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Abstract. Over the last three decades, progress in the organic photovoltaic field has resulted in some device features which make organic cells applicable in electricity generation configurations where the standard silicon-based technology is not suitable, for instance, when a semi-transparent photovoltaic panel is needed. When the thin film solar cell performance is evaluated in terms of the device’s visible transparency and power conversion efficiency, organic solar cells offer the most promising solution. During the last three years, research in the field has consolidated several approaches for the fabrication of high performance semi-transparent organic solar cells. We have grouped these approaches under three categories: devices where the absorber layer includes near-infrared absorption polymers, devices incorporating one-dimensional photonic crystals, and devices with a metal cavity light trapping configuration. We herein review these approaches. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.JPE.5.057212]

Keywords: photovoltaic cells; solar cells; transparent materials; organic materials; optical trapping; photonic crystals.

Paper 14066MVSS received Sep. 26, 2014; accepted for publication Jan. 19, 2015; published online Feb. 16, 2015.

1 Introduction

Research in organic photovoltaics (OPVs) escalated when it was proposed as one of the low cost alternatives to the silicon-based PV technology. For about three decades, progress in the field has brought to the forefront some specific features of organic cells, which are very interesting when considering them for applications where the silicon technology is less applicable. During those years, material science research has successfully pushed the band gap of PV polymers from the near UV or visible toward the near-infrared region (NIR). Today, one may find several PV polymers, known in the field as “low band gap polymers,” where the band gap is centered close to where the sun photon flux is maximum.1–35 When combined with certain derivatives of the fullerene molecule, single junction cells with power conversion efficiencies approaching 10% can be fabricated.36–40 Amazingly, in the majority of such high performance single junction devices, the absorber layer, consisting of a bulk hetero-junction (BHZ) of the above-mentioned polymers and fullerene derivatives, is typically not more than 100 nm thick. Visible light is partially transmitted through such thin absorber layers, making it possible to clearly see objects which appear unaltered in shape or color to the viewer. The potential for the integration of such a technology on transparent vertical surfaces, which dominate the landscape of any major city, is tremendous. Devices fabricated from other thin film PV technologies can be made semi-transparent. But when the solar cell performance is evaluated in terms of the power conversion efficiency (PCE) and the level and quality of the luminosity, corresponding to the integral of the

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This review manuscript is also part of the section on “Breakthroughs in Photonics and Energy,” highlighting primarily recent advances in the last three years.
transmission weighted by the product of the human eye photopic spectral response with illumination from the white standard illuminant CIE-D65, organic technology offers the most promising solution.

Approximately 10 years ago, attempts to fabricate semi-transparent OPV cells could already be found in the scientific literature. Given the intrinsic semi-transparency of the absorber layer, one of the main challenges researchers had to face was to obtain a good quality semi-transparent top electrode. This electrode must be deposited when the absorber layer has already been deposited on the substrate and a nonaggressive deposition procedure needs to be used. Several different options have been considered, such as low-temperature annealed indium tin oxide (ITO), a three-layer architecture combining a dielectric layer, an ultra thin metal layer, and a second dielectric layer, PEDOT, silver grid, graphene, carbon nanotubes, and silver nanowires (AgNW). However, the need for a nondestructive deposition technique for the top semi-transparent electrode is probably not the major issue that semi-transparent OPV cells must overcome before becoming an industrially viable solution. Indeed, when the top electrode of an OPV cell is made semi-transparent, the capacity of the solar device to trap the electromagnetic field in the absorber layer diminishes. Regardless of the type of semi-transparent top electrode used this occurs at all wavelengths leading to devices exhibiting PCEs which are about 60% of the devices corresponding to an equivalent opaque cell. During the last 2 or 3 years, research in the field has consolidated several approaches to partially limit such a dramatic loss in PCE.

We have grouped these approaches under three categories. First, we will consider what is, perhaps, the most straightforward approach consisting of further decreasing the polymer band gap to obtain a larger transparency in the visible spectrum. One of the most relevant features of this approach is that it provides a very nice colorless high level of transparency. On the other hand, the limited harvesting at all wavelengths resulting from the low reflectivity of the top electrode can be partially compensated with the incorporation of an additional absorber layer in a tandem configuration. The second approach to increase transparency in the visible spectrum and to limit the loss in PCE is the incorporation of multilayer anti-reflection coatings for the visible or Bragg reflectors to help to trap the near UV and NIR. The combination of both may further improve the balance between transparency and PCE. But an optimal performance is achieved when the multilayer structure is a nonperiodic structure designed ad hoc. In the latter case, an inverse integration design must be used to specifically determine each layer thickness for the extinction coefficient of the absorber layers, the rest of the materials used in the electrodes and buffer layers, and the architecture of the device as a whole. The last category we will discuss consists of enclosing the active layer in a Fabry–Perot type cavity formed by the two metallic semi-transparent electrodes. This approach which, until recently had been applied to opaque cells with limited success, was proven in 2014 to lead to high PCEs for opaque cells using low-band gap polymers in the absorber layer. The same approach has been applied to semi-transparent devices and cells exhibiting a PCE equivalent to 90% of the PCE of the opaque counterpart have been demonstrated.

2 Semi-Transparent Polymer Cells

2.1 Semi-Transparent Organic Photovoltaic Cells with Near-Infrared Region Absorption Polymers

A straightforward strategy to fabricate semi-transparent OPVs is to use donor polymers, harvesting most of the photons in the NIR. In Ref. 79, the authors used the as absorber film a blend of PBDTT-DPP and PCBM. PBDTT-DPP is a low-band gap polymer with a strong photosensitivity in the 650 to 850 nm wavelength range, while the absorption of PCBM is located below 400 nm. With a combination of these two materials, the PBDTT-DPP: PCBM photoactive layer has an average transmission of 68% over the visible range (from 400 to 650 nm), but is strongly absorbing in the NIR range (from 650 to 850 nm). This spectral coverage of the PBDTT-DPP:PCBM film ensures harvesting of UV and NIR photons leading to PCEs above 4%. More recently, a PCPDTFBT polymer with a similar spectral response, i.e., a major absorption located at the near infrared region, was used to fabricate semi-transparent OPV cells with a PCE above 5%. In the
fabricated devices, PCPDTFBT:PC$_71$BM was used as active BHJ layer, with a configuration of ITO/ZnO/PCPDTFBT:PC$_71$BM/PEDOT:PSS/ultra-thin Ag. With a 15 nm Ag as the semi-transparent top electrode, the device exhibited an average transmission of 39.4% while for device with a thinner Ag layer of 10 nm the average transmission was increased to 47.3% without significantly compromising its PCE. This finding was associated with the good wettability of Ag atoms on the polar PEDOT:PSS layer, which allowed Ag atoms to grow homogeneously.

Although the results reported above indicate the soundness of the NIR absorption polymer approach to obtain high performance semi-transparent cells, there is a limit linked to the decrease in harvesting capacity when a device incorporates two semi-transparent electrodes. This is the case because the semi-transparency of the electrodes is usually homogenously distributed in the UV-visible-NIR range and the device loses its capacity to trap invisible UV or NIR light as well. To compensate for this effect, the authors of Ref. 84 considered a transparent OPV having a tandem structure using two different polymers with an absorption band in the NIR. The front subcell in the device incorporated the transparent absorber PBDTT-FDPP-C12: PC61BM which exhibits an average visible transmission from 400 to 650 nm of approximately 60% and an IR transmission of 52% from 650 to 800 nm. Therefore, approximately half of the IR energy was not fully captured for energy conversion. The back subcell featuring PBDTT-SeDPP: PC61BM as the absorber exhibited a similar NIR transmission of 53% with an extended NIR response from 650 to 900 nm. By stacking these two transparent absorbers in a tandem structure, NIR transmission dropped to 26%. In other words, the photon absorption efficiency in the NIR range increased nearly twofold and semi-transparent OPV cells exhibiting a PCE above 7% were reported. Recently, an efficiency of 8.02% in a tandem OPV cell with a semi-transparency of 44.90% was achieved using solution-processed graphene as the front electrode and laminated nanowires as the top electrode.71 In all such tandem devices, the NIR energy was more completely harnessed while approximately half of the visible photons were transmitted.

### 2.2 Semi-Transparent Organic Photovoltaic Cells Incorporating One-Dimensional Photonic Crystals or Multilayers

A manipulation of the photon propagation inside the cell can be externally achieved with the use of one-dimensional (1-D) photonic crystals or dielectric multilayers. To enhance trapping of the electromagnetic field at the near UV and NIR wavelengths, one may consider 1-D photonic structures incorporated above the top semi-transparent electrode to reflect the NIR and UV and to transmit the visible spectrum. A combination of a Bragg reflector and an anti-reflective coating (ARC) has been used to increase NIR photon harvesting demonstrating that the efficiency of small molecule OPV cells could be increased from 1.3% to 1.7%.42 Similar configurations considered the use of a single Bragg mirror deposited on top of the back metal electrode to reflect the red and NIR wavelengths. This was shown to increase the short-circuit current density ($J_{sc}$) of OPVs as the number of layers was increased from 2 to 8.86

The 1-D photonic crystals or Bragg reflectors are designed to satisfy the Bragg condition to get maximum reflectivity at NIR wavelengths. However, in a photovoltaic device, interference must be optimal at all wavelengths of interest to achieve the highest visible transmission and optimal trapping for UV and IR light. One way to better reach the goal of a broadband photonic control using simple 1-D structures is to increase the degrees of freedom and use a numerical inverse problem solving method. For a semi-transparent OPV cell, there are essentially two parameters that will determine its level of performance: the efficiency in converting light to electricity and the device visible transmission or luminosity. Numerical inverse problem solving must be implemented by removing the periodicity constraint to design a photonic multilayer (cf. Fig. 1) that maximizes the contribution to the $J_{sc}$ for wavelengths below the near UV and above the NIR while keeping the device’s visible transparency above the desired lower limit value.

In an application of semi-transparent OPV cells of the inverse solving method, single junction cells using absorber layers of the PTB7:PC$_{71}$BM blend were considered.43 As shown in Fig. 2, the $J_{sc}$ obtained following such a procedure increases rapidly when layers are added in the photonic crystal but saturates beyond five layers. For the five-layer structure, the calculated $J_{sc}$ was 76.3% that of the corresponding opaque cell. On the contrary, for an optimal six-layer periodic structure, the best efficiency that can be reached is 72% that of the opaque cell. The better...
performance of the nonperiodic structure is attributed to reflectivity, as shown in Fig. 3, that adapts optimally not only to the absorption spectrum of the absorber blend but also to the sun photon flux. As seen in Fig. 3, the reflectivity of the nonperiodic structure is enhanced for the NIR photons at the expense of a reduction for the near UV photons when compared to the reflectivity of the six-layer periodic structure. This result is in correspondence to a larger photon flux in the NIR range relative to the UV. The reflectivity in the visible range is kept low in both cases, ensuring a visible device transparency or luminosity close to or above 30%.

This type of design has been tested and implemented in cells constructed either in a standard or inverted configuration using the PTB7:PC71BM blend as the absorber layer. For the standard configuration, ITO and a 10-nm thick Ag layer were used as electrodes while PEDOT:PSS and thermally evaporated BCP were used as an electron blocking layer (EBL) and hole blocking layer (HBL), respectively. The multilayer structure implemented on top of the Ag electrode combined layers of a low refractive index material such as LiF with layers of a high refractive index material such as MoO3. As shown in Fig. 4(a) where the calculated external quantum efficiency (EQE) of the cell including the multilayer is compared to the EQE of a semi-transparent cell not including the multilayer, one observes that contributions to J_sc from the NIR as well as near UV photons are clearly enhanced. For certain NIR photons, the EQE for the device incorporating the multilayer is close to matching the EQE of an equivalent opaque cell.41

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**Fig. 1** PTB7:PC71BM cells incorporating (a) a periodic one-dimensional (1-D) photonic crystal of six layers, (b) a nonperiodic multilayer of five layers. MoO3/MgF2 have been used as high/low refractive index materials.

**Fig. 2** As a function of the number of layers numerically determined relative to the short-circuit current (green solid dots) and luminosity (green circles) for devices incorporating the nonperiodic multilayer, and the relative short-circuit current (red solid squares) and luminosity (red empty squares) for devices incorporating optimal periodic 1-D photonic crystals of 2 and 3 periods. The short-circuit currents are given relative to the corresponding one from an equivalent opaque cell.
contribution from visible photons to the EQE remains similar to the one seen for a bare semi-transparent cell for the same type of photons.

For the inverted solar cells, the architecture considered was similar except that a thermally evaporated MoO$_3$ layer was used as EBL while a ZnO layer was used as HBL. The ZnO layer was grown by sol-gel where the precursor solution was prepared according to Ref. 94. In order to make the inverted devices semi-transparent, similar to the standard configuration, the back silver contact was made 10 times thinner than that for the opaque cells, i.e., a 10 nm instead of 100 nm thickness. To enhance the performance of the semi-transparent cells, a five-layer structure based on MoO$_3$ (high refractive index material) and MgF$_2$ (low refractive index material) was incorporated. The EQE shown in Fig. 4(b) shows a similar redistribution of photon harvesting as the one found for the standard configuration devices. In both cases, as seen in Fig. 4, the agreement between the experimentally measured EQE and the numerical design is remarkable.

2.3 Semi-Transparent Organic Photovoltaic Cells with Light Trapping Metal Cavities

Light trapping by using two metal electrodes has been considered in several OPV opaque cell configurations. Recently, OPV devices with an ITO-free microcavity structure that reached high
PCEs of 8.5% on both glass and flexible plastic substrates have been reported.\textsuperscript{91} This corresponds to $\sim 20\%$ improvement in PCE when compared to the equivalent ITO-based devices. The significantly enhanced performance was ascribed to the substantially improved photon collection by the resonant microcavity structure, which contributed to an improved photocurrent compared with devices built on ITO-coated substrates.

Photon trapping in between the two metal electrodes can also be applied to semi-transparent OPV cells. In that event, both electrodes in the device are kept thin to ensure a sufficiently high luminosity. In a recent implementation of this configuration, to increase light trapping an ARC was deposited on top of the front metal contact while a nonperiodic multilayer was inserted in between the back metal contact and the substrate. As for the configuration considered in the previous section, the optimal layer distribution was specifically designed for the cell architecture used. With a device architecture such as the one shown schematically in Fig. 5, semi-transparent cells whose PCE was 5.3%, corresponding to 90\% of the PCE of the corresponding opaque cell, were reported.\textsuperscript{92} The visible transparency of such cells differed little from the semi-transparent cell which did not include the multilayer, while the EQE closely matched that of the opaque cell as seen in Fig. 6. The opaque cell was in an inverted configuration with the following architecture: As the active material, a thin layer of PTB7:PC\textsubscript{71}BM blend was used. The bottom electrode was an opaque layer of 120 nm of Au and the top electrode was a semi-transparent layer of 10 nm of Ag. ZnO and MoO\textsubscript{3} were used as HBL and EBL, respectively. On top of the Ag electrode, a two-layer ARC made of MoO\textsubscript{3} and LiF was deposited. For the semi-transparent devices, the same exact architecture was used except that the Au electrode was thinned down to 13 nm. As seen in Fig. 5, in between the Au electrode and the substrate, a six-layer 1-D multilayer made of alternating TiO\textsubscript{2} and SiO\textsubscript{2} was incorporated. Following an inverse integration procedure as discussed above, such a structure was numerically designed to maximize the current while keeping the luminosity of the solar cell above 20\%.

The conclusion was that when the OPV architecture included two thin metallic electrodes with one of them being assisted with a 1-D multilayer to enhance reflectivity for the case of semi-transparent cells, one may obtain a broadband photon trapping capacity sufficient to match the performance of semi-transparent cells to opaque ones. It was demonstrated that it is the combined effect of such a 1-D multilayer and a thin-metal layer that prevents, to a large extent, the loss in photon harvesting capacity exhibited by the majority of semi-transparent cells. Indeed, the $J_{sc}$ for a cell device incorporating such a cavity configuration which exhibited a 21\% luminosity amounted to 96.4\% the $J_{sc}$ of the corresponding opaque cell.

**Fig. 5** Schematic picture of a PTB7:PC\textsubscript{71}BM cell in a metal cavity configuration incorporating a periodic 1-D photonic crystal of six layers and an anti-reflection coating.
3 Toward Fully Solution Processed Semi-Transparent Organic Photovoltaic Cells

A summary of the recent achievements in OPV is given in Table 1. From that table, we may conclude OPV cells with transparencies above 30% combined with PCE above 5% are feasible for the implementation of different kinds of approaches. It would make sense to combine the approach based on using NIR absorber layers with the one based on incorporating a photonic structuration to re-harvest the near UV and NIR light lost when the top electrode is made semi-transparent; this approach would push the PCE of highly semi-transparent cells closer to the corresponding PCE for the opaque devices, bringing the PCE of visibly transparent cells to

Table 1 Summary of high performance semi-transparent organic photovoltaic (OPV) cells reported during the 2012 to 2014 period.

<table>
<thead>
<tr>
<th>Structure</th>
<th>(J_{sc}) (mA/cm(^2))</th>
<th>(V_{oc}) (V)</th>
<th>FF</th>
<th>Eff (%)</th>
<th>Transmission (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITO/PEDOT:PSS/PBDTT-DPP:PCBM/TiO(_2)/AgNW</td>
<td>9.30</td>
<td>0.77</td>
<td>56.2</td>
<td>4.0</td>
<td>60</td>
<td>79</td>
</tr>
<tr>
<td>ITO/PEDOT:PPS/PIDT-PhanQ:PC(_{71})BM/Surfactant/thin Ag</td>
<td>9.99</td>
<td>0.84</td>
<td>61</td>
<td>5.1</td>
<td>24</td>
<td>Average visible</td>
</tr>
<tr>
<td>ITO/ZnO/PCPDTBT:PC(_{71})BM/PEDOT:PPS/thin Ag</td>
<td>11.9</td>
<td>0.73</td>
<td>58.3</td>
<td>5.1</td>
<td>39.4</td>
<td>Average 380–700 nm</td>
</tr>
<tr>
<td>ITO/PEDOT:PSS/PBDTT-FDPP-C12:PC71BM/PFN/TiO(_2)/PEDOT:PBDTT-SeDPP:PC71BM/TiO(_2)/AgNW</td>
<td>8.4</td>
<td>1.47</td>
<td>59</td>
<td>7.3</td>
<td>30</td>
<td>Average 400–650 nm</td>
</tr>
<tr>
<td>Graphene Mesh/PEDOT:PSS/PSEHTT/IC60BA/ZnO/PEDOT:PSS/PBDTT-DPP:PC71BM/TiO(_2)/AgNW</td>
<td>7.62</td>
<td>1.62</td>
<td>64.2</td>
<td>8.02</td>
<td>45</td>
<td>Average 400–650 nm</td>
</tr>
<tr>
<td>ITO/ZnO/P3 HT:PCBM/MoO(_3)/thin Ag/1-D photonic crystal</td>
<td>10.89</td>
<td>0.63</td>
<td>66</td>
<td>4.3</td>
<td>12</td>
<td>At 550 nm</td>
</tr>
<tr>
<td>ITO/PEDOT/PTB7:PC(_{71})BM/BCP/thin Ag/1-D photonic crystal</td>
<td>10.9</td>
<td>0.73</td>
<td>70</td>
<td>5.6</td>
<td>28</td>
<td>Luminosity</td>
</tr>
<tr>
<td>1-D photonic crystal/thin Au/ZnO/PTB7:PC(_{71})BM/MoO(_3)/thin Ag/ARC</td>
<td>10.7</td>
<td>0.728</td>
<td>67.9</td>
<td>5.3</td>
<td>21.4</td>
<td>Luminosity</td>
</tr>
</tbody>
</table>
the limit efficiencies that were recently established on a model based on the Shockley–Queisser theory.\textsuperscript{95}

However, there are several scientific and technical issues that must be addressed before OPV technology can become commercially applicable in any kind of semi-transparent device or element. Although the PCEs measured are considerably high (See Table 1), a drop of at least 20% in PCE is likely to happen when up-scaling from laboratory cells to modules. In the majority of the configurations from Table 1, the fabrication procedure followed includes several steps that require high vacuum thermal evaporation or sputtering, especially in the fabrication of the electrodes. It is likely that this would preclude a favorable cost efficiency ratio when this technology is compared to other thin-film inorganic-based technologies that also have the potential to become semi-transparent.

Several relevant steps in that direction have been recently achieved when a solution processing was implemented in all the fabrication steps for highly transparent cells. AgNW was used as the material in the semi-transparent electrodes on both sides of the OPV cell\textsuperscript{77,96} and, more recently, other alternatives to high vacuum processed transparent electrodes such as highly doped PEDOT,\textsuperscript{73} PEDOT:PSS:CNTs,\textsuperscript{67} graphene,\textsuperscript{71} have been implemented in OPV cells. In general, the fully solution-processed cells have been shown to perform similarly to equivalent cells fabricated using a sputtered ITO electrode.

On the other hand, although some companies or research centers are working toward improving the stability of the OPV cells, there are no systematic studies that demonstrate an optimal performance of OPV devices over the long timescales required for the majority of applications of transparent PV cells. Finally, it will be necessary to address other relevant issues related to the product life cycle, such as safe disposal and recovery of the materials used in the fabrication of OPVs. In summary, to achieve the industrial production of a semi-transparent PV technology, the main challenges are to increase the efficiency, establish and implement the appropriate up-scaling methodology and obtain stable devices while ensuring a low cost production.

The goal in the following years is to combine, in a fully solution processed single device, NIR polymers with photonic structures or 1-D multilayers. This will require the development of new nanomaterials that can be solution processed to fabricate the buffer layers (HBL and EBL) and the photonic multilayered architecture. The aim should be to completely eliminate all of the high vacuum steps. Indeed, fabrication using only solution processing may be critical when considering transparent devices with possible applications as building elements, since the production of large window panels using high vacuum technology is costly and technically complex. The challenge of enhancing the performance of semi-transparent cells also requires an improvement of the performance of opaque cells. To achieve such a goal, one may target the development of new cross-linkable absorber polymers adapted to better light harvesting in the NIR. To complement this approach, one may develop optically optimized tandem architectures to increase light harvesting.

**Acknowledgments**

The authors acknowledge support from the Ministerio de Economia y Competitividad (Grant Nos. MAT2011-28665, IPT-120000-2010-29, IPT-2012-0986-12000 and CSD2007-00046).

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