Video Article

Morphology Control for Fully Printable Organic–Inorganic Bulk-heterojunction Solar Cells Based on a Ti-alkoxide and Semiconducting Polymer

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Abstract

The photoactive layer of a typical organic thin-film bulk-heterojunction (BHJ) solar cell commonly uses fullerene derivatives as the electron-accepting material. However, fullerene derivatives are air-sensitive; therefore, air-stable material is needed as an alternative. In the present study, we propose and describe the properties of Ti-alkoxide as an alternative electron-accepting material to fullerene derivatives to create highly air-stable BHJ solar cells. It is well-known that controlling the morphology in the photoactive layer, which is constructed with fullerene derivatives as the electron acceptor, is important for obtaining a high overall efficiency through the solvent method. The conventional solvent method is useful for high-solubility materials, such as fullerene derivatives. However, for Ti-alkoxides, the conventional solvent method is insufficient, because they only dissolve in specific solvents. Here, we demonstrate a new approach to morphology control that uses the molecular bulkiness of Ti-alkoxides without the conventional solvent method. That is, this method is one approach to obtain highly efficient, air-stable, organic-inorganic bulk-heterojunction solar cells.

Video Link

The video component of this article can be found at https://www.jove.com/video/54923/

Introduction

Organic photovoltaic devices are considered promising renewable energy sources due to their low manufacturing cost and light weight[1-7]. Because of these advantages, a large number of scientists have been immersed in this promising area. In the past decade, dye-sensitized, organic thin-film, and perovskite-sensitized solar cells have achieved significant progress in power conversion efficiency in this area[8].

Specifically, organic thin-film solar cells and BHJ organic thin-film solar-cell technology are efficient and cost-effective solutions for the utilization of solar energy. Furthermore, the energy conversion efficiency has reached over 10% with the use of low-band-gap polymers as the electron donor and fullerene derivatives as the electron acceptor (Phenyl-C_{61}-Butyric-Acid-Methyl Ester: [60]PCBM or Phenyl-C_{71}-Butyric-Acid-Methyl Ester: [70]PCBM)[9-11]. Moreover, some researchers have already reported the importance of the BHJ structure in the photoactive layer, which is constructed with low-band-gap polymers and fullerene derivatives to obtain a high overall efficiency. However, fullerene derivatives are air-sensitive. Therefore, an air-stable electron-accepting material is required as an alternative. A few reports previously suggested new types of organic photovoltaic cells that used n-type semiconducting polymers or metal oxides as electron acceptors. These reports supported the development of air-stable, fullerene-free, organic thin-film solar cells[12-15].

However, in contrast to fullerene systems or n-type semiconducting polymer systems, obtaining a satisfactory performance of the BHJ structure in the photoactive layer, which has charge separation and charge transfer abilities, is difficult in metal oxide systems[16-17]. Furthermore, fullerene derivatives and n-type semiconducting polymers have high solubility in many solvents. Therefore, it is easy to control the morphology of the photoactive layer by selecting an ink solution as the solvent, which is the precursor of the photoactive layer[18-20]. In contrast, in the case of metal alkoxide systems used in combination with an electron-donating polymer, both semiconductors are insoluble in almost all solvents. This is because metal alkoxides do not have a high solubility in the solvent. Therefore, the selectivity of solvents for morphology control is extremely low.

In this article, we report a method for controlling the morphology of the photoactive layer by using molecular bulkiness to fabricate printable and highly air-stable BHJ solar cells. We describe the importance of morphology control for the progress of fullerene-free BHJ solar cells.

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Protocol

1. Preparation of Indium-tin-oxide (ITO) Glass for Solar Cell Fabrication

1. Cut the ITO/glass substrate.
    1. Using a glass cutter, cut the ITO/glass substrate (10 cm × 10 cm) into pieces measuring approximately 2 cm × 2 cm.

2. Chemically etch the ITO conductive layer.
    1. Using a digital multimeter, check that the top of the ITO/glass piece has a conductive side.
    2. Place masking tape on both sides of the ITO/glass piece, leaving a central area of 2 mm × 2 cm in the middle. Using masking tape, protect the rest of the ITO conductive layer from the etching.
    3. Pour a few drops of HCl (1 M) onto the ITO conductive layer to remove the ITO conductive layer from the surface of the ITO/glass piece. After approximately 3 min, wipe off the HCl using a cotton swab, and then remove the masking tape.

3. Pretreat the ITO/glass piece.
    1. Place the ITO/glass pieces in a glass case and fill the case with water.
    2. Place the glass case in a water bath that is two-thirds full of water and attach an ultrasonic cleaner. Then, turn on the ultrasonic cleaner for approximately 15 min to remove the few traces of chemical etchant remaining on the ITO/glass piece. Wash these pieces in an ultrasonic bath with water, acetone, and isopropyl alcohol, respectively, for 15 min each, and then dry them in a stream of dry air. Perform ultrasonication at an oscillatory frequency of 42 kHz.
    3. Place the ITO/glass pieces inside an ultraviolet-ozone (UV-O_3) cleaner and run the machine for 30 min.

2. Preparation of the Precursor Solution for the Photoactive Layer

1. Dissolve 0.5 mg of poly[2,7-(9,9-dioctylfluorene)-alt-4,7-bis(thiophen-2-yl)benzo-2,1,3-thiadiazole] (PFO-DBT) as an electron donor and 1.0 mg of Ti-alkoxide in 1 mL of chlorobenzene. Select the following Ti-alkoxides as electron acceptors: Ti(IV) isopropoxide, ethoxide, butoxide, and butoxide polymer. Then, dissolve 0.5 mg of PFO-DBT and 1.0 mg of [60]PCBM in 1 mL of chlorobenzene as a reference.
NOTE: Here, the HOMO-LUMO levels are as follows[21]. PFO-DBT: 5.4-3.53 eV, Ti(IV) isopropoxide: 7.49-3.86 eV, ethoxide: 7.55-3.90 eV, butoxide: 7.53-3.76 eV, and butoxide polymer: 7.57-3.83 eV.
2. On a magnetic hot stirrer, heat the precursor solution to 70 °C while stirring it with a stir bar at a rotational speed of 700 rpm. Do this for 20 min in the absence of light, until the solution is visually clear to the naked eye. Cool the solution to room temperature, again in the absence of light, for future use.

3. Fabrication of the Photoactive Layer

1. Deposit the film by spin-coating.
    1. Heat the precursor solution of the photoactive layer and the ITO/glass piece to 70 °C. For 10 min, heat the precursor solution on a magnetic hot stirrer heated to 70 °C and use a stir bar at a rotational speed of 700 rpm. Heat the ITO/glass piece on a ceramic hot plate heated to 70 °C for 5 min.
    2. Place the ITO/glass piece at the center of the vacuum stage of the spin coater, heat it with a heat gun to around 70 °C, and turn on the vacuum.
    NOTE: The vacuum is created by using a vacuum pump with a pumping speed of 30 L/min. The ultimate pressure of the vacuum pump is 26.6 × 10^3 Pa.
    3. Pour a few drops of the precursor solution of the photoactive layer onto the ITO/glass piece and start the spin coater at 2,000-6,000 rpm for 60 s in air.
    NOTE: The volume of precursor solution is 0.5 mL, measured with a 1-mL spuit.
    4. Dry the surface of the photoactive layer for 10 min at room temperature in an air atmosphere in the absence of light to obtain a 50 nm-thick film as the photoactive layer.

2. Remove the extra film.
    1. Wipe the extra photoactive layer from the surface of the ITO/glass piece with a cotton swab wetted with chlorobenzene.
    2. Dry the photoactive layer again for 10 min at room temperature in an air atmosphere in the absence of light.
    NOTE: The temperature of our experiment room is maintained at 25 °C.

4. Fabrication of the Electrode

1. Print the organic electrode.
    1. Using a screen printer, print an organic electrode by placing poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT-PSS) on the photoactive layer[22]. The metal mask is 50 µm-thick, and the printing area is 5 mm × 20 mm.
    2. Dry the organic electrode for 30 min at room temperature in an air atmosphere in the absence of light.

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5. Lamination for the Solar Cells

1. Cut the glass substrate into pieces with dimensions of 1.5 cm × 2.5 cm using a diamond cutter. Spread an epoxy resin onto the glass substrate using a plastic spatula. Place the glass substrate with epoxy resin on the photoactive layer to protect it.

6. Preparation for Measuring the Solar-cell Performance

1. Clean the electrodes by wiping them with a cotton swab wetted with acetone. Attach a supporting electrode onto the ITO using an ultrasonic soldering system. Operate the soldering iron at a 42-kHz frequency and at 230 °C.

7. Measurement of the Solar-cell Performance

1. Measure the current–voltage (J-V) characteristics of the solar cells by using a direct-current voltage current source/monitor integrated system, with the solar simulator calibrated to provide a simulated AM1.5G of 100 mW/cm^2 by the silicon photodiode.
   NOTE: More detailed information about the measurement of the J-V curves can be found elsewhere[23, 24].

8. Analysis of the Phase-separation structure

1. Prepare individual films of photoactive layers constructed with Ti-alkoxide and PFO-DBT, using same method for solar-cell fabrication, without the organic electrode and without the lamination process.
2. Use an optical microscope or a scanning electron microscope (SEM) to observe the morphology of the photoactive layer at a high magnification (50,000×) in order to analyze the phase-separation structure.
   NOTE: More detailed information about SEM operation can be found elsewhere[25, 26].

Representative Results

We have presented a protocol for fabricating fully printable organic-inorganic BHJ solar cells, as well as a method for controlling the phase-separation structure. The solar-cell performance has been extensively investigated[27-31] when Ti(IV) isopropoxide and ethoxide were used as electron-accepting materials (**Figure 1**). These solar cells exhibited a short-circuit current density (Jsc) that is approximately eight times higher than that of devices using the "Ti(IV) butoxide polymer" (**Table 1**). The resulting morphologies in the photoactive layer were adequate for photo-generation and the existence of free carriers and their transportation. In other words, it is possible to control the carrier management structure by selecting the bulkiness of the Ti-alkoxide. Some previous works have shown that the phase-separation structure for carrier management in the photoactive layer of a BHJ solar cell using fullerene derivatives is an important factor[32-34]. This is also important for the organic-inorganic system investigated in this work.

We can explain the relationship between Jsc by the carrier management and the phase separation structure using the three individual models summarized in **Table 2**. Furthermore, we investigated the phase-separation structure through SEM, and SEM images were compared with the phase-separation models (**Figure 2**). When the Ti(IV) butoxide polymer was used, the charge-generation field was insufficient. Consequently, this results in a lower Jsc value. That is, the self-organization of the Ti(IV) butoxide polymer is primarily promoted by the molecule's packing. When "Ti(IV) butoxide" was used as an n-type semiconductor, the phase domains were isolated, which is inadequate for the charge transfer of the free carriers to obtain a high Jsc value. The chemical structure of Ti(IV) butoxide is bulkier than that of Ti(IV) isopropoxide and ethoxide. Therefore, the chemical bulkiness of Ti(IV) butoxide excessively hindered the self-organization of the p-type semiconducting polymer. On the other hand, when Ti(IV) isopropoxide or ethoxide was used, these morphologies provided a good balance between domain size and phase continuity from the viewpoint of charge generation, the existence of free carriers, and their transportation.

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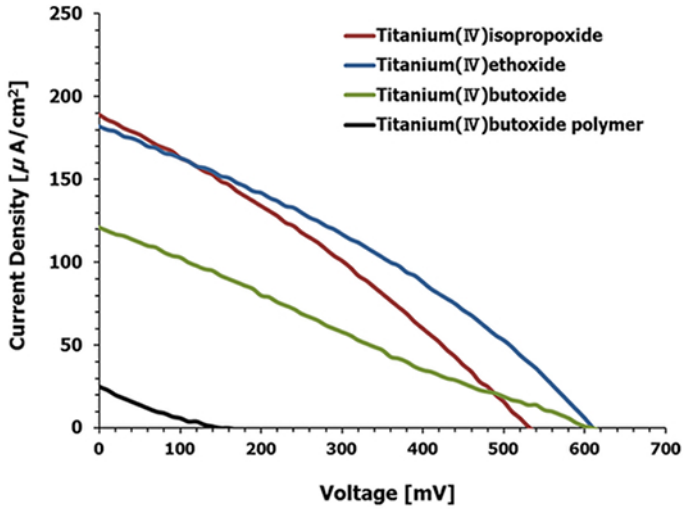


Figure 1: J-V characteristics of solar cells for different chemical bulkiness of Ti alkoxide. This figure is modified from Reference 21. J-V characteristics are drastically changed by selecting the Ti alkoxide molecule. Please click here to view a larger version of this figure.

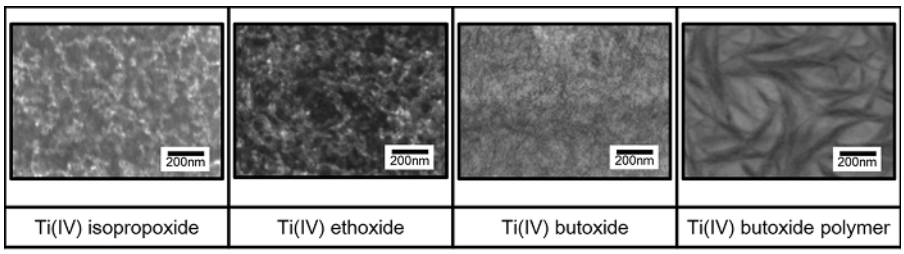


Figure 2: Scanning electron microscope (SEM) images for analyzing phase separation structures. This figure is modified from Reference 21. The morphology of the photoactive layer is obtained at a high magnification (50,000×). The phase separation structures of Ti(IV) isopropoxide or ethoxide were acceptable and had an adequate continuity. Please click here to view a larger version of this figure.

	Titanium(IV) isopropoxide	Titanium(IV) ethoxide	Titanium(IV) butoxide	Titanium(IV) butoxide polymer
Jsc [μA/cm^2]	191	182	121	25
Voc [V]	0.53	0.61	0.61	0.16
FF	0.31	0.33	0.23	0.18
PCE [%]	0.031	0.036	0.017	0.0007

Table 1: Solar-cell performance for different chemical bulkiness of Ti-alkoxides. This table is modified from Reference 21. The J-V characteristics of the BHJ solar cells for each Ti-alkoxide are shown in **Figure 1**, and the corresponding performance parameters are listed in this table.

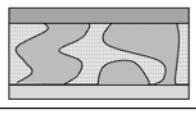
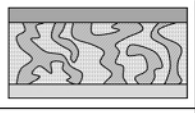
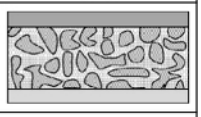
Model	(A)	(B)	(C)
			
Phase Separation (Overall carrier management)	coarse	medium	fine
Continuity (Free carrier existents and transportation)	continuous	continuous	isolation
p/n Interfacial Length (Charge generation)	low	medium	high
Current Density	low	high	low

Table 2: The representative phase-separation models for analyzing existent free carriers. This table is modified from Reference 21. Ideally, morphologies, such as that of model B, are required from the viewpoint of the existence of many free carriers.

Discussion

In order to utilize the molecule's bulkiness in this method, it is important to know the conditions for film formation by spin coating. First, the p-type and n-type semiconductors must be able to be dissolved in the solvents. When some material remains, it will become the large core of the domains in the photoactive layer. The use of an adequate commercial filter for individual solvents is recommended to remove the remaining material. Next, the precursor solution in which the molecules dissolve must be uniformly and homogeneously printed as the photoactive layer on the ITO/glass substrate in approximately 60 s. This process is executed with the following three steps. First, the precursor solution and ITO/glass substrate are maintained at a temperature of approximately 70 °C. Second, the substrate is promptly set on the stage of the spin coater. Finally, a few drops of the precursor solution are poured and spread on the surface of the substrate, as soon as possible, and the spin coater is promptly started. The heated substrate prevents a rapid decrease in the temperature of the precursor solution on the ITO/glass substrate. This method controls the educts from the precursor solution by a rapid thermal change. The effect of the heated precursor solution promotes smooth spreading on the substrate, due to the decrease in the viscosity, and facilitates the formation of a uniformly flat thin film. Furthermore, the spin-coating process is carried out uncovered by the lid. This promotes the evaporation of the solvents from the substrate during the ~60-s process.

If problems occur when using the abovementioned method due to the experimental and equipment conditions, the following methods are recommended. If the heated substrate cannot move on the stage of the spin coater, the substrate can be heated with a heat gun immediately before use. Furthermore, if more time is needed to drop the precursor solution, heating the precursor solution to approximately 75-80 °C is recommended.

Moreover, the phase-separation structure and phase-domain size will be different depending upon the selected individual electron donor. When an electron donor except PFO-DBT is selected, a change in the p/n ratio and a mixture of two Ti-alkoxides with different bulkiness as the electron acceptor are useful methods for obtaining a suitable phase-separation structure. Our method for controlling the phase-separation structure is different from the conventional solvent method[18-20, 33]. Therefore, our method can be modified to electron donors and acceptors that have solubilities in only a few limited solvents.

Finally, we have demonstrated a method for the fabrication of fully printable, fullerene-free, bulk-heterojunction solar cells based on the use of Ti-alkoxides as the electron acceptor and a semiconducting polymer as the electron donor. Furthermore, this protocol demonstrated that it is effective to control the phase-separation structure by using the molecular bulkiness, without using the conventional solvent method. This method may be applicable to systems using several n-type and p-type semiconductors, which only dissolve in a few solvents. We also mention the limitations of this method. We think that this method is useful only in a two-ingredient system. This is because this method can control the phase separation by hindering self-organization using the bulkiness of one molecule out of two kinds of molecules. Therefore, we cannot say that a three-ingredient system will be applicable. We will investigate the applicability to these systems in the future. We expect that, in addition to completely organic solar cells, hybrid solar cells will also become popular in the near future.

Disclosures

The authors declare that they have no competing financial interests.

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References

1. Price, C. S., Stuart, C. A., Yang, L., Zhou, H., & You, W. Fluorine substituted conjugated polymer of medium band gap yields 7% efficiency in polymer−fullerene solar cells. *J. Am. Chem. Soc.* **133** (12), 4625-4631 (2011).
2. Liang, Y. Y. *et al.* For the bright future-Bulk heterojunction polymer solar cells with power conversion efficiency of 7.4%. *Adv. Mater.* **22**, E135-E138 (2010).
3. Chu, T.-Y. *et al.* Bulk heterojunction solar cells using thieno[3,4-c]pyrrole-4,6-dione and dithieno[3,2-b:2',3'-d]silole copolymer with a power conversion efficiency of 7.3%. *J. Am. Chem. Soc.* **133** (12), 4250-4253 (2011).
4. Zhou, H. *et al.* Development of fluorinated benzothiadiazole as a structural unit for a polymer solar cell of 7% efficiency. *Angew. Chem. Int. Ed.* **50** (13), 2995-2998 (2011).
5. Janssen, J. A. R., & Nelson, J. Factors limiting device efficiency in organic photovoltaics. *Adv. Mater.* **25** (13), 1847-1858 (2012).
6. Nelson, J. Polymer:fullerene bulk heterojunction solar cells. *Mater. Today.* **14** (10), 462-470 (2011).
7. He, Z., Zhong, C., Su, S., Xu, M., Wu, H., & Cao, Y. Enhanced power-conversion efficiency in polymer solar cells using an inverted device structure. *Nat. Photonics.* **6**, 591-595 (2012).
8. Baena, J. P. C. *et al.* Highly efficient planar perovskite solar cells through band alignment engineering. *Energy Environ. Sci.* **8**, 2928-2934 (2015).
9. Shuttle, G. C., Hamilton, R., O'Regan, B. C., Nelson, J., & Durrant, R. J. Charge-density-based analysis of the current-voltage response of polythiophene/fullerene photovoltaic devices. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 16448-16452 (2010).
10. Dibb, G. F. A., Kirchartz, T., Credgington, D., Durrant, R. J., & Nelson, J. Analysis of the relationship between linearity of corrected photocurrent and the order of recombination in organic solar cells. *J. Phys. Chem. Lett.* **2** (19), 2407-2411 (2011).
11. Maurano, A. *et al.* Transient optoelectronic analysis of charge carrier losses in a selenophene:fullerene blend solar cell. *J. Phys. Chem. C.* **115**, 5947-5957 (2011).

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12. Yuan, Y., Michinobu, T., Oguma, J., Kato, T., & Miyake, K. Attempted inversion of semiconducting features of platinum polyyne polymers: A new approach for all-polymer solar cells. *Macromol. Chem. Phys.* **214** (13), 1465-1472 (2013).
13. Granström, M. *et al.* Laminated fabrication of polymeric photovoltaic diodes. *Nature.* **395**, 257-260 (1998).
14. Hal, A. P. *et al.* Photoinduced electron transfer and photovoltaic response of a MDMO-PPV:TiO_2 bulk-heterojunction. *Adv. Mater.* **15** (2), 118-121 (2003).
15. Das, K. S. *et al.* Controlling the processable ZnO and polythiophene interface for dye-densitized thin film organic solar cells. *Thin Solid Films.* **536**, 302-307 (2013).
16. Campoy-Quiles, M. *et al.* Morphology evolution via self-organization and lateral and vertical diffusion in polymer: fullerene solar cell blends. *Nature Materials.* **7**, 158-164 (2008).
17. Schmidt-Hansberg, B. *et al.* Moving through the phase diagram: morphology formation in solution cast polymer-fullerene blend films for organic solar cells. *ACS Nano.* **5** (11), 8579-8590 (2011).
18. Hou, Q. *et al.* Novel red-emitting fluorene-based copolymers. *J. Mater. Chem.* **12**, 2887-2892 (2002).
19. Zheng, L. *et al.* Synthesis of C60 derivatives for polymer photovoltaic cell. *Synth. Met.* **135**, 827-828 (2003).
20. Svensson, M. *et al.* High-performance polymer solar cells of an alternating polyfluorene copolymer and a fullerene derivative. *Adv. Mater.* **15** (12), 988-991 (2003).
21. Kato, T. *et al.* Morphology control for highly efficient organic-inorganic bulk heterojunction solar cell based on Ti-alkoxide. *Thin Solid Films.* **600**, 98-102 (2016).
22. Shibata, Y. *et al.* Quasi-solid dye sensitized solar cells with ionic liquid Increase in efficiencies by specific interaction between conductive polymers and gelators. *Chem. Comm.* **21**, 2730-2731 (2003).
23. Wu, J. *et al.* A thermoplastic gel electrolyte for stable quasi-solid-state dye-sensitized solar cells. *Adv. Funct. Mater.* **17** (15), 2645-2652 (2007).
24. Johansson, J. M. E. et al. Photovoltaic and interfacial properties of heterojunctions containing dye sensitized dense TiO_2 and Tri-arylamine derivatives. *Chem. Mater.* **19** (8), 2017-2078 (2007).
25. Echlin, P. *Handbook of Sample Preparation for Scanning Electron Microscopy and X-Ray Microanalysis.* Springer US (2011).
26. Flegler, S. L., Heckman, J. W., & Klomparens, K. L. *Scanning and Transmission Electron Microscopy: An Introduction.* Oxford University Press, UK, (1993).
27. Cowan, R. S., Roy, A., & Heeger, J. A. Recombination in polymer-fullerene bulk heterojunction solar cells. *Phys. Rev. B.* **82** (24), 245207 (2010).
28. Street, A. R., Cowan, S., & Heeger, J. A. Experimental test for geminate recombination applied to organic solar cells. *Phys. Rev. B.* **82** (12), 121301 (2010).
29. Shuttle, G. C. *et al.* Charge extraction analysis of charge carrier densities in a polythiophene/fullerene solar cell: Analysis of the origin of the device dark current. *Appl. Phys. Lett.* **93**, 183501 (2008).
30. Shuttle, G. C. *et al.* Bimolecular recombination losses in polythiophene: Fullerene solar cells. *Phys. Rev. B.* **78**, 113201 (2008).
31. Reyes-Reyes, M., *et al.* Methanofullerene elongated nanostructure formation for enhanced organic solar-cells. *Thin Solid Films.* **516** (1), 52-57 (2007).
32. Shuttle, G. C. *et al.* Experimental determination of the rate law for charge carrier decay in a polythiophene: Fullerene solar cell. *Appl. Phys. Lett.* **92**, 093311 (2008).
33. Mori, D., Benten, H., Ohkita, H., Ito, S., & Miyake, K. Polymer/polymer blend solar cells improved by using high-molecular-weight fluorene-based copolymer as electron acceptor. *ACS Appl. Mater. Interfaces.* **4** (7), 3325-3329 (2012).
34. You, J. *et al.* A polymer tandem solar cell with 10.6% power conversion efficiency. *Nature Commun.* **4**, 1446 (2013).

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