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Low-Frequency Noise in Quantum Point Contacts

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The low-frequency resistance noise of a quantum point contact is shown to be caused by fluctuations in the electrostatic potential. These fluctuations can be explained by the presence of a single electron trap in the vicinity of the point contact. The noise intensity is strongly suppressed at the quantized values of the resistance. From shifting the point contact laterally, the position of the trapped electron could be estimated.

We studied the kinetics of charge transport in the quantum ballistic regime using quantum point contacts (QPCs). A QPC is a constriction of variable width in a high-mobility two-dimensional electron gas (2DEG), defined by means of a split-gate lateral depletion technique. The time-averaged transport in the quantum ballistic regime has already been studied in detail before [1] and has shown a quantization of the conductance G in units of $2e^2/h$. The reason for this quantization is the nearly unit transmission probability for each of the occupied one-dimensional (1D) subbands in the point contact, which are the propagating modes in this 'electron waveguide' problem [2]. Recently, the kinetics of charge transport in QPCs has been studied experimentally [3-5], resulting in the observation of a *quantum size effect* on $1/f$-noise [3,4] as well as on *random telegraph signals* [4,5]. Theoretically [6], most attention has been directed to shot noise, which is expected to be reduced due to the deterministic electron transport in QPCs. In this contribution we will focus on some experimental results on random telegraph signals.

The experiments have been performed at 1.4 K on a GaAs/$Al_xGa_{1-x}As$ QPC, with x = 0.33. The MBE-grown structure consists of a thick GaAs layer, a 20 nm undoped AlGaAs spacer, a 40 nm Si-doped AlGaAs layer, and a 20 nm GaAs caplayer. At the interface between

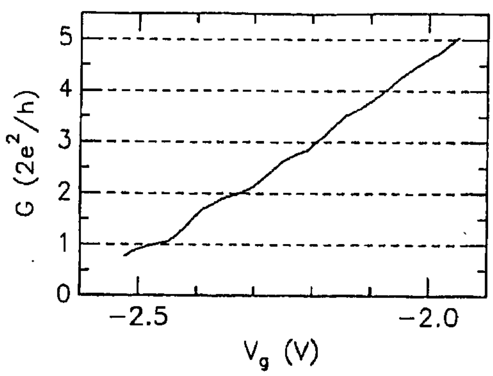

Fig. 1. Quantized conductance of the point contact at 1.4 K.

the GaAs-layer and the undoped AlGaAs-layer a 2DEG exists due to the different bandgap of both materials, and the presence of ionised donors in the doped AlGaAs layer. On top of this heterostructure a split Schottky gate has been defined. A negative voltage V_g on both half gates depletes the region beneath the gate, and a point contact will be formed between two wide regions in the 2DEG. The electron density in the wide 2DEG is 3.5×10^{15} m^{-2}, whereas the electron mobility amounts to 65 m^2/Vs, corresponding to an electron mean free path of about 6 μm. As can be seen in Fig. 1, the time-averaged point contact conductance clearly shows the expected conductance plateaus at 1.4 K.

The voltage fluctuations over the point contact were measured in a four-terminal configuration, biasing the point contact with a dc current I (typically 30 nA). The voltage fluctuations were fed into an ultra-low-noise preamplifier, and subsequently fast Fourier transformed by a digital spectrum analyzer, resulting in a voltage noise power spectrum. The excess-noise spectral density $S_V(f)$, which has a Lorentzian frequency dependence [4], has been found to vary quadratically with current, indicating that the fluctuations are genuine resistance fluctuations.

Direct measurements in the time domain have revealed random switching of the resistance $R \equiv 1/G$ between two discrete states, spending on the average a time τ_{low} in the low-resistive state R, and a time τ_{high} in the high-resistive state $R + \Delta R$. Such 'random telegraph signals' are known to yield a Lorentzian spectral density [7]

$$S_V(f) = \frac{4(\Delta V)^2}{\tau_{low} + \tau_{high}} \frac{\tau_{eff}^2}{1 + 4\pi^2 f^2 \tau_{eff}^2}, \quad (1)$$

with $1/\tau_{eff} = 1/\tau_{low} + 1/\tau_{high}$ and $\Delta V \equiv I\Delta R$. The switching of the resistance is caused by the presence of a *single* electron trap in the vicinity of the point contact. Due to the Coulomb potential of the trapped electron, charging and decharging of the trap modulates

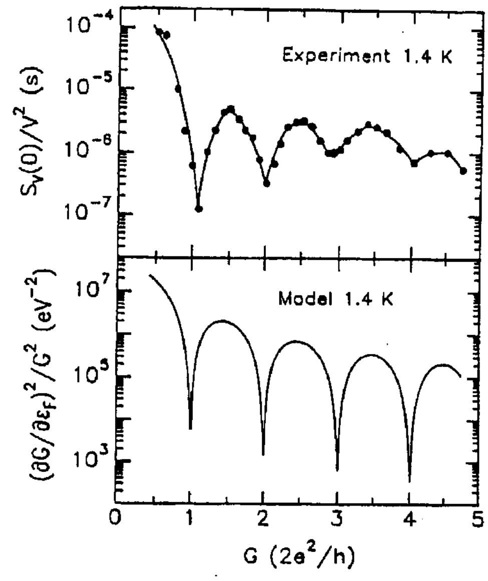

Fig. 2. Top figure: $S_V(0)/V^2$ vs G at 1.4 K (solid curve is a guide to the eye). Bottom figure: $(\partial G/\partial \varepsilon_F)^2/G^2$ vs G, calculated from Eq. 2 and 3.

the conductance, and thus the voltage V. The times τ_{low} and τ_{high} can be identified with the capture and emission times of the trapping proces. In Fig. 2 (upper part) the relative excess-noise spectral density $S_V(0)/V^2$ has been plotted versus G. Sharp minima occur for $G = n \times (2e^2/h)$, i.e., at the plateaus in G where the Fermi energy ε_F is right between the subband bottom energies ε_n and ε_{n+1} of two 1D subbands, whereas maxima are observed for $G = (n - \frac{1}{2}) \times (2e^2/h)$, i.e., between the plateaus in G, where $\varepsilon_F \approx \varepsilon_n$. This quantum size effect on the noise is a universal feature of QPCs and, remarkably, does not depend on the spectral dependence of the noise spectral density [4].

To illustrate the origin of the quantum size effect, we model the resistance fluctuations by fluctuations $\Delta\varepsilon_m$ in the subband bottom energies ε_m, and assume these fluctuations to be independent from m and G. This assumption will be relaxed in the second part of this paper. The relative voltage-noise spectral density for a QPC with idealized step-function transmission probability now equals

$$\frac{S_V(f)}{V^2} = \frac{1}{G^2}\left(\frac{\partial G}{\partial \varepsilon_F}\right)^2 S_0(f), \tag{2}$$

with $S_0(f)$ a measure of the fluctuations in ε_m, and

$$G = \frac{2e^2}{h}\sum_m f(\varepsilon_m - \varepsilon_F), \tag{3}$$

with $f(\varepsilon)$ the Fermi-Dirac function. The lateral confining potential in the QPC can be approximated by a parabolic potential of strength ω_0, in which case $\varepsilon_m = \varepsilon_0 + (m - \frac{1}{2})\hbar\omega_0$. Both $\hbar\omega_0$ (typically 1.3 meV) and ε_0 have been obtained from measurements of R as a function of gate voltage and magnetic field. In the lower part of Fig. 2, $(\partial G/\partial\varepsilon_F)^2/G^2$, containing the G dependence of S_V/V^2 (irrespective of the spectral dependence of S_0), has been plotted versus G. As can be seen from the figure, the simple model contained in Eq. 2 and 3 provides a satisfactory account of the experimentally observed quantum size effect on the noise.

In the next part of this contribution, we study the dependence of $S_V(0)/V^2$ on the position of the electron trap with respect to the constriction. The lateral position of the potential minimum x_0 of the point contact can be shifted by applying a voltage difference $\Delta V_g = V_{g1} - V_{g2}$ on the half gates. The shift over a distance x_0 is given approximately by [8]

$$2x_0 = \frac{V_{g1} - V_{g2}}{V_{g1} + V_{g2}} D, \tag{4}$$

with $D = 450$ nm the opening between the half gates. In Fig. 3 (upper part) $S_V(0)/V^2$ has been plotted versus x_0 for $G = (n - \frac{1}{2}) \times (2e^2/h)$, with $n = 1$, 2, and 3. As can be seen in the figure, the noise intensity in this sample clearly increases with x_0 for $n = 1$ and 2, whereas it is nearly constant for $n = 3$. The increase of $S_V(0)/V^2$ with x_0 is due both to a decrease of τ_{low} (which has not yet been understood and will not be discussed here), and to an increase of $\Delta G/G$. The latter effect can be satisfactorily explained by a change of the strength of the Coulomb potential due to the trapped electron. Because $\varepsilon_F \approx \varepsilon_n$ for the measurements of Fig. 3, the fluctuations in $G = (n - \frac{1}{2}) \times (2e^2/h)$ are expected to be dominated by fluctuations in ε_n, so that we may neglect the contribution of the completely occupied subbands ε_m $(m < n)$ below ε_n. From Eq. 3 and the measured $\Delta G/G$ we determine $\Delta\varepsilon_n$ (lower part of Fig. 3). As can be seen in the figure, $\Delta\varepsilon_n$ depends both on n and x_0.

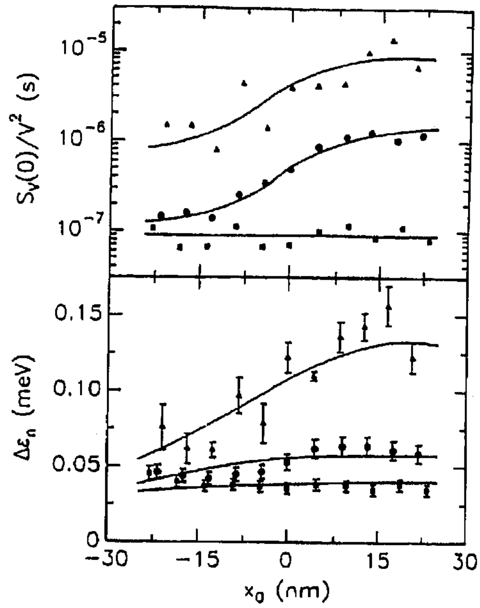

Fig. 3. Top figure: $S_V(0)/V^2$ vs x_0 at 1.4 K (solid curves are guides to the eye) for $n = 1$ (▲), $n = 2$ (•), and $n = 3$ (■). Bottom figure: $\Delta\varepsilon_n$ vs x_0 at 1.4 K (solid curves denote fits by Eq. 5) for $n = 1$ (▲), $n = 2$ (•), and $n = 3$ (■).

To model the effect of a change in x_0 on $\Delta\varepsilon_n$, we assume that the electron is trapped at a position $\mathbf{r}_t = (x_t, y_t)$ in the plane of the 2DEG, relative to the middle of the point contact at $\Delta V_g = 0$ (x denotes the lateral direction, y the direction of electron transport). From first order perturbation theory we expect that

$$\Delta\varepsilon_n = < n \mid U(\mathbf{r}) \mid n >, \tag{5}$$

with $< \mathbf{r} \mid n >$ the wavefunction of the n-th 1D subband in the constriction, and $U(\mathbf{r})$ a screened Coulomb potential of the form [9]

$$U(\mathbf{r}) = \frac{e^2}{4\pi\varepsilon_0\varepsilon_r}\left[\frac{1}{r} - \lambda\int_0^\infty \frac{1}{\sqrt{\eta^2 + r^2}} e^{-\lambda\eta} d\eta\right], \tag{6}$$

with $\varepsilon_r = 13.1$ (GaAs), and λ the screening parameter. Fits by Eq. 5 of the calculated values of $\Delta\varepsilon_n$ to the experimentally obtained data (lower part of Fig. 3) yield $\lambda = 0.12$ nm^{-1}, $x_t = 20$ nm, and $y_t = 45$ nm. The value of the screening parameter deviates from the 2DEG value of 4 nm^{-1}, which may be attributed to the small number of electrons near the point contact [10].

In conclusion, we demonstrated that the dominant low-frequency noise in the QPC originates from trapping and detrapping of electrons near the point contact. A simple model has been developed which accounts for the observed quantum size effect. From varying the lateral position of the point contact, we could estimate the position of the trapped electron. It has also been found, that screening is less effective near the point contact.

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