Multiple silicon nanowires-embedded Schottky solar cell

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Large area applicable silicon nanowire (SiNW)-embedded Schottky solar cell (SC) is fabricated. Multiple semiconducting SiNWs were positioned on two different metals. SiNW forms a Schottky or an Ohmic contact to each metal according to the Fermi level lineup. Electrons or holes have a barrier to transport resulting in a rectifying flow. Under 1 sun illumination, the SiNW Schottky SC provided 0.167 V of photovoltage and 91.91 nA of photocurrent with an ideality factor of 1.2. It discusses the fabrication scheme and mechanism of multiple SiNWs-embedded Schottky SC. [doi:10.1063/1.3245310]

Due to the high potential and fabrication of one-dimensional nanomaterials such as nanotubes and nanowires, intensive researches have been performed for practical applications. Carbon nanotube (CNT) is an ideal candidate for the high sensitive gas detection due to the peculiar hollow structure and a large surface area.[1,2] An electric conductive nickel silicide nanowire proved the high potential to be a functional microscopy tip,[3] field emitters,[4] and nanoscale interconnects.[5,6]

The solar energy conversion will take 10% of the global energy need by 2033.[7] A substantial demand of nanomaterials has been addressed for cost-effective solar cells (SCs). The nanostructure provides a large photoactive surface at a fixed volume, which is an advantage in the effective use of solar power.[7,8]

But the promising of nanostructure active SC has not been much fulfilled due mainly to the difficulty in architecture of nanostructures. Most reports of nanomaterials-based SCs have been mainly focused on the use of nanomaterial as a charge collector in polymer blends[9,10] and dyes.[11] Few researchers have pioneered the active use of nanomaterials as light absorbers. Double-walled CNT film was used for a photoinduced carrier generating site and a path of hole carriers.[12] There is another report of a single silicon nanowire (SiNW) SC, which demonstrated the architecture of coaxial junction in a SiNW showing a landmark of the nanowire SC application. It also proved the versatile manipulation of the SiNW SC units to be connected in series and parallel similar to the conventional SC integration.[8] Although it opened the possibility of the nanowire SC, the practical application needs a large area accessible approach freeing from the complex e-beam lithographic processes.

We present here the SiNW-embedded Schottky SC. Multiple SiNWs were connected to two different metals to form a Schottky or an Ohmic contact according to the metal work function values. It discusses the scheme of rectifying contact between metals and SiNWs and the SiNW-embedded Schottky SC performances.

Single crystalline SiNWs were grown by chemical vapor deposition. $AuCl_2$ catalyst (99 % Aldrich) was coated onto a Si substrate. Si powder (99.99 %, Aldrich), which is a Si source to grow SiNWs reacting to Au catalyst, was placed near the substrate. The SiNWs were grown by heating to 1200 °C under Ar flowing of 300–500 SCCM (SCCM denotes standard cubic centimeter per minute) for 60 min.

Field emission transmission electron microscope (FEI Tecnai F30 Super-Twin) was used to observe the crystallinity of a SiNW. Low magnification transmission electron microscopy (TEM) image of Fig. 1(a) shows that most nanowires were grown longer than 5 μm with 50–80 nm in diameter. High resolution TEM (HRTEM) images are presented in Figs. 1(b) and 1(c). The lattices were spaced by 0.31 nm, which is corresponding to the Si (111). The inset of Fig. 1(c) is a diffractogram showing a single crystallinity of a SiNW.

To make SiNWs-embedded Schottky SCs, two different metals of Pt and Al were employed. Optical lithography processes were performed to make Pt–Al metal electrodes in a 4 in. wafer. A unit device has 30 interdigitated fingers and each metal finger is 500 μm long with a 20 μm width.

The dielectrophoretic (DEP) method has been used to align nanomaterials,[2,6] which is a motion induced by the polarization effect performing a force under nonuniform electric field. The SiNW containing solution of 2 μl was dropped onto the electrodes under ac biasing of 10 $V_{P\text{-}P}$ at 100 kHz.

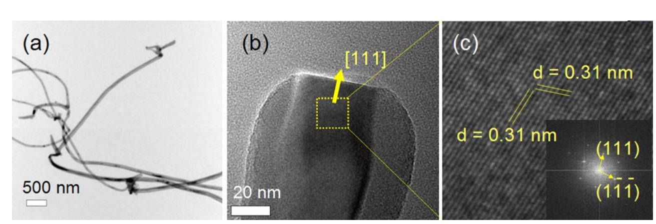

FIG. 1. (Color online) (a) Low magnification TEM image. (b) HRTEM image shows that the SiNW was grown in the [111] direction. (c) The lattice were spaced by 0.31 nm matching to the Si (111). The inset is a diffractogram obtained by HRTEM image.

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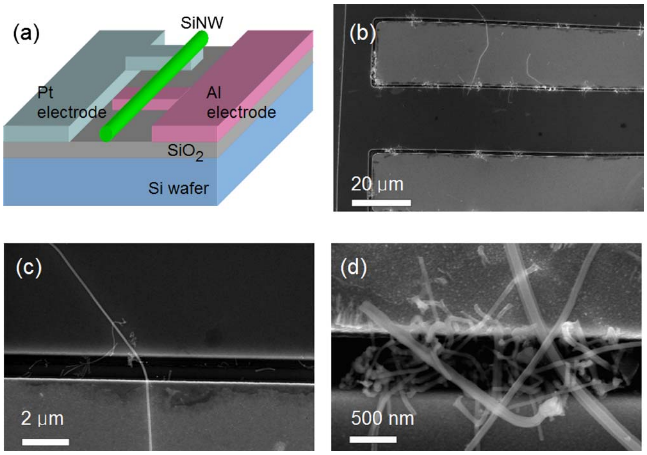

FIG. 2. (Color online) (a) Schematic diagram of the DEP-positioned SiNW bridging between Al and Pt electrodes. (b) SEM image shows SiNWs positioning on Al and Pt electrodes. (c) A single SiNW contacted to electrodes. (d) Multiple SiNWs contacted to electrodes.

The schematic diagram of DEP-positioned NW is depicted in Fig. 2(a). A field emission scanning electron microscope (SEM) (FEI Sirion) was used to observe the NW on metal electrodes as shown in Fig. 2(b). Figure 2(c) shows that a single NW is connected to Al and Pt electrode through a gap. Multiple NW connections are presented in Fig. 2(d).

Electrical characterization of the multiple SiNWs-embedded Schottky SC was measured by an instrument (Keithley 2400). The device was measured in dark condition and under 1 sun illumination ($100\ \mathrm{mW/cm^2}$). It obviously provided a photovoltaic behavior, as shown in Fig. 3(a). The open circuit voltage (V_{oc}) was 0.167 V implying no short circuit connection in a device. It is comparable to the V_{oc} values from a single SiNW of about 0.2 V for *p-n* type and 0.26 V for *p-i-n* structure, respectively.[8] Electrical heating formed Schottky type provided 0.19 V.[13] Additionally, thin Si-film type Schottky SCs also gave a similar open circuit voltage.[14,15]

The SiNW-embedded SC gave high photocurrent of 91.91 nA, which shows the collection of current from the Schottky contacts between metals and SiNWs. In previous reports, the current generation from a single NW was about 0.3–0.6 nA.[8,13] In this method, the group of SiNWs on interdigitated metals forms multiple Schottky junctions and the photoinduced current is considered to be the current sum from each Schottky contact.

The dark *I-V* characteristics are presented in Fig. 3(b). Under thermionic emission theory, the *I-V* characteristics are given by the following relations:

$$J = J_s(e^{qv/nkT} - 1) \quad \text{or} \quad J = J_s(e^{qv/nkT}) \quad \text{for} \quad V \gg kT/q, \tag{1}$$

$$J_s = A^{**}T^2 \exp\left(-\frac{q\phi_B}{kT}\right), \tag{2}$$

$$n \equiv \frac{q}{kT}\frac{\partial V}{\partial(\ln J)} = \frac{q}{kT}\frac{\partial V}{2.3 \times \partial \log I}, \tag{3}$$

where J_s, n, kT, A^{**}, and ϕ_B are saturation current density, ideality factor, thermal energy (eV), Richardson constant, and barrier height, respectively. The ideality factor of this

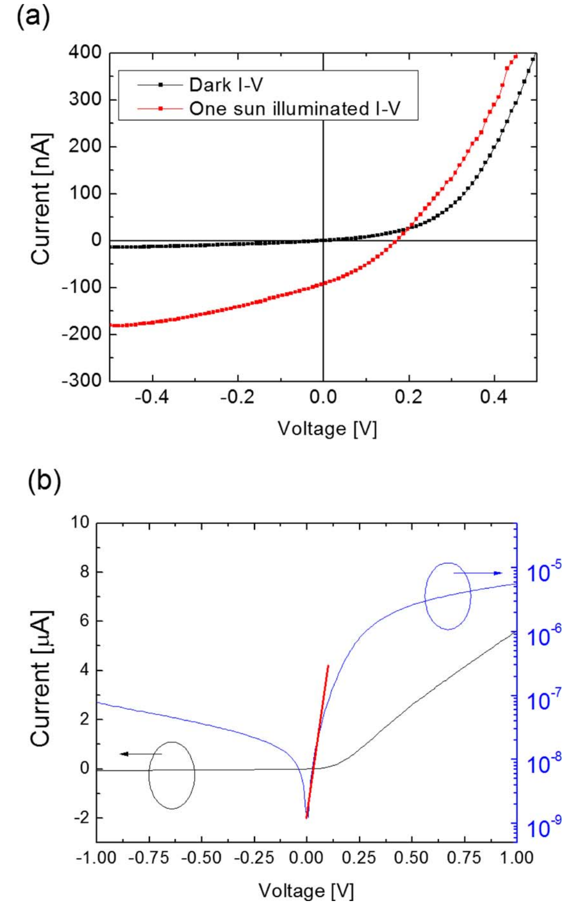

FIG. 3. (Color online) SiNW-embedded Schottky SC *I-V* characteristics (a) Dark and one sun ($100\ \mathrm{mW/cm^2}$) illuminated *I-V* performances. Under the illumination, the device exhibited an open circuit voltage of 0.167 V and photocurrent of 91.91 nA, respectively. (b) Dark *I-V* analysis. The device showed a clear rectifying flow. The ideality factor was obtained to be 1.2 eV. Schottky barrier was calculated as 1.14 eV.

SiNW Schottky SC is obtained to be 1.2, which is close to the unity. Some deviation of the value may be caused by the quality of SiNW or contact resistance between metal and SiNW. When the surface states are neglected, a general expression of the barrier height can be simplified to be

$$\phi_B = \frac{-kT}{q}\ln\left(\frac{J}{e^{qv/kT}}\frac{1}{A^{**}T^2}\right) = \frac{kT}{q}\ln\left(\frac{A^{**}T^2}{J_s}\right). \tag{4}$$

The Richardson constant value was chosen as $120\ \mathrm{A/cm\,K^2}$ with assumption of the little effect to barrier height calculation.[16] The Schottky barrier height is obtained from the diode linear region (0–0.1V) to be 1.14 eV, which is close to the value of 0.8 V of Si–Al (Ref. 13) or 0.9 V of Si–Pt contact.[16]

Figure 4(a) is a schematic diagram of the SiNW-embedded Schottky SC. The mechanism of this SiNW Schottky SC may be understood as follows. Each metal of Al or Pt Fermi level line up to the SiNW. Because the bandgap and electron affinity of Si are fixed as shown in Figs. 4(b) and 4(c), the energy bands are shifted to form a barrier to holes for SiNW-Al contact and electrons for SiNW-Pt contact, respectively. This barriers provide a rectifying junction between metals and the SiNW. The coming photon energy larger than the energy band of Si (1.12 eV) contributes the generation of electron-hole pairs mainly on the Si side forming a photovoltage.

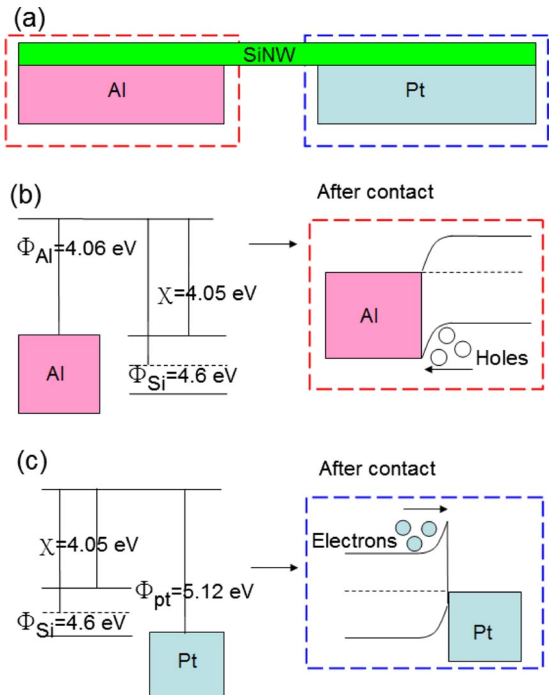

FIG. 4. (Color online) (a) A schematic of a SiNW contact to Al and Pt metal electrodes. (b) Energy band diagram of Al-SiNW. Holes see a barrier. (c) Energy band diagram of Pt-SiNW. Electrons see a barrier.

Further investigation will be performed to reduce the series resistance by removing the oxide coating layer of SiNW, which may substantially enhance the current response to the light. It is also under investigation to achieve the photocurrent density from a single SiNW-Schottky device.

In summary, we have showed the multiple silicon nanowires-embedded SC fabrication. The Schottky junctions were formed from the contacts between SiNWs and metal electrodes. The photodiode provides a good ideality factor of 1.2. In light *I-V* measurement, the photocurrent was obtained to be 91.91 nA indicating that the photocurrent is the current sum of each Schottky contact. This demonstrates the potential to fabricate semiconducting nanomaterial-based SCs for a large area application without complex fabrication processes.

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[1]J. Kim, J.-H. Yun, J.-W. Song, and C.-S. Han, Sens. Actuators B **135**, 587 (2009).
[2]J.-H. Yun, J. Kim, Y. C. Park, J.-W. Song, D. H. Shin, and C.-S. Han, Nanotechnology **20**, 055503 (2009).
[3]J. Kim, Y.-H. Shin, J.-H. Yun, and C.-S. Han, Nanotechnology **19**, 485713 (2008).
[4]J. Kim, E.-S. Lee, C.-S. Han, Y. Kang, D. Kim, and W. A. Anderson, Microelectron. Eng. **85**, 1709 (2008).
[5]J. Kim and W. A. Anderson, Nano Lett. **6**, 1356 (2006).
[6]J. Kim, Y. C. Park, D. H. Shin, E.-S. Lee, and C.-S. Han, Appl. Phys. Lett. **90**, 253103 (2007).
[7]E. S. Aydil, Nanotechnology Law and Business Fall 275, 2007.
[8]B. Tian, X. Zheng, T. J. Kempa, Y. Fang, N. Yu, G. Yu, J. Huang, and C. M. Lieber, Nature (London) **449**, 885 (2007).
[9]T. Hino, Y. Ogawa, and N. Kuramoto, Fullerenes, Nanotubes, Carbon Nanostruct. **14**, 607 (2006).
[10]J.-S. Huang, C.-Y. Hsiao, S.-J. Syu, J.-J. Chao, and C. F. Lin, Sol. Energy Mater. Sol. Cells **93**, 621 (2009).
[11]M. Law, L. E. Greene, J. C. Johnson, R. Saykally, and P. Yang, Nature Mater. **4**, 455 (2005).
[12]J. Wei, Y. Jia, Q. Shu, Z. Gu, K. Wang, D. Zhuang, G. Zhang, G. Z. Wang, J. Luo, A. Cao, and D. Wu, Nano Lett. **7**, 2317 (2007).
[13]M. D. Kelzenberg, D. B. Turner-Evans, B. M. Kayes, M. A. Filler, M. C. Putnam, N. S. Lewis, and H. A. Atwater, Nano Lett. **8**, 710 (2008).
[14]J. Kim and W. A. Anderson, Sol. Energy Mater. Sol. Cells **91**, 534 (2007).
[15]J. Kim, C.-S. Han, Y. C. Park, and W. A. Anderson, Appl. Phys. Lett. **92**, 043501 (2008).
[16]S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).