Transient drain current characteristics of ZnO nanowire field effect transistors

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We investigated the characteristics of the time-dependent drain current of ZnO nanowire field effect transistors (FETs). The drain current of ZnO nanowire FETs in ambient air decreases from an initial current level in the microampere range and saturates to the 1–100 nA range in tens of seconds. This transient phenomenon is ascribed to electrically interactive adsorption of oxygen ions to the nanowire surface. Exposure to ambient air during positive gate biasing reduces the conduction channel width by extending the depletion region, resulting in a higher resistivity with conduction only through the narrower nanowire core. © *2009 American Institute of Physics*.
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Semiconductor nanowires have been extensively studied due to their potential device applications.[1–4] In particular, ZnO nanowires have been widely applied as building blocks for nanoscale field effect transistors (FETs), optoelectronic devices, and energy harvesting devices due to their wide bandgap (3.37 eV), large exciton binding energy (60 meV), and piezoelectricity.[1,2] Reliable and precise control of nanowire material properties is required for further advancement toward practical applications.[5] The development of ZnO nanowire electronic device applications is hindered by the lack of control over and the poor reliability of the electrical conductivity.[6–12] When ZnO nanowires are exposed to an oxygen environment, adsorbed oxygen molecules on nanowire surface bind with electrons and become oxygen ions, which reduces the number of conduction electrons in the nanowire channel.[6,7] The carrier density in ZnO nanowires is particularly unreliable in oxygen environments due to the high surface-to-volume ratio of nanowires.[6,7] Reliable ZnO nanowire FETs are still a major technical challenge. A number of reports on the irreproducibility of and deviation in measurements of electrical conductivity demonstrate the difficulty associated with assuring highly stable ZnO nanowire FETs.[6–10]

The oxygen effect is the main cause of the instability of ZnO nanowires. The current passing through ZnO nanowires decreases with time due to the adsorption of oxygen on the nanowire surface. Thus, it would be particularly helpful to gain an understanding of the stability characteristics of ZnO nanowires by studying their time-dependent transient transport properties.

In this study, we investigated the transport characteristics corresponding to the width of the changed surface depletion region by analyzing the time-dependent drain currents of ZnO nanowire FETs. The drain current decreases with prolonged positive gate biasing time, due to the increase of the surface depletion region caused by increased adsorption of negative oxygen ions on the nanowire surface. Specifically, we characterized and compared the time-dependent transient effects of ZnO nanowire FETs at various gate and drain voltages to understand the influence of the surface depletion width on carrier density. This study will be useful to predict the reliability of ZnO nanowire FETs.

The ZnO nanowires in this study were grown on sapphire wafers coated with a gold thin film as the metal catalyst, using the vapor-liquid-solid mechanism. The details of the nanowire growth have been reported elsewhere.[6,7] Figure 1(a) is the high resolution transmission electron microscopy (HRTEM) image of an individual ZnO nanowire. The average atomic spacing along the growth direction is ~0.52 nm, corresponding to a lattice spacing of the (0001) planes of wurtzite ZnO.[13] The field emission scanning electron microscopy (FESEM) image [inset of Fig. 1(a)] indicates that the ZnO nanowire has a hexagonal shape with a side surface $(10\bar{1}0)$ and top a surface (0001). The grown ZnO nanowires were dispersed in isopropyl alcohol by sonication, and then dropped on a silicon wafer to fabricate ZnO nanowire FETs. A 100 nm thick thermally grown oxide layer was used as a gate insulator on a heavily doped *p*-type silicon substrate. Metal electrodes consisting of Ti/Au (30/40 nm) were deposited on the ZnO nanowires by an electron beam evaporator and patterned as source and drain electrodes via a photolithography processes. The electronic properties of ZnO nanowire FETs were measured using a semiconductor parameter analyzer (Agilent B-1500) at room temperature.

Figure 1(b) shows the typical drain current versus drain voltage (I_{ds}-V_{ds}) curves for a ZnO nanowire FET measured in ambient air at different gate voltages from −5 to 20 V

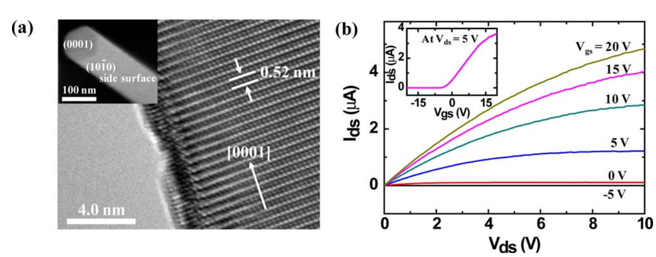

FIG. 1. (Color online) (a) HRTEM image of an individual ZnO nanowire. Inset is the FESEM image of the ZnO nanowire with hexagonal shape. (b) Typical I_{ds}-V_{ds} curves at different gate biases from −5 to 20 V, with 5 V steps. Inset is I_{ds}-V_{gs} curve measured at V_{ds}=5 V.

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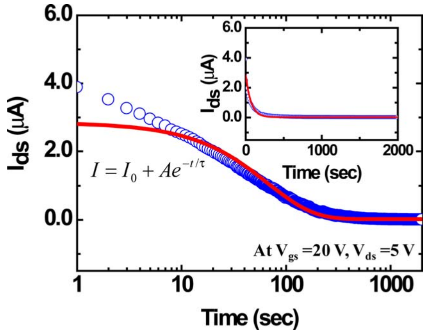

FIG. 2. (Color online) Experimental (circles) and exponential fitting curve (solid line) of drain current decay measured at $V_{gs}=20$ V and $V_{ds}=5$ V in ambient air.

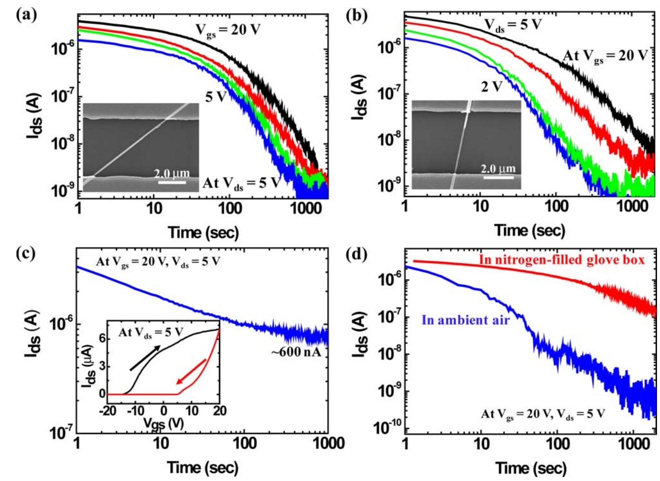

FIG. 3. (Color online) Drain current decay characteristics of different ZnO nanowire FET devices obtained (a) at $V_{gs}=20$, 15, 10, and 5 V with a fixed $V_{ds}=5$ V, (b) at $V_{ds}=5$, 4, 3, and 2 V with a fixed $V_{gs}=20$ V, (c) with a saturated current ~100 nA at $V_{ds}=5$ V with a fixed $V_{gs}=20$ V, and (d) under a nitrogen-filled glove box and ambient air at $V_{ds}=5$ V with a fixed $V_{gs}=20$ V. Insets in [(a) and (b)] are FESEM images of the measured devices. Inset in (c) is I_{ds}-V_{gs} curves from the forward and reverse sweep sequence.

with a step of 5 V. The inset of Fig. 1(b) shows the drain current versus gate voltage (I_{ds}-V_{gs}) curves for a fixed drain voltage of 5 V. Generally, as-grown ZnO nanowires exhibit n-type behavior due to defects incorporated during the growth process.[14]

The electronic properties of ZnO nanowire FETs were measured as a function of time at fixed gate and drain voltages in ambient air. Figure 2 shows the transient drain current curve measured at a fixed V_{ds} of 5 V and a fixed V_{gs} of 20 V. Here, $V_{gs}=20$ V was chosen arbitrarily because the negative oxygen ions are more strongly bound with higher positive gate bias in the ZnO nanowire FET of on-current state. The same transient drain current curve on a linear time scale is shown in the inset of Fig. 2. In this curve, the initial drain current (~4.0 μA) decays exponentially in time and saturates to ~1 nA after ~70 s. This saturated drain current is smaller than the initial current by three orders of magnitude.

An exponential decay of current has been observed elsewhere. Bera *et al.*[11] and Ahn *et al.*[15] have reported a similar exponential decrease in the photocurrent of ZnO nanowires under ultraviolet (UV) illumination. We have similarly fitted the experimental data of the transient drain current with the following exponential equation:

$$I = I_0 + Ae^{-t/\tau}, \tag{1}$$

where τ is the decay time constant.[11] The drain current reduction is mainly due to oxygen trapping at surface states between the nanowire and ambient air. Within a short period (1–10 s), the fitted curve deviates from measured data. This indicates the drain current decays quickly over a short period of time.

To further investigate the transient characteristics of the drain current, the decay phenomena of the transient drain current curves were investigated at various gate and drain voltages. Figure 3(a) shows the transient drain current curves measured at different gate bias (5, 10, 15, and 20 V) at a fixed drain voltage of 5 V in ambient conditions (same device of Fig. 2). Figure 3(b) shows the transient drain current curves measured at different drain biases (2, 3, 4, and 5 V) at a fixed gate voltage of 20 V in another device. Desorption and adsorption of oxygen strongly depend on measurement procedure such as gate bias sweep rate and sweep direction.[6,8] To maintain the equivalent measurement conditions, the transient drain current measurements in this study were performed after holding a fixed negative gate bias of −20 V and a positive drain bias of 5 V for ~180 sec. As shown in the FESEM (insets in Fig. 3), the diameter of the ZnO nanowires used in this study was ~90 and ~110 nm and the distance between source and drain was ~6 and ~4 μm for the data of Figs. 3(a) and 3(b), respectively. The decay time constants from a series of transient drain current curves of Fig. 3(a) were observed as 41.8, 37.7, 45.0, and 67.7 s for different gate biases (5, 10, 15, and 20 V, respectively). The decay time constants from Fig. 3(b) were observed as 10.4, 10.2, 22.0, and 46.0 s for different drain bias (2, 3, 4, and 5 V), respectively.

Figure 3(c) is the drain current decay curve measured from another ZnO nanowire FET device. It showed a current decay with the saturation current level of ~600 nA, while other devices showed the saturation current level of ~1 nA [Figs. 2, 3(a), and 3(b)]. This difference in the saturation current levels is due to the variation of the threshold voltage for the different nanowire FET devices and the shift of the threshold voltage during the electrical measurement in oxygen environment. For example, the change of sweep directions from the forward to reverse sequence induces a large threshold voltage shift from −15 to 5 V, as shown in inset of Fig. 3(c). It is expected that the interface states between the gate dielectric and the nanowire can be responsible for hysteresis, together with oxygen desorption and adsorption, as shown in inset of Fig. 3(c). These interface states can induce a deviation from the exponential decay fitting during initial periods (the first ~10 s in Fig. 2). In order to clarify the influence of oxygen, drain current decay curves of a ZnO nanowire FET were measured under ambient air and in a nitrogen-filled glove box (oxygen level is ~30 ppm), as shown in Fig. 3(d). The drain current of the ZnO nanowire FET device in the nitrogen environment more slowly decreased than the case in ambient air. In the nitrogen environment, the nanowire FET has fewer oxygen ions on the surface, thus less surface depletion of electrons, resulting in the slower decay.[6]

Now, we explain on the mechanism of the observed transient drain current characteristics. The reduction of the drain current indicates the change of conductivity in the conduction channel. This occurs because more negative oxygen ions

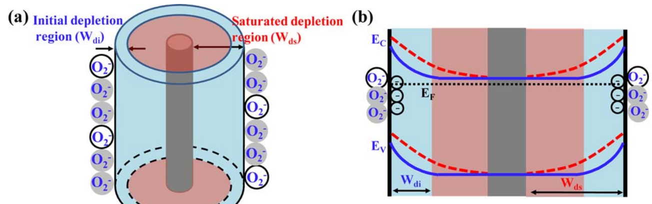

FIG. 4. (Color online) (a) Schematic diagram and (b) energy band diagram explaining the initial depletion region (W_{di}) and saturated depletion region (W_{ds}) of ZnO nanowire FET due to oxygen trapping at a prolonged positive gate bias. E_C, E_F, and E_V are the conduction band, the Fermi energy level, and the valence band, respectively.

can be adsorbed by the electrical interaction when a more positive gate bias is applied for prolonged times (i.e., a slow gate bias sweeping).[6] The width of the surface depletion region in ZnO nanowires can be changed by measurement conditions, since the high surface-to-volume ratio makes the electrical properties of ZnO nanowires very sensitive to the external environment. The gradual change from a more conducting state to a less conducting state in transient drain current curves of ZnO nanowires results from the increased surface depletion region through the steadily increase of oxygen ion-binding to the ZnO nanowire surface. Holding a positive gate bias induces more adsorption of oxygen due to the electrical interaction of the positive gate bias and the negative oxygen ions on the surface. The low steady-state drain current occurs when the nanowire surface is fully saturated with adsorbed oxygen ions and the surface depletion region of the nanowire is not changing with time.

The oxygen molecules on surface defect sites such as oxygen vacancies and zinc interstitials bind with electrons and become oxygen ions in the form of O_2^-, resulting in the reduction of the conductivity in the nanowire channel by reduction of conduction electrons ($O_{2(g)}+e^- \rightarrow O^-_{2(ad)}$).[6,16,17] Therefore, the exposure of the nanowire surface to ambient air decreases channel conductivity during gate biasing and leads to a remarkable reduction of drain current, yielding a much lower conducting state.

Figure 4 graphically explains the transient drain current behavior mechanism. Figure 4(a) is a schematic explaining the gradually changing conductivity from the more conducting state to the less conducting state. The ZnO nanowire already has a depletion region due to adsorbed oxygen ions (indicated by open circles) from the ambient air environment. When more oxygen ions (indicated by gray circles) are adsorbed on the nanowire surface, the depletion region extends and the drain current decreases, as shown in Fig. 4(a). Oxygen ions would not be easily desorbed, since the adsorbed oxygen ions are strongly attracted by the positive gate bias. Thus, long gate biasing times markedly reduce the concentration of conducting electrons in the nanowire, extend the surface depletion region from the initial depletion region (W_{di}) to the saturated depletion region (W_{ds}), and the nanowire-conduction channel eventually becomes the very narrow nanowire core under conditions of prolonged positive gate bias.

When a positive gate bias is applied to ZnO nanowire FETs for a prolonged time, increased oxygen trapping at the surface leads to the surfaces having different charges, which results in an increase in the depletion region width.[18,19] As shown in Fig. 4(b), the potential barrier at the surface rises (solid line to dashed line) due to more oxygen trapping. The extended and saturated depletion region (W_{ds}) resulting from the increased potential barrier influences the electronic transport properties of the ZnO nanowire FETs, and particularly reduces the conductivity of nanowire FETs.

In conclusion, we studied the characteristics of the transient drain current of ZnO nanowire transistors in ambient air. The drain current of ZnO nanowire FETs decreased by 1–3 orders of magnitude from an initial current value to a saturated current value in tens of seconds. This transient effect is due to the increase of the surface depletion region in ZnO nanowires by a higher oxygen absorption concentration over prolonged gate biasing. The transient behavior will be helpful in understanding the stability of ZnO nanowire electronic devices.

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