Low-frequency noise in transport through quantum point contacts

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We report the noise characteristics of quantum point contacts between 100 Hz and 100 kHz at 4.2 K. The noise consists of a $1/f$ component on top of a white background. The $1/f$ noise increases as the contact width decreases and shows peaks between the quantized resistance plateaus. The white noise background increases with current but is much lower than the full shot noise level, suggesting that shot noise is not generated in an ideal quantum point contact, where the electrons do not suffer backscattering as they enter and traverse the contact.

With modern microfabrication technology, conduction channels in a two-dimensional (2D) electron gas (EG) can be confined to a width comparable to the electron Fermi wavelength, giving rise to one-dimensional (1D) subbands. For such a 1D channel, if the length is much shorter than the electron mean free path, the transport becomes ballistic. If the opening to the outside 2DEG is smooth and gradual, electron transit from the 2D states to the 1D states can be regarded as adiabatic.[1] Such a ballistic and smooth 1D channel forms a quantum point contact,[2,3] whose resistance at zero temperature is quantized to $h/2e^2N$, where N is the number of occupied 1D subbands and h/e^2 is the resistance quantum ($\simeq 25.9$ kΩ). Quantization of the contact resistance was first observed by van Wees *et al.*[4] and by Wharam *et al.*,[5] in laterally confined 2DEG in GaAs/AlGaAs heterostructures at low temperatures.

We wish to report in this letter the first experimental study on the noise characteristics of similarly confined quantum point contact at 4.2 K. The purpose of our study is twofold. First, it has been predicted that electron transport through a ballistic constriction should generate shot noise.[6] Our experiment was to detect the shot noise and test this prediction. Second, most of the existing studies on the quantum point contact have been on the ordinary transport properties involving statistically averaged values of macroscopic quantities such as current and voltage. Noise measurements, involving the fluctuations of these quantities, can be used as an additional tool to study the transport. Our results show that, for frequencies f between 100 Hz and 100 kHz and dc current I below 0.6 μA, the noise consists of $1/f$ noise on a white background. The power density of the current fluctuations, S_i, has an I and f dependence of I^β/f^α for the $1/f$ noise, with $\alpha = 0.9 \pm 0.1$ and $\beta = 2 \pm 0.4$. It also strongly depends on the 1D channel width, and shows peaks between resistance plateaus. The white noise background increases with I but never reaches the full shot noise level, indicating that transport through a ballistic constriction does not necessarily generate shot noise.

Our sample is made from a molecular beam epitaxy (MBE) grown GaAs/AlGaAs heterostructure with a 2D electron density $\simeq 3.4 \times 10^{11}$ cm^{-2} and a mobility $\simeq 1 \times 10^6$ cm^2/V s. The conduction channel is confined with a pair of point-type gates as shown in the inset of Fig. 1 . When the gate voltage V_g is less than -0.6 V the 2DEG under the gates is completely depleted and the 1D channel is formed. Further decrease in V_g increases the area of the depletion regions and thus reduces the channel width. The gates start to leak for $V_g < -2.4$ V. The channel resistance R for $-2.4\ \text{V} < V_g < -1.4$ V (for $N = 2$–5) is shown in Fig. 1. It is apparent that R has plateaus, which are within 10% of the theoretical quantized values (except $N = 2$). The resistance outside the 1D channel ($\sim 64\ \Omega$ including contact resistance) is much smaller than the resistance of the 1D channel itself (e.g., 2.6 kΩ for $N = 5$), and the effect of series resistance on the noise measurement can be ignored. The measuring I is limited to below 0.6 μA so that the R quantizations are not quenched. The noise is measured for 100 Hz $< f <$ 100 kHz with a low noise preamp and a fast Fourier transform (FFT) spectrum analyzer. The background noise from the measurement circuit is subtracted from the data.

Figure 2 shows S_i as a function of f at $I = 0.43$ μA for $V_g = -1.6$ V (between $N=5$ and $N=4$ plateaus) and -1.8 V (approximately on the $N = 4$ plateau). It is evident that S_i follows an approximate $1/f$ dependence below 1 kHz and that S_i tends to become flat for higher frequencies. For $-2.4\ \text{V} < V_g < -1.4$ V and 0.2 μA $< I$ 0.6 μA, we find that $S_i \sim 1/f^\alpha$ with $\alpha = 0.9 \pm 0.1$ below 1 kHz, and that S_i is approximately independent of f above 50 kHz. We consequently fit $S_i(f)$ to $S_i(f) = A/f + S_{i0}$ for 100 Hz $< f <$ 100 kHz, where A and S_{i0} are fitting parameters. The $1/f$ component, A/f, is larger than the white noise background, S_{i0}, below 5 kHz for $I > 0.3$ μA, and S_{i0} is larger than A/f above 50 kHz for $I < 0.6$ μA. The measurements and numerical analysis allow us to determine A and S_{i0} to an accuracy of approximately 20%. The coefficient A, measured by sweeping I while keeping V_g fixed, is shown as a function of I^2 in the inset of Fig. 2, which reveals that A is proportional to I^2. In general, when keeping V_g fixed and sweeping I, we find that $A \sim I^\beta$ with $\beta = 2 \pm 0.4$ for $-2.4\ \text{V} < V_g < -1.4$ V and $I < 0.6$ μA.

To further characterize the $1/f$ noise, $A_0 \equiv A/I^2$ is plotted in Fig. 1 against V_g for $I = 0.4$, 0.5, 0.6 μA. The

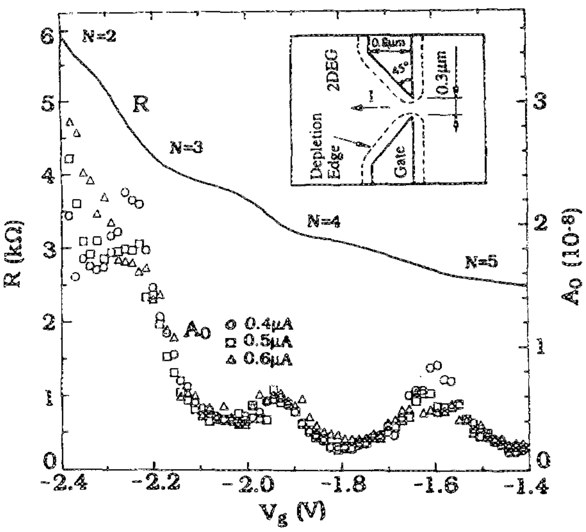

FIG. 1. R vs V_g and A_0 vs V_g. A_0 is obtained by fitting $S_i = A_0I^2/f + S_{i0}$ for $I = 0.4$, 0.5, and 0.6 μA. The approximate plateaus in R are assigned to the quantized resistances $h/2e^2N$, with $N = 2$, 3, 4, and 5. Inset shows the device geometry (not to scale).

data were taken by keeping I fixed while sweeping V_g from -1.4 to -2.4 V in about 2 h for each I value. We first note that A_0 is approximately independent of I (in agreement with $A \sim I^2$) except for $V_g < -2.2$ V and for $V_g \approx -1.6$ V, where large deviations from the $A \sim I^2$ law arise, probably due to the slow response of the sample to V_g changes. We also find that A_0 generally increases as the channel width is decreased by decreasing V_g, and has peaks between the R plateaus. It is noteworthy that $A_0 \sim 10^{-8}$, which is at least two orders of magnitude larger than for ordinary devices such as silicon bipolar transistors. We point out that in some cool downs of the same sample, the peaks of A_0 were severely smeared, although the R plateaus were still clear. The monotonic increase of $1/f$ noise with decreasing V_g was also observed in samples which show no clear plateaus in R.

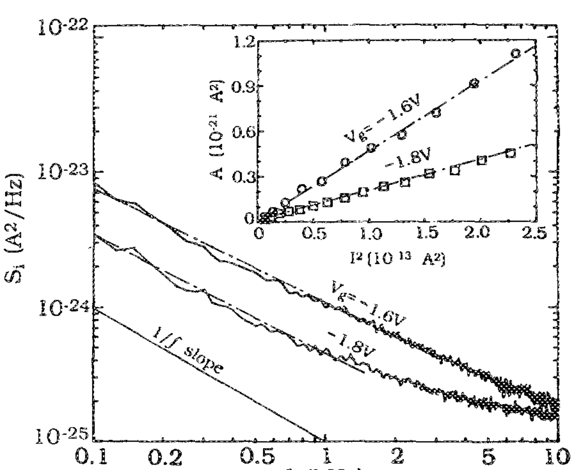

FIG. 2. S_i vs f for $I = 0.43$ μA, $V_g = -1.6$ V and -1.8 V. Inset shows A vs I^2, where A is obtained by fitting $S_i = A/f + S_{i0}$. Dash-dot lines serve as a guide to the eye. The solid line shows the $S_i \sim 1/f$ slope.

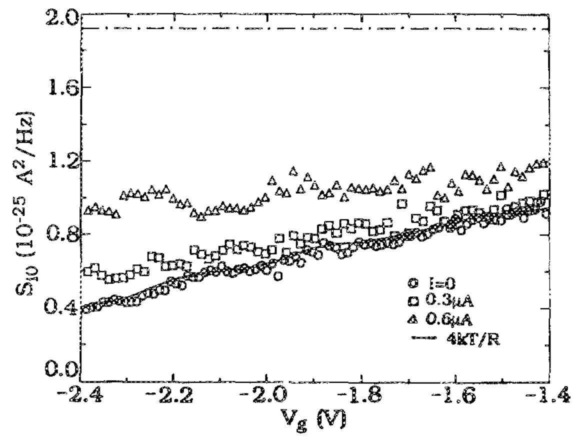

FIG. 3. S_{i0} vs V_g for $I = 0$, 0.3, and 0.6 μA, where S_{i0} is obtained by fitting $S_i = A_0I^2/f + S_{i0}$. The solid curve is the Johnson noise calculated using $4kT/R$. The dash-dot line indicates the theoretical full shot noise ($2eI$) at 0.6 μA.

In Fig. 3, the white noise background S_{i0} is shown as a function of V_g for $I = 0$, 0.3, and 0.6 μA. For $I = 0$, S_i averaged over 5–10 kHz is used directly for S_{i0}. S_{i0} agrees well with the Johnson noise calculated from R using $S_{i0} = 4kT/R$, which is shown as the solid curve. S_{i0} increases with I, but is always far below the theoretical full shot noise level ($2eI$), which is shown as the dash-dot line for $I = 0.6$ μA.

We visualize the $1/f$ noise, A_0I^2/f, as having two components. One is a smooth background, decreasing with V_g but unrelated to the resistance quantization, and is attributable to trapping and detrapping of the conduction electrons,[7] probably on the GaAs/AlGaAs interface. The other component has its peaks between the R plateaus, and is clearly correlated to the resistance quantization. This component may result from some processes which are related to the 1D density of states in the channel and have rates comparable to our measurement frequencies.

The observed increase in S_{i0} with I can result from several sources. First, the experiments were made at finite T and with finite I. Both may cause 1D subband mixing, which will generate noise in addition to the Johnson noise.[8] Besides, the neck of the 1D channel may not be sufficiently smooth and gradual so that the passing of the electrons from the 2D states to the 1D states is not completely adiabatic; the nonadiabaticity permits backscattering and produces noise. Moreover, after passing through the 1D channel, the electrons gain kinetic energy and become hotter than the lattice. The subsequent diffusion and relaxation of these hot electrons result in additional noise.

The fact that S_{i0} is below the full shot noise level at finite T suggests that transport in an ideal quantum point contact at $T = 0$ does not generate shot noise. To make this point clear, it is instructive to compare the quantum point contact with the thermal emission of electrons from the cathode of a vacuum tube. In the latter case, electrons must be thermally excited above the work function of the cathode to be emitted. The thermal excitation processes give rise to the randomness in the electron flow and hence the shot noise in the current.[6] However, the conduction of quantum point contacts can be described within the Landauer formalism.[9,1] At $T = 0$, all the electrons below the Fermi level participate in the conduction. The occupation of these electrons is not affected by any random processes and is not subject to fluctuations. In the ideal case, neither backscattering from the neck of the 1D channel nor scattering inside the 1D channel is present, and all electrons traverse the point contact with unit transmissivity. The 2D regions outside the 1D channel can also act as buffers to fluctuations associated with the emission and collection of electrons by the ohmic contacts. Therefore, unlike in the vacuum tube, electrons do not pass in random shots and shot noise is not generated. This result disagrees with the theoretical prediction that transport through a ballistic construction should generate shot noise.[6]

In conclusion, we have shown that the low-frequency noise in transport through a ballistic point contact of 2DEG in GaAs/AlGaAs heterostructures at 4.2 K consists of a $1/f$ component on top of a white background. The $1/f$ noise increases as the contact width decreases and shows peaks between the quantized resistance plateaus. The white noise background increases with current but is much lower than the full shot noise level. We have discussed these results using the Landauer formalism and suggest that shot noise is not generated in an ideal quantum point contact, where the electrons do not suffer backscattering as they enter and traverse the contact.

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