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High responsivity ultraviolet photodetector realized via a carrier-trapping process

J. S. Liu,[1,2] C. X. Shan,[1,a)] B. H. Li,[1] Z. Z. Zhang,[1] C. L. Yang,[3] D. Z. Shen,[1] and X. W. Fan[1]
[1]*Key Laboratory of Excited State Processes, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, People's Republic of China*
[2]*Graduate School of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[3]*Center for Photovoltaic Cells, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, People's Republic of China*

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Metal-semiconductor-metal structured ultraviolet (UV) photodetector has been fabricated from zinc oxide films. The responsivity of the photodetector can reach 26 000 A/W at 8 V bias, which is the highest value ever reported for a semiconductor ultraviolet photodetector. The origin of the high responsivity has been attributed to the carrier-trapping process occurred in the metal-semiconductor interface, which has been confirmed by the asymmetric barrier height at the two sides of the metal-semiconductor interdigital electrodes. The results reported in this paper provide a way to high responsivity UV photodetectors, which thus may address a step toward future applications of UV photodetectors. © *2010 American Institute of Physics*. [doi:10.1063/1.3527974]

Ultraviolet (UV) photodetectors fabricated from wide band gap semiconductors, such as gallium nitride, zinc oxide (ZnO), and silicon carbide, have the characteristics of small-size, high performance, low-cost, etc.; thus they may find potential applications in a variety of fields including flame sensing, missile warning, space monitoring, etc.[1,2] Among the wide band gap semiconductors, ZnO and related materials have relatively high radiation-resistance[3] and high electron saturation velocity.[4] The above properties make ZnO a promising candidate for ultraviolet photodetectors operating in harsh environments. Actually, ZnO based photodetectors with various types such as Schottky photodiodes, metal-semiconductor-metal (MSM) photodetectors, and p-n junction photodiodes have been demonstrated recently.[5–10] Nevertheless, the performance of ZnO based UV photodetectors is still below expectation, which is one of the largest hurdles that hinder the practical applications of ZnO based UV photodetectors. Responsivity is one of the most important parameters that determine the performance of a photodetector, which is defined as the photocurrent flowing in a photodetector divided by incident optical power. Therefore, it will be of great significance if some measures can be taken to improve the responsivity of a photodetector.

In this paper, in virtue of a carrier-trapping process, a ZnO based UV photodetector with a responsivity of 26 000 A/W has been obtained, which is the highest responsivity ever reported in a semiconductor-based UV photodetector. The ZnO thin films employed as the active layer of the photodetector were grown on *a*-plane sapphire by plasma-assisted molecular beam epitaxy technique. The cleaning process of the sapphire substrate can be found in our previous publication.[11] Elemental zinc of 6N purity and oxygen of 5N purity were used as precursors for the growth of ZnO. Zinc was evaporated in a Knudsen effusion cell and oxygen was activated by a radio-frequency plasma source at a fixed power of 300 W. During the growth process, the substrate temperature was fixed at 800 °C and the pressure in the growth chamber was fixed at 1×10^{-5} mbar. To fabricate the ZnO based photodetectors, a thin Au layer was evaporated onto the ZnO films using a vacuum evaporation method, and interdigital electrodes were configured on the ZnO films via a photolithography and wet etching process.

The structure characterization of the films was carried out in a Bruker D8 Discover (Germany) x-ray diffractometer using Cu Kα ($\lambda=1.54$ Å) as the excitation source. The electrical properties of the films and the photodetectors were measured in a Hall measurement system (Lakeshore 7707, Westerville, Ohio). To characterize the photoresponse properties of the photodetectors, a 150 W Xe lamp was used as the excitation source and the response was measured by a lock-in amplifier.

Figure 1 shows the x-ray diffraction (XRD) pattern of the ZnO films. Besides the diffraction from the sapphire substrate, only one peak can be observed, which can be indexed to the diffraction from (0002) facet of wurtzite ZnO. The strong (0002) diffraction peak indicates that the ZnO films are crystallized in wurtzite structure with *c*-axis preferred

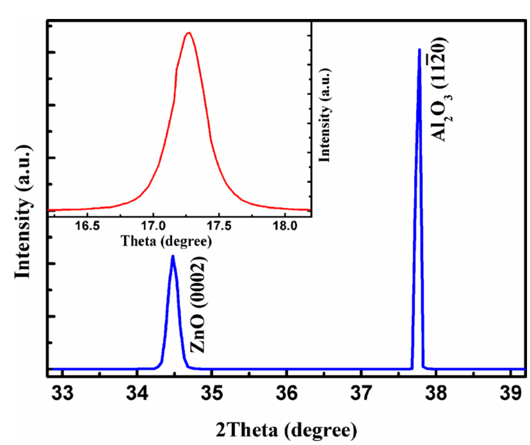

FIG. 1. (Color online) XRD pattern of the ZnO films and the inset shows the (0002) x-ray rocking curve of the films.

[a)]Electronic mail: phycxshan@yahoo.com.cn.

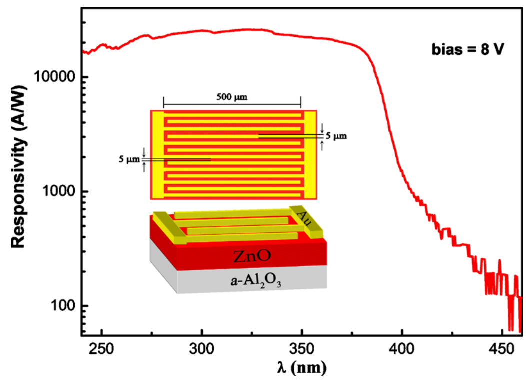

FIG. 2. (Color online) Spectral responsivity of the photodetector at 8 V bias and the inset shows a schematic illustration of the MSM structured ZnO photodetector.

orientation. The inset shows the (0002) x-ray rocking curve of the ZnO films and the full width at half maximum of the curve is about 936 arcsec.

The structure of the photodetector is schematically illustrated in the inset of Fig. 2. Interdigital Au electrodes are deposited onto the ZnO thin films. It consists of 12 fingers for each electrode, the fingers are 5 μm in width, 500 μm in length, and the spacing between the fingers is 5 μm. Figure 2 shows the characteristic photoresponse spectrum of the photodetector at 8 V bias. The peak responsivity of the photodetector is as high as about 26 000 A/W. This is the highest value ever reported for a semiconductor based photodetector. The quantum efficiency of a photodetector can be expressed by the following formula:[12]

$$\eta = R_v \frac{hc}{q\lambda g}, \tag{1}$$

where q is the electron charge, λ is the incident light wavelength, g is the internal gain, and R_v is the voltage-dependent responsivity. The gain/quantum efficiency for our photodetector is estimated to be about 9×10^4 at 8 V bias.

To explore the origin of such a high optical gain in our case, the current-voltage (*I-V*) curve of the photodetector was measured in dark, and the data of which were shown in Fig. 3. The *I-V* curve show an obvious Schottky behavior, which comes from the Au/ZnO interface. It is noteworthy that the *I-V* curve shows an asymmetric shape in the positive and negative voltage regions. Either thermionic emission or tunneling model may be employed to understand the carrier transportation process at the Au/ZnO interface. A rough criterion to determine the dominant transport process in a Schottky contact is to compare the thermal energy k_BT to E_{00}, where k_B is Boltzmann constant, T is absolute temperature, and E_{00} can be expressed by the following formula:[12] $E_{00}=(q\hbar/2)(N/m^*\varepsilon_s)^{1/2}$. In this formula q, N, m^*, and ε_s are elementary charge, carrier concentration, effective mass, and dielectric constant of the semiconductor, respectively. If $k_BT \gg E_{00}$, thermionic emission will dominate the Schottky behavior prevailing over tunneling process. In our case, $m^* = 0.24\ m_0$ and $\varepsilon_s=8.1$ (Ref. 13) for ZnO, and the carrier concentration N of the ZnO film obtained by Hall measurement is about $1.0\times10^{17}\ \text{cm}^{-3}$. By inserting the above values into the expression of E_{00} shown above, one can yield that $E_{00}=2.3$ meV, which is much smaller than the thermal energy k_BT at room temperature (26 meV). Therefore, it is reasonable to employ the thermionic emission model to analyze the Schottky behavior at the Au/ZnO interface in our case.

In the thermionic emission model, the *I-V* curve under forward bias can be expressed by the following formula:[14]

$$I = I_0\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right], \tag{2}$$

where I_0 is the saturation current, q is the elementary charge, V is the applied voltage, and n is the ideality factor. I_0 can be expressed as follows: $I_0=A_1A_n{}^*T^2\exp(-q\phi_b/k_BT)$, where A_1 is the area of the photodetector and A^* is the effective Richardson constant, which is 28.8 A cm^{-2} K^{-2} for ZnO and $q\phi_b$ is the height of the Schottky barrier.

Because the MSM structure in our case is basically two Schottky barriers connected back to back on a coplanar surface, the dependence of current on the bias applied can be expressed as follows:

$$I = I_1\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right] + I_2\left[\exp\left(-\frac{qV}{nk_BT}\right) - 1\right], \tag{3}$$

where $I_1=A_1A_n{}^*T^2\exp(-q\phi_{b1}/k_BT)$, $I_2=A_1A_n{}^*T^2 \times\exp(-q\phi_{b2}/k_BT)$, and $q\phi_{b1}$ and $q\phi_{b2}$ are the Schottky barrier height of the two Au/ZnO interdigital contacts. By fitting the *I-V* curve in Fig. 3 using Eq. (3), one can yield the Schottky barrier height at the two sides of the interdigital contact have very little difference in the positive voltage region (0.362 eV for $q\phi_{b1}$ and 0.356 eV for $q\phi_{b2}$), but $q\phi_{b1}$ is significantly larger than $q\phi_{b2}$ in the negative voltage region (0.417 eV for $q\phi_{b1}$ and 0.304 eV for $q\phi_{b2}$), as shown in Fig. 3. That is, an asymmetric barrier has been formed in the two Au/ZnO interfaces in the negative bias region. A model has been assumed to explain the formation of the asymmetric barrier, and a schematic illustration of the bandgap alignment of the Au/ZnO/Au MSM structure is shown in Fig. 4, in which the electrodes at the two sides of the interdigital were named as M_1 and M_2 for simplicity. When the bias is applied from M_1 to M_2, holes tend to accumulate at the M_2/ZnO interface, and may be trapped by the surface states at the interface, leading to an increase in hole concentration in that region, as shown in Fig. 4(a). The traps at the M_2/ZnO interface may come from surface damaging during the device processing or the interface states associated with the grain boundary defects[15] in ZnO thin films. It is known that the barrier height of a metal-semiconductor interface is greatly affected by the interface states.[16] The increased densities of

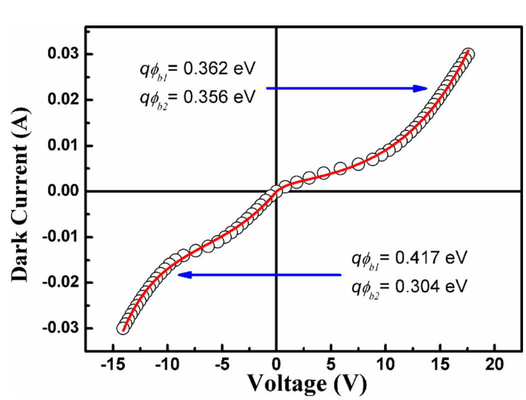

FIG. 3. (Color online) *I-V* characteristics of the ZnO MSM structure measured in dark, in which the scattered open circles are experimental data, while the solid line is a fitting to the experimental data.

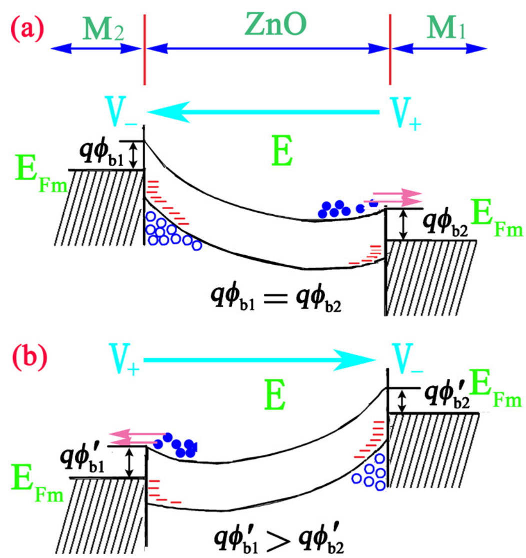

FIG. 4. (Color online) Bandgap diagram of the MSM structured photodetector when the bias direction is from M1 to M2 (a) and from M2 to M1 (b).

positive charge at the M_2/ZnO interface leading to a higher Schottky barrier height. Therefore, once the voltage reverses transiently, the unequal Schottky barrier height results in an asymmetric *I-V* shape, as shown in Fig. 4(b). Note that if the current under positive voltage and negative voltage were measured individually, it shows a symmetric shape, which indicates that the asymmetric *I-V* curve is caused by the carriers trapping at the Au/ZnO interface.

It is known that high optical gain can be achieved when $\tau > t$, where τ is the lifetime of the excess carriers, and t is the time taken to transport them to the respective contacts under the driven of the applied voltage.[17] In our case, the large gain may be caused by the carrier-trapping process as stated below. Electron-hole pairs will be generated under the illumination of the excitation source, and the generated carriers will drift toward opposite electrodes under the driven of the applied bias. When the holes arrive at the Au/ZnO interface, they are trapped by the interface states at the interface, while electrons will circulate though the external circuit many times before it recombines with holes. The above process is equivalent to the fact that many carriers have been generated after the photodetector was illuminated by one photon. Thus an enhanced gain has been resulted. As a result, the responsivity of the photodetector is greatly improved.

In conclusion, high responsivity UV photodetector has been demonstrated based on ZnO film. A responsivity of 26 000 A/W has been achieved at 8 V bias, the highest responsivity ever reported in a semiconductor based UV photodetector. The relatively high responsivity has been attributed to the carrier-trapping process at the metal-semiconductor interface, which has been confirmed by the asymmetric barrier height at the two sides of the Au/ZnO interdigital electrodes. The results reported in this paper provide a route to high responsivity UV photodetectors, thus may lay a solid ground for the future applications of this kind of photodetectors.

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