High-Mobility Semiconducting Nanotubes

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Abstract. Carbon nanotube transistors with channel length exceeding 300 microns have been fabricated. The gate-voltage dependence of carrier transport through these long-channel transistors is similar to short channel (few micrometer) transistors. We place a conservative lower bound for the hole mobility in nanotube transistors at 20,000 $cm^2/V\cdot s$ at room temperature, and offer evidence that the mobility is much greater. This high mobility corresponds with a mean free path for holes of 2.9 μm at a gate voltage of -10 V.

INTRODUCTION

Single wall carbon nanotubes (SWNT) are nanometer-diameter graphite cylinders. Depending on their diameter and chiral angle (the angle of the circumferential vector with respect to the graphite lattice vectors) they may be either metallic or semiconducting. While metallic SWNTs exhibit properties of a 1D-Luttinger liquid with ballistic conductance [1] over distances of several microns, the nature of conductance in semiconducting SWNTs is not completely understood. Recently several publications [2, 3] have established that the behavior of short (channel length less than 1 μm) field-effect transistors (FETs) fabricated from semiconducting SWNTs is governed by the Schottky-barriers between the contacts and the nanotubes. However the intrinsic mobility of the semiconducting nanotubes and the processes that limit it are not fully understood, though a first number for the mobility measured in top-gated SWNT-FETs has been reported to be 3000 $cm^2/V\cdot s$ [4]. To address this question we have fabricated devices with tube lengths of over 300 μm in which we may conservatively estimate a lower bound for the mobility of 20,000 $cm^2/V\cdot s$.

DEVICE FABRICATION

Our devices are fabricated using nanotubes grown with chemical vapor deposition (CVD) directly on the substrate (highly doped Si with 500 nm oxide) following a growth process adapted from [5, 6]. We deposit catalyst by first dipping the chips into a solution of $Fe(NO_3)_3$ in isopropanol and then in hexane to force the $Fe(NO_3)_3$ to precipitate onto the chip. After that we use methane to grow nanotubes at 900°C in a tube furnace. After depositing alignment markers with standard e-beam lithography technique we use a Field-Emission SEM with in-lens detector [7] to find individual nanotubes that are then contacted with Cr/Au-contacts. Figure 1 shows an image of two such devices.

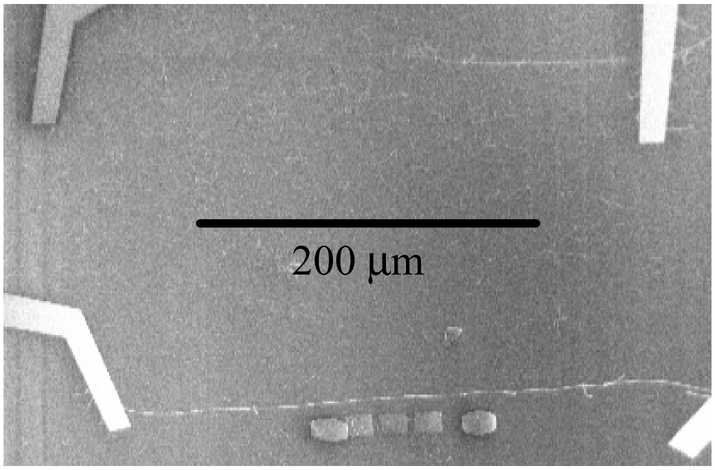

FIGURE 1. FESEM image of two long nanotube-devices. The upper device has a length of 325 µm the lower is 345 µm. The shapes at the bottom of the image are parts of a pattern of alignment markers.

RESULTS AND DISCUSSION

We have measured the electrical properties of devices with different length at different temperatures. Figure 2 shows the behavior of two tubes with lengths of 5 µm (2.7 nm diameter) and 325 µm (3.9 nm) respectively.

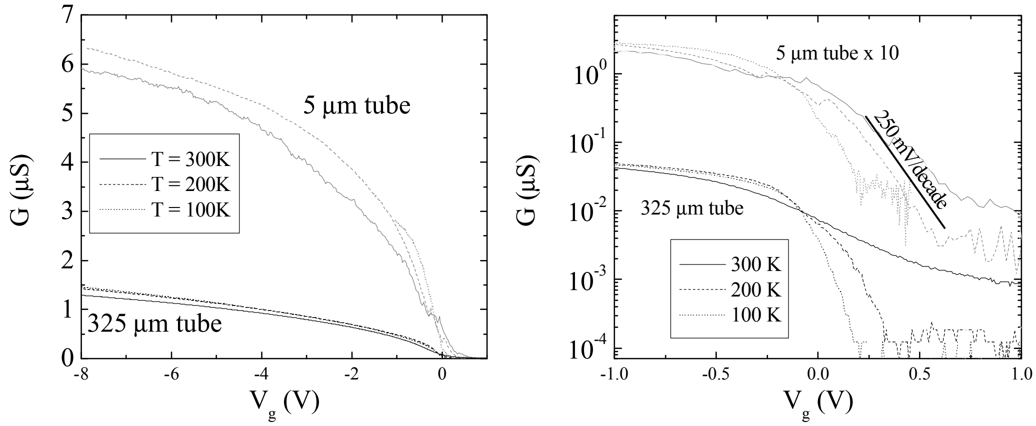

FIGURE 2. Left side: Conductance of two nanotube-FETs for different temperatures in linear scale; Right side: Conductance in log-scale for the same devices emphasizing the subthreshold region, which determines the turn-on behavior of a device. The subthreshold swing is very similar for both devices (250 mV/decade at 200 K).

Comparing the devices shown in Figure 2 one notices that their difference in total conductance is just a factor of five while their lengths differ by almost two orders of magnitude. Furthermore the subthreshold swing S ($S = dV / d\log I$) does not significantly depend on the device length. This agrees with the findings of Avouris, et al. [2, 3], which were interpreted as evidence of Schottky-barrier-dominated transistor behavior in short (< 1 μm) nanotube-FETs. In contradiction to [3] however, the subthreshold swing does show temperature dependence for both tubes and its value of 250 mV/decade is between the limits of an ideal FET (40 mV/decade) and the ideal Schottky-barrier model (1000-2000 mV/decade). Large subthreshold swings may also arise from the filling of localized states which do not contribute to the conductance of the device. Taking into account electrostatic-force-microscopy measurements [8] which show a potential drop along semiconducting nanotube devices we assume that for long tubes the conduction is diffusive and intrinsic tube resistance plays a significant role in determining the device resistance.

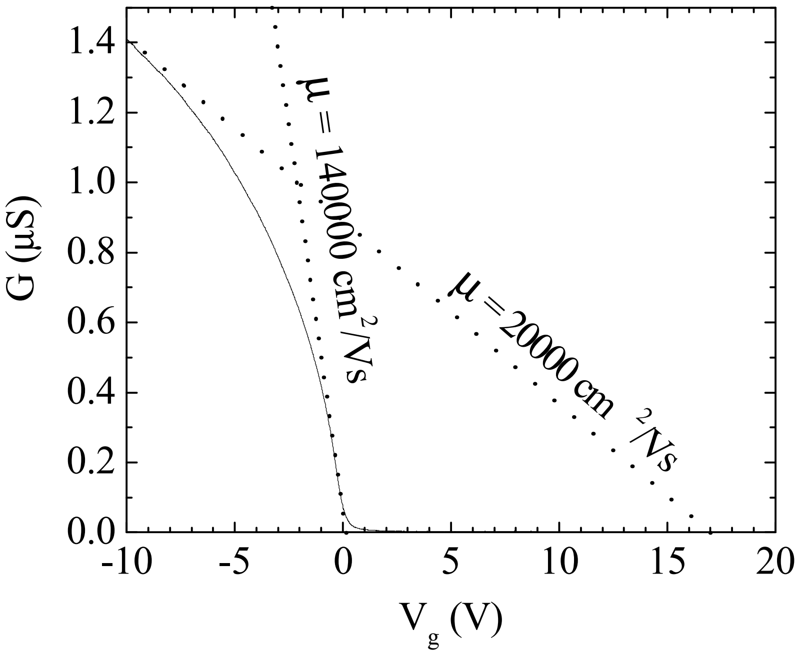

FIGURE 3. Estimate for bounds of the mobility. The intrinsic nanotube-threshold has been estimated from [4] and then rescaled for the backgate in our devices yielding V_{th}=17 V. A lower bound for the mobility is then calculated by drawing a tangent to the G(V_g)-curve. The upper bound represents the slope of this curve at its steepest part.

We examine the carrier mobility μ given by the formula:

$$m = \frac{L^2}{C_g} \frac{G}{(V_g - V_{th})}$$

where G is the conductance, L is the channel length, C_g the capacitance of the channel to the gate, V_g the gate voltage, and V_{th} the threshold voltage (the gate voltage where the first carriers enter the nanotube channel). The gate capacitance per unit length may be estimated from Coulomb blockade measurements on shorter nanotube devices on the same substrates to be approximately 10 aF/μm.

If we assume that the conductance shown in Figure 3 is the intrinsic conductance of the nanotube channel, then the mobility corresponds to the slope of the $G(V_g)$ curve. The maximum slope of this curve (near $V_g = 0$) would correspond to a mobility of about 140,000 cm^2/Vs. It is possible, however, that the steep portion of the curve is due to the rapid turn-off with increasing V_g of Schottky barriers at the contacts. In this scenario, the nanotube would still have a finite carrier density at $V_g = 0$, and the threshold would occur at positive V_g. We can make a conservative estimate of the positive threshold by estimating the carrier concentration at $V_g = 0$ in the top-gated devices of Javey, et al. [4]. We arrive at an estimate of $V_{th} = +17$ V (this is almost certainly too large, as many of our devices show a finite n-type conduction with an onset at V_g = 5-10 V). However using this estimate, the lowest slope of $G(V_g)$ which does not intersect our measured curve corresponds to a mobility of 20,000 cm^2/V·s. This very conservative lower bound would correspond to the rather artificial case in which the conductance is dominated by Schottky barriers near $V_g = 0$, but then becomes intrinsic (transparent Schottky barriers) at more negative V_g. We conclude that the true mobility of our devices is likely much higher than this estimate.

The two-terminal conductance of the nanotube transistor gives a lower bound for the 1D conductivity of the nanotube $s_{1D} = GL$. At $V_g = -10$ V, the conductivity of the nanotube shown in Figure 3 is 4.6 x10^{-8} S·cm. In a 1D conductor, the mean-free-path is given by $l = s/NG_o$, where G_o is the conductance quantum and N the number of 1D channels, which we assume to be 2 (if this nanotube is multiwalled, it is likely the outer wall carries most of the current [9]). We arrive at $l = 2.9$ µm at $V_g = -10$ V and room temperature, a lower bound (a contribution of Schottky barriers to the resistance would increase this number). This indicates that quantum transport will dominate in even micron-length semiconducting nanotube devices at room temperature.

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