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Improved performance of silicon nanowire/cadmium telluride quantum dots/organic hybrid solar cells

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ABSTRACT

We fabricated silicon nanowire/cadmium telluride quantum dots (CdTe QDs)/organic hybrid solar cells and investigated their structure and electrical properties. Transmission electron microscope revealed that CdTe QDs were uniformly distributed on the surface of the silicon nanowires, which made PEDOT:PSS easily filled the space between SiNWs. The current density–voltage (*J*–*V*) characteristics of hybrid solar cells were investigated both in dark and under illumination. The result shows that the performance of the hybrid solar cells with CdTe QDs layer has an obvious improvement. The optimal short-circuit current density (J_{sc}) of solar cells with CdTe QDs layer can reach 33.5 mA/cm^2. Compared with the solar cells without CdTe QDs, J_{sc} has an increase of 15.1%. Power conversion efficiency of solar cells also increases by 28.8%. The enhanced performance of the hybrid solar cells with CdTe QDs layers are ascribed to down-shifting effect of CdTe QDs and the modification of the silicon nanowires surface with CdTe QDs. The result of our experiments suggests that hybrid solar cells with CdTe QDs modified are promising candidates for solar cell application.

1. Introduction

Silicon is the most widely used material for solar cells due to its abundance, nontoxity, reliability and mature fabrication process. However, silicon is an indirect band-gap semiconductor, which results in moderate absorption length. In order to absorb enough solar radiation and improve the efficiency of silicon based solar cells, many researches have been performed, mainly focusing on three aspects: (1) texturing the surface of silicon with nanostructure (nanocones, nanowires or nanoholes) [1–4]. Theoretical and experimental studies have shown that these structures can improve light absorption and carrier collection, leading to higher efficiency; (2) increasing the number of band gaps to form tandem solar cell structures [5,6]. Some research has been done on which quantum dots are applied in tandem solar cells based on silicon. Utilizing confinement in the quantum dot to control the cell band gap, solar cells achieved enough absorption in the solar spectrum; (3) the integration of down-shifting materials [7,8]. These down-shifting processes converted the solar spectrum to match the absorption properties of Si solar cells via luminescence, in order to overcome the low optical response of Si in UV/blue light region. In this case, high energy light is absorbed, and subsequently re-emitted in longer wavelength where external quantum efficiency (EQE) of the solar cell is much higher. Down-shifting can improve the spectral response of silicon based solar cells [9].

On the other hand, hybrid solar cells based on silicon nanowire and conjugate polymer poly (3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) have attracted much attention for their simple fabrication process and low-cost in recent years [10–12]. The main disadvantage is that its photoelectric conversion efficiency (PCE) is not high enough for mass production. Over the past few years, many studies have been carried out, particularly on using silicon textures, for light trapping characteristics of hybrid solar cells, which leaded to notable efficiency improvement [13–16]. According to reports, it has been identified that light absorption plays a significant role in device characteristics.

In the present paper, we introduce an intermediate cadmium telluride quantum dots (CdTe QDs) layer between the organic with silicon nanowires of hybrid solar cells as a down-shifting layer. Scanning electron microscope (SEM) and transmission electron

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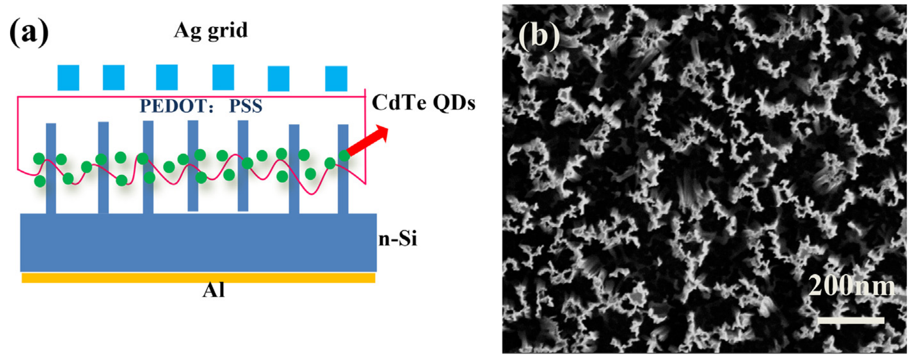

Fig. 1. Photovoltaic device structure. (a)Schematic illustration of the hybrid solar cell based on silicon and PEDOT:PSS with an intermediate CdTe QDs layer; (b) Top-view scanning electron microscope image of silicon nanowires. The scale bar is 200 nm.

microscope (TEM) were used to observe the structure of the hybrid solar cells. The *J*–*V* characteristics of the solar cells were measured both in dark and under illumination. At last, we further discuss the mechanism of the function that CdTe QDs layer act on the silicon nanowires hybrid solar cell.

2. Experiment

The procedure of SiNW/CdTeQD/PEDOT:PSS hybrid solar cells was as following: (1) the fabrication of SiINWs Arrays. The c-Si wafer (CZ, 1.7–3.2 Ω cm, 300 μm thickness) was cleaned by the RCA1 and RCA2 procedures. Silicon nanowires were performed by being immersed into the solution composed of Hydrofluoric acid and silver nitrate mixtures for an anisotropic wet-chemical etching process at the room temperature [17]. SiNW arrays prepared by this method are aligned vertically to the wafer. Fig. 1(b) shows top-view SEM image of silicon nanowires. Oriented Si nanowire forests could be clearly seen; (2) the spin-coating of CdTe QDs and PEDOT:PSS. CdTe QDs were synthesized by using Te, NaBH4, and CdCl2 as precursors in aqueous solution [18]. CdTe QDs with diameters around 3 nm were synthesized. CdTe QDs were dispersed in deionized water (0.6 mol/L) and then deposited on the upper surface of SiNWs by spin coating. CdTe QDs were spread over the silicon nanowires surface with a spin speed of 550 revolutions per minute (rpm) and a spin time of 6 s, and then with a spin speed of 1840 rpm for 20 s. Repeating the spin-coating process, different density of CdTe QDs layers can be formed. Then highly conductive PEDOT:PSS (Clevios PH1000) with 5 wt.% dimethyl sulfonate was deposited; (3) the preparation of the electrode. Argentum grids were evaporated as positive electrodes with a shadow mask. Aluminum was deposited onto the rear side of the substrates to obtain an ohmic contact as negative electrode. Fig. 1(a) depicts the schematic illustration of the hybrid solar cell based on silicon and PEDOT:PSS with an intermediate CdTe QDs layer. We have fabricated three devices with different density of CdTe QDs layer, the different density of CdTe QDs were gained by controlling the cycles of the spin-coating, that was: (a) 4 cycles (sample 1#), (b) 6 cycles (sample 2#), and (c) 8 cycles (sample 3#) respectively; as well as the corresponding hybrid solar cells without CdTe QDs layers (sample 0#) was also prepared for comparison.

3. Results and discussion

3.1. Characterization of SiNWs/CdTe QDs/PEDOT:PSS hybrid structure

Fig. 2 shows cross-sectional view SEM images of the hybrid solar cell without CdTe QDs layers (Fig. 2a) and with 6 cycles spin-coated CdTe QDs (Fig. 2b), which indicates straight growth of nanowires vertical to the substrate. It is also obviously observed that PEDOT:PSS was spin-coated onto the SiNWs with a uniform surface and the hybrid solar cell with CdTe QDs layer was better filled up with PEDOT:PSS. The inset of Fig. 2(b) shows TEM image of silicon nanowires after the deposition of CdTe QDs. We can clearly see that CdTe QDs are uniformly distributed on the surface of the silicon nanowires and the particle size of CdTe QDs is around 3 nm.

3.2. Performance of solar cells

In order to investigate the effect of CdTe QDs on the overall performance of the solar cell, the current density–voltage (*J*–*V*) characteristics of hybrid solar cells were measured. Fig. 3(a) shows the *J*–*V* characteristics of hybrid solar cell under simulated AM 1.5 G at 100 mW/cm^2 illumination. Their photovoltaic parameters of short circuit current density (J_{sc}), open circuit voltage (V_{oc}), fill factor (FF) and PCE, calculated from the *J*–*V* data, are summarized in Table 1. Compared with the hybrid solar cell without CdTe QDs, the PCE of the SiNW solar cells with CdTe QDs maximally increases 28.8%. The enhancement is higher than that of the previous literature with introducing an intermediate TAPC layer into hybrid heterojunction solar cells [13]. The short circuit current density also enhances obviously with an intermediate CdTe QDs layer between silicon nanowires and PEDOT:PSS. The optimal value for spin-coating cycles is 6, at which solar cell displays the largest short circuit current density of 33.5 mA/cm^2. If the spin-coating cycles exceed the optimal value, the J_{sc} decreases, FF and PCE are also reduced in much the same way.

The enhanced performance of the silicon nanowires solar cells with CdTe QDs should mainly be ascribed to the addition of CdTe QDs. First, the frequency down-conversion effect in the near-UV region of CdTe QDs will increase carrier collection efficiency. The absorption and photoluminescence (PL) spectra of CdTe QDs were measured at room temperature (shown in Fig. 4). It can be deduced from Fig. 4 that the CdTe QDs absorb the shorter wavelength sunlight (300–500 nm) and emit the longer wavelength light (500–600 nm). Compared to the EQE of the silicon nanowire hybrid solar cells without CdTe QDs (see Fig. 3b), we can see that the PL spectra (see Fig. 4)) of the CdTe QDs ovelap with the maximum spectral response region of the SiNW hybrid solar cell. When light

Table 1
Performance of the hybrid solar cells.

	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	PCE (%)
Sample 0#	541	29.1	37.5	5.9
sample 1#	501	32.9	42.7	7.0
sample 2#	511	33.5	44.1	7.6
sample 3#	521	30.4	43.2	6.8

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