow; i++) { // y-Bewegung
    for (int j = 0; j < DotsPerRow; j++) { // x Bewegung
        Laser(LaserP,LaserD); //Laser an-aus
        MoveX(pitch); //Bewegung in X um je 1 Schritt
        delay(1);
    }
    MoveX(DotsPerRow*-pitch); //Zurück an den Anfang der Zeile
    delay(1);
    MoveY(pitch); //Bewegung in Y um je 1 Schritt
    delay(1);
}
MoveY(DotsPerRow*-pitch); //in die Ausgangsposition fahren Y
MoveX(-25); // in die Ausgangsposition fahren X
} // Ende If schleife Taster
//-----END sixth laser pattern -----
}

```

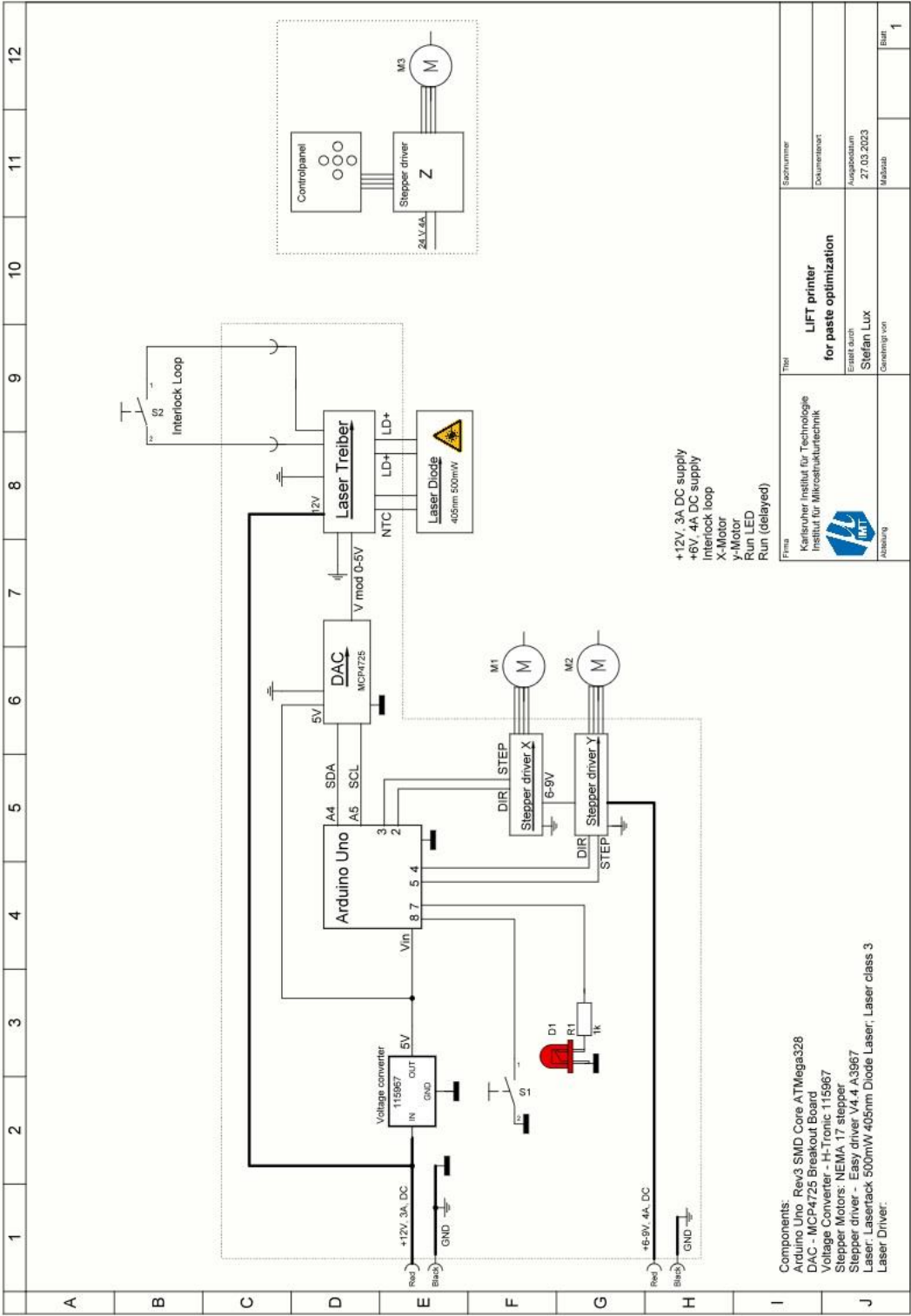


Figure A.13: Circuit diagram of the test LIFT printer. The central components, including the x-y movement and the laser, are under the control of the Arduino. However, the z-movement is independently managed. In this configuration, the existing electronics from the former CNC machine were repurposed. Typically, the z-height requires initial adjustment and remains fixed in place thereafter. Source: Lux et al. [P1]

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