AIP Applied Physics Letters

Folded reflective tandem polymer solar cell doubles efficiency

Kristofer Tvingstedt, Viktor Andersson, Fengling Zhang, and Olle Inganäs

Citation: Applied Physics Letters **91**, 123514 (2007); doi: 10.1063/1.2789393
View online: http://dx.doi.org/10.1063/1.2789393
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/91/12?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **91**, 123514 (2007)

Folded reflective tandem polymer solar cell doubles efficiency

Kristofer Tvingstedt,[a] Viktor Andersson, Fengling Zhang, and Olle Inganäs
Biomolecular and Organic Electronics, Center of Organic Electronics, IFM, Linköping University, SE-581 83 Linköping, Sweden

(Received 13 July 2007; accepted 3 September 2007; published online 20 September 2007)

Conjugated polymers are promising materials for the production of inexpensive and flexible photovoltaic cells. Organic materials display tunable optical absorption within a large spectral range. This enables the construction of organic tandem photovoltaic cells. The authors here demonstrate a reflective tandem cell where single cells are reflecting the nonabsorbed light upon another adjacent cell. By folding two planar but spectrally different cells toward each other, spectral broadening and light trapping are combined to give an enhancement of power conversion efficiency of a factor of 1.8 ± 0.3. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2789393]

The promise of organic photovoltaics lies in the potential to produce photovoltaic modules by printing methods at low temperatures, at a very low materials and energy budget, to compensate for the low power conversion efficiencies found in organic semiconductors.[1] We here demonstrate a simple geometrical modification of polymer solar cells leading to a significant increase of power conversion efficiency (PCE) in a single step. By folding of the substrates carrying solar cells (Fig. 1), we enhance the photovoltaic conversion efficiency in three ways. First, the folded structures cause light trapping at high angles and absorb more photons from incoming solar light. Thinner absorbing layers can hence be exploited, which relieve demands for mobility of charge carriers. Second, as the cell is folded, the device occupies less surface and photocurrents per intercepted illuminated area increases. Third, and perhaps the most important, the folded structures allow tandem or multiple bandgap solar cells in optical and electrical series or parallel connection. These effects combine to give an enhancement of PCE of 1.8 ± 0.3, in our present experimental systems.

We use polymer solar cells based on alternating copolymers of fluorene[2] (APFOs) combined with[6,6]-phenyl-C_{61} butyric acid methyl ester (PCBM) acceptors. The polymer blends are spin coated into films with thickness of 50–60 nm and sandwiched between a transparent electrode [indium tin oxide/poly(3,4-ethylene dioxythiophene): poly(styrene-sulphonate) (PEDOT:PSS)] and LiF/Al. This polymer class can generate high photovoltage, typically 1 V and PCE at AM1.5 of 3.5% from the high bandgap material APFO3 with absorption up to 650 nm. When absorption is extended up to 900 nm in the low bandgap APFO-Green9 polymer, we still obtain a high photovoltage of 0.8 V and a 2.3% PCE at AM1.5. The chemical structure of our high and low bandgap polymers and the acceptor PCBM is shown in Fig. 1.

By combining two cells in a folded geometry, forming the shape of a V, all of the reflected lights of the first solar cell will be directed to the next solar cell. This geometry causes strong optical absorption through multiple absorption events as well as via optical path length enhancement within the film. At small entrance angles, this structure is more reminiscent of the blackbody absorbers of early quantum physics, as almost all lights impinging on the structure will be absorbed.[3] Two APFO3/PCBM cells in a folded geometry show optical reflectance indicating an almost complete absorption of light within the spectral range of the material [Fig. 2(a)]. We further note a more pronounced increase of absorption in the spectral region where the individual planar cells have lower absorption. We can therefore use thinner films, which are optimized in thickness and stoichiometry with respect to charge carrier collection, and not consider optical absorption as limiting. The behavior of two similar photovoltaic cells in the folded V geometry, with the same photovoltage and almost the same photocurrent, is observed under series or parallel connection [Fig. 2(b)]. When folding the structure at very high angles, we note an increase of photocurrent density per projected illuminated area, but a reduction of the photocurrent density per active unit area of solar cells. The double photovoltage in the series connection gives an almost twofold increase in PCE upon folding and so does the 1.8 increase of photocurrent density in the parallel connection.

Light trapping geometries on a microstructured ($\approx 1\ \mu$m) substrate were previously reported, but with poor device performance due to electrode roughness problems.[4] Better results were recently reported with microprisms of larger dimensions. In that work, electrical limitations were, however, still induced by the microstructures themselves, and no serial tandem cell was possible.[5] Much larger scale

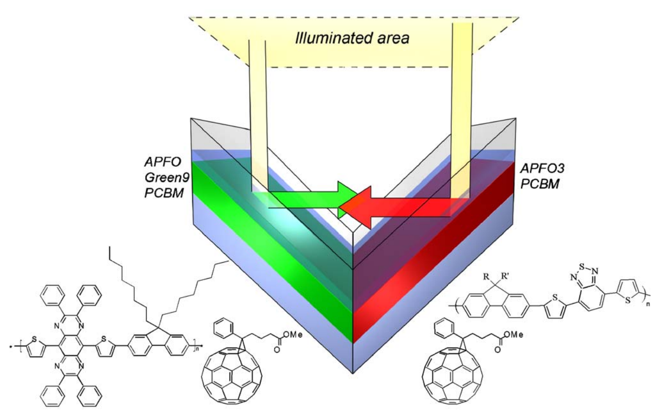

FIG. 1. (Color online) Sketch of the folded tandem cell and the chemical structures of the exploited alternating polyfluorenes APFO3, APFO Green-9, and the acceptor molecule PCBM.

[a]Electronic mail: kritv@ifm.liu.se

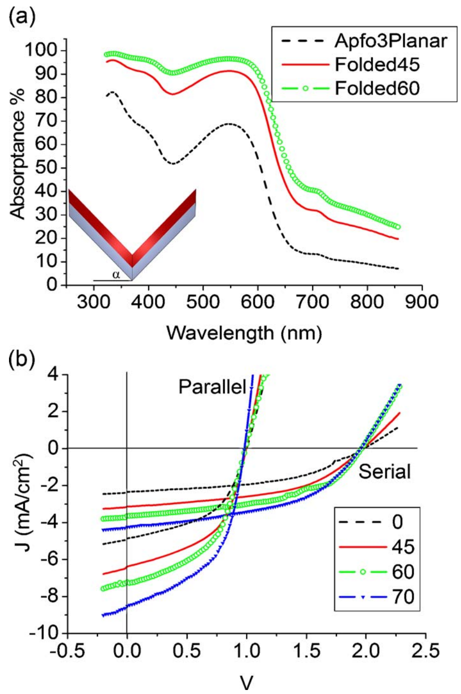

FIG. 2. (Color online) (a) Measured absorptance from a folded cell with APFO3 on both sides (without PEDOT). (b) *IV* characteristics of parallel and series connections of such folded cell for different folding angles under simulated AM1.5 100 mW/cm^2 solar light.

silicon components have been utilized in a tilted manner[6] but not allowing the important concept of the reflective tandem cell. The folded organic tandem cell presented here displays benefits that are not possible with nonflexible crystalline photovoltaics.

The attraction of folded structures in the micron to centimeter range is that they allow an alternative solution to the problem of assembling tandem and multiple junction solar cells. Early demonstrations of organic molecular solar cells with tandem junctions[7,8] are based on sequential layer deposition by sublimation from vacuum, leading to a series of connected tandem cell with two contacts. Balancing of photocurrents between cells is essential in two contact devices and necessitates optimization depending on the illumination conditions.[9] For polymer solar cells built by deposition of active materials from liquids, it is essential to leave deposited layers undisturbed by the next deposition step, presumably from a different solvent. In examples of semisolution processed serial tandem cells where photocurrent is generated from both layers, the added voltage does not lead to higher efficiency.[10,11] Recently, better performance from fully solution processed tandem cells are reported.[12,13] By stacking identical or different thin film solar cells on top of each other, with the possibility of four contact points, good performance has also been obtained.[14,15] This requires transparent electrodes on both anode and cathode in at least one device. Simulations have further indicated that enhancement from such stacked devices may be obtained,[16] and transparent polymer cathodes to be used in transmittive stacked organic tandem cells have also recently been shown.[17] By exploiting a reflective tandem configuration as described in this work, problems related to multijunctions, extra transparent electrodes, and solvent incompatibility are simply avoided.

The folded structures can be used with cells of different bandgaps on each of the two sides of a V geometry, or with

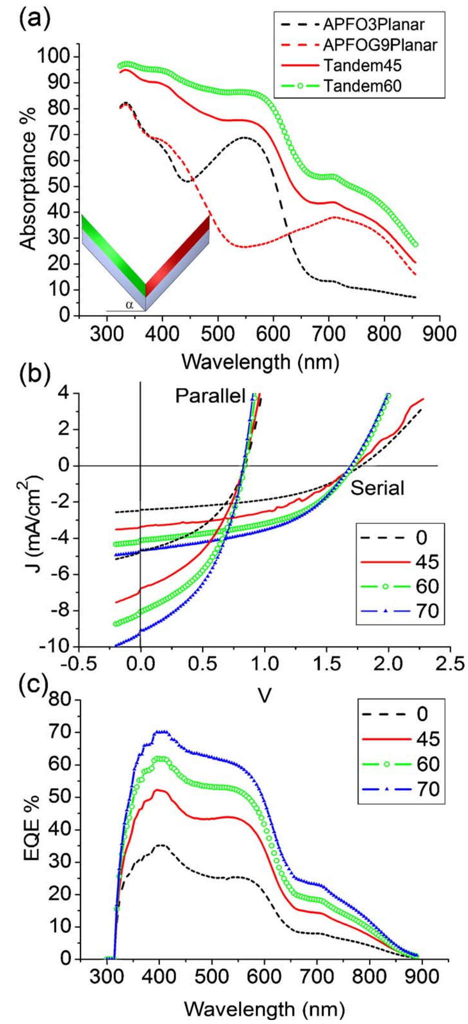

FIG. 3. (Color online) (a) Measured absorptance from a reflective tandem cell with APFO3/PCBM on one side and APFO-Green9/PCBM on the other side (without PEDOT). (b) *IV* characteristics of folded tandem cell in parallel and series connections for different folding angles. (c) EQE of such tandem cell in parallel connection under different folding angles.

several cells of different bandgaps located on one of the two sides, forming a reflective tandem or multijunction cell. With one high and one low bandgap part, as described in Fig. 1, optical reflectance from the combined cells in a folded configuration demonstrates broadening of optical absorption [Fig. 3(a)], and the overall absorptance is strongly influenced by the fold angle.

J-*V* characteristics under one sun illumination in the folded tandem geometry under different folding angles in parallel and series connections are presented in Fig. 3(b). For our devices, photocurrents are quite similar and voltages can be added in a series connection without significant loss of current. The well performing low bandgap polymer APFO-Green9 hence allows for the construction of a comparatively balanced tandem cell. The PCE in series connection increases from 2.0% to 3.7% (3.3–4.4)% upon folding from 0° to 70°.[18] In Fig. 3(c), we record the external quantum efficiency (EQE) under weak monochromatic illumination of the V geometry tandem cell in parallel connection which displays the long spectral range of photocurrent combined with the improved performance from folding into higher angles. The significant increase of EQE upon folding into higher angles originates from the high photon absorption from light trapping as well as the simultaneous good charge carrier collection provided by the exploited thin film. Additional experimental details can be found in the online supplementary information.[18]

In summary, we have presented a simple geometrical modification of polymer solar cells enhancing optical absorption and increasing photocurrent generation from intercepted light, without modification of materials. The geometry enables construction of tandem or multiple bandgap solar cells with arbitrary electrical parallel or series connection. When folding to high angles, we estimate almost a doubling of the PCE in both the single bandgap and the two bandgap tandem devices. Our devices in this study are not the best performing devices, a consequence of the experimental difficulties of assembly of low entrance angle folded cells. We expect that the folding of the reflective tandem cell is less effective for obliquely impinging and diffuse light.

We see no fundamental obstacles for large scale production of folded reflective cells by roll to roll printing. Two or more photovoltaic materials can be printed on a flat flexible surface, side by side, in a pattern determined by the folding geometry. The support is then buckled under compression to form the V geometries. The folded reflective solar cell gives a generic solution to better extraction of free energy from sunlight, using multiple organic photovoltaic bulk heterojunction materials in optical/electrical parallel/series connections.

We thank Mats R. Andersson and his group at Chalmers for polymer supply. This work was financed by the Center of Organic Electronics at Linköping University and funded by the Strategic Research Foundation SSF.

[1] H. Hoppe and N. S. Sariciftci, J. Mater. Res. **19**, 1924 (2004).
[2] O. Inganas, M. Svensson, F. Zhang, A. Gadisa, N. K. Persson, X. Wang, and M. R. Andersson, Appl. Phys. A: Mater. Sci. Process. **79**, 31 (2004).
[3] O. Lummer and E. Pringsheim, Verh. Dtsch. Phys. Ges. **2**, 163 (1900).
[4] K. Tvingstedt, M. Tormen, L. Businaro, and O. Inganäs, Proc. SPIE **6197**, 61970C (2006).
[5] M. Niggemann, M. Glatthaar, P. Lewer, C. Muller, J. Wagner, and A. Gombert, Thin Solid Films **511**, 628 (2006).
[6] J. M. Li, M. Chong, L. Q. Yang, J. D. Xu, X. F. Duan, M. Gao, F. L. Wang, H. T. Liu, L. Bian, X. Chi, and Y. H. Zhai, Sol. Energy Mater. Sol. Cells **86**, 585 (2005).
[7] A. Yakimov and S. R. Forrest, Appl. Phys. Lett. **80**, 1667 (2002).
[8] J. G. Xue, S. Uchida, B. P. Rand, and S. R. Forrest, Appl. Phys. Lett. **85**, 5757 (2004).
[9] T. Trupke and P. Wurfel, J. Appl. Phys. **96**, 2347 (2004).
[10] G. Dennler, H. J. Prall, R. Koeppe, M. Egginger, R. Autengruber, and N. S. Sariciftci, Appl. Phys. Lett. **89**, 073502 (2006).
[11] A. Hadipour, B. de Boer, J. Wildeman, F. B. Kooistra, J. C. Hummelen, M. G. R. Turbiez, M. M. Wienk, R. A. J. Janssen, and P. W. M. Blom, Adv. Funct. Mater. **16**, 1897 (2006).
[12] J. Y. Kim, K. Lee, N. E. Coates, D. Moses, T. Q. Nguyen, M. Dante, and A. J. Heeger, Science **317**, 222 (2007).
[13] J. Gilot, M. M. Wienk, and R. A. J. Janssen, Appl. Phys. Lett. **90**, 143512 (2007).
[14] K. Triyana, T. Yasuda, K. Fujita, and T. Tsutsui, Thin Solid Films **477**, 198 (2005).
[15] V. Shrotriya, E. H. E. Wu, G. Li, Y. Yao, and Y. Yang, Appl. Phys. Lett. **88**, 064104 (2006).
[16] N. K. Persson and O. Inganas, Sol. Energy Mater. Sol. Cells **90**, 3491 (2006).
[17] A. Gadisa, K. Tvingstedt, S. Admassie, L. Lindell, X. Crispin, M. R. Andersson, W. R. Salaneck, and O. Inganas, Synth. Met. **156**, 1102 (2006).
[18] See EPAPS Document No. E-APPLAB-91-058739 for experimental details and error estimations. This document can be reached via a direct link in the online article's HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).