6.4

Organic PV Module Design and Manufacturing

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6.4.1 Introduction

6.4.1.1 From Cells to Modules

World-record organic photovoltaic (OPV) devices have reached efficiencies up to 12% and up-scaling and industrialization of the technology are now in progress. In academia, cell efficiencies of up to 10.6% in the lab (Li *et al*., 2012; You *et al*., 2013) have been published and 11.5% has been the latest certified record in the NREL Best Research-Cell Efficiencies chart. In industry, the Heliatek company has announced a cell efficiency record of 12%, and Certified efficiencies of 11% at the cell level have been demonstrated by both Toshiba and Mitsubishi Chemical. In the first step towards modules, Toshiba also holds the record certified efficiency of 9.7% for an organic mini-module (Green *et al*., 2015).

Overall, OPV holds great promise to become a cost-effective renewable energy platform, because it can be deposited on flexible substrates using low temperatures, enabling roll-to-roll production. Since the technology is still relatively new and there is no commercial production yet, the estimated cost prices for OPV modules vary enormously. It is good to note that OPV is expected to create new markets with its unique selling points such as flexibility, semitransparency and freedom of color and shape. As with all PV technologies, there is a balance between power conversion efficiency and the lifetime of the modules versus the cost of production and requirements of the application.

In this chapter, several methods and processes to realize and manufacture OPV modules are described in three stages. First, general considerations for large-scale production of OPV modules are described. Then, different processes for manufacturing are explained, with an emphasis on the different wet processing technologies that have been successfully

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demonstrated for OPV layers. Finally, different processes of making interconnections for modules will be described.

6.4.1.2 Advantages of R2R Production

There are two methods of applying the layers of an organic solar cell: (1) small organic molecules can be applied using thermal evaporation under reduced pressure; and (2) alternatively, soluble organic molecules or polymers can be applied using solution processing. For solution processing, the active materials are dissolved in a solvent (mixture), creating an ink which is applied using a coating or printing technique (see Section 6.4.2). Both evaporated small molecule OPV as well as solution-processed OPV are compatible with roll-to-roll production, though there are differences in equipment and the respective cost for materials and processes. Roll-to-roll (R2R) production is a production process in which a roll of flexible material is used as a substrate, which is unrolled and fed into the production line and re-reeled after the process to create an output roll. The main advantages of R2R production of solution-based OPVs are given in Table 6.4.1.

In general, cheap production using R2R processes is possible owing to the high process efficiency through the sequential application of successive layers on a web. Since OPV is a relatively young PV technology, the development of stable processes and the equipment needed for manufacturing is still ongoing. Evaporation of small molecule OPV stacks in a R2R production facility is challenging, due to the need for low vacuum processing and the optimization of uniform deposition on large areas. Solution processing of OPVs on an industrial scale brings other additional challenges, such as finding alternative, non-chlorinated solvents and using roll-to-roll compatible processes. The latter will be further discussed in the second part of this chapter.

6.4.1.3 Module Design for Organic PV

Where module design for traditional silicon PV is limited due to the use of wafers, organic PV module design has more flexibility as a result of the application of the sequential OPV layers on a substrate. Also semi-transparency is one of the unique features of OPV modules that can be exploited for design purposes. Modules can literally become flexible through the use of substrates such as PET foils, but also the shape of the cells and modules can be adjusted to fit the purpose. R2R production of OPV is still in the pilot phase and typically is done on a substrate with a width of 30 cm, as shown in Figure 6.4.1. The length

Table 6.4.1 Benefits and challenges for roll-to-roll solution processing

Benefits	Challenges
Steady state processing; high throughput and high yield	Development of stable processing and defect repair
Flexible and low weight	Shorter drying times needed
Better scaling	New equipment needs
Energy and materials efficiency	Patterning
Low substrates costs	Use of benign solvents

of these modules can be adjusted to fit the purpose. As mentioned before, R2R production is scalable and also the width of the modules can be adjusted, depending on the equipment available. Nevertheless, R2R production of OPVs is mainly suitable for large-scale, high-volume market areas such as façade elements for building integrated photovoltaics (BIPV), as shown in Figure 6.4.1.

Next to roll-to-roll manufacturing, roll-to-sheet as well as sheet-to-sheet production methods are of interest for low-volume applications that require more flexibility in module design. Two examples of these free-form modules are shown in Figure 6.4.2. The fact that the size, shape, color and transparency of OPV modules are free for the designer's choice, makes

Figure 6.4.1 HeliaFilm™ encapsulation output and vision on low-cost solar cell in BIPV ©Heliatek. (*See insert for color representation of the figure*)

Figure 6.4.2 Two examples of free-form OPV modules; left, the Solarte garden lamp by Belectric OPV and, right, the world's first polychrome solar module by DisaSolar. (*See insert for color representation of the figure*)

custom-made OPV modules very attractive for architects and designers who want to integrate PV, for example, into the built environment.

6.4.2 Important Module Parameters

6.4.2.1 Cell Size

As a consequence of the low conductivity of the typical electrode and charge transport materials used in OPV, such as PEDOT:PSS, ITO and other metal oxides, the cell size that can be used efficiently in modules is limited to the centimeter scale, as Slooff *et al*. (2014) have shown when optimizing the silver grid lines that are used with PEDOT:PSS as a bottom electrode. These type of calculations are important when determining the cell dimensions that lead to the highest efficiencies of OPV modules.

6.4.2.2 Series Connection

By going from cells to modules, individual cells have to be connected in series and/or parallel. Serial interconnection is used most frequently in OPV modules and will be further discussed in Section 6.4.4 on interconnections. By using a serial interconnection, the voltages of the cell that are connected are added up (Sommer-Larsen *et al*., 2013). At the Technical University of Denmark the *Infinity concept* has been developed that uses serial connections in large OPV modules that build up to a very high voltage. Krebs (Krebs *et al*., 2014, p. 32) explains: "The rows that are 100 m long result in a voltage build-up along the row of >10 kV, achieved through serial connection of the 21 000 individual junctions along each lane of solar cell foil." These high voltages lead to increased need for safety precautions and in this case the need for a fence around the site.

6.4.2.3 Barrier Requirements

Another important parameter in the module production of OPV is the need for proper encapsulation to enhance the operational lifetime of the modules. OPVs are known for their degradation due to exposure to water and oxygen and therefore protection from the ingress of water and oxygen is essential. Where in crystalline silicon modules glass-glass encapsulation is used, which has great barrier properties, this is not the preferred solution for OPVs when the flexibility of these modules is considered such an important feature (Ahmad *et al*., 2013). When OPV is processed on a flexible foil such as PET, typical bending angles of 60° are possible with ITO layers, and even higher when less rigid electrodes are used (Gomez de Arco *et al*., 2010).

Flexible foils with oxygen and moisture barrier properties have been investigated to increase the lifetime of flexible organic electronics, such as the barrier made of alternating inorganic and organic layers on PET foil that was developed at the Holst Centre (van Assche *et al*., 2008). The cost of these types of barrier foils is still relatively high compared to all the other materials used in the flexible OPV modules. The barrier and the adhesive actually make up the largest part of the weight and the volume. As a result, it has the major role in the energy balance, cost and environmental impact of OPV modules (Krebs *et al*., 2014).

6.4.3 Wet Processing Technologies

In organic solar cells each layer has a specific function, such as the photoactive layer that converts light into charges and the electron or hole transporting layers as explained in Part 6. Each of these layers can be deposited in an ink using a variety of coating and printing processes. All functional layers have specific layer thicknesses and the specific processing of these different layers depends on the combination of the ink, the processing technology used, drying time, temperature, etc. All these parameters need to be optimized for each layer in the solar cell stack.

Going from cell processing to (roll-to-roll) module production, lab-scale technologies such as spin coating and blade coating need to be replaced by up-scalable coating and printing techniques such as slot-die coating, inkjet printing, and (rotary) screen printing. The ink formulations that can be used depend on the technique that is chosen and the layers that have been previously deposited. The commonest techniques for solution processing on a large scale are shown in Figure 6.4.3 and explained in the following sections.

Next to processing techniques, the ink formulations that are used for the application of the layers are a very important subject of research. The inks that are used should match the processing method and, for large-scale production, the solvents should be environmentally-friendly and nontoxic. The specific requirements for the ink vary with the technology that is chosen for the deposition, for example, inks for inkjet printing require viscosities that are in between 3 and 50 mPa·s, while for slot-die coating, the viscosity range is much wider and can be less than 1 mPa·s, but also several Pa·s. Sequential deposition of layers on top of each other, which is essential in OPVs, requires that the deposition of one ink does not destroy the functional layer underneath. This can be done by using combinations of so-called orthogonal solvents. A widely used combination is the use of organic hydrophobic solvents for the deposition of the photo-active layer on top of the water-soluble PEDOT:PSS layer. However, for other layers, it is less straightforward. Hence, careful optimization of the inks, the deposition method and the use of orthogonal solvents is key to the successful up-scaling of OPVs.

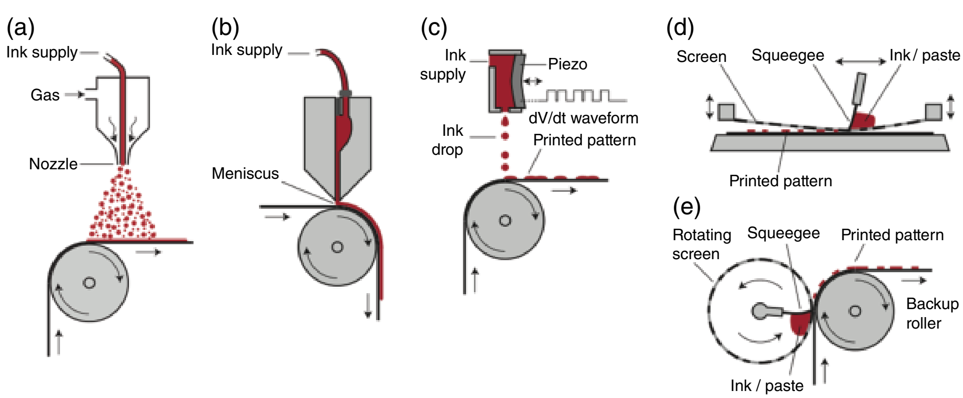

Figure 6.4.3 Schematic representations of (a) spray coating; (b) slot-die coating; (c) inkjet printing; (d) screen printing; and (e) rotary screen printing. Adapted from (Søndergaard *et al.*, 2013) © 2012 Wiley Periodicals, Inc

6.4.3.1 Slot-Die Coating

Homogeneous and uniform layers can be deposited on large areas using the slot-die coating process. Slot-die coating is a non-contact processing method that can use inks with a large variety in viscosities, including relatively volatile inks. The working principle is the deposition of a wet layer by supplying an ink through a die as shown in Figure 6.4.3. The film thickness obtained after drying depends on the flow rate of the ink, the coating width and the speed and the concentration of material in the ink. Stripe coating can be obtained by using slower speeds and an insert that splits the meniscus of the ink. In direct roll-to-roll OPV module production, this one-dimensional stripe coating is the preferred technique, since it allows for the alignment of the layers for series-connected cells in modules (Krebs, 2009a). Homogeneous coatings can also be used for module production when combined with (laser) scribing.

6.4.3.2 Inkjet Printing

Inkjet printing is probably the best-known wet processing technique, since nowadays it can be found in almost every household. The inkjet printing technique that is mostly used for OPVs is the drop-on-demand inkjet printing based on piezo-electrical elements as shown in Figure 6.4.3. The nozzle is filled with the ink that is maintained in the chamber due to surface tension and static pressure. When a voltage waveform is applied to the piezo element, a mechanical force is put on the chamber and droplets are ejected from the nozzle. Full OPV devices can be obtained by inkjet printing, as was shown by Eggenhuisen *et al.* (2015a).

One of the main challenges using inkjet printing for OPV is that the formation of the layers specific for the inkjet printing process (wetting and pinning) depends not only on the formulation of the ink that is used for the printing, but also on the surface energy of the layer/material that the layer is processed on. The formation of droplets and the merging of droplets on the surface are influenced by the print head, the printing parameters, and the ink formulation that is used. Also the interaction of the formed droplets with the surface and the environment plays an important role in the layers that are obtained.

Another challenge of inkjet printing on a large scale is the clogging of the nozzles, which needs careful optimization of the printing bar. In general, inkjet printing is a very complex technology that needs a lot of optimization of all the different parameters. On the other hand, inkjet printing is one of the few techniques that allows for waste-free printing and digital processing. Especially the latter makes inkjet very interesting for free form, smaller-scale, individualized production of OPV modules.

6.4.3.3 Spray Coating

Spray coating of OPV layers has been shown to be possible for lab-scale fabrication (Girotto *et al.*, 2011) and is compatible with high througput R2R processing. Similar to inkjet printing, there is low material waste for large area depositions. However, no patterning is possible without the use of shadow masking. In spray coating, as shown in Figure 6.4.3, the functional fluid or ink is forced out of the nozzle of the spray head using pressurized air or gas, which generates a continuous flow of droplets. The droplets hit the surface at high speed and dry quickly due to the small size of the droplets and the gas flow.

Spray coating allows for a broad range of solvent and material systems and the setup can be equipped with multiple spray heads. With this technique the surface tension, viscosity, fluid density, gas flow properties and nozzle design are important parameters for optimizing the spray production. To obtain uniform coatings with the sprayed inks, also the working distance, the coating speed, the droplet sizes, and all the interactions between the fluid and the surface are vital parameters to investigate. These are similar to the other techniques and include wetting behavior, surface properties, coating speed, spreading (of the droplets), and the surface temperature.

6.4.3.4 Other Techniques and Comparisons

Other techniques such as screen printing, gravure printing, or flexographic printing that are typically used in high volume traditional printing can also be used in the production of OPV modules. The most commonly used of those is screen printing.

Screen printing is commonly used in the manufacturing of printed circuit boards and the metallization of silicon solar cells and is illustrated in Figure 6.4.3 in the flatbed approach as well as the rotating application. First, the screen is covered with an ink by a floodbar, which fills the mesh. After that, a squeegee forces the ink through the open areas onto the substrate. In rotary screen printing, the cylindrical screen rotates with the same speed as the substrate, while the squeegee is kept at the same position, distributing the usually rather viscous ink. The features in the screen are transferred to the substrate, hence structured layers can be applied. This is also true for gravure and flexographic printing (Välimäki, 2015). However, since the structuring for all these techniques is based on the equipment, either a screen or a cylinder, changes to the structure involve a change in these elements.

When comparing the different techniques in Table 6.4.2, it is clear that there is no obvious choice for one single process for all processes and layers in an OPV layer stack. Hence, in the R2R solution processing of OPV, a combination of techniques is often used. All functional layers have specific layer thicknesses and a desired film morphology that need to be optimized for the chosen wet processing technique and ink. Also the accuracy of the positioning of the inks and the alignment of different layers depend on the combination of ink and technique used. In the end, all the parameters are optimized to lead to optimized solar module

Table 6.4.2 Comparing different major wet processing technologies

Technique	Webspeed	Coating options	Drawbacks
Slot-die coating	1-600 m/min	Uniform or stripe coating	Structuring only in stripes
Inkjet printing	>50 m/min	Full digital freedom	High requirements on inks
Spray coating	all speeds*	Uniform or patterned using shadow mask	Use of shadow masking in R2R is challenging
Screen printing	<180 m/min	Structured	New solar cell structure requires new equipment
Flexographic printing	>20 m/min	Structured	
Gravure printing	15-900 m/min	Structured	

*depending on the exact spray coating technology efficiencies. An extensive review of all different coating and printing techniques was produced for solution-processed OPV specifically (Krebs, 2009b).

6.4.4 Interconnections

The sizes of efficient OPV cells are limited to about 1 cm in width. The resistance of the transparent conductive oxide (TCO) that is typically used is the limiting factor. For that reason, interconnections between solar cells are an important aspect of module fabrication. The interconnections that are used in modules are made by connecting the bottom electrode of one cell to the top electrode of the next cell, creating an electrical series connection. Through this series connection, the area of the module is split into cells. The area that is needed to create the interconnection does not contribute to the power output of the module and is referred to as the dead area. The active area or zone is the area that does contribute to the power and is the part where the layer stack is complete. The ratio of active area to total area of the modules is referred to as the geometric fill factor (GFF).

The series interconnection of cells results in lower current and a higher voltage output of the module, since for an electrical series connection, the voltages are added, while the currents should be identical. The total power output of the modules is the maximum power point current and voltage multiplied together. Increasing the number of cells in the module decreases the area per cell and hence lowers the current output of the module. Though this is compensated for by the increase in voltage, there is a trade-off due to the loss of active area.

There are several options to create interconnections between adjacent cells in an OPV module. Two of the most common are shown in Figure 6.4.4. In order to directly make interconnections using only (wet) processing techniques, structuring of the applied layers is needed as shown on the left side of Figure 6.4.4. This structuring is referred to as tiled. Alternatively, interconnections can be made by combining uniformly coated layers with the partial removal of the layers, also known as scribing, in between the (wet) processing steps. Both of these options can also be used in evaporated OPV modules, for the tiled structure, shadow masks are used.

The in-process scribing that is shown in Figure 6.4.4 (right) shows three labeled scribes that are used to create the interconnection. The P1, P2, P3 numbering of the scribes is related to the order in which they are made in the in-process procedure; however, they are now used as a convention for their function. The P1 scribe isolates the bottom electrode of the neighboring cells in the module, the P2 creates the interconnection between the top electrode of one cell to the bottom electrode of the other cell, and the P3 isolates the top electrode of the two neighbouring cells.

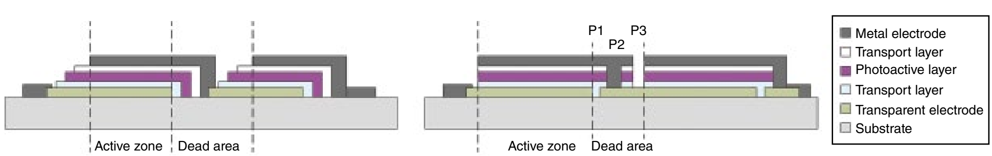

Figure 6.4.4 Schematic representations of interconnections using only wet processing techniques (left) and P1, P2, P3 in-process scribing (right)

6.4.4.1 Tiled Coating

Of all the wet processing techniques described before, the slot-die stripe coating is the most obvious choice for direct processing of interconnected modules. OPV modules have been shown that can use up to three sequential layers using inkjet printing (Eggenhuisen *et al.*, 2015b) and four layers using slot-die coating (Krebs, 2009a). In these modules the interconnection is made by the tiled application of stripes of active layers, creating a direct contact by application of the top metal electrode to a free section in the bottom electode. Next to slot-die stripe coating and inkjet printing, also other coating methods can be used (Välimäki *et al.*, 2015), as long as direct structuring of the applied layers is possible as indicated in Table 6.4.2.

The main drawback of this tiled coating for wet processing techniques is that a large area is needed for the interconnection, due to the low resolution of the coated line. The tiled coating means that wetting and pinning of the layers have to deal with interactions between the ink with the previously deposited layer and the substrate simultaneously. These tiled coatings typically have a 8 mm-wide interconnection zone (the dead area) and a similar cell width, which results in an active area which is only about 50% of the total module area. No significant improvements are expected on the width needed for interconnection in this tiled approach using wet processing techniques. However, development in the conductivity of the electrodes could increase the cell width and with that increase the GFF.

6.4.4.2 In-Process Scribing

The second most used option is combining full area homogeneous coatings with P1, P2 and P3 scribes, as indicated in Figure 6.4.4 (right). The scribing can be done by either mechanical scribing, by making a scratch in the layers with a stylus, or by laser ablation of part of the layer (Gebhardt *et al.*, 2013). With laser scribing, line widths below the mm scale can be obtained. Typical widths of a laser-scribed interconnection that have been published are between 100 and 500 μm, which results in >95% active area of the module (Kubis *et al.*, 2014). Although this can result in much higher power output of the module, it also makes the processing of the modules more complicated. Instead of processing layer after layer, a scribe has to be made inbetween the processing of layers. This invokes the need for cleaning inbetween steps, since the material that is removed will inevitably also end-up on the substrate. Also alignment becomes an issue, which is a costly and time-consuming step in high-throughput production.

6.4.4.3 Back-end (Laser) Processing

As an alternative to the inline fabrication of interconnections, a back-end approach can be used. In this approach, the large area production can be separated from the production of the modules. The module production can be digitally mastered, a specialized production which enables more freedom in the module design, especially when laser scribing and, for example, inkjet printing are combined.

A back-end interconnection can be created on full area deposited layers by first scribing a P1 through all layers, including the bottom contact, and scribing a P2 and a P3 by the selective removal of the layer stack without removing the bottom contact. Then P1 and P3 are filled

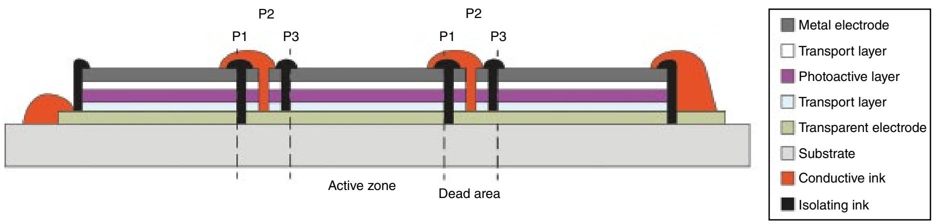

Figure 6.4.5 Schematic representations of back-end interconnections by combining P1,P2,P3 scribes and isolating and conductive inks

with isolating material and a conductive material is deposited onto the P2 and over the isolated P1 onto the top contact (Wipliez *et al.*, 2011). In this way, an interconnection is created between the top contact of the cell next to the P1 and the bottom contact of the cell adjacent to the P3, as indicated in Figure 6.4.5. This technology, however, is still relatively new for OPV and has not been demonstated in the literature yet.

6.4.5 Future Outlook

The progress in up-scaling production of OPV has been tremendous in the past five years. Though the market prospects for PV in general have not been too bright in the last few years, OPV is expected to create new markets owing to their unique selling points such as freedom of shape, color, and transparency. For the creation of OPV modules, a trend is seen towards the use of lasers in scribing for interconnections, which leads to increasing the power output and enables the creative design of modules. Though OPV modules are not commercially available yet, progress is being made in both evaporated as well as solution-processed OPV modules. The first pilot production plants have been built and products are being showcased and are expected to be commercialized soon.

List of Acronyms

Acronym	Description
BIPV	Building integrated photovoltaics
GFF	Geometric fill factor
ITO	Indium tin oxide
OPV	Organic photovoltaics
PEDOT:PSS	Poly(3,4-etheylendioxythiophene):poly(styrenesulfonate), a conductive polymer blend often dispersed in water
PET	Polyethylene terephthalate
R2R	Roll-to-roll
TCO	Transparent conductive oxide
V	Voltage

References

Ahmad, J., Bazaka, K., Anderson, L.J. *et al*. (2013) Materials and methods for encapsulation of OPV: A review. *Renewable and Sustainable Energy Reviews*, **27**, 104–117.

Assche, F. van, Rooms, H., Young, E. *et al*. (2008) Thin-film barrier on foil for organic LED lamps. Paper presented at AIMCAL Fall Technical Conference and 22nd International Vacuum Web Coating Conference, Myrtle Beach, NC.

Eggenhuisen, T.M., Galagan, Y., Biezemans, A.F.K.V. *et al*. (2015a) High efficiency, fully inkjet printed organic solar cells with freedom of design. *Journal of Materials Chemistry A*, **3**, 7255–7262.

Eggenhuisen,T.M., Galagan, Y., Coenen, E.W.C. *et al*. (2015b) Digital fabrication of organic solar cells by inkjet printing using non-halogenated solvents. *Solar Energy Material and Solar Cells*, **134**, 364–372.

Gebhardt, M., Hänel, J., Allenstein, F. *et al*. (2013) Laser structuring of flexible organic solar cells: manufacturing of polymer solar cells in a cost-effective roll-to-roll process. *Laser Technik Journal*, **10**, 25–28.

Girotto, C., Moia, D., Rand, B.P., and Heremans, P. (2011) High-performance organic solar cells with spray-coated hole-transport and active layers. *Advanced Functional Materials*, **21**, 64–71.

Gomez de Arco, L., Zhang, Y., Schlenker, C.W. *et al*. (2010) Continuous, highly flexible, and transparent graphene films by chemical vapor deposition for organic photovoltaics. *ACS Nano*, **4**, 2865–2873.

Green, M.A., Emery, K., Hishikawa, Y. *et al*. (2015) Solar cell efficiency tables (version 46) *Progress in Photovoltaics: Research and Applications*, **23**, 805–812.

Krebs, F.C. (2009a) All solution roll-to-roll processed polymer solar cells free from indium-tin-oxide and vacuum coating steps. *Organic Electronics*, **10**, 761–768.

Krebs, F.C. (2009b) Fabrication and processing of polymer solar cells: a review of printing and coating techniques. *Solar Energy Material and Solar Cells*, **93**, 394–412.

Krebs, F.C., Espinosa,N., Hösel, M. *et al*. (2014) 25th anniversary article: rise to power – OPV-based solar parks. *Advanced Materials*, **26**, 29–39.

Kubis, P., Lucera, L., Machui, F. *et al*. (2014) High precision processing of flexible P3HT/PCBM modules with geometric fill factor over 95%. *Organic Electronics*, **15**, 2256–2263.

Li, G., Zhu, R., and Yang, Y. (2012) Polymer solar cells. *Nature Photonics*, **6**, 153–161.

Slooff, L.H., Veenstra, S.C., Kroon, J.M. *et al*. (2014) Describing the light intensity dependence of polymer:fullerene solar cells using an adapted Shockley diode model. *Physical Chemistry Chemical Physics*, **16**, 5732–5738.

Sommer-Larsen, P., Jørgensen, M., Søndergaard, R.R. *et al*. (2013) It is all in the pattern: high-efficiency power extraction from polymer solar cells through high-voltage serial connection. *Energy Technology*, **1**, 15–19.

Søndergaard, R.R., Hösel, M., and Krebs, F.C. (2013) Roll-to-roll fabrication of large area functional organic materials. *Journal of Polymer Science B, Polymer Physics*, **51**, 16–34.

Välimäki, M., Apilo, P, Po, R. *et al*. (2015) R2R-printed inverted OPV modules – towards arbitrary patterned designs. *Nanoscale*, **7**, 9570–9579.

Wipliez, L., Löffler J., Heijna, M.C.R. *et al*. (2011) Monolithic series interconnection of flexible thin-film pv devices. Paper presented at 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany.

You, J., Dou, L., Yoshimura, K. *et al*. (2013) A polymer tandem solar cell with 10.6% power conversion efficiency. *Nature Communications*, **4**, 1446.