1/f NOISE IN CARBON NANOTUBES [a]

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The low-frequency electronic noise properties of individual single-wall metallic carbon nanotubes are investigated. The noise exhibits a $1/f$ frequency dependence and a V^2 voltage dependence. The noise power at 8 K appears to be three orders of magnitude smaller than at 300 K. As a demonstration of how these noise properties affect nanotube devices, a preliminary investigation of the noise characteristics of a fabricated intramolecular carbon nanotube single-electron transistor is presented.

The electronic properties of carbon nanotubes have attracted a lot of interest in both fundamental as well as application-driven studies.[1] Almost all of these studies focussed on the DC electronic properties, and little is known about the AC or noise properties. Only recently, the noise characteristics of carbon nanotubes have become the subject of investigation. The first measurements show that the low-frequency electronic noise is dominated by $1/f$ noise.[2,3] Many issues remain unclear, however, for example, how the noise power depends on temperature. Knowledge of the noise characteristics is important to characterize performance of nanotube devices. The study of the fluctuation phenomena will also enable one to examine, for instance correlation-induced reduced shot noise[4] in Luttinger liquids or bunching/anti-bunching-type phenomena that probe the quantum statistics[5,6] of electrons in nanotubes. Here, we report a characterization of the low-frequency electronic noise properties of individual metallic single-wall carbon nanotubes. The frequency dependence follows Hooge's law. Upon lowering temperature to 8 K, the noise power is reduced by three orders of magnitude. As an example of how this low-frequency noise affects the performance of nanotube devices, we study the charge sensitivity of an intramolecular carbon-nanotube single-electron transistor.

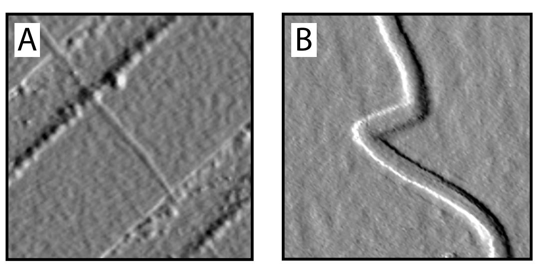

Figure 1: Atomic force microscope amplitude images of metallic carbon nanotubes. **a**) A straight nanotube connected by two Au electrodes lying on a SiO_2 surface. The image is 1 μm^2. **b**) A metallic nanotube with two buckles which have been induced with the atomic force microscope. The image size is 100×100 nm^2.

Individual carbon nanotube samples are fabricated as described before.[7] Figure 1a shows an example of a straight nanotube, connected by metallic electrodes. On such samples we have characterized the amount of $1/f$ noise present in nanotubes. In Fig. 1b, a double-buckle nanotube is shown. We recently reported that these devices act as room-temperature single-electron transistors.[8] Here we present a first analysis of its noise properties and discuss the charge sensitivity of such devices.

The noise power spectral density has been measured for individual nanotubes as a function of the DC current I_{DC} at room temperature (Fig. 2). At $I_{DC} = 0$, the voltage noise is

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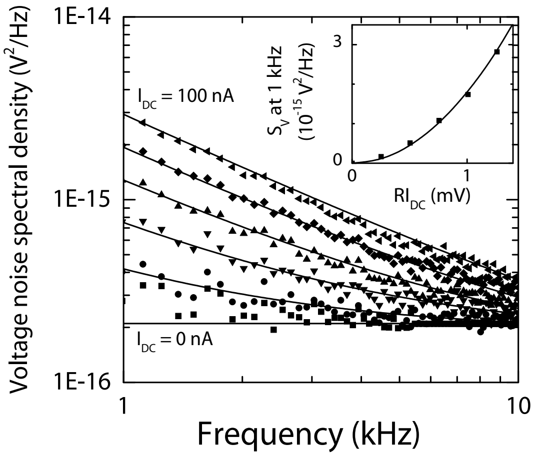

Figure 2: Noise spectra at $T = 300$ K for a nanotube with resistance $R = 12.6$ kΩ for various DC currents from 0 to 100 nA. The white noise visible at low I_{DC} is the expected thermal or Johnson-Nyquist noise of the sample $S_{V,JN} \equiv 4k_BTR = 2.1 \times 10^{-16}$ V^2/Hz, where k_B is Boltzmann's constant. The deviations from $1/f$ spectra at low current are due to $1/f$ noise from the amplifiers. The solid lines are fits with the function $S_V = S_{V,JN} + B/f$. The inset shows the excess $1/f$ noise at 1 kHz versus DC voltage $V_{DC} = RI_{DC}$. From the fit (solid line) we obtain $B = AV_{DC}^2 = 1.8 \times 10^{-6} V_{DC}^2$. The same value for A is found in voltage-biased measurements of the current noise $S_I = S_{I,JN} + AI_{DC}^2/f$, where $S_{I,JN} \equiv 4k_BT/R$.

white, i.e., it does not depend on frequency, and equals the expected value for thermal noise $4k_BTR = 2.1 \times 10^{-16}$ V^2/Hz of the nanotube, where $R = 12.6$ kΩ for this device. With increasing current, additional noise appears, which exhibits a $1/f$ frequency dependence. These two noise powers appear to add incoherently, i.e., $S_V = 4k_BTR + B/f$. The current dependence is studied in the inset to Fig. 2, where it is found that $B = AV_{DC}^2$.[9] The proportionality constant A thus found describes the full current and frequency dependence. All of these results are qualitatively consistent with the phenomenological dependence known as Hooge's law.[10]

As postulated by Hooge, A depends on the number of charge carriers in the conductor N through $A = \gamma/N$, where $\gamma \approx 2 \times 10^{-3}$.[11] Although it is now understood that the γ value is not universal, it is a good starting point to compare the magnitude of noise in nanotubes to that in bulk conductors described by Hooge's law. The nanotubes described here contain about 2000 conduction electrons.[12] Using the magnitude of A found above, we find $\gamma_{nanotubes} \approx 4 \times 10^{-3}$. Earlier, Collins *et al.* found that this number was about 2 orders of magnitude larger.[2] Our material, however, shows much less noise and is in fact quite a low-noise conductor.

The temperature dependence of the $1/f$ noise is displayed in Fig. 3. With the current and frequency dependence given above, it suffices to display the value of A. It appears that the noise is reduced in a monotonous way by three orders of magnitude upon lowering the temperature. This has been measured in many individual nanotube samples that we have studied.

In the commonly employed model for $1/f$ noise, it is assumed that fluctuating two-level systems in the surrounding give rise to a fluctuating potential profile, which leads to this low-frequency noise.[10] Within this model it is reasonable that a reduction of the temperature will lead to reduction of the noise, since at lower temperatures these two-level systems will freeze into local energy minima. The chemical stability, high degree of regularity and detailed knowledge of the electronic and mechanical structure of carbon nanotubes provide the right ingredients to study the origin of $1/f$ noise in detail. This, however, is beyond the scope of this brief report.

As an example of how the low-frequency noise affects the performance of a nanotube device, we have studied the noise properties of the double-buckle sample in Fig. 1b. In these samples, the addition of a single electron to the island between the two buckles costs a large energy due to the Coulomb charging of the island.[14] When the thermal energy k_BT is smaller than

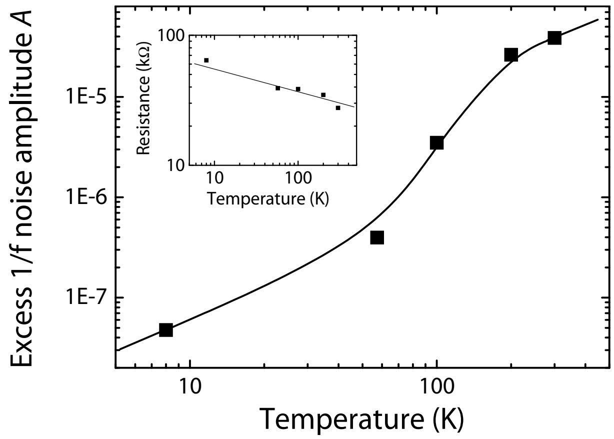

Figure 3: Excess $1/f$ noise power versus temperature for a single carbon nanotube. Plotted is the proportionality constant A of the $1/f$ noise spectral density $S_V = AV_{DC}^2/f$ as obtained from an analysis of the voltage and frequency dependence as is shown in Fig. 1. The inset shows the temperature dependence of the resistance of the nanotube. The lines are guides to the eye.

this charging energy, current is blocked. The blockade can be lifted, however, by increasing the electrostatic potential of the nanotube by means of a nearby conducting gate. Current can then flow. If the gate voltage is increased further, however, current is again blocked. This leads to a series of current peaks as a function of gate voltage, see Fig. 4a. The noise at 10 Hz has been measured versus gate voltage. Again peaked features are observed, see Fig. 4b. To characterize the performance of such a single-electron transistor, one determines how accurately charge on the gate can be measured. Thus, the measured current noise $\sqrt{S_I}$ is divided by the gate voltage sensitivity (dI/dV_g), and multiplied by the gate capacitance to obtain the so-called input equivalent charge noise $q_{noise} = C_g\sqrt{S_I}/(dI/dV_g)$, which is being displayed in Fig. 4c.[15] It diverges periodically (with a period twice as small as the distance between current peaks), every time the gate voltage sensitivity vanishes. In between, it reaches its optimum value of $2 \times 10^{-3} e/\sqrt{\text{Hz}}$ at the gate voltage indicated by the vertical dashed lines. This compares favorably to values $q_{noise} \approx 0.5 \times 10^{-3}$ e$/\sqrt{\text{Hz}}$ for conventional single-electron transistors which operate at mK temperatures,[16] because the data on the nanotube device are obtained at 60 K and the noise is reduced considerably as a function of temperature (see above).

We conclude with an estimate of the measurement bandwidth needed to observe shot noise $S_I = 2eI_{DC}$, which is a good approximation of the bandwidth needed to observe reduced shot noise or bunching/anti-bunching type effects. For this estimate we – optimistically – assume that samples may be fabricated with a 10 kΩ resistance and a $1/f$ noise power amplitude $A \approx 10^{-8}$ and we focus on the properties at 4 K. For simplicity we assume that all the amplifier noise can be reduced sufficiently such that only the thermal noise of the sample (2.2×10^{-26} A^2/Hz) dominates at low current. The total noise may then be written as $S_I = 4k_BT/R + 2eI_{DC} + AI_{DC}^2/f$. For the observation of shot noise, we obviously require that $\eta = (4k_BT/R + AI_{DC}^2/f)/2eI_{DC} < 1$, from which we deduce two boundary conditions for $I_- < I_{DC} < I_+$. At low current $I_{DC} < I_- \approx 4k_BT/\eta 2eR$, the thermal noise dominates, whereas at high current $I_{DC} > I_+ \approx 2ef\eta/A$ the $1/f$ noise dominates. Finally we require that $I_+ \gg I_-$ since one needs to observe the current dependence of the shot noise. If an experimental uncertainty of 10 % is sufficient ($\eta = 1/10$) and $I_+/I_- = 10$, we find $f > 2.2$ MHz. This frequency range is not accessible with our current setup, but is certainly accessible with a dedicated setup.

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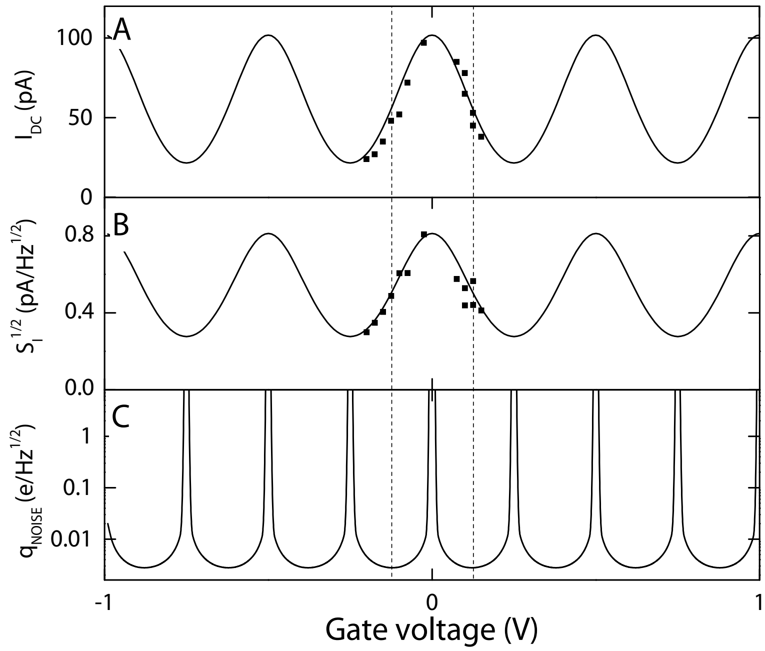

Figure 4: Noise characteristics of the carbon nanotube single-electron transistor shown in Fig. 1b at 60 K and 10 Hz. Both current and current noise depend on the gate voltage as is visible in *a* and *b*. Both are fit (solid lines) with a superposition of Coulomb conductance peaks.[13] In *c*, the results of these fits are used to determine the input equivalent charge noise of the device.

Community SATURN project.

References

1. C. Dekker, *Physics Today* **52 (5)**, 22 (1999).
2. P.G. Collins, M.S. Fuhrer, and A. Zettl, *Appl. Phys. Lett.* **76**, 894 (2000).
3. L. Roschier, R. Tarkiainen, M. Ahlskog, M. Paalanen, and P. Hakonen, *Appl. Phys. Lett* **78**, 3295 (2001).
4. R. De-Picciotto *et al.*, *Nature* **389**, 162 (1997).
5. M. Henny *et al.*, *Science* **284**, 296 (1999).
6. W.D. Oliver, J. Kim, R.C. Liu, and Y. Yamamoto, *Science* **284**, 299 (1999).
7. Z. Yao, H.W.Ch. Postma, L. Balents, and C. Dekker, *Nature* **402**, 273 (1999).
8. H.W.Ch. Postma, T.F. Teepen, Z. Yao, M. Grifoni, and C. Dekker, *Science* **293**, 76 (2001).
9. It is often convenient to assume that $S_{V,1/f} \propto V^2/f$ or $S_{I,1/f} \propto I^2/f$. In general, however, it is found that $S_{1/f} \propto V^{2+\alpha}/f^{1+\beta}$, where $|\alpha| \ll 1, |\beta| \ll 1$ are material dependent numbers. Here, we assume $\alpha = \beta = 0$.
10. P. Dutta and P.M. Horn, *Rev. Mod. Phys.* **53**, 497 (1981).
11. F.N. Hooge, *Phys. Lett. A* **29**, 139 (1969).
12. This estimate is for this nanotube with a length of 500 nm. We did not perform a systematic study of the $1/N$ dependence.
13. C.W.J. Beenakker, *Phys. Rev. B* **44**, 1646 (1991).
14. H. Grabert and M. Devoret (eds) in *Single Charge Tunneling* (Plenum, New York, 1992).
15. Please note that while $eV_{DC} \ll k_B T$, both the current noise and the DC current depend on bias voltage through the relations $I_{DC} \propto V_{DC}$ and $\sqrt{S_I} \propto V_{DC}$, so the bias voltage dependence of q_{noise} cancels.
16. A.B. Zorin *et al.*, *Phys. Rev. B* **53**, 13682 (1996).