

Temporal Correlation of Electrons: Suppression of Shot Noise in a Ballistic Quantum Point Contact

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Wideband shot noise, associated with dc current flow through a quantum point contact (QPC), is measured in the microwave frequency range of 8–18 GHz. As the number of conducting channels in the QPC changes the noise power oscillates. Consistent with existing theories, the noise peaks depend linearly on the dc current. Surprisingly, however, in the pinch off region, where QPC is expected to behave as a classical injector, we find strong noise suppression, possibly mediated by the Coulomb interaction.

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The *granularity* of the electrons and the stochastic nature of their transport lead to unavoidable temporal fluctuations in electrical currents, called *shot noise*, first observed in vacuum diodes [1]. In truly stochastic (Poisson-like) electron emission processes the average of the squared current fluctuations Δi , measured in a frequency range $\Delta\nu$, is given by the classical *shot noise* expression [2]

$$\langle(\Delta i)^2\rangle_{\Delta\nu} = S(\nu)\Delta\nu = 2Ie\Delta\nu, \quad (1)$$

where $S(\nu)$ is the *white* spectral density and I the average current. In a classical conductor, however, shot noise is not observed. This *noise suppression* is due to self-averaging of independent current fluctuations in different parts of the conductor [3,4]. The suppression is of the order of l_{in}/L (and normally $l_{\text{in}} \ll L$), where l_{in} is the inelastic mean free path and L is the sample's length. In contrast, in *mesoscopic systems*, where $L < l_{\text{in}}$, shot noise can be profound. For example, in diffusive mesoscopic systems, where $l_e \ll L \ll l_{\text{in}}$, with l_e the elastic mean free path, shot noise is predicted to be 1/3 of the classical value given in Eq. (1) [3]. At the extreme case of ballistic transport, $L < l_e$, shot noise is expected to vanish if all the one-dimensional (1D) quantum channels fully transmit. This fact, first pointed out by Khlus and by Lesovik [5] to result from Fermi statistics, leads to temporally correlated conduction. We study here the nature of shot noise in a ballistic *quantum point contact* (QPC) thus gaining information about temporal correlation between electrons, not provided by low frequency conductance measurements.

The QPC, electrostatically defined in the plane of a two-dimensional electron gas (2DEG), exhibits conductance quantization [6]. The measured conductance, at zero temperature, can be expressed via the multichannel Landauer formula [7],

$$G = \frac{2e^2}{h} \sum_{i=1}^N T_i, \quad (2)$$

with N being the number of occupied 1D ballistic channels and T_i the transmission probability through channel i . For an adiabatic transition from a 2D medium to the quasiconfined QPC, theory predicts [8] and experiments show [6] that for occupied channels $T_i \cong 1$, making the QPC fit for observing noise suppression. Indeed, the theoretically obtained low frequency spectral density of the current fluctuations at zero temperature θ , for energy independent T_i 's is [5,9]

$$S(\nu = 0) = 2e \frac{2e^2}{h} V_{DS} \sum_{i=1}^N T_i (1 - T_i);$$

$$k_B\theta \ll eV_{DS}, \quad (3)$$

where V_{DS} is the injection voltage across the QPC. Since $\frac{2e^2}{h} V_{DS} T_i = I_i$ is the i 's channel current, a noise suppression of $(1 - T_i)$, relative to the classical noise for the i 's channel, is expected. In an experiment where the T_i 's are being continuously varied, the shot noise is expected to have maxima whenever the transmission of the uppermost conducting channel is 1/2. Note that the frequency dependent $S(\nu)$ was shown (neglecting Coulomb interactions between electrons) to decrease linearly with ν with $S(\nu_{\text{cutoff}}) = 0$ for $h\nu_{\text{cutoff}} = eV_{DS}$ (i.e., for $V_{DS} = 1$ mV, $\nu_{\text{cutoff}} = 250$ GHz) [10].

The first attempt to measure noise in a QPC was by Li *et al.* [11] followed later by others [12,13]. All measurements had been restricted to low frequencies ($\nu < 100$ kHz) where $1/f$ noise or fluctuations and instabilities of the conductance are dominant, and the noise power was found to have a square dependence on the dc current and not the expected linear dependence. Note though that Li *et al.* [11] attributed the noise measured at the highest frequency to quantum shot noise and found it to be less than the classical shot noise. A linear dependence of noise on the dc current, though, was observed for noise measured in diffusive mesoscopic conductors [14].

First, we make some order of magnitude estimates. The injected dc current, I_{in} , and the applied voltage, V_{DS} ,

should be as small as possible in order to (a) prevent electron heating, and (b) prevent injection into higher 1D channels. However, the applied voltage V_{DS} should be greater than $k_B\theta/e$ in order to make Eq. (3) applicable. For example, $V_{DS} = 1$ mV leads, according to Eq. (3), to a peak noise $S(0) = 6.2 \times 10^{-27}$ A²/Hz. At high enough frequencies this *shot noise signal* has to compete with the noise of the amplifiers. Even a cold amplifier has an equivalent noise temperature of 40 K at its 50Ω input impedance, leading to a spectral density of unwanted noise $k_B\theta/50 \Omega = 10^{-23}$ A²/Hz, more than 3 orders of magnitude higher than the *shot noise* we are searching for. Consequently, in order to improve the *signal-to-noise ratio* (S/N) we modulate the dc current through the QPC at a low frequency f (less than 1 kHz) and measure the amplified *excess noise*, synchronously with f , using a lock-in technique. It turns out that the wideband measurements improve the S/N relative to the ratio of the spectral densities given above by a factor of $(\Delta\nu/\Delta f)^{1/2}$, where Δf is the low frequency bandwidth (determined by the time constant of the lock-in amplifier) [15]. We thus expect that measuring the shot noise synchronously, in a band $\Delta\nu = 8-18$ GHz ($\Delta\nu = 10$ GHz), with $\Delta f < 1$ Hz will improve the S/N by a factor of $(1-3) \times 10^5$, leading to an acceptable $S/N \approx 10^2$.

Our QPC is induced electrostatically in the plane of a 2DEG, embedded in a GaAs-AlGaAs heterostructure only 33 nm below the surface. The 2DEG has an areal electron density of 4.6×10^{11} cm⁻² and a low temperature mobility of 5×10^5 cm²/V s. The QPC is formed by direct electron beam writing and metal gate (TiAu) deposition, with a 100 nm gap between the two gates (shown schematically in Fig. 1). The voltage, applied to the gates via a low pass filter with an upper frequency of 1 MHz, controls the number of 1D conducting channels in the QPC. Under all conditions of the experiment no measurable gate leakage current

was found. The dc voltage drop across the sample was monitored during the measurement with a lock-in amplifier and was kept constant via a feedback loop (taking into account series resistance). Similarly, the dc current was kept constant by monitoring the dc voltage drop on a series 1 M Ω resistor. Note that high frequency path to ground is provided via the capacitor C_i , effectively maintaining a constant voltage on the sample. The high frequency current fluctuations are being fed to the amplifier through an isolator, are amplified in the 8–18 GHz band, and are finally applied to a high frequency diode and a load capacitor C_l . The isolator is used to eliminate the effect of the sample impedance changing with the current on the noise of the amplifier. This effect, usually negligible, could be essential when measuring very small signals. The low frequency output $V_{out}(f) \propto \langle(\Delta i)^2\rangle_{10\text{GHz}}$ [16] is converted, after calibration, to the spectral density at the input S (A²/Hz) assuming the noise is *white* in the measuring band. The calibration in turn was done separately for the losses of the cables, the amplification of the two amplifiers, and the sensitivity of the diode, over the integrated spectrum in the 10 GHz band. Losses due to coupling of the sample to the output cable were minimized and the accuracy was estimated to be 1–1.5 dB.

Typical results for the dc conductance G and the noise signal S , measured as a function of gate voltage V_G , at $T = 1.5$ K, are shown in Fig. 2. The linear conductance is quantized in units of $2e^2/h$, after subtracting the series resistance of the Ohmic contacts. The noise signal, $S \propto V_{out}(f)$, is measured for different injection voltages, $V_{DS}(f) = \frac{V_{DS}}{2}(1 + \cos 2\pi ft)$, imposed on the QPC. As predicted by Eq. (3), keeping V_{DS} constant allows the injected current $I_{in}(f)$ to change as the conductance of the QPC varies, leading to a noise dependence proportional to $T(1 - T)$. Indeed the measured noise signal, as a function of V_G and for different V_{DS} , exhibits strong

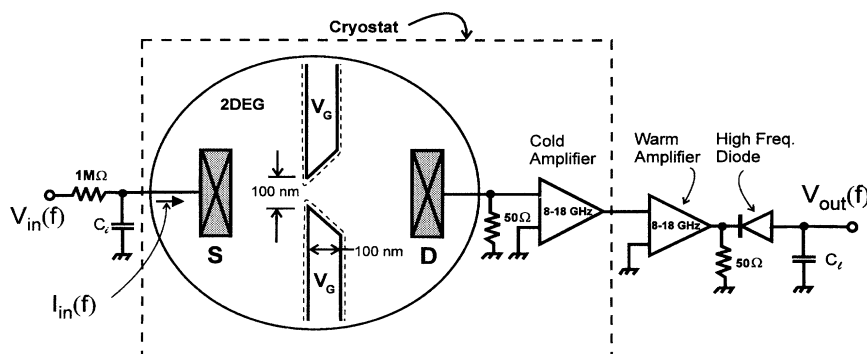


FIG. 1. The experimental setup. The voltage controls the number of 1D conducting channels in the QPC. The current, modulated at low frequency f , is provided to the QPC via a variable current source, with a voltage $V_{DS}(f)$ appearing across the QPC. A high frequency path to ground is provided via capacitor C_i . The current and its high frequency fluctuations are fed into a low noise cooled amplifier with a power gain of 10^3 in the band 8–18 GHz. Another “warm amplifier” follows—terminated by a high frequency diode and load capacitor C_l , providing the low frequency output $V_{out}(f) \propto \langle(\Delta i)^2\rangle_{10\text{GHz}}$.

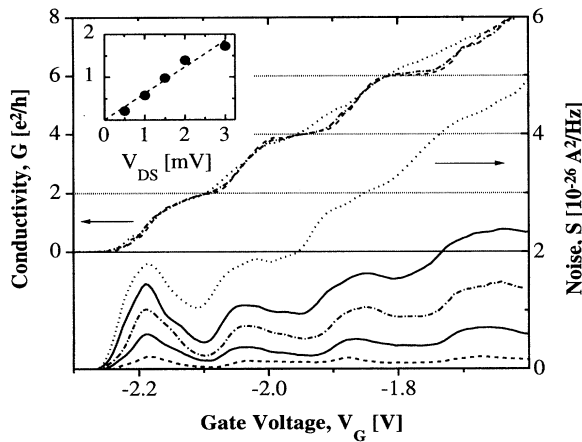


FIG. 2. Noise spectral density $S(\nu)$ and normalized linear conductance G vs gate voltage V_G . The noise is measured for $V_{DS} = 0.5, 1, 1.5, 2,$ and 3 mV. Inset: Dependence of the first peak height (same scale as in main figure) on injection voltage V_{DS} . The dashed straight line is the predicted behavior. The conductance is shown for $V_{DS} = 0.5, 1.5,$ and 3 mV.

oscillations on top of a background that monotonically increase with the current through the sample. The magnitude of the first peak agrees rather well with the predicted noise maximum, being $(1/4)2e(2e^2/h)V_{DS}$. All peaks' positions correspond roughly to the conductivity $(2i + 1)e^2/h$ and hence to $T_i = 1/2$, assuming the T_i 's are energy independent. As was pointed out, we are measuring *excess noise*, which is the difference between the noise with and without current. This noise consists of a *shot noise* component proportional to $T_i(1 - T_i)$ and a *thermal noise* component [17]. Thermal noise is expected to increase with the current due to the overheating of the electrons and hence also should be in phase with the current through the contact. We attribute the monotonic rise of the background noise with the number of channels and thus with the current through the QPC to this effect. Note, however, that the reason the noise peaks corresponding to the higher occupied channels are smaller than the first one is not clear yet.

Equation (3) predicts the linear growth of the *shot noise* with V_{DS} for $k_B\theta \ll V_{DS}$. This dependence is shown for the first noise peak in the inset in Fig. 2 and is found to agree with the prediction not only qualitatively but also quantitatively within accuracy of our calibration (1–1.5 dB). This “linear” dependence of the noise spectral density on current is a crucial fact in substantiating the origin of the noise.

We also performed detailed investigations of the noise in the pinch-off region of the QPC where only the first channel is relevant. As the gate voltage becomes more negative and the resistance of the QPC increases, the current and its fluctuations tend to zero. We thus performed noise measurements (on a different device)

at a constant current I , expecting to get the behavior $S = 2eI(1 - T_1)$, which is nearly classical when $T_1 \ll 1$. The noise signal is expected to rise monotonically with decreasing V_G , saturating eventually at a value twice as large as that for $T = 1/2$ (as shown in Fig. 3 by the dotted lines). Contrary to that, we find, with and without application of a magnetic field, that the noise signal peaks around V_G corresponding to $T_1 = 1/2$, drops at lower V_G 's, and saturates with values more than three times smaller than expected. We wish to stress again that, unlike the measurements with constant V_{DS} , these measurements are done with constant dc currents; hence the peaks near $T_1 = 1/2$ are not expected. Another remarkable fact is that for highly negative gate voltage, as the dc current increases above some 100–150 nA, the noise signal does not increase.

One possible explanation for this noise suppression is that correlation due to Coulomb repulsion between electrons sets in; this correlation is not accounted for by the existing theories. We rule out noise suppression resulting from a possible reduction of I_{in} at high V_{DS} since $I_{in} \gg L$ (where $L \sim 100$ nm) all through the experiment.

Coulomb-mediated correlation should become significant when the dwell time in the QPC becomes the limiting factor in determining the current rather than the transmission coefficient, T , through the barrier. This happens when the dwell time becomes comparable to the average time interval $\Delta t = e/I$ between electrons entering the barrier. The saturation of the noise signal is apparent at $I > 150$ nA, then $\Delta t < 1$ ps. The dwell time, on the other hand, is the tunneling time or the traveling

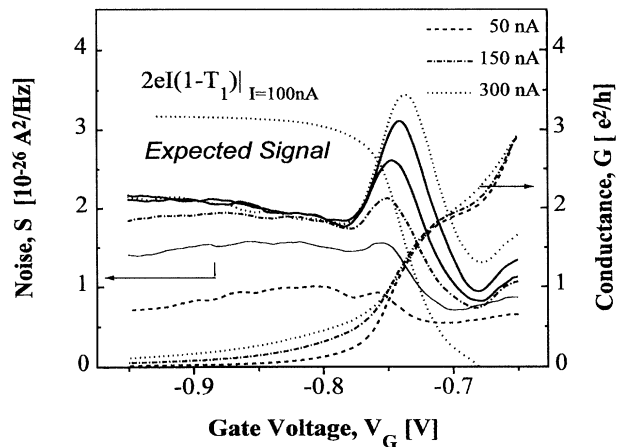


FIG. 3. Noise spectral density $S(\nu)$ vs gate voltage V_G for different currents through the QPC (50 to 300 nA with 50 nA step). Curves for expected noise according to Eq. (3) for $I = 100$ nA are added. The noise is sharply suppressed for highly negative gate voltages and is smaller than expected by approximately a factor of 3 for a current of 50 nA and even much more for larger currents. Conductance curves measured at three different currents are given.

time of the thermally activated electrons through the barrier. Even though there is no common accepted view for the tunneling time we chose to estimate it via the semiclassical time $\Delta t_{\text{tunn}} = \Delta x/v$, where Δx is the tunneling length and v is the value of the tunneling velocity given by $\sqrt{2(\Phi - E_F)/m}$, with $\Phi - E_F$ the effective barrier height above the Fermi energy [18]. For our barrier with dimension of the metallic gates, $\Delta x \approx 100$ nm, a tunneling transmission of the order of $T_1 \approx 0.1$ is achieved when the effective barrier is on the order of 1 meV. The tunneling velocity is then $v \approx 10^7$ cm/s and the dwell time is $\Delta t_{\text{tunn}} \approx 1$ ps. Similarly, if transport is via thermionic emission we have to take for the velocity the thermal velocity, leading to a dwell time of the same order. Since the dwell time is quite similar to the average entering time interval, transport is correlated and the current is $I = e/\Delta t_{\text{dwell}}$. As the current increases Δt_{dwell} becomes smaller.

Is the Coulombic repulsion energy sufficiently high to correlate the electrons? For a distance $\Delta x \approx 100$ nm and with negligible screening we find a repulsive energy ~ 1.3 meV. It is sufficiently large, relative to the temperature (~ 0.13 meV) and the effective barrier height (~ 1 meV), to suppress transfer of a second electron when one electron dwells in the barrier. If true, the resultant temporally correlated transport persists for currents larger than ~ 100 nA and is expected to have a spectral peak at $\nu > 1$ THz. We thus propose that our measured noise, when $T \ll 1$, could represent a sample of the spectral tail in the 8–18 GHz band, with peak noise increasing in magnitude and shifting to higher frequencies as the current increases, thus keeping the noise signal in the tail almost constant. This rather crude estimate is consistent with our data in Fig. 3. In preliminary tests, with longer QPC (dwell region longer than 100 nm), we find that the current at which noise saturation takes place is lower than 150 nA—agreeing in principle with our hypothesis.

Another possible explanation for the noise saturation could be [19] due also to Fermi related correlations. At large enough currents voltage drop across the QPC becomes comparable or even bigger than the Fermi energy of the 2D electron gas. This may lead to injection of electrons over the barrier with transmission close to unity and hence to noiseless conduction. Only electrons with energies near the top of the potential barrier have large $T(1 - T)$ value and thus contribute to the observed noise.

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 - [15] The shot noise spectral density is almost constant for $\nu \ll \nu_{\text{cutoff}} \sim 250$ GHz. Hence the shot noise signal, associated with the current modulated at frequency f , indeed scales with the bandwidth. We have to compare it not with the total noise of the amplifier at the same band, but only with its *fluctuations* at the modulating frequency f . These fluctuations, independent for every Fourier component of the amplifiers' noise, add stochastically and thus increase with the *square root* of the bandwidth.
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