Organic Photovoltaics: Status and Perspectives

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Abstract

Organic solar cells have a great potential in establishing a broad technological basis to provide a reliable and sustainable energy supply. Their properties complement classic silicon solar cells in various aspects, regarding e.g. their flexibility, light weight, adjustable color and transparency, and their positive temperature dependence and improved low-light performance. For many applications, these properties make them an attractive option in spite of the lower absolute power output per area compared to classic solar cells. This article gives an overview over the status of research and development of organic photovoltaics, outlines the physics behind the photovoltaic energy conversion in organic solar cells, and describes probable perspectives for the further development. Technologically, the focus of this article is on vacuum deposited small molecule semiconductors, though the comparison to solution processed devices is drawn wherever relevant. The general discussion and physical basics are discussed independently of the fabrication technique.



Fig. 1: Flexible organic photovoltaic module. Solar film HeliaFilm® copyright Heliatek, Photographer: Baldauf&Baldauf

Introduction

Photovoltaics are one of the key elements of a long-term sustainable energy supply, directly converting the optical energy from sunlight into technically usable electric energy. Compared to classic solar cells consisting of inorganic semiconductors¹, organic photovoltaics have a number of advantages which make them an attractive alternative for a number of applications and open up the possibility to use solar cells in places which are not commonly associated with photovoltaics today. Especially the possibility to produce flexible and extremely lightweight modules of adjustable color and transparency opens the way for applications in architecture and mobile applications. At the current stage, where commercial products with application-relevant device efficiencies start to enter the market [1], these modules cannot yet compete in terms of absolute module module efficiencies with the classic solar cells, of which they achieve approximately a half. Today, organic solar cells rather aim at entering market segments where classic solar cells are not a feasible option due to their mechanical or aesthetic constraints. Besides upscaling and cost reduction in the production, the major

¹ mainly silicon

frontiers in organic solar cell research remain the development of improved organic materials, mainly light absorbing materials, and reducing electronic losses by understanding and avoiding the predominant recombination paths for the photo-generated charge carriers.

Fabrication – classification

Talking about a photovoltaic technology which aims at producing solar cells to contribute to the general energy supply, the objective is the production on a large scale in the range of square kilometers in area. Such production has to be economically competitive, i.e. it must be realized at an as low as possible cost, both per area and per output power. This aim can be best achieved in a roll-to-roll process. For other applications of organic electronics, e.g. $OLED^2$ TV screens, where the requirement for a high lateral accuracy is more predominant, the competitive cost benchmarks per area are higher, and the required production volume is lower, batch-to-batch production of vacuum deposited devices is already today in commercial production. Roll-to-roll fabrication, in contrast, is just at the edge of commercial use.

Vacuum deposition and solution processing

In the fabrication of organic solar cells, two classes of production are distinguished: vacuum deposition and deposition from solution. In vacuum deposition, the organic materials consist of relatively small molecules which can be sublimed or evaporated without thermal decomposition of the molecules. This requirement imposes an upper limit for the molecule size respectively requires a rigidly bound molecular structure. The materials are available as solid powders, which are heated in a material source within a vacuum chamber to evaporate them. Upon evaporation, the molecules leave the source and are deposited onto the substrate, which is situated in the same vacuum chamber opposite to the source. This way, extremely smooth and homogeneous film can be achieved, and the thickness can be controlled with an accuracy in the range of 1 nm. The morphology of the layer is typically adjusted by selecting a suitable substrate temperature during deposition.

Deposition from solution, on the other hand, is closely related to classical printing technology. The organic materials are dissolved in a suitable solvent and this solution is brought onto the substrate, where the organic material remains while the solvent evaporates either during the deposition process or during the subsequent processing steps, e.g. heating. This deposition



Fig. 2: Schematic illustration of the two dominant technologies for the deposition of organic semiconductors: thermal evaporation in vacuum (left) and solution processing by printing or similar techniques (right).

² organic light emitting diode

technique does not impose a limit on the molecular size and allows for the usage of polymers, which are typically used in this case. In literature, polymer solar cells are often also referred to as plastic solar cells. The primary prerequisite for a material to be used in solution processing is a good solubility of the molecules. Then, deposition from solution provides additional handles to influence the layer morphology, e.g. varying the drying speed, using different solvents, or introducing additives into the solution.

Going along with the processing technique, also the available techniques for material purification differ. Regarding that material purity is an essential benchmark for any semiconductor technology, vacuum gradient sublimation represents a particularly powerful technique yielding very high material purity, typically exceeding the purity achieved in large-scale wet-chemical processes. Since it implies the evaporation of the semiconductor material in vacuum, it is usually not accessible for materials used in solution processed solar cells, but readily available for materials used in vacuum deposited devices.

Commercial perspective

A discussion about commercially competitive technologies needs to cover both the physical and chemical basics of cell design and the implications for large-scale production. In this context, only an outline about some prominent points shall be given. At first sight, printing is the technologically more advanced technique and seems more feasible for large-scale application. However, it brings along a number of drawbacks and lacks some of the advantages of vacuum processed solar cells. These partially complementary advantages have made the two technologies progress in a very competitive way. In vacuum processing, especially the high achievable degree of accuracy in layer thickness allows for a more straight-forward transfer from laboratory scale to production facilities. The subsequent deposition of many material layers in one production line is "only" a technical challenge for the design of the production line, but it does not impose additional constraints on the chemical or physical design of the cell. Blending ratios of mixed films, which are an essential part of highly efficient organic solar cells, as well as doping concentrations can be finely controlled, and this way, complex multi-layer stacks can be directly realized. During the deposition, no solvents are required, which in solution processing imply additional toxicological risks and subsequent cost for exhaust treatment. These, in turn, have to be compared to the effort of vacuum generation for vacuum processing. In the recent years, scientific solutions for many of these challenges have been found and concepts for up-scaling are being discussed on every major conference in the field. For the further development, an essential decision line will be the scalability of cost, i.e. which efforts scale with the production volume, and which are independent.

In summary, solution processing profits from printing technology with its extremely broad technological basis of expertise. Vacuum deposition, on the other hand, certainly requires larger initial investment, but promises a large potential for cost reduction in upscaling and imposes fewer constraints on cell design, allowing for faster upscaling of high-efficiency solar cell designs.

Functioning

Organic materials – commonly known for plastic-like materials or textiles – are typically considered as particularly good insulators rather than materials for electronics. Although from a scientific perspective this statement is highly generalized, it visualizes one of the most fundamental challenges in organic electronics: the requirement for extremely short path lengths for electronic transport to achieve reasonably low Ohmic losses in spite of the comparably low conductivity of the materials.



Fig. 3: Design of a module connecting stripe shaped organic solar cells in series. The scheme shows a cross-section through one of the cells (not to scale, substrate and encapsulation omitted). The real thicknesses are in the range of 100 nm, the stripe width in the range of 1 cm. In a semi-transparent module, the back contact is also made transparent. Photo (top) source: [1, Photographer Tom Baerwald, Berlin]

Device geometry

In organic solar cells, the required short transport lengths are realized by designing extremely thin thin-film devices³ between large-area contacts⁴ with the direction of current perpendicular to the surface. In the last decades, substantial progress has been achieved to improve the conductivity of organic semiconductors: Materials with strongly improved charge carrier mobilities are available, doping enhances the conductivity by several orders of magnitude, and especially for solar cell applications, the thickness limit can be partially compensated by the extremely strong light absorption of organic dyes. But the general limitation compared to inorganic semiconductors remains and the competition of the film thinness with other parameters is omnipresent in organic solar cell research.

Sandwiching the light absorbing layer between large-area contacts requires at least one of the contacts to be transparent towards the incoming light. This transparent contact – representing a field of research on its own – is characterized by the need for a simultaneous increase of optical transparency perpendicular to the substrate and lateral electrical conductivity parallel to the substrate. Today, the best results are typically achieved with solid indium tin oxide, fine metal networks, or thin metal layers.[3] Still, the residual resistance of all these solutions leads to electric losses scaling with the lateral size of a single solar cell. In large-area modules, this size limitation competes with the requirement for large active cell areas to minimize the relative share of unused area originating from the technologically required space between neighboring cells. The optimum geometry is typically a series of stripe-shaped solar cells next to each other with approximately one or few centimeters of stripe width, see Fig. 3.

³ on the scale of some tens or few hundreds of nanometers

⁴ on the scale of mm^2 to cm^2

Electricity from sunlight

The aim of photovoltaic energy conversion is the photo-induced creation of electron-hole pairs, their spacial separation and selective extraction at the two contacts of the solar cell. The opposing loss mechanism is the recombination of such photocreated electrons and holes, leading to the dissipation of their energy as heat inside the solar cell instead of the energy being extracted in the form of a technically usable electric current and potential. The solar cell's power conversion consequently efficiency is obtained as $\eta = p_{out} / I_{sun}$.⁵

In the following paragraphs, the process of converting optical energy into electric energy is summarized along the lines of the main equation defining the achievable output power per area p_{out} of an illuminated solar cell:



Fig. 4: Solution processed organic photovoltaic module (top) and a transparent conductive substrate separately (bottom). Picture source: [2]

$$p_{\text{out}} = j_{\text{MPP}} \cdot V_{\text{MPP}} = j_{\text{SC}} \cdot V_{\text{OC}} \cdot FF \tag{1}$$

In this equation, which is generally valid for solar cells, MPP denotes the "maximum power point", i.e. the point on the current-voltage (i-V) characteristic of the cell, where their product is maximized.⁶ The functioning of an organic solar cell is discussed on the basis of the three fundamental figures of the j-V characteristic, given on the right-hand side of Equation (1), further detailing the output power: The short-circuit current density j_{SC} is the current density generated by the solar cell in short-circuit without an external resistance. In common cases it equals the photo-current density j_{ph} , i.e. the current density which is generated by the illumination by sunlight. The open-circuit voltage V_{OC} is the photo-voltage which is achieved by the solar cell when no external current is extracted. These figures j_{ph} and V_{OC} constitute the maximum separately achievable output current density and output voltage of the cell. The fill factor FF finally is the measure, how far the MPP is from these values. It is a number between 0% and 100%, indicating which share of j_{ph} and V_{OC} can be simultaneously generated and, thus, utilized from the photovoltaic energy conversion. In summary, to obtain an efficient solar cell, all these three figures need to be as high as possible: the photo-current, the photovoltage, and the fill factor, each of them being a research task on its own, however, entangled among each other in various aspects.

⁵ The illumination intensity which is used for standardized solar cell characterization is the AM1.5 spectrum, regarded as representative for a sunny midday in temperate climate, with an intensity of $I_{sun} \approx 100 \text{ mW/cm}^2$.

⁶ In this context, variables are defined in such a way that photo-current and photo-voltage are both positive.

Generation of photo-current

The basis for photo-current generation is the absorption of sunlight, which is realized by the organic dyes constituting the core of every solar cell. Very colorful organic dyes can have extremely high extinction coefficients $> 10^5$ /cm in specific wavelength regions, facilitating good absorption even in very thin layers below 100 nm thickness. Still, the development of dyes with improved absorption (absorption strength and wavelength range) is one of the currently very active research areas in the field of organic photovoltaics.

In an organic dye, the absorption of a photon leads to a molecular electronic excitation, i.e. an electron is lifted onto a previously unoccupied molecular orbital, while the molecule as a whole stays electrically neutral. Molecules are typically arranged amorphously, with a low degree of order, or in a micro-crystalline arrangement, though even in crystallites the weak binding between neighboring molecules usually does not allow the formation of electronic bands at room temperature. Therefore, the electronic structure of a molecule within the layer very much resembles that of a single molecule. The minimum energy for the optical excitation from an electron in the neutral ground state is roughly defined by the energetic distance between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of the relaxed ground state of the molecule. These two orbitals, thus, represent the analog to the valence band and the conduction band in classic semiconductors. The excited molecule can now be regarded as a molecule with a missing electron, a hole, on the HOMO and an additional electron on the LUMO, i.e. as an electronhole pair on the organic semiconductor molecule. This electron-hole pair, respectively excitation, can be transferred to neighboring molecules, giving it the nature of a quasiparticle, which in analogy to classic semiconductors is denominated as exciton.[4] For the generation of a photo-current, the pair needs to be split into an electron and a spatially independent hole. In classic inorganic solar cells, this separation is immediate, because the binding energy is below $k_{\rm B}T$ at all relevant operating temperatures. Organic semiconductors, however, have a much smaller dielectric constant, which leads to exciton binding energies in the range of few hundred millielectronvolts, which is one order of magnitude larger than $k_{\rm B}T$ at room temperature. This implies that an exciton is a quasi-stable state with a defined average lifetime, which eventually recombines through heat generation and is lost for electric power generation. However, an exciton has a certain diffusive mobility, leading to an average diffusion length, which is typically in the range of approximately 10 nm. This diffusion is utilized for photovoltaic energy conversion.

In order to split an exciton, a second dye is required, with a parallel offset in HOMO and LUMO energy levels compared to the first dye. The dye with lower energy levels is denoted as "acceptor", the one with higher energy levels as "donor" (see Fig. 5b). If the exciton is initially situated on the donor⁷, the electron from the exciton can be transferred onto the acceptor. During this transition, the electron on the one hand requires energy to overcome the Coulomb binding with the hole. On the other hand, it simultaneously gains energy due to the energetic difference between the LUMO levels. This process is preferred if the final separated state is energetically favorable compared to the initial state, i.e. the LUMO offset is larger than or equal to the difference in binding energy between the two sites. If both figures coincide, the electron moves without energetic loss, if the energy levels of a couple of donor and acceptor dyes to facilitate efficient exciton splitting and minimize energy losses is another current research topic, which includes the detailed investigation of the electronic processes occurring during exciton splitting, which is today not yet well understood on a satisfactorily

⁷ The following discussion is analogously valid for an exciton on the acceptor, interchanging the roles of donor and acceptor as well as of electron and hole, etc..

generalizable level. After splitting of the exciton, the offset of the respective HOMO and LUMO energy levels between donor and acceptor leads to a spatial confinement of holes to the donor and electrons to the acceptor.

In a first-approach simplistic organic solar cell, donor and acceptor are deposited as two thin films on top of each other, constituting a "planar heterojunction" or "flat heterojunction". As long as the film thicknesses are below the exciton diffusion length of typically several nanometers, most excitons reach the interface where they are directly split, charging the acceptor negatively and the donor positively, respectively, driving a photo-current if contacts are present. Despite the strong absorption of organic dyes, the mentioned thickness limit is typically not sufficient to absorb a large part of the incident light. On the other hand increasing the film thickness beyond the exciton diffusion length would only increase the absorption, but the majority of the additionally created excitons would not reach the donor-acceptor interface before recombining, and thus not contribute to the energy conversion.



Fig. 5: a) Schematic stack sequence of a p-i-n solar cell (left) and realization of the absorber layers in planar heterojunction (PHJ), bulk heterojunction (BHJ), and hybrid geometry (from left to right). b) Simplified illustration of the energy levels (disregarding level bending and built-in field) in a PHJ, a BHJ, and a p-i-n solar cell based on a BHJ with transparent transport materials. The heterojunction could also be realized as PHJ or hybrid. Source: [5]

To overcome this thickness limit, the "bulk heterojunction" concept was introduced, where donor and acceptor are co-deposited as one mixed layer.[6] Due to different surface energies of the materials, they partially de-mix during film formation, leading to an interwoven percolation network of donor and acceptor domains. By fine control of the deposition parameters, the average size of these domains can be matched to a value which is in the range of the exciton diffusion length, constituting the optimum compromise between very small domains for efficient exciton separation and very large domains for an efficient transport of charges through the interwoven network to the contacts. Still, this transport along percolation paths limits the electric conductivity of the bulk and leads to a new – though larger – thickness limit for the blend layer, which is typically several tens of nanometers. This bulk heterojunction is a key concept to achieve reasonably high photo-current generation and is used in most organic solar cells today.

Optimization of the photo-current

To contact a bulk heterojunction for usage as a solar cell, simple sandwiching between metal contacts is not an efficient solution, because the bulk heterojunction does not contain a selectivity for extraction of electrons or holes on either side and is not able to drive a photocurrent. Some selectivity can be introduced by using metal contacts with different work functions, however, this imposes a reduced limit for the achievable voltage as will be discussed below. Furthermore, the interface to a metal facilitates the immediate recombination of an exciton, i.e. a direct contact between the absorbing semiconductor and metal introduces an exciton sink which would be a major loss mechanism for energy conversion. To avoid the direct contact between the absorber material and the metal contact, additional spacer layers can be introduced, consisting usually of organic semiconductors with a larger gap between HOMO and LUMO compared to the donor and acceptor dyes. The larger gap has a twofold advantage: On the one hand, it makes the material transparent towards visible light, which is to be absorbed by donor and acceptor. On the other hand, excitons from the donor-acceptor system cannot be transferred to the spacer layer and are confined to the donor-acceptor system without introducing a recombination channel at the interface.

While spatially decoupling the donor-acceptor system from the metal contacts, the spacer layers need to allow the extraction of the photo-generated charge carriers from the donoracceptor system to the metal contacts. For this reason, two different spacer materials are used at the two contacts: At one side, a hole transporting material is used, which has a HOMO equal to the HOMO of the donor dye, and at the other side an electron transporting material with a LUMO equal to the acceptor is placed. These transport layers now define the polarity of the solar cell: Due to the large HOMO-LUMO gap in the spacer materials, the electron transporting material constitutes an energetic barrier for hole extraction and consequently prevents holes to be extracted at this electrode, and vice versa. This way, the selectivity of the semiconductor system is directly restored and an ideal solar cell structure as suggested by Würfel [7] is realized. Besides their transparency, the main criterion for the quality of transport layers are their electronic properties, specifically their conductivity and the level alignment at the metal-semiconductor interface. Both are substantially improved by electric doping⁸, increasing the conductivity and leading to the formation of an energetically wellaligned low-resistance tunneling contact at the semiconductor-metal interface, analogous to classic semiconductors. [8,9]

The solar cell design discussed up to now contains all essential elements required to build a highly efficient device, though some further optimization can be done to maximize the photocurrent: The thickness of the cell is in the range of 100 nm, i.e. within the coherence length of sunlight (several hundred nm). The incident light entering the solar cell through the transparent contact is only partially absorbed in its first pass through the heterojunction. The remaining intensity is reflected at the back metal contact and interferes with the incoming light, forming a partially standing wave inside the solar cell. The maximum intensity of the optical field distribution is found at an optical distance of $\lambda/4$ from the back contact. The absorption and photo-current generation can, thus, be optimized by placing the bulk heterojunction exactly at this position, by means of adjusting the thickness of the transparent doped transport layer between the heterojunction and the back contact (see Fig. 6). The second transport layer can be similarly optimized with respect to partial reflection at the interface between the transparent top contact and the organic layers. Organic solar cells which are optimized to this level yield very high quantum efficiency values of 75% [11], i.e. 75% of

⁸ p-doping for the hole transport layer, n-doping for the electron transport layer



Fig: 6: Optimization of the thin-film optical interference of the back-electrode reflection. The short-circuit current density j_{SC} is measured in solar cells with varying thickness of the electron transport material (ETM). The j_{SC} is highest if the ETM thickness is adjusted to place the absorbing heterojunction at the field maximum of the standing wave pattern. Two different electron transport materials are investigated, n-doped C_{60} and n-doped HATNA- Cl_6 , and compared to optical simulation data. Picture (left) adapted from Christiane Falkenberg. Graph (right) reprinted with permission from [10], copyright 2011, AIP Publishing LLC.

the incoming photons in the respective spectral range are converted into electron-hole pairs and successfully extracted as short-circuit current. However, since most organic dyes have a rather narrow absorption peak with a typical width of 100 nm .. 200 nm, several complementarily absorbing dyes are required to cover the complete relevant range of the solar spectrum⁹ and reach high overall device efficiencies. Two dyes are already combined in every organic solar cell, the donor and the acceptor constituting the heterojunction. More dyes can be combined in multi-junction cells, which will be discussed below, or in novel cell architectures like cascade structures [12] or ternary blend systems [13], which are beyond the scope of this article.

In summary, an organic solar cell consists of the bulk heterojunction of absorbing donor and acceptor dyes, which is sandwiched between a p-doped hole transport layer and an n-doped electron transport layer, and this whole organic stack is placed between a reflecting back electrode and a transparent top electrode (see Fig. 5a). This whole stack consisting of rather soft and mechanically instable materials needs to be processed on and carried by a mechanically robust substrate, which is usually either glass or plastic foil, but can in principle be any material with a sufficiently smooth surface. The solar cell stack can be fabricated either on top of a substrate or at the back of a transparent substrate¹⁰. Especially in lab cells, the latter arrangement is the commonly used one, with the transparent electrode being the first layer to be deposited and the solar cell being illuminated through the substrate.

⁹ approximately 400 nm to 1200 nm, in multi-junction devices (see below) even wider

¹⁰ In the latter case, the technically correct term would be "superstrate", but in agreement with large part of literature, we use the more commonly used term "substrate" here.

Photo-voltage

When a solar cell is operated at open circuit, the photo-generation of charge carriers leads to a positive charging of the donor and a negative charging of the acceptor, including the transport layers and electrodes. The increased charge density leads to an increased probability of electrons and holes in the donor-acceptor system to recombine back to the neutral state with their energy difference dissipating as heat. Understanding and reducing this charge recombination is today a particularly active and challenging area of research. The charge density dependent recombination rate leads to an equilibrium charge density where the photogeneration of charges equals the recombination. In terms of the Fermi levels of the semiconductors, the increased hole density is expressed as a shift of the holes' quasi-Fermi level on the donor towards its HOMO energy, and vice versa for electrons on the acceptor towards its LUMO energy. The difference between these quasi-Fermi levels is in the ideal case measured as the open-circuit voltage V_{OC} at the electrodes. Without spacer layers, the direct contact between the donor-acceptor system and the metal contacts limits $V_{\rm OC}$ to the difference of the work functions of the electrode materials. When the contacts, however, are decoupled from the active system by doped layers, the description illustrates that the positions of the quasi-Fermi levels only depend on the donor-acceptor system itself and that only the energetic difference between the donor's HOMO energy and the acceptor's LUMO energy constitutes the upper limit for $V_{\rm OC}$ [14]. This difference is termed the "effective gap", since it plays a similar role like the band gap in inorganic photovoltaics. In current research, the adjustment of the relative energy levels of donor and acceptor by minor chemical modifications allows to increase the effective gap within certain limitations without essentially changing the absorption of the dyes and is thereby an interesting handle to optimize the cell voltage and in consequence the device efficiency.[15, 16]

The fill factor

Finally, the fill factor FF is the third factor in Equation (1) determining the solar cell efficiency. While j_{SC} and V_{OC} constitute the upper limits of photo-current and photo-voltage achievable in a specific device at a given illumination intensity, neither the short-circuit nor the open-circuit case allow the extraction of electrical energy from the solar cell. Energy extraction is only possible in a situation where voltage and current are simultaneously generated, and the FF illustrates which share of $j_{SC} \cdot V_{OC}$ remains as electrically usable energy at the maximum power point. It is, thus, directly related to the charge density dependence of the recombination process, which is expressed as the ideality factor of the solar cell. Furthermore, a number of non-idealities of the cell can lead to a further reduction of the FF: e.g. parasitic Ohmic losses (typically illustrated in terms of series or parallel resistors), a nonoptimized built-in field, energy level misalignment between the donor-acceptor system and the transport layers, limited electric conductivity of the active layers, or charge density gradients within the donor-acceptor system, which are often a secondary effect of the previous ones. Many of the listed effects reducing the FF are especially detrimental at high current density, as is understandable considering, for example, the limited conductivity of organic semiconductors and the transparent electrode. Tandem and multi-junction devices can reduce these losses due to their advantageous serial connection, where only the cell voltage is added, but not the current density.

Tandem and multi-junction devices

A particularly attractive possibility to improve the performance of organic solar cells is the possibility to easily fabricate tandem or multi-junction devices.[19] In contrast to inorganic photovoltaics, where a cell is typically made from a monolithic block, the layer-by-layer

deposition allows for the easy and straight-forward implementation of such devices. In a tandem solar cell, two complete organic solar cells, termed sub-cells, are fabricated directly on top of each other without an additional electrode in between.¹¹ The sub-cells are connected in series, i.e. their efficiencies add up in terms of their voltages while the overall current density is the same as in each sub-cell. This way, the Ohmic thickness limit of the heterojunction can be compensated, and the absorption of the two sub-cells enables a more efficient absorption and photo-conversion of light, while Ohmic losses stay small.[11] Beyond homo-tandem device, where the same active materials are used in both sub-cells, hetero-tandem devices further exploit the potential of organic solar cells: By combining different absorber molecules in the sub-cells, larger parts of the solar spectrum can be harvested, compensating for the narrow absorption spectrum of organic dyes.[16] Furthermore, the sub-cell absorbing in the shorter-wavelength region of the sun spectrum can be designed to yield a higher voltage, which is not possible in a cell with a long-wavelength absorber limiting the size of the effective gap. The design is furthermore not limited to two sub-cells, but also multi-layer stacks with three or more sub-cells are possible. This way, the advantages of the homo- and the hetero-tandem concept can be combined to specifically exploit the advantages and compensate the drawbacks of each used dye.

Current state and outlook

The highest efficiency achieved with organic solar cells is currently 12%, demonstrated by Heliatek with an undisclosed multi-junction device stack.[1] This value is especially remarkable, because is was achieved with a cell with $> 1 \text{ cm}^2$ active area and with a stack which is producible on a suitable roll-to-roll machine. Supporting the relevance of this value, comparisons on the basis of currently produced modules show that in vacuum deposition technology, the difference between the efficiency of a batch-to-batch and a roll-to-roll produced module can be small. The history of efficiency records shown in Fig. 7 illustrates the rapid progress achieved in organic photovoltaics over the last few decades.



Fig. 7: History of record values in organic photovoltaics. Inset: Record device by Heliatek in cooperation with IAPP (TU Dresden). Graph source: [17] Photo source: [1, Photographer Jürgen Lösel, Dresden]

11 Among other concepts, the direct contact between a p- and an n-doped layer realizes an efficient conversion contact.[18]

O-factor

For comparing organic and inorganic solar cells, the direct comparison of the module efficiency is not sufficient: In applications, solar cells rarely operate at room temperature and under the standardized AM1.5 spectrum with perpendicular full midday sun illumination. Variations in temperature, illumination intensity, angle, etc. are omnipresent though site-specific. They can have a major influence on the device performance, and the quality of this influence is substantially different between organic and inorganic solar cells. The most obvious difference is that the efficiency of organic solar cells typically has a positive or no temperature gradient, while inorganic solar cells have a negative efficiency gradient towards increasing temperature. Also the low-light behavior of organic solar cells is advantageous with the device efficiency increasing at reduced illumination intensity. These differences are reflected by the observation that an organic module with the same nominal output power as its inorganic counterpart produces up to 15% to 20% more energy over the course of a year when installed in central Europe. This difference, termed the "O-factor", needs to be kept in mind when comparing efficiency values of different solar cell technologies measured at standard reporting conditions.

Outlook

Several years ago, a series of initial demonstrator consumer products¹² with limited practical benefit, but aiming at technology enthusiasts and early adopters, was the initial step of organic photovoltaics into a commercial environment. After the insolvency of their manufacturer Konarka, who made the first large attempt to commercially up-scale organic photovoltaics, parts of the company are now being re-established in Nürnberg, Germany under the brand name Solarte, focusing continuously on solution processing. During the same period, the company Heliatek, based in Dresden and Ulm, Germany, has not entered the market but focused on improving and upscaling their cells and production tools, fabricating their cells exclusively with vacuum deposition technology. Today, both companies are regularly establishing lighthouse applications, which are mostly building integrated installations in facades or on rooftops. These applications demonstrate the unique applications implementable

with organic photovoltaics, e.g. partially transparent roofs or vertical facades with improved specific energy harvesting. Especially the advantageous low-light behavior makes them attractive for installations at facades and on roof surfaces which are not in an optimally inclined southward direction. Thanks to the time characteristics of such installations, they support the stability of a continuous energy supply over the electricity grid. The flexibility of the cells during manufacturing is furthermore exploited in demonstrators for mobile applications, e.g. in parts of a car body, which are directly coated with photovoltaic



Fig. 8: Concept for an energy selfsufficient air dome. Picture source: [1]

films. Future applications might include the installation of solar foil on light building structures, which are not rigid enough to support heavy modules including their mechanical support, covering various materials for miscellaneous mobile, indoor, and outdoor applications with solar cells, or even ideas like energy self-sufficient air domes (see Fig. 8).

¹² e.g. the "energy sun bag" by Neuber's, based on Konarka modules

In summary, the progress of organic photovoltaics promises that in future organic solar cells might be found in places where we have not thought about photovoltaics yet.

Further reading

General introduction to organic electronics (German and English) at Organic Electronics Saxony:

www.oes-net.de/de/organische-elektronik | www.oes-net.de/en/organic-electronic

Organic Semiconductor World: Physical basics, research groups, conferences, companies: www.orgworld.de

OSA direct: up-to-date news about organic electronics: www.osadirect.com

Organic and Printed Electronics Association: www.oe-a.org

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Der vorliegende Band versammelt schriftliche Ausarbeitungen von Vorträgen auf der Tagung des Arbeitskreises Energie in der Deutschen Physikalischen Gesellschaft des Jahres 2015 in den Räumen der Technischen Universität Berlin. Leider ist es nicht gelungen, von allen Vortragenden Manuskripte zu erhalten. Die Präsentationsfolien der meisten Hauptvorträge können auf der Webseite des Arbeitskreises über:

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Hardo Bruhns