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Improved photovoltaic properties of solar cells based on poly [9, 9′-dioctyl-fluorene-co-bithiophene] and a soluble fullerene by microwave annealing

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Abstract Enhanced photovoltaic characteristics of bulk heterojunction organic solar cells based on blends of poly [9, 9′-dioctyl-fluorene-co-bithiophne] (F8T2) and 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6,6) C61 were achieved through microwave annealing treatment. The absorption and photoluminescence spectra of the active layers with 1:1 ratio in weight were characterized under microwave and common annealing oven. Compared with the oven annealing, the absorption spectra of active layer were enhanced in intensity as well as the wavelength range of absorption little broadened after microwave annealing; the intensities of PL spectra of the blends were also further quenched compared with that of pristine F8T2. The highest power conversation efficiency of 1.18% was achieved by microwave annealing for 90 s compared with 0.86% using annealing oven. The enhanced performance of cells is attributed to the improved morphology and modified charge transport pathways through microwave annealing.

Introduction

Organic solar cells based on conjugated polymers are attractive in recent years due to their unique advantages, such as low cost, light weight, solution processibility, and easy processing [1–6]. However, the power conversion efficiency (PCE) of solar cells based on polymers is still limited by the imbalance of electron and hole mobility. Several ways have been proposed to solve this mismatch of the charge mobility [7–13]. Among those methods, it is found that the PCE can be remarkably improved by thermal annealing on the cells [14, 15]. A solvent annealing method was used and a remarkable efficiency of 4.4% was approached [15]. Ma [16] reported polymer solar cells based on P3HT and PCBM with PCE of 5% were achieved through post-production annealing. However, the common thermal annealing through thermal ovens is time consuming process; what's more, it is suggested that the device performance and energy could unavoidably decay and lost during the process of annealing [14, 17, 18].

To solve this problem, microwave annealing are chosen as an alternative way to introduce the cells, which can heat materials selectively and need less time compared with traditional oven [19–22]. Moreover, microwave can not only causes the self-arrangement of polymer chains and facilitate the charge hopping, which induces the charge mobility and the drift velocity of charge carriers become larger, but also can result in lower internal resistance of the solar cell and higher PCE. So it is a potential approach toward enhancing the efficiency of energy usage.

In this paper, a significant performance improvement of the [9, 9′-dioctyl-fluorene-co-bithiophne] (F8T2) and 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6, 6) C61 (PCBM) solar cell by annealing through a microwave (600 W, 2.45 GHz) will be introduced compared with the conventional annealing oven. The HOMO and the LUMO energy levels of F8T2 were estimated from the onset oxidation and reduction potentials as 5.4 and 3.0 eV, respectively, relative to the vacuum level, which can have a more balanced charge transport with that of the PCBM (6.1 and 3.7 eV). In the fabrication of cells, Au was used as the electrode

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because of the high stability to the oxidation in air, an adhesive lay of Ti was applied to further optimize the transport of carriers. The best device yielded a PCE of 1.18% after microwave annealing for 90 s. Photovoltaic characteristics of films based on F8T2 and PCBM were also studied through related absorption and photoluminescence (PL) measurements.

Experiment details

The chemical structures of the F8T2 and PCBM for active layer are shown in Fig. 1. Prior to cell fabrication, the indium tin oxide (ITO) coated glass substrates were ultrasonically cleaned in acetone, ethanol, and de-ionized water sequentially. Afterward, the substrates were treated with plasma cleaning for 5 min, and then a layer of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) at 3,000 rps for 60 s was spin coated onto ITO substrates, followed by baking at 150 °C for 15 min in oven. Subsequently, the active layer containing a mixture of F8T2 and PCBM were spin-coated from 1, 2-dichlorobenzene to the substrates. Finally, the top electrodes of aluminum (Al) were evaporated by thermal evaporation at a pressure below 1×10^{-4} Pa through a shadow mask with the diameter of active areas as 0.3×0.3 cm^2. The cells were annealed with microwaves at 2.45 GHz, 600 W in a multimode cavity and annealing oven, respectively.

The UV–visible absorption spectra were measured using a UV-2501PC (UV–VIS Spectrophotometer); the films of the F8T2 and PCBM were prepared through spin coating from 1,2-dichlorobenzene on quartz substrates. The PL spectra were obtained through a Fluorescence Spectrometer LS55, samples were illuminated by a Xenon lamp, and the emission was recorded through another monochromator by a photo multiplier. The photovoltaic characteristics of cells were performed by a Source-Meter (Keithley, model 2400) and illuminated by a Xe lamp solar simulator with an AM1.5 and the intensity of 100 mW/cm^2. All electrical measurements were carried out at room temperature in air.

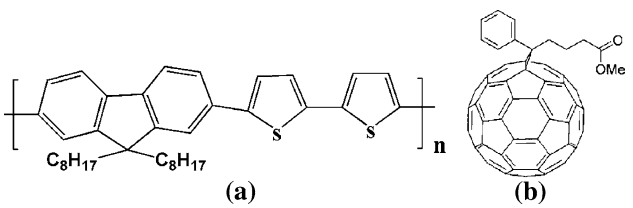

Fig. 1 The chemical structure of materials used in this article. **a** F8T2 and **b** PCBM

Results and discussions

Absorption spectra

In order to study the effect of microwave annealing on the active layer, the UV–visible absorption of films of F8T2 and the blends with PCBM were prepared through spin coating on the quartz glasses. The absorption spectra are shown in Fig. 2.

It is obvious that the film of pristine F8T2 shows strong absorption intensity in the visible range with two peaks at around 460 and 500 nm, respectively. It is known that absorption spectra of conjugated polymer depend on its molecular conformation due to changing conjugation length of the polymer. Compared with the pristine F8T2, the maximum absorption peaks of three blends shows little red shifted it may be ascribed to the increased effective conjugation length of F8T2 in the blend with PCBM. And the films of blend have an addition absorption peak at 338 nm, which corresponds with that of PCBM.

Moreover, the film after microwave annealing exhibits high intensity of absorption compared with oven annealing ones, which further increases the number of photons absorbed in the visible region.

Photoluminescence spectra

To get more careful investigation of the photo-physics in the F8T2: PCBM systems, the PL spectra of the blend of F8T2: PCBM in dichlorobenzene solution were measured under the photo-excitation wavelength of 460 nm, which is corresponding to the absorption peak wavelength of the F8T2. Figure 3 shows the PL spectra of the pure F8T2 and blend films with PCBM (1:1 in weight) under different conditions.

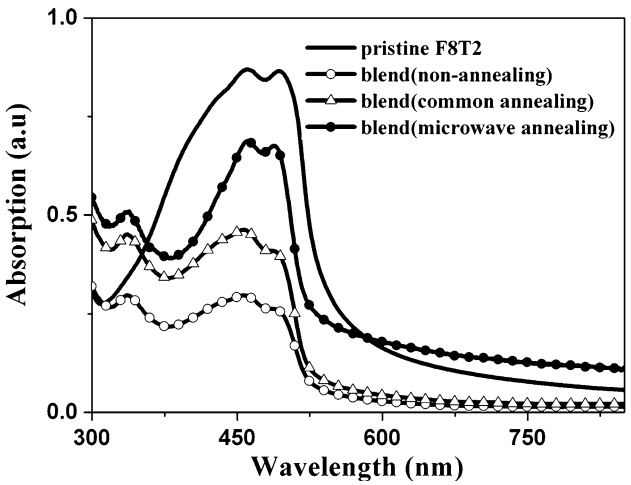

Fig. 2 The absorption spectra of F8T2 and blended films with the PCBM

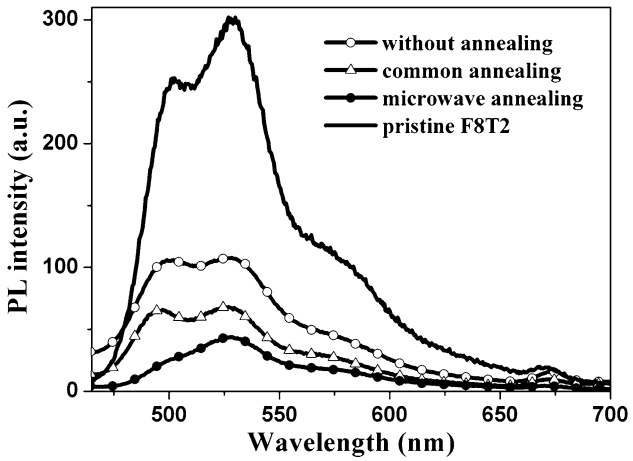

Fig. 3 The PL spectra of the F8T2 and blend films with PCBM

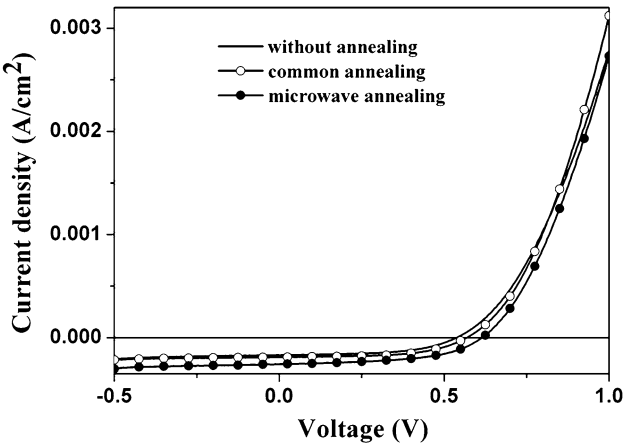

Fig. 4 The current–voltage curve of cells under illumination with 100 mW/cm^2

For the pristine F8T2, the predominant PL band with central peaks around 530 nm have been observed, but the band is significantly quenched in the F8T2: PCBM blended films. Among the three blend films, the film after microwave annealing is quenched largest to about 14% of the pure F8T2 layer emission showing that 86% of the excitons are dissociated. The result indicates that electron transfer occurred from the photo-excited F8T2 backbone to PCBM.

IV characteristics

Bulk heterojunction photovoltaic cells were fabricated with configurations of ITO/PEDOT: PSS/F8T2: PCBM/Au. Au was used as the electrode because of the high stability to the oxidation in air, an adhesive lay of Ti was applied to further improve the transport of carriers. As it shows good performance of cells based on F8T2 and PCBM with annealing temperature of 70 °C in some literatures [23, 24], so the same annealing temperature is chosen for common annealing in this article. The other cell was irradiated through microwaves in a multimode cavity for 90 s.

Figure 4 shows the current density–voltage characteristics of the cells under illumination.

It is obvious that the device without annealing exhibited poor performance with an open circuit voltage (V_{OC}) of 0.53 V, a short circuit current density (J_{SC}) of 2.39 mA/cm^2, a fill factor (FF) of 0.55, and the PCE (η) was 0.7%. The cells after annealing at 70 °C for 15 min showed the increased η of 0.86%; the microwave annealed ones exhibited the best performance with the values of V_{OC}, J_{SC}, FF, and η reached to 0.61 V, 3.66 mA/cm^2, 0.53%, and 1.18%, respectively. The enhanced performance of cells is attributed to the improved morphology and modified charge transport pathways through microwave annealing treatment. Nevertheless, as implied by the measured fill factor, which attributes to the large series resistance of devices, so there are significant improvements to be made that could lead to more efficient solar-energy conversion.

Conclusions

In this paper, enhanced performance of cells using the microwave annealing treatment has been presented. Using the microwave annealing could avoid the deterioration of cells properties during the process. It is applicable not only for the active layer but also to the metal electrode. The result showed that not only the absorption intensity has enhanced, but also the PL has further quenched. Moreover, the enhanced performance of cells through microwave annealing has achieved compare with that of common annealing oven. So the microwave is an effective and promising treatment for post annealing the devices. Moreover, the insertion of Ti between the Au electrode and active layer leads to further optimize photovoltaic characteristics.

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