HAIRLIKE CARBON-FIBER-BASED SOLAR CELL

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ABSTRACT

This paper reports the fabrication and photovoltaic (PV) demonstration of macro-length, micron-diameter hairlike solar cells. In this design of cylindrical silicon solar cell with a radial *p*-*n* architecture, the carbon fiber (CF) serves as the core electrode as well as fabrication substrate, and polysilicon (poly-Si) is used as the shell photoactive material. Uniform deposition of poly-Si on the cylindrical-shape CF substrate was achieved by low pressure chemical vapor deposition (LPCVD) with the silicon layer thickness ranging from 0.85um to 10um. A preliminary study of an 11um-diameter single-fiber solar cell demonstrates that this initial device exhibits photovoltaic effect with an open-circuit voltage (V_{oc}) of 0.14 V, a short-circuit current density (J_{sc}) of 1.7 mA/cm^2 and an efficiency of 0.04%.

INTRODUCTION

Miniaturized photovoltaics, in comparison to large solar panels, may serve as integrated renewable power sources for nano/microelectronics such as those for wireless sensor network (WSN) and robots [1]. In particular, photovoltaic structures with unusual geometries that complement the devices they are powering, or that can be assembled into larger sources with unusual geometries, can be enabled by MEMS-based fabrication techniques. Reported nanowire or micro-sized PV devices can yield output power in the range of pW to μW with photocurrent up to μA and output voltage of 0.1~0.4V [1-3]. Their output power can also be scaled up by growing nanowire arrays or connecting each individual cell in series and/or in parallel [1, 3, 4]. Particularly, MEMS devices such as electrostatic or piezoelectric motors usually require the driving voltage/current in the range of 3V~400V/nA~μA, which can be readily provided by appropriately interconnected, micro-sized solar cells as the self-contained on board power supply [3].

Among micro/nano solar cells, flexible fiber-type solar cells with hairlike structure are attractive due to their potential applications in the fields of smart textiles/wearable electronics and stealth devices to provide energy [5-6]. Silica and plastic optical fibers have been utilized as the building substrates to construct organic solar cells, which may enable large scale weavable PVs with light weight and low cost. Another benefit of such cylindrical architecture is that solar cells with radial p-n junctions can induce efficient carrier separation/collection when the direction of light absorption and carrier collection are orthogonalized [7]. In the case of solar cells with reduced photoactive area, gallium arsenide (GaAs), single-crystal silicon or poly-silicon is preferred because of their high energy conversion efficiency. This usually requires cell substrates with good thermal stability to endure the high processing temperature.

The work proposed herein explored the possibility of fabricating coaxial core-shell solar cells by incorporating radial *p*-*n* poly-Si diode onto a carbon fiber (CF) which also serves as the core electrode in the device. CF is a flexible and light-weight material in cylindrical geometry with a diameter of 5-20 um. Researchers are beginning to utilize this material in MEMS applications [8], exploiting the excellent strength and fatigue properties of the CF. Furthermore, CF is a conductor with a resistivity of 1.8×10^{-5} Ω·m and can withstand temperature up to 1500ºC, which is compatible with the high processing temperature of silicon diodes. This micro-fiber can therefore be utilized as a building block to construct silicon-based solar cells.

The fabricated hairlike solar cell demonstrates macro-scale cell lengths while maintaining micron-level integration capability. The hairlike solar cell benefited from the properties of the CF such as cylindrical geometry, extremely low cost and excellent thermal stability, which enables the deposition of high quality co-axial

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poly-Si onto this lightweight substrate. In addition, the conductive CF also serves as an electrode to collect photogenerated carriers. The fabricated device not only demonstrated the feasibility of utilizing CF as a MEMS fabrication substrate, but also resulted in solar cells of spatial format suitable for high-degrees of co-integration into MEMS devices.

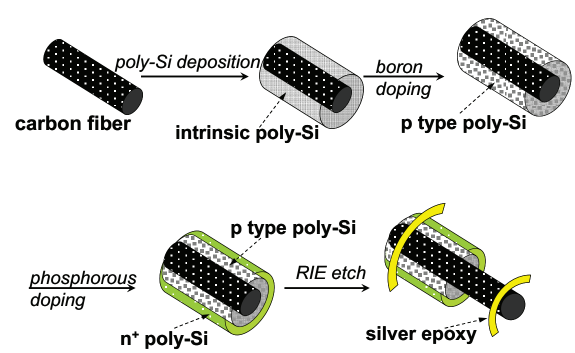
EXPERIMENTAL/THEORY

The fabrication process of creating fiber PV with a radially-modulated *p-n* poly-Si diode is illustrated in Figure 1(a). The CF serves as the core electrode as well as the mechanical backbone and poly-Si is utilized as the photoactive shell material. A layer of intrinsic (*i*) poly-Si was first deposited onto a 7-um-diameter CF (*34-700, Grafil Inc.)* by LPCVD at 588 °C. Boron-doping of the polysilicon was then performed by thermal diffusion with a solid dopant source (*Techneglas Technical Products Planar Dopants, GS-183*) at 1050°C, which turned the intrinsic poly-Si layer into p type. Phosphorus diffusion into the p-type poly-Si layer was further performed to generate a shallow p-n junction in the radial direction of the fiber. A water soluble polymer (polyvinylpyrrolidone: water=1:2) was cast to cover part of the fiber and to serve as a mask for the subsequent dry etching process. The uncovered poly-Si shell was then etched away by reactive ion etching (RIE) process using SF_6 plasma in order to expose the underlying carbon fiber core electrode and make an electrical contact. The polymer was removed after the RIE process. In the last step, silver epoxy was applied on both the exposed CF core electrode and the top n-type poly-Si layer, serving as the electrode pads of the fiber PV to be connected to the external circuit.

Under illumination, the photosensitive diode will absorb photons whose energies are equal to or greater than the bandgap of the PV material. The photogenerated electrons (e^-) and holes (h^+) are swept into the outer n-type and inner p-type poly-Si layer, respectively, by the established built-in electric field at the junction (Fig. 1b). The holes diffused into the p-type layer will be further collected by the CF core electrode. The electrons will be transported within the top n-type layer. Radial architecture may endow the cell with a better charge collection efficiency since the carrier collection distance can be smaller or comparable to the minority carrier diffusion length in this configuration. This will reduce the charge recombination opportunities and enable the short range and efficient radial carrier separation [9].

The photovoltaic behavior of an 11 um-diameter single-fiber solar cell with a 500 um-long and 2 um-thick Si shell was investigated with current density–voltage (J–V)-curve measurements in a solar simulator (imitating an air mass (AM) 1.5 spectrum) with a light intensity of 128 mW/cm^2. The fiber PV was placed directly under the lamp with the light area of 2 in × 2 in. The structure and the surface morphology of the fiber PV were characterized by scanning electron microscopy (Zeiss SEM Ultra60).

(a)



(b)

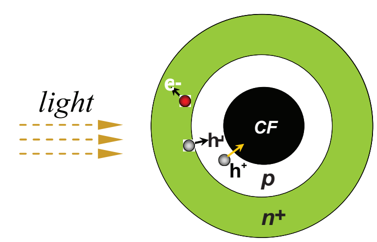


Figure 1: Scheme of (a) the fabrication process of the radial polysilicon p-n fiber solar cell, and (b) cross section of the solar cell and separation of the photogenerated electron (e^-) and hole (h^+) under illumination.

RESULTS AND DISCUSSION

The process flexibility of building uniform coaxial *p-n* diode on a micro-sized CF substrate through the proposed process was investigated. Poly-Si layer thicknesses ranging from 0.85 um (Fig. 1a) to 10um (Fig. 1c) exhibited conformal and uniform deposition onto the cylindrical CF. In addition, the poly-Si was able to create a conformal coating around the two adjacent fibers (Fig. 2b). A good interface between the poly-Si shell and the CF core was achieved, with the aid of slow ramp-up and ramp-down rates of the processing temperature during the deposition, which minimized the negative effects due to the mismatch of the coefficients of thermal expansion between the poly-Si (3×10^{-6} K^{-1}) and the CF (0.5×10^{-6} K^{-1}) (Fig. 2d).

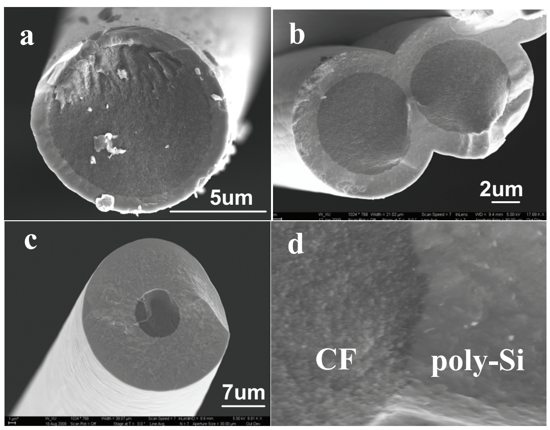


Figure 2: SEM image of cross-section of the CF coated with poly-Si with the thickness of (a) 0.85um, (b) 2 um, (c) 10 um, and (d) close up view of the CF/poly-Si interface.

SEM images in Fig. 3a show the surface morphology of the fiber PV after the dry etching process of the poly-Si shell on CF to provide the electrical connection between the CF and the external circuit. The top n-type poly-Si layer exhibits a smooth texture with the grain size in the range of nanometers (Fig. 3b). The CF after the RIE process maintained a relatively smooth surface topography (Fig. 3c). The bulk resistivity of the CF before and after the device fabrication were 1.8×10^{-5} Ω·m and 1.9×10^{-5} Ω·m, respectively, which indicated its good thermal stability under the processing temperature of above 1000°C for several hours.

Figure 4 is the macro- and micro-scale views of a hairlike single fiber solar cell, with the digital image of a 4 cm-long PV fiber (Fig. 4a) and the cross-sectional view of the solar cell (Fig. 4b).

A fiber-shape solar cell with a 2 um-thick *p-n* polysilicon layer was fabricated on a 7 µm-diameter CF electrode for the examination of the photovoltaic behavior of the proposed PV protocol.

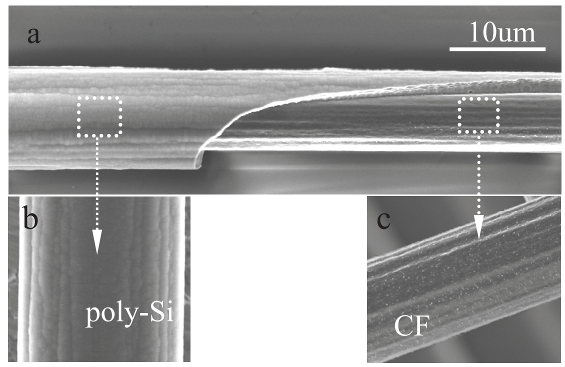


Figure 3: SEM image of (a) top surface of the solar cell, (b) carbon fiber (CF) after RIE etching of the poly-Si, and (c) a single fiber solar cell device.

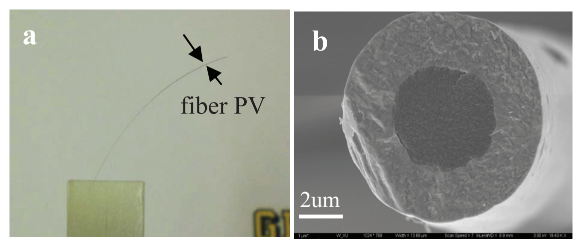


Figure 4: (a) Digital image of a hairlike solar cell (11 um-diameter), and (b) SEM image of the cross sectional view of a fiber type PV device with 2 um-thick doped poly-Si.

The performance of aforementioned single-fiber solar cell was characterized with current density–voltage (J–V) curve measurements (Fig. 5). Under illumination, the CF based solar cell with a 1.4×10^{-4} cm^2 effective area exhibited photovoltaic effects and produced an open-circuit voltage of 0.14 V and a short-circuit current density of 1.7 mA/cm^2. The efficiency is calculated to be 0.04%. The low efficiency may be attributed to two factors of this un-optimized PV: the high series resistance (R_s) and the thin active photovoltaic poly-Si layer. The series resistance of this initial cell device is 17 $\Omega\cdot cm^2$, which is high compared to most of the commercialized silicon solar panels ($<1\Omega\cdot cm^2$). According to the equation of the photocurrent density of a diode [10],

$$J = J_{sc} - J_0(\exp(\frac{q(V+JAR_s)}{kT}) - 1) - \frac{V+JAR_s}{R_{sh}} \quad (1)$$

a high value of R_s can greatly reduce the photogenerated current density of the device. It will then lead to a low fill factor (FF), which is 0.246 for the current device, and therefore result in a low energy conversion efficiency. This high series resistance is partially due to the high resistance of the CF itself because of its small diameter (7 um). The high surface resistance of the top thin n-type emitter, as well as the contact resistance in the device, also adds up to the R_s. In addition, the p type layer of the initial device is

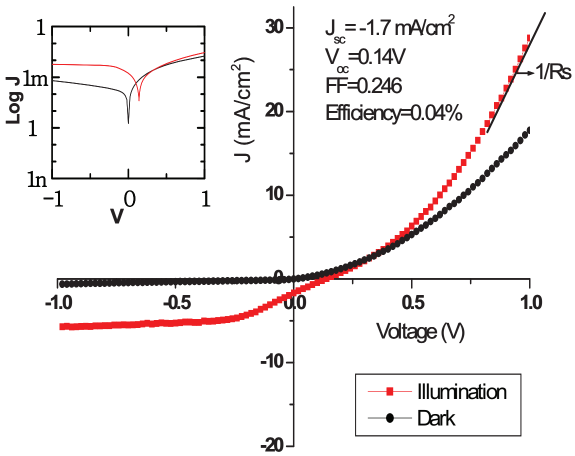


Figure 5: Experimental J-V characteristics of the CF based PV in the dark (black) and under illumination (red). Inset: Full-range curve in semi-logarithmic scale.

only 2 um thick, whereas at least 20 um of poly-Si is required in theory to absorb the majority of the incident energy. Further studies will be focused on reducing the R_s and optimizing the device architecture. Strategies for improving the fiber PV performance include increasing the doping level of the top n-type emitter, incorporating thicker p-type poly-Si base layer, as well as providing better ohmic contacts.

CONCLUSIONS

The hairlike CF-based solar cell with a radially-modulated *p-n* silicon diode has been designed and successfully fabricated through the conventional CMOS fabrication process. The photovoltaic effects of the fiber PV was demonstrated with an output power density of 0.059mW/cm^2. The output current/voltage could be further increased by connecting each fiber solar cell in series and/or in parallel to meet the specific power requirement of certain MEMS systems and wearable devices. The proposed hairlike PV may also be incorporated or embedded into flexible substrates such as PDMS or parylene film to enable applications in foldable microelectronic systems. .

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