Author(s): Ahlskog, M. & Tarkiainen, R. & Roschier, L. & Hakonen, Pertti J.

Title: Single-electron transistor made of two crossing multiwalled carbon nanotubes and its noise properties

Year: 2000

Version: Final published version

Please cite the original version:

Ahlskog, M. & Tarkiainen, R. & Roschier, L. & Hakonen, Pertti J.. 2000. Single-electron transistor made of two crossing multiwalled carbon nanotubes and its noise properties. Applied Physics Letters. Volume 77, Issue 24. 4037-4039. ISSN 0003-6951 (printed). DOI: 10.1063/1.1332107

AIP Applied Physics Letters

Single-electron transistor made of two crossing multiwalled carbon nanotubes and its noise properties

M. Ahlskog, R. Tarkiainen, L. Roschier, and P. Hakonen

Citation: Applied Physics Letters **77**, 4037 (2000); doi: 10.1063/1.1332107
View online: http://dx.doi.org/10.1063/1.1332107
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/77/24?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 24 11 DECEMBER 2000

Single-electron transistor made of two crossing multiwalled carbon nanotubes and its noise properties

M. Ahlskog,[a] R. Tarkiainen, L. Roschier, and P. Hakonen
Low Temperature Laboratory, Helsinki University of Technology, FIN-02015 HUT, Finland

(Received 29 August 2000; accepted for publication 19 October 2000)

A three-terminal nanotube device was fabricated from two multiwalled nanotubes by pushing one on top of the other using an atomic-force microscope. The lower nanotube, with gold contacts at both ends, 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 sub-Kelvin temperatures. The voltage noise of the nanotube single-electron transistor (SET) was gain dependent as in conventional SETs. The charge sensitivity at 10 Hz was $6\times10^{-4}\ e/\sqrt{\mathrm{Hz}}$. © *2000 American Institute of Physics.* [S0003-6951(00)05150-0]

Carbon nanotubes are currently being investigated as extraordinary realizations of one-dimensional quantum wires. Due to their mechanical robustness, they are freestanding even at the smallest diameters of around 1 nm. From the point of view of technological applications, nanotubes are proposed as building blocks of future molecular-scale electronic devices. Single-electron transistors (SETs) are one possibility, since the Coulomb blockade has been observed especially in devices made from single-walled nanotubes (SWNTs),[1,2] while in multiwalled nanotubes (MWNTs) only very few results have been reported.[3] Field-effect transistors based on semiconducting nanotubes have been demonstrated, made both from SWNTs and SWNT ropes.[4,5]

Recently, Collins, Fuhrer, and Zettl[6] reported electrical noise measurements at room temperature on both individual and networked SWNT samples. They found exceptionally large $1/f$ noise which was proportional to I^2. This kind of noise is generally ascribed to resistance fluctuations. In conventional SET devices, the $1/f$ noise is ascribed either to resistance fluctuations at the tunneling barriers[7] or to background charge fluctuations.[8] The latter can be distinguished since the noise caused by charge fluctuations is gain dependent, that is, follows the gate modulation. In this letter, we report on a nanotube-SET device made of two crossing MWNTs. One of these tubes exhibited Coulomb blockade, while the other one was used to gate the nanotube. The noise properties of this MWNT were measured in the Coulomb blockade regime.

The carbon nanotubes were synthesized using the arc-discharge method, and the nanotube material deposited onto a piece of Si/SiO_2 wafer[3] with Au alignment markers. After deposition, suitable tubes were located. The selected tubes, 15 nm in diameter, had the lengths $L=1.5$ and 2.3 μm for the upper and lower tubes, respectively. Originally, the tubes were separated by a few micrometers. To make a cross, the shorter tube was moved on top of the longer one according to the atomic-force microscope (AFM) manipulation scheme described in Ref. 9. Only one end of the upper tube was in contact with the surface, while the other end was a few tens of nanometers above the surface. Gold contacts (30 nm thick), in a two-probe configuration, were fabricated on top of the nanotubes with a 3 nm sticking layer of chromium. In addition, a planar gate electrode was placed 10 μm from the nanotube. The noise measurements were performed using a SR 570 current amplifier and a HP 3561 A spectrum analyzer.

An AFM image of the contacted crossing nanotubes is shown in Fig. 1. The lower nanotube had a room-temperature resistance $R_{300\ \mathrm{K}}=71$ kΩ, while the two-point resistance over the crossing was $\cong 10$ MΩ, a value significantly higher than those found for the resistance between crossing metallic SWNTs.[10] Furthermore, the zero-bias resistance increased to ~ 1 GΩ below 4 K. According to zero-bias resistances at low temperatures, the lower tube is metallic while the upper one is semiconducting. In this letter, we describe the transport properties of the lower tube as the island in a SET while the upper tube has been used as a highly proximate gate electrode.

Figure 2 displays I–V curves measured at temperatures from 300 K down to 150 mK. A Coulomb blockade develops fully only at sub-Kelvin temperatures, with a gap of about 1 mV at 150 mK. In the Coulomb blockade regime, the potential of the nanotube could be modulated employing either the designated gate electrode or the upper nanotube. Figure 3 shows the source–drain current I as a function of the bias voltage U_b and the gate voltage V_g. Figure 3 clearly portrays Coulomb blockade within the slightly inclined rhombic regions. *A priori*, symmetry is expected since the fabricated Au-MWNT contacts have approximately the same overlap size. Furthermore, from the shape of the Coulomb oscillations in the I vs V_g curves, it is concluded that $R_1\simeq R_2$, where R_1 and R_2 are the junction resistances at the opposite ends of the nanotube. We estimate the corresponding capacitances from Fig. 3 as $C_1=0.32$ fF and $C_2=0.22$ fF. We get for the charging energy $E_c=\frac{1}{2}e^2/(C_1+C_2+C_{\mathrm{tube}})=0.14$ meV, where we estimate the nanotube self-capacitance as $C_{\mathrm{tube}}=5\times10^{-7}$ F.

The gate modulation period was measured as $\Delta V_g=440$ mV using the planar gate electrode (Fig. 2, inset). This corresponds to $C_g=4\times10^{-19}$ F, a value clearly smaller than the nanotube self-capacitance. A Fourier analysis of the gate

[a]Electronic mail: markus@boojum.hut.fi

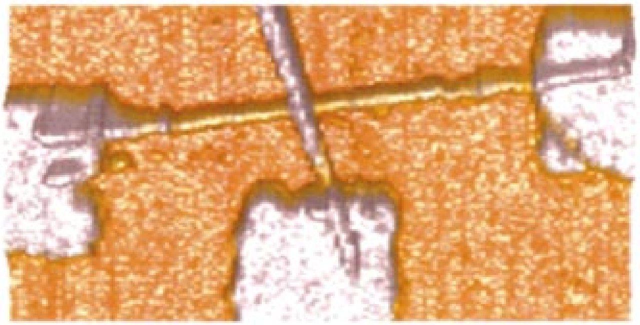

FIG. 1. (Color) AFM image of the fabricated multiwalled nanotube device. The lower tube has gold contacts at both ends, while the upper tube has only one end contacted (at the bottom of the image).

modulation curves also 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.[11]

The modulation period was much smaller, $\Delta V_g = 4.0$ mV, with the upper nanotube as the gate. We calculate the gate capacitance to the upper tube as $C_g = e/\Delta V_g = 4 \times 10^{-17}$ F. The present configuration with a crossing nanotube as a large-capacitance gate electrode is useful in certain SET applications for reducing cross talk between the gate and the other electrodes. Furthermore, since the voltage gain of a current-biased SET is C_g/C_2, such a construction allows for devices with high-voltage gain.[12]

We also measured the noise characteristics of our nanotube device as a charge detector. The current noise was measured over one period of the gate modulation curve (at a bias of $U_b = 0.4$ mV), starting from a point of minimum current, moving over the point of maximum current (0.35 nA) to the next point of minimum current. The noise measured at the output of our SET device had approximately a $1/f$ power spectrum. The $1/f$ noise at 10 Hz over one gate modulation period is shown in Fig. 4. 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

$$q_n = C_g i_n / (\partial I/\partial V_g). \quad (1)$$

We obtain as the minimum charge noise at 10 Hz 6×10^{-4} $e/\sqrt{\mathrm{Hz}}$ (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. Assuming equal background charge noise for the two nanotubes, we estimate that 20% of the measured noise comes from the upper tube. Compared with the gain variation, the modulation of the noise is imperfect in two ways. First, the noise displays a more irregular behavior with abrupt changes as a function of V_g. Second, the dip in the middle of the noise curve, corresponding to a zero-gain point at a maximum in current, is clearly rather shallow. Thus, this point exhibits a significantly larger noise level than the left and right minima (also with zero gain). One possibility is the presence of another, current-dependent, noise mechanism in addition to the charge fluctuations amplified by the SET. In fact, we have measured the noise outside the Coulomb blockade regime for a large range of currents.[13] At room temperature the noise

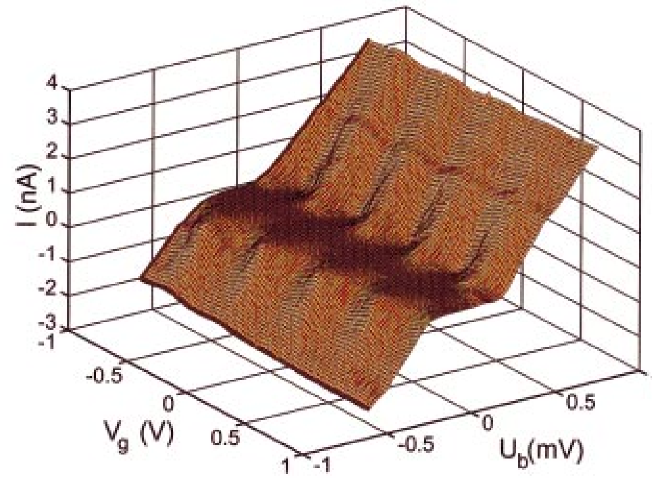

FIG. 3. (Color) Current of the nanotube SET as a function of gate voltage V_g and bias voltage U_b. The Coulomb blockade is clearly seen in the rhombic regions in the center.

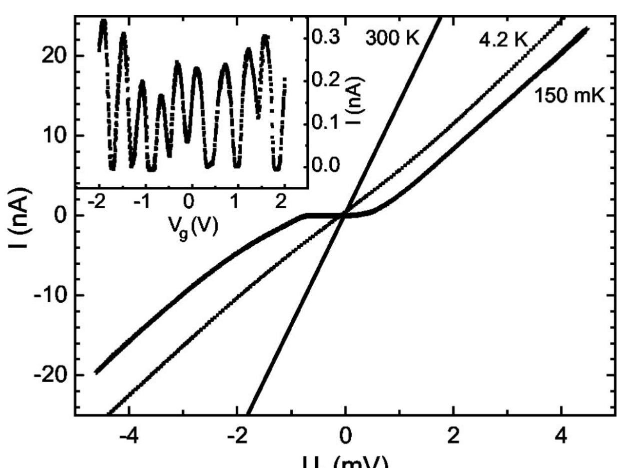

FIG. 2. Current–voltage characteristics of the lower tube at different temperatures. Inset: gate modulation of the current at $T = 150$ mK and $U_b = 0.4$ mV.

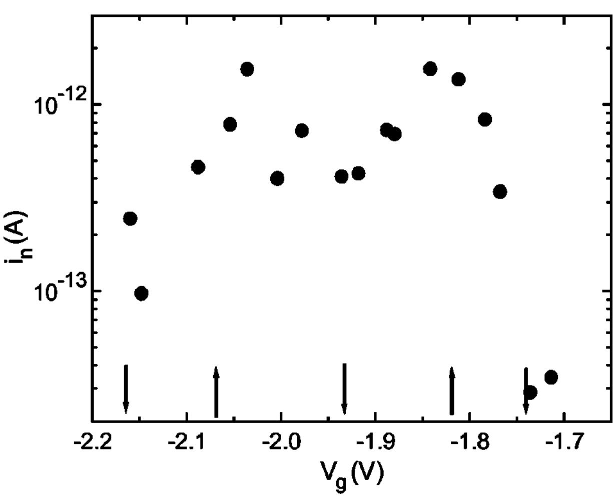

FIG. 4. Current noise (i_n) measured over one modulation period of the gate voltage in the regime of the Coulomb blockade. The bias voltage (U_b) was 0.4 meV. Arrows indicate points of maximum (up arrows) and minimum (down arrows) gain.

power of the MWNT (100× the 4 K power) is roughly equal to the noise measured in single SWNTs in Ref. 6. However, from these measurements we infer that the $i_n \sim 1$ pA noise in the middle of the modulation period is much larger (by two orders of magnitude) than what would be expected from the 0.35 nA current that passes through the nanotube SET. Thus, the noise mechanism of this nanotube SET seems to be more complicated than in conventional SETs.

We have described a three-terminal nanotube device that functions as a SET. Although the lower MWNT that forms the central island is rather extended, about 2 μm long, a single island picture can describe the SET properties. Also, the upper tube did not split the lower one in two sections. Due to the high intertube resistance, the upper tube could be used as a gate electrode with a relatively large capacitance. Our measurements show that strong resistance fluctuations do not compromise the behavior of the MWNT as a SET and that most of the noise is due to background charge variation, as in usual metallic devices. However, another unknown noise mechanism was also observed in the measurements.

This work was supported by the Academy of Finland and Takes of Finland via the Nanotechnology program. The authors thank Catherine Journet and Patrick Bernier from the University of Montpellier for supplying them with the nanotubes, and Mikko Paalanen, Jari Penttilä, and Christian Schönenberger for useful discussions.

[1] S. Tans, M. Devoret, H. Dai, A. Thess, R. Smalley, L. Geerligs, and C. Dekker, Nature (London) **386**, 474 (1997).
[2] M. Bockrath, D. Cobden, P. McEuen, N. Chopra, A. Zettl, A. Thess, and R. Smalley, Science **275**, 1922 (1997).
[3] L. Roschier, J. Penttilä, M. Martin, U. Tapper, C. Journet, P. Bernier, E. Kauppinen, P. Hakonen, and M. Paalanen, Appl. Phys. Lett. **75**, 728 (1999).
[4] S. Tans, R. Verschueren, and C. Dekker, Nature (London) **393**, 49 (1998).
[5] R. Martel, T. Schmidt, H. Shea, T. Hertel, and Ph. Avouris, Appl. Phys. Lett. **73**, 2447 (1998).
[6] P. Collins, M. Fuhrer, and A. Zettl, Appl. Phys. Lett. **76**, 894 (2000).
[7] V. Krupenin, D. Presnov, M. Savvateev, H. Scherer, A. Zorin, and J. Niemeyer, J. Appl. Phys. **84**, 3212 (1998).
[8] B. Starmark, T. Henning, T. Claeson, P. Delsing, and A. Korotkov, J. Appl. Phys. **86**, 2132 (1999).
[9] M. Martin, L. Roschier, P. Hakonen, Ü. Parts, M. Paalanen, B. Schleicher, and E. Kauppinen, Appl. Phys. Lett. **73**, 1505 (1998).
[10] M. Fuhrer, J. Nygård, L. Shih, M. Forero, Y.-G. Yoon, M. Mazzoni, H. Choi, J. Ihm, S. Louie, A. Zettl, and P. McEuen, Science **288**, 494 (2000).
[11] T. Hertel, R. Walkup, and P. Avouris, Phys. Rev. B **58**, 13870 (1998).
[12] E. Visscher, S. Verbrugh, J. Lindeman, P. Hadley, and J. Mooij, Appl. Phys. Lett. **66**, 305 (1995).
[13] M. Ahlskog, R. Tarkiainen, L. Roschier, and P. Hakonen (unpublished results).