Fabrication and photoelectrical characteristics of ZnO nanowire field-effect transistors*

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Abstract: The fabrication and photoelectrical characteristics of suspended ZnO nanowire (NW) field-effect transistors (FETs) are presented. Single-crystal ZnO NWs are synthesized by a hydrothermal method. The fabricated FETs exhibit excellent performance. When V_{ds} = 2.5 V, the peak transconductance of the FETs is 0.396 μS, the average electron mobility is 50.17 cm^2/(V·s), the resistivity is 0.96 × 10^2 Ω·cm at V_{gs} = 0 V, and the current on/off ratio (I_{on}/I_{off}) is approximately 10^5. ZnO NW-FET devices exposed to ultraviolet radiation (2.5 μW/cm^2) exhibit punch-through and threshold voltage (V_{th}) shift (from –0.6 V to +0.7 V) and a decrease by almost half of the source–drain current (I_{ds}, from 560 nA to 320 nA) due to drain-induced barrier lowering. Continued work is underway to reveal the intrinsic properties of suspended ZnO nanowires and to explore their device applications.

Key words: ZnO nanowire; back-gate; suspended; field-effect transistor; ultraviolet radiation

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1. Introduction

Recently, quasi one-dimensional nanostructures such as nanowires (NWs) and nanotubes have been intensively studied due to their physical and electrical properties, which are suitable for fabricating both nanoscale devices and interconnections[1]. The ZnO NW is one of the most promising materials because of its multifunctional properties: direct wide bandgap (E_g = 3.37 eV) and metal oxide semiconducting characteristics. A variety of device studies have been carried out with ZnO such as gas sensors, optical sensors, and field effect transistors (FETs)[2–8]. Research into this field in China is still in its infancy; most reports focus on the synthesis of nanowire with fewer on nanowire FET devices[9]. The advantage of nanometer devices has been seriously restricted.

In this study, we report the growth of ZnO NWs and the fabrication of devices with ZnO NWs configured as FETs. In particular, we investigate their photoelectrical characteristics by testing the effects of ultraviolet irradiation on ZnO NW-FET devices. Study of NWs under ultraviolet irradiation will provide useful information for future aerospace applications. We have obtained a ZnO NW FET which shows a typical p type because of annealing[10]. The fabricated suspended NW FETs exhibit excellent performance; high current on/off ratio (I_{on}/I_{off}) is approximately 10^5. When V_{ds} = 2.5 V, the peak transconductance of the suspended FETs is 0.396 μS, the electron mobility is on average 50.17 cm^2/(V·s), the resistivity of the ZnO NW channel is estimated to be 0.96 × 10^2 Ω·cm at V_{gs} = 0 V. ZnO NW-FET devices exposed to ultraviolet radiation (2.5 μW/cm^2) exhibit punch-through and threshold voltage shift, and a decrease of source–drain current (I_{ds}) of almost half due to drain-induced barrier lowering.

2. Device fabrication

The ZnO NWs were synthesized by hydrothermal technology on semi-insulating SiO_2 substrates, which were provided by the University of Sciences and Technology of China. Alternative low temperature techniques for the synthesis of nanowires of metal oxides usually involve a hydrothermal growth process inducing epitaxial, anisotropic crystal growth in a solution. The hydrothermal process is usually substrate independent, and offers fairly good control over the morphology of the obtained nanowires. Among the various synthetic techniques for obtaining ZnO NWs, the sol–gel based strategy involving hydrothermal growth of ZnO particles is probably the most energy efficient, by avoiding the complexities of vacuum environment and the need for high temperatures[11]. The SEM picture of NWs is shown in Fig. 1.

As shown in Fig. 2, device fabrication starts with a 4 inch oxidized p-type Si wafer. The wafer was then etched in HF until the back oxide was etched away using an e-beam metal evaporator, and then 20/400 nm thick Ti/Au was deposited on the back of the wafer to form back-gate metal. Then the oxide layer on the Si substrate was etched with a depth of about 400 nm. The chip was prepared by the usual lithographic

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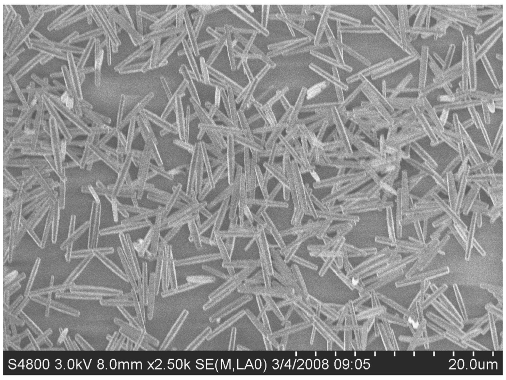

Fig. 1. SEM image of the ZnO NWs.

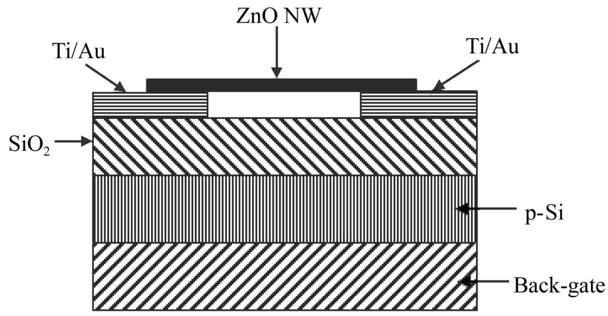

Fig. 2. Schematic of the suspended ZnO NW-FET.

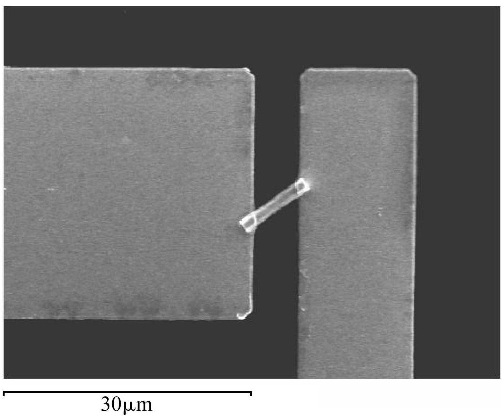

Fig. 3. Image of ZnO NW-FET.

techniques to form source–drain, and a bi-layer of titanium (30 nm) and gold (500 nm) was evaporated onto the Si substrate in an array pattern of source–drain electrodes. The distance between source–drain of 7 μm provides contacts for a NW-FET. The substrate containing the NW bundles was sonicated in isopropyl alcohol (IPA) to release the individual NW and form suspension. Then the IPA suspension was deposited onto a previously prepared array of metal contacts on a p-type Si substrate with back gate. Once the NWs were deposited on the chip, it was viewed under a high-powered optical microscope so that FET devices can be found. Figure 3 shows an optical image of a suspended NW-FET device.

For the ultraviolet irradiation experiments, ultraviolet beams were generated using a PAS5500 (at the Institute of Microelectronics, Chinese Academy of Sciences). Typical ultraviolet radiation conditions are energy = 2.5 μW/cm^2 and irradiation time = 20 min.

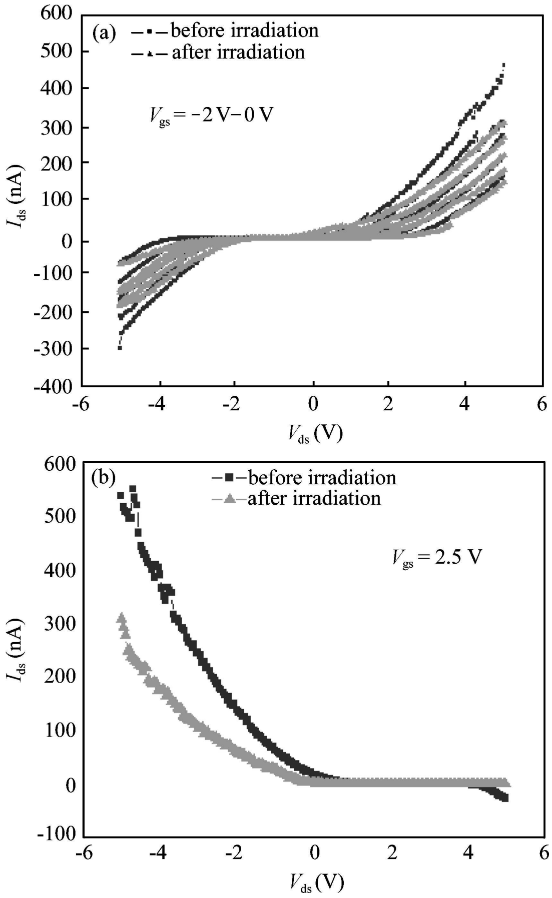

Fig. 4. (a) Output characteristics (I_{ds}–V_{ds}) and (b) transfer characteristics (I_{ds}–V_{gs}) of ZnO NW-FET before and after ultraviolet irradiation.

3. Results and discussion

In order to characterize the electrical properties of ZnO NW-FETs, we measure the current–voltage characteristics using a semiconductor parameter analyzer 4155C. Figures 4(a) and 4(b) show the representative data for the ZnO NW-FETs. Figure 4(a) is the source–drain current versus voltage (I_{ds}–V_{ds}) characteristics at different gate voltages and Figure 4(b) is the source–drain current versus gate voltage (I_{ds}–V_{gs}) characteristics at V_{ds} = 2.5 V. These results show typical p-type nanowire transistor behavior because of annealing.

The mobility of ZnO NW-FETs can be estimated using $\mu_e = g_m L \ln(2h/r_{nw})/2\pi\varepsilon\varepsilon_0 V_{DS}$, where ε is the dielectric constant of SiO_2 (3.9), L is the channel length of the nanowire FET (7 μm), h is the thickness of SiO_2 (400 nm), and r_{nw} is the radius of the nanowire (300 nm). From these calculations, the transconductance is estimated to be 0.396 μS, the mobility is 50.17 cm^2/(V·s) at V_{ds} = 2.5 V. The resistivity is calculated from $\rho = V_{ds}\pi r_{nw}^2/I_{ds}L$. From these calculations, the resistivity of the ZnO nanowire channel is estimated to be 0.96×10^2 Ω·cm at V_{gs} = 0 V.

In order to investigate the effects of ultraviolet irradiation (2.5 μW/cm^2, 20 min), we compare a ZnO NW-FET before ultraviolet irradiation with that after ultraviolet irradiation. Figure 4(a) shows the output characteristics (source–drain current versus voltages, I_{ds}–V_{ds}) of a ZnO NW-FET device at different gate voltages before and after ultraviolet irradiation. Figure 4(a) displays five drain–source current versus drain–source bias (I_{ds}–V_{ds}) curves obtained under different gate voltages (V_g) varying from −2 to 0 V. After irradiation, the ZnO NW-FET exhibited a punch-through phenomenon[12], as shown in Fig. 4(a). Punch-through occurs when depletion widths on the drain side of the body and source side of the body sum up to the physical length of the body. When V_{ds} increases, the channel length due to the depletion region decreases. When this region extends to an extreme case, there is no channel and electrons (or holes) punch through. So the reduction of current is suggested to occur due to punch-through.

Figure 4(b) shows the transfer characteristics (source–drain current versus gate voltages, I_{ds}–V_{gs}) at V_{ds} = 2.5 V before and after ultraviolet irradiation. The threshold voltage (V_{th}) of the ZnO NW-FET is changed from a negative value (–0.6 V) to a positive value (0.7 V) after irradiation. There are several possible origins of the short channel effects such as punch-through and the shift of threshold voltage. The reduction of I_{ds} by half (from 560 to 320 nA) results from the combination of three effects: (1) source/drain charge sharing, (2) drain-induced barrier lowering, and (3) punch-through. However, further studies are needed to clearly understand the short channel effects of ZnO NW-FET after ultraviolet irradiation.

4. Conclusion

NWs are used as a back-gate FET with a suspended ZnO NW channel. Single crystal ZnO NWs are synthesized by a hydrothermal method. The fabricated suspended NW-FETs show a p-channel depletion mode and exhibit a high on–off current ratio of approximately 10^5. When V_{ds} = 2.5 V, the peak transconductance of the suspended FETs is 0.396 μS, the electron mobility is on average 50.17 $cm^2/(V\cdot s)$. The resistivity of the ZnO nanowire channel is estimated to be $0.96 \times 10^2\ \Omega\cdot cm$ at V_{gs} = 0 V. ZnO NW-FET devices exposed to ultraviolet radiation (2.5 $\mu W/cm^2$) exhibit punch-through and threshold voltage shift (from –0.6 to +0.7 V) and a decrease of source–drain current (I_{ds}) of almost half due to drain-induced barrier lowering. Continued work is underway to reveal the intrinsic properties of suspended ZnO NWs and to explore their device applications.

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