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High-performance polymer solar cells via Al-doped ZnO cathode interlayer

Recently accomplished landmark power conversion efficiency (PCE) over 10% of polymer solar cells (PSCs) presents promising potential for the practical application of the printable photovoltaics. However, for achieving the top-level performances, particular design and huge effort have to be done at the interlayers. Most of them comprise organic molecules, composites, hybrid materials or multiple-layers, which are usually complicated and costly in synthesis and fabrication. Moreover, the limited thicknesses of the interlayers (a few to tens of nanometers) have to be avoided in commercial production, as the stable and reproducibility issues.

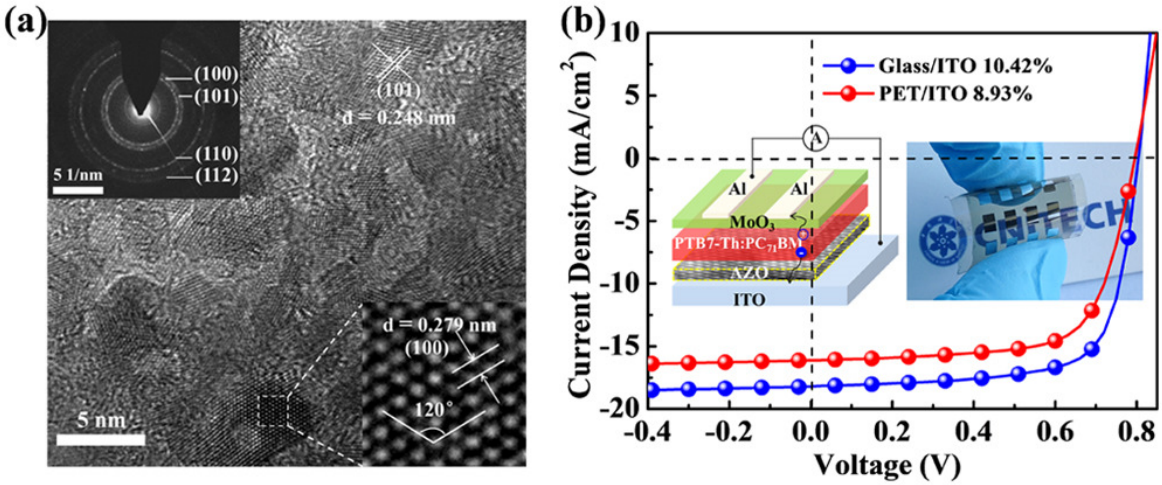

Fig. 1 (a) TEM images of the AZO sample. (b) The inverted device structure, image of flexible devices, and the *J*-V curves under AM 1.5G irradiation.

In this study, we report high performance PSCs by preparing the cathode interlayer with inorganic semiconductor aluminum-doped zinc oxide (AZO), spin-coated from a solution of our lab-made AZO nanocrystals, based on poly [[2,6'-4,8-di(5-ethylhexylthienyl)benzo[1,2-*b*;3,3-*b*]dithiophene][3-fluoro-2[(2-ethylhexyl)carbonyl]thieno[3,4-*b*]thiophenediyl]] (PTB7-Th): [6,6]-phenyl C_{71}-butyric acid methyl ester ($PC_{71}BM$) blends.

The AZO crystals were synthesized through a simple low-temperature solution process. Figure 1a shows the clear lattice fringes of as-prepared AZO nanocrystals, with measured *d*-spacing of 0.279 and 0.248 nm, corresponding to lattice plane (100) and (101), respectively. Transmission Electron Microscope (TEM) analysis indicates that the size of AZO particles is about 5 nm. The AZO nanocrystals take the same crystal phase of ZnO (wurtzite structure), as confirmed by the X-ray diffraction (XRD) measurements, and all the diffraction peaks can be indexed to the classical hexagonal phase of ZnO. From the X-ray photoelectron spectroscopy (XPS) spectra, the typical core line of the Al 2p is observed for the AZO film with a weak peak at 74.7 eV, confirming the existence of Al in the AZO matrix.

Inverted PSCs were fabricated with configuration of ITO/AZO/PTB7-Th: $PC_{71}BM/MoO_3$/Al, as shown in Fig. 1b. The optimum thermal-annealing temperature of AZO interlayer was determined to be at about 140 ^oC, which can guaranty a low temperature fabrication of PSCs and thus applicable on flexilbe substrates. The effect of AZO film thickness on the device performance was also investigated. A champion PCE of 10.42% was achieved, with a V_{OC} of 0.804 V, a J_{SC} of 17.91 mA cm^{-2} and a FF of 72.3%. Meanwhile, a prominent PCE approaching 9% was accomplished even with a 120 nm-thick AZO interlayer, suggesting low performance-sensitivity to the film thickness. To explore the reasons for the higher performance of AZO-based devices than those of ZnO, we performed electronic and morphological studies. Compared to the ZnO film, much higher current intensity was recorded on the AZO film by conductive atomic force microscopy (C-AFM) tests. The dramatically increased vertical current suggests promoted electrical properties of AZO upon Al doping, which could have improved the charge transport and collection. Higher apparent charge carrier mobility was confirmed as well for the AZO-device, which was consistent with the results of the C-AFM analysis. In addition, with the AZO CIL, we fabricated flexible PSCs on PET/ITO substrate to evaluate its usability in practical application. A best PCE of 8.93% was achieved for the PTB7-Th:$PC_{71}BM$ device (Fig. 1b). Mechanical stability of the flexible devices was tested by performing mechanical bending by applying a nominal bending strain (ε_{nom}) of 0.68%. Excellent mechanical robustness was demonstrated for the AZO-based flexible PSCs by keeping ~88% of its initial PCE after 500 times bending, which would fulfill the requirement and set a good example to pave the way of flexible PSCs. Our study implies promising potential for this interlayer system in low-temperature solution-based printing PSCs and could speed up the commercialization of this technology.

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