LOW-NOISE ELECTROMETER MADE OF MULTIWALLED CARBON NANOTUBE

L. ROSCHIER, R. TARKIAINEN, M. AHLSKOG, and P. HAKONEN
Low Temperature Laboratory, Helsinki University of Technology, FIN-02015 HUT, Finland

We investigate the possibility of using multiwalled carbon nanotubes for constructing low-noise single-electron transistors (SETs). 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 sec, heat treatment at 1000 K after the manipulation results in contact resistances of 10-20 kΩ. The $1/f^{\alpha}$-noise is minimized in these free-standing constructions owing to the missing contact area with the SiO_2 substrate insulator that contains trapping centers of charge. The measured equivalent background charge noise is in the range $2{\cdot}10^{-5}$ ... $6 \cdot 10^{-6} e/\sqrt{Hz}$ at frequencies 10 ... 45 Hz. Good noise properties seem to be connected with the increase of conductance observed near zero bias.

1 Introduction

Multiwalled carbon nanotubes present a new, versatile class of building blocks for nanoelectronics [1,2,3]. Owing to their large kinetic inductance, MWNTs have been found to work as high impedance transmission lines with characteristic impedance $Z \sim 5$ kΩ [4]. Single electron transistors (SET) with regular gate modulation and charge-noise properties have been manufactured [5]. An additional feature that makes MWNT-SETs appealing is their small island capacitance, which makes it simple to produce devices working at a temperature of $T = 4.2$ K.

SETs are often characterized by their $1/f^{\alpha}$-noise. Typically, α varies between $1-2$ and the magnitude of the noise lies in the range $2{\cdot}10^{-3}$ ... $1{\cdot}10^{-4} e/\sqrt{Hz}$ at 10 Hz. Some Al- devices of stacked design have reached noise levels of $8{\cdot}10^{-6} e/\sqrt{Hz}$ [6]. The $1/f^{\alpha}$-noise in SETs is often caused by background charge variations in the dielectric substrate material [7].

The only known way to reduce this $1/f^{\alpha}$-noise in SETs is to avoid contact of the central island with any dielectric material [6]. In our devices, this is achieved by using a free-standing nanotube as an island. We use manipulation by atomic force microscope [8] to move a multiwalled carbon nanotube (MWNT) on top of two 20-nm-thick gold electrodes separated by 0.3 μm. For constructional details, we refer to Ref. 9.

When fabricating a SET-device with optimum charge sensitivity, current modulations should be maximized by using low impedance tunneling barriers such that they are on the order of quantum resistance $R_K = 26$ kΩ. In our samples low resistance is achieved by a rapid, 10 - 30 second heat treatment. Typically, contact resistances on the order of 10-20 kΩ are obtained, but substantial variation is observed. Owing to such a small contact resistance, our devices are already in the strong tunnelling regime, where the Coulomb-blockade in the IV-characteristics becomes slightly smoothened. In this paper we present results and analyze the conductance and noise properties of one particularly good sample manufactured of arc-discharge grown nanotube material. This sample exhibits low noise and good conductivity, both features of which we assign to the good purity of our samples

2 IV-characteristics and Noise Measurements

Fig. 1a illustrates the IV-curve of our sample measured at $T = 150$ mK. It shows a total resistance of $R \simeq 40$ kΩ at voltages $V > 10$ mV outside the Coulomb blockade regime. For the average junction capacitance we estimate $C_T = 40$ aF using the offset voltage in the IV-curve measured at $V > 10$ mV. Here we neglect the small asymmetry in the size of the Au-NT contact areas at the ends: 200/400 nm in length, respectively.

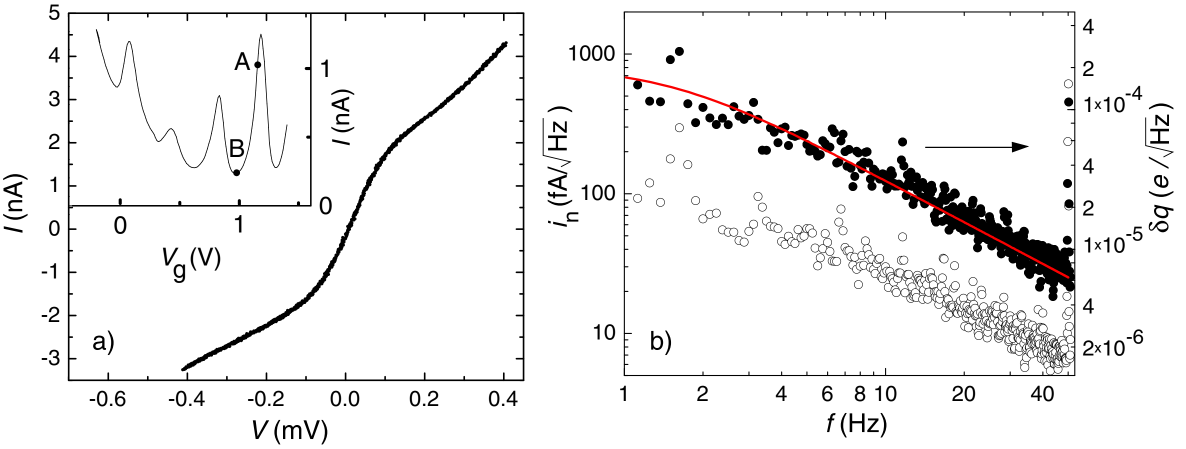

Figure 1: a) IV-curve of the device in Fig. 1 measured at $T = 150$ mK. In the middle of a rather weak Coulomb blockade there is an increase of conductance indicating resonant tunnelling over the multiwalled nanotube sample. The inset illustrates the gate modulation at a bias voltage of $V_{bias} = 70\ \mu$V. Points marked by A and B denote biasing conditions for noise measurements at maximum and zero gain, respectively. b) Current noise i_n measured at minimum (lower) and maximum gain (upper trace). The right axis, obtained by scaling with the inverse of charge sensitivity $1/g_{ch} = 0.25$ e/nA, gives the equivalent charge noise δq for the upper trace.

In Fig 1a, there is an increase of conductance near zero bias voltage, contrary to the expected Coulomb blockade. We attribute this to resonant tunnelling which, however, leads to only two weakly quantized steps in the IV-curve. Thus, we regard our sample as semiballistic, *i.e.*, intermediate between ballistic and diffusive behavior. We believe that ballisticity of a free-standing tube is enhanced over a regular sample mostly for two reasons: 1) impurities on the substrate are further away and fluctuations induced by them become more unlikely, and 2) the amount of dirt on the surface of the nanotube is reduced during the AFM manipulation [10] and vacuum brazing.

Current modulation with respect to the gate voltage, shown in the inset of Fig. 1a, illustrates the sensitivity of our SET device. The modulation curve has been measured with voltage bias at $V_{bias} = 70\ \mu$V which corresponds to a peak current of 1.2 nA. At the point marked by A in Fig. 1a, we have the maximum slope of $k = 11$ nA/V. The roundedness of the modulation curve is assigned to strong tunnelling effects since the tunnelling resistances, $10 - 20$ kΩ are below R_Q. Note that the gate modulation curve in the inset of Fig. 1a is not fully periodic: it does not show any effects related with even-odd number of electrons, which have been observed by Nygård *et al* in relation to the Kondo-effect in single-walled carbon nanotubes [11].

The noise current, measured both at maximum and minimum gain of the electrometer (points A and B in Fig. 1a, respectively), is displayed in Fig. 1b. As argued in Ref. 9, we interpret our current noise measurements in a similar fashion as in regular metallic devices. From the inset of Fig. 1a, we deduce a value for the charge sensitivity $g_{ch} = \frac{\Delta I}{\Delta q} = \frac{dI}{dV_g}\Delta V_{gate}/e = 4$ nA$/e$ at point A. At the maximum gain, we obtain the minimum equivalent input charge noise of our device. The frequency dependence of this minimum noise power is close to $1/f^2$, a relationship that has occasionally been observed on metallic samples as well [6]. The observation of this kind of noise spectrum is an indication of a strong single fluctuator (random telegraph noise) which yields a Lorentzian spectrum [13] of the form

$$S_Q = \frac{B}{1 + 4\pi^2\tau^2 f^2} \tag{1}$$

The solid curve in Fig. 1b illustrates the fitting of this formula using the parameters $A = 1.52 \cdot 10^{-9} e^2$, $B = 4.4 \cdot 10^{-8} e^2/Hz$ and $\tau = 0.11$ s. The agreement of Eq. (1) with data measured on other samples is found to be good as well. For further details of random telegraph noise in MWNTs, we refer to Ref. 12.

At a frequency of $f = 45$ Hz, we obtain a charge noise of $6{\cdot}10^{-6}$ e/$\sqrt{Hz}$, which is close in the performance to the best metallic devices with 8 $\cdot 10^{-6}$ e/$\sqrt{Hz}$ at 10 Hz and ($\sim 4{\cdot}10^{-6}$ e/$\sqrt{Hz}$ at 45 Hz extrapolated using $1/f$ noise dependence) [6].

The minimum noise level for a SET is given by $\delta Q_{min} = \sqrt{\hbar C_\Sigma \Delta f R_Q / 4R_T}$ where $C_\Sigma \sim 2C_T$ is the total island capacitance and Δf denotes the bandwidth of the measurement [14]. Taking $R_Q/4R_T \sim 1$ and assuming that the cotunneling rate is not large, we get for the minimum noise $1 \cdot 10^{-6}$ e/$\sqrt{Hz}$. This means that white noise will dominate over $1/f^2$-noise above 3 kHz in our device. Hence, the shot noise dominated region can in principle be reached using low-noise, high-band current preamplifiers. Recently, we have succeeded in measuring shot noise in MWNTs at $f = 10$ kHz using currents of 100 nA, *i.e.*, slightly above the Coulomb-blockade region [12].

3 Conductance vs. Gate Voltage

The general behavior of the sample described above is a bit exceptional when compared with our other samples. To elucidate its properties, we show the measured conductance for this sample at eight different gate voltages in Fig. 2. The conductance traces display clear peaks which are spaced apart by about 0.7 mV. According to length-quantized single-particle states , $eV = \hbar v_F / 2L$, the effective length L would be 350 nm. Note that these peaks in the $G(V)$ curves are rather wide, clearly broader than expected on the basis of temperature $T = 150$ mK.

Another possible explanation for the measured $G(V_g)$ is provided by Kondo-resonances, observed recently by Nygård *et al*[11] in single walled nanotubes. The observed shape and gate dependence of the peaks in Fig. 2 are similar to those reported in Ref. 11. However, since tuning of the gate voltage moves the peak off from the Fermi-level in our data, these results cannot be assigned to typical Kondo-resonance behavior in which the resonance stays always at the Fermi level. Nevertheless, we believe that our results are caused by the presence of some kind of resonance states which go hand in hand with the good quality (and small noise) of the present sample. A comprehensive theory for this must be worked out before our data can be explained properly.

4 Summary

We have shown that free-standing multi-walled carbon nanotubes provide excellent SET-devices for electrometer applications in nanoelectronics. The noise performance of our good-quality sample is dominated by random telegraph type of noise with Lorentzian spectrum. The background charge noise at small bias, $6{\cdot}10^{-6}$ e/$\sqrt{Hz}$ at $f = 45$ Hz, is close to that of the best state-of-the-art metallic devices. The reasons behind the good operation are the absence of contact with dielectric material and the probable nearly ballistic propagation in this system.

Acknowledgments

We wish to thank Catherine Journet and Patrick Bernier from the University of Montpellier for the high-quality, arc-discharge-grown nanotubes. Fruitful discussions with Frank Hekking, Edouard Sonin, and Andrei Zaikin are gratefully acknowledged. This work was supported by the Academy of Finland and by the Human Capital and Mobility Program ULTI of the European Union.

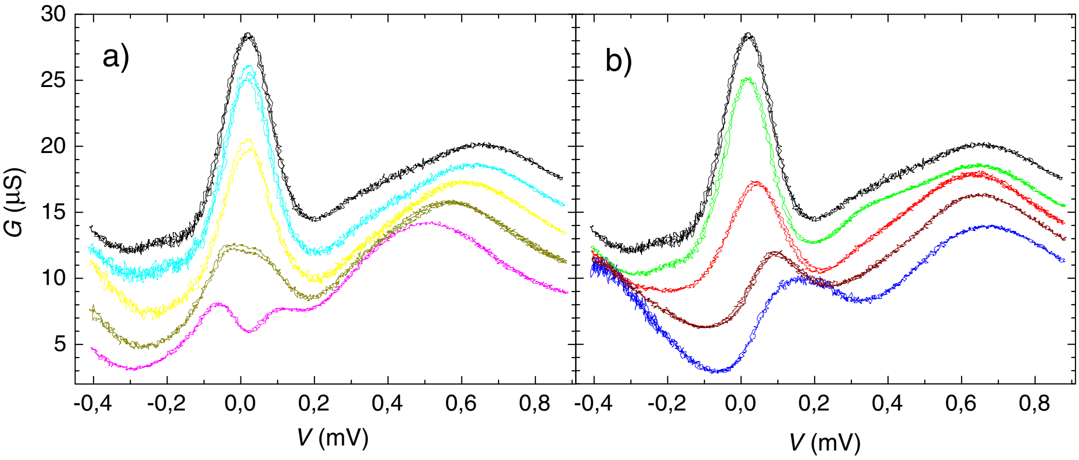

Figure 2: a) Conductance G vs. bias voltage V measured at $V_{gate} = -0.6, -0.65, -0.7, -0.75, -0.8$ V and (b) at $V_{gate} = -0.4, -0.45, -0.5, -0.55, -0.6$ V. $V_{gate} = -0.6$ V corresponds to the best conductance at small bias voltages.

References

1. See, *e.g.*, "Special Issue on Nanotubes" in Physics World, June 2000, p. 29, and also C. Dekker, Physics Today, May 1999, p. 22.
2. C. Schönenberger, A. Bachtold, C. Strunk, J.-P. Salvetat, and L. Forro, Applied Physics A **69**, 283 (1999).
3. M. Ahlskog, P. Hakonen, M. Paalanen, L. Roschier, and R. Tarkiainen, cond-mat/0104256.
4. R. Tarkiainen, M. Ahlskog, J. Penttilä, L. Roschier, P. Hakonen M. Paalanen, and E. Sonin, submitted to Phys. Rev. B.
5. M. Ahlskog, R. Tarkiainen, L. Roschier, and P. Hakonen Appl. Phys. Lett. **77**, 4037 (2000).
6. V.A. Krupenin, D.E. Presnov, M.N. Savvateev, H. Scherer, A.B. Zorin, and J. Niemeyer, J. Appl. Phys. **84**, 3212 (1998); V.A. Krupenin, D.E. Presnov, A.B. Zorin, and J. Niemeyer, J. Low Temp. Phys. **118**, 287 (2000).
7. See, *e.g.* B. Starmark, T. Henning, T. Claeson, P. Delsing, and A.N. Korotkov, J. Appl. Phys. **86**, 2132 (1999), and refrences therein.
8. L. Roschier, J. Penttilä, M. Martin, P. Hakonen, M. Paalanen, E. Kauppinen, U. Tapper, C. Journet, and P. Bernier, Appl. Phys. Lett. **75**, 728 (1999).
9. L. Roschier, R. Tarkiainen, M. Ahlskog, M. Paalanen, and P. Hakonen, Appl. Phys. Lett. **78**, 3297 (2001).
10. S. Frank, P. Poncharal, Z.L. Wang, W. A. de Heer, Science **280**, 1744 (1998).
11. J. Nygård, D.H. Cobden, and P.E. Lindelöf, Nature **408**, 342 (2000).
12. R. Tarkiainen *et al.*, to be published.
13. See *e.g.* Sh. Kogan, *Electronic Noise and Fluctuations in Solids* (Cambridge University Press, Cambridge, 1996), p. 31.
14. A.N. Korotkov, D.V. Averin, K.K. Likharev, and S.A. Vasenko, in *Single-Electron Tunneling and Mesoscopic Physics*, edited by H. Koch and H. Lubbig (Springer, Berlin, 1992), p.45; A. Korotkov, Phys. Rev. B **49**, 10381 (1994).