

Improved photovoltaic performance of silicon nanowires/conjugated polymer hybrid solar cells



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ABSTRACT

In this study, we investigate the effect of incorporation of Si nanowires (SiNWs) on the organic/inorganic hybrid nanocomposites based on poly [2-methoxy-5-(2'-ethylhexyloxy)-1,4-phenylene vinylene] (MEH-PPV) and SiNWs. A huge potential for SiNWs for an amelioration of optical properties of investigated structures was shown, and particularly a more efficient charge transfer was guaranteed. The impact of SiNWs incorporation on photoluminescence properties of polymer:Si nanowires nanocomposites have been correlated with morphological characteristics. MEH-PPV:SiNWs (1:2) is the optimum composition where the device performance displays a J_{sc} of 0.328 $\mu\text{A}/\text{cm}^2$, a V_{oc} of 0.680 V and FF of 38%.

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1. Introduction

Polymer solar cells have been considered as attractive candidates for renewable energy sources due to their several and multiple advantages of environmental friendliness, low cost and large area processing [1–3]. The bulk heterojunction structure composed of interpenetrating network of polymer donor and electron acceptor has deeply promoted the development of polymer solar cells [4,5]. Both inorganic and organic electron acceptors are investigated; the latter are mainly fullerene derivatives [6–8]. Although power conversion efficiency (PCE) of polymer solar cells with these fullerene derivatives electron acceptors reached up to 9%, the complicated synthesis process and easy oxidation of fullerene in ambient still hinder their practical investigation [9,10]. Alternatively, a multitude of concepts have been demonstrated by combining p-type donor polymers with n-type acceptor inorganic nanostructures such as CdSe [11], TiO₂ [12] and ZnO [13]. One dimensional (1-D) inorganic semiconductor nanostructures are among some of the most attractive nanomaterials for solar cell

devices because they provide a direct path for charge transport. Other advantages include high carrier mobility, solution processability, thermal and ambient stability, and high electron affinity necessary for charge injection from the complementary organic donor material. Silicon nanowires (SiNWs) are an example of this class of materials that have been used for hybrid solar cells [14–18]. The particular structure of SiNWs can provide high-mobility pathway from the active interface to the electrodes for carriers. They can significantly reduce the reflection and induce strong light trapping between nanowires, resulting in strong absorption. Whilst their volume is low, SiNWs participate to the increase of the contact area between the two materials and hence restrain the back charge recombination and consequently improve the charge transfer at polymer/SiNWs interfaces. From the relationship between structure and performance, the morphology changes of the photoactive layer are derived from a combination of dopant and conjugated polymer. It has been shown that the power conversion efficiency of bulk heterojunction solar cells can be improved drastically by controlling the morphology of the blend.

Herein, we report enhanced performance of bulk heterojunction hybrid solar cells based on poly[2-methoxy-5-(2'-ethylhexyloxy)-1,4-phenylene vinylene] (MEH-PPV) as electron donor and Si nanowires as electron acceptor. In order to evaluate the performance of the SiNWs effect, we have prepared different compositions of polymer:SiNWs (1:0.25; 1:0.5; 1:1; 1:2 and 1:4).

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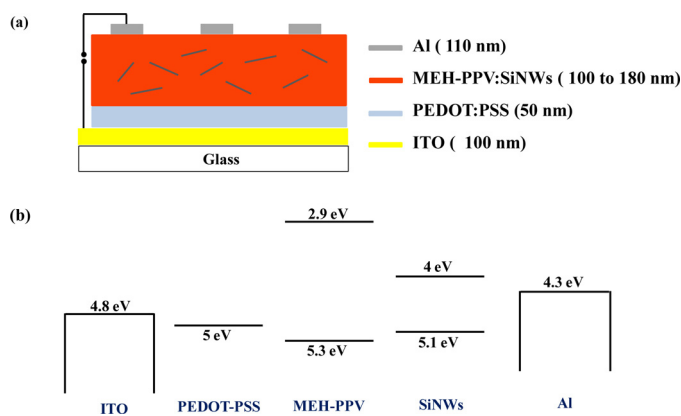


Fig. 1. Schematic of the MEH-PPV:SiNWs organic hybrid solar cell. (a) ITO/PEDOT:PSS/MEH-PPV:SiNWs/Al solar cell structure; (b) Energy band diagram of investigated device.

Hybrid solar cells with the structure of ITO/PEDOT:PSS/MEH-PPV:SiNWs/Al were fabricated and characterized with optical, morphological and electrical tools.

2. Experimental

2.1. Materials

MEH-PPV was purchased from Aldrich (weight average molecular weight (M_w) = 86,000 g/mol). Silicon nanowires (SiNWs) were grown using Vapor–Liquid–Solid (VLS) mechanism on n-doped Si (111) wafer. The growth step was performed in a horizontal low pressure chemical vapor deposition (LPCVD) reactor at 600 °C growth temperature and 3 Torr total pressure. Gold colloids were used as catalyst, hydrogen (H_2) was used as the carrier gas and silane (SiH_4) was used as Si precursor [19]. The average diameter and length of synthesized SiNWs are around 100 nm and 16 μ m, respectively.

2.2. Device elaboration

Si nanowires are removed from the substrate wafer by sonication in 1,2-dichlorobenzene (ODCB) for 20 min. Homogenous solution of MEH-PPV in ODCB (15 mg/ml) was mixed with dispersed SiNWs for different ratios of volume (1:0.25; 1:0.5; 1:1; 1:2 and 1:0.4). The mixed blends were stirred for 2 h at room temperature. Before obtained blends coating, poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT/PSS) was deposited onto ITO-coated glass by spin coating (3000 rpm, 30 s) from an aqueous solution and then dried in vacuum condition at 120 °C for 20 min. Blends based on MEH-PPV:SiNWs were spin coated (Step 1: 800 rpm for 15 s; Step 2: 1500 rpm for 30 s) into suprasil glass (for optical and structural measurements) and ITO/PEDOT:PSS substrate (for electric measurements), and then annealed at $T = 110$ °C for 30 min under vacuum condition, in order to remove the residual solvent. Post-fabrication treatment such as heating to the point beyond the glass transition temperature of polymer (T_g (MEH-PPV) = 80 °C) is beneficial for manipulating the phase separation of the blend. Overall, this annealing will improve charge transfer, charge transport, and charge collection throughout the device [20,21]. The thickness of the different elaborated layers varies versus blend composition. It ranges from 100 to 180 nm. Al contacts, serving as electrode, were thermally evaporated on top of the active layer, at a pressure below 10^{-6} Torr. The schematic and energy band diagrams of our hybrid solar cells are shown in Fig. 1.

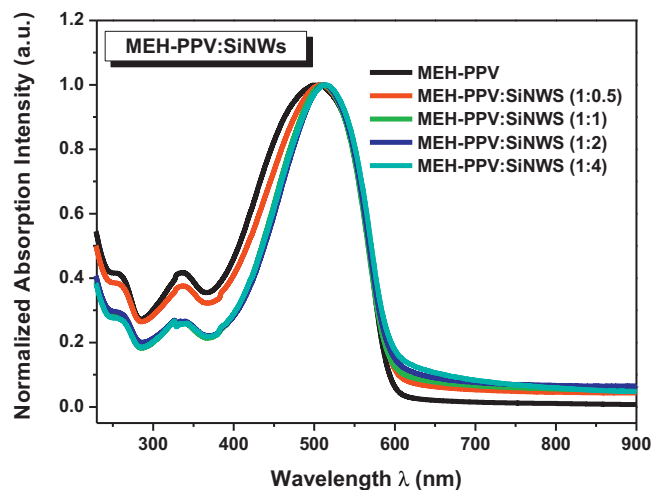


Fig. 2. Absorption spectra of pristine MEH-PPV and MEH-PPV:SiNWs with different volume ratios (1:0.5; 1:1; 1:2 and 1:4).

2.3. Instrumentation

The UV–vis spectra were performed using a PERKIN ELMER Lambda 35 spectrophotometer. Photoluminescence spectra have been performed with a “JOBIN YVON-SPEX Spectrum One” CCD detector, cooled at liquid nitrogen temperature. The current–voltage characteristics under illumination with Xe Oriel solar simulator were obtained with a Keithley 2640 source. Characterizations of the composite morphologies were performed by scanning electron microscopy (SEM Hitachi S800) and optical microscope (Nikon).

3. Results and discussion

3.1. Absorption and photoluminescence study

To elucidate the role of SiNWs in the elaborated devices, we measure the photo-absorption spectra of the pure MEH-PPV and MEH-PPV/SiNWs thin films. The normalized absorption spectra of MEH-PPV:SiNWs for different contents of SiNWs are displayed in Fig. 2. The pure MEH-PPV thin film shows a well-ordered absorption behavior: the π – π^* transition was observed at 500 nm wavelengths. Upon blending with SiNWs, the whole absorption spectra show a light red-shift as the content of SiNWs increases. These observations prove that there is an interaction between pristine MEH-PPV and SiNWs, by increasing the polymer conjugation length and avoiding the coiled form of conjugated MEH-PPV backbone to be formed [22,23]. The overall effect is that SiNWs act as templates for increasing the π -conjugation of the MEH-PPV phase, an effect resulting from the one dimensional NW geometry and the π – π stacking interaction at the interface between the MEH-PPV backbone and the SiNWs.

The investigation of photoluminescence (PL) response represents an efficient tool to control the efficiency of the charge transfer process at donor/acceptor bulk heterojunction. In fact, the extinction of the PL intensity in the bulk heterojunction materials is consistent with the increase of the charge transfer efficiency, which is carried out before the radiative recombination of electron–hole pairs, excitons [24]. Further, the degree of PL quenching is mostly related to the available interface areas between donor and acceptor moieties, provided for exciton dissociation [25]. The study of photoluminescence features of MEH-PPV/SiNWs has been followed by varying the concentration of SiNWs. Fig. 3a shows the PL spectra of MEH-PPV/SiNWs nanocomposites, with different SiNWs volume

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