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One-dimensional transport of In_2O_3 nanowires

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The gate-dependent one-dimensional transport of single-crystal In_2O_3 nanowire field effect transistors is studied at low temperature by measuring current (I-V) and differential conductance (dI_{ds}/dV_{ds}). At a smaller positive gate bias, gaps at near-zero source-drain bias were observed for both current and differential conductance spectra due to the absence of the density of states in the source-drain energy window for a small V_{ds}. The transport can be explained using conventional low-temperature field effect transistor theory. On the other hand, at a large gate bias when the Fermi energy of the nanowire moves up into its conduction band, the differential conductance of the semiconducting In_2O_3 nanowire exhibits zero-bias anomalies, following a power-law behavior. *© 2005 American Institute of Physics*. [DOI: 10.1063/1.1928323]

Zero-bias anomalies (ZBAs) have been observed in different kinds of carbon nanotubes at low temperature.[1–4] It is generally believed that the ZBAs in the metallic single-walled carbon nanotubes (SWNTs) exhibit the Luttinger liquid behavior, because of nearly one-dimensional (1D) ballistic transport channels.[1,3,5] However, the origin of ZBAs of multiwall carbon nanotubes remains unclear and controversial as to whether they behave like Luttinger liquid.[6–8] Likewise, various types of self-assembled nanowires for electronic and optoelectronic applications have recently been grown,[9] but their transport behavior is also not well understood.[10] Thus, it is important and timely to clarify the transport properties of 1D wires. In this letter, we study the transport characteristic of high-quality In_2O_3 nanowires using field effect transistors (FETs). With the three-terminal device structure, we can control the carrier density and thus electron-electron correlation behavior. The results show the temperature dependent transport characteristic of single-crystalline semiconducting In_2O_3 nanowire FETs as a function of gate bias. Our studies shed light on the understanding of gate-control 1D transport of semiconductor nanowires.

Single-crystal semiconducting In_2O_3 nanowires with a diameter of 10 nm and a length of 2 μm were synthesized by a laser ablation process as described in a Ref. 11. A back gate was formed using a highly-doped silicon substrate with a gate oxide thickness of 0.5 μm. Ti/Au was used for the source and drain contacts to complete the FETs. Current (I-V) and source-drain differential conductance (dI_{ds}/dV_{ds}) were measured through a preamplifier, and the dI_{ds}/dV_{ds} signals were obtained by a lock-in amplifier with an ac sinusoidal voltage modulation of 1 kHz. All of the data were collected by a computer, which read the outputs of multimeters through a set of general purpose interface bus cards.

At the temperature of 4.2 K, current and the differential conductance of the nanowires were measured at different gate biases (V_g) shown in Fig. 1. Nearly symmetric spectra for positive and negative source-drain biases (V_{ds}) are the result of the small applied V_{ds} biases and the symmetric structures of the nanowire FETs. There are voltage gaps near $V_{ds} \approx 0$ V in both I-V and differential conductance spectra when $V_g < 7$ V [more clearly shown in Fig. 1(b)]. The voltage gaps become larger at lower gate biases. Similar phenomena were observed in various 1D nanowires and carbon nanotubes.[12] In order to explain our results, the energy band diagrams of the In_2O_3 FET is shown in Fig. 1(c) under low and high gate biases and with a small V_{ds}. Schottky contacts are formed between the In_2O_3 nanowire and Ti/Au electrodes. Both the transport inside the wire and transport through the two contacts need to be considered. At a small V_g bias, the source and drain quasi-Fermi potentials are pinned to within the bandgap of the In_2O_3 nanowire, and thus there is no density of states in the nanowire; conductance and current vanish. When a larger positive V_g is applied, the nanowire energy band moves down until the Fermi energy enters into the conduction band shown in the lower diagram, i.e., the nanowire becomes degenerate and the V_{ds} gaps of the

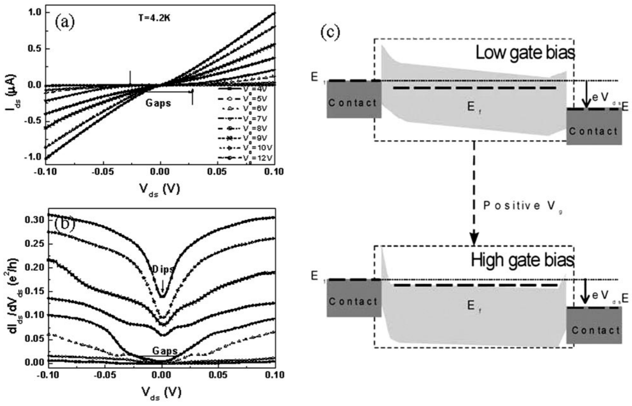

FIG. 1. (a) I-V characteristics of In_2O_3 nanowires with different V_g at 4.2 K. The strong gate dependence indicates that the In_2O_3 nanowire is semiconducting. Gaps are observed near $V_{ds}=0$ when $V_g<7$ V. (b) Source-drain differential conductance (dI_{ds}/dV_{ds}) as a function of V_{ds} at different V_g at 4.2 K. Gaps in differential conductance spectra for low V_g are clearly observed. And there are dips near zero source-drain bias when the V_g is larger than 10 V. (c) The energy band diagrams for the In_2O_3 nanowire FET under a low gate bias and a high gate bias with a small V_{ds} bias.

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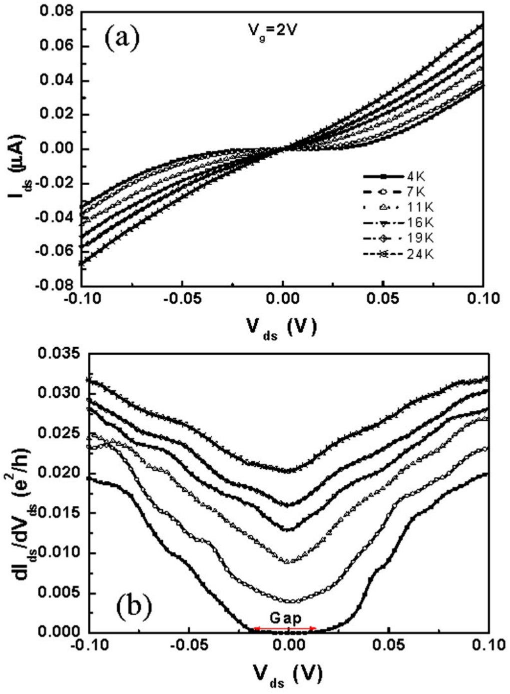

FIG. 2. (a) Temperature dependence of *I-V* characteristics at $V_g=2$ V. (b) Corresponding temperature dependence of source-drain differential conductance.

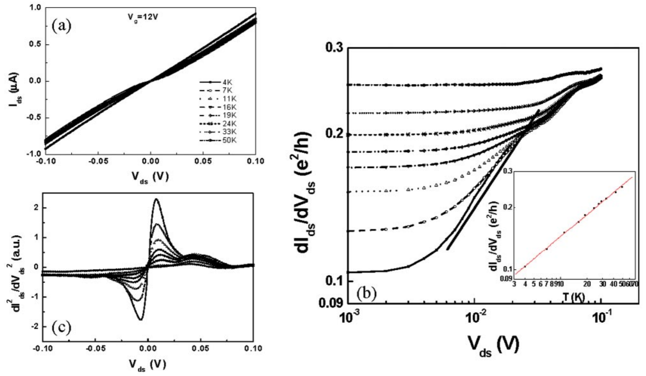

FIG. 3. (a) Temperature dependence of *I-V* characteristics at $V_g=12$ V. (b) Temperature dependence of source-drain differential conductance in a double-logarithmic scale. A power law is observed with an α of 0.33. The inset shows the temperature conductance relation in a double-logarithmic scale with α of 0.33. (c) Temperature dependence of the second derivative of the current ($d^2I_{\mathrm{ds}}/dV_{\mathrm{ds}}^2$). The peaks at $V_{\mathrm{ds}}=6$ mV have a strong temperature dependence.

conductance and current disappear.[13] Furthermore, for a large V_{ds} bias but a small V_g bias, the quasi-Fermi energy of the source contact can go up to the conduction band of the nanowire and the other go down underneath the conduction band so that electrons are injected through the source barrier into the nanowire conduction band, and the differential conductance increases. Our measurement reflects global transport characteristics of the In_2O_3 nanowire FET, in contrast to the case in which scanning tunneling spectroscopy was used for measuring local properties. The Schottky contacts of Ti/Au on In_2O_3 nanowires[14,15] and defect fluctuations on the nanowire surface and/or at the In_2O_3/SiO_2 interface as well as inside SiO_2 may contribute to some detailed fine features of the conductance spectra. To further support our explanation, temperature dependent transport characteristics were measured at a small gate bias of $V_g=2$ V shown in Fig. 2. The gap near $V_{\mathrm{ds}}=0$ decreases with increasing temperature, and the zero-conductance gap vanishes at higher temperatures. The current has a strong temperature dependence, i.e, the current doubled when the temperature increases from 4 K to 24 K for a V_{ds} range of 0.1 V. These are due to the broadening of the Fermi–Dirac function of the two contacts and the nanowire at higher temperature. Here, the transport phenomena at a small V_g bias can be explained well by using conventional low-temperature FET theory.

On the other hand, there are conductance dips (ZBAs) at $V_{\mathrm{ds}}=0$ when $V_g > 10$ V as shown in Fig. 1(b). Temperature dependent transport characteristic was also carried out at a large gate bias ($V_g=12$ V). Figure 3(b) gives differential conductance at different temperatures in a double-logarithmic plot. The inset shows differential conductance ($dI_{\mathrm{ds}}/dV_{\mathrm{ds}}$) versus temperature at zero source-drain bias in a double-logarithmic scale. Linear relations are seen for both $dI_{\mathrm{ds}}/dV_{\mathrm{ds}}$ versus V_{ds} and $dI_{\mathrm{ds}}/dV_{\mathrm{ds}}$ versus T. Similar power laws of ZBAs have been studied extensively in carbon nanotubes, as mentioned in the introduction. It is shown that a Luttinger liquid, being different from a Fermi liquid, has power-law dependences on physical quantities, such as temperature, voltage, and frequency:[16]

$$dI_{\mathrm{ds}}/dV_{\mathrm{ds}} \propto T^{\alpha}, \text{ at small } V_{\mathrm{ds}} \text{ biases } (eV_{\mathrm{ds}} \ll k_BT);$$

$$dI_{\mathrm{ds}}/dV_{\mathrm{ds}} \propto V_{\mathrm{ds}}^{\alpha}, \text{ at large } V_{\mathrm{ds}} \text{ biases } (eV_{\mathrm{ds}} \gg k_BT).$$

After fitting these power laws of both temperature and source-drain voltage dependences, an α of 0.33 was obtained. This α is close to that of the SWNT and MWNT.[1,7] But, the In_2O_3 nanowires here are semiconductors with its bulk band-gap energy of 3.4 eV. The reason for observing the power-lawlike behavior may be that, as discussed previously, the *n*-type In_2O_3 nanowire becomes degenerate for large V_g biases.[17] As a result, the Luttinger liquid like behavior, similar to that of metallic carbon nanotubes, is observed. It is also observed that α has a gate-voltage dependence. This dependence indicates that the ZBA depends on the density of carriers in the nanowire. In 1D Luttinger liquid theory, the strength of electron-electron correlations in the 1D depends on the carrier density and electron-electron separation distance.[16] Because differentiation techniques are known to be sensitive to a change of slope in a curve,[18] here, the second derivative of current in Fig. 3(c) is used to show that the peak amplitudes at $V_{\mathrm{ds}}=\pm 6$ mV have a strong temperature dependence, consistent with the strong temperature dependence of the differential conductance. In an In_2O_3 wire FET, we can control the carrier density and thus electron-electron correlations. It can provide two distinct regions of transport: Fermi liquid and Luttinger liquid. For the latter, however, instead of a clear Luttinger picture, weak localization and disorder may also affect electron-electron correlations in the In_2O_3 nanowire for the present ZBA. Furthermore, Schotky contact should be taken into consideration carefully. Further experiments are needed to ascertain the mechanisms of the ZBA.

In conclusion, different 1D transport behaviors as a function of gate bias were studied at different temperatures in terms of current and differential conductance. The differential conductance gaps and current gaps at a relatively low gate bias could be explained using conventional low-temperature FET theory. A power-law dependence was observed when the In_2O_3 nanowire FET was at a large positive gate bias. This might be evidence of 1D Luttinger liquid behavior, suggesting that electron-electron correlations became significant for the nanowires at degenerate carrier density.

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