Materials Letters 160 (2015) 305–308

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

# Solution-processed transparent conducting Ag nanowires layer for photoelectric device applications

Hong-Sik Kim [a], Malkeshkumar Patel [a], Hyunki Kim [a], Ja-Yeon Kim [b], Min-Ki Kwon [c], Joondong Kim [a,*]

[a] Photoelectric and Energy Device Application Lab & Department of Electrical Engineering, Incheon National University, Incheon 406772, Republic of Korea
[b] Korea Photonics Technology Institute (KOPTI), 9 Chemdan venture-ro, Buk-gu, Gwangju 500460, Republic of Korea
[c] Department of Photonic Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju 501759, Republic of Korea

ARTICLE INFO

*Article history:*
Received 1 May 2015
Received in revised form
22 July 2015
Accepted 28 July 2015
Available online 30 July 2015

*Keywords:*
Ag nanowires
Si
Schottky junction
Mott–Schottky
Photodetector

ABSTRACT

Electrically conductive and optically transparent Ag nanowires (AgNWs) were spin-coated on a Si substrate for high-performing Schottky junction device. The AgNWs window layer significantly improved transmittance for broad wavelengths, comparing to that of the conventional indium-tin-oxide (ITO) film structure. This optical benefit spontaneously provides significantly improved photodetection for broad wavelengths. The junction properties were investigated using current–voltage and voltage–capacitance characteristics. The AgNWs/Si formed a built-in potential of 0.62 eV at the interface and this photodetector provided a considerably high rectification ratio with a low saturation current value. These intrinsic advantages simultaneously induced substantially enhanced signal to noise ratio different from the ITO/Si heterojunction device. This solution-processed architecture of a transparent conductor (TC) is also beneficial for non-vacuum designs. We demonstrated that AgNWs would be the competitive alternative for the conventional TC coating techniques. Electrical analyses and photoresponses were systematically investigated for AgNWs/Si Schottky device.

## 1. Introduction

The movement of carriers in semiconductor materials can be controlled by potential difference between semiconductor and metal [1]. Metals such as Ag, In and Al can form the Schottky junction with p-Si. Light management is a significant parameter of Schottky junction devices for photoelectric applications. Meanwhile, conventional metal electrodes readily cause high reflection of the incoming light, which simultaneously reduces the Schottky device performances. In the aspect of light management, transparent conducting oxide (TCO) has a high potential to a route for light path the semiconductor layer. Various TCO materials, such as $In_2O_3$:Sn (ITO), F:$SnO_2$, Al:ZnO, have been well studied in photoelectric device applications [2–4].

Recently, silver nanowires (AgNWs) have been emerged as a promising transparent conducting material [5,6] due to their flexibility in manipulation of optical properties without compromising electrical properties. This is an important advantage for flexible photoelectric devices [7]. Additionally, transparent electrode coating layer can be realized by transfer printing, spraying or bar and spin coating methods in atmospheric condition [6,8–15], different from the conventional TCO deposition in vacuum condition.

Herein, we present high-performance AgNWs-based Schottky devices for photodetection applications. AgNW-contained solution was spin-coated on a Si substrate, which spontaneously forms a Schottky device. The optical and electrical properties of the AgNWs-embedding Si Schottky photodetector were systematically investigated including the current–voltage (*I–V*) and capacitance–voltage (*C–V*) characteristics. We report a band bending analyses of AgNW/Si junction and propose a potential of AgNW-transparent conductor for next generation photoelectric devices.

## 2. Experimental procedures

A p-type Si wafer (resistivity, $\rho = 1–10\ \Omega\,\text{cm}$) was used as a substrate. To deposit AgNWs on a Si substrate, AgNWs-contained solution was spin-coated onto the Si wafer surface at a speed of 1000 rpm for 30 s following by baking at 150 °C [6]. As a comparator, we also prepared ITO-coated Si device. A 200 nm thick ITO was coated by DC-sputtering method (RSP-500, SNTEK). Both TC layers (AgNWs and ITO film) were also prepared on glass substrates to investigate the optical transmittance profiles. Al metal

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* Corresponding author. Fax: +82 32 835 0773.
*E-mail address:* joonkim@incheon.ac.kr (J. Kim).

http://dx.doi.org/10.1016/j.matlet.2015.07.142
0167-577X/

coating was performed by DC sputtering to form a back contact and a grid-patterned front contact. Thereafter, rapid thermal treatment was performed at 500 °C. Both AgNWs and ITO Schottky devices tailored in a same size of $1\times 1\ \text{cm}^2$. The morphologies of AgNW and ITO film were observed by a field emission scanning electron microscope (FE-SEM, FEI Sirion). Transmittance profiles were measured by using UV–vis–NIR photo-spectrometer (V-570, JASCO). Dark *I–V* measurements were performed by a source meter unit (2400, Keithley). The Mott-Schottky analyses (*C–V* characteristics) of photoelectric devices were obtained by applying AC signal (0.1 mV) in the frequency ranges 10–500 kHz by sweeping DC bias range from $-0.6$ V to $+0.6$ V using the Potentiostat/Galvanostat (ZIVE SP1, WonA Tech). Photoresponses of Schottky devices were obtained in a quantum measurement system (K3100, McScience) with on and off a pulsed light. One dimensional continuity equation solver (SCAPS) was employed to trace the energy band diagram [16].

## 3. Results and discussion

The coated AgNWs were presented by SEM images (Fig. 1a and b), which showed uniformly dispersed AgNWs on a Si substrate. An average diameter of AgNWs was measured to be 38.5 nm with an effective coverage area of 33% (Supplementary information Fig. S1).

To investigate an optical transparency, we measured the transmittance of an AgNWs-coating layer, as shown in Fig. 1(c). Compared to an ITO film, the AgNWs-coating layer has higher transmittance values in long wavelengths ($\lambda > 600$ nm). It is noteworthy that the AgNWs-coating layer has a prominent transparency for a short wavelength region. Meanwhile, the ITO film showed significantly low transmittance profiles for $\lambda < \sim 350$ nm. This is attributed to the energy band gap of ITO ($E_{g\text{-}ITO}$), which is about 3.7 eV, corresponding to $\lambda = 337$ nm. Shorter λs are readily absorbed in ITO due to their higher photon energy values than $E_{g\text{-}ITO}$. Hence the transmittance is close to zero for short λs due to high optical absorption in the ITO film [3].

We can get the integrated area of the transmittance profiles, which indicates the quantitative information of the enhanced transmittance performance of the AgNWs-coating layer from the ITO film. It was found that AgNWs-coating layer has the transmittance coverage of 87.6% for a given spectrum range. Meanwhile, ITO film has only 69.4%. This indicates that a significantly improved transmittance can be achieved by using AgNWs.

For electrical aspects, the lower resistance is strongly desired for a TC material. We measured the sheet resistance by using four-point probe. The AgNWs-coating layer provided a much lower value of 15.7 Ω/□ than that of ITO film (22.5 Ω/□), which confirms that the individually scattered AgNWs are electrically well connected. Schematics of Schottky junction devices fabrication were presented in Fig. 1(d).

We investigated diode parameters for the AgNWs/Si device and the ITO/Si device, as shown in Fig. 2(a). Both devices clearly showed the current-rectifying behaviors. Meanwhile, the AgNWs/Si device has a higher rectifying ratio of 85.5 than 5.7 of the ITO film device (Table 1). From the current density–voltage (*J–V*) profile, we can see considerable difference in the reverse saturation current density ($J_r$) of each device. A substantially low $J_r$ value ($0.15\ \mu\text{A cm}^{-2}$) was obtained from the AgNWs/Si device. In the case of ITO/Si device, two orders higher $J_r$ value ($0.02\ \text{mA cm}^{-2}$) was produced. This less $J_r$ value of AgNWs/Si device strongly suggests that the reduced noise current and therefore lead to the higher photoresponses than those of the ITO/Si device.

In order to inspect the interface of AgNW/Si, *C–V* characteristics were investigated by Mott–Schottky analyses. Fig. 2(b) shows the $1/C^2$ profiles along to voltage changes. The negative slope ($d(1/C^2)/dV$) specify holes as majority carriers with an acceptor concentration ($N_A$) of $2\times 10^{15}\ \text{cm}^{-3}$ in the Si wafer. The details on the Mott–Schottky analysis is given elsewhere [1]. An intersect trace

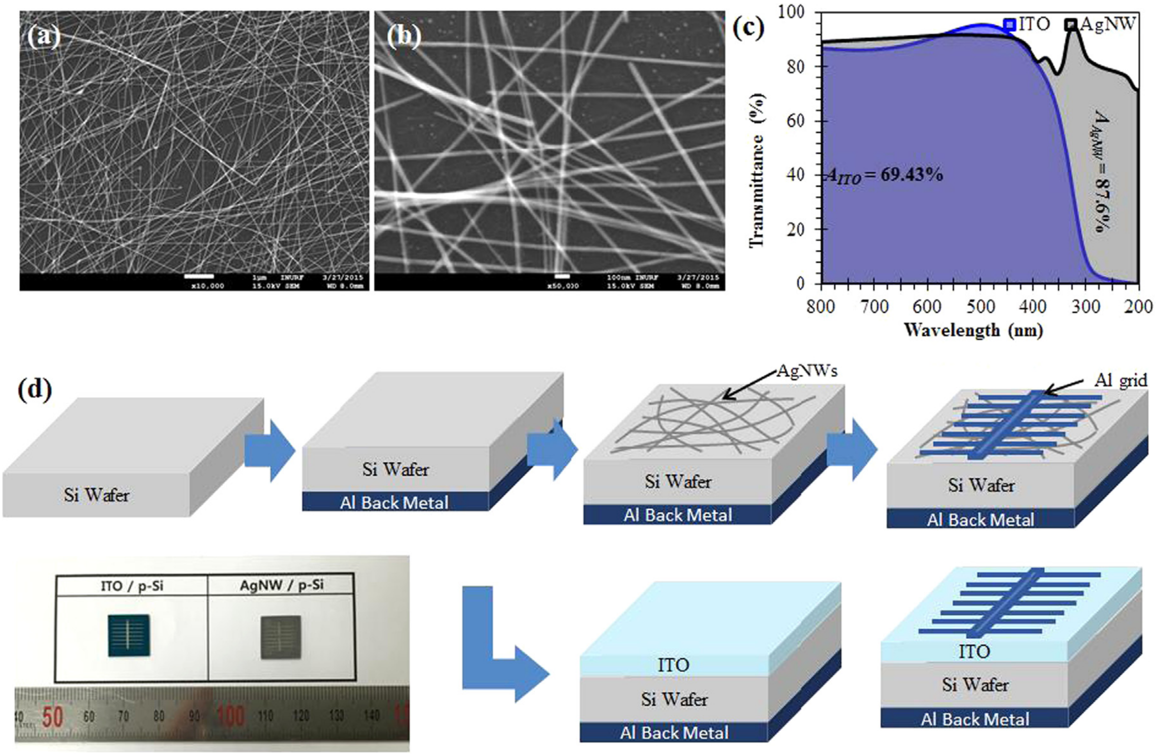

**Fig. 1.** FESEM images of AgNW on a Si substrate (a) 10k×, and (b) 50k×. (c) Transmittance profiles of AgNWs and ITO on a glass substrate. (d) Schottky junction device fabrication scheme.