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The performance of *in situ* grown Schottky-barrier single wall carbon nanotube field-effect transistors

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Abstract
Electrical transport measurements were used to study device behavior that results from the interplay of defects and inadvertent contact variance that develops in as-grown semiconducting single wall carbon nanotube devices with nominally identical Au contacts. The transport measurements reveal that as-grown nanotubes contain defects that limit the performance of field-effect transistors with ohmic contacts. In Schottky-barrier field-effect transistors the device performance is dominated by the Schottky barrier and the nanotube defects have little effect. We also observed strong rectifying behavior attributed to extreme contact asymmetry due to the different nanoscale roughness of the gold contacts formed during nanotube growth.

1. Introduction

The exceptional electrical properties of single wall carbon nanotubes (SWCNTs) promise dramatic performance enhancements in field-effect transistor (FET) devices based on metal–semiconductor junctions. The device physics of SWCNT FET devices fabricated from pristine SWCNTs has been extensively studied [1]. However, controlled electron- and hole-doping by incorporation of foreign atoms that is believed to be necessary for implementation of most nanoelectronic device concepts is known to create structural defects in the wall of the SWCNTs [2]. Doping and fabrication related defects affect the performance of SWCNT FETs by obstructing or altering the one-dimensional transport behavior of SWCNTs. While the role of isolated defects in SWCNTs has been extensively studied [3, 4], little work has been done on understanding the role of defects in 'real' devices with varying contact barriers. Specifically, semiconducting SWCNTs can form either ohmic contacts or Schottky barriers (SB) at the metal/CNT interface, depending on the work function difference between the metal and the SWCNT [5, 6]. In this paper, we study the effect of the nature of the contact barrier on the performance of SWCNT FETs that are known to contain fabrication related defects. Our measurements show that the presence of defects has little effect on the transistor characteristics of SWCNT FET devices with finite SBs. Instead, contact barrier effects dominate the transport in semiconducting SWCNT devices giving rise to interesting and useful device properties.

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2. Experimental details

The SWCNT FET devices were fabricated by directly growing a SWCNT to bridge the gap between two electrodes predeposited on degenerately doped Si wafers with 500 nm of thermal SiO_2 [7]. In brief, the electrodes were defined using electron beam lithography (EBL) followed by electron beam assisted deposition of a 5 nm Ti adhesion layer and 200 nm of Au. Small metal catalyst islands (300 nm wide and 4 μm long) consisting of 10 nm of Al and 1 nm of Fe were fabricated on top of the Au electrodes using a second EBL step and subsequent metal deposition. The growth of SWCNTs from these small catalyst islands was essential to making good metal/CNT contacts. This electrode configuration allowed the SWCNTs to directly contact the Au electrodes without formation of a barrier layer by oxidation of Al. In contrast

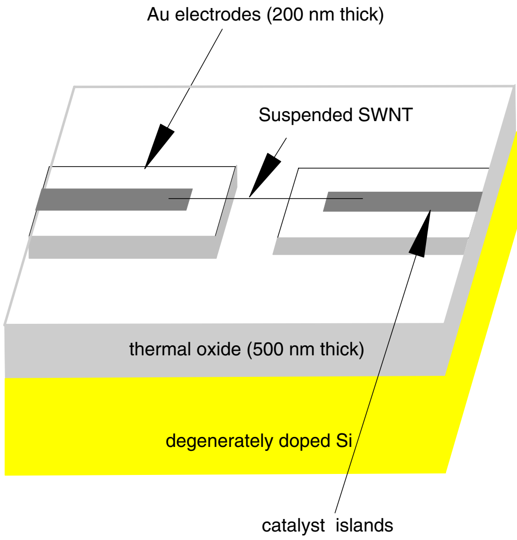

Figure 1. A schematic diagram of the SWNT device. EBL was used to pattern the electrodes followed by deposition of 5 nm of Ti and 200 nm of Au. The smaller catalyst islands were fabricated by a second EBL step and subsequent deposition of 10 nm of Al and 1 nm of Fe.

(This figure is in colour only in the electronic version)

devices fabricated by growing SWCNTs on Au electrodes completely covered by the Al/Fe double layers were nearly insulating. The SWCNTs were grown using a molecular beam to suppress amorphous carbon formation from secondary gas phase reactions and to control precisely the impingement rate of acetylene molecules on the heated wafer with a predeposited electrode pattern. The growth gas consisted of a mixture of 2% acetylene, 10% hydrogen, and the balance inert gas (helium or argon). The substrate temperature was in a range from 650 to 700 °C [7, 8]. A schematic illustration of the device is shown in figure 1.

This fabrication method allows us to systematically study how the impact of defects incorporated during growth varies with contact transparency without possible interference introduced by post-growth processing steps. Our previous study has shown that addition of methane to the acetylene gas mixture is necessary to produce low defect or nearly defect free SWCNTs at 825 °C [7]. Without methane in the gas mixture the SWCNTs were defective in the entire growth temperature range as characterized by low temperature transport measurements on metallic SWCNTs [7]. We assume that the devices used in this study are not defect free because they were grown without methane in the gas mixture. In addition, semiconducting SWCNTs are known to be more susceptible to disorder than metallic SWCNTs due to the reduced symmetry in the band structure of the former [9, 10]. We performed the measurements on suspended individual SWCNT to eliminate interference resulting from the interactions of the SWCNTs with the substrate.

Electrical transport measurements were carried out in air at room temperature using the degenerately doped Si substrate as a back gate. Of the dozens of semiconducting SWCNT devices measured, most exhibited characteristics of SB FETs,

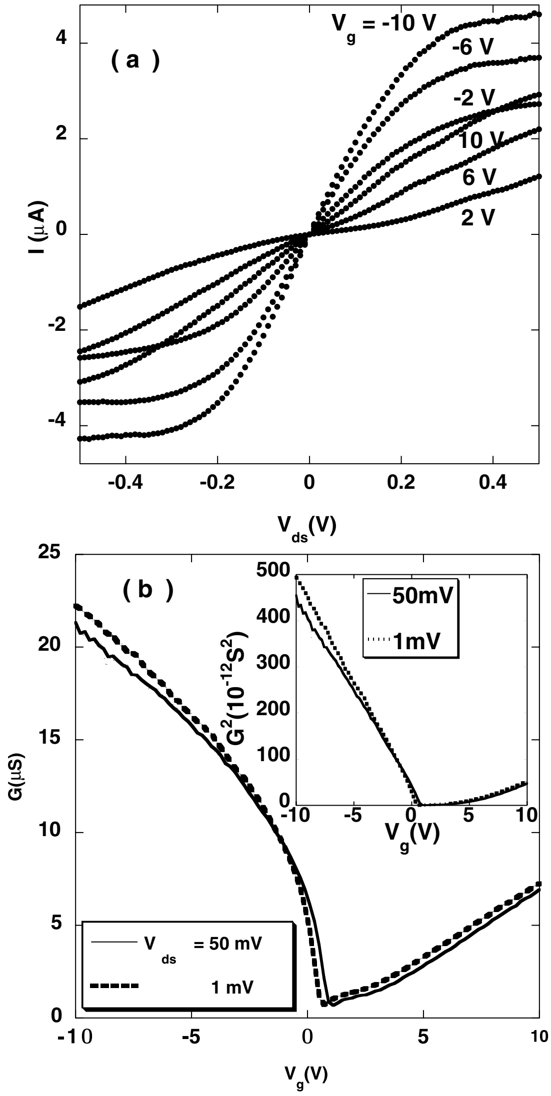

Figure 2. Electrical transport properties of semiconducting SWCNT FET devices with near ohmic contacts measured in air at room temperature: (a) I–V curves as a function of gate voltage, and (b) conductance (I/V_{ds}) as a function of gate voltage. Inset of (b) shows G^2 as a function of V_g.

with a few showing near ohmic behavior. Because direct measurement of the diameter of the suspended SWCNT was not feasible we determined a statistical average diameter in a range of 1–2 nm from atomic force microscopy (AFM) images of low density SWCNTs grown on identical substrates under identical growth conditions [5, 6].

3. Results and discussion

A representative SWCNT device with on-state resistance (dV_{ds}/dI for $V_{ds} = 0$ and $V_g = -10$ V) of approximately 50 kΩ is shown in figures 2(a) and (b). The relatively small on-state resistance, highly symmetric I–V curves and their linear behavior in the low bias region (between −0.1 and 0.1 V) indicate near ohmic contacts. The low bias conductance (I/V_{ds}) of the device as a function of gate voltage is nearly bias independent, further signifying near ohmic metal/nanotube contacts (see figure 2(b)). Similar to the observation of Durkop *et al* in their ohmically contacted ultra long diffusive CNT devices, the conductance of our device also closely follows the relationship $G \propto (V_{th} - V_g)^{1/2}$ for $V_g < V_{th}$, where V_{th} is the threshold voltage (see the inset of figure 2(b)) [11]. Although the channel length of our device (~500 nm) is much smaller than the estimated mean free path of their CNT devices, the similarity in the gate dependence of conductance suggests that our device is also diffusive due to the presence of defects. The gate modulation of conductance is less than 2 orders of magnitude, indicative of a rather small band gap. The relatively large room temperature subthreshold swing (~500 mV/decade) is in reasonable agreement with the standard MOSFET model given the relatively thick SiO_2 dielectric layer as well as the gap between the suspended SWCNT and the substrate. But, it is still smaller than what is expected for a SB SWCNT FET of similar configuration (~1000 mV/decade) [12]. The saturation current ($I_{sat} \sim 5\ \mu$A for $V_g = -10$ V) is substantially lower than $I_{sat} \sim 25\ \mu$A expected for a ballistic SWCNT, demonstrating that scattering from defects considerably reduces the on current of the device [6]. Figure 2(a) also shows that the I–V curves at $V_g = 2$ and -2 V follow a similar general trend but cross over at $|V_{ds}| \sim 0.3$ V. Although the exact origin of the crossovers is unclear, we surmise that they may be attributed to the slightly different scattering rates of holes and electrons as a function of V_{ds} in the CNT.

A number of devices show signatures of a SB at the contacts as manifested by the low on current combined with nonlinear and slightly asymmetric I–V curves. A representative SB device is illustrated in figures 3(a) and (b). The on-state resistance of ~20 MΩ is much larger than that of the near ohmic contact devices in figure 2. The gate modulation of drain–source current I_{ds} approaches 6 orders of magnitude. These device characteristics combined with an on current I_{on} of less than 0.1 μA at $V_{ds} = 1$ V and $V_g = -10$ V, are indicative of a relatively large band gap and non-negligible SBs at the metal/nanotube contacts. Despite the presence of significant transport related defects in the SWCNTs that were confirmed to strongly affect the transport behavior of the ohmic devices, the overall transfer characteristics of the SB SWCNT device closely resemble the results of Appenzeller *et al* [12]. These data show that the defects in SWCNTs do not notably limit the performance of a SWCNT FET device with finite SBs. This finding provides further experimental confirmation to the contention by Appenzeller *et al* that the existence of SBs at the metal/nanotube interface and their response to V_g and V_{ds} dominate the performance of SB FETs [12].

Another example of the critical role that the metal/nanotube contacts play in the performance of *in situ* fabricated semiconducting SWCNT devices is illustrated by intriguing rectifying behavior. Rectifying I–V curves were obtained for all gate voltages V_g in the range $-10\ \text{V} < V_g < 5$ V as shown in figures 4(a) and (b). A positive gate voltage higher than 5 V was found to turn off the current completely. In figure 4(b) we see an on–off ratio over 6 orders of magnitude under a forward bias of 2 V. The overall transfer characteristic of this device is similar to that of typical p-type SB SWCNT FETs [12].

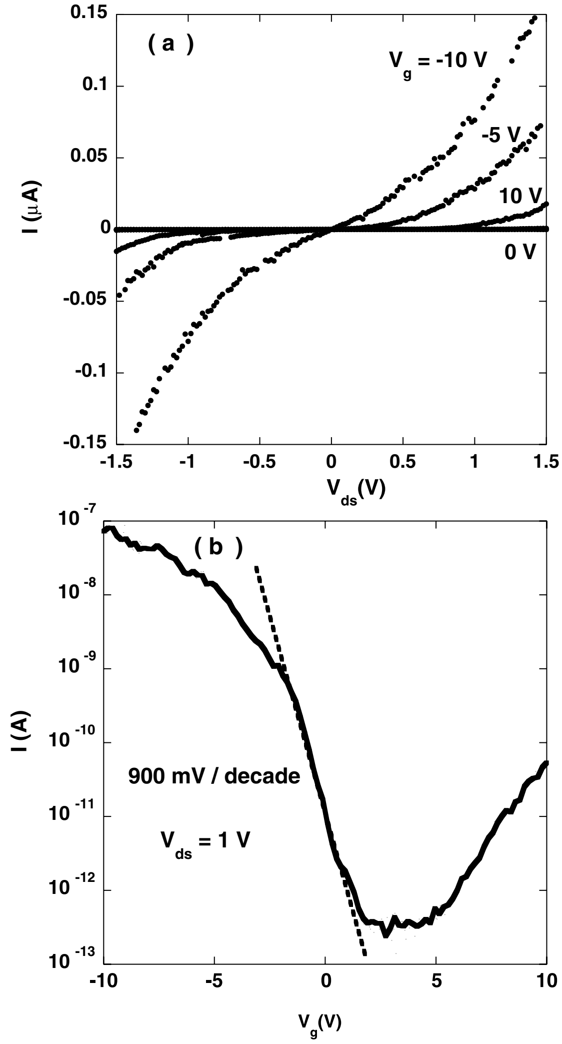

Figure 3. Electrical transport properties of semiconducting SWCNT FET devices with SB contacts measured in air at room temperature: (a) I–V curves as a function of gate voltage, and (b) current I_{ds} as a function of gate voltage V_g for $V_{ds} = 1$ V.

Rectifying behavior previously observed in semiconducting SWCNTs was attributed to various factors including localized impurities near one contact [13], different metals contacting the two ends of the tube [14–18], or chemical modification of one end [19]. Although we cannot completely rule it out, a localized impurity is unlikely to be the primary cause of the observed rectifying behavior because of the presence of other defects in our SWCNTs. Unlike previously reported CNT diodes intentionally fabricated using two different metal contacts or chemical modification, our devices were contacted by Au at both ends and no post-growth chemical modification was used. Nevertheless, the rectifying effect in our devices must be associated with some type of contact asymmetry. The most likely origin of the difference in transparency and, hence, the asymmetry in the device is uneven surface roughness on the electrodes contacting the opposite ends of the SWCNT. The inset in figure 4(b) illustrates a situation in which the SWCNT lies flat on one electrode without discernable bending, and contacts the other end through Au nanoparticles. Under

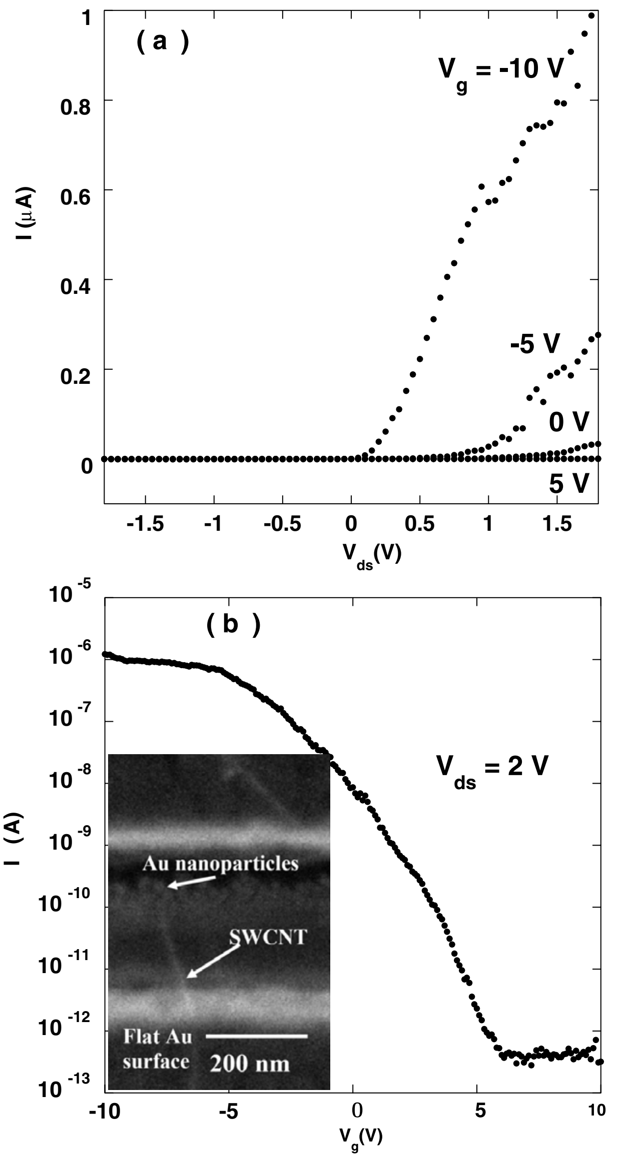

Figure 4. Electrical transport properties of a semiconducting SWCNT device with asymmetric SB contacts measured in air at room temperature: (a) I–V curves at different gate voltages, (b) current I_{ds} as a function of gate voltage V_g at a forward bias $V_{ds} = 2$ V. Inset of (b) shows the SEM image of the SWCNT in the device contacting a flat Au electrode on one end and Au nanoparticles on the other.

forward and reverse bias, the current of the device is mainly limited by the SBs at the contacts with the flat surface and nanoparticles, respectively [12, 18]. We surmise that the changes at the SWCNT/electrode interface are attributed to Au nanoparticles. In particular, one possibility is that surface contamination or oxidation of the Au nanoparticles causes an increase in the effective SB of the Au nanoparticle/SWCNT interface [5, 13, 15, 20, 21]. A second possibility is that the interaction between the SWCNT and Au nanoparticles reduces the Au/CNT bonding distance, which has been theoretically predicted to increase the SB [22]. A third and remote possibility is that the CNT in the device is actually contacting the Ti under-layer at one end and Au at the other. However, the I–V characteristics of our device are significantly more asymmetric than those of a Ti–SWCNT–Au device shown in figure 3 of [15] at all gate voltages. Therefore, the rectifying effect in our device cannot be explained by the work function difference between Ti and Au alone. On the other hand, their Al–SWCNT–Au devices (see figure 4 of [15]) show considerable rectifying behavior attributed to the possible formation of interfacial aluminum oxide species (thickening the barrier width), in agreement with the scenario of surface contamination or oxidation of the Au nanoparticles for our device. Further investigations are under way to determine the exact origin of the increased SB in these devices.

4. Summary

In summary, we report on a wide range of device behavior that is dominated by inadvertent contact variance that develops in as-grown semiconducting SWCNT FETs with nominally identical Au contacts. In semiconducting devices with near ohmic contacts, the SWCNT defects incorporated during growth significantly limit the mean free path and thus determine the overall FET characteristics of the devices. In contrast, the performance of semiconducting SWCNT devices with non-negligible SBs is dominated by the SBs, and the existence of defects has no observable effect. With some devices we observe strong rectifying behavior that indicates extreme SWCNT/contact asymmetry. These devices illustrates that the transparency of SBs in semiconducting SWCNTs is in addition to the diameter of the SWCNT and the work function of the metal also sensitive to nanoscale contact roughness. These results suggest the intriguing possibility that metallic nanoparticles could be effectively used to impose contact asymmetry and expand the parameter space for device functionality with SWCNTs.

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