Shining Light on Organic Solar Cells

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Organic solar cells have come a long way from fundamental considerations of charge carrier dynamics in organic semiconductors to devices with laboratory power conversion efficiencies exceeding 17% and first power harvesting installations. Despite this story of success, these days, the scientific community witnesses a shift of research effort to other solar concepts, leaving behind a high-potential solar technology with better applicability forecasts than ever before. Very compelling reasons still exist why organic solar cells can become the solar technology of the future that offers design versatility and enables unprecedented applications while offering the lowest energy payback times and ecologic sustainability. This perspective article highlights why organic solar cells remain a research field of the highest socioeconomic relevance, which challenges remain to be overcome in the future, and how organic solar cells can make a difference in the future energy landscape.

1. Introduction

In 2017, the Karlsruhe Institute of Technology introduced their *Solar Glasses* at the *Hannover Messe*, which is the leading industry fair in Germany, to showcase integrated light harvesting for energy supply to mobile applications.[1] Semitransparent (see-through) organic solar cells were implemented as shading lenses of sunglasses with their color designed to match the chassis (**Figure 1**a). Although the produced energy was "only" used to monitor the illumination intensity and the temperature, this demonstration of the unique features of organic solar cells strongly reverberated in the international media and visitors enthusiastically appreciated the new opportunities. The most common question was when the versatile organic solar cells will become available at retailers to be used as camping gear, in model making or for powering a variety of mobile applications.

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Indeed, the Solar Glasses were a convincing application of organic solar cells, featuring their semitransparency, their applicability to arbitrary surfaces, their excellent lowlight performance, and their design opportunities in form and color. The overwhelming echo paired with many ideas on their fields of application gave some prospect of the market-pull that an introduction of organic solar cells to consumer products may foster. Their integration into rather expensive lifestyle products may conceal the initially high production costs of organic solar cells, before increasing mass production would reduce their price. Likewise, enthusiasts of camping and model making will be happy to pay some extra for the realization of features that cannot be supported by the 'old bull' silicon photovoltaics.

While mobile applications may mark a first market-entry point for organic solar cells, their full potential and the lowest fabrication cost will only become available in large-scale solar module production. The very same features and the very same toolbox that render organic solar cells attractive for the consumer market can be used to apply solar cells for power harvesting in yet unused spaces. Classical silicon solar cells, which vastly dominate the market due to their very good power conversion efficiencies (PCEs) and reliability, are commonly installed in huge solar power plants and on rooftops where the building structure can support their weight. The constantly increasing demand of photovoltaic energy will require the exploitation of more and more space to mount solar modules. Instead of using precious agricultural crop land, future photovoltaic installations will better expand into already sealed urban areas such as roofs of factory buildings, which often cannot support heavy silicon solar cells, overhead glazing, or building facades. Combining solar energy harvesting with architectural features, however, would call for lightweight solutions which are flexible in design and color. Semitransparent organic solar cells could even be implemented as shading elements in glass facades, as shown in Figure 1b. First-principle demonstrations of facade integration and versatile design can be viewed in many places with the most prominent arguably being the *Solar Trees* of the German pavilion at the World Expo in Milan, 2015.[2] Other applications featuring the unique properties of organic solar cells include heat shielding of windows[3] or power supply for greenhouses.[4,5]

Despite the intriguing properties of organic solar cells, after more than two decades of intense research by academia and industry, nowadays, the scientific community witnesses a strong decay of research efforts on organic solar cells which is driven by severe cuts in funding budgets and the rise of perovskite solar cells. While it is certainly true that the expectations in organic solar cells
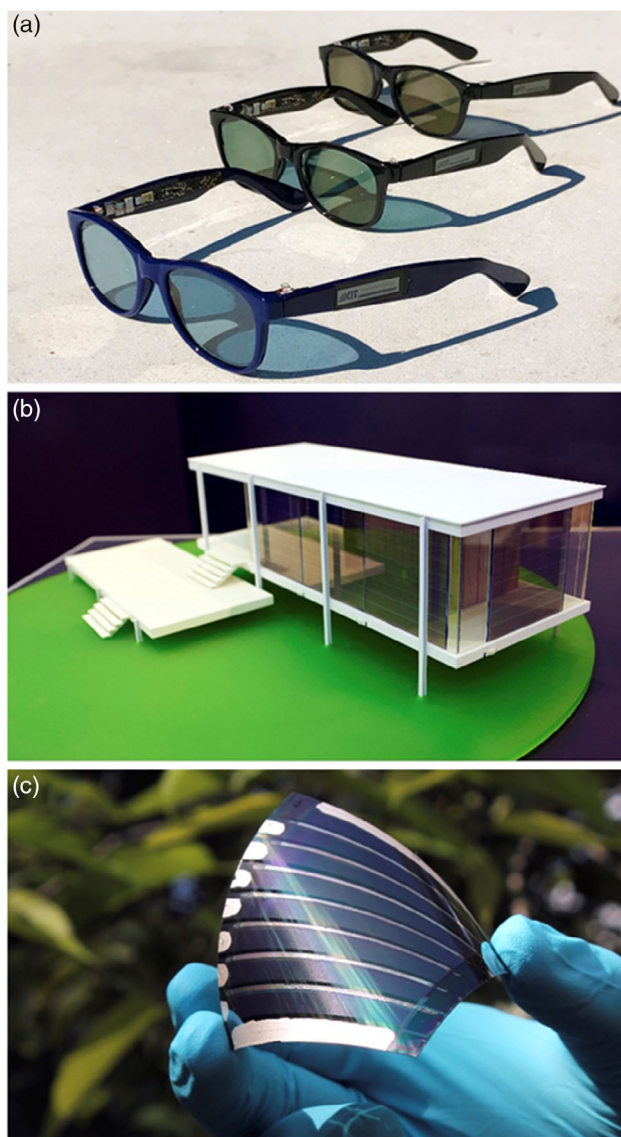
Figure 1. a) The Solar Glasses feature two semitransparent organic solar cells as lenses which can harvest sufficient energy, e.g., for mobile sensing applications, even under lowlight conditions (indoors). The color of the solar cells can be chosen to match the color of the chassis. Reproduced with permission, Copyright KIT. b) Likewise, semitransparent solar cells can be used as shading elements in glass facades as demonstrated in this model house. Reproduced with permission, Copyright KIT. c) Their mechanical flexibility, their freeform design, and their low weight render organic solar modules perfect enablers for novel applications. Reproduced with permission.[1] Copyright 2017, Wiley-VCH.

were very high, fueled by too ambitious research plans and too optimistic promises, it is also true that organic solar cells have come a long way, gradually maturing toward a unique solar technology serving their own fields of applications. Ironically, recent budget cuts have coincided with some of the most important breakthroughs in the field, such as the introduction of high-performance nonfullerene acceptors (NFAs), producing higher PCEs and enhanced device stabilities, and concepts for large-scale and eco-friendly device fabrication, bringing the technology closer to market.

Alexander Colsmann studied physics at the Ludwig-Maximilians-Universität in Munich, where he received his diploma in 2003. In 2008, he received his Ph.D. in electrical engineering from the University of Karlsruhe (TH). Since then he has been leading the organic photovoltaics research group at the Karlsruhe Institute of Technology (KIT), exploring printable organic and perovskite solar cells as well as OLEDs. In 2016, he accomplished his habilitation. He is a spokesperson of the KIT Energy Center and member of the board of directors at KIT's Material Research Center for Energy Systems.

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Christian Sprau studied electrical engineering and information technology at the Karlsruhe Institute of Technology (KIT) and received his bachelor's and master's degree in 2011 and 2014. He was awarded his Ph.D. from KIT in 2019. In his thesis, he focused on the characterization of novel semiconductors for organic solar cells and advancing their eco-friendly processing. His research interests include all aspects of organic photovoltaics, spanning from fundamental loss mechanism over novel materials and device architectures to industrial processing and applications.

Therefore, this perspective article will discuss why organic solar cells can still be considered a unique technology and readjust some targets for future organic photovoltaics research and implementation. Two schools of organic photovoltaics exist: one utilizes polymers for light harvesting and their deposition from solution, whereas the other deposits smaller molecules in vacuum processes. This article deliberately focuses on the former, but most considerations also apply to the latter.

2. Progress in Organic Solar Cell Performance

It was long believed that the PCEs of organic solar cells are intrinsically limited to about 10%,[6] but recent developments have exceeded expectations and have shown pathways to overcome this
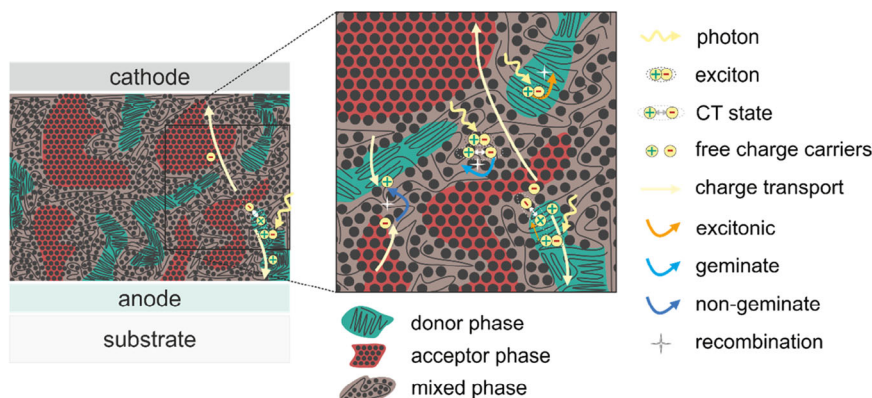
Figure 2. Working principle of a polymer:fullerene bulk-heterojunction. Light is absorbed on the polymer, upon which an exciton is generated. The exciton dissociates into the CT state between the polymer donor and the (fullerene) acceptor from which it further dissociates into free charge carriers. Recombination can occur from the excitonic state, from the subsequent CT state (geminate recombination) or when two opposite charge carriers meet on their way to the electrodes (nongeminate recombination). Adapted under the terms and conditions of the CC BY-SA 4.0 license.[7] Copyright 2019, KIT.

limitation. Archetypical organic solar cells comprise blends of polymers and functionalized fullerenes (bulk-heterojunction), as shown in **Figure 2**. Upon the absorption of sunlight on the polymers, strongly bound excitons are formed. The energetically more favorable states on the fullerene trigger an electron transfer from the polymer (electron donor) to the fullerene (electron acceptor), leaving behind a hole on the polymer. Then the charge carriers migrate via the respective material domains to the electrodes. To optimize both at the same time, exciton dissociation and charge carrier transport, the morphology of the blend is crucial. In the past, PCEs were mostly enhanced by lowering the optical energy gaps E_g for a better match of the polymer absorption with the solar spectrum and by adjusting the charge carrier transport energies of the two bulk-heterojunction compounds for enhanced open-circuit voltages (V_{OC}). As shown in **Figure 3**, one of the most important breakthroughs in polymer design was the implementation of copolymers (e.g., poly[2,6-(4,4-bis-(2-ethylhexyl)-4*H*-cyclopenta [2,1-*b*;3,4-*b*′]dithiophene)-*alt*-4,7(2,1,3-benzothiadiazole)], PCPDTBT[17]) which exhibited smaller E_g than the previously used homopolymers (e.g., poly[2-methoxy-5-(3′,7′-dimethyloctyloxy)-1,4-phenylenevinylene], MDMO-PPV or poly(3-hexylthiophene-2,5-diyl), P3HT). Modifications of the side chains of the polymers provided handles to fine-tune the energy levels, to change the solubility, and to control the molecular aggregation, the latter
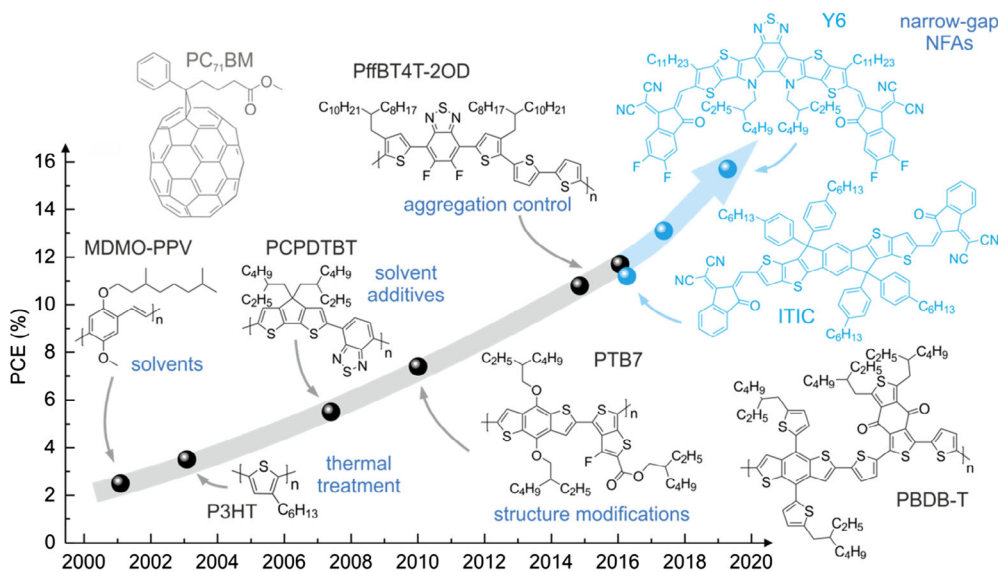
Figure 3. The most important milestones in the conceptual development of novel light-harvesting polymer donors and, lately, acceptors for implementation in organic solar cells.[8–16] Gradually increasing PCEs were achieved mostly by the continuous development of polymer donors which were blended with functionalized fullerenes. In recent years, the employment of novel NFAs yielded even higher PCEs and changed the focus of organic semiconductor developments. Key findings on processing conditions (choice of solvents, solvent additives, aggregation control) were similarly important as the development of the light-harvesting semiconductors themselves in order to adjust the bulk-heterojunction morphology and to yield high PCEs. Adapted under the terms and conditions of the CC BY-SA 4.0 license.[7] Copyright 2019, KIT.

improving domain formation and charge carrier transport. Today, the best performing polymer:fullerene solar cells achieve PCEs of 11.7%.[13] More recently, the device performance was advanced by introducing NFAs. While fullerenes absorb only weakly in the visible spectrum but rather strongly toward the ultraviolet (UV), recent NFAs were designed to have a smaller E_g than the donor, thus expanding the absorption of the blend toward the infrared spectrum. At the same time, the transport energies of the NFAs can be controlled for shallower lowest unoccupied molecular orbitals (LUMOs) and therefore for an increased V_{OC} of the corresponding solar cells. Based on these synergistic effects as well as good charge carrier transport and low charge carrier recombination, the best performing polymer:NFA solar cells, today, yield PCEs up to 17%,[16,18–20] and even semitransparent devices can produce PCEs beyond 10% at an average visible transmission of 37%.[21] On the downside, to date, the synthesis of NFAs is rather laborious and produces only moderate yields. To translate NFAs to industrial applications, more facile synthetic routes with much better yields and therefore much lower production costs are needed.

In contrast to their inorganic counterparts, common organic solar cells suffer from significant energy losses, typically quantified as the difference of E_g (determined from the absorption onset of the blend) and e · V_{OC}. In the past, these energy losses have been attributed in first place to energy-level offsets between the donor and the acceptor phases which are necessary to overcome the exciton binding energies for efficient charge carrier separation. Today, this picture has been refined, breaking down the energy losses into different contributions. In this picture, the charge-transfer (CT) state energy plays an important role, which represents a coulombically bound electron–hole pair with the electron being located on the acceptor and the hole on the donor. The difference of E_g and E_{CT} is often interpreted as the driving force for charge carrier separation. From the CT state recombination occurs, which directly influences the V_{OC} of the solar cell.[22–24] Interestingly, some recent examples demonstrated high free charge carrier generation efficiencies in blends where E_{CT} is close to the energy gap of the neat donor (or acceptor). In such blends, the driving force for charge carrier separation is negligible,[14,25–27] effectively disabling the (to date) most dominant loss mechanism in organic solar cells. Still, the remaining energy losses are on the order of 0.6 eV. Unlike most other types of solar cells, in organic solar cells, nonradiative recombination dominates the loss mechanisms. Reducing these nonradiative energy losses is therefore the key target to further increase the PCE of organic solar cells toward the single-junction limit. Recently, a linear relationship between the energy of the CT state and the amount of nonradiative energy losses has been observed and linked to the energy gap law:[28–30] in a nutshell, the lower the energy of the CT state is, the higher are the loss contributions from nonradiative recombination. But even if the nonradiative recombination losses cannot be reduced substantially because they turn out to be intrinsic to organic semiconductors, the theoretic maximum achievable PCE of single-junction organic solar cells would be around 25%.[28] Assuming more realistic quantum efficiencies and fill factors, the solar cells would still exhibit PCEs up to 20%.[28] To reach this goal, the identification of donor-acceptor combinations with negligible driving forces but high charge carrier generation is pivotal. The design of novel materials needs to be guided by understanding the role of morphology, phase purity, exciton and CT delocalization, mixed phases, energy cascades, molecular orientation and the relative permittivity.

The most promising concept to improve the PCE of organic solar cells beyond the single-junction limit is the tandem architecture, in which two solar cells with spectrally complementary absorption are monolithically stacked, connected by an intermediate recombination zone. This concept reduces the thermal losses of excess energy upon exciton relaxation from higher energetic states to E_g. In the wide-gap subcell of the tandem device, blue photons produce a higher V_{OC} which would be lost in narrow-gap solar cells. Using NFAs, recently, a record PCE of 17.3% was reported,[31] marking significant progress over previous state-of-the-art, whereas optimistic semiempirical predictions lure with 22%.[31] The tandem concept can be extended to three, four, or even more junctions for even lower energy dissipation, but the increasing technical complexity questions their practical use.[32,33] Whether or not tandem solar cells will be the mainstream implementation for organic solar cells will remain a question of performance gain versus increasing device complexity, and may be answered differently for solution-processed or vacuum-processed organic solar cells. Another concept to improve power harvesting by an enhanced coverage of the solar spectrum uses ternary blends of organic semiconductors which, in contrast to tandem solar cells, would not improve V_{OC} though.[19,34,35]

Although, nowadays, the PCEs of organic solar cells have exceeded many predictions and projections, their nominal performances still lag behind established photovoltaic technologies. However, nominal PCEs are always measured under standard test conditions (AM1.5 direct sun light, 25 °C) which most solar cells are rarely exposed to during operation. In real-life conditions, most solar cell technologies exhibit a negative temperature coefficient, i.e., a reduction of the PCE toward higher operation temperatures due to a reduction of E_g and a concomitant decrease in the V_{OC}. In contrast, some organic solar cells gain from slightly higher photocurrents and higher fill factors at elevated temperatures of up to 50 °C which can overcompensate the V_{OC} losses, resulting in slightly positive overall temperature coefficients.[36,37] At low light intensities, organic solar cells can furthermore benefit from reduced recombination losses,[38] and ohmic losses in the electrodes become negligible.[1] Likewise, organic solar cells and all other solar technologies have to be assessed differently, if the irradiation spectrum is modified away from the AM1.5 standard, because the PCE depends on the spectral overlap of radiation and external quantum efficiency of the solar cell. For example, under modern light emitting diode indoor illumination which, for energy efficiency reasons, is mostly restricted to visible light, organic solar cells show a significant relative performance gain whereas, e.g., silicon solar cells exhibit reduced performance.[39,40] Therefore, the question which solar technology is the best may be answered differently for different applications, environments, and working conditions. In general, under real-life conditions, the performance gap between, for example, silicon solar cells and organic solar cells will be smaller than under standard test conditions, which put the performance of organic solar cells into a different perspective.

3. Long-Term Device Stability

It is worth dispelling the myth that organic solar cells are intrinsically unstable. Although lifetimes of organic solar cells still lag behind modern and highly optimized silicon solar cells, the semiconductors used in organic solar cells can be compatible with many years of operation. Recent reports estimated the intrinsic extrapolated lifetime of an organic solar cell to about 10 years.[41] While it is true that this device lifetime can only be achieved with certain device architectures and light-harvesting materials, it clearly demonstrates that the goal of long-term stable solar cells is achievable with organic semiconductors.

Depending on the envisaged applications, the long-term stability of organic solar cells may be even more critical than their PCEs. While mobile applications such as telephone chargers require high solar cell performance for fast charging, their lifetime does not have to exceed the lifetime of the phone itself. In contrast, solar building skins require best long-term stabilities because the replacement of highly integrated solar installations is rather laborious. Improving the device stability is a complex task and requires different solutions for different kinds of solar cells. Stable materials under continuous lighting are of highest importance for any solar cell. Classical polymer:fullerene solar cells show strong photooxidation of the fullerene[42] and fullerene dimerization.[43] In addition, changes to the bulk-heterojunction morphology, i.e., the separation of material phases toward a thermal equilibrium, are critical to the device stability and can be triggered by elevated temperatures, for example, during operation in sunlight.[44] In particular, polymer:fullerene blends suffer from fullerene crystallization over time, enhanced by the temperature during operation.[45] Mitigation measures to suppress fullerene crystallization have been developed, using third compounds inside the bulk-heterojunction[46,47] or cross-linking.[48,49] NFAs seemed to enable much better solar cell stabilities than fullerenes—currently setting the record with extrapolated device lifetimes of $T_{80} = 10$ years (80% of the initial PCE).[41] Further progress on the bulk-heterojunction stability can be expected if the multiphase morphology can be fixed in its optimal state. Here, the miscibility of the donor and the acceptor phase plays an important role.[44,50–52]

Apart from the internal demixing of the bulk-heterojunction components, the solar cell lifetime is also affected by external processes such as UV irradiation or oxygen and water ingress. The former can be suppressed by using UV blocking layers, and the latter requires excellent encapsulation that withstands changing weathering conditions. Commonly accepted oxygen and water vapor transmission rates (OTR and WVTR) are on the order of $10^{-3}\,\mathrm{cm^3\,m^{-2}\,day^{-1}\,atm^{-1}}$ and $10^{-4}\,\mathrm{g\,m^{-2}\,day^{-1}}$, respectively.[53] Today's high-performance add-on encapsulation foils use alternating layers of polymers to maintain the mechanical device flexibility and dense oxides to provide oxygen and water barriers. In the future, the currently high costs of such advanced encapsulation concepts may be reduced by printing of the layer stack directly atop the solar cell.[54] In either case, concepts for edge sealing will be needed to avoid lateral ingress of oxygen or water from the edges of the solar cell.

4. Organic Solar Cells and Their Environmental Footprint

The probably most intriguing advantage and unique selling point of organic solar cells is their positive environmental track record all along the value chain. While light-harvesting polymers and NFAs are highly specialized semiconductors and their synthesis incurs high production costs, only very little material is needed to deposit the ultrathin absorber layers—1 g is sufficient to fabricate about 10 m² of solar cells. Notably, the majority of organic semiconductors for light-harvesting in solar cells do not contain any rare elements, rendering the technology vastly independent of critical supply chains which otherwise indeed would be a showstopper for this technology. This also applies to many of the other functional layers in organic solar cells such as hole or electron transport layers or interfacial modifiers. Being independent of rare elements will be gradually more appreciated during the next couple of decades when the supply of certain elements will become critical. Not only are organic semiconductors free of rare elements, they are often also nontoxic which allows an unproblematic end-of-life disposal. These days, concepts are being developed to synthesize light-absorbing polymers using eco-friendly synthesis,[55] e.g., by direct arylation polymerization to replace Stille coupling and therefore to omit toxic catalysts.[56] Although direct arylation provides several pitfalls for the synthetic procedure, and although, as of today, not all polymers can be synthesized using nontoxic chemistry, the results that have been reported so far are very encouraging for a future sustainable polymer synthesis. Attempting to use more natural educts for the synthesis of organic semiconductors in the future would add further sustainability to the technology. The eco-compatibility is not only an asset of the organic semiconductors but also of their processing by large-area printing and coating processes. While, initially, light-absorbing layers were deposited by spin coating from chlorinated aromatic solvents in laboratory processes, meanwhile, less hazardous or even non-hazardous agents can be used. For example, the commonly used 1,2-dichlorobenzene which was often paired with the solvent additives 1,8-diiodooctane or 1-chloronaphthalene for better morphology formation, all of which are rated strongly hazardous, can nowadays be replaced by less hazardous o-xylene, anisole, or limonene,[57] and even all-eco-friendly solvent additives such as p-anisaldehyde have been used successfully.[58] Lately, the sequential deposition of layers of donors and acceptors, creating the bulk-heterojunction by interdiffusion, pointed out a new path for the formation of optimal morphologies from nonhazardous solvents.[59] The use of eco-friendly processing agents will also reflect upon the fabrication costs, as the large-scale evaporation of toxic and eco-harming solvents would require extensive and expensive solvent vapor capturing facilities and work space safety. In contrast, when using eco-friendly solvents, standard printing and coating facilities would become available for the fabrication of solar cells which again reduces the production costs. More recently, it was demonstrated that even nonsolvents such as water or alcohol can be used to fabricate organic solar cells if the organic semiconductors are dispersed as nanoparticles in the agents.[60–62] Here, two approaches exist: on the one hand, organic nanoparticle dispersions are formed via mini-emulsions.[61,62] The advantage of
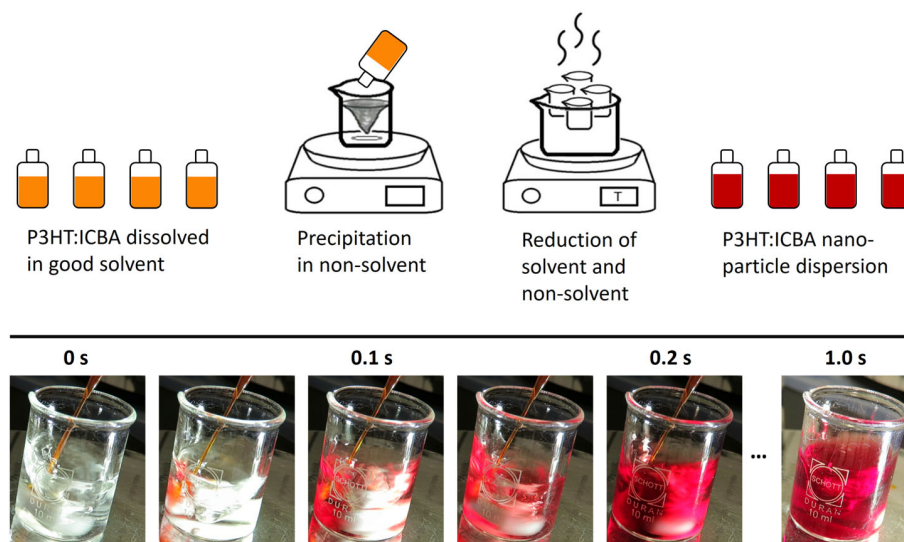
Figure 4. Surfactant-free P3HT:ICBA nanoparticle synthesis by precipitation in a lab-beaker. The P3HT:ICBA mixture is dissolved in chloroform. Upon injection into ethanol, the solubility of the P3HT:ICBA mixture is reduced immediately, leading to the formation of bulk-heterojunction nanoparticles within less than 1 s as visualized in the image sequence. The color change from the orange solution to the purple dispersion indicates aggregation of the P3HT. The chloroform is then evaporated from the dispersion.

this process is the broad applicability to different semiconductors and semiconductor mixtures, whereas the disadvantage often lies in the stabilizing agents that remain in the photoactive layer where they hamper the device performance. On the other hand, nanoparticles can be formed by precipitation omitting any stabilizers, as shown in **Figure 4**.[60] In this case, the polymer:fullerene mixture is dissolved in chloroform and injected into ethanol. The miscibility of ethanol and chloroform leads to an immediate reduction of the solubility of the polymer and the fullerene and therefore the formation of nanoparticles. The respective nanoparticles already exhibit a close-to-ideal bulk-heterojunction morphology in dispersion,[63] but, so far, the approach is limited to the use of the archetypal semiconductor blend of P3HT and indene-C_{60} bisadduct (ICBA). If a general design rule was developed to formulate nanoparticle inks from arbitrary semiconductors omitting stabilizers, this would fundamentally change the way organic solar cells are fabricated. Notably, the use of chloroform or similar agents during nanoparticle synthesis does not conflict with the goal of an eco-friendly device production as the evaporating chloroform can be captured during synthesis in a closed chemical environment which is different from toxic solvents evaporating during large-scale coating processes. Although the use of aqueous dispersions requires process modifications for better ink wetting during thin-film deposition and the often used ethanol should be better replaced by less inflammable dispersion media, this nanoparticle approach appears highly rewarding and worth future research efforts. The beauty of organic nanoparticle dispersions does not only lie in the usability of eco-friendly solvents. The separation of solution processing from the need of solubility would allow to sequentially deposit an arbitrary number of functional layers on top of each other,[64] which is currently limited by the availability of a sufficient number of orthogonal solvents. Altogether, the printing of ultrathin functional layers from eco-compatible solvents and the smallest material consumption will warrant

lowest energy payback times between days and a few months[65] and concurrently unrivaled CO_2 footprints.[66] Higher energy payback times as they are known, in particular, for silicon solar cells effectively reduce the net energy gain during the solar cell lifetime. Likewise, the ultrashort energy payback times of organic solar cells further reduce the energy yield gap to the established solar technologies. Although often forgotten, this envisaged all-eco-friendly cradle-to-grave lifetime cycle makes organic solar cells stand out from all other solar technologies, and it is a real asset when ramping up the industrial device fabrication in a socioeconomic environment of fading resources, energy resourcing, and climate change.

5. Process Scaling by Printing

Most research laboratories use solution processing for the fabrication of organic solar cells because spin coating is an easy-to-implement laboratory process, whereas vacuum processing requires a rather elaborated laboratory infrastructure such as clustertools. The solution processing of organic solar cells aims at industrial device fabrication by printing and coating. Research articles often motivate their work on solution processed organic solar cells with reduced fabrication costs from printing. However, this motivation is somewhat overstated. Technically, large-scale printing and coating requires a lot of efforts, e.g., the alignment of subsequently deposited layers or structuring processes (registration). When producing tandem or even triple solar cells with many functional layers, vacuum processing may turn out superior to printing or coating as solution processing is limited by the choice of solvents and the solubility of the materials. In fact, estimations have shown that, on large scale and at high throughput, the fabrication costs of organic solar cells are rather determined by the costs of the highly specialized

organic semiconductors, the substrate, the electrode materials, and the encapsulants than by the deposition method.[67]

The beauty of printing processes lies in other production parameters rather than in costs. Printing allows the flexible design of organic solar cells to match the requirements of specialized photovoltaic applications such as facade integration or consumer electronics. For example, ink-jet printing allows a most flexible change of the shape of the solar cells by simply uploading the required pattern onto the production system.[68] In contrast, vacuum processing would require a change of shadow masks each and every time a customer requires a different solar cell layout. Likewise, the rather low energy consumption of printing and coating processes reflects on the lower energy payback times. Not least, to date, most of the modern NFAs, which enable highest PCEs, can only be processed from solution. Belonging to the class of oligomers with rather high molecular weights, most high-performance NFAs would decompose when heated up in vacuum.

Whether printing and coating or vacuum sublimation will be the ultimate method of choice to fabricate organic solar cells is debatable and will depend on future research outcomes and the feasibility of technology implementations. To date, industrial cases for both exist. If a choice is made for solution deposition, it may be advisable to replace the vacuum processes that are used in research laboratories to apply the conductive electrodes, by solution processes as well. Latest efforts targeted the replacement of indium tin oxide (ITO) electrodes and metal counter electrodes, e.g., by conductive polymers,[69] often supported by printed silver[70] or random metal nanowire[71] grids, as exemplified in **Figure 5**. The generally reduced conductivity and increased resistivity of printed electrodes requires a smart current management in large-scale solar cells, which is typically accomplished by implementing a monolithic interconnection: as shown in **Figure 6**a, the series connection of the individual solar cells increases the voltage of the module while reducing the photocurrent, the latter of which accounts for resistive losses in the electrodes. Here, laser scribing can be used to subdivide solar modules into smaller solar cells. As the area that is used for interconnection is lost to the photovoltaic power conversion
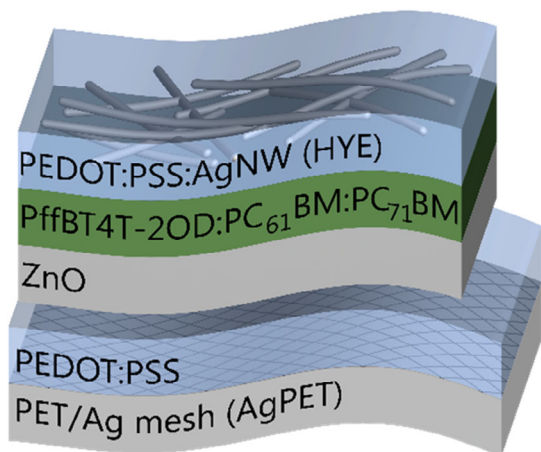

Figure 5. Exemplary illustration of an all-solution processed semitransparent solar cell comprising a printed silver-mesh bottom electrode and a silver-nanowire top electrode, both supported by a conductive polymer. Reproduced with permission.[70] Copyright 2016, Wiley-VCH.

process ("dead area"), high-precision lasers will provide an advantage over mechanical scribing in minimizing areal losses and maximizing solar power harvesting.[72] To date, laser scribing is performed utilizing pulsed ns- and ps-laser systems. While such systems work well for the structuring of other (inorganic) thin-film solar modules, organic solar cells with much more sensitive and even thinner layers may be better manipulated by using pulsed fs-laser systems (Figure 6b) which are becoming much more popular and which produce less detrimental side effects (Figure 6c).

6. Conclusions

So—what comes next? Will organic solar cells sustain their case in the photovoltaic market or were they only a two-decade curio and the field will move on? The targeted objectives of future organic solar cells are obvious: on the fundamental scientific side, further progress on increasing the organic solar cell PCEs will be expected from new organic compounds such as nonfullerene acceptors or smart device architectures such as multijunction solar cells. Finding concepts to further reduce energy losses will directly translate into higher V_{OC} and therefore into improved PCEs, setting perspectives for PCEs of more than 20%. Likewise, on the industry side, pivotal tasks have to be mastered to foster the market uptake. For example, how will solar windows be installed? As of today, hardly any applicable standards exist. Will an electrician install the photovoltaic windows, who is mostly not an expert for window installation, or rather a window manufacturer, who is not knowledgeable on electrical installations? Or will new job qualifications be needed to cope with the new demands of the two merging fields of building construction and solar power harvesting?

Organic solar cells have reached a level of maturity, which allows the support of first pilot applications with requirements that can only be satisfied by the versatile design opportunities of organic solar cells. With PCEs constantly well beyond 10% and lifetimes of several years, they have advanced to an enabler of new markets. During the past two decades, the field has progressed slower than initially expected, but sometimes scientific progress requires patience. The past has taught that timelines are difficult to estimate but the strong future needs for photovoltaics motivate a long-term commitment. All predictions for future energy scenarios sustain a most significant share of photovoltaic energy harvesting. This share is so huge that it will be more than critical for any future energy supply scenario. In particular, developed industrial countries have to ensure building their own capacities along the photovoltaic value chain to avoid dependencies on other countries as they are in place for oil today. The photovoltaic technologies used must comply with the particularities of the respective countries. Due to the dense population in developed industrial countries, a photovoltaic technology better makes use of the already sealed urban areas, which is where organic photovoltaics can play an important role. But, notably, also developing countries without reliable energy supply infrastructures can build on the flexible design and the lightweight of organic solar cells to power off-grid applications.

These days, organic solar cells face strong competition from perovskite solar cells, which have grown on the strong shoulders
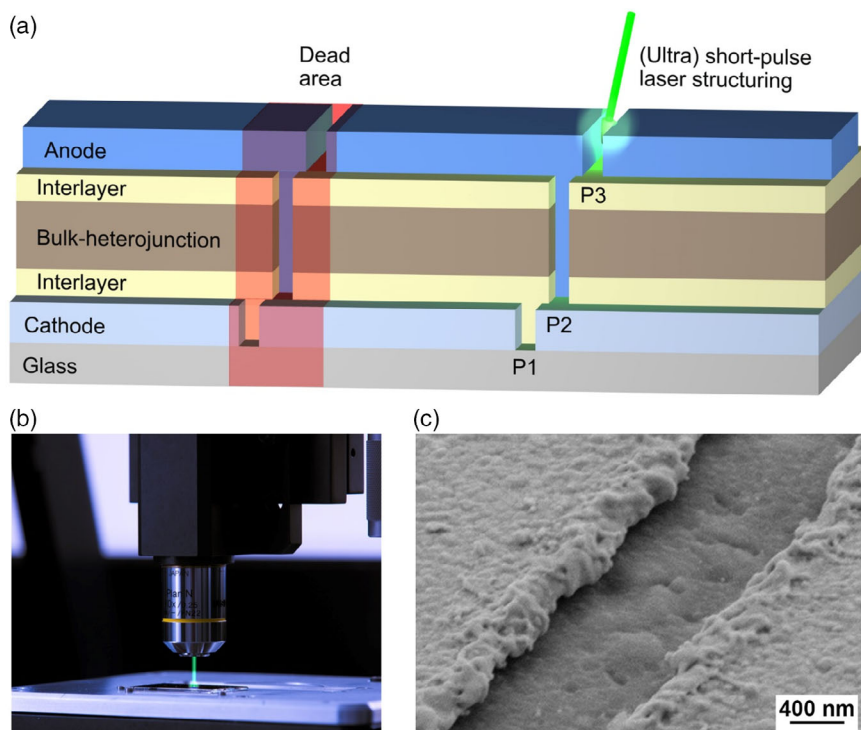
Figure 6. a) The subdivision of and interconnection within (organic) thin-film solar modules is accomplished by the ablation of three lines (P1, P2, and P3) which effectively establish an electrical connection between the top electrode of each solar cell and the bottom electrode of the adjacent solar cell to the right. b) Pulsed fs-laser work station for the high-precision manipulation of organic solar cells and therefore the minimization of the interconnection area ("dead area"). c) Electron microscopy image of a 1 μm wide line, scribed into a silver electrode with a high-precision pulsed fs-laser. Reproduced with permission, J.A. Fragoso Garcia, KIT.

of organic photovoltaics over the last couple of years and still continue to grow, adopting their device architectures, many of their functional materials and their fabrication processes. While perovskite solar cells are extraordinarily remarkable in their working principle, today delivering PCEs beyond 25%,[73] they also have to stand their case for better device stability and to find solutions to handle or mitigate the comprised toxic compounds. Competition is good and drives the field forward, but active cannibalism of competing photovoltaic technologies as it is sometimes observed these days, damages the diversity and knowledge within the field, which is the natural DNA for progress. We do need the cross-fertilization of different photovoltaic technologies as it was successfully implemented, e.g., on perovskite solar cells in the past. Maybe different photovoltaic technologies will also identify different key applications in the future which we do not even think of today and for which they are unique.

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Conflict of Interest

The authors declare no conflict of interest.

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