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Semitransparent organic solar cells with organic wavelength dependent reflectors

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Semitransparent organic solar cells employing solution-processable organic wavelength dependent reflectors of chiral nematic (cholesteric) liquid crystals are demonstrated. The cholesteric liquid crystal (CLC) reflects only in a narrow band of the solar spectrum and remains transparent for the remaining wavelengths. The reflective band is matched to the absorption spectrum of the organic solar cell such that only unabsorbed photons that can contribute to the photocurrent are reflected to pass through the active layer a second time. In this way, the efficiency of semitransparent organic solar cells can be enhanced without significant transparency losses. An efficiency increase of 6% was observed when a CLC reflector with a reflection band of 540–620 nm was used, whereas the transparency of the organic solar cells is only suppressed in the 80 nm narrow bandwidth. © 2011 American Institute of Physics. [doi:10.1063/1.3546171]

There has been increasing interest in organic photovoltaics (OPVs) due to the possibility of their low-cost roll-to-roll production.^{1–3} Compared with sheet-to-sheet produced crystalline-Si-based photovoltaics (PVs), large area roll-to-roll OPVs should be less expensive and more easily manufactured.^{4,5} Furthermore, OPVs offer increased flexibility, lower weight, and cell transparency, opening new application possibilities. Thin organic semiconductor layers absorb only a narrow band of the solar spectrum, allowing a wide band of visible light to be transmitted. One could take advantage of this property in such applications as power-generating windows.⁶ It is obvious that semitransparent organic solar cells have lower power conversion efficiencies when compared to nontransparent cells employing reflective metal electrodes. Rear metallic electrodes reflect incident light that passes through the photoactive active layer, allowing a second passage of light through the photoactive layer and resulting in an increase of light absorption and, consequently, an increased PV efficiency. In this paper, we demonstrate a semitransparent organic solar cell with an additional organic optical layer. The optical layer selectively reflects a narrow band of the solar spectrum and remains transparent to the remainder of the light. The reflective band is adjusted to reflect the fraction of the light spectrum that coincides with the absorption spectrum of the OPV cell. The biggest advantages of organic-based wavelength dependent reflectors over inorganic-based Bragg reflectors are that they are easier to apply with a one-step solution process and at a significantly lower cost, enabling large area applications. Moreover, organic reflectors based on chiral nematic (cholesteric) liquid crystals provide very sharp narrow reflection bands and remain transparent for the rest of the light, whereas Bragg reflectors have more losses in the overall transparency due to a lot of “satellite” reflections. In this way, the efficiency of the semitransparent OPV cell can be increased without significant transparency losses.

The device architecture of a semitransparent OPV as used in this study is shown in Fig. 1. Patterned glass/ITO substrates were coated in PEDOT:PSS (Clevios P VP AI 4083, H. C. Starck) films of 40 nm thickness and baked at 150 °C for 10 min. Poly(3-hexylthiophene) (P3HT) and [C60]PCBM were dissolved in 1,2-dichlorobenzene in a 1:1 weight ratio, 2 wt % of each and then spin coated on top of the prepared PEDOT:PSS to form layers with thicknesses of 80, 150, 220, and 280 nm. The spin coating of the PEDOT:PSS and photoactive layers were performed in ambient atmosphere. The devices were then placed in a glove-box and annealed at 130 °C for 10 min in a nitrogen atmosphere. The transparent cathode (1 nm LiF, 1.5 nm Al, 10 nm Ag, and 30 nm ZnS) was thermally evaporated in a vacuum chamber through a shadow mask. Finally, the OPV devices were encapsulated. The active areas of the devices were 3 × 3 mm².

The chiral nematic (cholesteric) liquid crystal films were made on separate polymer hosts. Varying amounts of the

FIG. 1. (Color online) Schematic illustration of incident light distribution in a semitransparent solar cell.

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right-handed chiral dopant LC756 (BASF) were mixed in the host nematic LC 242 (BASF), which also contained 1% of the photoinitiator Irg184 (Ciba) and a surfactant. The solids were mixed in a 1:1 weight ratio with xylene at 80 °C for several hours. The cholesteric solutions were spin coated on either side of a rubbed halfwave plate (Edmund Optics) at 1000 rpm for 30 s. The rubbing of the polymeric halfwave induced planar alignment of the cholesteric: The sample was subsequently heated on a hotplate at 85 °C for ~20 s to enhance the alignment of the LCs and then transferred to a box under nitrogen. The films were exposed for ~10 min to an UV light source to crosslink the film and form a solid layer. The halfwave plate effectively converted transmitted left-circularly polarized light to right-circular, which was then reflected by the back cholesteric.

Current-voltage curves were measured using simulated AM 1.5 global solar irradiation (100 mW/cm²), using a xenon-lamp-based solar simulator (Oriol (LS0104) 150 W). Each measurement was repeated twice with at least three identical solar cells. UV-Vis transmission/absorption spectra were measured using a Perkin-Elmer Lambda 12 UV/Vis spectrophotometer.

Semitransparent OPVs are able to absorb photons incident from both the cathode and anode side. A difference in power conversion efficiency between cathode and anode side illumination results from differences in the transparency and reflectivity of the transparent electrodes and substrates. In this paper, we only report the results on OPV cells illuminated from the anode side, as in such cases, the efficiency of the solar cells was much higher than cathode side illumination, which demonstrates high parasitic absorption by the cathode layer. The power conversion efficiency of the cell with an 80 nm thick photoactive layer was 0.85% (V_{oc} :459 mV, J_{sc} :3.07 mA/cm², and fill factor (FF): 62%), with a 150 nm thick layer: 1.18% (V_{oc} :470 mV, J_{sc} :3.91 mA/cm², and FF: 64%), with a 220 nm thick layer: 1.49% (V_{oc} :462 mV, J_{sc} :5.06 mA/cm², and FF: 64%), and 1.02% (V_{oc} :446 mV, J_{sc} :3.74 mA/cm², and FF: 61%) for the cell with a 280 nm thick photoactive layer.

Typical back-side reflectors such as 100 nm Al or Ag layers usually significantly improve the OPV device's performance but obviously cannot be used for semitransparent solar cells. To improve the performance for such devices, only a narrow band of the solar spectrum should be reflected, corresponding to the absorption spectrum of the photoactive layer. A solution-processable layer that allows selective reflection is a chiral nematic (cholesteric) liquid crystal (CLC). A CLC, which is formed by the addition of a chiral molecule to a nematic liquid crystal host, will reflect a bandwidth of light of a handedness matching the handedness of the helix formed in the CLC.⁷ The reflected bandwidth corresponds to $\Delta\lambda=(n_e-n_o)p$, where n_o and n_e are the ordinary and extraordinary refractive indices of the liquid crystal (LC), respectively, and p is the pitch of the cholesteric, corresponding to the distance taken by the CLC helix to rotate the director 360°. The peak reflectance may easily be "tuned" by specific doping of the host LC with the chiral dopant. Light with wavelengths outside of the reflection band will pass through the CLC unimpeded. By using acrylate-terminated LCs, it is possible to polymerize the LC by exposing it to ultraviolet light to form a thin solid film.⁸ The optical features of the CLC are schematically depicted in Fig. 2(a). These materials

FIG. 2. (Color online) (a) Schematic representation of the reflection of incident light within the reflection band of a cholesteric liquid crystal. (b) Transmission spectra of right-handed cholesteric liquid crystal thin films on either side of a rubbed halfwave plate demonstrating selective reflection in different wavelength regions superimposed on an absorption spectrum of P3HT.

have previously been used to reduce surface losses in other solar energy generating devices, such as the luminescent solar concentrator.⁹

As photoactive materials with different absorption bands can be used in semitransparent solar cells, the reflective layer should be matched to the characteristics of the absorber. In this study, we demonstrate semitransparent solar cells based on P3HT, which absorbs between 400 and 650 nm. Several cholesteric thin films with a different reflection band have been tested as a reflection layer for semitransparent OPVs. The reflection bandwidth of the LC thin films was ~80 nm with the centers of the reflection bands at 430, 505, 530, 550, 580, and 630 nm, respectively, as shown in Fig. 2(b). The effectiveness of the CLC depends on both the position of the reflection band in the solar spectrum as well as on the thickness of the photoactive layer in the OPV. In Fig. 3, the increase in the efficiency resulting from the application of the CLC is shown for P3HT:PCBM layers with different thicknesses. The measured efficiency enhancement depended on the spectral position of the CLC reflection band and correlated with the absorption spectrum of the photoactive layer. The use of the CLC reflector that coincided with the peak absorption of the photoactive layer led to the largest efficiency increase of the solar cell. However, a moderate red-shift in the correlation is observed. This is because the photoactive layer already absorbs a large fraction of the 550 nm incident light. As a result, the amount of reflected light is not as large as when red-shifted CLC reflectors are used. The maximum efficiency increase is observed with the usage of a 580 nm (~540–610 nm bandwidth) reflector. The red-shift between the P3HT absorption spectrum and the bandwidth of

FIG. 3. (Color online) (a) Efficiency increase as a function of the central reflection wavelength of the cholesteric-based rear reflector in a semitransparent solar cell. (b) J-V curves of the 80 nm thick device with and without CLC reflectors.

the reflector is more pronounced for solar cells with a thicker active layer. For 80 nm devices, the variation in efficiency when using 550 and 580 nm reflectors was quite small. For thicker devices, the red-shifted reflector leads to an efficiency increase.

By using organic reflectors, the efficiency increases due to an enhanced J_{sc} in the devices (Fig. 3(b)). The efficiency increase of 6% for the 80 nm device is typically twice as large as compared to the 220 nm device. For the thicker layer, the efficiency increase is not as large because only a smaller fraction of the incident light will reach the semitransparent cathode, and so the CLC reflection will have a smaller overall effect. The use of CLCs is therefore especially attractive for organic solar cells that have layer thicknesses in the range of 80–100 nm.

The application of the CLC as a selective reflector increases the efficiency of the (semi)transparent solar cell but will also reduce transparency. However, the transmission is only suppressed in the narrow bandwidth of the CLC. In Fig. 4, the transmission spectrum of the solar cells with 80 and 220 nm active layer thicknesses are shown. CLCs may be

FIG. 4. (Color online) Optical transmission of the encapsulated solar cells with different thicknesses of the photoactive layer, with and without the cholesteric-based selective reflector (The center of the reflective band is at 550 nm) superimposed on the solar spectrum.

applied that cover a broader range of wavelengths, if desired, which would enhance the OPV performance but at the cost of the loss of some transparency.¹⁰

In conclusion, the use of solution-processable organic wavelength dependent reflectors of chiral nematic (cholesteric) liquid crystals with transparent organic solar cells is demonstrated. Their ease of application is a distinct advantage over multilayer inorganic Bragg-type reflectors, which are much more difficult to apply and are much more expensive. An efficiency increase of 6% is obtained when the reflective band of the CLC is matched to the absorption spectrum of the organic solar cell. Since the CLC only reflects in a narrow spectral band, the efficiency of semitransparent organic solar cells can be enhanced without significant transparency losses.

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¹F. C. Krebs, *Org. Electron.* **10**, 761 (2009).

²F. C. Krebs, S. A. Gevorgyan, and J. Alstrup, *J. Mater. Chem.* **19**, 5442 (2009).

³Y. Galagan, I. de Vries, A. Langen, R. Andriessen, W. Verhees, S. Veenstra, and J. Kroon, "Technology development for roll-to-roll production of organic photovoltaics", *Chem. Eng. Process.* (2010) (in press).

⁴J. Kalowekamo and E. Baker, *Sol. Energy* **83**, 1224 (2009).

⁵F. C. Krebs, T. Tromholt, and M. Jorgensen, *Nanoscale* **2**, 873 (2010).

⁶R. Koeppel, D. Hoeglenger, P. A. Troshin, R. N. Lyubovskaya, V. F. Razumov, and N. S. Sariciftci, *ChemSusChem* **2**, 309 (2009).

⁷C. Oseen, *Trans. Faraday Soc.* **29**, 883 (1933).

⁸D. J. Broer, G. N. Mol, J. A. M. M. v. Haaren, and J. Lub, *Adv. Mater.* **11**, 573 (1999).

⁹M. G. Debije, M.-P. Van, P. P. C. Verbunt, M. J. Kastelij, R. H. L. van der Blom, D. J. Broer, and C. W. M. Bastiaansen, *Appl. Opt.* **49**, 745 (2010).

¹⁰D. J. Broer, J. Lub, and G. N. Mol, *Nature (London)* **378**, 467 (1995).