APPLIED PHYSICS LETTERS **87**, 253116 (2005)

Carbon nanotube Schottky diode and directionally dependent field-effect transistor using asymmetrical contacts

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(Received 24 August 2005; accepted 14 November 2005; published online 16 December 2005)

We demonstrate the fabrication and operation of a carbon nanotube (CNT) based Schottky diode by using a Pd contact (high-work-function metal) and an Al contact (low-work-function metal) at the two ends of a single-wall CNT. We show that it is possible to tune the rectification current-voltage (*I*-*V*) characteristics of the CNT through the use of a back gate. In contrast to standard back gate field-effect transistors (FET) using same-metal source drain contacts, the asymmetrically contacted CNT operates as a *directionally dependent* CNT FET when gated. While measuring at source-drain reverse bias, the device displays semiconducting characteristics whereas at forward bias, the device is nonsemiconducting. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2149991]

Single-wall carbon nanotubes (SWCNTs) are attractive materials in both fundamental science and technology due to their unique electrical, mechanical, and chemical properties.[1] In particular, SWCNTs are being investigated as active materials for building electronic devices, such as, the carbon nanotube (CNT) field effect transistor (FET) (Refs. 2 and 3) and CNT diode.[4–10] Diodelike rectification across a CNT has been achieved by forming a *p*-*n* junction through chemical doping,[4,5] polymer coating,[6] impurities,[7] or intramolecular junctions.[8] In addition, the *p*-*n* junction can be manipulated by electrical gating using AFM tip scanning probe[9] or using a pair of split gates.[10] The reported CNT diodes to date have mostly focused on *p*-*n* junctions instead of metal/semiconductor Schottky junctions. It was only very recently that Manohara *et al.*[11] has reported the use of Pt and Ti contacts to form CNT Schottky diodes. The Schottky diode fundamentally operates differently to a *p*-*n* diode. The reverse current of a *p*-*n* diode arises from minority carriers diffusing through the depletion layer, and the forward current is due to minority carrier injection from *n* and *p* sides. On the other hand, the Schottky diode's reverse current is due to carriers which overcome the barrier, and the forward current is due to majority carrier injection from the semiconductor; this leads to diode devices with a small threshold voltage.[12]

Metal-semiconductor junctions play very important roles in electronic devices. Nanoscale CNT devices rely upon the fundamental understanding of the CNT-metal interface. SWCNT FETs (CNT FETs) built from as-grown CNTs are found to be either *p* type, or ambipolar. This behavior has been attributed to the presence of a Schottky barrier at the metal-nanotube contact.[13] Most of the reported CNT FET utilize symmetrical CNT-metal contacts, i.e., the same elemental metal contact on both terminals of the CNT channel.[14–16] In this work, we demonstrate the CNT Schottky diode and, for the first time, the directionally dependent CNT FET.

The SWCNTs used in this work were grown by the chemical vapor deposition method.[17] Highly *n*-doped (degenerate) silicon substrates, with a 900 nm thermal oxide, were used as the silicon substrate. The SWCNTs were grown from prepatterned catalyst islands followed by the fabrication of metallic contacts on the SWCNT using electron-beam lithography, metal sputtering, and lift off. The substrate was used as the back gate for the SWCNT devices. The spacing between the metal contacts defined the channel length—this was fixed at 1.2 microns, as shown in Fig. 1(a).

The electrical results of symmetrically (i.e., same metal) contacted SWCNT are first presented. Electrical measurements were carried out at room temperature in air by using an Agilent 4140B semiconductor parameter analyzer. The following metals were used for contacts—Pd, Al, and Ti. Using the substrate as the back gate, the gate transfer characteristics of these devices were determined and are presented in Figs. 1(b)–1(d), respectively. We find that the Pd contacted SWCNT exhibits *p*-type characteristics (i.e., majority carriers are *p* type) and the device of Fig. 1(b) exhibits an on-off ratio of 10^6. The Ti contacted SWCNT of Fig. 1(c) exhibits ambipolar characteristics with an on-off ratio of 10^4. The Al contacted SWCNT, with an on-off ratio of 10^3 at the *p* region of operation (i.e., negative gate voltage) and 10^6 at *n* region of operation (i.e., positive gate voltage), is slightly ambipolar with strong *n*-type conduction as shown in Fig. 1(d). These charactieristics suggest that the CNT-Al contact has a higher Schottky barrier at CNT-Al interface to *p* carriers than *n* carriers.

The characteristics of CNT FETs are determined by the barriers at the CNT-metal junctions, which arise due to the differences of metal work function and Fermi levels between the CNT and metal.[16] Pd has a high work function of 5.12 eV, and ohmic contact behavior with Pd contacts for *p*-type conduction has been reported previously.[14] In the ambipolar device with Ti contacts (Ti work function 4.33 eV), the contacts have equal barriers for both electrons and holes. The Schottky barriers in this case could also be possibly due to the pinning of the Fermi level at the CNT-metal interface.[18] Al has a lower work function at 3.9–4.2 eV, and the Al contacted CNT FET has higher Schottky barriers for *p* carriers, but has smaller barrier to *n* carriers since the *n*-type

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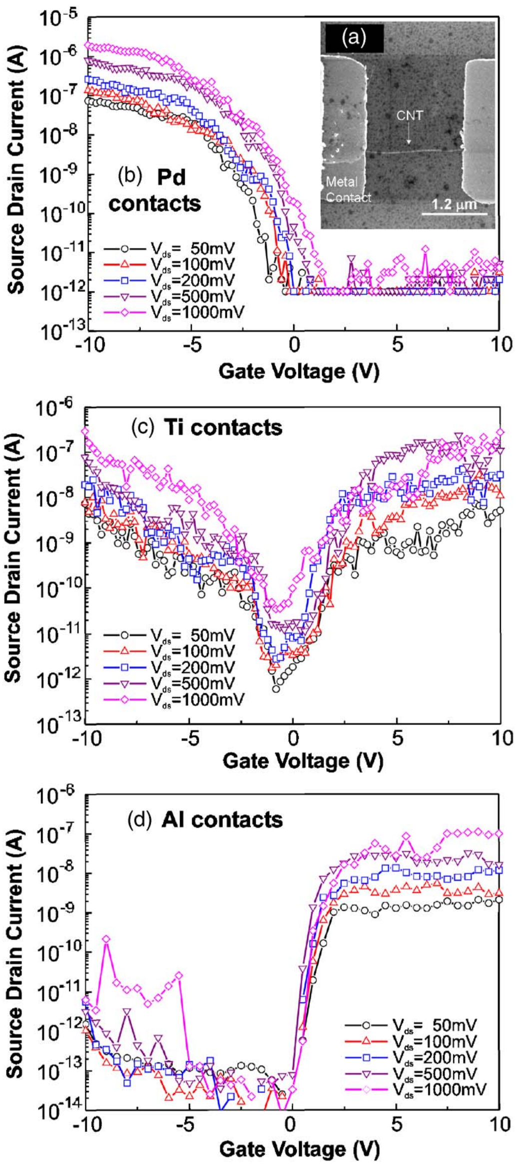


FIG. 1. (Color online) (a) Scanning electron micrograph of a bottom gate CNT FET. Gate transfer characteristics of symmetrically Pd contact, Ti contact, and Al contact CNT FETs are shown in (b), (c), and (d) respectively.

characteristics of the same device have higher currents. One should also note that since the barrier heights at the CNT-metal interface are sensitive to the work function and work functions are sensitive to adsorbed gases, the metal work function could have changed due to the exposure of the metal contacts and CNT to O_2 or other atmospheric gases.[18]

A CNT Schottky diode was thus fabricated using Pd (ohmic for *p*-type carriers) and Al metal (highest barrier for *p*-type carriers) as source-drain contacts as shown in Fig. 2(a). This device exhibits rectification as shown in Figs. 2(b) and 2(c). Note that the substrate bias was also varied to determine its effect on the Schottky diodes' characteristics. Under forward bias, the device exhibits almost ohmic conduction, with little dependence the substrate bias. The threshold voltage (on voltage) of the Schottky diode is 0.1 ~ 0.2 V.

In reverse bias, the diode is blocking. Interestingly, the substrate gate bias affects the reverse leakage current under reverse bias. At high positive gate voltage ($V_g = +10$ V), the rectification $I_{\mathrm{Forward}}/I_{\mathrm{Reverse}}$ ratio is $\sim 10^3$ whereas at high negative gate voltage $V_g = -10$ V, the rectification

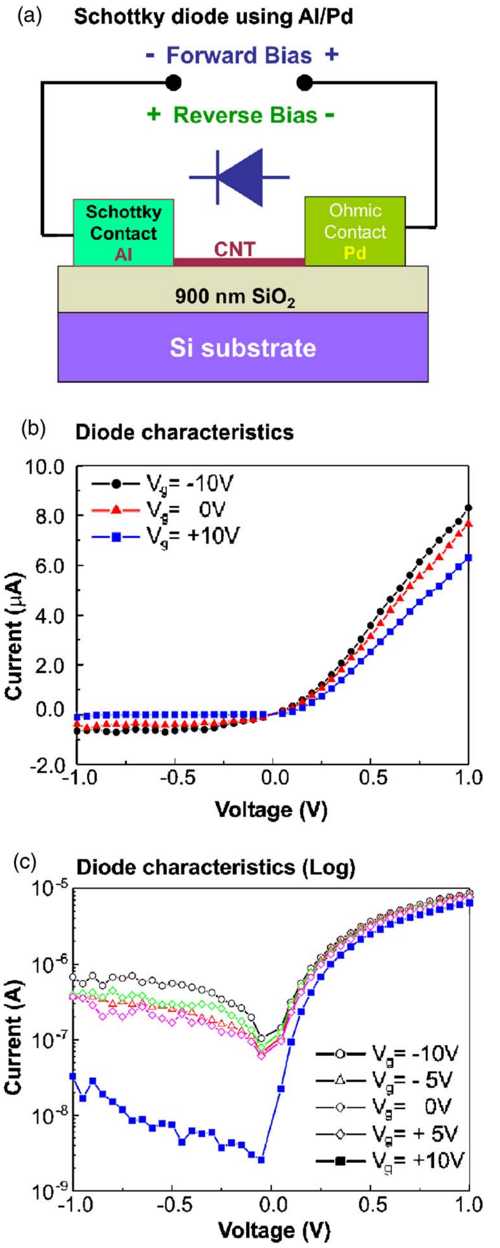


FIG. 2. (Color online) (a) Schematic of the CNT Schottky diode and direction dependent FET using Pd and Al contacts. The diode characteristics are shown in linear (b) and logarithmic (c) scales.

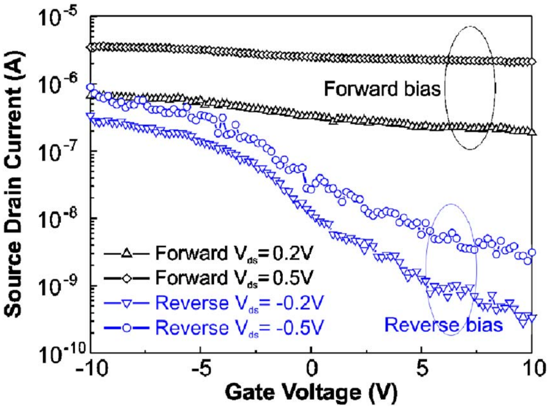
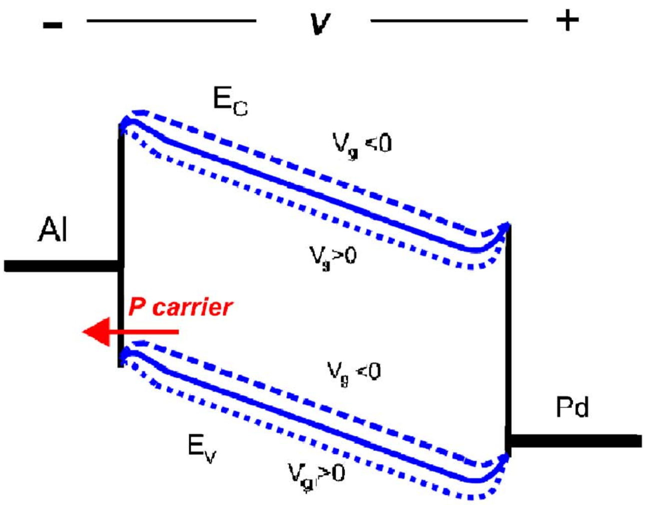


FIG. 3. (Color online) Gate transfer characteristics of the direction dependent CNT FET. Under forward bias, the device is nonsemiconducting. However, at reverse bias, the device is semiconductiing with 10^3 on-off ratio.

(a) **Forward Bias**



(b) **Reverse Bias**

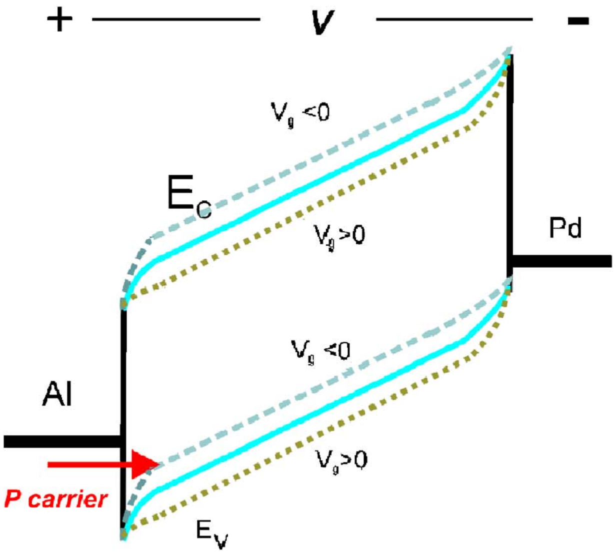


FIG. 4. (Color online) Band diagrams for the case of the CNT under forward (a) and reverse bias (b). The conduction mechanism is dominated by the barrier to *p* carriers at the Al/CNT contact. Under forward bias, *p* carriers can overcome the Al/CNT barrier. Under reverse bias, *p* carriers are blocked by the Al/CNT barrier which can be controlled by the applied gate voltage.

$I_{\text{Forward}}/I_{\text{Reverse}}$ ratio is only $\sim$3 due to the increase in reverse current. Note that the reverse bias characteristics are transistorlike where the barrier height of the Al Schottky contact, which determines carrier injection (i.e., reverse current), is modulated by the gate voltage. Thus, a tunable Schottky diode has been constructed in which the rectification ratio is determined by the gate bias.

The tunable Schottky diode could also be operated as a directionally dependent FET. This is demonstrated in Fig. 3, in which the gate transfer characteristics of the FET were determined under forward and reverse source-drain biases. Clearly, under forward bias, the device is nonsemiconducting, whereas under reverse bias, the device is a *p*-type transistor. These results can be explained using the band diagrams of Figs. 4(a) and 4(b), depicting the cases of forward and reverse bias, respectively. Note that the CNT-Pd contact is ohmic and can be ignored in this discussion. The application of a forward bias across the device allows *p*-type carriers to overcome the CNT-Al barrier at the valence band. The application of the gate voltage changes the barrier height, as shown in Figure 4(a), but because the majority of the *p*-type carriers are arising from the forward bias, the gate effect is small (hence leading only to an on-off ratio of $\sim$3). Under reverse bias conditions across the CNT [Fig. 4(b)], the barrier at the CNT-Al contact becomes even higher, and thus no significant *p*-type current arises under reverse bias conditions. *p*-type conduction is only made possible in this case when the barrier is reduced by the application of a negative gate voltage. Thus, in reverse bias, the device essentially operates as a *p*-type field effect transistor where the application of the gate voltage affects the conduction across the CNT.

In conclusion, the carrier transport through symmetrically and asymmetrically contacted carbon nanotube devices has been investigated. We demonstrated the fabrication and operation of *p*-type, ambipolar and *n*-type CNT FETs using symmetric (i.e., same metal) contacts. Using asymmetric (i.e., different metal) contacts, we demonstrated the CNT Schottky diode and directionally-dependent FET. These new CNT-based devices extend the "toolbox" of fundamental devices available as building blocks for next generation nanoelectronic based integrated circuits and systems.

One of the authors (K.B.K.T.) acknowledges the support of the Royal Academy of Engineering and Christ's College Cambridge. This work was also supported by the EPSRC Carbon-Based Electronics project.

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