Optoelectronic characterisation of an individual ZnO nanowire in contact with a micro-grid template*

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Optoelectronic characterisation of an individual ZnO nanowire in contact with a micro-grid template has been studied. The low-cost micro-grid template made by photolithography is used to fabricate the ohmic contact metal electrodes. The current increases linearly with the bias, indicating good ohmic contacts between the nanowire and the electrodes. The resistivity of the ZnO nanowire is calculated to be 3.8 Ω·cm. We investigate the photoresponses of an individual ZnO nanowire under different light illumination using light emitting diodes ($\lambda = 505$ nm, 460 nm, 375 nm) as excitation sources in atmosphere. When individual ZnO nanowire is exposured to different light irradiation, we find that it is extremely sensitive to UV illumination; the conductance is much larger upon UV illumination than that in the dark at room temperature. This phenomenon may be related to the surface oxygen molecule adsorbtion, which indicates their potential application to the optoelectronic switching device.

Keywords: ZnO nanowire, optoelectronic, micro-grid template

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1. Introduction

In recent years, ZnO nanostructures attracted great interest due to their unique properties, such as a wide direct bandgap (3.37 eV), large exciton binding energy (∼ 60 meV), piezoelectricity and larger surface-to-volume ratio. Significant progress has been made for the fabrication of various electronic and optoelectronic devices based on ZnO nanowires (NWs). Many nanodevices like field-effect transistors,[1−4] sensor[5−8] and UV photodetectors[9−12] have been widely studied and demonstrated. Since the performance of devices critically depends on the quality of the ohmic contacts, the development of low-resistance contacts in the semiconductor device attracted considerable attention. Consequently, a key requirement of ZnO NW-based devices is the availability of low-resistance ohmic contacts. Several methods have been used to fabricate micro-electrodes of the ZnO nanodevice, for example, some groups have formed source–drain electrode by e-beam lithography and evaporation.[13,14] In their work, ZnO NWs are sonicated in alcohol directly,[1,13] then the suspension is deposited onto prefabricated electrodes. In addition, atomic force microscope[15−17] and focus ion beam technique [18,19] are also used to achieve ohmic contacts. However, these processes are costly.

In this study, we try the micro-grid template method, which is an easy and low-cost fabrication method for ZnO device ohmic contacts. The photoconductivity of an individual ZnO NW is studied by low power light emitting diodes (LEDs) as the excitation sources. In the literature there has been reported the use of hand-held UV-lamp or laser as the excitation, but few reports concentrate on LED. By conventional current–voltage measurements, we find that ZnO NW is extremely sensitive to UV light exposure. The increase of light-induced conductivity allows us to switch the nanowire between 'Off' and 'On' states.[20]

2. Expermental details

The ZnO NWs used in this study are synthesised by conventional chemical vapour deposition method. Micro-grid template made by photolithography is used

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to fabricate the ohmic contact metal electrodes. A micro-grid is used as a mask when the NWs are long enough. The ZnO NWs is first extracted from the Si substrate by the electrostatic forces between the micro-grid and NWs, which is fixed on a cleaned p-type Si substrate with 300 nm thick SiO_2 as the insulating layer. Together with the micro-grid, Ti and Au metal layers are deposited separately on the p-type Si substrate by thermal evaporation as source and drain electrodes. After deposition, the micro-grid is detached and a device based on an individual ZnO NW is fabricated. Finally, the device is annealed at 450 °C for 3 min in pure N_2 atmosphere to improve the contact between the ZnO NW and the Ti /Au electrodes. The sample is bonded using silver wires to provide electrical connections. In this study, the characteristics of current–voltage and photoresponses of the ZnO NW are measured by Agilent B1500A in atmosphere at room temperature.

3. Results and discussion

Figure 1(a) depicts a schematic diagram of the ZnO nanodevice the Fig. 1(b) (inset) shows a scanning electron microscope (SEM) image of the individual nanowire device. The diameter and the length of the ZnO NW are about 500 nm and 40 μm, respectively. The source and drain electrodes are separated from each other by a distance of ~ 20 μm. The typical characteristics of drain current (I_{DS}) and drain voltage (V_{DS}) are given in Fig. 1(b). A linear I_{DS}–V_{DS} curve is observed from the individual ZnO NW as the voltage scanning from -1.5 V to 1.5 V in the dark at room temperature. The resistivity of the ZnO NW is calculated to be 3.8 Ω·cm and the value of the measured conductance is about 2.6×10^{-7} s, indicating good ohmic contacts between ZnO NW and Ti /Au electrodes. As the work function of Ti (4.0 eV) and the ZnO (4.3 eV) match well, the ohmic contact could be achieved on a perfect clean surface. Moreover, the annealing treatment at the appropriate temperature is crucial for reducing the contact resistance. It could improve the contact quality between Ti/Au electrodes and ZnO NW.

In order to study the photoresponse of the ZnO NW, series measurements on the response of the ZnO NW under different light irradiation are carried out by using LEDs (λ = 505 nm, 460 nm, 375 nm, no light) as excitation sources, as shown in Fig. 2. The device is fixed at a distance of about 2 cm away from the LEDs. When ZnO NW is exposed to visible light for 4 min (■: 460 nm, ★: 505 nm), no obvious change can be observed in the current. However, when ZnO NW is exposed to UV illumination for 4 min (⋆: 375 nm), the current increases obviously compared to the dark. The conductance of ZnO NW increases greatly from 2.6×10^{-7} S to 6.1×10^{-7} S.

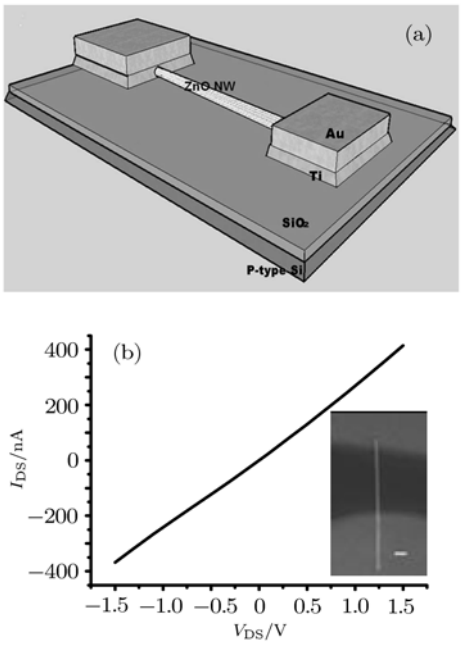


Fig. 1. (a) schematic diagram and (b) the typical characteristics of the I_{DS}–V_{DS} curve for ZnO NW device. Right inset: SEM image of an individual ZnO NW between Ti /Au electrodes. (scale bar: 2 μm).

To better estimate the relationship between the light irradiation and the photoresponse, the evolution of the photocurrent is studied, which is shown in Fig. 2 as inset. The nanowire exposed to different light irradiation and 'Off'/'On' state is switched. ZnO NW is exposed to the UV-light at 375 nm (▲ black line) corresponds to the conditions of light on and light off for 60 s. We find that the current increases when LED is switched on. When the LED is switched off, the current declines significantly. However, when the ZnO NW is exposed to visible light at 460 nm (black line) and switched on and off alternately, the change of the current is not obvious compared with the UV exposure. The results show that the photoconduction of ZnO NW is extremely sensitive to the UV illumination.

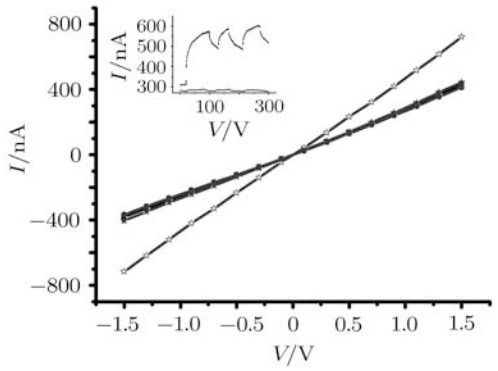


Fig. 2. ZnO NW exposed in different light irradiation (☆: 375 nm, •: in the dark, ■: 460 nm, ★: 505 nm). Top left inset: The relative current as a function of time as 375 nm UV light (▲ black line) or 460 nm visible light (black line) is switched on and off. in atmosphere at room temperature.

Figure 3 shows the typical photoresponse of ZnO NW to an LED ($\lambda = 375$ nm) being switched on and off alternately as a function of time. The power density of UV light is about 60 μW/cm^2. The instantaneous change of the conductance induced by the ultraviolet illumination can be observed at $V_{\rm DS} = 1.0$ V. Moreover, the amplitude of the fluctuation is dependent on the $V_{\rm DS}$.

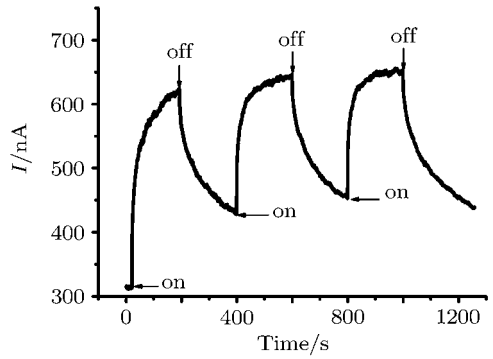


Fig. 3. The photoresponse of the nanowire in air for repetitive switching of the UV light at $V_{\rm DS} = 1.0$ V. The voltage is applied across the two electrodes.

The risetime $T_{\rm r}$ can be defined as the time needed for the current to rise from the dark current level to $(1 - {\rm e}^{-1})$ its maximum level ($I_{\rm max}$), and the decay time $T_{\rm d}$ as the time needed for the current to drop to $I_{\rm max}{\rm e}^{-1}$.[9] So the risetime $T_{\rm r} \sim 39$ s and decay time $T_{\rm d} > 260$ s can be estimated from Fig. 3.

The slow UV response and recovery of the Ohmic contact ZnO NW may be attributed to the oxygen adsorption and desorption process. In the dark, oxygen molecules absorb on the nanowire surface as negatively charged ions by capturing free electrons from the n-type ZnO NW,[11] [O_2+e$^-$ $\rightarrow O_2^-$], which will widen the depletion region and decrease the current. Upon UV illumination at photon energies larger than ZnO band gap, electron-hole pairs are generated, [hν $\rightarrow$e$^-$+h$^+$]. Photo-generated holes migrate to the surface and discharge the absorbed oxygen ions from the surface, [h$^+$+O_2^- $\rightarrow O_2$]. Meanwhile, the unpaired electrons accumulate gradually, so resulting in the increase of the current. However, when the desorption and readsorption of O_2 reach an equilibrium state, the current would be saturated slowly. When the UV light is turned off, the recombination of holes and electrons becomes quickly, leading to the current decreasing. This relatively slow time scale indicates that the decay process is limited by oxygen readsorption. On the other hand, the lower sensitivity may be related to the lower power of LED light source we use. The sensitivity of Ohmic contact ZnO NW also could be improved by using small sized NWs.[5]

4. Conclusion

In summary, we have used a low-cost micro-grid template method to study the optoelectronic properties of individual ZnO NW. The conductance of the ZnO NW is sensitive to UV exposure, while the current is almost unchanged when ZnO NW is exposed to visible light. The characteristics of the photoconductivity of ZnO NW suggest that ZnO NWs are good candidates for optoelectronic switches with the dark insulating state as 'OFF' and the UV-exposed conducting state as 'ON'. ZnO NWs could be useful for nanoscale optoelectronic applications.

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