Measurement for quantum shot noise in a quantum point contact at low temperatures

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Abstract. We report an experimental development for the high-frequency shot noise measurement system in the $^3$He-$^4$He dilution refrigerator. The target frequency of the measurement was set to a few MHz with the cross correlation scheme adopted for high accuracy. The system was calibrated by measuring Johnson-Nyquist noise of the quantum point contact (QPC). We prove that our system has enough accuracy for the quantitative evaluation of the quantum shot noise.

1. Introduction

Shot noise in mesoscopic systems has been invoking much interest because it provides a lot of information about quantum transport properties which would be impossible to obtain through the conventional conductance measurement [1], as demonstrated, for example, in the experiment for the fractional charge in the quantum hall regime [2, 3]. One of the today’s directions of the noise measurement is to measure the current correlation of the noise of the two distinct currents. Detection of the anti-bunching of electrons in the electronic Hanbury-Brown-Twiss interferometer [4, 5] is a successful example of such kind of measurements. It is also predicted that the current correlation measurement will enable the experimental detection of the entanglement of electrons by testing the Bell inequalities [6], and the two-particle interference was really observed in the recent current-correlation measurement [7].

The technique of measuring the power spectral density of the noise is mainly composed of the following processes: taking the time-domain signal from the sample, amplifying it, and performing the fast Fourier transformation (FFT) for the data. The measurement system can be characterized by its target frequency. Low-frequency (~ kHz) signal is easy to be taken by commercial coaxial cables, though the undesirable noises (1/f, random telegraph, etc…) are unavoidable to occur [8]. The high-frequency (~ MHz) system is more complicated because the MHz signal from typical mesoscopic devices (~ kΩ) is lost by the capacitive loss in the coaxial cables. However, the above undesirable noises are expected to be reduced in the high-frequency range. This is a great advantage of the high-frequency measurement [9].

The purpose of this study is to establish a high-frequency noise measurement system with a cross correlation setup in a $^3$He-$^4$He dilution refrigerator. Recently, DiCarlo et al. [10] succeeded in making the cross correlation noise measurement system at 300 mK in a $^3$He cryostat. Their system is sensitive enough for the quantum shot noise measurement. However, to observe the phenomena based on the quantum coherence more vividly, the noise measurement system should be realized at lower temperature by using a dilution refrigerator, which has never been reported in the literature so far. In
In this paper, we report the development of the electrical circuits in the dilution refrigerator and the calibration of the system by measuring the thermal noise (Johnson-Nyquist noise). We also report the quantum shot noise measured in a quantum point contact (QPC).

2. Experiments

Figure 1(a) shows the block diagram of the noise measurement system developed in a commercial dilution refrigerator (Oxford Instruments Kelvinox 400). The system contains the homemade inductor-capacitor (LC) resonant circuit and the cryogenic amplifier. The resonant circuit is composed of a 30 µH inductor and the capacitance of the coaxial cable (C_{coax} \approx 100 pF), and thus the resonant frequency is tuned to be 3.0 MHz. The resonant circuit is grounded at the mixing chamber in the dilution refrigerator to reduce the electron temperature in the sample. The cryogenic amplifier made of HEMT (Agilent ATF34143) was installed at the 1 K pot of the refrigerator, as the 1 K pot has enough cooling power to absorb the heat from the amplifier. While the DC current injected into the sample flows into the cryogenic ground, the AC current noise caused in the sample is converted to voltage fluctuation by the impedance of the resonant circuit and is extracted as an output signal of the cryogenic amplifier, which has 50 Ω output impedance. The resultant signal amplified by the secondary amplifier (MITEQ AU1447) is captured by the two-channel digitizer (National instruments PCI-5922) and is converted to spectral density data.

To obtain a higher resolution in the noise spectral density data by the cross-correlation technique [10, 11], we connected the two amplification lines in the refrigerator as shown in Fig. 1 (b).

The example of the results of the noise measurement is shown in Fig. 1 (c). Although the spectrums obtained by using each amplifier lines (channel 1 and 2) clearly show the resonant peaks of the noise in the sample, the peaks are on top of the background noise such as the noises of the secondary amplifier. The background noise is efficiently reduced by measuring the cross correlation of the two signals because it occurs independently in each line. Thus, the cross correlation technique enables us not only to measure the voltage fluctuation smaller than the extrinsic noises in each amplifier line, but also to increase the accuracy of the intrinsic noise power.

The QPC was fabricated by the split-gate method on the the GaAs/AlGaAs two-dimensional electron gas with an electron density 2.3 × 10^{11} cm^{-2} and mobility 1.1 × 10^6 cm^2/Vs.

The noise measurements were carried out with 0.2 T magnetic field applied perpendicular to the substrate to obtain quantitatively better comparison between the experiment and theory [11]. At the
3. Results and discussions

3.1. Calibration of the noise measurement system

The measured noise in a QPC is the sum of the thermal noise and the shot noise. At first, we calibrated the developed measurement system by measuring the thermal noise at the zero-bias state. Figure 2 shows the noise power of the QPC whose conductance $G$ was set to $G = 2e^2/h$ (transmission of the QPC: $T = 1.0$) and $G = 2 \times 2e^2/h$ ($T = 2.0$) at various temperatures. The noise power between 200 and 800 mK have a linear dependence on the system temperature. From the slopes of the linear fitting functions, we obtain both the impedance $Z$ and the square of the gain $A$ of the measurement system, as the measured noise power ($P_0$) is represented as the following function,

$$P_0 = A \left( S_v^{\text{gate}} + \left( \frac{ZR}{Z + R} \right)^2 S_i^{\text{gate}} + \left( \frac{Z}{Z + R} \right)^2 4k_BT R \right),$$

(1)

$S_v^{\text{gate}}$ and $S_i^{\text{gate}}$ are the voltage- and current- gate noises of the amplifier, respectively, $k_B$ is the Boltzmann constant, and $R$ is the impedance of the sample. From the fitting, the values of $A$ and $Z$ are evaluated to be $A = 1.45 \times 10^5 \, \text{V}^2/\text{V}^2$ and $Z = 68 \, \text{k} \Omega$. These values are comparable to the calculated values from the impedance and the gain of each amplifier line ($A_1 = 1.75 \times 10^5$, $A_2 = 1.08 \times 10^5$, $Z_1 = 120 \, \text{k} \Omega$, and $Z_2 = 190 \, \text{k} \Omega$) with less than 10% error. Below 200 mK, the measured noise power dose not reduce linearly with the system temperature, because the cooling of the sample through the coaxial cables is not sufficient. At the lowest base temperature of the refrigerator (45 mK), the electron temperature is estimated to be 125 mK from the noise power.

3.2. Quantum shot noise in the QPC

Figure 3 (a) presents the conductance of the QPC at zero bias voltage as a function of the gate voltage. We carried out the quantum shot noise measurements at the red ($T = 1.5$), green ($T = 1$), and blue ($T = 0.5$) gate voltages shown in Fig. (a). (c) Evaluated Fano factor at the various conductance.

![Fig. 2](image-url)

**Fig. 2** Temperature dependence of the thermal noise of the QPC. The data is fitted by linear function for the points over 200 mK.

![Fig. 3](image-url)

**Fig. 3 (a)** Conductance of the QPC as a function of the gate voltage. (b) Shot noise vs. source-drain voltage plot. Solid lines are fitted curves. These noise measurements were carried out at the gate voltages shown in Fig. (a). (c) Evaluated Fano factor at the various conductance.
and blue ($T = 0.5$) points shown in the figure. The results of the noise measurement are shown in Fig. 3 (b). When $T = 1.5$ and 0.5, the shot noise power ($P_{IS}$) gradually increases with the increase of the source-drain voltage ($V_{sd}$), while $S'_{n}$ vanishes when $T = 1$. These results are consistent with the previous works [11, 12]. To be more quantitative, the markers of the measured noise power are fitted to the following function,

$$S'_{n}(V_{sd}) = \frac{2F}{R} \left( eV \coth \left( \frac{eV}{2k_{B}T} \right) - 2k_{B}T \right). \quad (2)$$

From the fitting, we can estimate the Fano factor $F$. The Fano factor estimated for the various conductances is shown in Fig. 3 (c). In the figure, one can clearly see that the Fano factor becomes small at the conductance plateaus and becomes larger when the transmission of the uppermost conducting channel is close to 0.5.

The result shown in Fig. 3 is explained by the theoretical model, although the measured Fano factor is a slightly larger than that. The origin of the deviation is expected to be explained by following reasons: (1) the calibrated values of the gain and the impedance of the measurement system may be different from the accurate values by a few percent error, (2) extrinsic noises such as the $1/f$ noise may occur, (3) the electron temperature may become higher by the heating effect when the source-drain voltage is applied to the QPC, as pointed out in ref. [11].

To take an example of the extrinsic noise, we compared the noise at the conductance plateaus of the QPC in 0 T and in 0.2 T magnetic fields applied perpendicular to the substrate. As shown in Fig. 4, while there is no remarkable difference of the DC conductance (Fig. 4 (a)), the measured power of the shot noise in 0.2 T was strongly suppressed in Fig. 4 (b). The Fano factors, which ideally equals to zero, are 0.051 and 0.015 for 0 T and 0.2 T, respectively. This result suggests that there are uncontrollable extrinsic noise-sources which are sensitive to the external magnetic field, and that the slight deviation from the theory observed in Fig. 3 (c) can be reduced by optimizing the magnetic field.

4. Conclusions
We successfully established the measurement system for the quantum shot noise of the mesoscopic devices by the cross correlation method in the dilution refrigerator. By using this measurement system, we succeeded in quantitatively obtaining the power spectral density of the shot noise in a quantum point contact (QPC) at around 100 mK. Such an experimental scheme will be a powerful tool for on the future current-correlation measurements of the two distinct currents.
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References

[1] Ya. M. Blanter and M. Büttiker, Phys. Rep. 336, 1 (2000).
[2] L. Saminadayar, D. C. Glattli, Y. Jin, and B. Etienne, Phys. Rev. Lett. 79, 2526 (1997).
[3] R. De-Picciotto M. Reznikov, M. Heiblum, V. Umansky, G. Bunin, and D. Mahalu, Nature 389, 162 (1997).
[4] M. Henny S. Oberholzer, C. Strunk, T. Heinzel, K. Ensslin, M. Holland, and C. Schönenberger, Science 284, 296 (1999).
[5] W. D. Oliver, J. Kim, R. C. Liu, and Y. Yamamoto, Science 284, 299 (1999).
[6] P. Samuelsson, E. V. Sukhorukov, and M. Büttiker, Phys. Rev. Lett. 92, 026805 (2004).
[7] I. Neder, N. Ofek, Y. Chung, M. Heiblum, D. Mahalu, and V. Umansky, Nature 448, 333 (2007).
[8] C. Dekker, A. J. Scholten, F. Liefrink, R. Eppenga, H. van Houten, and C. T. Foxon, Phys. Rev. Lett. 66, 2148 (1991).
[9] M. Hashisaka, S. Nakamura, Y. Yamauchi, S. Kasai, T. Ono, and K. Kobayashi, Physica Status Solidi (in press).
[10] L. DiCarlo Y. Zhang, D. T. McClure and C. M. Marcus, Rev. Sci. Instrum. 77, 073906 (2006).
[11] A. Kumar, L. Saminadayar, D. C. Glattli, Y. Jin, and B. Etienne, Phys. Rev. Lett. 76, 2778 (1996).
[12] M. Reznikov, M. Heiblum, H. Shtrikman, and D. Mahalu, Phys. Rev. Lett. 75, 3340 (1995).