Multiwalled Carbon Nanotubes as Single Electron Transistors

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Abstract. Single electron transistors (SET) are fabricated from multiwalled carbon nanotubes (MWNT) by manipulation with an atomic force microscope. The devices consist of either a single MWNT with Au contacts at the ends or of two crossing tubes. In the latter device, the lower nanotube acted as the central island of a single electron transistor while the upper one functioned as a gate electrode. Coulomb blockade oscillations were observed on the nanotube at low temperatures. The voltage noise of the nanotube-SET was gain dependent as in conventional SETs. The charge sensitivity at 10 Hz was 6×10^{-4} e/√Hz. Furthermore, in another device where the MWNT is suspended above the substrate between the electrodes, we measure an extremely high charge sensitivity of 6×10^{-6} e/√Hz at 45 Hz, comparable to the best of the conventional SETs.

INTRODUCTION

Carbon nanotubes are proposed as building blocks of future nanoscale electronic devices (for a review, see [1]). Single electron transistors (SET) are one possibility, since the Coulomb blockade has been observed especially in devices made from single walled nanotubes (SWNT), while in multiwalled nanotubes (MWNT) only very few results have been reported [2]. Field effect transistors based on semiconducting nanotubes have been demonstrated, made both from SWNTs and SWNT ropes.

The atomic force microscope (AFM) plays often an essential role in the fabrication of nanotube based electronic devices. Besides using the AFM for locating and imaging an individual tube, it can be used more actively for manipulating nanotubes [2]. Our group has developed a method for the manipulation of nanoscale particles using the AFM in non-contact mode. This method has the advantage that manipulation and imaging can be performed simultaneously. It is possible to move with this method a multiwalled nanotube over a distance of several micrometers. It is also possible to push a tube over an obstacle with a height of several tens of nanometers. Armed with these capabilities we have fabricated two types of nanotube-SETs: One made from two nanotubes where a MWNT has been pushed on top of another (Device1) and one where a MWNT has been pushed on top of two adjacent gold electrodes (Device2).

Results and Discussion

Figure 1(a-c) shows AFM images of how a crossing from two MWNTs separated by a few micrometers is made. The moved MWNT is ultimately positioned on top of the other nanotube. The other end of this MWNT is hanging above the substrate by 30-40 nm:s. In Figure 1(d) is shown how this "nanotube cross" is contacted with Au electrodes, resulting in a three terminal device where the upper MWNT functions as a gate electrode [3]. We call this device Device1. In the other type of a device (Device2) a MWNT has been positioned on top of two 25 nm thick Au electrodes very close to each other. The section of the nanotube between the electrodes is 275 nm:s long and is separated from the SiO_2 substrate, that is, the tube is suspended. The diameters of all nanotubes were ≅ 15 nm.

The lower nanotube of Device1 had a room temperature resistance R_{300K} = 71 kΩ, while the two-point resistance over the crossing was ≅ 10 MΩ, a value significantly higher than those found for the resistance between crossing metallic SWNTs. Furthermore, the zero-bias resistance increased to ~ 1 GΩ below 4 K. Thus we could utilize the upper tube for gating the current in the lower tube. Figure 2 (a) displays IV curves measured at temperatures from 300 K down to 150 mK. A Coulomb blockade develops fully only at subkelvin temperatures, with a gap of about 1 mV at 150 mK. Figure 2 (b) shows the source-drain current I as a function of the gate voltage V_g, applied from the upper tube. From the shape of the Coulomb oscillations in the I vs. V_g curves, it is concluded that $R_1 \cong R_2$, where R_1 and R_2 are the junction resistances at the opposite ends of the nanotube. We estimate [3] the corresponding capacitances as C_1 = 0.32 fF and C_2 = 0.22 fF. We get for the charging energy $E_c = \frac{1}{2}e^2/(C_1+C_2+C_{tube})$ = 0.14 meV, where we estimate the nanotube self-capacitance as $C_{tube} = 5\times10^{-17}$ F.

The gate modulation period was measured as ΔV_g = 4 mV. We calculate the gate capacitance to the upper tube as $C_g = e/\Delta V_g = 4\times10^{-17}$ F. A Fourier analysis of the gate modulation curves in general (including those from a more remote side-gate [3]) revealed only one period, indicating the existence of only one island. Particularly, this implies that the lower tube is not electrically split into two parts separated by a tunneling junction at the point of crossing with the upper nanotube, where considerable mechanical forces between the tubes are known to exist [4].

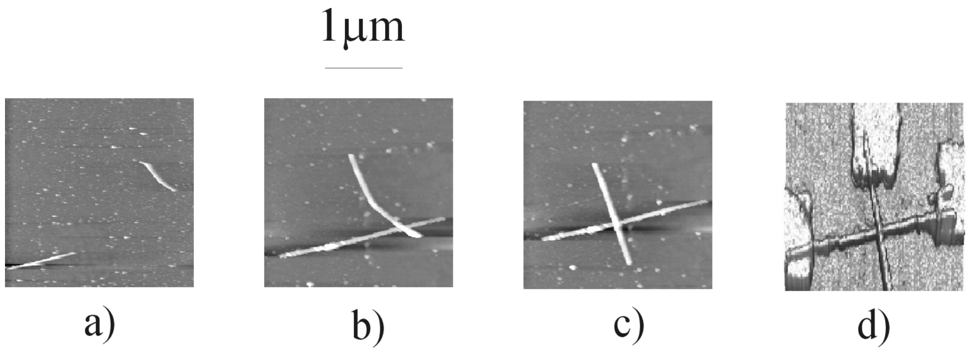

FIGURE 1. (a-c) Manipulation with AFM in non-contact mode to make a nanotube cross. (d) Gold electrodes deposited on the same nanotubes (Device1).

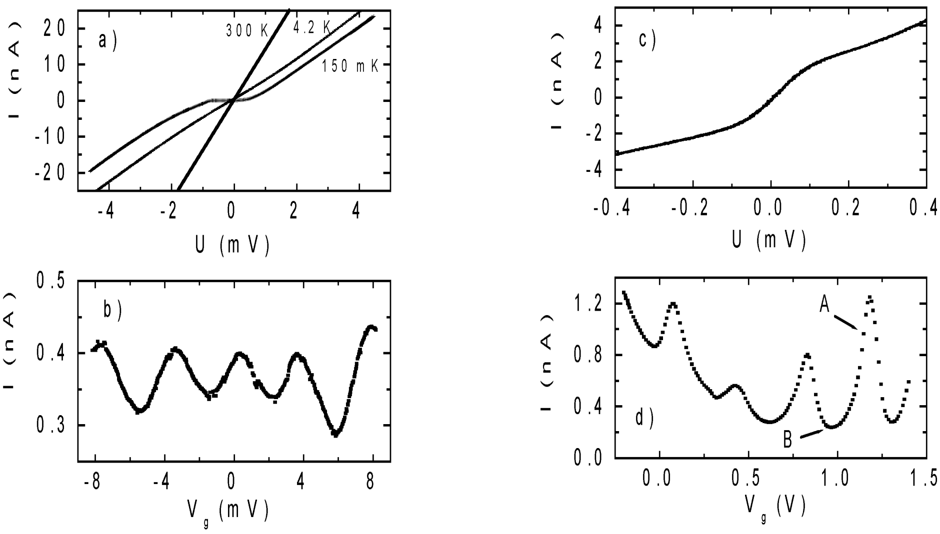

FIGURE 2. (a) IV characteristics of Device1. (b) Gate modulation from the upper tube of the current of Device1 (at U = 0.4 mV) (c) IV characteristics of Device2 at T = 150 mK (d) Gate modulation of Device2, applied from a side gate. A and B refer to the points of maximum and minimum gain where the noise data of Fig. 3(b) was measured .

The IV characteristics of Device2 is shown in Fig. 2 (c). The nanotube had a room temperature resistance of 28 kΩ. As opposed to the usual case of a Coulomb blockade at low voltages (and low temperatures), this nanotube exhibited increased conductance around zero bias, which we attribute to resonant tunnelling. Two weakly quantized steps are seen, therefore this tube can not be said to be fully ballistic. The ballisticity of freestanding samples are likely to be enhanced for several reasons; besides the absence of contact with impurity states of the surface, the plasmon speed, which is sensitive to the permittivity of the substrate, is increased. We measured a total resistance of ≅ 40 kΩ outside the Coulomb blockade regime. The junction resistance of the nanotube-Au contacts are thus less than the quantum of resistance $R_Q \cong 26$ kΩ, which means that the Coulomb blockade can not fully develop. Consequently, the Coulomb oscillations that we measure are smoothened.

We have measured the low frequency noise characteristics of these nanotube devices as charge detectors. The frequency dependence of the cross was roughly 1/f while Device2 had more of a $1/f^2$ character (f < 50 Hz). The current noise was measured for Device1 over one period of the gate modulation curve (at a bias of U_b = 0.4 mV), The 1/f noise at 10 Hz over one gate modulation period is shown in Fig. 3(a). As expected for a SET, the noise level varied with the gain of the nanotube device. The input equivalent charge noise q_n is obtained from the measured current noise i_n according to the formula $q_n = C_g i_n/(\partial I/\partial V_g)$. We obtain as the minimum charge noise at 10 Hz 6×10^{-4} e/√Hz (using i_n = 1 pA, $\partial I/\partial V_g$ = 3.5 nA/V) which corresponds to a typical value for a metallic SET device.

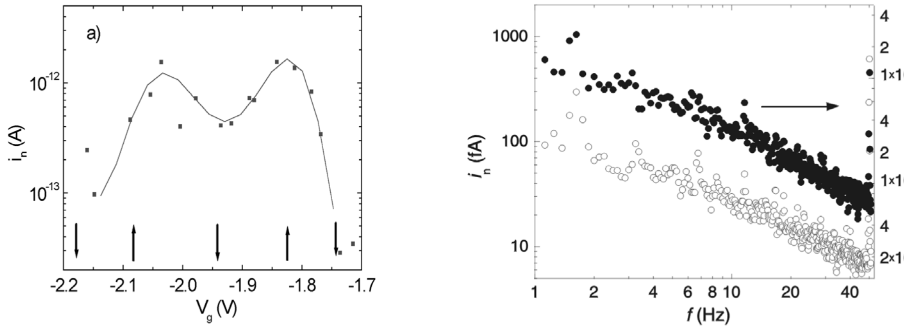

FIGURE 3. (a) Current noise (at 10 Hz) of Device1 measured over one Coulomb blockade oscillation. The up- and down-arrows refer to maximum and minimum gains, respectively. (b) Current noise of Device2 measured at minimum (lower) and maximum gain (upper trace). The right axis gives the equivalent charge noise δq for the upper trace.

Similar modulation of the noise was seen in Device2. At a frequency of 45 Hz we obtain the charge noise q_n as 6×10^{-6} e/√Hz, which is comparable to the best metallic SET devices reported to date [5]. Theoretically the minimum noise level for a SET is $\delta Q_{min} = \hbar C \Delta f R_Q / R_T$, where C is the total capacitance, Δf the frequency range and R_T is the tunneling resistance [6]. Taking $R_Q/4R_T \cong 1$ and assuming no cotunneling, we obtain the minimum noise as 1×10^{-6} e/√Hz. This implies that white noise would dominate over 1/f noise above 3 kHz.

In summary, we have demonstrated the good performance of multiwalled carbon nanotubes as building blocks of nanoscale electronic devices. Under proper conditions, such as separating the tube from the substrate, it is possible to minimize the noise level and in other aspects as well to approach the theoretical limits of performance.

ACKNOWLEDGMENTS

We thank C. Journet and P. Bernier from Universitè Montpellier II for supplying us with the nanotube material and F. Hekking, E. Sonin, and A. Zaikin for useful discussions.

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