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Characterization of ZnO nanowire field-effect transistors exposed to ultraviolet radiation*

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A ZnO nanowire (NW) field-effect transistor (FET) is fabricated and characterized, and its characterization of ultraviolet radiation is also investigated. On the one hand, when the radiation time is 5 min, the radiation intensity increases to 5.1 μW/cm^2, while the saturation drain current ($I_{\rm dss}$) of the nanowire FET decreases sharply from 560 to 320 nA. The field effect mobility (μ) of the ZnO nanowire FET drops from 50.17 to 23.82 cm^2/(V·s) at $V_{\rm DS} = 2.5$ V, and the channel resistivity of the FET increases by a factor of 2. On the other hand, when the radiation intensity is 2.5 μW/cm^2, the DC performance of the FET does not change significantly with irradiation time (its performances at irradiation times of 5 and 20 min are almost the same); in particular, the $I_{\rm dss}$ of NW FET only reduces by about 50 nA. Research is underway to reveal the intrinsic properties of suspended ZnO nanowires and to explore their device applications.

Keywords: ZnO nanowire, suspended, field-effect transistor, ultraviolet radiation

PACC: 7200, 7280E

1. Introduction

Recently, one-dimensional nanostructures such as nanowires and nanotubes have been intensively studied due to their physical and electrical properties suitable for fabricating both nanoscale devices and interconnections.[1] The ZnO nanowire is one of the most promising materials because of its multifunctional properties: direct wide band gap ($E_{\rm g}$ = 3.37 eV) and metal oxide semiconducting characteristics. A variety of devices have been studied with ZnO such as gas sensors, optical sensors, and field effect transistors (FETs).[2−8]

To apply ZnO nanostructures to photoelectric devices more widely, it is necessary to understand their transport properties and their characteristics under ultraviolet irradiation. The study of nanowires under irradiation will provide useful information for future aerospace applications.[9]

In 2006, it was reported in America for the first time[10] that the field effect mobility (μ) and on/off current ratio ($I_{\rm on}/I_{\rm off}$) had reached 928 cm^2/(V·s) and 10^6 respectively. At that time, however, research into this field in China was still in its infancy, and most focused on the growth of ZnO nanowires (NWs) and the fabrication of optical diodes: few reports concentrated on P-type NW FET,[11] and even fewer reports were concerned with the characteristics of ultraviolet radiation. The photoelectric advantages of ZnO NW FETs have been seriously restricted.

In the present work, we report on the growth of ZnO NWs and the fabrication of FETs with ZnO NWs configured as FETs, in which there is a back-gate and the nanowire is suspended between the sources and drain electrodes. We investigate the features of ZnO NW FETs exposed to ultraviolet at different radiation intensities (2.5 and 5.1 μW/cm^2 separately) and for different radiation times (5 and 20 min), and some interesting results are gained. The radiation intensity increases while the $I_{\rm dss}$ of nanowire FETs declines sharply, which may result from source/drain charge sharing.[12] However, when the intensity of radiation is 2.5 μW/cm^2, with increasing irradiation time, the DC performance of the devices does not change significantly; there is only 50 nA decline in $I_{\rm dss}$.

2. Device fabrication

The nanowires were prepared by the hydrothermal method on catalyser (Ag) coated silicon oxide substrate. As grown ZnO nanostructures typically

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show n-type conductivity due to intrinsic defects, p-type doping of ZnO nanostructures is difficult to achieve. Recently, p-type conduction was reported in ZnO nanowire arrays grown by using P_2O_5 as a dopant.[13] However, the p-type conduction was unstable and changed to n-type after 2 months of storage in air ambient. The instability is probably due to the larger atomic size of phosphorus than that of oxygen. Unlike the thin-film counterpart,[13,14] controlled doping in 1D ZnO nanomaterials remains a challenge to overcome. Nitrogen, with an atomic radius similar to that of oxygen (0.75 vs 0.73 Å), should be a better candidate than phosphorus as a p-type dopant in ZnO NWs.[15] Further, a gaseous dopant source should be better than a solid one in the sense of controllability and effectiveness.[16] Guided by these explanations, we achieve the production of p-type conduction nanowires by annealing in N_2 ambience for 2 min at 600 °C. The nanowires have typical lengths of 3.0–30.0 μm and radii of 150–450 nm, and are provided by the University of Sciences and Technology of China.

An SEM picture of nanowires is shown in Fig.1; the scale bar is 1 μm. As shown in Fig.2, device fabrication starts with a 4″ (1″ = 2.54 cm) oxidized p-type Si wafer. The gate oxide thickness is 400 nm. The wafer is then etched in HF until the back oxide is etched away, and an e-beam metal evaporator is used to deposit a 20/400 nm thick Ti/Au layer on the back of the wafer to form back-gate metal. The substrate containing the nanowire bundles is then sonicated in isopropyl alcohol (IPA) to release the individual nanowires. The chip is prepared by the ordinary lithographic techniques to form the source–drain. A bi-layer of titanium (30 nm) and gold (500 nm) is evaporated onto the Si in an array pattern of source–drain electrodes. The source–drain distance is 7 μm. The IPA solution is dropped onto a p^{++} type Si substrate

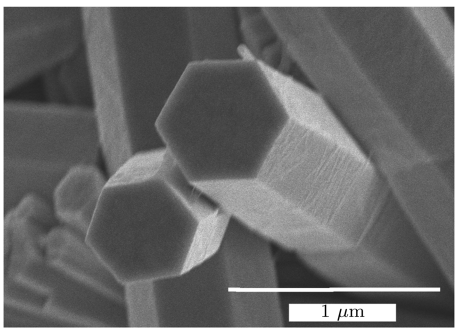


Fig.1. SEM image of ZnO nanowires.

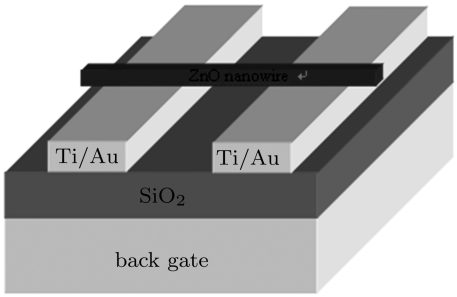


Fig.2. Schematic of suspended ZnO nanowire FET.

covered with SiO_2 (gate oxide). The nanowires are viewed under a high-powered optical microscope so that FET devices can be found. In the ultraviolet irradiation experiments, ultraviolet beams were generated by using a PAS5500 (at the Institute of Microelectronics, Chinese Academy of Sciences). Typical ultraviolet radiation conditions are intensity = 2.5 μW/cm^2, 5.1 μW/cm^2 and irradiation time = 5 min 20 min respectively.

3. Results and discussion

In order to characterize the electrical properties of ZnO NW FETs, we measure the current–voltage characteristics by using a semiconductor parameter analyser HP4155. Figure 3 shows representative data for the ZnO NW FETs. The inset displays an SEM image of the devices. Figures 3(a) and 3(b) show the curves for the source–drain current versus voltage (I_{DS}–V_{DS}) characteristics and source–drain current versus gate voltage (I_{DS}–V_{GS}) characteristics under two different ultraviolet radiation intensities (2.5 μW/cm^2 and 5.1 μW/cm^2); the irradiation time is 5 min. These results show typical p-type nanowire transistor behaviour without a saturation regime, and display rectifying behaviour[17] as shown in Fig.3(a). As proposed by Harnack *et al*,[18] the factor that produces this rectifying behaviour could be the alternating zinc and oxygen layers parallel to the basal plane; they produce a dipole moment that leads to a potential gradient and then introduce the asymmetry of current flowing along the *c* axis. This assumption is given based on the non-central symmetric and layered distribution of cations and anions in the wurtzite structure. The channel of the suspended ZnO nanorod FET is not fully depleted in the I_{ds}–V_{ds} curve (inset) of Fig.3. This is attributed to the high concentration of charge carriers within the ZnO nanowire channel.

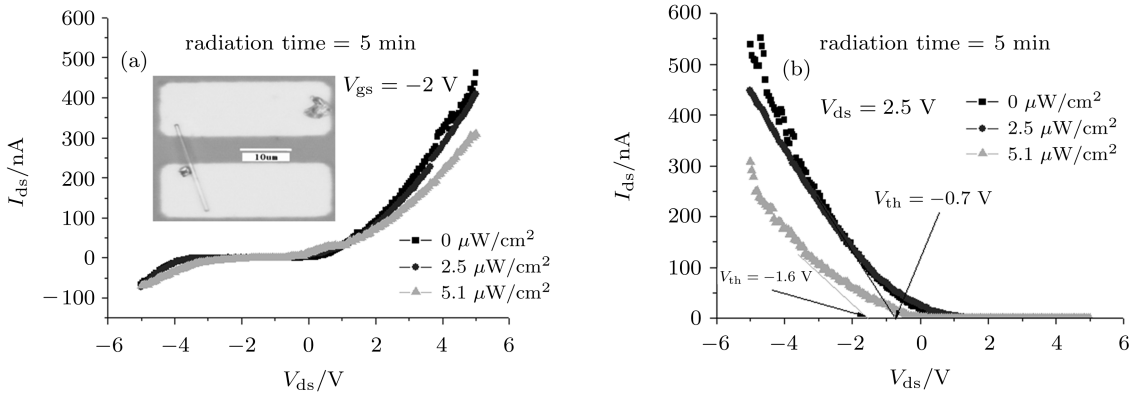


Fig.3. DC characteristics (a) and transfer characteristics (b) of ZnO nanowire FET at different ultraviolet irradiation intensities.

As shown in Fig.3, with the increase of radiation intensity, the I_{ds} of nanowire FETs declines sharply, and when radiation intensity = 5.1 μW/cm^2, I_{dss} declines by half (from 560 nA to 320 nA), at the same time the threshold voltage (V_{th}) of the ZnO NW-FETs increases (from –0.7 V to –1.6 V), which may result in the decline of the Schottky-barrier[19] under ultraviolet irradiation. The reduction of I_{ds} may result from source/drain charge sharing. The field effect mobility (μ) of the ZnO nanowire FET can be derived from the relationship $\mu_e = g_m L \ln(2h/r_{nw})/2\pi\varepsilon\varepsilon_0 V_{DS}$, where ε is the dielectric constant of SiO_2 (3.9), L the channel length of the nanowire FET (7 μm), h the thickness of SiO_2 (400 nm), and r_{nw} the radius of the nanowire (300 nm). When the irradiation intensity is 5.1 μW/cm^2, the values of extrinsic transconductance (g_m) of the device at 2.5 V drain–source voltage are 0.396 and 0.188 μS respectively. The resistivity of the ZnO nanowire channel can be derived from the following relationship: $\rho = V_{ds}\pi r_{nw}^2/I_{ds}L$. From these calculations, with intensity of radiation increasing to 5.1 μW/cm^2, the field effect mobility (μ) of the ZnO nanowire FET decreases from 50.17 to 23.824 cm^2/(V·s) at V_{DS} = 2.5 V. However, the resistivity of the NW FETs increases by a factor of 2 when the intensity increases from 0 to 5.1 μW/cm^2, showing a typical semiconductor I–V characteristic. When the intensity of radiation is 5.1 μW/cm^2 the carrier transportation is depressed greatly.

We also investigate the ultraviolet irradiation characteristics of the same devices for two different irradiation times: 5 and 20 min. Figure 4 shows the DC characterization of ZnO nanowire field-effect transistors exposed to ultraviolet irradiation for two different irradiation times: 5 and 20 min with an intensity of 2.5 μW/cm^2. As can be seen from Fig.4, with the increase of irradiation time, the DC performance of the devices does not change significantly; there is only a 50 nA decline in I_{dss}.

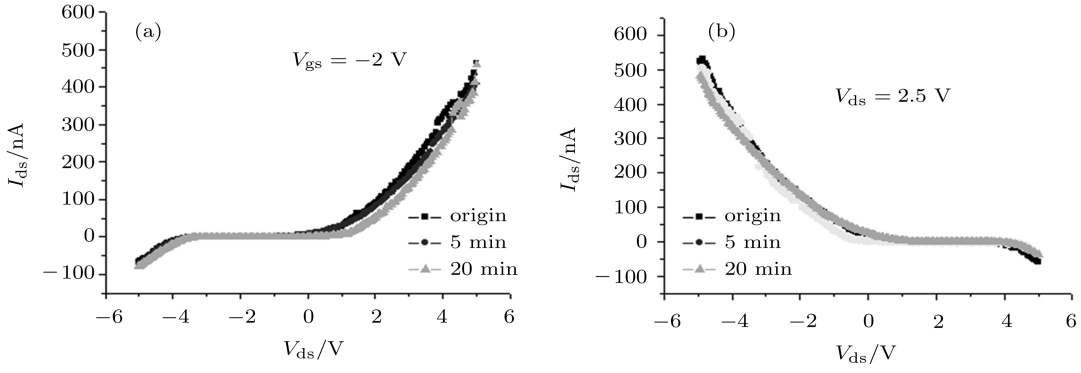


Fig.4. DC characteristics (a) and transfer characteristics (b) of a ZnO nanowire FET at two different irradiation times: 5 and 20 min.

4. Conclusion

An FET structure using a suspended ZnO nanowire is demonstrated. The fabricated suspended nanowire FETs show a p-channel depletion mode. Ultraviolet characteristics have been investigated and some interesting results have been gained. With irradiation intensity increasing to 5.1 μW/cm^2, the $I_{\rm dss}$ of nanowire FETs declines sharply, and the field effect mobility (μ) of the ZnO nanowire FET decreases from 50.17 cm^2/(V $\cdot$ s) to 23.824 cm^2/(V $\cdot$ s) at $V_{\rm DS} = 2.5$ V, along with the channel resistivity of the FETs increasing by a factor of 2. However, when the intensity of radiation is 2.5 μW/cm^2, with irradiation time increasing from 5 to 20 min, the DC performance of the devices does not change significantly: there is only a 50 nA decline in $I_{\rm dss}$. Work is underway to reveal the intrinsic properties of suspended ZnO nanowires and to explore their device applications.

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