# Hybrid Transparent Conductor by using Solution-Processed AgNWs for High-Performing Si Photodetectors

**Hong-Sik Kim · Joondong Kim**

Department of Electrical Engineering and Photoelectric And Energy Device Application Lab (PEDAL), Incheon National University, Incheon, Korea

**ABSTRACT:** A hybrid transparent conducting layer was applied for Si photodetector. To realize the hybrid transparent conducting layer, a 200 nm-thick ITO layer was deposited onto a Si substrate, following by a solution-processed AgNWs-coating on the ITO. The hybrid transparent conducting layer showed an excellent low electric resistance of 15.9 □/Ω with a high optical transparency of 86.89%. Due to these optical and electrical benefits, the hybrid transparent conductor-embedding Si diode provides an extremely high rectifying ratio of 3386. Under light-illumination, the hybrid transparent conductor device provides extremely high photoresponses for broad wavelengths. This implies that a functional design for hybrid transparent conductor is crucial for photoelectric devices and applications.

**Key words:** Photodetectors, Hybrid transparent conductor, Silver nanowires, Solution-process

## 1. Introduction

Photodetection has been used in various fields such as sensors, optical communication, optoelectric circuit, optical waveguides, imaging and medical diagnostics. Photodetection is fundamentally based on the conversion of light energy to electrical energy, usually appearing as photo current of a photodetector[1-4)].

Various design schemes have been reported with the objective of improving the performances of photodetectors. These include to modulate junction formations such as, Schottky, PIN[2,4,5)] and Metal -Insulator-Metal with functional materials of nanowires, graphenes, silicides[1,6)].

Typically, photodetectors require a bias voltage, which has the effect of increasing the electric field strength[7,8,9)]. This kind of operation has many advantages, such as lower capacitance, high speed and enhanced the photocurrent. However, the bias operation readily causes not ignorable off-state current, which may reduce the general photoresponse ratio, beside the unnecessary power consumption. In order to resolve the problem, zero-bias operation is highly desirable[3,9)]. Zero bias voltage can be achieved by applying a transparent conductor onto a semiconductor layer. It is effective for operating photodetectors without external bias[9-11)]. Optically transparent and electrically conductive window layer such as ITO, AZO, FTO and etc.,[12)] transmits the incident light into the photo reactive semiconductor material and is also beneficial to collect photo generated carriers[9)].

In this work, we propose an efficient design scheme for high performing Si photodetectors, operating at zero bias. A hybrid transparent conducting layer of AgNWs/ITO used for various wavelengths to reveal the substantially enhanced photoresponse compared to those of the conventional single ITO use method. Optical and electrical properties of the hybrid transparent conducting layer were systematically investigated. We may propose a design route to improve the photoelectric devices.

## 2. Experimental Procedures

A hybrid transparent conducting layer was coated on a Si wafer to realize the Si photodetectors. A p-type Si was cleaned and doped with phosphoryl oxychloride ($POCl_3$) in thermal furnace to form the n/p Si substrate. In order to realize the hybrid transparent conducting layer, an ITO layer was dc-sputtered onto the Si substrate. A 200 nm-thick ITO film was coated by 300 W dc-power supply for 10 min at 500°C. After then, AgNWs-layer was coated onto the ITO layer. AgNWs-diluted solution was spin-coated at a speed of 1000 rpm for 30 seconds. A thermal treatment was performed at 150°C to provide the stable attachments of AgNWs on the ITO layer.

Al Metal was used to form the front and back electrodes, which has been dc-sputtered for 10 minutes at room temperature.

*Corresponding author: joonkim@incheon.ac.kr
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A rapid thermal process (RTP) was performed at 500°C for 10 min to stabilize a contact property. A field emission scanning electron microscopy (FE-SEM, FEI Sirion) was used to observe the AgNWs. The I-V characteristics of the photoelectric device (AgNWs/ITO/n-Si/p-Si) was obtained by a probe station with measureing instruments (Keithley, 2400). A commercial quantum measurement system (McScience, K3100) was employed to generate light pulses. Photoresponse was measured by exposing the photodetector to the targeted wavelength of light.

## 3. Results and Discussion

Fig. 1(a) presents the processes of AgNWs/ITO structures on a Si substrate. The coated AgNWs were presented by SEM image (Fig. 1(b)), which showed uniformly dispersed AgNWs on an ITO/Si substrate. An average diameter of AgNWs was measured to be 41.6 nm.

For transparency measurements, AgNWs were coated on a glass. As a comparator, a single ITO layer was also prepared. The sole ITO sample showed very low transmittance at short wavelengths due to the free carrier loss, which causes no photo-generated carriers. Different from the sole-ITO sampled, AgNWs-coated layer showed higher transmittance for broad wavelengths. The average transmittance (300 ≤ λ ≤ 1400 nm) of 86.89% value was obtained, as shown in Fig. 1(c). This strongly indicates that the use of AgNWs for a transparent electrode can enhance the short wavelength light response.

Beside the optical aspect, the electrical performance of a transparent conductor is a crucial factor to manipulate the photoelectric device performances. Sheet resistance values were obtained by using four-point probe system.

The hybrid AgNWs/ITO film provided a much lower sheet resistance value of 15.9 Ω/□ compared to 21.7 Ω/□ from the sole ITO film. This also confirmed that the dispersion of AgNWs was uniformly distributed to lower the electrical resistance. To determine the AgNWs was uniformly distributed to lower the electrical resistance. To absorb more photons is a significant factor to improve the photo responses at a fixed photon energy amount. To determine the AgNWs-coated surface, we measured the reflectance profiles from the AgNWs/ITO hybrid layer, as

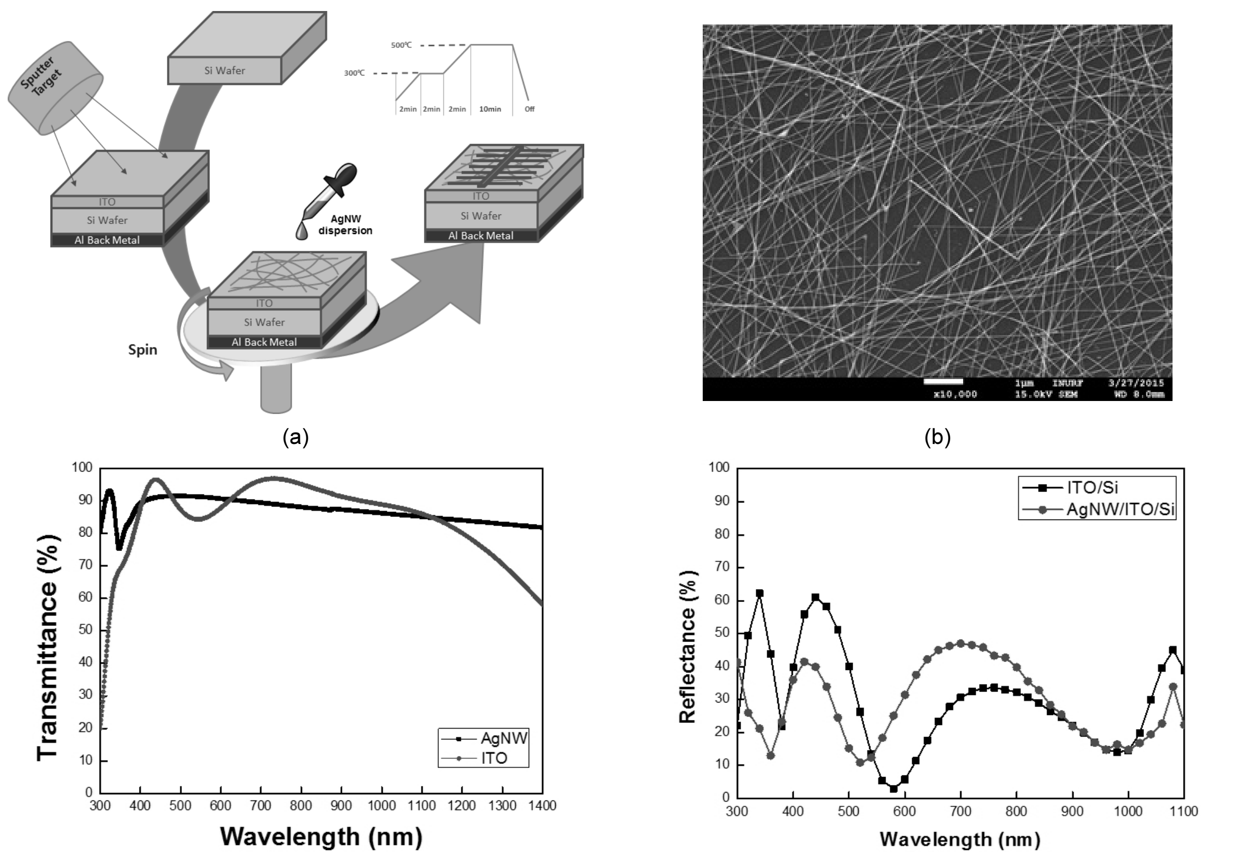


**Fig. 1.** (a) Process flow of a Device, (b) FESEM image of AgNW on a ITO/Si, (c) Transmittance of AgNWs and ITO, (d) Reflectance comparison

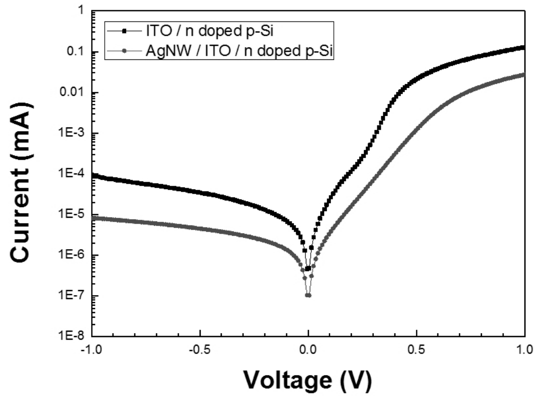


**Fig. 2.** Dark IV profiles of the AgNWs/ITO/Si device and ITO/Si device

shown in Fig. 1(d). Compared to the sole ITO film, AgNWs/ITO hybrid structure showed lower reflectance values for wavelengths around 500 nm or shorter. This can be attributed to the surface plasmonic effect of AgNWs to propagate the incident photons to drive-in the Si substrate.

In order to determine the junction properties, dark current-voltage (I-V) profiles were measured from the AgNWs/ITO/Si sample as shown in Fig. 2. A reference sample (ITO/Si) was also measured for dark I-V. Both devices fairly showed the rectifying current flows. The hybrid AgNWs/ITO/Si device has a much lower leakage current value, compared to that of the ITO/Si device, which is a significant advantage for photodetectors. Meanwhile, the ITO/Si device has a higher forward current value than that of the hybrid AgNWs/ITO device. The quality of the junction in a photoelectric device is mainly determined by its rectification property. We calculated the rectifying ratio of each device, by a ratio of the current value at +1 V over the current value at −1 V by the following relation :

$$Rectifying\ ratio = \frac{I_{at+1V}}{I_{at-1V}} \tag{1}$$

The ITO device gave a rectifying ratio (RR) about 1059. Otherwise, the AgNWs/ITO device provided a larger RR value of 3386. This indicates that the hybrid AgNWs/ITO/Si device is substantially effective to collect the charge carriers.

To measure the photoresponse, a sample was loaded in

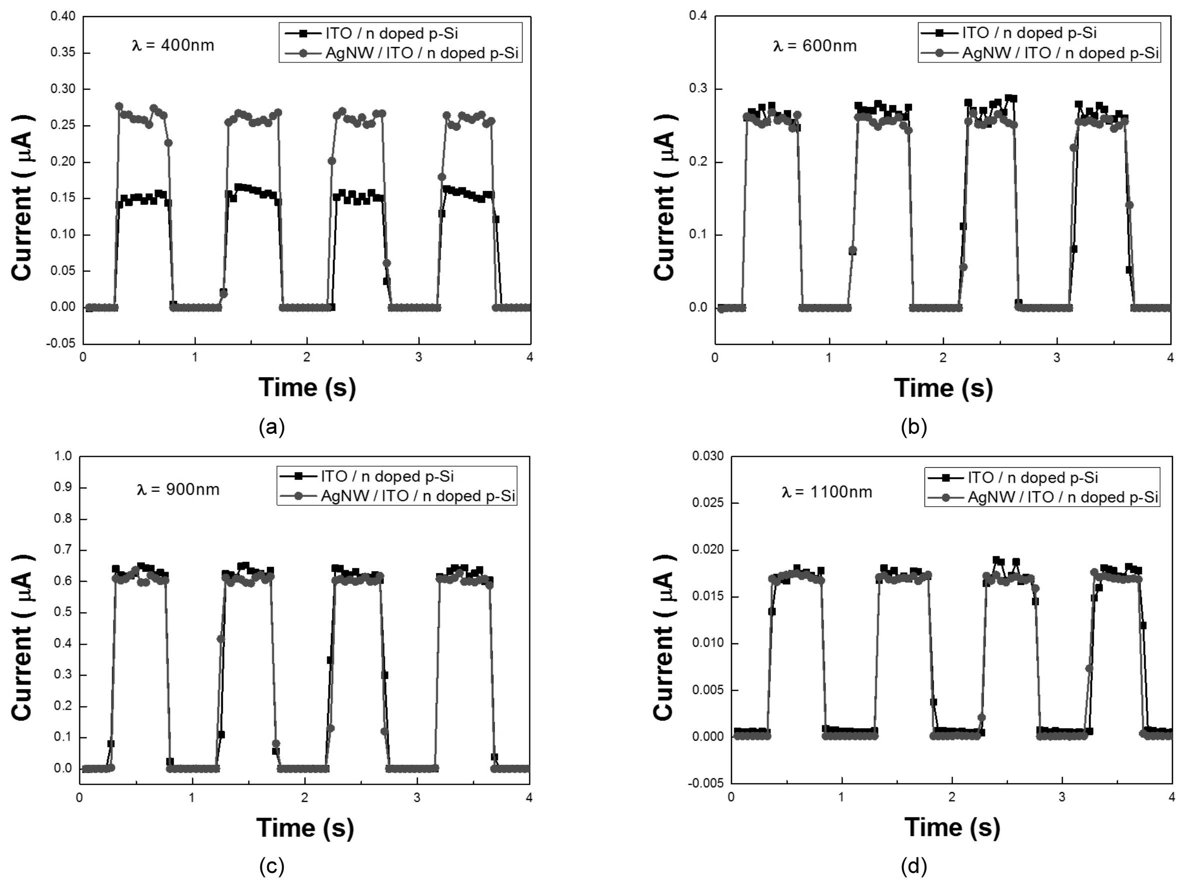


**Fig. 3.** Photoresponses from the hybrid AgNWs/ITo/Si photodetector and ITO/Si photodetector for (a) λ=400 nm, (b) λ=600 nm, (c) λ =900 nm, and (d) λ=1100 nm

quantum measurement system by pulsed light illumination. Various wavelengths were applied to a photodetector to characterize the photoresponses for a corresponding wavelength without any external bias. The photoresponse was characterized by following equation.

$$Photoresponse = \frac{I_{Light-on}}{I_{Light-off}} \quad (2)$$

As the equation implies, smaller light-off current and larger light-on current are the factor for high photoresponse properties. The hybrid AgNWs/ITO/Si photodetector provides highly-sensitive photoresponses for broad wavelengths compared to those of ITO/Si device.

For a short wavelength of 400 nm, ITO device provided a photoresponse value of 1311.16. Otherwise, the hybrid AgNWs/ITO transparent conducting layer used device showed almost double value to be 2584.65. This is mainly attributed to the plasmonic effect of AgNWs and reduction of reflection at short wavelengths, as shown in Fig. 1(d).

The advantage of the AgNWs/ITO structure can be clearly shown at a short wavelength of 400 nm. Typically, ITO layers showed poor photoresponses at short wavelengths due to the large energy bandgap of ITO. Consequently, the light absorption of ITO layer is comparatively high at the shorter wavelength regions. The AgNWs/ITO structure may be a route to expand photodetection potential for short wavelength region.

At a long wavelength of 900 nm, the ITO/Si device showed the lower photoresponse than those of λ=600 nm or 400 nm. Meanwhile, the hybrid AgNWs/ITO/Si photodetector showed the highest photoresponse at λ=900 nm. This strongly suggests that the AgNWs-coated surface is extremely efficient to modulate the incident photons into Si. As a result, functional light management can be obtained from the AgNWs/ITO hybrid transparent conducting layer.

## 4. Conclusions

A functional design of transparent conducting layer was achieved by forming AgNWs on an ITO film. This hybrid structure was demonstrated for the optical and electrical advantages to provide higher a transmittance profile with a low sheet resistance value. Due to the AgNWs, more photons can be driven into Si by the surface plasmon effect. According to the optical and electrical of hybrid structure of AgNWs/ITO, we prepose this concept can be adopted in various photoelectric devices, such as photodetectors, LEDs, lightings, and solar cells.

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