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Electrical characteristics of Ultraviolet photodetector based on ZnO nanostructures

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Abstract

ZnO nanostructures were grown on p-type Si substrate by spray pyrolysis technic. A UV light was used as an illuminating source at 365 nm. The current–voltage characteristics of the device under UV illumination showed an enhancement that dark current. The dark current is about 58 $\mu$A, and the photocurrent is about 97 $\mu$A under a reverse bias voltage of 6 V. The photocurrent characteristic of photodetector is measured under 3 V forward biases and after 18 min it saturated. Continuous measurements indicate the reproducibility and stability of this UV photodetector. The Schottky diode parameters as the barrier height, the ideality factor, and the series resistance as calculated using a method developed by Cheung’s method. It was found that ideality factor was greater than unity and barrier height was larger than 0,8 eV.

1. Introduction

Photodetectors UV are devices that convert an optical signal into an electrical signal. They are important active elements for various applications, such as ozone layer monitoring, flame detection and missile warning systems [1, 2], space communications and they are also widely used in various medical applications such as detectors for computed tomography [3], blood gas monitors [4], and immunoassay [5]. In these applications, high responsivity, fast response time, and good signal-to-noise ratio are common desirable characteristics. Many compact UV detectors have been fabricated on wide band gap materials,
such as SiCN [6], diamond, SiC [7], III–V compounds [8–10], and some II–V compounds [11,12]. Among them, zinc oxide (ZnO) has numerous attractive characteristics for electronics and optoelectronics devices. It has direct bandgap energy of 3.37 eV [13], which makes it transparent in visible light and operates in the UV to blue wavelengths. The exciton binding energy is \( \sim 60 \text{ meV} \) for ZnO, as compared to GaN \( \sim 25 \text{ meV} \); the higher exciton binding energy enhances the luminescence efficiency of light emission. The room temperature electron Hall mobility in single crystal ZnO is \( \sim 200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \), slightly lower than that of GaN, but ZnO has higher saturation velocity. ZnO has exhibited better radiation resistance than GaN for possible devices used in space and nuclear applications. ZnO can be grown on inexpensive substrate, such as glass, at relatively low temperatures. High quality ZnO epitaxial layers can be grown by metalorganic chemical vapor deposition (MOCVD) [14,15], molecular beam epitaxy (MBE) [16], the sol–gel process [17–21], radio frequency magnetron sputtering [22], spray pyrolysis [23] and pulsed laser deposition (PLD) [24] on top of ZnO substrates [25], sapphire substrates [26] and epitaxial GaN layers [27].

In this investigation, we synthesis ZnO nanostructures on p-Si substrate by spray pyrolysis technic. MSM photodetector was realized by Cu-ZnO-Cu and tested under UV illumination. The electrical parameters of ZnO Schottky diodes with Cu contact electrodes were investigated and the photoresponse of the photodetector were also discussed.

2. Experimental procedure

ZnO nanostructures were grown on p-Si substrates by spray pyrolysis process in ambient atmosphere. The spraying set up used was a home-made system that we have developed to perform a good spraying sample. The experimental set up was shown schematically in Fig.1(a). The precursor solution of ZnO was prepared from zinc acetate (Zn (CH3CO2)2·2H2O, purity 99.5%) dissolved in methanol (CH3OH, purity 99%). Then, the molarity of the solution was fixed at 0.085 M and the volume of the sprayed solution was 60 ml. The resultant solution was very clear and transparent. Possible reaction to formation of ZnO was given by

\[
2\text{CH}_3\text{O}^- + \text{Zn}^{++} + \text{H}_2\text{O} \rightarrow \text{ZnO} + 5\text{CO}_2 + 6\text{H}_2
\]

The p-Si substrates were cleaned. The distance between the substrate and the spray gun nozzle was fixed at 27 cm. Compressed nitrogen is used to atomize the solution. Substrate temperature was kept at 550°C with an accuracy of \( \pm 2^\circ\text{C} \) and controlled by using an electronic temperature controller K-type thermocouple kept on the metallic hot plate surface.

A UV photodetector was fabricated with metal-semiconductor- metal (MSM) structure, which was shown as Figure 2. A Metal contact was formed by placing a Cu contact on ZnO surface. The distance of the metal electrodes was 2 mm. The schematic structure of the ZnO nanostructures UV photodetector is shown in fig.1 (b).

The photoelectrical properties of ZnO UV photodetector were characterized by two point probe. A UV light with a wavelength of 365 nm and power of 0.8 W was used as the illuminating source. Digital Multimeter was employed to measure the current–voltage (I–V) characteristics of the system. The measurements were performed at ambient conditions.
The slow UV response and recovery of the ZnO photodetector may be attributed to the oxygen adsorption and desorption process. In dark, oxygen molecules adsorb on the ZnO surface by capturing free electrons from the n-type ZnO \( O_2(gaz) + e^- \rightarrow O_2^{(adsorption)} \), thereby creating a depletion layer with low conductivity near the surface.

Upon UV illumination at photon energies above ZnO band gap, electron-hole pairs are generated \( h\nu \rightarrow e^- + h^+ \). Photon-generated holes migrate to the surface and discharge the adsorbed oxygen ions \( O_2^{(adsorption)} + h^+ \rightarrow O_2(gaz) \), to photon-desorbed oxygen from the surfaces. The unpaired electrons accumulate gradually with time until desorption and readsorption of O2 reach an equilibrium state, resulting in a gradual current rise until saturation during UV illumination. Although holes recombine quickly with electrons upon turning off UV light, there are still a lot of electrons left in the ZnO. O2 molecules gradually reabsorb on the surface and capture these electrons, which results in a slow current decay [28].

Fig.1. (a) schematic diagram of spray pyrolysis process; (b) structure of ZnO nanostructures UV photodetector
3. Result and discussion

Figure 3 plots the current–voltage characteristics of ZnO UV photodetector based on Cu/ZnO/Si structure measured both in the dark and UV light with a wavelength of 365 nm at room temperature and in ambient atmosphere. A current–voltage characteristic curves of the Cu/ZnO/Si structure in the forward and reverse bias by sweeping the bias voltage from -6 to 6 V, as seen in fig.3. The difference between the dark current and photocurrent is clearly observed, which is similar to other reported results [29], [30]. Upon UV illumination the current increases with both the forward and the reverse voltage. However, the reverse current under illumination is clearly exceeded that in the dark. When a -6 V reverse voltage is applied, the dark current and the photocurrent were 0.58x10^{-4} and 0.97x10^{-4} A, respectively. The increase in the photocurrent in the reverse biased condition is greater than that in the forward bias, which is the characteristic of a photodiode [31]

![Image of current-voltage characteristics](image_url)

**Fig.2:** characteristics of the ZnO UV photodetector in the dark and under illumination (365 nm)

The dark current and photocurrent voltage characteristics appear nearly symmetric and nonlinear behavior. This curves show back-to-back Schottky characteristics rather than ohmic contact characteristics. This behaviour of the device indicates the presence of Schottky barriers. For a Schottky barrier diode (SBD) in the presence of an interfacial layer and other effects the barrier height depends on the bias voltage; thermionic emission (TE) theory predicts that the current–voltage characteristic with the series resistance is thus given as follows [32]

\[
I = I_0 \exp \left( \frac{q(V - IR_S)}{nkT} \right) - 1 \tag{1}
\]

where \( I_0 \) is the saturation current derived from the straight line intercept of \( \ln I \) at \( V = 0 \) and is given by

\[
I_0 = AA^* T^2 \exp \left( - \frac{q\Phi_b}{kT} \right) \tag{2}
\]

where \( k, T, R_s, n, A^* \) and \( \Phi_b \) were Boltzmann’s constant, absolute temperature, series resistance, ideality factor, effective Richardson coefficient and barrier height, respectively. Here, we assumed \( A^* = \)
The value of the saturation current $I_0$ was found to be $7.33 \times 10^{-9}$ A. This value was used to calculate the apparent barrier height by the following function:

$$q\Phi_b = kT \ln \left( \frac{AA^*T^2}{I_0} \right)$$

(4)

The value of the barrier height is found to be 0.87 eV, which is comparable with the reported values of Ag/ZnO Schottky diode based on ZnO thin film fabricated on F-doped SnO$_2$ glass substrates [34].

The series resistance is an important parameter on the electrical characteristics of Schottky barrier contacts. Rs is influenced by the presence of the interface layer between the metal and the semiconductor and leads to non-ideal forward bias current–voltage plots. When the applied voltage is sufficiently large, the effect of the Rs can be seen at the non-linear regions of the forward bias I–V characteristics [35]. The Schottky diode parameters as the barrier height, the ideality factor, and the series resistance can also be achieved using a method developed by Cheung’s method [36], [37].

The $IR_s$ term in Eq. (1) is the voltage drop across series resistance of device. The values of the series resistance can be determined from following functions using Eq. (1):

$$\frac{dV}{d\ln I} = \frac{nkJ}{q} + IR_s$$

(5)

**Fig. 3.** A plot of $\frac{dV}{d\ln I}$ vs. I and $H(I)$ vs. I obtained from forward bias current–voltage characteristics of the Cu/ZnO structure

Hence $R_s$ and $n$ can be determined by plotting $d(V)/d(ln I)$ vs I which gives $R_s$ as the slope and $nkT/q$ as the y-axis intercept. We can further define a function $H(I)$, where [38]:
Then, we can deduce the following equation:

\[
H(I) = V - \frac{n k T}{q} \ln \left( \frac{I}{A A' T^2} \right)
\]

(6)

Figure 3 shows a plot of \(dV/d(ln I)\) vs. \(I\) and \(H(I)\) vs. \(I\) at room temperature. The values of \(n\) and \(R_s\) have been calculated as \(n = 2.5\) and \(R_s = 6281\Omega\), respectively. It is observed that the value of \(n\) obtained from the forward-bias of the \(dV/d(ln I)\)--\(I\) curves is larger than unity. High values of \(n\) can be attributed to the presence of the interfacial thin native oxide layer at Cu and ZnO interface, barrier in homogeneities, to the series resistance effect and to the bias voltage dependence of the SBH [34]. This can be attributed to the existence of the series resistance and interface states and to the voltage drop across the interfacial layer [39]. Moreover, by plotting \(H(I)\) vs \(I\), we can determine \(R_s\) as the slope and \(n \Phi_b\) as the y-axis intercept. \(H(I)\) vs. \(I\) plot have to be linear according to the Refs. [39], [40]. The slope of this plot gives a different determination of \(R_s\). Using the value of the \(n\) obtained from Eq. (7), the value of \(\Phi_b\) is obtained from the y-axis intercept. From \(H(I)\) vs. \(I\) plot, \(\Phi_b\) and \(R_s\) have been found as 0.90 eV and 5600 \(\Omega\), respectively. It can be obviously seen that the value of \(R_s\) obtained from \(H(I)\)–\(I\) curve is in close agreement with the value obtained from the \(dV/d(ln I)\)–\(I\) plot.

Figure 4 shows a time-dependent photocurrent characteristic of photodetector under a bias voltage of 3 V. Under UV illumination, the current increased swiftly to a certain level and then gradually became saturated after 18 min. After turning off, the current tends to come back to its initial state and this change is exponential. Continuous testing can establish the reproducibility and stability.

The photocurrents almost proportionally increase with voltage, due to the proportionally linear relationship between the collected carriers and external electrical field, conformed to a simple photogeneration and collection model [41] where the photocurrent can be written:
\[ I_{ph} = \frac{qF_0 \eta_{abs} \mu \tau E}{d} \]  

(8)

Where \( q \) is the electron charge, \( F_0 \) the number of incident photons per unit time, \( \eta_{abs} \) the optical absorption efficiency, \( \mu \tau \) the mobility-lifetime product of photo-generated carriers, \( d \) the interelectrode spacing and \( E \) is the applied electrical field.

In addition, the responsivity \( (R) \) of the ZnO based photodetector at 1 V was estimated to be 4.45 \( \mu \text{A/W} \) according to the following equation:

\[ R = \frac{I_{ph} - I_{dark}}{P_{op}} \]  

(9)

Where \( I_{ph} \) and \( I_{dark} \) are the magnitudes of the photocurrent and dark current, respectively, and \( P_{op} \) is the laser power.

4. Conclusion

In summary, the electrical characteristics of ZnO Schottky diodes with Cu contact electrodes were investigated. The Schottky barrier height determined was larger than 0.8 eV at room temperature. The ideality factor of Cu/ZnO Schottky diodes was obtained is larger than 2. UV photodetector based on Cu/ZnO Schottky diode exhibited fairly good diode like I-V characteristics. The photocurrent was found to be increased with the illumination of UV light. Continuous measurements photoresponses as function of time upon switching of UV lamp 365 nm on and off at 3 V forward bias indicates the reproducibility and stability of this UV photodetector.

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