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The $1/f$ noise in multiwalled carbon nanotubes

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The $1/f$ noise in multiwalled carbon nanotubes bundles has been investigated between the frequency range of 0.1 to 30 Hz. At room temperature the noise spectrum is standard $1/f$, and its level is proportional to the square of the bias voltage. With decreasing temperature the noise level also decreases. At 4.2 K the noise level follows a non-monotonic dependence against the bias voltage, showing a peak at a certain bias voltage, meanwhile its frequency dependence also deviates from the $1/f$ trend. This anomalous behaviour is discussed within the picture of environmental quantum fluctuation of charge transport in the samples.

Keywords: carbon nanotubes, $1/f$ noise, environmental quantum fluctuation
PACC: 7110A, 7127, 8670J

1. Introduction

Noise measurements may provide us useful information on various dynamical processes involved in the charge transport at different time and energy scales. For example, shot noise is related to discrete charge transport, white noise is due to thermal fluctuation of charge motion, and $1/f$ noise may reflect many specific mechanisms such as positional fluctuation of defects or impurities.[1−3] Noise in bulk metallic samples is usually very small. With reduced sample dimensions its level gets increased and becomes easily measurable. Large noise has been observed at room temperature in both single and multi-walled carbon nanotubes.[4,5] For single-walled carbon nanotubes (SWNTs) at low temperatures, wherein the electrons are believed to form a Luttinger liquid,[6] the noise measurement shows that the effective charge carriers are fractional electrons.[7] For multiwalled carbon nanotubes (MWNTs), noise measurement may also provide useful information and help to clarify among different electron conduction mechanisms such as ballistic,[8] diffusive[9] or hopping-like[10] transport processes. Previous investigations show that the $1/f$ noise in single MWNT comes mainly from the fluctuation of the background charge, similar to the usual metallic samples.[5] In this experiment, through investigation on the low-frequency noise in MWNTs bundles, we find anomalies in both the level and the frequency dependences of the noise spectrum when the voltage on the sample is biased to the vicinity of 40meV. The phenomenon is discussed in terms of the environmental quantum fluctuation process in the MWNTs samples.

2. Measurement

The samples used in this experiment were MWNTs bundles of millimeter-long in length, grown by chemical vapour deposition.[12] They are composed of loosely entangled nanotubes that roughly parallel to each other, but with some occasional inter-tube contacts. The bundles were placed on a sapphire substrate, then electrodes were attached to the bundles using sliver epoxy. The contact resistance of the electrodes was found to be much lower than the bundles' body resistance, the latter was around 10kΩ at room temperature and 25kΩ at 4.2K. The temperature of the samples was controlled to an accuracy of ± 1mK, and the noise spectrum was measured from 0.1 to 30Hz using a SR560 pre-amplifier and a HP89410A spectrum analyser. Figure 1 illustrates the measurement circuit.

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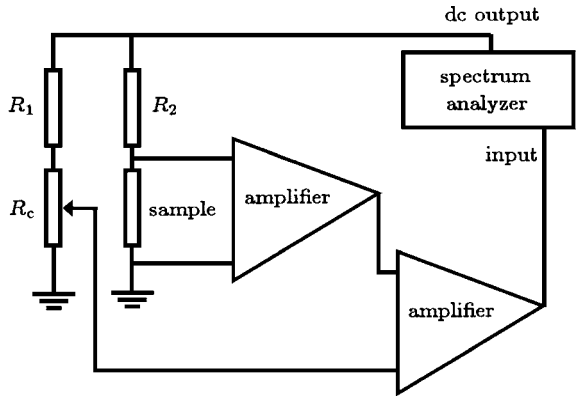


Fig.1. Illustration of the measurement circuit. The noise signal together with the normal voltage drop is first amplified by a preamplifier SR560. The normal voltage drop part is subtracted by using another amplifier, and is then sent to the spectrum analyser HP89410A. The bias voltage or current is supplied by HP89410A.

3. Data analysis

In principle every noise spectrum contains three parts: Johnson Nyquist thermal noise, shot noise and low-frequency $1/f$ noise. In the frequency range of our measurement the thermal noise and shot noise are small compared with the $1/f$ noise. Figure 2 shows the noise spectrum measured on one of our samples at 295K. It can be seen that $1/f$ behaviour is dominant over the frequency range studied.

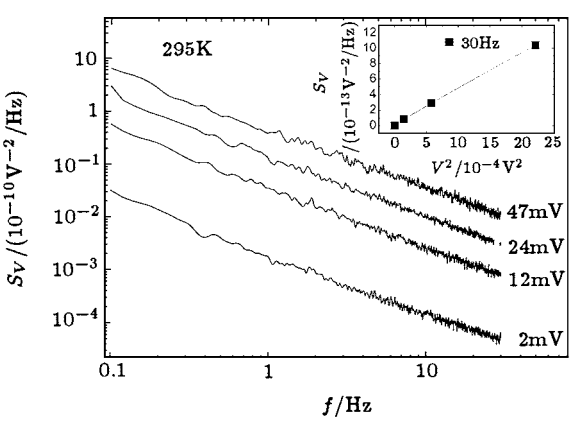


Fig.2. Noise spectrum of a multiwalled carbon nanotube bundle measured at several different bias voltages at 295 K. The inset shows that the noise level is proportional to the square of the bias voltage.

$1/f$ noise can be described by the Hooge's formula:[13]

$$\frac{S_V(f)}{V^2} = \frac{\gamma}{N_{\rm tot}} \frac{1}{f^{\alpha}}, \qquad (1)$$

where $S_V(f)$ is the noise spectrum at frequency f, V is the voltage drop across the sample, $N_{\rm tot}$ is the total number of charges in the sample, and γ is a proportional constant. The inset of Fig.2 shows that the noise level measured at room temperature is proportional to V^2 as expected by the Hooge's formula. For all the four samples measured the exponent $\alpha \approx 1 \pm 0.2$, which is lower than that of the crossing MWNTs experiment.[5] The quantity A/R is $8.0\times10^{-13}\Omega$ (where $A = \gamma/N_{\rm tot}$, R is the sample resistance), much lower than that of the SWNTs sample[4] but higher than that of the MWNT sample.[13]

Figure 3 shows the temperature dependence of the $1/f$ noise spectrum. The S_V decreases monotonically with decreasing temperature while keeping the current passing through the sample unchanged. This phenomenon can be explained by using the common picture that the fluctuation of some structural instability in the sample, usually described by the two-level mechanism, freezes out with lowering temperature.[14]

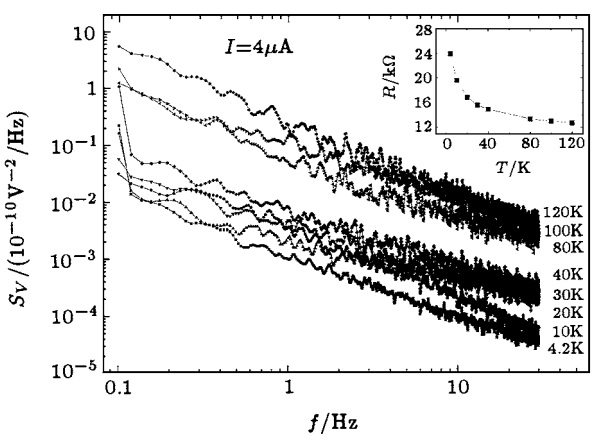


Fig.3. Noise spectra measured at different temperatures, using a constant bias current of 4μA. The noise level decreases with decreasing temperature. The inset is the temperature dependence of the sample resistance.

The bias voltage dependence of the noise spectrum was studied at fixed temperature of 4.2K by dipping the sample holder into liquid helium. The results are shown in Fig.4. It is found that at low bias voltages the spectra (the lower four lines) are proportion to $1/f$, and their level increases with increasing bias voltage. However, at higher bias voltages of 30 to 40meV the noise level increases abruptly and deviates from the $1/f$ behaviour. With further increase of the bias voltage the noise spectra goes back to the normal $1/f$ trend. The noise level at 20 and 30Hz is plotted in Fig.5(a) as a function of the bias voltage. It peaks at $30-40$meV.

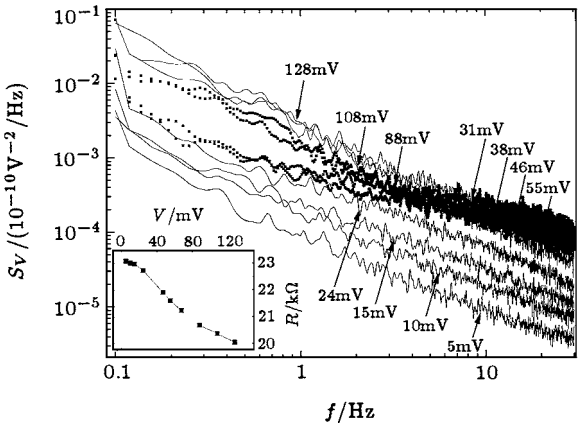


Fig.4. Noise spectrum measured at 4.2K under difference bias voltages. The inset shows the non-ohmic sample resistance as a function of the bias voltage.

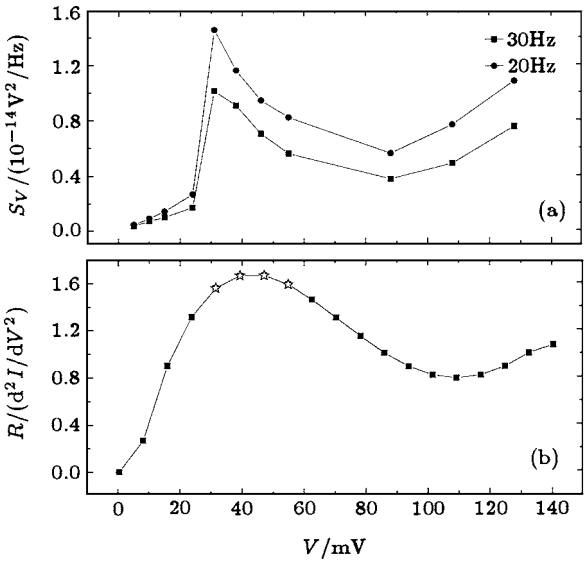


Fig.5. (a) The bias voltage dependence of the noise levels at frequencies of 20 and 30Hz, showing a peak at $30-40$meV. (b) The bias voltage dependence of the second derivative $\mathrm{d}^2I/\mathrm{d}V^2$ of the MWNT sample, also showing a broad peak around 40meV.

Since $1/f$ noise is closely related to resistance fluctuation, we thus checked the bias voltage dependence of the sample resistance.[15] The I-V curve of the MWNTs bundle is non-ohmic at 4.2K, as shown in the inset of Fig.4. In Fig.5(b) we further plot the second derivative of current as a function of the bias voltage. The peak of the second derivative takes place interestingly close to the bias voltage where the level of the $1/f$ noise peaks.

This correlation may imply that the anomalous noise peak is related to the so-called environmental quantum fluctuation (EQF) process of the charges. In our previous study we found that EQF is the dominant mechanism of charge transport at low temperatures in this type of MWNTs.[16] In the EQF theory the second derivative $\mathrm{d}^2I/\mathrm{d}V^2$ is related to the quantity $P(E)$ which describes the quantum fluctuation probability of having an electromagnetic mode of energy E propagating in the MWNT sample (and thus allowing charge transport along the sample). In this picture the MWNT sample is treated as a highly resistive mesoscopic transmission line. The quantum fluctuation, if it is broad-banded, might be the origin of the anomalously large $1/f$ noise around 40meV.

Large noise might be expected in the EQF theory when resonant charge transport happens between different conduction mechanisms. For example, large noise is predicted in Josephson junctions when the depairing process occurs.[17] In our case, phenomenologically the $\mathrm{d}I/\mathrm{d}V$ curve of the sample switches from the power law below the peak bias voltage of $\sim$40meV to a more logarithmic-like behaviour above, possibly indicating that there is a conduction mechanism crossover around 40meV.

4. Summary

We have investigated the low-frequency noise in MWNT bundles, and found anomalously large noise levels as well as anomalous spectra deviating from the $1/f$ trend at certain bias voltages. We try to discuss the anomaly within the picture of environmental quantum fluctuation of charge transport in the MWNT samples, but further experimental and theoretical investigations are still needed to fully clarify this issue.

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