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Manufacture of single electron transistors using AFM manipulation on multiwalled carbon nanotubes

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Abstract

We have investigated the potential of using multiwalled carbon nanotubes for constructing low-noise single-electron transistors (SETs). In our best devices, we use free-standing structures where the carbon nanotube is positioned on top of two 20-nm thick gold leads using AFM manipulation. A rapid, 10–30-s, heat treatment at 1000 K after manipulation results in a contact resistance of 10–20 kΩ. The $1/f$-noise is minimized in these free-standing constructions owing to the missing contact area with the SiO_2 substrate insulator that contains the trapping centers of charge. The measured equivalent background charge noise is in the range $2 \cdot 10^{-5}$–$6 \cdot 10^{-6}$ e/Hz$^{1/2}$ at frequencies of 10–45 Hz. These results are equal to those obtained on the best metallic devices available at present.

Keywords: Single electron transistor; Low noise electrometer; Carbon nanotubes

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1. Introduction

Carbon nanotubes, discovered in 1991 [1], represent a new building block for nanotechnology. They are like graphite sheets wrapped into seamless cylinders, the ends capped off by bucky-ball-like structures. The two types of nanotubes are multiwalled carbon nanotube (MWNT), where many tubes are arranged in a coaxial fashion, and a single walled nanotube (SWNT), consisting of only a single layer. The tubes are either metallic or semiconducting depending on how the graphite sheets are wrapped around (for example, see Ref. [2]).

The electrical properties of individual carbon nanotubes have been studied intensively during the

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past few years (for as recent review, see Ref. [3]). The behavior of MWNTs has turned out to be more complex than that of single walled tubes. One of the problems in MWNTs originates from the interlayer coupling which is poorly understood at present. It has been shown recently that several layers take part in the electrical conduction of MWNTs [4], whereas only one layer appears to dominate at low T [5]. One of the basic attractive features of single electronics devices made of MWNTs is that operation at 4 K and above is achievable in a straightforward manner [6,7].

In our work [8–11], we have elucidated transport properties of individual MWNTs, using atomic force manipulation in sample selection and fabrication. Owing to large contact resistance, these tubes tend to behave as single electron transistors (SET). We have measured I–V and noise characteristics of about ten such devices altogether. In this paper, we briefly describe the fabrication and noise characteristics of our best MWNT SETs.

2. Construction of nanotube circuits using AFM manipulation

In construction of our good quality MWNT SETs, we use arc-discharge-grown tubes (AD).[1] In addition to the better electrical properties of AD tubes as compared with CVD tubes [6], AD tubes also behave more stiffly and regularly during AFM manipulation. The deposition of MWNTs was done as described in Ref. [8], after first patterning 200-nm wide gold leads lithographically. The AFM manipulation was done on a PSI CP operated in the non-contact mode [11]. Using our method, the location of the object can be seen *in real time* during the movement by monitoring the cantilever oscillation amplitude. This allows us to construct electrical circuits containing several nanotubes at optimum speed or accurately position MWNTs on top of gold electrodes. An illustration of this process is given in Fig. 1.

The Au–NT contact resistance R_{cont} is typically around 100 kΩ after the AFM manipulation, unless special measures are taken to reduce it. Bachtold et al. [12] successfully used electron bombardment in SEM, while Lee et al. [13] used quick heating at high temperature to decrease R_{cont}. We have also employed this method: R_{cont} was reduced considerably by a 30-s annealing of the sample in vacuum at 700 °C. After the heat treatment, the nanotube was slightly embedded, about 5 nm, into the underlying gold. We also observed that the mechanical strength of the contact was increased.

3. Free-standing MWNTs as single electron transistors

Fig. 1b illustrates the structure of a single electron transistor made out of a 0.5-μm long free-standing MWNT. For this particular sample, the total resistance was measured to be $R_{TOT} \approx 40$ kΩ outside the Coulomb blockade regime. As the Au–NT contact resistance R_T is smaller than the quantum resistance $R_Q = h/e^2 \approx 26$ kΩ, the sample is in the strong tunneling regime. Hence, sub-Kelvin temperatures were required to characterize its SET behavior properly.

[1]Synthesized by C. Journet and P. Bernier, University of Montpellier, France.

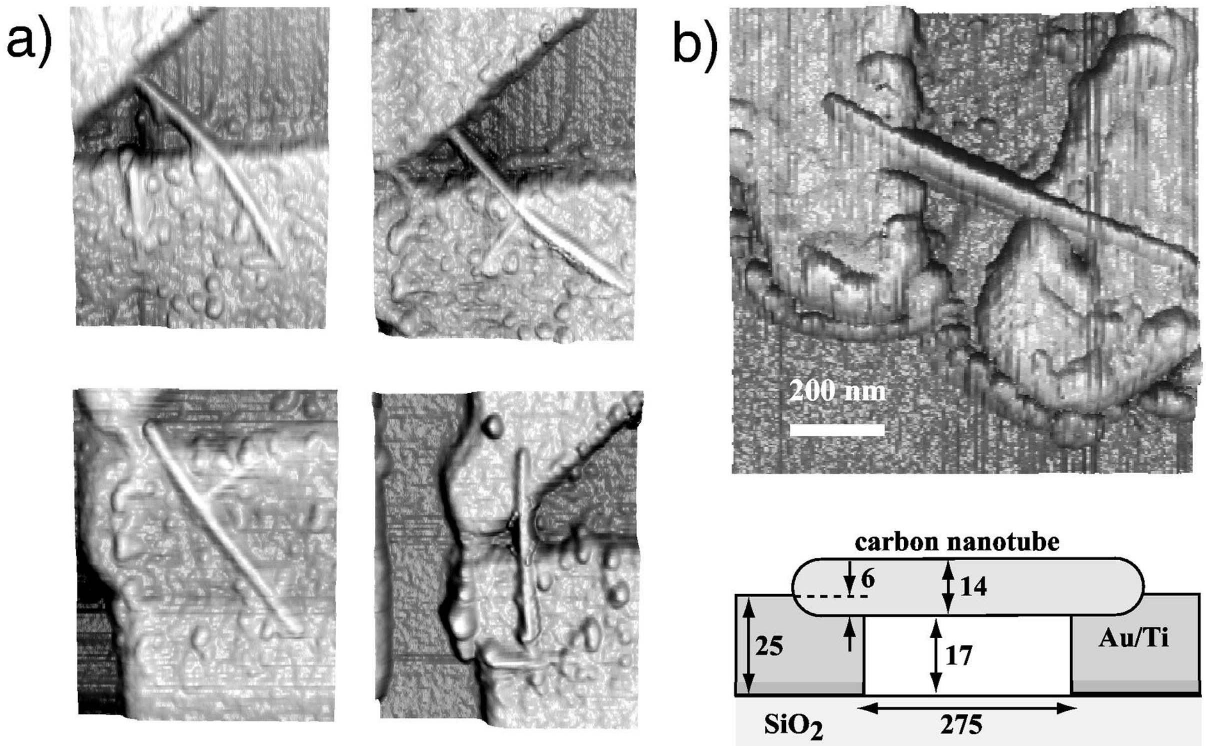

Fig. 1. (a) A sequence of AFM images illustrating the construction of a single electron transistor made of a 0.5-μm long arc-discharge-grown nanotube. (b) The final electrometer configuration with a free-standing section of 0.3 μm after the heat treatment. Gate leads (not visible in the figures), having the same width as the other electrodes, terminate at a distance of 2 μm from the nanotube island.

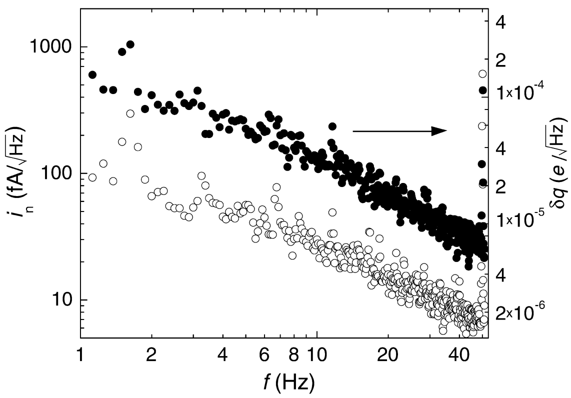

Fig. 2. Current noise i_n measured at $T = 0.15$ K [10]; equivalent background charge fluctuation δq is given on the right scale. Open circles denote the amplifier noise in the measurement setup.

Current noise i_n, measured at a small voltage bias of 70 μV, is displayed in Fig. 2. Frequency dependence of the noise power (i_n^2) has a $1/f^2$ character over the range $5 < f < 50$ Hz. The input equivalent charge noise q_n is obtained from the measured current noise according to the formula: $q_n = C_g i_n / (\partial I / \partial V_g)$. At a frequency of 45 Hz, we obtain the charge noise $q_n = 6 \cdot 10^{-6}\ e/\sqrt{\mathrm{Hz}}$, which is comparable to the best metallic SET devices reported to date [14]. The good noise properties are assigned to the nearly ballistic nature of conduction in our samples. The ballisticity of a free-standing sample is likely to be enhanced by the decreased capacitive coupling between impurity states of the substrate and the MWNT.

Compared with Al-devices, the gate modulation curves of our MWNT SETs are not as sharp. This is partially caused by strong environmental fluctuations in the MWNT itself due to the large real part of its impedance at high frequencies. The softening in the gate modulation curve can be reduced in structures equipped with a backgate. Using strong electrostatic doping by backgate, the characteristic impedance is lowered by an enhancement of the number of conduction channels in the MWNT.

In summary, we have demonstrated that multiwalled carbon nanotubes can be employed as low-noise electrometers. According to our results, background charge noise in a MWNT SET is strongly suppressed by minimizing the contact area of the nanotube island with any dielectric material in its surroundings. At frequencies around 50 Hz, our MWNT devices are equally good as the best Al/AlO_x SETs available at present.

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References

[1] S. Iijima, Nature 354 (1991) 56.
[2] R. Saito, G. Dresselhaus, M.S. Dresselhaus, Physical Properties of Carbon Nanotubes, Imperial College Press, London, 1998.
[3] Special Issue on Nanotubes, Physics World, June (2000) 29.
[4] P.G. Collins, R. Martel, P. Avouris, in: Proceedings of the NT-2001 Conference (CD-ROM), July 22–25, Potsdam, Germany, 2001.
[5] C. Schönenberger, A. Bachtold, C. Strunk, J.-P. Salvetat, L. Forro, Appl. Phys. A 69 (1999) 283;
A. Bachtold, C. Strunk, J.-P. Salvetat, J.-M. Bonard, L. Forro, T. Nussbaumer, C. Schönenberger, Nature 397 (1999) 673.
[6] M. Ahlskog, P. Hakonen, M. Paalanen, L. Roschier, R. Tarkiainen, J. Low Temp. Phys. 124 (2001) 335.
[7] Recently, even a room temperature device with kink tunnel junctions on a SWNT has been constructed; H.W.Ch. Postma, T. Teepen, Z. Yao, M. Grifoni, C. Dekker, Science 293 (2001) 76.
[8] L. Roschier, J. Penttilä, M. Martin, P. Hakonen, M. Paalanen, U. Tapper, E.I. Kauppinen, C. Journet, P. Bernier, Appl. Phys. Lett. 75 (1999) 728.

[9] M. Ahlskog, R. Tarkiainen, L. Roschier, P. Hakonen, Appl. Phys. Lett. 77 (2000) 4037.
[10] L. Roschier, R. Tarkiainen, M. Ahlskog, M. Paalanen, P. Hakonen, Appl. Phys. Lett. 78 (2001) 3297.
[11] M. Martin, L. Roschier, P. Hakonen, Ü. Parts, M. Paalanen, B. Schleicher, E.I. Kauppinen, Appl. Phys. Lett. 73 (1998) 1505.
[12] A. Bachtold, M. Henny, C. Terrier, C. Strunk, C. Schönenberger, J.-P. Salvetat, J.-M. Bonard, L. Forró, Appl. Phys. Lett. 73 (1998) 274.
[13] J.-O. Lee, C. Park, J.J. Kim, J. Kim, J.-W. Park, K.-H. Yoo, J. Phys. D 33 (2000) 1953.
[14] V.A. Krupenin, D.E. Presnov, M.N. Savvateev, H. Scherer, A.B. Zorin, J. Niemeyer, J. Appl. Phys. 84 (1998) 3212; V.A. Krupenin, D.E. Presnov, A.B. Zorin, J. Niemeyer, J. Low Temp. Phys. 118 (2000) 287.