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Short Communication

Thermostable single-junction organic solar cells with a power conversion efficiency of 14.62%

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Organic solar cells (OSCs) have drawn substantial attention in recent two decades due to their features of solution processability, low cost, and light weight [1]. The active layer of OSCs is usually composed of an electron donor (D) and an electron acceptor (A). The D/A system can form interpenetrated nanoscale network, which allows efficient exciton dissociation and hence charge carrier generation. However, the efficiency of such binary OSCs is generally limited by its insufficient light absorption [2]. To overcome this drawback, ternary OSCs (consist of two donors and one acceptor, or one donor and two acceptors) have been widely explored due to their expected broader absorptions [2]. Owing to the rapid material development, suitable material combination and optimized device engineering, the power conversion efficiencies (PCEs) of OSCs by now have reached 12%–14% [3,4].

Despite of the great progress in PCEs, there are still several factors limiting the future marketing of OSCs, such as low-level efficiency of large-size devices, poor reproducibility and stability, etc. Among them, long-term stability is crucial for the commercialization. OSCs are known to degrade under high temperatures, and upon the presence of water and oxygen [5]. The influence of water and oxygen can be eliminated by encapsulation techniques. However, for practical applications, the temperature inside an OSC can reach as high as 80 °C or even higher in a typical sunny day, especially in tropical region [5]. Therefore, it is of great importance to develop OSCs with good thermal stability [6,7].

Recently, we designed a highly efficient low-bandgap non-fullerene acceptor (CO_i8DFIC) with strong NIR absorption [8]. The PTB7-Th:CO_i8DFIC:$PC_{71}BM$ ternary solar cells offered a PCE of 14.08% [4]. In this work, we further adopted a post-annealing process and achieved an outstanding PCE of 14.62%. Encouragingly, the device exhibited a good thermal stability with PCEs over 13.5% in a wide temperature range (70–160 °C).

The chemical structures of PTB7-Th, CO_i8DFIC and $PC_{71}BM$, and the energy diagram are provided in Fig. 1a. The device structure is indium tin oxide (ITO)/ZnO/PTB7-Th:CO_i8DFIC:$PC_{71}BM$/MoO_3/Ag. The lowest unoccupied molecular orbitals (LUMOs) for PTB7-Th (−3.12 eV), $PC_{71}BM$ (−3.67 eV) and CO_i8DFIC (−3.88 eV) demonstrate a favorable energy level alignment, suggesting that electrons can effectively transfer from PTB7-Th to CO_i8DFIC via $PC_{71}BM$. The solar cells were annealed at various temperatures (10 min each) from 70 to 160 °C to optimize the performance. Fig. 1c gives the *J-V* curves of the device before and after annealing, and the corresponding performance data are listed in Table S1 (online). The device before annealing gave a PCE of 13.65%, with an open-circuit voltage (V_{oc}) of 0.702 V, a short-circuit current density (J_{sc}) of 27.74 mA/cm^2, and a fill factor (FF) of 70.1%. Thermal annealing at 70 °C enhanced PCE to 14.35%. The highest PCE of 14.62% was achieved at an annealing temperature of 80 °C, with a V_{oc} of 0.727 V, a J_{sc} of 27.39 mA/cm^2, and a FF of 73.4% (Fig. 1b). Remarkably, the PCE only varied slightly and kept over 13.5% at higher annealing temperatures (90–160 °C), indicating that the device has a very good thermal stability. The post-annealing process could improve the quality of the active film/electrode interface [9,10], thus enhancing the device performance (Fig. S1 and Table S1 online).

Fig. 1d presents the absorption spectra for the PTB7-Th:CO_i8DFIC:$PC_{71}BM$ film without/with annealing. The absorption spectra only show slight variation upon the thermal treatments, consisting with the very small variation in J_{sc} (Table S1 online). Fig. S2 (online) shows the atomic force microscopy (AFM) images

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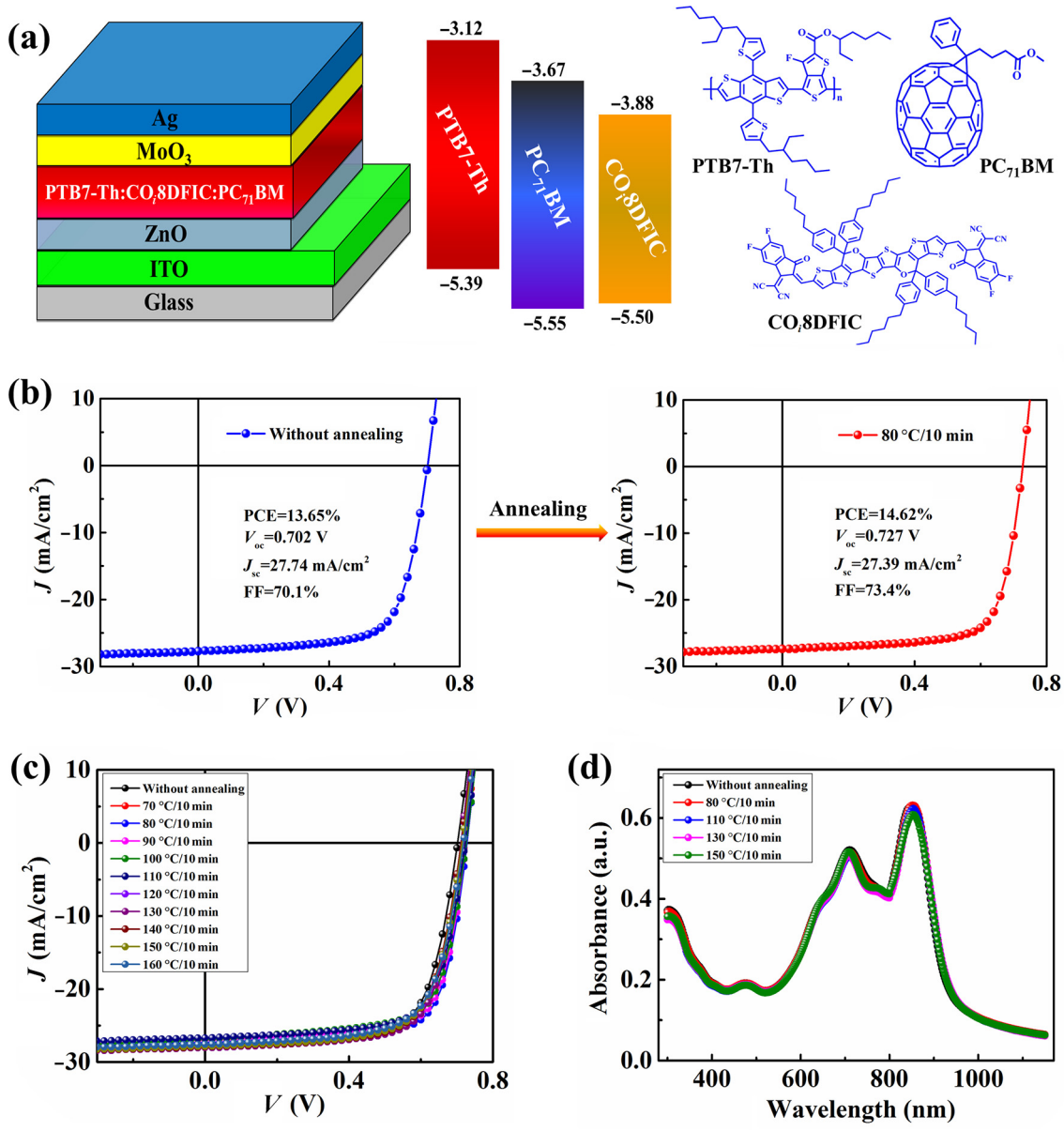

Fig. 1. Ternary organic solar cells with 14.62% PCE. (a) Schematic of the device, energy level diagram, and chemical structures of PTB7-Th, CO_i8DFIC and $PC_{71}BM$. (b) *J-V* curves for the device without/with annealing at 80 °C. (c) *J-V* curves for the device without/with annealing at various temperatures. (d) Absorption spectra for the film without/with annealing at various temperatures.

of these films. The root-mean-square (RMS) roughness of the film without annealing is 4.86 nm, and that of the films annealed at 80, 110, 130, 150 °C are 2.54, 3.23, 2.45, 3.07 nm, respectively. The annealing could make a more favorable nanoscale phase separation, which benefits exciton dissociation and charge carrier transport, thus enhancing PCE effectively.

We studied the thermal stability of the device. As shown in Table S2 (online), after being heated at 80 °C (130 °C) for 20 h, the device still gave a decent PCE of 13.92% (13.51%).

In summary, the post-annealed PTB7-Th:CO_i8DFIC:$PC_{71}BM$ ternary solar cells delivered a PCE of 14.62%, with a V_{oc} of 0.727 V, a J_{sc} of 27.39 mA/cm^2, and a FF of 73.4%. Moreover, the devices exhibited a good thermal stability with PCEs over 13.5% in a wide temperature range (70–160 °C). Our progress here indicates that CO_i8DFIC and its coming derivatives could be applied in the commercialization of organic solar cells in the future.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2018.02.015.

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