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Approaches for Solution-Processed Encapsulation of Printed Medical Wearable Devices

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Abstract: Wearable medical devices offer a great opportunity to monitor human vital signs to improve healthcare. The use of printing technologies is a promising approach to fabricate the wearables. An encapsulation must be applied to achieve long-term stability and reliability of the printed wearables. In this paper, we discuss the encapsulation requirements of printed wearable medical devices. Different encapsulation approaches are illustrated by means of various examples. Thereby, the focus lies upon solution-processed encapsulation, including the compatible materials and printing technologies.

Keywords: encapsulation, wearable devices, printed electronics, medical applications

1 Introduction

Wearable medical devices are electronic systems attached to the body, either with direct skin contact or integrated into the clothing, that fulfil medical functionalities. Applications include, but are not limited to, vital signs monitoring, sweat analysis, saliva analysis, wound monitoring, motion/fall detection or magnetic resonance imaging (MRI).

Printing technologies are a promising fabrication process for wearable devices [1, 2]. The main advantage is the applicability of electronic circuits on surface-conformal substrates that can adapt to the skin, like flexible plastic foils, fabric or paper. The inexpensive substrates and low material consumption due to the additive manufacturing techniques allow for the production of disposable devices, thus avoiding elaborate sterilisation processes. Since a variety of established as well as novel materials can be structured by printing, new functionalities can be realised, especially for sensors. Furthermore, the use of digital printing technologies like inkjet printing or aerosol-jet printing opens up the possibility of manufacturing personalised devices [3]. To realise devices mainly containing electrodes and antennas, the most commonly used technique is screen printing due to a high layer thickness and thus a higher conductivity [4, 5].

An overview of applications of printed wearable medical devices as well as selected examples are presented in figure 1, including researched approaches and commercial products.

2 Encapsulation requirements

For printed wearable medical devices, a conformal encapsulation that protects the printed circuit or components from water (or body fluids like salivary, sweat), oxygen, dirt and dust is required [15, 16]. The encapsulation methods can be divided into two types, namely, global encapsulation and local encapsulation. A global encapsulation should protect the entire printed structure, while a local encapsulation covers the sensitive parts of the printed structures and leaves parts with sending functions uncovered. It must be biocompatible and should add little volume and weight to the devices. Apart from this, there are some specific requirements, which vary from application to application, e.g for monitoring devices, a selective encapsulation which only allows the analyst to permeate the encapsulation layer is required [17]. Furthermore, it is quite common for wearable devices to work under bending, stretching or twisting forces. Therefore, another requirement of the encapsulation is its flexibility to make sure that even under those forces, the device still works stably [18]. When it comes to commercialization, the cost and the aesthetic appearance of the wearable devices also play an important role for customer's choices. Printed wearable devices should be well designed and fit the customer's taste.

3 Encapsulation approaches

Due to the aforementioned encapsulation requirements, flexible encapsulation is used instead of conventional rigid encapsulation like glass or metal [19]. Nowadays, a flexible encapsulation is mostly achieved by barrier foil lamination, thin film encapsulation (TFE) or solution-processed encapsulation. All of them can not only provide high barrier properties but also preserve the flexibility of printed structures [20, 21].

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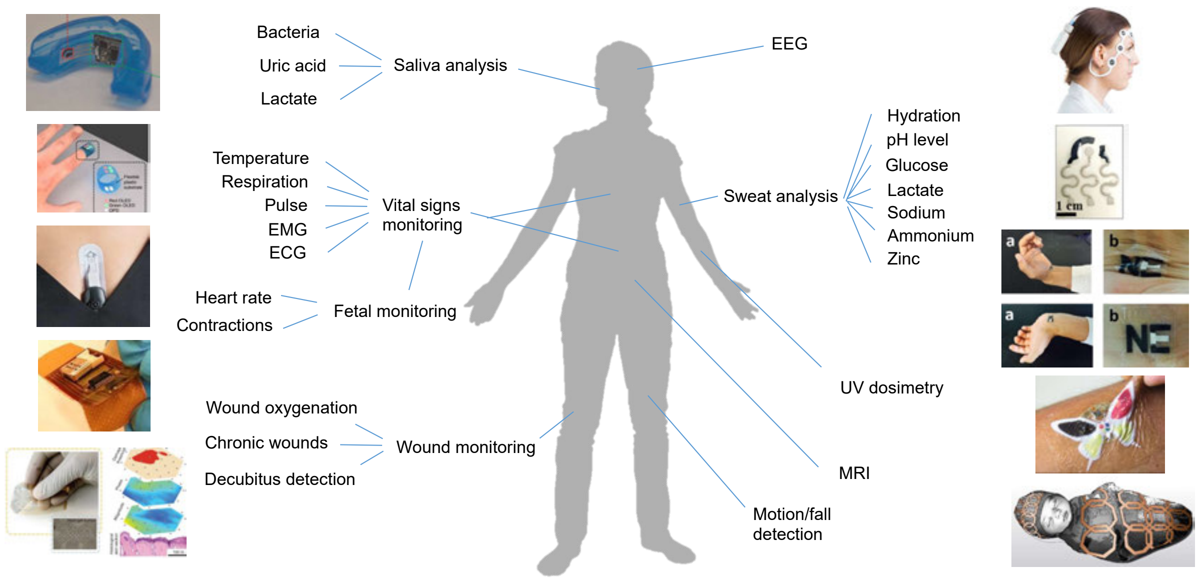


Fig. 1: Overview of applications and selected examples for printed wearable devices, top to bottom left: Screen-printed uric acid mouthguard biosensor [6]. Spin-coated and blade-coated optoelectronic sensor for pulse oximetry [7]. "Bittium Faros™" wearable ECG monitor using screen-printed electrodes [8]. Inkjet-printed smart bandage to monitor chronic wounds [9]. Early detection of pressure ulcers by impedance sensing using an inkjet printed electrode array [10]. Top to bottom right: "Bittium BrainStatus™" screen-printed disposable EEG electrode set [11]. Stretchable and screen-printed glucose sensor [12] and screen-printed tattoo sensor for monitoring in human sweat [13]. Screen-printed colorimetric UV dosimeter [14]. Screen-printed flexible MRI receiver coils [4]. *all figures reprinted with permission.*

3.1 Barrier foil lamination

In barrier foil lamination, a barrier foil is attached to the substrate mostly by using adhesion, thermal or laser welding. One example is discussed in [22]. Here, an one-step laser encapsulation of a nano-cracking strain sensor was applied. They utilized a laser to cut and bond two polyurethane (PU) films in one step.

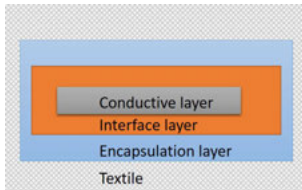
3.2 Thin film encapsulation

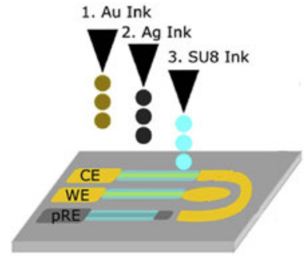
Thin film encapsulation is often used for global encapsulation to protect the whole device. It has been successfully applied to flexible organic light-emitting devices (OLEDs) used for displays as well as wearable devices. E.g. Jeon et al. used multilayer thin film encapsulated flexible OLEDs as light sources in a wearable Photobiomodulation (PBM) patch for skin treatment [23]. In addition, vacuum deposited Parylene coatings are often used in medical devices [17]. Because of the vapor deposition method, Parylene can be applied in very thin layers, but it still provides superior resistance to moisture, solvents. Yokota et al. formed a multilayer consisting of five inorganic (SiON) and organic (Parylene) layers as passivation layer for a smart electronic skin (e-skin) system, the water vapor transmission rates (WVTR) of the passivation layer was approximately $5.0 \times 10^{-4} g/m^2$ per day [24].

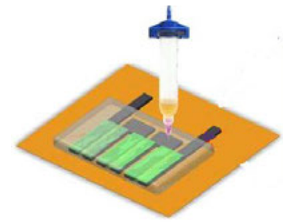
3.3 Solution-processed encapsulation

A drawback of barrier foil lamination is that it cannot offer a conformal encapsulation on a 3D surface. Thin film encapsulation requires additional equipment such as atomic layers deposition (ALD) reactor or vacuum chambers [19]. Thus, we highlight a novel encapsulation approach for printed wearable devices and sensors, that is solution-processed encapsulation. Using this approach, the solvent based, fluid inks or pastes can be applied as encapsulation layer onto printed structures. This allows the encapsulation process to be integrated into the printing process chain. Moreover, both global and local encapsulation can be realised by using different technologies. The methods for solution-processed encapsulation are drop-casting, spin-coating, screen-printing and inkjet-printing, etc.. Drop-casting is a facile coating technique by applying one or more droplets on the target surface [21]. In spin-coating, the solution is deposited and a uniform layer can be formed on a rotating substrate [28]. A low viscosity material is suitable for both drop-casting and spin-coating. These two approaches are usually used for global encapsulation [21]. In screen-printing, an ink with high viscosity is spread over the screen. This approach can not only be applied for global, but also for local encapsulation by using masks. Inkjet-printing is a digital printing process. A low viscosity ink is deposited drop by drop onto the target position. Both global and local encapsulation can be

Tab. 1: Selected examples for solution-processed encapsulation







Printing technology	Screen-printing	Inkjet-printing	Inkjet-printing
Material	Ecoflex	SU-8	Silicone rubber
Kind of encapsulation	Global	Local	Global
Ref.	[25]	[26]	[27]

realised without the need for a mask [3, 29]. Some solution-processed encapsulation examples are listed in Table 1.

Materials that are compatible with solution-processed encapsulation are fluid inks or pastes such as Ecoflex, SU-8, formulated polymer solutions (PDMS, PI, PVC, etc), dielectric paste [6, 12, 25, 26, 30–36]. Ecoflex is a printable bioplastic with special properties such as flexibility, toughness and water resistance [37]. SU-8 is a photoresist. The viscosity of SU-8 can be adjusted from 1cp to 15cp [38], thus SU-8 inks with different viscosities are compatible with inkjet printing and spin-coating [39]. Polymer solutions with different formulations can reach different viscosities which are compatible with various solution-processed encapsulation methods. Besides, specific functions of an encapsulation layer can be realised, e.g. Hah et al. indicated that by adding 33% of pure butyl rubber (PIB) into Polydimethylsiloxan (PDMS), a transparent, flexible encapsulant with high moisture stability can be formed [33].

In [35], a bioresorbable polymer solution (poly lactic-co-glycolic acid, PLGA) was dropped as an encapsulation layer on top of a screen printed flexible radio frequency (RF) antenna for wireless devices. The PLGA overcoat protects the conductive particles from direct contact to the air and water. Cazalé et al. casted on an inkjet printed electric platform with PVC and dropped the formulated PVC solution to form a Na^+-sensitive sealing PVC membrane in a potentiometric microsensor for sweat analysis [34]. In [30], a SU-8 layer was spin-coated on a flexible field effect transistor (FET). The FET can work over 9 days in air and over 65 hours in water stably, which has shown good air stability and water resistance of the SU-8 encapsulation layer. Oh et al. fabricated a PDMS encapsulated transistor, and the PDMS encapsulation layer was formed by spin-coating. This work also indicated that by adjusting the thickness of the encapsulation, a neutral axis position for the conductive layer can be established to maintain the flexibility of the transistor [32]. Khan et al. deposited a thin layer of a fluoropolymer using spin-coating to encapsulate the inkjet printed flexible gold traces. The resistance of the gold traces was monitored via bending to the radius of 5mm and 10mm, and twisting to an angle of 30°. The resistance data remained stable during the bending and twisting test [36]. Kim et al. fabricated a wearable screen printed salivary uric acid mouthguard biosensor and the DuPont 5036 dielectric paste was screen printed on the sensor to confine the electrode areas [6]. In [25], the Ecoflex encapsulation layer was screen printed on the textile strain sensor, which can be used on a glove to detect the finger motion. The strain sensor consists of interface layer, conductive layer and encapsulation layer. All layers were fabricated by screen printing. In this work, waterproof performance of the Ecoflex encapsulation layer was confirmed by demonstrating that after an hour of immersion in water, the LED sample still worked well. Furthermore, in stretching, bending, folding , twisting and dynamic endurance tests, the strain sensors have shown excellent stretchability of 70%. It can be bent to the radius of 1.5mm, and withstand dynamic stretching and bending endurance tests of 10,000 cycles. Kim et al. demonstrated a wearable temporary screen printed tattoo-based electrochemical sensor for the real-time monitoring of Zn^{2+} in human perspiration. A transparent insulator was screen printed on the surface of the electrode pattern to confine the electrode and contact areas [13]. Moya et al. demonstrated the fabrication of flexible all-inkjet-printed dissolved oxygen sensors in ambient conditions and without the need for a clean room environment. In this work, a printable SU-8 ink was inkjet printed as passivation layer onto the sensor devices. This all-inkjet-printing approach shorts the processing time and enables rapid prototyping [26]. In [27], a layer of silicone rubber was inkjet printed to cover an entire direct ink written supercapacitor.

4 Conclusion

In this paper, we have discussed the encapsulation requirements of the printed wearable medical devices. Materials and encapsulation approaches such as barrier foil lamination, thin film encapsulation and printable encapsulation were demonstrated. Barrier foil lamination and thin film encapsulation can provide a good protective performance but they have their own drawbacks or limitations. For instance, by using barrier foil lamination, a 3D surface cannot be well encapsulated. For thin film encapsulation, an additional equipment like ALD reactor or a vacuum chamber is needed. Thus, it is concluded that integrating the solution-processed encapsulation with compatible materials into the printing process can be a novel fabrication approach for printed wearable medical devices. Applications were given that illustrate the potential of this encapsulation approach.

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