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Metal-oxide Semiconductor Field-effect Transistors using Single ZnO Nanowire

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ABSTRACT

Single ZnO nanowire metal-oxide semiconductor field effect transistors (MOSFETs) were fabricated using nanowires grown by site selective Molecular Beam Epitaxy. When measured in the dark at 25°C,the depletion-mode transistors exhibit good saturation behavior, a threshold voltage of ~-3V and a maximum transconductance of order 0.3 mS/mm .Under ultra-violet (366nm) illumination, the drain-source current increase by approximately a factor of 5 and the maximum transconductance is ~ 5 mS/mm. The channel mobility is estimated to be ~3 cm^2/V.s, which is comparable to that reported for thin film ZnO enhancement mode MOSFETs and the on/off ratio was ~25 in the dark and ~125 under UV illumination.

INTRODUCTION

There is great current interest in fabrication of ZnO channel thin film transistors for applications in transparent flat panel displays[(1-10)]. Other transparent conducting oxides such as Sn-doped In_2O_3 , Al-doped ZnO, and Sb-doped SnO_2 have been widely applied as transparent electrodes for liquid crystal displays , organic light-emitting diodes , and solar cells [(11)]. ZnO nanowires and nanorods are attracting attention for use in gas, humidity and ultra-violet(UV) detectors [(12-14)]. ZnO is attractive for a broad range of applications in thin film form [(15-20)], but the ability to make arrays of nanorods with large surface area which has been demonstrated with a number of different growth methods has great potential for new types of transparent electronics that operate with low power requirements [(21)]. Appreciable channel mobilities (25 cm^2/V.s) have been obtained in thin film ZnO transistors [(1)], indicating that even when grown on non-lattice-matched substrates the electrical performance can be impressive. We have previously reported enhancement-mode thin-film metal-oxide semiconductor field-effect transistors (MOSFETs) using phosphorus-doped (Zn,Mg)O channels. The transistors exhibited an on/off ratio of 10^3 and a channel mobility on the order of 5 cm^2/V s, with HfO_2 employed as the gate dielectric. There have been initial reports of electrical transport through individual ZnO nanowires. The initial reports show a pronounced sensitivity of the nanowire conductivity to ultraviolet illumination and the presence of oxygen in the measurement ambient [(22-24)].

In this paper we report on the dc performance of single ZnO nanowire MOSFETs using (Ce,Tb)$MgAl_{11}O_{19}$ gate oxides , measured both in the dark and under UV illumination .We have also fabricated nanowire Schottky diodes,UV detectors and pH sensors ,but will not space kin this paper to discuss those results. Under illumination, both the channel conductivity and maximum transconductance are greatly increased .The devices show excellent pinch-off characteristics in both cases with low gate leakage currents.

The preparation of the nanowires has been described in detail previously[25,26]. Discontinuous thin films (~20 Å) of e-beam evaporated Au were deposited on Al_2O_3. ZnO nanowires were deposited by MBE with a base pressure of $5x10^{-8}$ mbarr using high purity (99.9999%)Zn metal and an O_3/O_2 plasma discharge as the source chemicals. The Zn pressure was varied between $4x10^{-6}$ and $2x10^{-7}$ mbar, while the beam pressure of the O_3/O_2 mixture was varied between 5×10^{-6} and $5x10^{-4}$ mbarr The growth time was ~2 h at 600 °C. The typical length of the resultant nanowires was ~ 14 μm, with typical diameters in the range of 30 – 150 nm. Selected area diffraction patterns showed the nanowires to be single-crystal. They were released from the substrate and then transferred to SiO_2-coated Si substrates. E-beam lithography was used to pattern sputtered Al/Pt/Au electrodes contacting both ends of a single nanowire. The separation of the electrodes was ~7 μm. Au wires were bonded to the contact pad for current –voltage (I-V) measurements. $(Ce,Tb)MgAl_{11}O_{19}$ with thickness 50nm was selected as the gate dielectric as it exhibits a large band gap sufficient to yield a positive band offset with respect to ZnO. The top gate electrode was e-beam deposited Al/Pt/Au. Figure 1 shows a schematic of the ZnO nanowire MOSFET. A scanning electron micrograph of the completed device is shown in Figure 2. Note that less that 50% of the nanowire channel is covered by the gate metal. Current–voltage (*I–V*) characteristics were performed at room temperature using an Agilent 4155A Semiconductor Parameter Analyzer.

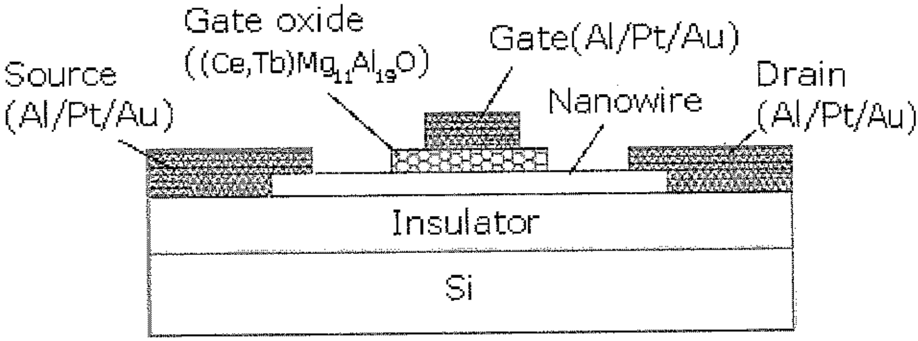


Figure 1 . Schematic of ZnO nanowire depletion-mode FET.

Figure 3 shows the drain current–drain voltage (I_D–V_{DS}) characteristics (top) and the transfer characteristics (bottom) measured at room temperature in the dark. The modulation of the channel conductance indicates that the operation of the device is an n-channel depletion mode. The gate leakage current is low and the nanowire MOSFETs exhibit excellent saturation and pinch-off characteristics, indicating that the entire channel region under the gate metal can be depleted of electrons. The threshold voltage is ~3V with a maximum transconductance of ~ 3 mS/mm.The on/off current ratio at V_G of 0-2.5V and V_D of 10V was of order 25.The field-effect mobility μ_{FE} can be determined from the transconductance using the relation $I_{DS}=(W/L)\ \mu_{FE}C_{OX}(V_{GS}-V_T)V_{DS}$ where W is the channel width, L is the channel, C_{OX} the gate oxide capacitance and V_T is the threshold voltage. The extracted mobility was ~ 0.3 $cm^2/V.s$, which is comparable to that reported previously for thin film ZnO enhancement mode MOSFETs [3].The carrier concentration in the channel is estimated to be ~10^{16} cm^{-3}.

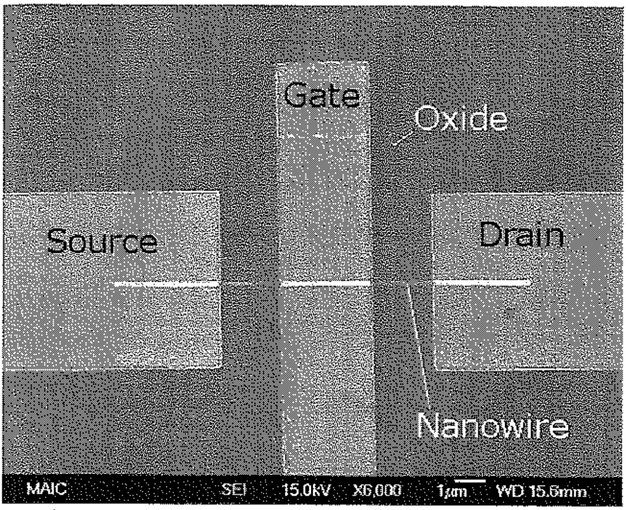


Figure 2. SEM micrograph of fabricated FET.

The nanowire showed strong photoresponse to UV illumination. Figure 4 shows the shows the drain current–drain voltage (I_D–V_{DS}) characteristics (top) and the transfer characteristics (bottom) measured at room temperature under 366nm illumination. The drain-source currents increase by approximately a factor of 5 and the maximum transconductance increases to 5 mS/mm . Part of the increase in drain-source current reflects photoconductivity in the portion of the wire uncovered by the gate metal.The on-off current ratio at V_G of 0-3V and V_D of 10V increases to ~ 125.In this case the extracted mobility was still ~3 $cm^2/V.s$, but the carrier density in the channel was ~$5x10^{16}$ cm^{-3}.The photoresponse was rapid, being limited by the switching characteristics of the UV lamp, which may suggest the photocurrent is bulk-related[15] and there is not a strong contribution from surface states that produce long recovery times.

In conclusion, ZnO nanowire depletion mode MOSFETs show excellent pinch-off and saturation characteristics and a strong UV photoresponse. These devices look promising for transparent transistor applications requiring low leakage current and indicate that the nanowires can be grown and transferred to another substrate without major degradation of their electrical transport properties.

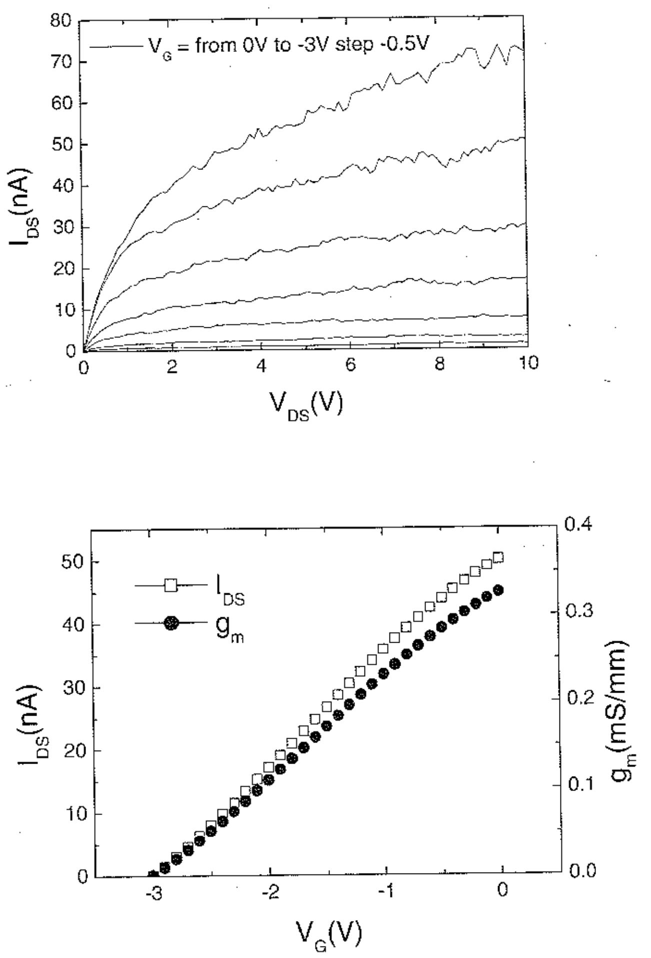
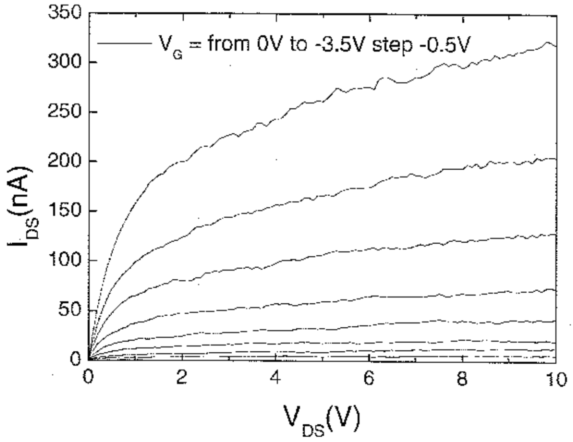


Figure 3. I_{DS}-V_{DS} (top) and transfer characteristics (bottom) of ZnO nanowire FET at room temperature in the dark.



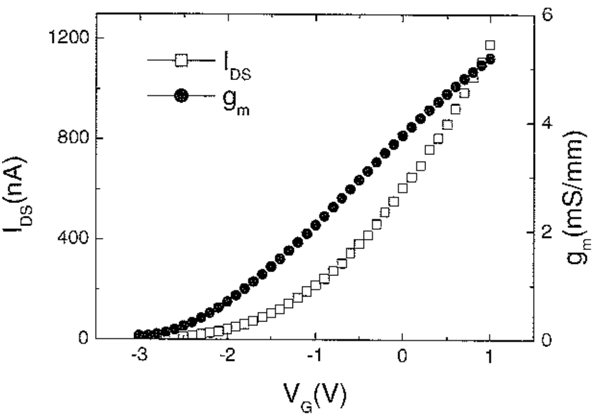


Figure 4. I_{DS}-V_{DS} (top) and transfer characteristics (bottom) of ZnO nanowire FET at room temperature measured with illumination from UV(366nm) light.

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