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Multiwalled carbon nanotubes as ultrasensitive electrometers

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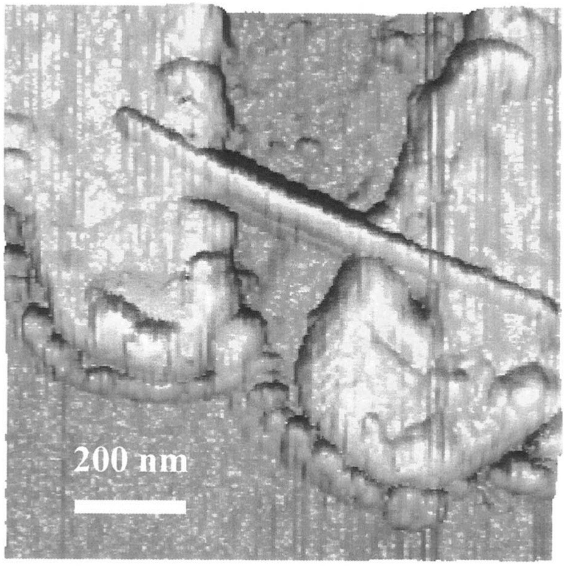
We show that it is possible to construct low-noise single-electron transistors (SETs) using free-standing multiwalled carbon nanotubes. The $1/f^{\alpha}$-noise of our devices, 6×10^{-6} e/$\sqrt{\mathrm{Hz}}$ at 45 Hz, is close in the performance to the best metallic SETs of today. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1362281]

Carbon nanotubes present a promising class of building blocks for nanoelectronics.[1] Single walled nanotubes (SWNT) are believed to be ballistic conductors,[2] whereas experimental work on multiwalled nanotubes (MWNT) has yielded conflicting results on the nature of conduction: Frank *et al.*[3] have obtained evidence that conductance in MWNTs is ballistic, while the magnetoresistance investigations by Langer *et al.*[4] and by Schönenberger and coworkers[5] suggest diffusive conduction.

Contact resistance between a metal and a nanotube is commonly on the order of quantum resistance $R_Q=h/e^2=26.5$ kΩ. Hence, quantum fluctuations do not destroy charge quantization[6] and it is possible to construct sensitive electrometers based on electrostatically-controlled single electron tunneling. Such devices, called single electron transistors (SETs), are the best electrometers known at present. The sensitivity of SETs approaches the quantum limit at high frequencies,[7] but at frequencies below 1 kHz, these devices are plagued by the presence of $1/f^{\alpha}$-noise ($\alpha\sim1-2$). The present picture of $1/f^{\alpha}$-noise, based on several investigations,[8] indicates that typically the fluctuations are caused by trapping centers of charge, either in the vicinity of the island or in the tunnel barriers, while sometimes conductance variations in the tunneling resistances are the main cause of noise.[9]

The only known way to reduce $1/f^{\alpha}$-noise in SETs is to avoid contact of the central island with any dielectric material.[9] In our device, this is achieved by using a free-standing nanotube as an island. We used manipulation by atomic force microscope[10] to move a multiwalled carbon nanotube (MWNT) on top of two adjacent gold electrodes (see Fig. 1). Vacuum brazing at 700 C for 30 sec was employed to embed the tube 6 nm into the gold. In the final structure, the MWNT ($\phi=14$ nm) has a 275 nm long free-standing section hanging at a distance of 17 nm above the substrate. We measured a total resistance of $R\simeq40$ kΩ at voltages $V>10$ mV outside the Coulomb blockade regime. We estimate $R_T\sim15$ kΩ for the tunneling resistance of the 200–400 nm long Au-NT overlap sections using the assumptions that the device has a symmetric structure and a resistance of $R\sim10$ kΩ for the tube itself. The junction capacitance $C_T=40$ aF corresponds to the offset voltage in the *IV*-curve measured at $V>10$ mV.

Figure 2 displays a *IV*-curve of our device measured at $T=150$ mK. Contrary to the expected Coulomb blockade, there is an increase of conductance near zero bias voltage. We attribute this to resonant tunneling which, however, leads to only two weakly quantized steps in the *IV*-curve. Thus, our sample is semiballistic, i.e., its behavior is intermediate between ballistic and diffusive propagation. We believe that ballisticity of free-standing tubes is enhanced over regular samples for three reasons: (1) impurities on the substrate are further away and fluctuations induced by them become more unlikely, (2) the amount of dirt on the surface of the nanotube is reduced during the AFM manipulation, and finally (3) the plasmon speed, sensitive to the permittivity of the substrate material, is increased.



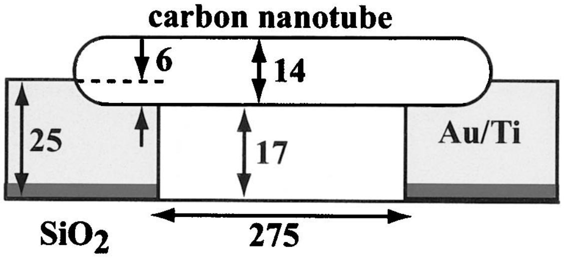


FIG. 1. Top: Non-contact-mode atomic force microscope image of a free-standing, multiwalled carbon nanotube stretching between two gold electrodes. The gold-nanotube contact sections are seen to be slightly asymmetric. Distance from the nanotube to the side gate, not shown in the image, is 700 nm. Bottom: Schematic cross-sectional view of our nanotube sample showing the most important geometrical dimensions in nanometers. The titanium sticking layer between gold and silicon dioxide is 2 nm in thickness.

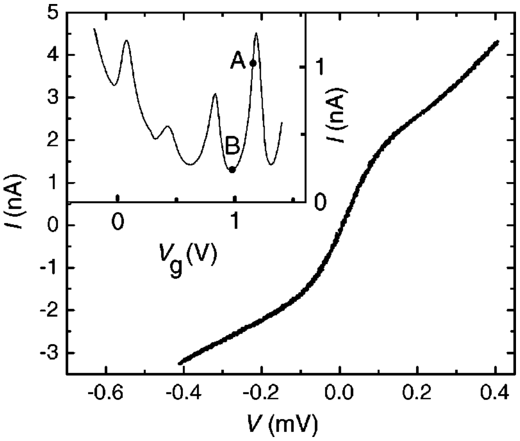


FIG. 2. IV-curve of the device in Fig. 1 measured at $T = 150$ mK. In the middle of a rather weak Coulomb blockade there is an increase of conductance indicating resonant tunneling over the multiwalled nanotube sample. The inset illustrates the gate modulation at a bias voltage of $V_{bias} = 70$ μV. Points marked by A and B denote biasing conditions for noise measurements at maximum and zero gain, respectively.

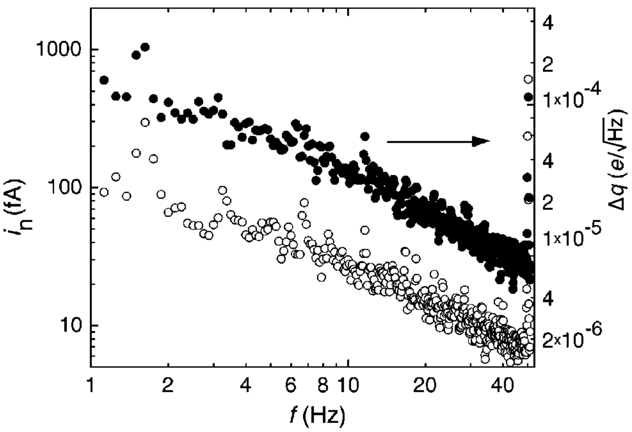


FIG. 3. Current noise i_n measured at minimum (lower) and maximum gain (upper trace). The right axis, obtained by scaling with the inverse of charge sensitivity $1/g_{ch} = 0.25$ e/nA, gives the equivalent charge noise Δq for the upper trace.

Current modulation with respect to the gate voltage, shown in the inset of Fig. 2, illustrates the sensitivity of our SET device. The modulation curve has been measured with a voltage bias at $V_{bias} = 70$ μV which corresponds to a peak current of 1.2 nA. At the point marked by A in Fig. 2, we have the maximum slope of $k = 11$ nA/V. The roundedness of the modulation curve is assigned to strong tunneling effects since the tunneling resistances are below R_Q. In terms of the total SET resistance, the modulation curve corresponds to a variation over the range $R = 60–300$ kΩ.

In addition to Coulomb blockade phenomena, one has to account for the quantum-dot-like behavior in a semiballistic device. In order to obtain the charge sensitivity, we rely on the arguments presented for semiconducting nanostructures: for a small carrier density on the island, as should be for a nanotube, the gate modulation period is given by the formula $\Delta V_{gate} = \Delta E/e + e/C_{gate}$.[11] Since the single-particle level separation $\Delta E = hv_F/2L \sim 1$ mV (using Fermi velocity $v_F = 8\times10^5$ m/s and length $L = 1$ μm), and since our device is equipped with a remote side gate having $C_{gate} = 0.44$ aF, the gate modulation period is governed by Coulomb effects. Here we neglect effects related with the fact that the coupling of the gate is stronger to the free-standing part than to the sections sitting on gold, which may lead to interesting phenomena of their own.[12] Due to the large number of modes in a MWNT, Luttinger liquid behavior observed in single walled nanotubes[13] is expected to be weakened strongly. Hence, our current noise measurements can be interpreted in a similar fashion as in regular metallic devices. From the inset of Fig. 2, we deduce a value for the charge sensitivity $g_{ch} = \Delta I/\Delta q = k\Delta V_{gate}/e = 4$ nA/e at point A.

The noise current, measured both at maximum and minimum gain of the electrometer (points A and B in Fig. 2, respectively), is displayed in Fig. 3. At the maximum gain, we obtain the minimum equivalent input charge noise of our device. The frequency dependence of this minimum noise is close to $1/f^2$, a relationship that has occasionally been observed on metallic samples as well.[9] At a frequency of $f = 45$ Hz, we obtain a charge noise of 6×10^{-6} $e/\sqrt{\mathrm{Hz}}$, which is close in the performance to the best metallic devices with 8×10^{-6} $e/\sqrt{\mathrm{Hz}}$ at 10 Hz ($\sim 4\times10^{-6}$ $e/\sqrt{\mathrm{Hz}}$ at 45 Hz extrapolated using $1/f$ noise dependence).[9] We note that our results have been obtained in the range of large currents where the separation of preamplifier noise does not pose any problems, unlike in many previous works.

According to theoretical analysis,[14] the minimum noise level for a SET is given by $\delta Q_{min} = \hbar C_\Sigma \Delta f R_Q/4R_T$ where $C_\Sigma \sim 2C_T$ is the total island capacitance and Δf denotes the frequency span of the measurement. Taking $R_Q/4R_T \sim 1$ and assuming that the cotunneling rate is not large, we get for the noise floor 1×10^{-6} $e/\sqrt{\mathrm{Hz}}$. In fact, the actual noise limit for a resonant tunneling structure might be slightly less, as the ultimate energy sensitivity of such a device was recently shown to be $\hbar/\sqrt{3}$.[15] Thus, we expect that white noise will dominate over $1/f^2$-noise above 3 kHz in our device. This shot noise dominated region is just within reach using available, high-quality current preamplifiers.

In summary, we have shown that multi-walled carbon nanotubes provide excellent building blocks for nanoelectronics and that they allow the construction of record-sensitive electrometers based on single electron tunneling in the semiballistic regime. Owing to the 15 kΩ impedance of the gold-nanotube junctions, quantum limited performance can be easily reached at frequencies around 3 kHz, without any recourse to elaborate microwave read-out schemes.[7]

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