Facile preparation of TiO$_x$ film as an interface material for efficient inverted polymer solar cells†

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Titanium oxide (TiO$_x$) is an effective electron transport layer in polymer solar cells (PSCs). Here, we report an efficient inverted polymer solar cell based on P3HT and fullerenes using a high density, single-step solution processed amorphous TiO$_x$ (a-TiO$_x$) film as an electron transport layer. The a-TiO$_x$ film was prepared by spin coating tetrabutyl titanate (TBT) isopropanol solution onto ITO coated glass in a glovebox filled with N$_2$ and then annealing at different temperatures in air. The films with high light transmittance are very smooth. The PSCs with the a-TiO$_x$ electron transport layer showed enhanced photovoltaic performance in comparison with the device using PEDOT:PSS as the anode buffer layer. The optimized power conversion efficiency (PCE) of the PSCs based on P3HT/PC$_61$BM and P3HT/PC$_71$BM with the a-TiO$_x$ electron transport layer reached 4.25% and 4.65%, respectively, under AM1.5G illumination (100 mW cm$^{-2}$). In addition, the PSCs with the a-TiO$_x$ electron transport layer exhibited good stability. The results indicate that facile preparation of a-TiO$_x$ films using cheap TBT is promising for high-efficiency PSCs and large-scale fabrication of flexible electronics.

1. Introduction

In recent years, bulk heterojunction (BHJ) polymer solar cells (PSCs) have attracted great attention because of their low weight and the potential low cost of printing on flexible substrates at low temperatures. In spite of a high power conversion efficiency (PCE), conventional architecture has limitations in device stability due to the use of low-work-function metal cathodes (such as Ca/Al) and the indium tin oxide (ITO)/poly(3,4-ethylenedioxythiophene):(polystyrene sulfonic acid) (PEDOT:PSS) interface. The low-work-function metals are susceptible to degradation by oxygen and moisture whereas PEDOT:PSS is corrosive to the ITO electrode due to its acidic and hygroscopic nature. Both of these are detrimental to the device lifetime of BHJ PSCs. The rapid advancement in the PCE of PSCs, means that the poor stability of PSCs is becoming one of the crucial obstacles to commercialization. One approach to solve this issue is using an inverted structure in which the charge separation and collection nature of the electrode are reversed. In the inverted structure, air-stable high-work-function metals (Au, Ag) are used as the top anode, covering p-type metal oxides (vanadium oxide: V$_2$O$_5$,
molybdenum oxide: MoO$_3$,
and cesium carbonate (Cs$_2$CO$_3$). Among the n-type metal oxides that are used in inverted PSCs, TiO$_x$ is a promising candidate due to its large band gap, high transparency, good environmental stability, and relatively high electron mobility. Various methods have been applied to prepare TiO$_x$ thin films such as atomic layer deposition (ALD)[18,19] and traditional chemical processing.[20,21] However, the ALD procedure is inconvenient and high-cost, which restricts its application in large-scale production. For conventional chemical methods, the preparation of TiO$_x$ films needs a high annealing temperature (over 200 °C) or the preparation of TiO$_x$ nanoparticles first before preparing the films. These methods increase the complexity of device processing and make them incompatible with spin coating or roll-to-roll processing that uses flexible plastic substrates. As we know, TiO$_x$ films are suitable electron transport layers in organic solar cells.[22,23] However, high quality and feasible solution-processed TiO$_x$ nanofilms applied via coating or roll-to-roll processing still need to be developed. Tetrabutyl titanate (TBT) is widely employed as the Ti precursor to obtain TiO$_x$ by the traditional sol-gel method.[24] However, there are few reports directly using TBT to fabricate high density amorphous TiO$_x$ thin films as electron transport layers in PSCs.

† These authors contributed equally to this work.
In this study, we introduced a single-step and low-temperature solution method to prepare high density TiO\textsubscript{x} thin films using TBT isopropanol solution. The TiO\textsubscript{x} film with a very smooth surface and high transmittance was used as an electron transport layer on ITO coated glass as the cathode in inverted PSCs. The TiO\textsubscript{x} film was prepared by spin coating the TBT isopropanol solution onto ITO coated glass in a glovebox filled with N\textsubscript{2} and then thermally treating it at 25–200 °C for 0–180 min in air. The active layers of the PSCs were a blend of P3HT and fullerenes (PC\textsubscript{61}BM or PC\textsubscript{71}BM). The highest PCE of the PSCs, which were treated at 90 °C for 60 min, isopropanol solution was 4.65% with the TiO\textsubscript{x} film treated at 90 °C for 60 min. TBT is very cheap and solution processable. In addition, the novel preparation method can make its use possible in spin coating and roll-to-roll processing for large-scale applications.

2. Experimental

2.1. Materials

Patterned ITO glass with a sheet resistance of 15 Ω per sq was purchased from Shenzhen Display (China). Tetraethyl titanate (TBT) was purchased from Aladdin (AR grade). P3HT was obtained from Lumtec. PC\textsubscript{61}BM and PC\textsubscript{71}BM were purchased from American Dye Sources (ADS). All of these commercially available materials were used as received without further purification.

2.2. Device fabrication

The inverted solar cells were fabricated with the structure ITO/ TiO\textsubscript{x}/P3HT:fullerene/MoO\textsubscript{3}/Ag. The fullerenes were PC\textsubscript{61}BM and PC\textsubscript{71}BM. Patterned ITO coated glass was cleaned with ITO detergent, deionized water, acetone and isopropanol in an ultrasonic bath for 20 min each time, and then exposed to oxygen plasma for 6 min. The amorphous TiO\textsubscript{x} thin film was prepared in a glovebox filled with N\textsubscript{2} (named α-TiO\textsubscript{x}, in order to distinguish it from traditional TiO\textsubscript{x} nanoparticles) and in air (named α-TiO\textsubscript{x} (in air)) by spin coating (3000 rpm) 3% v/v TBT isopropanol solution onto the precleaned ITO coated glass, and annealing at different temperatures in air. Subsequently, the substrates were transferred to a glovebox and irradiated under AM1.5G illumination (100 mW cm\textsuperscript{-2}) for 5 min. The active layers were prepared by spin coating (800 rpm) the solution of P3HT and a fullerene derivative (PC\textsubscript{61}BM or PC\textsubscript{71}BM) onto the α-TiO\textsubscript{x} modified ITO coated glass for 40 s. The weight ratio of P3HT: fullerene derivative was 1 : 1, and the total concentration was 36 mg ml\textsuperscript{-1} in chlorobenzene (CB). Then the active layers were annealed at 150 °C for 10 min. Finally, the samples were transferred to a vacuum chamber, and 4 nm of MoO\textsubscript{3} and 100 nm of Ag were thermally deposited onto the active layer under a pressure of 2 × 10\textsuperscript{-2} Pa. The active area of the device was 0.1 cm\textsuperscript{2} and defined by a shadow mask. Meanwhile, the other two inverted PSCs based on P3HT:PC\textsubscript{61}BM were prepared on ZnO modified ITO coated glass and bare ITO coated glass. Here, the ZnO layer was prepared according to the literature.\textsuperscript{29} As a comparison, conventional PSCs were fabricated based on P3HT:PC\textsubscript{61}BM with PEDOT:PSS as the anode buffer layer and Ca/Al as the cathode.

2.3. Film and device characterization

Analysis of the structure of α-TiO\textsubscript{x} was performed with grazing incidence X-ray diffraction (GIXRD) using a D8 Advance X-ray diffractometer. X-ray photoelectron spectroscopy (XPS) data were obtained with an ESCA Lab250i-XL electron spectrometer from Thermo using 150 W Al K\textsubscript{α} radiation. The transmission spectra of the α-TiO\textsubscript{x} layers on ITO coated glass were observed using a Varian Cary 50 UV/vis spectrophotometer in the range of 250–800 nm at room temperature. The thicknesses of the α-TiO\textsubscript{x} films and active layers were measured using a Veeco Dektak150 surface profiler.

The current density–voltage (J–V) characteristics of the PSCs were recorded using a Keithley 2420 source measurement unit under AM1.5G illumination (100 mW cm\textsuperscript{-2}) from a Newport solar simulator. The light intensity was calibrated with a standard silicon solar cell. To investigate the conductivity of the films, current–voltage curves were measured with a Keithley 236 source measurement unit. The stability of the PSCs was explored, and the un-encapsulated devices were stored in ambient conditions and periodically tested for 10 days.

3. Results and discussion

3.1. Structure characterization of the α-TiO\textsubscript{x} film

Fig. 1a shows the GIXRD pattern of the α-TiO\textsubscript{x} film prepared by drop casting TBT solution onto a silicon substrate in a glovebox and then treating it in air at 90 °C for 60 min. There is a broad diffraction peak at 2θ of 15–35°, which indicates the presence of an amorphous phase with low crystallinity or a semicrystalline phase with very small crystallites.\textsuperscript{33}

In order to further characterize the composition of the α-TiO\textsubscript{x} films, X-ray photoelectron spectroscopy (XPS) measurements were taken. Fig. 1b–d show the XPS results of the α-TiO\textsubscript{x} films.
prepared by spin coating (3000 rpm) 3% v/v TBT isopropanol solution on Si substrates in a glovebox and treating it in air for 60 min. The binding energies obtained in the XPS analysis were corrected by taking the C 1s peak at 284.8 eV as a reference. In Fig. 1b, the complete XPS spectra of the $\alpha$-TiO$_x$ film reveal characteristic peaks for Ti, O and C. For the unannealed $\alpha$-TiO$_x$ film, the peaks for Ti 2p appear clearly at 458.94 eV, for O 1s at 530.5 eV, and for C 1s at 284.8 eV. After being annealed at 90 °C for 60 min, the peaks of Ti 2p, O 1s, C 1s are at 458.81, 530.33 and 284.78 eV, respectively. As shown in Fig. 1c, the binding energies of Ti 2p$_{3/2}$ and Ti 2p$_{1/2}$ for the unannealed $\alpha$-TiO$_x$ film are 458.94 and 464.67 eV, respectively. The Ti 2p$_{3/2}$ and Ti 2p$_{1/2}$ spin orbital splitting is 5.73 eV, which is consistent with a Ti$^{4+}$ bond to oxygen. For the $\alpha$-TiO$_x$ film annealed at 90 °C, the peak positions of Ti 2p$_{3/2}$ and Ti 2p$_{1/2}$ shift slightly towards lower binding energy values (458.81 eV and 464.57 eV, respectively). The O 1s core level XPS spectra of the samples are shown in Fig. 1d. One strong peak at 530.5 eV has emerged for the unannealed $\alpha$-TiO$_x$ film, which corresponds to O atoms in titanium oxide, and the spectrum shows a shoulder at higher binding energies. The shoulder is due to the hydroxyl (OH) functional group on the $\alpha$-TiO$_x$ film surface. After being annealed at 90 °C, the peak shifted to 530.33 eV and the shoulder decreased remarkably, indicating that most of the OH functional groups were removed. The XPS results reveal that TBT decomposed into amorphous TiO$_x$ after being annealed in air at 90 °C for 60 min as a thin film.

3.2. Surface morphologies and optical properties

The surface morphologies of bare ITO coated glass and the $\alpha$-TiO$_x$ films on ITO were investigated by tapping-mode atomic force microscopy (AFM), as shown in Fig. 2. It can be seen that the surface of bare ITO coated glass is a little rough with a root mean square (RMS) value of 4.04 nm. The surface became very smooth with an RMS value of only 1.89 nm after the addition of the $\alpha$-TiO$_x$ film and placement in air at room temperature for 60 min. The surface roughness increased slightly (RMS: 2.12 nm) when the film was annealed at 90 °C for 60 min. Moreover, Fig. 2D shows the $\alpha$-TiO$_x$ film produced by spin coating 3% v/v TBT isopropanol solution in air at the same speed and annealing at 90 °C for 60 min. One can observe that the film is not homogenous with lots of “island” particles. The optical image (insert Fig. 3) of the $\alpha$-TiO$_x$ film (in air) is slightly white. It is known that TBT is very reactive, and it could therefore be hydrolyzed and clustered during the spin coating process in air.

The transmittance spectra of the TiO$_x$ films on ITO coated glass are presented in Fig. 3. The spectrum of the bare ITO coated glass was included as a reference. The thicknesses of the $\alpha$-TiO$_x$ films are 32 nm (annealed at room temperature) and 30 nm (annealed at 90, 160, and 200 °C) as measured by a Veeco Dektak150 surface profiler. For the $\alpha$-TiO$_x$ films, the antireflective effects of optical transmittance in the ranges of 350–440 nm and 580–800 nm are thought to contribute to the smoothness of the ITO surface with the $\alpha$-TiO$_x$ modification layer (RMS from 4.04 nm to 1.89 nm), as they reduce dispersion and extinction of light caused by a rough surface. The antireflective phenomenon has been explained systemically by the coherence theory in our previous report. However, the optical transmittance of the $\alpha$-TiO$_x$ (in air) film is lower than that of both the bare ITO and the $\alpha$-TiO$_x$ film due to its rougher surface. The optical images shown in the inset of Fig. 3 are consistent with the transmittance spectra.

3.3. Photovoltaic performance of the PSCs

Fig. 4 shows the influence of annealing temperatures for the $\alpha$-TiO$_x$ films on the $J$–$V$ characteristics of the inverted PSCs. The conductivity of $\alpha$-TiO$_x$ films and the device performance parameters with different annealing temperatures from 25 to
200 °C are summarized in Table 1. For the device based on P3HT:PC$_{61}$BM with the unannealed (25 °C) α-TiO$_x$ film as an electron transport layer, the PCE was only 2.98% with an open circuit voltage ($V_{OC}$) of 0.604 V, a short circuit current density ($J_{SC}$) of 7.99 mA cm$^{-2}$, and a fill factor (FF) of 61.6%. The low efficiency is attributed to a relatively low $J_{SC}$ due to the poor conductivity of the α-TiO$_x$ film which is caused by the presence of OH in the α-TiO$_x$ film under room temperature (discussed in Fig. 1d). When the annealing temperature was increased to 90 °C, the optimized performance of the device was obtained, where the PCE was 4.25% with a $V_{OC}$ of 0.616 V, a $J_{SC}$ of 10.92 mA cm$^{-2}$, and an FF of 63.0%. Further increasing the annealing temperature (to 160 and 200 °C) of the α-TiO$_x$ films shows no significant difference in device performance with the PCEs stable at around 4.20%. The OH in the α-TiO$_x$ film was completely removed at 90 °C, and the conductivity of the α-TiO$_x$ film improved. The films remained stable when further increasing the treatment temperature. It is quite consistent with the change in the performance of the device with the α-TiO$_x$ film as the electron transport layer.

Table 1 The conductivity of the α-TiO$_x$ films and the photovoltaic performances of the inverted P3HT:PC$_{61}$BM solar cells with the α-TiO$_x$ layer annealed at different temperatures for 60 min$^{a,b}$

<table>
<thead>
<tr>
<th>Sample</th>
<th>$T$ (°C)</th>
<th>$\gamma$ (S cm$^{-1}$)</th>
<th>$V_{OC}$ (V)</th>
<th>$J_{SC}$ (mA cm$^{-2}$)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>α-TiO$_x$</td>
<td>25</td>
<td>$2.6 \times 10^{-6}$</td>
<td>0.604</td>
<td>7.99</td>
<td>61.6</td>
<td>2.98</td>
</tr>
<tr>
<td>α-TiO$_x$</td>
<td>90</td>
<td>$7.4 \times 10^{-6}$</td>
<td>0.616</td>
<td>10.92</td>
<td>63.0</td>
<td>4.25</td>
</tr>
<tr>
<td>α-TiO$_x$</td>
<td>160</td>
<td>$6.5 \times 10^{-6}$</td>
<td>0.622</td>
<td>10.46</td>
<td>64.5</td>
<td>4.19</td>
</tr>
<tr>
<td>α-TiO$_x$</td>
<td>200</td>
<td>$5.8 \times 10^{-6}$</td>
<td>0.615</td>
<td>10.82</td>
<td>63.0</td>
<td>4.20</td>
</tr>
<tr>
<td>α-TiO$_x$ (in air)</td>
<td>90</td>
<td></td>
<td>0.395</td>
<td>9.10</td>
<td>50.7</td>
<td>2.75</td>
</tr>
</tbody>
</table>

$^a$ $T$: treatment temperature of α-TiO$_x$ films. $^b$ $\gamma$: the conductivity of α-TiO$_x$ films.

In contrast, when the α-TiO$_x$ film was cast in air, and then annealed at 90 °C, the device performance decreased. As can be seen from Fig. 4 and Table 1, the PCE was only 2.75% with a $V_{OC}$ of 0.595 V, a $J_{SC}$ of 9.10 mA cm$^{-2}$, and an FF of 50.7%. The main reason may be that the TBT solution has been hydrolyzed into TiO$_2$ during the spin coating process.

The effect of the annealing time of the α-TiO$_x$ film on the device performance (at 90 °C) was explored, as shown in Fig. 5 and Table 2. From 0 min to 60 min, the $J_{SC}$ and FF increase gradually, which leads to an enhancement of the PCE. As we have discussed, the α-TiO$_x$ film decomposed into amorphous TiO$_x$ gradually as the annealing time was extended. The transformation was completed under 90 °C for 60 min in air. The electrical conductivity of the α-TiO$_x$ film increased gradually (0–60 min), leading to a high electron collection and low series resistance, and hence the device performance was improved. Further extending the annealing time (60–180 min), the conductivity of the α-TiO$_x$ films and the four parameters of the devices remained stable. It is probably due to the fact that the amorphous α-TiO$_x$ film formed after 60 min annealing has good stability.

Five types of device with different structures were designed to verify the effect of the α-TiO$_x$ electron transport layer on the performance of the PSCs. Fig. 6 shows the $J$–$V$ curves of the inverted PSCs under AM1.5G illumination (100 mW cm$^{-2}$). The structures of the PSCs are as follows: Device A, ITO/P3HT:PC$_{61}$BM (180 nm)/MoO$_3$ (5 nm)/Ag (100 nm); Device B, ITO/α-TiO$_x$ (30 nm)/P3HT:PC$_{61}$BM (180 nm)/MoO$_3$ (5 nm)/Ag (100 nm); Device C, ITO/α-TiO$_x$ (30 nm)/P3HT:PC$_{71}$BM (180 nm)/MoO$_3$ (5 nm)/Ag (100 nm); Device D, ITO/ZnO (30 nm)/P3HT:PC$_{61}$BM (180 nm)/MoO$_3$ (5 nm)/Ag (100 nm); and the conventional device E is composed of ITO/PEDOT:PSS (30 nm)/P3HT:PC$_{61}$BM (180 nm)/Ca (10 nm)/Al (100 nm). All of the device performances are summarized in Table 3. For device A without the electron transport layer, the PCE was only 1.92%, with a $J_{SC}$ of 8.54 mA cm$^{-2}$, a $V_{OC}$ of 0.470 V, and an FF of 47.5%.

![Fig. 4 $J$–$V$ curves of the inverted PSCs with the α-TiO$_x$ (in air) and α-TiO$_x$ films as the electron transport layer. All films were treated in air for 60 min.](image-url)
Table 2: The conductivity of \( \alpha \)-TiO\(_2\) films and photovoltaic performance of the inverted P3HT:PC\(_{61}\)BM solar cells with the \( \alpha \)-TiO\(_{2}\) electron transport layer annealed in air at 90 °C for different times

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>( \gamma ) (S cm(^{-1}))</th>
<th>( V_{OC} ) (V)</th>
<th>( J_{SC} ) (mA cm(^{-2}))</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( 2.4 \times 10^{-6} )</td>
<td>0.610</td>
<td>9.51</td>
<td>50.0</td>
<td>2.91</td>
</tr>
<tr>
<td>30</td>
<td>( 5.5 \times 10^{-6} )</td>
<td>0.610</td>
<td>10.23</td>
<td>57.6</td>
<td>3.63</td>
</tr>
<tr>
<td>60</td>
<td>( 7.4 \times 10^{-6} )</td>
<td>0.616</td>
<td>10.92</td>
<td>63.0</td>
<td>4.25</td>
</tr>
<tr>
<td>90</td>
<td>( 7.2 \times 10^{-6} )</td>
<td>0.615</td>
<td>10.87</td>
<td>63.1</td>
<td>4.22</td>
</tr>
<tr>
<td>120</td>
<td>( 7.3 \times 10^{-6} )</td>
<td>0.616</td>
<td>10.88</td>
<td>63.3</td>
<td>4.23</td>
</tr>
<tr>
<td>150</td>
<td>( 6.9 \times 10^{-6} )</td>
<td>0.620</td>
<td>10.47</td>
<td>64.9</td>
<td>4.22</td>
</tr>
<tr>
<td>180</td>
<td>( 6.3 \times 10^{-6} )</td>
<td>0.618</td>
<td>10.48</td>
<td>65.0</td>
<td>4.22</td>
</tr>
</tbody>
</table>

Fig. 6 J–V curves of the PSCs with different structures.

As discussed above, the device performance was greatly improved with the \( \alpha \)-TiO\(_2\) electron transport layer prepared in a glovebox and annealed in air at 90 °C for 60 min (device B). Furthermore, when using PC\(_{71}\)BM as an acceptor, the PCE of device C reached 4.65%, with a \( V_{OC} \) of 0.629 V, and an FF of 62.8%. In comparison, the PCE of device D with ZnO as an interfacial layer was only 3.88%, which is mainly due to the low \( J_{SC} \) (9.33 mA cm\(^{-2}\)). Similarly, the PCE of conventional device E was 3.90%, which is restricted by the low \( J_{SC} \) (9.10 mA cm\(^{-2}\)). One can observe that the enhanced device performance with the \( \alpha \)-TiO\(_{2}\) electron transport layer can be mainly ascribed to the improved \( J_{SC} \), which is a result of the relative smooth surface of the \( \alpha \)-TiO\(_{2}\) film prepared by the above method and thus the better conductivity of the film.

Table 3: Device parameters of the PSCs with different structures

<table>
<thead>
<tr>
<th>Device structure</th>
<th>( V_{OC} ) (V)</th>
<th>( J_{SC} ) (mA cm(^{-2}))</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.470</td>
<td>8.54</td>
<td>47.5</td>
<td>1.92</td>
</tr>
<tr>
<td>B</td>
<td>0.616</td>
<td>10.92</td>
<td>63.0</td>
<td>4.25</td>
</tr>
<tr>
<td>C</td>
<td>0.629</td>
<td>11.77</td>
<td>62.8</td>
<td>4.65</td>
</tr>
<tr>
<td>D</td>
<td>0.638</td>
<td>9.33</td>
<td>65.2</td>
<td>3.88</td>
</tr>
<tr>
<td>E</td>
<td>0.642</td>
<td>9.10</td>
<td>66.8</td>
<td>3.90</td>
</tr>
</tbody>
</table>

Fig. 7 (a) Normalized PCE of unencapsulated inverted device B and conventional device E stored 10 days in air under ambient conditions. (b) \( V_{OC} \), \( J_{SC} \), and FF of device B in 10 days.

Furthermore, we also fabricated one polymer solar cell based on the low bandgap polymer P1 and the result is shown in the ESI. One can observe that its \( J_{SC} \) was improved compared to the reported data. The \( J–V \) characteristics of the devices indicate that the \( \alpha \)-TiO\(_{2}\) film prepared by TBT solution is an effective electron transport layer.

The stability of the inverted and conventional devices was investigated. The unencapsulated devices were stored for 10 days in air under ambient conditions, and the photovoltaic curves are shown in Fig. 7. The conventional device has proven to be very unstable as its PCE reduced to only 13% of its original value after 1 day of exposure to air and the device totally degraded after 2 days. In contrast, the inverted device shows good stability, and its PCE only drops by 32% after 10 days in ambient conditions with the use of the \( \alpha \)-TiO\(_{2}\) film as the electron transport layer and MoO\(_{3}\)/Ag as the anode. The \( V_{OC} \) almost remains constant and the observed decrease in the PCE is mainly due to the deterioration of both the \( J_{SC} \) and the FF (Fig. 7b), which is due to the intrusion of oxygen and water into the active layer from the side of the electrode. The improved stability can be attributed to the use of both the \( \alpha \)-TiO\(_{2}\) layer and the MoO\(_{3}\)/Ag electrode. \( \alpha \)-TiO\(_{2}\) is very stable and has compatible work functions with ITO with no negative effects on the performance. In addition, the Ag electrode in air can form a layer of silver oxide which increases its effective work function to \(-5.0\) eV. This matches well with the HOMO of the stable MoO\(_{3}\) (\(-5.3\) eV), which can improve its electrical coherence at the interface. The results reveal that PSCs with an inverted device structure using \( \alpha \)-TiO\(_{2}\) as an electron transport layer exhibit very good stability.

4. Conclusions

We demonstrated the production of efficient polymer solar cells (PSCs) using a facile solution-processed \( \alpha \)-TiO\(_{2}\) electron transport layer prepared by spin coating TBT isopropanol solution...
onto ITO coated glass in a glovebox and annealing it at different temperatures. The GIXRD and XPS results indicate that the TBT film was converted to amorphous TiO$_2$ by thermal annealing at 90 °C for 60 min in air. The α-TiO$_2$ films are quite smooth with high light transmittance. The PSCs with α-TiO$_2$ as the electron transport layer show enhanced photovoltaic performance compared to the device with PEDOT:PSS as the anode buffer layer. The optimized power conversion efficiency (PCE) of the PSCs based on P3HT/PC$_{61}$BM and P3HT/PC$_{71}$BM with the α-TiO$_2$ layer reached 4.25% and 4.65% under AM1.5G illumination (100 mW cm$^{-2}$). Meanwhile, the PSCs with the α-TiO$_2$ electron transport layer exhibit good stability. In addition, the preparation process is quite easy and low cost, and it is compatible with the roll-to-roll production of flexible PSCs.

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Notes and references