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Short Communication

A ZnO Nanowire Photodetector with an Ir Electrode Integrated on a Triple Junction Solar Cell

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A ZnO nanowire ultraviolet photodetecto with an iridium electrode fabricated on a GaInP/GaAs/Ge triple-junction solar cell. The ZnO NW PD can detect the UV light below 370 nm without detecting solar light. It should be noted that solar light was transformed to electrical power by the TJ solar cell and provided a light bias of 2.5 V for the PD. At a light bias of 2.5 V, the UV-to-visible rejection ratio of the ZnO NW PD with an Ir Schottky contact electrode was around 396, and the measured responsivity was 5.54×10^{-4} A/W.

Keywords: Nanowire、Triple Junction、Solar Cell、ZnO、Photodetector

1. INTRODUCTION

Ultraviolet (UV) photodetectors (PDs) are important devices that can be used in various applications such as space communication, ozone-layer monitoring, and flame detection. For portability and independence of external power, self-powered UV PDs without external power have already been studied.[1–3] In this study, the UV PDs were fabricated on the top of a triple-junction (TJ) solar cell. For detecting UV light, zinc oxide (ZnO) was chosen to be the detector because of its chemical and thermal stability.[4–7] With an energy band gap of 3.37 eV and the cutoff wavelength of 370 nm, ZnO detects the UV light below 370 nm without detecting the visible light that the TJ solar cell can utilize. It should be noted that the ZnO PDs were biased by the TJ solar cell.

Other than planar films, it is also possible to fabricate ZnO nanowire (NW)-based PDs. A one-dimensional (1-D) semiconductor NW structure has attracted great attention. Compared with bulk or thin film-based devices, 1-D nanowire PDs should provide a high internal photoconductivity gain owing to the surface-enhanced electron-hole separation efficiency.[8–12] Furthermore, the growth methods of a ZnO NW structure by using a low temperature hydrothermal method have been reported,[13–17] and adding NW designs on optoelectronic devices to enhance the light harvesting has been studied.[18–19] No previous attention has been focused to analyze the NW PD-Solar Cell integrated device.

However, no report on the fabrication of ZnO NW PDs with Ir metal as electrodes could be found in the literature to our knowledge. In this study, we report the growth of a ZnO NW structure with the hydrothermal method and an especially large work-function metal Ir (Φ = 5.76 eV) was used as the Schottky contact metal to enhance the barrier height and collect more electrons. The electrical and optical properties of the fabricated PDs will be discussed.

2. EXPERIMENTS

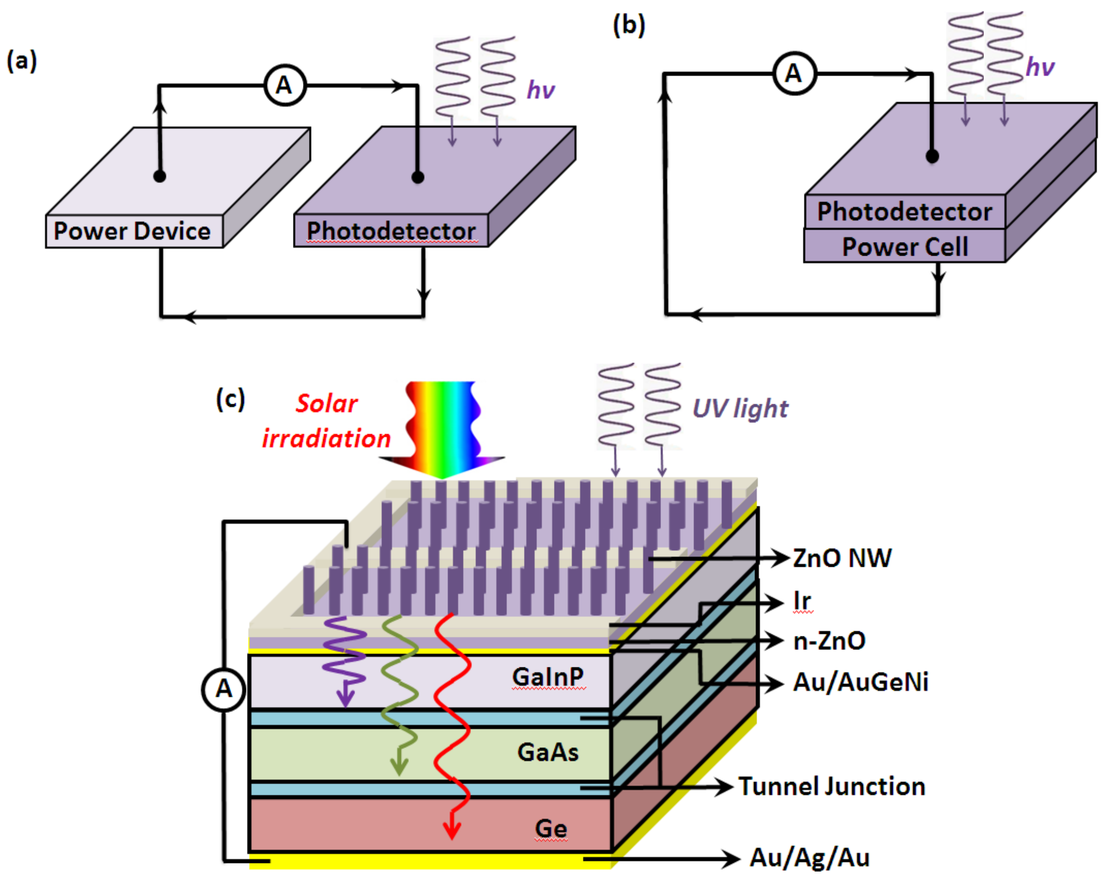


Figure 1. Schematic diagrams of (a) the planar and seperated self-powerd UV detection design, (b) the vertical and integrated self-powerd UV detection design, and (c) the fabricated UV PD integrated with the triple-junction (TJ) solar cell.

Figure 1(a) and 1(b) show schematic diagrams of the planar and the vertical seperated self-powerd UV detection design, respectively. The triple-junction (TJ) solar cells composed of three subcells, GaInP (top cell, band gap energy (Eg) = 1.9 eV), GaAs (middle cell, Eg = 1.42 eV), and Ge (bottom cell, Eg = 0.67 eV) junctions. To understand the merits of a NW structure, a bare TJ solar cell and a TJ solar cell with NW were measured at standard test conditions (STC, an irradiation intensity of 100 mW/cm^2, an Air Mass of 1.5 G, and a temperature of 24°C) with a source meter (Keithley 2400).

For fabricating the ZnO PDs on the TJ solar cells, Au/AuGeNi (2nm/5nm) was deposited by an electron-beam evaporation system and used as the ohmic contact between ZnO PDs and TJ solar cells. Similar contact was also fabricated on the TJ solar cells by Tseng et al.[20)] Then, the 100-nm-thick unintentionally doped ZnO was deposited on an Au/AuGeNi layer by using the sputter system. The concentration and type of ZnO were measured by the Hall measurement system. Finally, the 100-nm-thick Ir grid pattern was designed on the ZnO layer to form a metal–semiconductor Schottky diode to collect photons**.** For comparing the photoresponses of the Ir contact, another Schottky diode PD was prepared with Au metal.

To further enhance the performances of the TJ solar cells and the ZnO PDs, ZnO NW was grown on these devices. The TJ solar cells with ZnO films were vertically positioned in a 60-mL mixture solution with 40 mL of zinc nitrate hexhydrate [$Zn(NO_3)_2 \cdot 6H_2O$ (0.025 mol/L)] and 10 mL of ethylenetetramine [$C_6H_{12}N_4$ (0.025 mol/L)] and placed into a metal can with a capacity of 100 mL. The metal can was sealed and heated at 90°C for 2 hours. After the processes, the wafers were cut into 2 mm × 2 mm samples. To understand the merits of the NW structure, the electrical properties of the TJ solar cells with and without NW structure were also measured. With a light bias from the solar cell, spectral responsivity and dynamic responsivity of the PDs were measured by employing a calibrated monochromator with an Xe arc lamp serving as the light source, as shown in Fig. 1(c).

3. RESULTS AND DISCUSSION

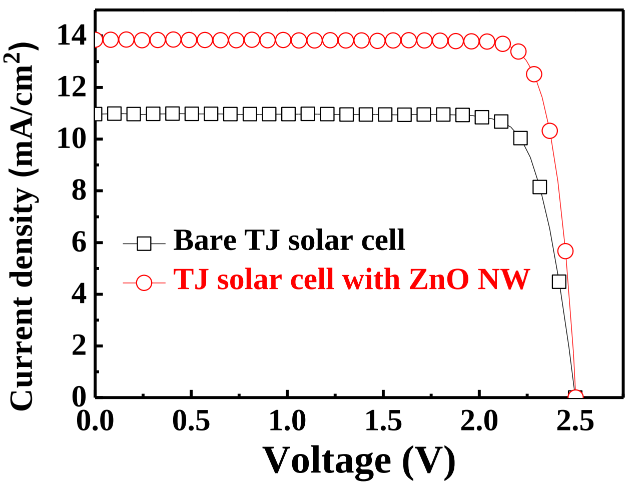


Figure 2. The illuminated (AM of 1.5 G) I-V characteristics of the bare TJ solar cell and TJ solar cell with a ZnO NW design under 100 mW/cm^2 illumination.

Figure 2 shows the illuminated (AM of 1.5G) I-V characteristics of the TJ solar cells with and without ZnO NW designs under 100 mW/cm^2 illumination. The short circuit current densities (J_{sc}) of the bare TJ solar cell and the TJ solar cell with NW structure were 10.94 and 13.84 mA/cm^2. The open-circuit voltages (V_{oc}) of solar cell samples were both around 2.5 V. This result indicated the NW structure can enhance the photocurrent.

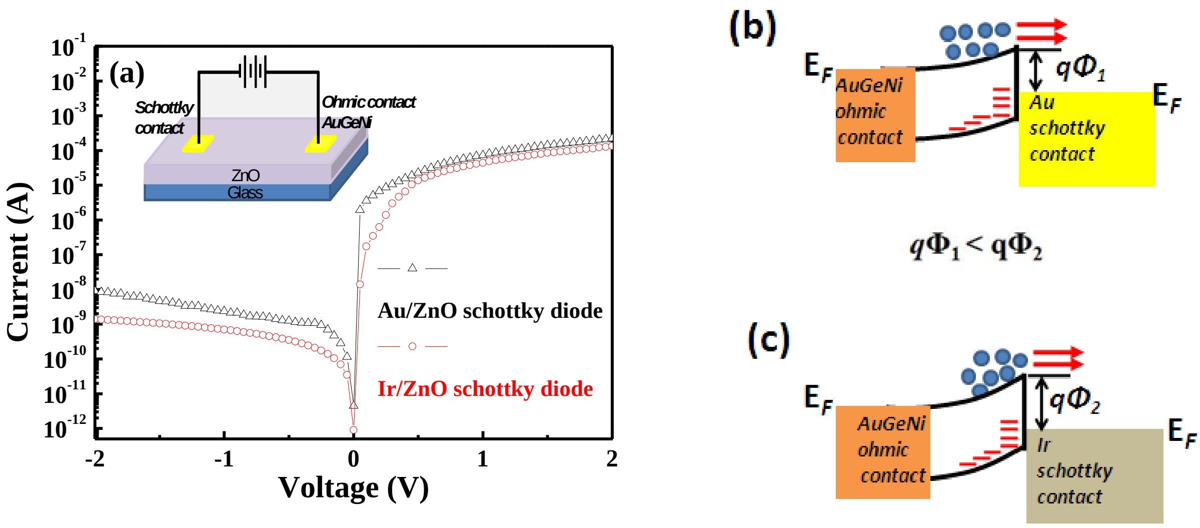


Figure 3. (a) Room-temperature I-V characteristics of the metal–semiconductor contact on the SiO_2 substrate and the schematic illustration of the Schottky diode behaviors of the (b) Ir/ZnO and (c) Au/ZnO structures.

The room temperature electron concentration and mobility of ZnO thin film were 10^{17} cm^{-3} and 190 cm^2/V-s by using hall measurement, respectively. The inset of Fig. 3(a) describes the experimental scheme of the metal/ZnO Schottky diode measurement. The current-voltage (I−V) curve presented in Fig. 3(a) indicates the Schottky behaviors of the Ir/ZnO and Au/ZnO contact. The general diode equation in forward bias is

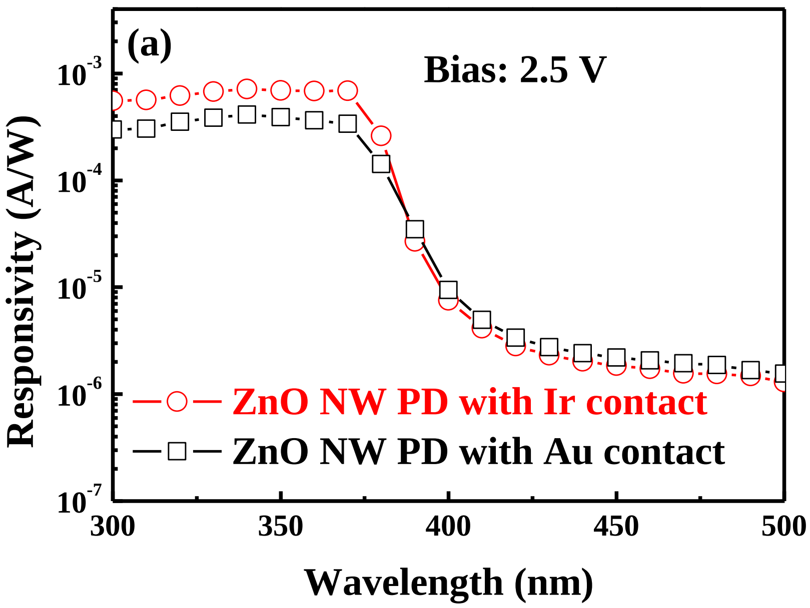
$$I = I_s \{\exp[(qV - IR_s)/nkT)] - 1\}, \qquad (1)$$

where I is the forward current, q is the charge of an electron, V is the voltage, n is the ideal factor, k is the Boltzmann constant, and T is the absolute temperature. The saturation current, I_s, is given by

$$I_s = AA^* T^2 \exp(-q\phi_B / kT), \qquad (2)$$

where A is the effective contact area (2.7×10^{-3} cm^2) and A^* is the effective Richardson constant (32 A/cm^{2}K^2). Fitting the forward I−V curve into the above Eqs. (1) and (2) at 1 V, the effective barrier height of Ir/ZnO contact is 1.72, larger than the 1.22 of the Au/ZnO contact. The results indicated the larger Schottky barrier height of Ir/ZnO with the larger work-function of Ir (Φ =

5.76 eV). In contrast, Au had the lower-work-function (*Φ* =5.1 eV) and Au/ZnO had a lower Schottky barrier height, as shown in Fig. 3(c).



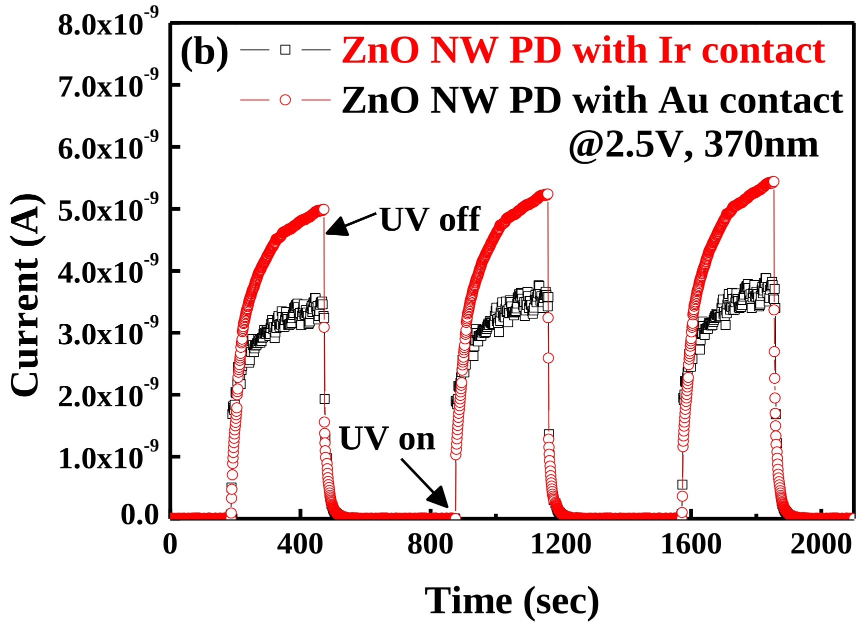


Figure 4. (a) Room-temperature spectral responses of the fabricated ZnO NW PDs with Ir and Au electrodes and (b) transient response of the fabricated ZnO NW PDs with Ir and Au electrodes as the UV excitation was switched on and off

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Figure 4(a) shows the room-temperature spectral responses of the ZnO NW MS-PD with Ir and Au contacts. Both of them were biased by the TJ solar cell. It should be noted that the operating current values of the PDs were about nano-ampere scale and the light bias provided by the TJ solar cell should almost be equal to 2.5 V of theV_{oc} value. For comparing the performance of the ZnO NW PD with an Ir contact, another PD sample with an Au contact was also prepared. It was observed that the photoresponses of the fabricated PDs were both flat in the short-wavelength region, while a sharp cutoff occurred at 370 nm. This also indicates that the fabricated ZnO NW PDs were indeed visible-blind. It was found the measured responsivity values of the PDs with Ir and Au contacts were 5.54×10^{-4} A/W and 2.99×10^{-4} A/W, respectively. Furthermore, the UV-to-visible rejection ratio value (370 nm/500 nm) of a ZnO NW PD with an Ir/ZnO contact could reach 396, better than the 217 of the Au/ZnO contact. This result corresponded to Figs. 3(b) and 3(c), with the larger Schottky barrier height of the PDs having obtained more electronic transition to the conduction band from the metal to the semiconductor under an external bias.

The transient response of the fabricated ZnO PDs with and without NW designs were measured and compared in Fig. 4(b), as the UV excitation was switched on and off. It was found that the dynamic response of the ZnO NW PD with the Ir electrode was stable and reproducible with a higher on/off current contrast ratio of around 1510. In contrast, the PD with the Au electrode has a contrast ratio of around 1000. It was also found that the photocurrent increased rapidly initially and then increased much more slowly as the UV excitation turned on. Similar slow response was also observed as we turned off the UV light. With a rough NW surface, the surface defect-related trapping center could retard the speeds of charge-carrier collection upon UV illumination and charge-carrier recombination as the UV light was turned off. It should be noted that the transient response measured from our Photodetectors was much less than that reported.[21)]

In conclusion, the authors reported a ZnO NW PD with an Ir electrode fabricated on a GaInP/GaAs/Ge TJ solar cell. The PD can detect the UV light below 370 nm with a light bias of 2.5 V provided from the TJ solar cell. To show the merits of the Ir metal contact, samples with Ir/ZnO and Au/ZnO Schottky contact electrodes were compared. At a light bias of 2.5 V, the UV-to-visible (370 nm to 500 nm) rejection ratio and the measured responsivity of the ZnO NW PD with an Ir Schottky contact electrode were around 396 and 5.54×10^{-4} A/W, respectively, a better result than the 217 and 2.99×10^{-4} A/W of the Au Schottky contact electrode. Furthermore, the dynamic response of the ZnO NW PD with an Ir electrode was stable and reproducible with an on/off current contrast ratio of around 1510, larger than the 1000 of the Au electrode. The related studies, which focused on nanowires photodetectors integrated with Solar Cell to realize a GaAs-based optoelectronic integrated circuit (OEIC) are now under the way.

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