

Photovoltaic enhancement of Si solar cells by assembled carbon nanotubes

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Photovoltaic conversion was enhanced by directly assemble of a network of single-walled carbon nanotubes (SWNTs) onto the surface of n-p junction silicon solar cells. When the density of SWNTs increased from 50 to 400 tubes μm^{-2} , an enhancement of 3.92% in energy conversion efficiency was typically obtained. The effect of the SWNTs network is proposed for trapping incident photons and assisting electronic transportation at the interface of silicon solar cells.

Keywords: Solar cell; Carbon nanotube; Photovoltaic enhancement; Heterojunction

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Photovoltaic (PV) cells are of immense interest due to their application potential in the fields of energy and communication [1-3]. Despite different PV cell technologies are being explored, over 85% of the current production is based on the well-established silicon wafer technology. Although the theoretical limiting efficiency of silicon solar cell is 30%, most of the efficiency of commercial silicon solar cell is about 15-20% [4]. Thus, designing novel structured silicon solar cell with high efficiency is certainly of major importance for PV technology.

The 1D nanoscale structure, high mobility, and excellent mechanical, electrical properties, as well as environmental stability [5,6] of carbon nanotubes (CNTs) offer great promise in the development of high-efficiency solar cells [7,8]. CNTs have been embedded in polymer matrix [9] or other semiconductors [10] and as transparent electrodes [11], facilitate the separation, transport and collecting of charge carriers. Recently, that CNTs and silicon can form heterojunctions [12] in solar cells has become a hot topic. For example, the pioneering work by Wei [13] *et al.* has shown solar cells based on CNTs and n-type silicon heterojunction, with nanotubes serving as both photogeneration sites and charge carriers collecting/transport layer. In particular, solar cells based on CNT/silicon heterojunctions [14] have produced a high efficiency of 7%. In addition, improved-efficiency [15,16] solar cell has been reported that based on SWNT photodiode it can generate multiple electron-hole pairs. Thus, it is expected that the integration of CNTs and silicon can lead to

high-performance of traditional silicon wafer solar cells.

Here, carbon nanotube network on Si solar cell for photovoltaic enhancement was demonstrated. After fabricating p-n heterojunction, SWNT networks were directly assembled onto the surface of n-p junction silicon solar cell for trapping incident photons and assisting electronic transportation at the interface of silicon solar cells.

SWNTs were synthesized by arc discharge method [17], and typically grown as mixtures of metallic (33%) and semiconducting (67%) tubes. The silicon solar cells were processed on 190 μm thick boron-doped p-type Cz-silicon wafers with a base resistivity of 2~5 $\Omega\cdot\text{cm}$.

A schematic diagram of monocrystalline silicon solar cell assembled with SWNT network is shown in Fig. 1. The experimental steps of the cells fabrication are summarized

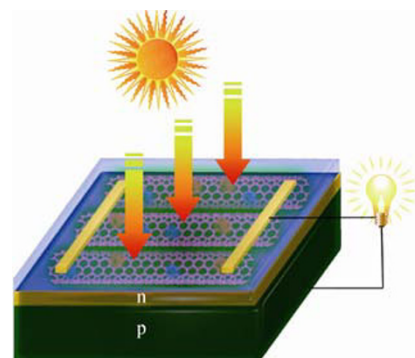


FIG. 1. Schematic diagram of SWNTs assembled silicon solar cell.

below. The cells exhibit a textured surface with an emitter sheet resistance of $40 \Omega/\text{sq}$ was obtained by etching with low concentration of NaOH/KOH solution. The n-type emitter (90 nm) was realized on the top of the wafer by diffusion process from a POCl_3 source. After fabricating the p-n junction, the piranha-cleaned p-n junction silicon substrate was immersed in a 1 mM 3-aminopropyltrimethylsilane (APS) aqueous solution for 2 h and then kept in vacuum evaporator at 90°C for 90 min to form the amino-terminated silane monolayer on the surface [18,19]. The surface modified with amino groups was immersed in SWNTs-water suspension. Uniform SWNT network formed on the modified surface. After assembling SWNTs, Al back electrode, Si_3N_4 passivated layer (70 nm) and Ag gridline were fabricated onto the silicon device under the conventional silicon cell fabrication technology. All cells were fabricated at the similar conditions. Typical active area of the OPV cells is 37.15 cm^2 . The power conversion efficiencies of the PV cells were recorded under $100 \text{ mW}/\text{cm}^2$ simulated AM 1.5 illumination. The AM 1.5 sunlight was produced from a model SS150W solar simulator and the illumination intensity was calibrated with standard silicon diode. Current-voltage characteristics were measured by a Keithely 2400 under ambient conditions. The morphology of the assembled SWNTs was characterized by scanning electron microscopy (SEM, JSM-7401F). The absorption spectra of SWNT networks were recorded by the UV-2500 spectrophotometer.

Figure 2 shows SEM images of as-assembled SWNT network on n-p junction surface with different densities. The density of SWNTs could be controlled by the concentration of the SWNTs suspension and the deposition time. The transmittance of the as-assembled SWNTs was also collected by transparent quartz glass. It was reported that SWNT films have both high transparency and conductivity, with the potential to replace ITO [8,20]. Our SWNTs with different density show a transmission of $>98\%$ in the visible light region (see Fig. 2d). Such transparency ensures that SWNTs trap incident photons and convert them to the underlying Si. Our SWNT films presented here can be used as transparent and conductive layer for solar cells.

Figure 3 shows the typical current density-voltage (J - V) characteristics of silicon cell without and with SWNTs

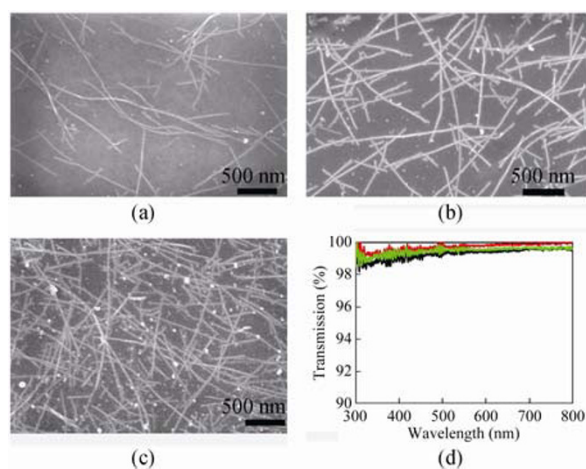


FIG. 2. SEM images of SWNT-assembled p-n junction substrate with different densities. (a) $50\sim 120 \text{ tubes } \mu\text{m}^{-2}$, (b) $150\sim 200 \text{ tubes } \mu\text{m}^{-2}$, (c) $300\sim 400 \text{ tubes } \mu\text{m}^{-2}$. (d) Optical transmission of SWNT networks with different density in visible region.

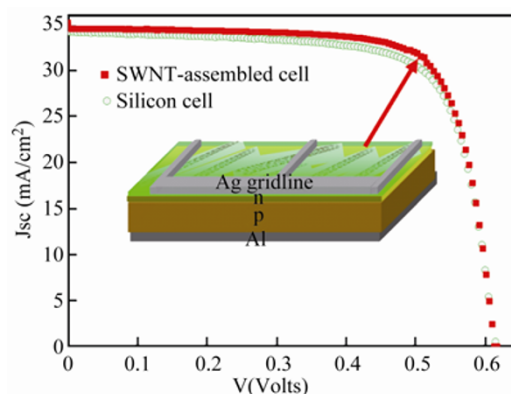


FIG. 3. The current density (J)-voltage (V) characteristics of silicon cell assembled without and with SWNTs under white light illumination (AM 1.5, $100 \text{ mW}/\text{cm}^2$). The inset gives the device configuration of SWNTs-assembled silicon solar cell.

assembled under white light illumination (AM 1.5, $100 \text{ mW}/\text{cm}^2$), with the device configuration shown in the inset. The excellent enhancement of performance was obtained under a density of $\sim 400 \text{ tubes } \mu\text{m}^{-2}$. The short current density (J_{sc}) of cell assembled with SWNTs was $35.15 \text{ mA}/\text{cm}^2$ and was about 1.71% higher than that of silicon cell without SWNTs. The η was 16.18% and was about 3.92% higher than that of silicon cell without SWNTs. The comparison of the J - V characteristics of the cells assembled with and without SWNTs highlights that SWNTs are effective in increasing the performance of the silicon cell. Although larger improvements should be attained for higher SWNT densities, the distribution of the assembled SWNTs become not uniform when the density is higher than $400 \text{ tubes } \mu\text{m}^{-2}$ according to our method presented here.

Figure 4 shows the device performance of silicon cell with various SWNTs density. The open-circuit voltage (V_{oc}) was relatively constant at 0.62 V when the SWNTs were assembled, which indicated that the charge carriers were still separated at the SWNT/p-n junction interface. J_{sc} was increased from $34.56 \text{ mA}/\text{cm}^2$ to $35.15 \text{ mA}/\text{cm}^2$ when the density varied from $\sim 50 \text{ tubes } \mu\text{m}^{-2}$ to $400 \text{ tubes } \mu\text{m}^{-2}$. The high J_{sc} of the as-assembled silicon solar cells indicated that the separation/transport of charge carriers from the as-assembled SWNTs silicon solar cell had been enhanced dramatically due to the presence of SWNT network.

The series resistance (R_s) was significantly decreased from $1.83 \Omega\cdot\text{cm}^2$ to $1.55 \Omega\cdot\text{cm}^2$ for the as-assembled SWNTs density at $\sim 400 \text{ tubes } \mu\text{m}^{-2}$. In consequence, η was increased from 15.57% to 16.18%, and fill factor (FF) was increased from 73.09% to 74.60%, when the density of the as-assembled SWNTs is about $400 \text{ tubes } \mu\text{m}^{-2}$. Figure 4d shows the FF of the experimental solar cells plotted against R_s in comparison to the theoretical obtained values. The experimental results we observed are very close to the simulated values and within the uncertainty range of the theoretical calculated values.

A defining term in the overall behavior of a solar cell is the FF. This is the ratio of the maximum power points that divided by V_{oc} and short-circuit current (I_{sc}). For the obtainment of enhancement of performance, FF, an important factor can be attributed to the as-assembled SWNTs, which causes reduction R_s of the device. Previous studies have shown that increasing the series resistance of the solar cell by about $0.1 \Omega\cdot\text{cm}^2$ can result in a large power loss increase [21-26]. A simulation using

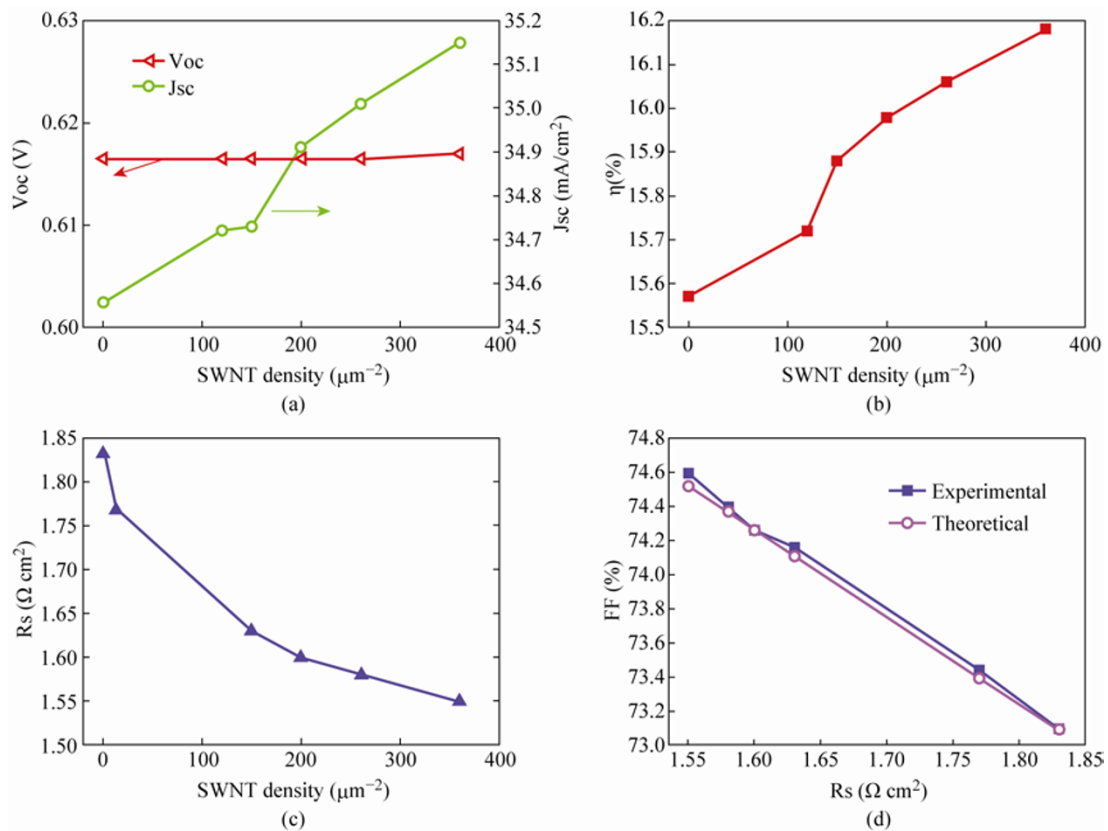


FIG. 4. The device parameters of (a) V_{oc} (red), J_{sc} (green), and (b) η , and (c) R_s of SWNT-assembled silicon cell with various SWNTs densities, (d) The FF of the experimental solar cells plotted against the R_s (solid squares) in comparison to the theoretical obtained values (open circles).

the two-diode equation function was performed to analyze the effect of the series resistance on the FF. The series resistance for each FF point can be approximated by:

$$\Delta R_s \approx \frac{FF_0 - FF_{measured}}{m} \quad (1)$$

Where, FF_0 , the fill factor at $R_s = 0 \Omega \cdot \text{cm}^2$, almost remains the same. For typical industrial silicon solar cell the m is equal to $5.1\%/\Omega \cdot \text{cm}^2$ [26,27]. According to Equation 1, decreasing R_s will lead to higher fill factor, thus resulting in greater efficiency, and pushing the cells output power effectively improved.

We should note that the SWNTs we used here were typically grown as mixtures of metallic (33%) and semiconducting (67%) tubes, whose optic-electronic properties depends on the chirality of the nanotubes. To find outstanding property, such as multiple exciton effect [15], requires separating semiconducting tubes from metallic species. Higher-improved efficiency solar cells may be obtainable by using only semiconducting SWNT networks.

In conclusion, photovoltaic conversion was enhanced by directly assemble of a network of SWNTs onto the surface of n-p junction silicon solar cells. The SWNTs can be assembled on n-p junction surface with controllable density. For a SWNTs density of ~ 400 tubes μm^{-2} , a typical enhancement of 3.92% in energy conversion efficiency was observed. The SWNTs network was proposed for trapping incident photons and assisting electronic transportation at the interface of silicon solar cells. Our results demonstrate the vast potential of SWNTs for developing higher-efficiency energy conversion solar cell.

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