Electrical properties of ZnO nanowire field effect transistors characterized with scanning probes

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Single ZnO nanowires are configured as field effect transistors and their electrical properties are characterized using scanning probe microscopy (SPM). Scanning surface potential microscopy is used to map the electric potential distribution on the nanowire. Potential drop along the nanowire and at the contacts are resolved, and contact resistances are estimated. Furthermore, conductive SPM tip is used as a local gate to manipulate the electrical property. The local change of electron density induced by a negatively biased tip significantly affects the current transport through the nanowire. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1851621]

A quasi-one-dimensional (Q1D) system such as nanotubes and nanowires (NWs) has remarkable properties and potential as the building blocks for nanoscale electronic devices. They are often configured in field effect transistor (FET) structure[1–3] with a back gate for current transport studies. However, this method is insufficient to explore the local electronic property of Q1D FET devices. As known, the scanning probe microscope (SPM) has high spatial resolution, and can be used to probe the local electronic properties of materials.[4–9] Therefore, the combination of the SPM technique and the current transport study could assist in characterizing the Q1D nanodevices microscopically. Q1D ZnO nanostructures have been extensively studied for their unique optical,[10] mechanical,[11] and magnetic properties.[12] In this work, individual *n*-type ZnO NW is configured as FET, and scanning surface potential microscopy (SSPM) is performed. Potential drop at Schottky barrier contact is analyzed and contact resistances are estimated. In addition, conductive SPM tip is used as a movable local gate and a comparison between tip gating effect and back gating effect is made. It is found that local gating can modify the effective Schottky barrier heights when applied at the contact region. When applied in the middle of the nanowire, a negative tip bias results in a local potential barrier which obstructs the electron transport, whereas a positive tip gating does not affect the conductance significantly. Finally, a scanning tip gating effect is demonstrated in which the conductance of the nanowire is modulated periodically by the negatively biased scanning tip.

Single crystalline ZnO NWs were synthesized by chemical vapor deposition method.[13] Fabrication of nanowire FETs and their *n*-type behavior had been reported elsewhere.[14] SSPM of a ZnO NW FET is obtained using a SPM (DI Nanoscope IIIa) with a Ti–Pt coated tip operating in the tapping mode. SSPM is based on the principle in which the electrostatic force between the biased SPM tip and the sample can be represented as[6]

$$F = \frac{dC}{dz} V_{ac}(V_{tip} - V_{sample}), \quad (1)$$

where F is the electrostatic force, dC/dz is the derivative of the tip-sample capacitance with respect to their separation, V_{ac} is the magnitude of the ac signal applied to the tip to drive its vibration near the resonant frequency, $V_{tip} - V_{sample}$ gives the dc potential difference between the tip and sample. Thus, when the tip and sample have the same electrostatic potential, the interaction force between the tip and sample diminishes. Figures 1(a) and 1(b) show, respectively, the topographic image and surface potential image of a ZnO NW FET under a 1.5 V drain-source bias which illustrates the potential contrast between the drain and source electrodes. Figure 1(c) depicts the section profile of the potential image along the NW channel which shows the electrostatic potential distribution from the drain to the source. To analyze the potential distribution along the nanowire and at the contacts, A, B, C and D four points are selected. The potential drop is observed to vary linearly along the nanowire channel, between B and C. The larger potential drop observed between C and D ($V_{CD} = 0.89$ V) as compared to between A and B ($V_{AB} = 0.26$ V), implies a larger contact resistance at the source. From the electrical transport data shown in Fig. 1(d), at 1.5 V drain-source bias, the current is measured to be 46 pA. Thus, the drain and source contact resistances can be approximated to be $R_{drain} = 5.7$ GΩ, and $R_{source} = 19.3$ GΩ. For the devices with Ni electrodes, it is expected from the work functions of Ni (5.2 eV) and ZnO (4.3 eV) that Schottky barrier forms between the Ni electrode and the *n*-type ZnO NW. The large difference between the contact resistances is attributed to the asymmetric Schottky barriers [Fig. 1(e)] formed at the source and the drain due to the different interface properties.[15] This contributes to the asymmetric *I-V* characteristics, which are dominated by the channel pinch-off effect at large forward bias.[14]

Electrical transport results from a ZnO NW FET using Si back gate and SPM tip gate are compared to elucidate how tip gating modulates the electron density in the nanowire. Figure 2(a) shows typical *I-V* curves of a *n*-type ZnO NW under different back gate voltages ranging from −20 to 20 V. Conductance of nanowire monotonically increases with increasing back gate voltage which can be simply explained

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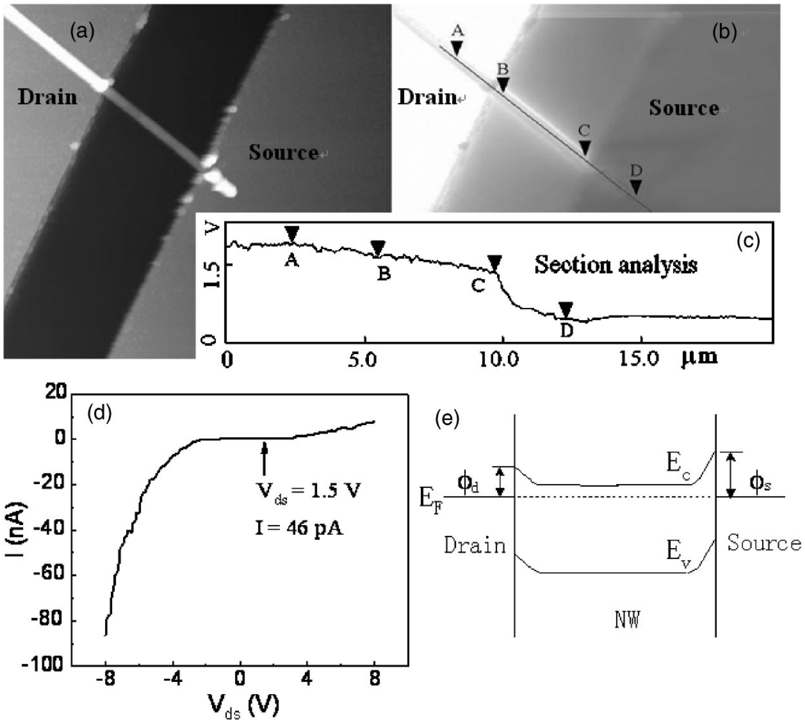

FIG. 1. (a) Topography image and (b) surface potential image of a ZnO nanowire FET with Ni electrodes. (c) Section analysis of the potential profile along the nanowire channel. (d) *I-V* characteristic from electrical transport measurement. (e) Energy band diagram illustrates the asymmetric Schottky barriers at the source and the drain contacts.

using energy band bending caused by back gating.[1] As shown in the inset of Fig. 2(a), the positive back gate potential increases electron concentration and bends the conduction band towards the Fermi level, thus resulting in higher conductance; likewise, a negative back gate depletes the electron concentration, bends the conduction band away from the Fermi level, yielding lower conductance. In contrast, when a gate voltage is locally applied to the middle of the ZnO NW using a sharp conductive SPM tip [circuit diagram is shown in Fig. 2(b) inset], the *I-V* characteristics demonstrate significant differences. As shown in Fig. 2(b), the conductance of nanowire does not increase considerably for positive tip gate voltage (V_{tg}). On the other hand, for negative tip gate voltages at −10 and −20 V, the conductance decreases with the presence of a clear reverse turn-on voltage (V_{on}). At $V_{tg}=-10$ and −20 V, V_{on} can be extracted to be −2.1 and −4.2 V from the *I-V* curves, respectively, as compared to $V_{on}=-1.0$ at $V_{tg}=0$ V. This can be explained from the perspective of local energy band bending. Since the conductive SPM tip has a diameter ~30 nm at the tip end, its electrostatic potential has a localized effect on the electronic structure of ZnO NW. It is known that band structure modulation by local electrostatic potential could significantly alter the transport property of Q1D system.[7,8,16] When a positive V_{tg} is applied, as shown in Fig. 2(c), the conduction band (E_c) bends downward in the center due to local electron accumulation, thus causing little change in the conductance.

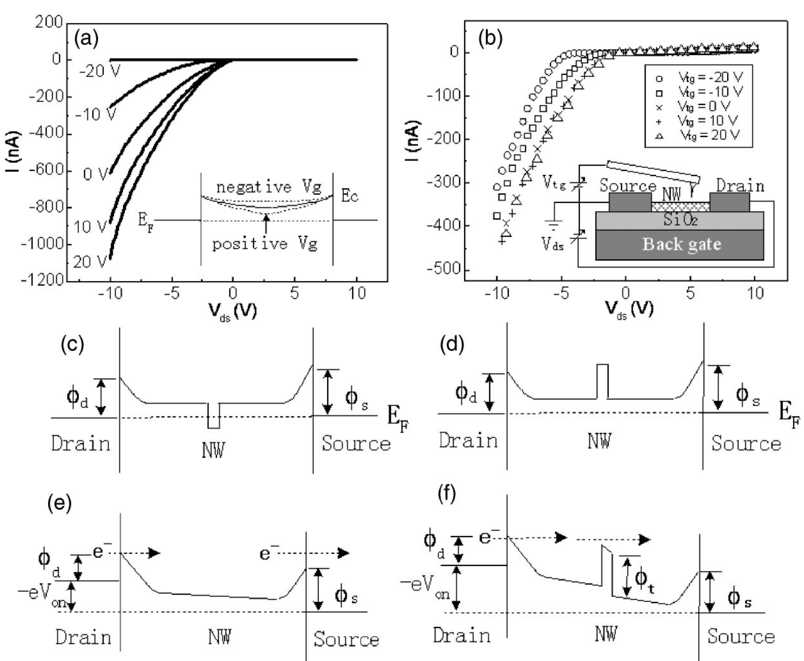

FIG. 2. (a) *I-V* curves under different back gate voltages of −20, −10, 0, 10, and 20 V. Inset: A diagram illustrating band bending caused by back gating; (b) *I-V* curves under different tip gate voltages. Inset: schematic showing the circuit measurement setup. (c) Local energy band bending caused by positive SPM tip gate voltage, and (d) negative tip gate voltage. (e) At negative drain-source bias, energy diagram for zero bias SPM tip gating and (f) negatively biased tip gating.

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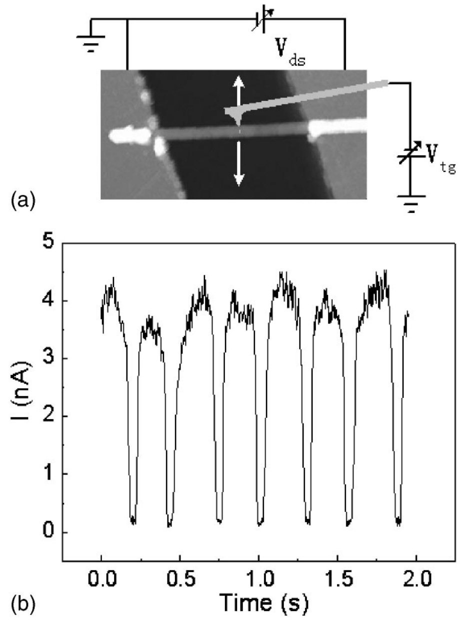

FIG. 3. (a) A schematic of scanning tip gating, a negatively biased conductive tip is scanned across the nanowire; (b) time domain measurement of scanning tip gating. Nanowire conductance is modulated periodically.

On the other hand, a sharp potential barrier is induced when a negative V_{tg} depletes the local electron concentration, as illustrated in Fig. 2(d). In this case, the nature of conduction through the nanowire changes due to the local barrier. Furthermore, it was observed that tip gating at the contact regions also affects the current transport (data not shown). The effect on the conductance change is stronger when the tip is gated near the higher-barrier contact.

To better understand the local gating effect in the transport measurements, energy diagrams are delineated with negative drain-source bias, for $V_{tg}=0$ V [Fig. 2(e)] and $V_{tg}<0$ V [Fig. 2(f)], respectively. For the sample with higher Schottky barrier height at the source than at the drain contact, a turn-on voltage arises in order for the electrons to transport from the drain to the source, as depicted in Fig. 2(e). As shown in the transport measurement [Fig. 2(b)], a turn-on voltage $V_{on}=-1.0$ V is measured at $V_{tg}=0$ V. Upon the application of a local negative tip gate voltage, a potential barrier (ϕ_t) is induced in the conduction channel. As a result, only those electrons with energy large enough to overcome the tip induced barrier ϕ_t and subsequently ϕ_s can transport across the nanowire channel, as illustrated in Fig. 2(f). Thus, in the case of $\phi_t > \phi_d$, $V_{on} > -1.0$ V is expected. Since ϕ_t increases with the applied tip gate voltage, the reverse turn-on voltage is observed to increase in magnitude with the tip gating strength.

The study of scanning tip gating on the ZnO nanowire FET is carried out to demonstrate the conductance modulation. As shown in Fig. 3(a), the ZnO NW is first located by SPM operating in tapping mode. Then the Ti–Pt coated tip is biased at −7.7 V and performing line scan perpendicular to the nanowire at a speed of 20 μm/s. At the same time, a 3 V drain-source voltage is applied and the current through the nanowire is detected by an external circuit. Figure 3(b) demonstrates the time domain measurement of the drain-source current. As the negatively gated tip scans over the nanowire, the conductance decreases; and when the tip moves away from the nanowire, the conductance recovers exponentially. Therefore, the nanowire conductance is periodically switched "on" and "off." Such scanning tip gating effect indicates the potential application in the nano electromechanical system.

In summary, conductive SPM tips have been used as nanoprobes to study *n*-type ZnO nanowire FET. Scanning surface potential microscopy is utilized to analyze the contact resistances between the electrodes and nanowire. The transport property under local tip gating is compared with that of back gating. Scanning probe gating is performed to tune the electrical conduction through the nanowire channel.

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