Effect of gate bias sweep rate on the electronic properties of ZnO nanowire field-effect transistors under different environments

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We report the effects of gate bias sweep rate on the electronic characteristics of ZnO nanowire field-effect transistors (FETs) under different environments. As the device was swept at slower gate bias sweep rates, the current decreased and threshold voltage shifted to a positive gate bias direction. These phenomena are attributed to increased adsorption of oxygen on the nanowire surface by the longer gate biasing time. Adsorbed oxygens capture electrons and cause a surface depletion in the nanowire channel. Different electrical trends were observed for ZnO nanowire FETs under different oxygen environments of ambient air, N_2, and passivation. © *2008 American Institute of Physics*.
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ZnO nanostructures, such as nanowires, nanobelts, and nanowalls, have attracted great interest due to their unique properties, including a wide direct bandgap (~3.4 eV), large exciton binding energy (~60 meV), and piezoelectricity.[1–4] ZnO nanomaterials have been widely applied as building blocks for nanoscale transistors, sensors, and optoelectronic and piezoelectric devices.[1–8] In particular, the large surface area to volume ratio of ZnO nanowires has a strong influence on electrical transport by adsorption and desorption of ambient active elements onto and from the ZnO surface.[9] Adsorbed molecules such as oxygen are easily bound at the oxygen vacancy site of the ZnO surface. Adsorbed oxygens that bind the electrons localized at the nanowire surface become oxygen ions in the forms of O^-, O^{2-}, or $O_2{}^-$, resulting in a surface depletion in the nanowire channel.[10] Therefore, a change in the oxygen environment is expected to significantly influence the electrical characteristics of ZnO nanowire field-effect transistors (FETs).[7,8] In particular, the oxygen adsorption and the corresponding transistor characteristics of nanowire FET devices are sensitively dependent on the measurement environment to which the devices are exposed, and whether or not the devices are passivated.[11–13] Other characterization conditions can also influence electrically interactive absorption of oxygen ions on the nanowire surface. Recently, Dayeh *et al.* reported that the transfer characteristics of InAs top-gated nanowire FETs were strongly dependent on the gate bias sweep rate due to its influence on donor-type trap levels of the surface.[14,15]

In this study, we investigated the effect of gate bias sweep rate on the electronic transport properties of ZnO bottom-gated nanowire FETs. The adsorption of oxygen on the ZnO nanowire surface is dependent on the gate bias sweep rate, influencing its transport properties. In particular, we characterized and compared the effects of the gate bias sweep rate for ZnO nanowire FETs under different oxygen environments; the nanowire FETs were characterized in ambient air, in a N_2-filled glovebox, and in ambient air after the nanowire FETs were passivated.

The ZnO nanowires in this study were grown on the *c*-plane sapphire coated with a gold thin film as the catalyst, using a carbothermal reduction process. The details of nanowire growth have been reported elsewhere.[16] Figure 1(a) is the field emission scanning electron microscopy (FESEM) image of the grown ZnO nanowires. The ZnO nanowires were then dispersed in isoprophyl alcohol by sonication, and dropped on a silicon wafer to fabricate ZnO nanowire FETs, as shown schematically in Fig. 1(b). 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 (30/70 nm) were deposited on the ZnO nanowires by an electron beam evaporator and patterned as source and drain electrodes by photolithography and lift-off processes. The source and drain electrodes are typically separated by 3–4 μm. A ZnO nanowire FET device is shown in the FESEM image in Fig. 1(c). The electronic properties of ZnO nanowire FETs were measured as a function of gate bias sweep rate using semiconductor parameter

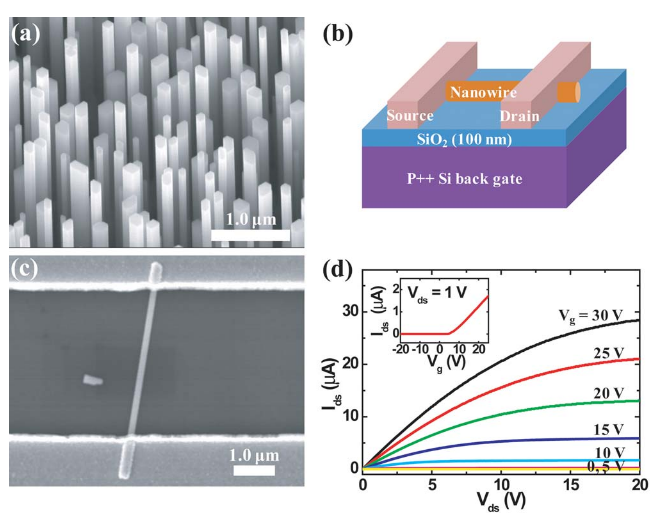

FIG. 1. (Color online) (a) FESEM image of grown ZnO nanowires. (b) Schematic of a ZnO nanowire FET. (c) FESEM image of a ZnO nanowire across metal electrodes. (d) Typical I_{ds}-V_{ds} curves for different gate biases from 0 to 30 V with 5 V step. The inset is I_{ds}-V_g curve measured at V_{ds}=1 V.

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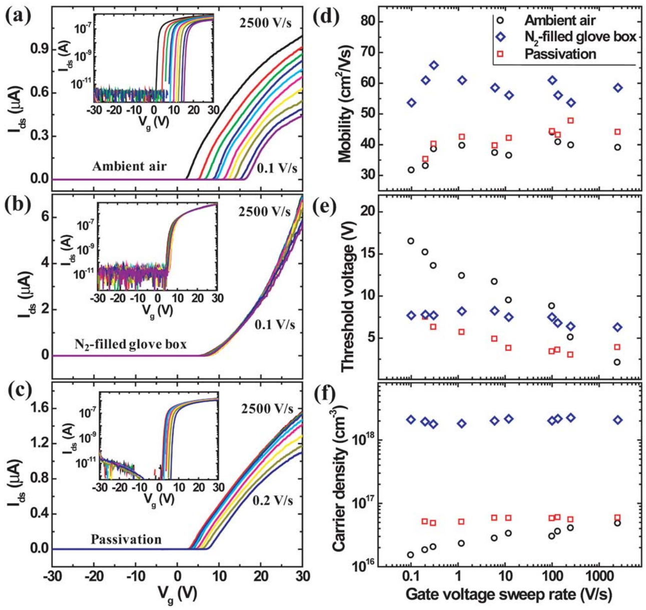

FIG. 2. (Color online) Series of I_{ds}-V_g curves for a ZnO nanowire FET as a function of gate bias sweep rate (2500, 250, 130, 100, 12, 6, 1.2, 0.3, 0.2, and 0.1 V/s) measured at $V_{ds}=0.5$ V (a) under ambient air, (b) N_2-filled glovebox, and (c) ambient air after PMMA passivation. The semilogarithmic plots of I_{ds}-V_g curves are shown in the insets. (d) Field-effect mobility, (e) threshold voltage, and (f) carrier density as a function of gate bias sweep rate for the three different environmental conditions.

analyzers (HP 4155C or Keithley 4200) at room temperature. Figure 1(d) shows representative data of the drain-source current versus drain voltage (I_{ds}-V_{ds}) curves for a ZnO nanowire FET (unpassivated) measured in ambient air at different gate voltages from 0 to 30 V with a step of 5 V. The inset of Fig. 1(d) shows the drain-source current versus gate voltage (I_{ds}-V_g) for a fixed drain voltage (V_{ds}) of 1.0 V.

The electronic properties of ZnO nanowire FETs were measured as a function of gate bias sweep rate in different measurement environments. Figures 2(a)–2(c) show a series of I_{ds}-V_g curves measured at different gate bias sweep rates (2500, 250, 130, 100, 12, 6, 1.2, 0.3, 0.2, and 0.1 V/s) at a fixed drain voltage (V_{ds}) of 0.5 V under various environments. A ZnO nanowire FET device was systematically measured in ambient air, in a N_2-filled glovebox, and in ambient air after the same device was passivated with a polymethyl methacrylate (PMMA) layer. The I_{ds}-V_g plots on a semilogarithmic scale are shown in the insets of Figs. 2(a)–2(c).

Figure 2(a) shows the case of a ZnO nanowire FET (unpassivated) measured in ambient air. As the gate bias sweep rate was decreased from 2500 to 0.1 V/s, the current decreased and the threshold voltage shifted to the positive gate bias direction. These phenomena can be explained by the depletion of electrons by oxygen adsorption on the surface of the ZnO nanowire. As previously mentioned, the increase in oxygen concentration causes the change in conductivity by surface depletion in the nanowire channel,[8] i.e., the adsorbed oxygens that bind the electrons localized at the nanowire surface become oxygen ions in the forms of O^-, O^{2-}, or $O_2{}^-$, resulting in depletion of electrons and thus lowering the conductivity.[7–10] It is expected that more oxygen ions will be adsorbed by the electrical gate coupling when the ZnO nanowire FET is applied with a positive gate bias with a longer gate biasing time. Oxygen adsorption is sustained at an equilibrium condition in ambient air at zero gate bias. However, the gate bias induces more adsorption of oxygen ions due to the applied positive gate bias. Therefore, when the nanowire FET is applied with a slower gate bias rate, more electrons on the ZnO nanowire surface are trapped by the adsorbed oxygen ions, which results in a reduction in nanowire conduction channel region by the more depleted region. Thus, the current decreases and the threshold voltage shifts to the positive gate bias direction.

The effect of the gate bias sweep rate on the ZnO nanowire FET was investigated under different oxygen environments. We placed the same ZnO nanowire FET device that was measured in ambient air [Fig. 2(a)] into a N_2-filled glovebox where the oxygen level was kept at less than 30 ppm after holding at a vacuum (1×10^{-5} Torr) for 24 h. The I_{ds}-V_g curves measured in this N_2 environment are shown in Fig. 2(b). The conductivity of the ZnO nanowire FET device in the N_2 environment increased by about one order of magnitude, compared to the case of ambient air [for example, current $\sim$0.5 μA in Fig. 2(a) versus $\sim$2.5 μA in Fig. 2(b) at $V_g=20$ V and gate bias sweep rate of 20 V/s]. In the N_2 environment, the nanowire FET has fewer oxygen ions on the surface, thus less surface depletion of electrons, resulting in an increase in the current. Unlike the case of the nanowire measured in ambient air, the nanowire device (unpassivated) in the N_2 environment was not influenced by the gate bias sweep rate, as shown in Fig. 2(b). The current did not change and the threshold voltage did not shift. This is because of the relative absence of oxygen in the N_2-filled glovebox; therefore, there is a negligible effect of oxygen absorption even at different gate bias sweep rates.

In addition, we explored the effect of the gate bias sweep rate on the same ZnO nanowire FET device after the device was passivated by a PMMA layer. The resulting I_{ds}-V_g curves after the passivation, measured in ambient air, are shown in Fig. 2(c). The I_{ds}-V_g curves exhibited somewhat similar trends of the current change and threshold voltage shift for different gate bias sweep rates as the case of Fig. 2(a), although the change and shift are not as significant. Oxygen contained in the PMMA could influence this effect, or the PMMA passivation might not completely protect the nanowire against the oxygen exposure. Note that we could not get I_{ds}-V_g curve for the gate bias sweep rate of 0.1 V/s because of a device failure by repeated measurements.

Note that the measurement sequence of sweep rate also influences the transport characteristics of ZnO nanowire FETs. The measurement sequence for the data in Figs. 2(a)–2(c) was from fast sweep rate to slow sweep rate. If we reverse the measurement sequence, i.e., change from slow to fast sweep rate, we did not observe the similar phenomena of threshold voltage shift. Particularly, the threshold voltage shift was negligible when we changed from slow to fast sweep rates (data not shown here). This is because many oxygens are absorbed at the very first sweep with the slowest sweep rate. Then, the next measurement with a little fast sweep rate is affected by many oxygens already absorbed on the nanowire surface during the previous measurement.

In Figs. 2(d)–2(f), we summarized the field-effect mobility, threshold voltages, and carrier densities as a function of the gate bias sweep rate for the three environmental conditions. The field-effect mobility (μ) of the ZnO nanowire FET is calculated by[17]

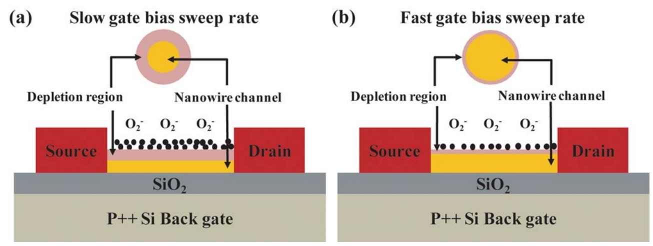

FIG. 3. (Color online) Schematics illustrating the effect of gate bias sweep rate. A larger depletion region is formed with slower gate bias sweep rates (a) than the case for faster gate bias sweep rate (b).

$$\mu = \frac{dI_{ds}}{dV_g}\frac{L^2}{V_{ds}C}, \quad (1)$$

where C is the gate capacitance given by Eq. (2) for a model of a cylinder on an infinite metal plate,[13]

$$C = \frac{2\pi\varepsilon_0\varepsilon L}{\cosh^{-1}(1+t/r)}, \quad (2)$$

where r is the nanowire radius ($\sim$50 nm), L is the nanowire channel length ($\sim$3 μm), t is the SiO_2 thickness (100 nm), ε_0 is the permittivity of free space, and ε is the dielectric constant of SiO_2. From Eqs. (1) and (2), we calculate μ of $38 \pm 3\ cm^2/V\,s$ (ambient air), $58 \pm 3\ cm^2/V\,s$ (N_2-filled glovebox), and $42 \pm 3\ cm^2/V\,s$ (passivation), as shown in Fig. 2(d), indicating that the field-effect mobility of the ZnO nanowire was improved when less oxygen is adsorbed on the ZnO nanowire. This observation is consistent with previous reports that field-effect mobility of the ZnO nanowire decreased with increasing oxygen partial pressure.[7]

As already explained for the data in Fig. 2(a), the threshold voltages shifted to the positive gate bias direction for the cases of ambient air for slower gate bias sweep rates, whereas the threshold voltage did not quite change for the case of the N_2 environment in Fig. 2(e). As mentioned earlier, this is due to the relative absence of oxygen in the N_2-filled glovebox. The nanowire channel was not influenced without the surface depletion by oxygen absorption.

Carrier density (n) was calculated from the equation $n = \sigma/q\mu$, where σ is conductivity estimated at $V_g = 20$ V.[17,18] Here, $V_g = 20$ V was chosen because the ZnO nanowire is on-current state for all the cases at this voltage [Figs. 2(a)–2(c)]. The conductivity σ of the ZnO nanowire is extracted from the Ohmic region of I_{ds}-V_{ds} curve using $\sigma = L/A \times dI_{ds}/dV_{ds}$ (at $V_{ds} = 0.5$ V), where A is the nanowire cross-sectional area.[17,18] The carrier density as a function of gate bias sweep rate is shown in a log-log plot in Fig. 2(f). Due to suppression of the oxygen absorption on the nanowire surface by passivation and the N_2-filled glovebox, the change in carrier density was slightly reduced or negligible for slower gate bias sweep rates. On the contrary, the carrier density under ambient air was considerably decreased by more oxygen adsorption as the gate bias sweep rate became slower.

Figure 3 explains the effect of gate bias sweep rate on the nanowire channel. Takata *et al.* reported that the stable oxygen ions are O_2^- below 100 °C, O^- between 100 and 300 °C, and O^{2-} above 300 °C.[19,20] The oxygen influence of the ZnO nanowire FETs would be mainly attributed to adsorption of O_2^- ions due to measurements conducted at room temperature. Slower gate bias sweep rates imply longer gate biasing time. Captured oxygen ions are strongly bonded by positive gate bias, so that oxygen ions would not be easily detached. Thus, slow gate bias sweep rates will cause more oxygen absorption than fast gate bias sweep rates. More adsorbed oxygens extend the surface depletion region. As a result, a larger depletion region in the nanowire occurs by slower gate bias sweep rates and longer gate biasing time, as schematically illustrated in Fig. 3(a). On the contrary, faster gate bias sweep rates are applied in relatively shorter gate biasing time. Therefore, fast gate bias sweep rates lead to less oxygen absorption [Fig. 3(b)].

In conclusion, we studied the electronic transport properties of ZnO nanowire transistors as a function of gate bias sweep rate under various oxygen environments, including ambient air, an N_2-filled glove box, and passivation. The current, threshold voltage, and carrier density were sensitively dependent on the gate bias sweep rate. Slower gate bias sweep rates result in larger depletion regions in the nanowire channel with more oxygen adsorption for longer gate biasing time, resulting in reduction in current and carrier density and shift of gate bias in the positive gate bias direction. These phenomena became more pronounced under environments with increased oxygen. The results of our study may offer how to characterize the surface effects of ZnO nanowire devices or other materials.

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