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Cross-correlation measurement of current noise in mesoscopic conductors using a homemade cryogenic transimpedance amplifier

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1. Introduction

Noise measurement is a powerful tool to investigate transport characteristics in quantum conductors [1]. While time-averaged current is related to the transmission and reflection probability of the conductor, the noise contains information on the unit charge and statistical characteristics of the charge carriers. For example, fractional charge of quasiparticles in fractional quantum Hall (QH) systems [2] and Fermionic correlation of electrons in quantum conductors [3] were evidenced by noise measurements.

There have been many reports on auto-correlation measurements revealing various transport characteristics in measoscopic conductors. However, there have been only a few reports on cross-correlation measurements [3-5], despite various interesting proposals to exploit cross-correlation measurements, e.g., for observation of fractional statistics [6] or detection of electron entanglement [7]. Therefore, developing a reliable cross-correlation measurement technique is an important experiment challenge in this field.

Here, we demonstrate a method to derive shot noise in quantum conductors from cross-correlation measurements. Homemade cryogenic transimpedance amplifiers (TIA) play an essential role in our method. While conventional methods using voltage amplifiers are useful for measuring *current noise from a single terminal* of a device, the high input impedance of the voltage amplifiers and the resultant crosstalk often preclude measurements of *correlation of currents*, because of the crosstalk. Our homemade TIAs are designed to have small input and output impedance, making such extrinsic crosstalk negligible. Our technique will thus facilitates new experiments on quantum transport aimed at, e.g., elucidating the current correlation between two interacting mesoscopic conductors [8].

2. Homemade transimpedance amplifier

The schematic setup of our noise measurement using a TIA is shown in Fig. 1(a). The TIA, which consists of four commercially available high electron mobility transistors (HEMTs: ATF35143; Avago Technologies), has the 10 kHz ~ 2 MHz (–3 dB) frequency band. The TIA, cooled at 1.5 K in a cryostat, converts the time-dependent current $I(t)$ from the sample to a voltage as $V(t) = R_{FB} \times I(t)$, which is amplified by a following voltage amplifier placed at room temperature and then measured using a spectrum analyzer.

Figure 1(b) shows the transimpedance of the whole system as a function of frequency. The flat gain (5.42×10^6 V/A ± 3 %) obtained over the 50 ~ 600 kHz frequency band, where the $1/f$ noise is negligible, is suitable for shot noise measurements.

3. Cross-correlation measurement

We performed cross-correlation measurements for shot noise in a quantum point contact (QPC) by using two TIAs. The schematic setup is shown in Fig. 2. When a current is injected to the QPC, shot noise is generated by partitioning currents. The transmitted and reflected currents are negatively correlated with each other, as each electron is either forward-scattered or backscattered at the QPC. We quantitatively estimated the correlation between these currents.

The QPC is fabricated on a two-dimensional electron gas (2DEG) in an AlGaAs/GaAs heterostructure (electron density $n_e = 2.3 \times 10^{11}$ cm^{-2} and mobility $\mu = 3.3 \times 10^6$ cm^{2}V^{-1}s^{-1}). Measurements were performed in the quantum Hall regime (bulk filling factor $\nu = 4$) by applying a perpendicular magnetic field of 2.3 T at 1.5 K. The current

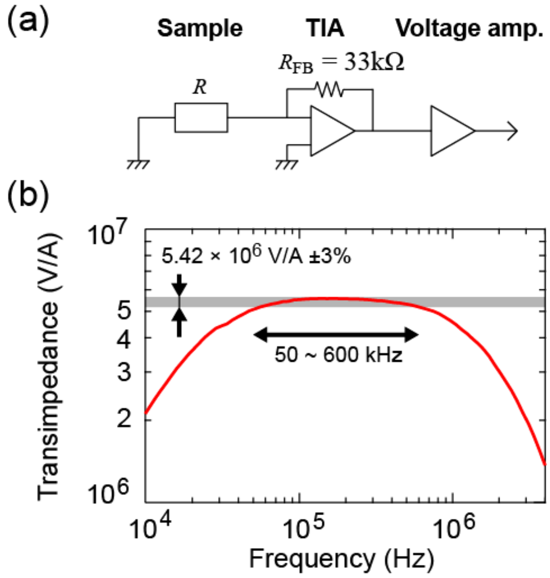

Fig. 1 (a) Schematic of the noise measurement system. (b) Frequency dependence of the transimpedance of the system shown in (a).

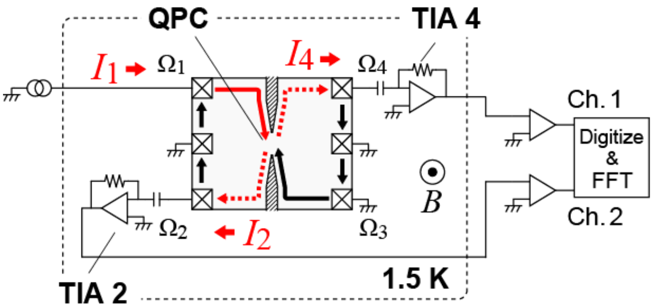

Fig. 2 Schematic setup of the cross-correlation measurement.

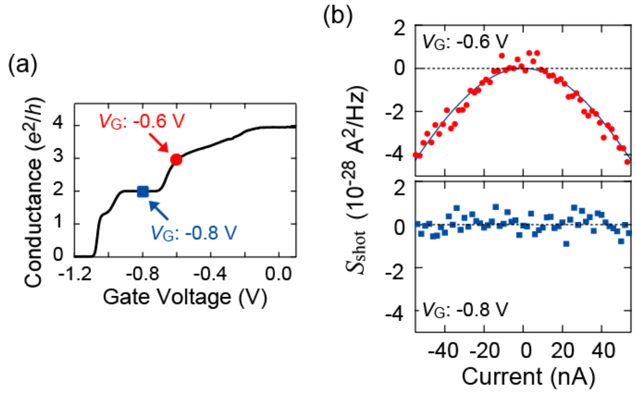

Fig. 3 (a) Conductance of the QPC as a function of the gate voltage. (b) Shot noise as a function of the current I_1. We observed negative S_{shot} at $V_G = -0.6$ V (upper panel), while no shot noise at $V_G = -0.8$ V (lower panel).

I_1 injected from an Ohmic contact Ω_1 chirally travels along the edge channels and is partitioned at the QPC, generating two currents drained at Ω_2 and Ω_4. The current fluctuations in Ω_2 [$\Delta I_2(t) = I_2(t) - \langle I_2 \rangle$, where $\langle I_2 \rangle$ is the time-averaged current] and Ω_4 [$\Delta I_4(t) = I_4(t) - \langle I_4 \rangle$] are individually amplified by TIAs and measured in the time domain. We performed FFT for $\Delta I_2(t)$ and $\Delta I_4(t)$ to extract the current correlation $S_{24} = \langle \Delta I_2(\omega) \Delta I_4(\omega) \rangle$.

Typical results of the noise measurement are shown in Fig. 3(b); they were obtained when the conductance of the QPC was tuned to be $G \cong 3e^2/h$ ($V_G = -0.6$ V) and $G \cong 2e^2/h$ ($V_G = -0.8$ V) [see Fig. 3(a)]. In these figures, we plotted S_{shot}, which is defined as $S_{shot} = S_{24}(I_1) - S_{24}(I_1 = 0)$. At $G \cong 3e^2/h$, where the inner edge channel is partitioned at the QPC, S_{shot} becomes more negative with increasing the I_1. This negative correlation is the evidence of the partitioning of currents at the QPC [3]. On the other hand, when the gate voltage V_G is set at the center of the conductance plateau (–0.8 V), where the inner (outer) edge channel is completely reflective (transmissive), no shot noise was observed. These observations agree well with the theory [1] and previous experiments [3,5,9].

When inter-channel scattering is negligible at the QPC, $S_{shot}(I_1)$ can be expressed in the following form [1];

$$S_{shot}(I_1) = 2eI_1F^* \coth(eI_1/2k_BTG),$$

with $F^* = \Sigma_{n,\sigma}T_{n,\sigma}(1-T_{n,\sigma})\ /N$, where n denotes the Landau level index, $\sigma = \uparrow$ or $\downarrow$ denotes the spin, $T_{n,\sigma}$ is the transmission probability of n-th up- or down spin channel, and N is the number of these channels. We have $N = 4$ for $\nu = 4$. If all the relevant channels are spin degenerate, $T_{n,\uparrow} = T_{n,\downarrow}$. In this case, $G = 3 \times e^2/h$ implies $T_{1,\sigma} = 1$ and $T_{2,\sigma} = 0.5$ [see Fig. 3(a)], from which $F^* = 0.125$ is expected. On the other hand, if the spin degeneracy is lifted, we expect $F^* < 0.125$, because $T_{n,\sigma}$ can vary independently. We fitted the data in Fig. 3(b) with the above equation using F^* as a fitting parameter. The data for $G = 3 \times e^2/h$ is well fitted with $F^* \cong 0.06$ and $T = 1.5$ K (blue solid line). From the equations $F^* = \Sigma_{n,\sigma}T_{n,\sigma}(1-T_{n,\sigma})\ /4 = 0.06$ and $G = e^2/h \times \Sigma_{n,\sigma}T_{n,\sigma} = 3e^2/h$, we can estimate that $T_{2,\uparrow} = 0.86$ and $T_{2,\downarrow} = 0.14$ (Here we assumed $T_{1,\uparrow(\downarrow)} = 1.0$). Although the conductance of the QPC does not show a well developed plateau structure near $V_G = -0.6$ V, the noise measurement reveals a finite spin polarization $P = (T_{2,\uparrow} - T_{2,\downarrow})/(T_{2,\uparrow} + T_{2,\downarrow}) = 0.72$ in the upper Landau level ($n = 2$) at 2.3 T [9].

4. Summary

We have demonstrated a technique to measure cross-correlation of currents in quantum conductors using homemade TIAs. The correlation of forward-scattered and backscattered currents from a QPC is quantitatively evaluated. Through these measurements, we found that the present method is suitable for cross-correlation measurements in quantum conductors.

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