Solar Energy Materials & Solar Cells 93 (2009) 1963–1967

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Flexible polymer photovoltaic modules with incorporated organic bypass diodes to address module shading effects

Roland Steim [a,b,*], Pavel Schilinsky [a], Stelios A. Choulis [c,1], Christoph J. Brabec [a,**]

[a] Konarka Technologies GmbH, Landgrabenstr. 94, D-90443 Nürnberg, Germany
[b] Light Technology Institute, Universität Karlsruhe (TH), Kaiserstr. 12, D-76131 Karlsruhe, Germany.
[c] Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, 3603 Limassol, Cyprus

ARTICLE INFO

Article history:
Received 23 April 2009
Received in revised form
16 July 2009
Accepted 21 July 2009
Available online 11 August 2009

Keywords:
Polymer photovoltaics
Flexible organic solar cells
Shading
Degradation
Reverse bias
Organic bypass diodes
Large-area flexible organic solar cells

ABSTRACT

We present experimental results on large-area low-cost processed flexible organic photovoltaic (OPV) modules incorporating organic bypass diodes to eliminate the negative effects of shading on the module power output. A fully organic-based structure (organic solar module combined with an organic bypass diode) is essential to allow monolithic interconnection of the bypass diode during the solar module production within the same printing steps. The origin of shading losses in organic photovoltaic modules is analyzed in detail, and guidelines for the design and architecture of flexible OPV modules are derived. Inorganic and organic diodes were tested on their functionality as bypass diodes, and a set of diode specifications to minimize shading losses is summarized. Organic bypass diodes were found to efficiently reduce the adverse shading effects in OPV modules.

1. Introduction

In this paper we present experimental data on flexible organic photovoltaic (OPV) modules. Monolithic interconnection of photovoltaic cells into modules is necessary to prevent ohmic power losses, which otherwise do limit large-area photovoltaic elements. Further, serial interconnection of modules is an elegant and advantageous method to achieve the desirable supply of voltage as needed for applications.

Despite the obvious positive effect of module interconnection on the power conversion efficiency (PCE) of large-area solar cells, it is also well known that serial interconnected modules are sensitive to a specific failure mechanism, which otherwise does not arise in single solar cells. The most important one is the so-called "shading" failure [1,2]. Shading occurs when individual cells of the module or even only a part of a cell in a module under operation is shaded. In such a case, the shaded cells have to transport the current of the module in reverse bias, and the excess photovoltaic power of the residually working module can get dissipated across the "dark" cell.

The stress of shading is usually put on the same level as reverse bias stressing, which is a well-known degradation effect, being proven as adverse for organic solar cells [3]. Depending on the leakage current of organic solar cells and on the negative applied bias, reverse bias stressing was found capable to induce irreversible degradation effects, so-called hot-spot failure. As such, shading is expected to cause similar degradation in large-area and high-bias organic solar cells, and first preliminary testing of organic modules seems to confirm that.

The formation of hot spots is a well-investigated phenomenon in photovoltaics since the early space applications [4]. Hot spots define localised regions in a PV module, where the operating temperature exceeds the temperature of the surroundings. Generally speaking, this situation occurs when the cell under investigation generates less power than the rest of cells connected in series, which frequently is a result of partial shading. Other mechanisms leading to hot spots can be cell damage, a mismatch in the size and/or power or interconnection failure. As a result, the defective cell is reverse biased and behaves like a load that dissipates the power generated by the remaining cells in the form of heat.

The protection against hot spots is also well-known and consists of a connecting bypass diode, with reverse polarity, in parallel with a group of solar cells within the module.

* Corresponding author at: Konarka Technologies GmbH, Landgrabenstr. 94, D-90443 Nürnberg, Germany.
** Corresponding author.
E-mail addresses: rsteim@konarka.com (R. Steim), cbrabec@konarka.com (C.J. Brabec).
[1] Work performed at Konarka Technologies GmbH.

0927-0248/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.solmat.2009.07.013

The frequency of diodes depends on cell technology. While Si typically uses one bypass diode for each 12–18 cells, the current generation of dye-sensitized solar cells (DSSC) does not require bypass diodes. In order to ensure that the PV modules are protected against this damage, international standards require that modules must be subjected to hot-spot endurance tests before their qualification [2,5–8].

Although numerous publications exist discussing the shading effects of inorganic cells, there is no report addressing this issue on OPV technology to the best of our knowledge. This failure needs to be made up. OPV technology has recently demonstrated PCE values in the range of 6% [9–11] and extrapolated product lifetimes beyond 3 years [12]. In combination with the successful demonstration of module production by printing technologies, [13,14] first applications are about to enter the market. That requires addressing module failing mechanisms due to shading in time. This manuscript reports how organic bypass diodes can significantly reduce adverse shading effects for OPV modules.

2. Shading effects on OPV modules

According to results from inorganic PV technologies, failure from shading has been classified into two classes, where one of them is reversible and the other is irreversible. To address these two failure mechanisms and their impact on OPV modules, it is important to understand the shading-induced processes on a cell level. As mentioned before, a shaded cell has to transport the module photocurrent driven in reverse bias. Depending on the diode characteristics of the shaded cell, two scenarios can be distinguished, which are typically called Type I or Type II behaviour [6–9]:

- Type I cells have an excellent dark rectification and a high shunt resistance. Shading of one cell will result in a shutdown of the module operation, since the shaded diode is blocking in reverse bias operation. The shunt resistance (R_{sh}) of the shaded cell determines the current transported across the cell according to module voltage (V_{module})/R_{sh}. In case of large R_{sh}, the photovoltaic power of the non-shaded part of the module will be dissipated across the shunt resistance of the shaded cell, and the whole module will be shut down.
- Type II cells, on the other hand, have a lower rectification, and specifically a smaller shunt resistance. In the case of Type II cells the photocurrent of the partially shaded module can be transported across the shaded cell. Thus, the shaded cell is driven into reverse bias until the leakage current of the cell can match the photocurrent of the partial shaded module. As such, the module can deliver the photovoltaic power of the shaded module minus the power loss required to drive the shaded cell into reverse bias.

Reverse bias testing of OPV cells and modules has shown that Type II cells are more responsible to irreversible degradation, while Type I cells could pass the IEC hot-spot tests [3].

In this paper we discuss the impact of a fully shaded organic solar cell to the current density–voltage (J–V) characteristic of a module. The J–V characteristic of a (partially) shaded cell in the 3rd quadrant determines the J–V characteristic of the whole module. The short-circuit current of a module is determined by the leakage current of the shaded cell at the voltage provided by the non-shaded cells, plus the current generated by the half-shaded module. Thus, the investigated impact of full shading of a cell is the most severe case for a module. Half shading, the most likely case under operation, is less severe to the losses in the power output characteristics and can be discussed in analogy. Novel designs for OPV modules, i.e. concentrically connected rings [15], might reduce the possibility of a fully shaded single cell within a module and thus reduce the losses in the power output while shading.

The standard method to control shading failure in PV technologies is to incorporate so-called bypass diodes anti-parallel to the individual solar cells of the module. Under shading, respectively under reverse bias, the bypass diode opens up and can form an alternative electrical path for the module's photocurrent. The voltage drop on the shaded cell is then limited to the voltage required opening up the bypass diode [16,17].

3. Experimental

We investigated monolithically integrated organic solar modules (see Fig. 1), where the bottom electrode of one solar cell is connected to the top electrode of the next. Modules with 3 and 9 interconnected cells were investigated. OPV modules were prepared on flexible PET/ITO substrates according to the procedure outlined elsewhere [13,14,18,19]. All production steps, except for evaporation of the back electrode, were performed in air. As a semiconductor layer, regio-regular poly (3-hexylthiophene):([6,6]-phenyl C61 butyric acid methyl ester) (RR-P3HT:PCBM) was used. To investigate shading, bypass diodes were interconnected anti-parallel to the single organic solar cells of the module. The last cell of the module was shaded. The organic bypass diodes are processed in the same way as the organic solar cells [13,14,18,19]. The J–V characteristics were measured with a Keithley source measurement unit (SMU 2400). A calibrated Steuernagel solar simulator was used for illumination providing an AM 1.5G spectra at 100 mW/cm^2.

4. Results and discussion: organic bypass diodes

The processing of monolithically interconnected OPV modules is quite different from the one for inorganic PV modules. OPV modules are manufactured by roll-to-roll printing processes [20–24], while inorganic solar cells are processed by either wafer-based or vacuum-based processing technologies. Integration of inorganic bypass diodes by the pick-and-place process, as typically used with inorganic PV modules, would be technically possible for OPV modules as well. However, combining such a discontinuous low-speed process with roll-to-roll printing is anything else than desirable and would eliminate some of the advantages of the OPV technology in terms of processing. Thus, for process reasons, a hybrid structure should be avoided. A natural solution to that problem is the use of organic, printed diodes as bypass diodes. There are several reports and types of organic diodes [25–27]. Among those, the desirable solution for a module bypass diode would be of course diodes that are based on the same process materials as the photovoltaic modules themselves, i.e. based on the same electrode and semiconductor materials.

In the following, we will discuss the design requirements for organic bypass diodes essential to address module shading issues for OPV modules. First, the bypass diodes have to be integrated within the flexible OPV modules without or with only little further processing steps. Second, the diode characteristics of the bypass diode should match the demands of the module to overcome shading effects. That point will be elaborated in more detail later on when the turn on bias of various diode technologies are compared to each other. The proper choice of the organic semiconductor and the electrodes will determine the performance of the bypass diodes. Third, there is process compatibility. Being able to use the same semiconductor for the bypass diodes, which

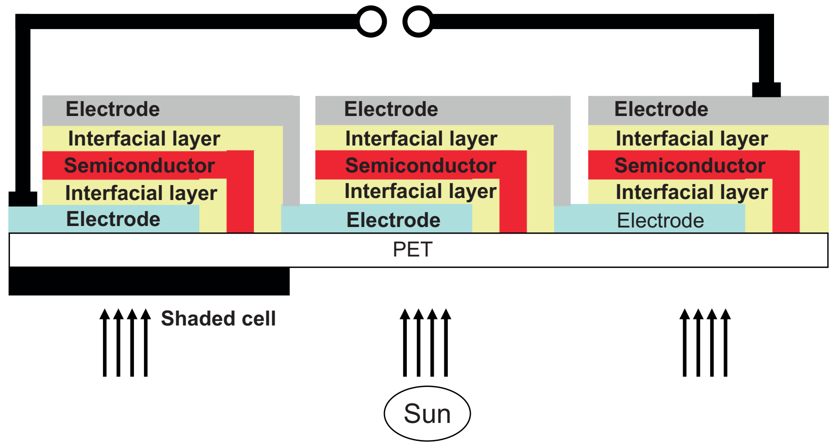

Fig. 1. The structure of a 3 stripe monolithic integrated OPV module is schematically depicted. The left cell of the module is shaded.

is also used for the active layer of the solar cells, allows coming along with a "one color" printing process, as compared to a "two color" printing process. Naturally, we propose using inverse interconnected organic solar cells as the most attractive concept to overcome shading in OPV modules. As such, we have used non-illuminated organic solar cells in reverse operation as bypass diodes to address our goal for a fully organic-based structure (OPV module plus organic bypass diodes).

In the following we discuss the effect of shading exemplarily for a module with 9 single cells connected in series. The discussion can be transferred to modules with more then 9 cells in analogy, differing in the reverse voltage that adjusts on the shaded cell. This reverse voltage depends on the number of non-shaded cells connected in series in a module. The upper limit of this reverse voltage is the number of non-shaded cells times the open-circuit voltage of the single OPV cells.

In the following paragraphs we present data showing that organic solar cells are suitable for bypass diodes in OPV modules, discuss in detail the properties of an organic solar cell operated as bypass diode and compare organic bypass diodes with the conventional one from inorganic diodes (based on silicon (Si) and gallium arsenide (GaAs) semiconductor technology).

Fig. 2a shows the dark *J–V* curves of the organic, GaAs and Si bypass diodes side by side. The 3 diodes differ in their core parameters, namely the threshold voltage, the *J–V* characteristic in injection mode and the leakage current. These parameters are most important to judge bypass diodes and in the following we discuss their impact on the performance of bypass diodes. The GaAs carries the lowest injection current, while the organic diode shows the highest leakage current. Note that this is an atypically large leakage current for organic solar cells and diodes. OPV cells with excellent leakage currents in the $\mu A/cm^2$ regime from -1 to -5 V were already published [3,27]. A too large leakage current of the bypass diode induces power losses when the module is operated in normal conditions. The magnitude of the power loss is the diode's leakage current at reverse voltage of the maximum power point (MPP) multiplied with the corresponding voltage. However, we decided to work with an average leaking organic diode as bypass diode to better understand the induced loss mechanisms.

Fig. 2b shows the current–voltage characteristics of a 9 stripe flexible OPV module with and without shading. For reference, the module characteristics are compared to the same module when only 8 cells are contributing, i.e. the last cell of the module, which otherwise was shaded, was externally shunted. The shading test confirms organic modules as Type I modules. The leakage current of the cells under reverse bias is insufficient to pass by the photovoltaic power of the non-shaded part of the module. As a consequence, the whole module is shut down, with the power being dissipated across the shaded cell.

Fig. 2c shows the situation of a partially shaded module bypassed by an organic, GaAs- or Si-based bypass diode. The figure of merit for the bypass diodes is the power output of the shaded module under MPP operation. This is depicted in Fig. 2d, where the power generation for the module with various bypass diodes is compared to one of the unshaded module that has a power output of 1.76 mW/cm^2 under MPP operation. The dramatic loss in the power output of the shaded flexible OPV module can be reduced significantly with a bypass diode. The power loss for the module without a bypass diode is as high as 99%. Using an organic bypass diode, this loss is reduced to approximately 30% (1.23 mW/cm^2). Similar values for the power loss are found when using inorganic diodes as bypass diode. The theoretical minimum power loss due to shading in a 9 stripe module is 11% (1.57 mW/cm^2), which is the geometrical area loss from the shaded cell, given that the bypass diode does not cause any electrical losses. This theoretical optimum is shown in Fig. 2b by the *J–V* curve of a 9 stripe module with only 8 stripes operated. Nevertheless comparing the organic diode with commercially available Si and GaAs diodes, we find that the organic bypass diode is working as well as its inorganic counter parts.

Bypass diodes can reduce the performance of normally operated modules (i.e. non-shaded) for two reasons. On the one hand, they occupy some area on the front side of the module. On the other hand, their leakage current reduces the module photocurrent at MPP. The necessary size of the bypass diode is determined by its current-carrying capacity in injection, which has to be large enough to let pass the photocurrent of the module under forward bias. The necessary voltage, at which the bypass diode is able to pass by the photocurrent of the shaded module, is taken from the photovoltage of the module under operation and thus lost for the module operation. The bypass diode will be adjusted at the voltage required to pass by the photocurrent, and, as such, a low turn on voltage is essential to reduce the bypass diode losses under shading. Naturally, this voltage is higher for small-area organic bypass diodes compared to large-area organic bypass diodes. Summarizing, on the one hand large-area bypass diodes are favourable for little losses in the module voltage under shading. On the other hand a large bypass diode does decrease the geometrical fill factor of the device and thus the power output/square of the module, since it is printed on the module's front side. A bypass diode sized 2 cm^2 results in a voltage drop of

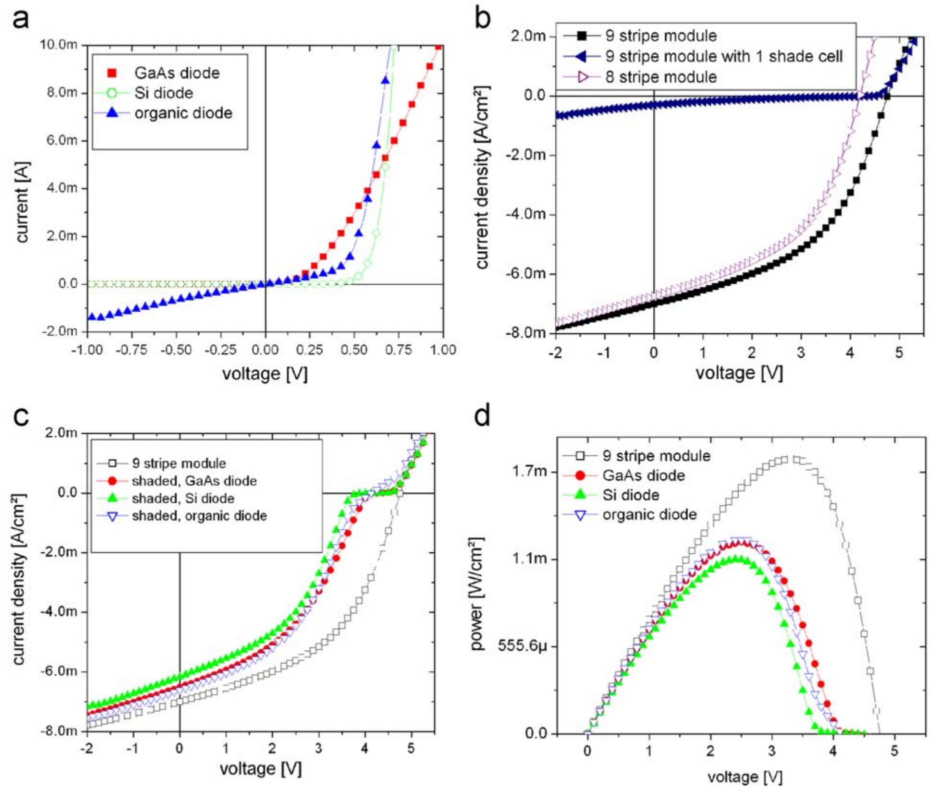

Fig. 2. (a) Dark J–V characteristic of the organic, GaAs and Si bypass diode under study. (b) J–V characteristics of a 9 stripe flexible OPV module with and without shading. For reference, the module characteristic is compared to the same module when only 8 cells are contributing. The last cell of the module is externally shunted. (c) J–V curves and (d) power output–voltage plot of a shaded 9 stripe module when the shaded cell is bypassed by an organic, GaAs and Si diode. As reference the non-shaded 9 stripe module is depicted.

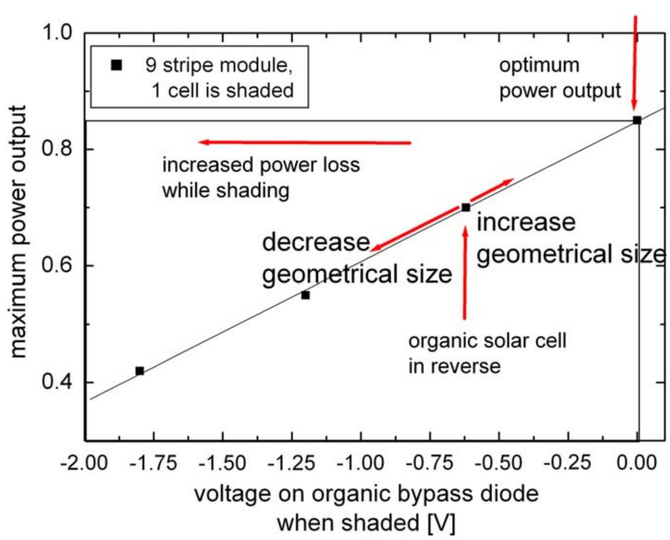

Fig. 3. Loss in power output (normalized to 1) versus the voltage that adjusts on the bypass diode. This voltage is needed to bypass the current of the 8 non-shaded cells. The optimum power output and the power output of the module when the organic bypass diode bypasses the current are depicted. The other data points correspond to organic diodes with higher threshold voltages. For higher voltages that adjust on the bypass diode the power loss increases. An increase of the geometrical size of the bypass diode decreases the power loss. A decrease of the geometrical size of the bypass diode increases the power loss.

0.62 V, and a bypass diode sized 1 cm^2 results in a voltage drop of 0.7 V. These values are derived from the J–V characteristics in injection of the organic bypass diodes depicted in Fig. 2a. The impact of the turn-on voltage of the bypass diode on the module losses under shading are summarized in Fig. 3.

Another important parameter to determine the best bypass diode is the leakage current. Under normal, non-shaded operation, the leakage current of the bypass diode is a loss for the photocurrent. Typical leakage currents of the investigated organic solar cell structures are $\sim$50 μA/cm^2 at -0.5 V [3]. For a solar cell operated at its MPP of 0.45 V, such a bypass diode results in a permanent ohmic loss of 25 μW/cm^2 or less. Compared to the AM 1.5 power output of a P3HT/PCBM solar cell with $\sim$3–4 mW/cm^2, this is a loss smaller than 1% when the active area of the bypass diode and the solar cell are equal. Geometrical fill factor losses by the size of the bypass diode are neglected in this calculation. This loss is further decreased when the geometrical size of the organic bypass diode is reduced. Note that good organic diodes have leakage currents in the very low μA/cm^2 regime, in which case the organic bypass diode losses for a solar cell will be negligibly small. Thus we conclude that an organic solar cell can be used as a bypass diode for an organic PV module. The module power losses under normal operation due to an organic bypass diode are well below the 1% regime.

4. Conclusion

In summary, we have investigated shading in organic PV modules and found that OPV modules show Type I behaviour, where the whole module is shut down if one cell becomes shaded (99% power loss). We further demonstrated that organic bypass diodes are the most elegant and practical technology to reduce the shading losses to $\sim$30%. No substantial advantage was found when using inorganic diodes (Si and GaAs) as bypass diodes. In the sum of the properties, organic bypass diodes were shown to be superior to their inorganic counterparts:

- the module losses under shading were as low as for the inorganic diodes investigated;
- the leakage current and current carrying capacities are sufficient to keep the module losses under normal operation well below 1%;
- process wise, it takes the lowest efforts to integrate an organic diode as bypass diode into an organic PV module.

Thus, we propose the use of organic bypass diodes and in particular organic bypass diodes based on organic solar cell structure operating in reverse as ideal bypass diodes to address OPV module shading effects.

References

[1] M.C. Alonso-Garcıa, J.M. Ruız, Analysis and modelling the reverse characteristic of photovoltaic cells, Sol. Energy Mater. Sol. Cells 90 (2006) 1105–1120.
[2] M.C. Alonso-Garcia, W. Herrmann, W. Böhmer, B. Proisy, Thermal and electrical effects caused by outdoor hot-spot testing in associations of photovoltaic cells, Prog. Photovoltaics 11 (5) (2003) 293–307.
[3] R. Steim, S.A. Choulis, P. Schilinsky, U. Lemmer, C.J. Brabec, Formation and impact of hot spots on the performance of organic photovoltaic cells, Appl. Phys. Lett. 94 (2009) 043304.
[4] F.A. Blake, K.L. Hanson, The hot-spot failure mode for solar arrays, in: Proceedings of the Fourth Intersociety Energy Conversion Engineering Conference, 1969, pp. 575–581.
[5] European Norm EN-61215, Crystalline silicon terrestrial photovoltaic (PV) modules—design qualification and type approval, 1995.
[6] European Norm EN-61646, Thin-film terrestrial Photovoltaic (PV) modules—-design qualification and type approval, 1997.
[7] UL1703, UL standard for safety for flat-plate photovoltaic modules and panels, 1993.
[8] IEEE 1262, IEEE recommended practice for qualification of photovoltaic (PV) modules, 1995.
[9] See press release on 〈www.konarka.com〉, December 2008.
[10] W. Ma, C. Yang, X. Gong, K. Lee, A.J. Heeger, Thermally stable, efficient polymer solar cells with nanoscale control of the interpenetrating network morphology, Adv. Funct. Mater. 15 (10) (2005).
[11] J.Y. Kim, K. Lee, N.E. Coates, D. Moses, T.-Q. Nguyen, M. Dante, A.J. Heeger, Efficient tandem polymer solar cells fabricated by all-solution processing, Science 317 (2007) 222–225.
[12] J.A. Hauch, P. Schilinsky, S.A. Choulis, S. Rajoelson, C.J. Brabec, The impact of water vapor transmission rate on the lifetime of flexible polymer solar cells, Appl. Phys. Lett. 93 (2008) 103306.
[13] C. Hoth, S.A. Choulis, P. Schilinsky, C.J. Brabec, High photovoltaic performance of inkjet printed polymer:fullerene blends, Adv. Mater. 19 (22) (2007) 3973–3978.
[14] Claudia N. Hoth, Pavel Schilinsky, Stelios A. Choulis, Christoph J. Brabec, Printing highly efficient organic solar cells, Nano Lett. 8 (9) (2008) 2806–2813.
[15] F.C. Krebs, M. Jørgensen, K. Norrman, O. Hagemann, J. Alstrup, T.D. Nielsen, J. Fyenbo, K. Larsen, J. Kristensen, A complete process for production of flexible large area polymer solar cells entirely using screen printing—first public demonstration, Sol. Energy Mater. Sol. Cells 93 (2009) 422–441.
[16] E. Molenbroek, D.W. Waddington, Conference Record of the IEEE Photovoltaic Specialists Conference, vol. 1, 1992, pp. 547–552.
[17] A. Woyte, J. Nijs, R. Belmans, Sol. Energy 74 (3) (2003) 217–233.
[18] P. Schilinsky, C. Waldauf, C.J. Brabec, Performance analysis of printed bulk heterojunction solar cells, Adv. Funct. Mater. 16 (2006) 1669–1672.
[19] C. Waldauf, M. Morana, P. Denk, P. Schilinsky, K. Coakley, S.A. Choulis, C.J. Brabec, Highly efficient inverted organic photovoltaics using solution based titanium oxide as electron selective contact, Appl. Phys. Lett. 89 (2006) 233517.
[20] F.C. Krebs, Polymer solar cell modules prepared using roll-to-roll methods: knife-over-edge coating slot-die coating and screen printing, Sol. Energy Mater. Sol. Cells 93 (2009) 465–475.
[21] L. Blankenburg, K. Schultheis, H. Schache, S. Sensfuss, M. Schrödner, Reel-to-reel wet coating as an efficient up-scaling technique for the production of bulk-heterojunction polymer solar cells, Sol. Energy Mater. Sol. Cells 93 (2009) 476–483.
[22] F.C. Krebs, S.A. Gevorgyan, J. Alstrup, A roll-to-roll process to flexible polymer solar cells: model studies, manufacture and operational stability studies, J. Mater. Chem. (2009)10.1039/B823001C.
[23] F.C. Krebs, Roll-to-roll fabrication of monolithic large-area polymer solar cells free from indium-tin-oxide, Sol. Energy Mater. Sol. Cells 93 (2009) 1636–1641.
[24] F.C. Krebs, All solution roll-to-roll processed polymer solar cells free from indium-tin-oxide and vacuum coating steps, Org. Electron. 10 (5) (2009) 761–768.
[25] M. Punke, S. Valouch, S.W. Kettlitz, N. Christ, C. Gärtner, M. Gerken, U. Lemmer, Dynamic characterization of organic bulk heterojunction photodetectors, Appl. Phys. Lett. 91 (2007) 071118.
[26] D. Zipperer, Organische Gleichrichter, Friedrich-Alexander-Universität Erlangen-Nürnberg.
[27] S.F. Tedde, J. Kern, T. Sterzl, J. Fürst, P. Lugli, O. Hayden, Fully spray coated organic photodiodes, Nano Lett. 9 (3) (2009) 980–983.