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Measurements of Shot Noise in Single Walled Carbon Nanotubes

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Abstract. We have measured shot noise in single walled carbon nanotubes (SWNT) at 4.2K over frequencies $f = 600 - 850$ MHz. Here we report results obtained on shot noise without DC bias by applying an AC modulation at ω_0 and recording the noise variation at $2\omega_0$; the Fano factor is obtained by extrapolating down to zero excitation amplitude. We also discuss the applicability of this method in samples which have strongly non-linear IV characteristics like carbon nanotubes. The obtained results are compared with regular differential noise measurements where both DC and AC bias are employed.

Keywords: Carbon nanotubes, Shot noise

PACS: 73.63.Fg, 72.70.+m, 05.40.-a

INTRODUCTION

Noise in single walled carbon nanotubes (SWNT) is expected to reflect several interesting physical phenomena of one-dimensional, interacting quantum conductors [1, 2, 3, 4, 5, 6, 7, 8, 9]. In order to reach some of these phenomena, there are two experimental challenges: 1) the non-linear IV curve (the non-linear conductance) changes the coupling between the source and the noise detector, 2) heating may interfere with the generation of desired non-equilibrium noise and, therefore, the bias voltage should be kept small. The former problem can be handled by using a measurement scheme with total unmatching [10]: then the coupled power is directly proportional to the current noise spectral density. The latter point requires that the shot noise should be measured already in the cross-over regime between thermal and shot noise ($eV \sim k_B T$). In the cross-over region, the noise appears quadratically as a function of applied voltage. Using AC modulation at ω_0 , this quadratic dependence can be utilized at zero bias to achieve highly sensitive noise measurements at $2\omega_0$, since the noise will be modulated fully at the double frequency.

MEASUREMENT METHOD

Here we analyze how the 2ω measurement scheme works in a sample with non-linear IV characteristics. We assume that the non-linearity can be described with the following generic form:

$$I(V) = \frac{V}{R} + \frac{V^3}{3\delta V^2 R}, \quad (1)$$

where R denotes the resistance in the limit $V \rightarrow 0$ and δV^2 describes the strength of the non-linearity. The differential resistance has thus a Lorentzian zero-bias anomaly given by

$$\frac{dV}{dI} = \frac{R}{1 + \frac{V^2}{\delta V^2}}. \quad (2)$$

For the shot noise, we assume that there is no explicit voltage dependence in the Fano-factor F . Then, we may write for the voltage dependent noise in the cross-over regime as

$$S(V) = 2eF \left(\frac{V}{R} + \frac{V^3}{3\delta V^2 R} \right) \coth\left(\frac{eV}{2k_B T}\right), \quad (3)$$

where k_B stand for the Boltzmann constant and T is the temperature. By differentiating Eq. (3) with respect to voltage, and multiplying with differential resistance from Eq. (2), we get dS/dI , which is the basic modulated quantity in our ordinary measurements [8]. Its series expansion up to third order reads

$$\frac{dS}{dI}(V)_{ser} = \left(\frac{2e^2 F}{3k_B T} + \frac{8F k_B T}{3\delta V^2} \right) V - \left(\frac{e^4 F}{45k_B^3 T^3} + \frac{2e^2 F}{9\delta V^2 k_B T} + \frac{8F k_B T}{3\delta V^4} \right) V^3 + O(V)^4. \quad (4)$$

The 2ω measurement, on the other hand, is sensitive to the second derivative with respect to voltage. An expansion yields

$$\frac{d^2 S}{dV^2}(V)_{ser} = \left(\frac{2e^2 F}{3R k_B T} + \frac{8F k_B T}{3R \delta V^2} \right) + \left(-\frac{e^4 F}{15R k_B^3 T^3} + \frac{4e^2 F}{3R \delta V^2 k_B T} \right) V^2 + O(V)^3. \quad (5)$$

It is seen that the first terms of Eqs. (4) and (5) contain the same parameter combinations, while the V^2 and V^3 correction terms have different prefactors. Using experimentally relevant parameters $T = 4.2$ K, $F = 0.5$, $R = 30000 \Omega$, and $\delta V = 0.01$ V, we obtain that the AC excitation V_{AC} has to be $V_{AC} \ll 2$ mV and $V_{AC} \ll 1.2$ mV for the ω and 2ω schemes, respectively. Note that, in the first term, there is a correction due to non-linearity that depends only on the ratio of $(e\delta V/k_B T)^2$ not on the drive amplitude. With relevant parameters, however, this correction is in the range of 1%.

SAMPLE AND EXPERIMENTAL TECHNIQUES

We have experimentally applied the 2ω scheme to a SWNT sample with non-linear IV characteristics. Our single-walled nanotube material was grown using surface-CVD method with Fe catalyst particles. A $0.7 \mu\text{m}$ -long tube, with a diameter of $\phi = 2$ nm,

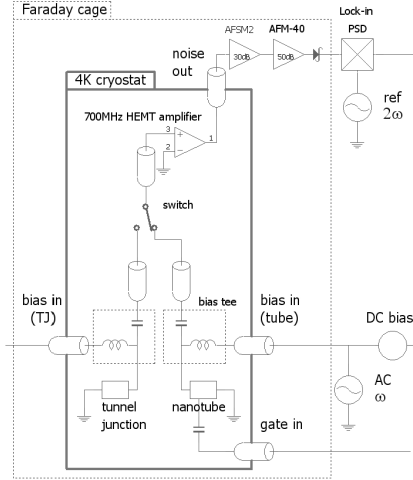


FIGURE 1. Our setup for measuring noise using AC modulation. In the absence of DC-bias, the noise signal is detected by the lock-in at 2ω , which reflects the curvature of the shot noise as a function of voltage. With DC-bias, the lock-in is employed to track noise at ω , yielding the differential shot noise.

was first located by an FE-SEM, and then the electrodes were patterned on it by standard e-beam lithography. The electrodes have a width of 200 nm and the gap between them is around 300 nm. We employed a 10 nm-thick Ti layer for the contact, which was covered by a 70 nm-thick Al layer. The highly doped body of the substrate is used as the back gate, separated from the sample by a 100 nm-thick oxide layer.

Figure 1 illustrates our measurement setup. The measurements were done in a liquid helium cryostat which was operated in a Faraday cage to cut off external noise, mostly caused by mobile phones. Noise power at microwave frequency is separated from the DC signals using surface mount bias-tees. A microwave switch selects either the nanotube sample or a tunnel junction whose role is to provide a calibration for the total gain and bandwidth product of the system. Ref. [10] can be consulted for further details of the calibration procedure (for differential shot noise) using the tunnel junction. In the present work, the modulated tunnel junction noise signal, measured at the second harmonic, was multiplied by the ratio of resistances to give the reference of shot noise with $F = 1$ for the nanotube sample. Immediately after the switch, signals are amplified by a home-made HEMT-based amplifier with operating frequency range of 600-950 MHz [11]. A series of room temperature amplifiers gives 80 dB of amplification to noise signals before they are converted into a DC signal by a Schottky diode with $0.5 \text{ mV}/\mu\text{W}$.

RESULTS

A few of our results using 2ω measurements are displayed in Fig. 2. The filled circles have been obtained on a tunnel junction sample. The triangles and open circles were measured on our SWNT sample at the gate voltages of $V_g = -1.5$ and 0 V , respectively.

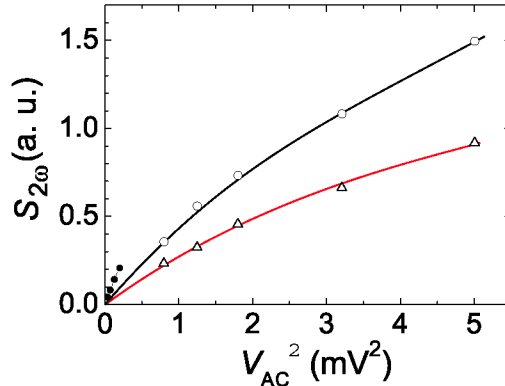


FIGURE 2. Amplitude of the measured noise power variation at 2ω as a function of the squared AC-excitation amplitude V_{AC}^2 . The triangles and open circles were measured at $V_g = -1.5$ and 0 V, respectively. The filled circles represent reference data taken on a tunnel junction.

By extrapolating the curves down to zero AC excitation we obtain $F = 0.32 \pm 0.1$ and $F = 0.50 \pm 0.1$, respectively. These values are pretty close to the values obtained in regular, differential shot noise measurements [8]. The error, however, appears to be clearly larger, which we is due problems in stabilizing the phase of the 2ω signal. In conclusion, we have shown that the 2ω method is a useful tool for non-linear mesoscopic samples but the resolution achieved so far has not yet reached the level obtained using regular differential shot noise measurements.

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