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Correlation measurement of 1/*f* noise in semiconductor point contacts with a common lead

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1. Introduction

Quantum point contacts (QPCs) and single electron transistors are known as sensitive charge detectors, and are often utilized to measure charge and spin states in nearby quantum dots (QDs) [1,2]. Advanced quantum devices can be fabricated by integrating multiple QDs and charge detectors. Uncorrelated detectors, which are sensitive to local charge states, are desirable for independent readout of dot states [3]. In contrast, when the two detectors are coupled to the same QD, the signal-to-noise ratio can be improved by correlation measurements [4,5]. However, detectors can be correlated through various types of coupling, such as Coulomb interaction [6,7], the photon and phonon environments [8,9], and external circuit conditions [10]. Therefore, understanding correlation between detectors is important to improve the detector characteristics.

Here, we investigate the auto- and cross-correlation noise spectrum between tunneling currents through point contacts (PCs) for so-called 1/*f* noise associated with the background charge fluctuation in a semiconductor device [11,12]. Since this originates from the hopping on and off electronic traps, they can be regarded as ensembles of mimic QDs randomly distributed in the device. In this work, we evaluate the correlation coefficient, which is defined as the cross correlation normalized by the auto correlation. The long-range Coulomb interaction from a trap to both PCs should contribute to a positive correlation. However, we observed negative correlation, which can be understood by considering the common resistance existing in the sample. Observed distance dependence suggests the importance of channel resistance in the common lead.

2. Correlation measurement

The experiments were performed on a device fabricated by the standard split-gate technique in an AlGaAs/GaAs heterostructure. All measurements were performed at 4.2 K. The sample consists of 7 PCs, as shown in Fig. 1(a). A common DC bias voltage, V_{SD}, is applied to the source ohmic contact. Current through one of the left PCs (P_1 or P_2), $I_1(t)$, and that through one of the right PCs (from P_3 to P_7), $I_2(t)$, are simultaneously recorded with current-voltage converters and high-resolution (24 bit) analog-to-digital converters. Auto- and cross correlation power spectrum is obtained by numerical Fourier transformation. The distance between PCs, d, was selected from 0.4 um to 3.4 μm by activating two PCs with the other gates grounded. These PCs did not show quantized conductance probably due to the potential profile in a narrow gap (~100 nm) of the gates. We set the conductance of the selected PCs, G_1 and G_2, less than $G_0 = 2e^2/h$ to ensure the tunneling regime. The equivalent circuit of the device is shown in Fig. 1(b), where the common source contact serves common resistances. R_{EXT} is the external circuit resistance which includes ohmic resistance, and R_{CH} the resistance for the narrow channel in two-dimensional electron gas (2DEG). These resistances play a role in the correlated noise as shown below.

Figure 2 shows typical power spectral density, S_1 and S_2, in (a), and the cross-spectral density S_X in (b). They were averaged over $N = 10^4$ times the Fourier transformations. All data show 1/*f* dependence, where *f* is frequency. The broad shoulder-like features may be associated with a specific charge trap around each PC. Here, we define the Fourier-transformed correlation coefficient $C(f)$ as

$$C(f) = \frac{S_X(f)}{\sqrt{S_1(f)S_2(f)}} = \frac{\left\langle I_1^*(f)I_2(f)\right\rangle}{\sqrt{\left\langle |I_1(f)|^2\right\rangle}\sqrt{\left\langle |I_2(f)|^2\right\rangle}}$$

where the ensemble averaging $\langle\ldots\rangle$ of $N = 10^4$ times allows $|C|$ to vary from 0.01 ($=1/\sqrt{N}$) to 1. Figure 2(c) shows a typical $C(f)$ spectrum, which exhibits almost no frequency dependence. Therefore, the correlation coefficient C is evaluated by averaging over the frequency range from 10 Hz to 100 Hz (except for 50 Hz harmonics) in the following analysis.

The 1/*f* noise originates from the fluctuating potential barrier $\Delta U(t)$ associated with the charge fluctuation of the traps. The current noise $\Delta I(t)$ is proportional to $\Delta U(t)$ as

$$\Delta I(t) = \frac{1}{\alpha}\frac{dG}{dV_g}\Delta U(t) V_{SD}$$
,

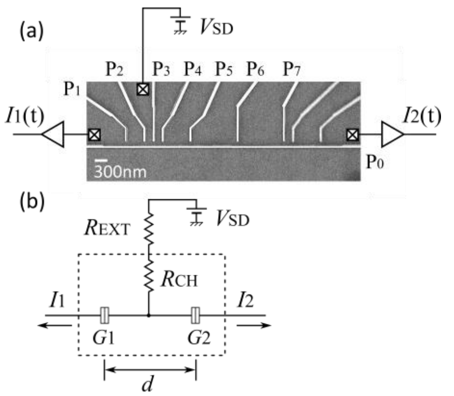

Fig.1. (a) Experimental set up with an SEM micrograph of the device. (b) Equivalent circuit for the correlation measurement.

where α is the conversion factor relating the gate voltage to the potential energy, dG/dV_g is the transconductance, and V_{SD} is the applied bias voltage. When extrinsic correlations can be ignored, $C(f)$ is directly related to the frequency spectra of time-dependent potentials, U_1 and U_2, as

$$C(f) = \frac{\langle U_1^*(f) U_2(f) \rangle}{\sqrt{\langle |U_1(f)|^2 \rangle} \sqrt{\langle |U_2(f)|^2 \rangle}}$$

which should be independent of device conditions like α and dG/dV_g. Therefore, C can be used as a measure of Coulomb correlation.

3. Correlation associated with a common resistor

Figure 3 summarizes the measurement of C as a function of the bias V_{SD} in (a), the conductance G (adjusted to have equal G_1 and G_2) in (b), and the distance d between PCs in (c). Note that C is always negative, where increasing I_1 coincides with decreasing I_2. The absence of V_{SD} dependence is consistent with the linear transport regime of the device. However, the observed negative C and its linear G-dependence contradict the above expectation from the Coulomb correlation. The weak d-dependence indicates the significance of the narrow channel between two PCs.

The above observation can be explained with the common resistors, R_{EXT} and R_{CH} as introduced in Fig. 1(b). Effective potential of the source changes due to the voltage drop $(R_{EXT} + R_{CH})(I_1 + I_2)$. Even in the absence of Coulomb correlation, the common resistance gives rise to negative correlation coefficient as

$$C_R \cong -(R_{EXT} + R_{CH}) \frac{G_2 S_1 + G_1 S_2}{\sqrt{S_1 S_2}} \sim -2G(R_{EXT} + R_{CH})$$

obtained for the small resistance limit $R_{EXT} + R_{CH} << G_1^{-1}$, G_2^{-1}, identical conductance $G = G_1 = G_2$ and noise $S_1 = S_2$. This explains the linear G-dependence with $R_{EXT} + R_{CH} \sim 1$ kΩ in Fig. 3(b). The weak d-dependence can be explained with the channel resistance R_{CH}. Although R_{CH} is negligibly small for a wide 2DEG, R_{CH} reaches ~1.6 kΩ (corresponding to 8 one-dimensional channels) for a narrow source channel with d = 0.4 μm in our device. This simple resistance analysis qualitatively agrees with the observed increase (about a factor of 3) of C. In the context of quantum transport, electron distribution in the narrow channel can be disturbed by contact with the two PCs. The results suggest the importance of a common circuit environment for multiple PC detectors.

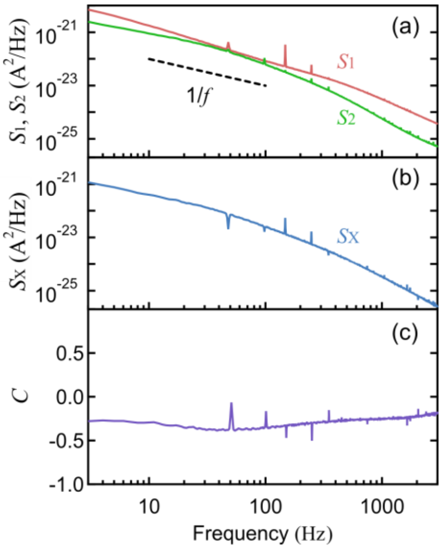

Fig. 2. (a) Auto-correlation spectral density. (b) Cross-spectral density. (c) Correlation coefficient defined in the text.

4. Summary

We have investigated the current correlation of PCs with a common source electrode. The observed correlation arises from the common resistance, which is significantly enhanced when the source lead has a few 1D channels. The results suggest the significance of the circuit environment in current correlation.

Acknowledgments

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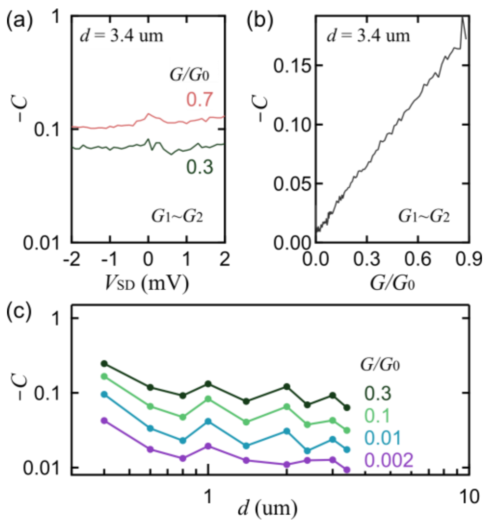

Fig. 3. Correlation coefficient (sign reversed) as a function of (a) V_{SD}, (b) conductance, and (c) distance between the PCs.