Spontaneous Resistance Switching and Low-Frequency Noise in Quantum Point Contacts

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The kinetics of charge transport in quantum point contacts has been studied by low-frequency noise spectroscopy. Temperature and frequency (Lorentzian and $1/f$) dependences of the noise spectral density are found to vary strongly from device to device, but the low-T conductance dependence universally exhibits a strong quantum size effect. Based on the direct observation in the time domain of spontaneous resistance switching, the noise is identified to be due to trapping processes which affect the local electrostatic potential. A model is presented which explains the main experimental observations.

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Many of the most striking characteristics of transport in the quantum ballistic regime have been found using quantum point contacts (QPCs), short constrictions of variable width defined by means of a split-gate lateral depletion technique in a high-mobility two-dimensional electron gas (2DEG).[1] A primary finding[2] has been the quantization of the conductance G in units of $2e^2/h$—an effect due to the nearly unit transmission probability for each of the occupied one-dimensional (1D) subbands in the quantum point contact, which are the propagating modes in this "electron-waveguide" problem. An adequate understanding of the time-averaged transport has thus been achieved,[1] but the *kinetics* of charge transport in the quantum ballistic regime remains largely unexplored. Noise spectroscopy may be utilized advantageously in this context.

Recently, Li *et al.* reported the first noise measurements in a QPC at 4.2 K.[3] They found white noise, although not of the expected shot-noise level, and $1/f$ noise showing peaks between the quantized conductance plateaus. The origin of the latter effect remained unclear. It is the purpose of this Letter to show that the low-frequency noise characteristics of quantum point contacts vary strongly from device to device, yet that they have a common origin in temporal fluctuations in the electrostatic potential due to trapping and detrapping of electrons. Indeed, in one device the noise spectral density has been found to be Lorentzian, whereas in another the noise is $1/f$-like and weaker by many orders of magnitude. Also the temperature dependence of the noise intensity is found to be strikingly different. However, both devices similarly exhibit a strong quantum size effect in the low-temperature noise intensity: As shown in Fig. 1, it oscillates with G by more than an order of magnitude with sharp minima at the quantized conductance plateaus. This aspect of the noise is universal, and is explained by the fact that the transmission of the 1D subband closest to its population threshold is the most sensitive to changes in the local electrostatic potential. These potential changes are found to be due to the fluctuating occupancy of electron traps located at or near the point contact. This identification is primarily based on the

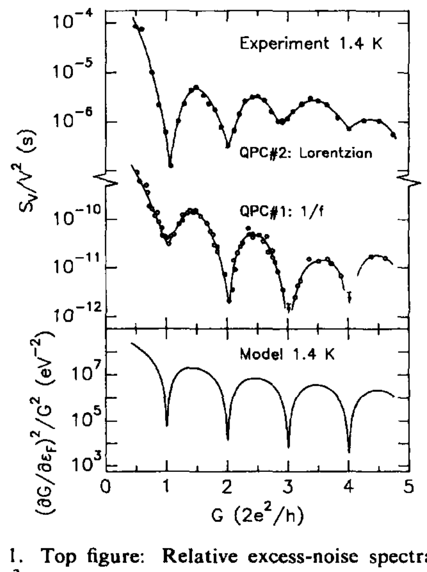

FIG. 1. Top figure: Relative excess-noise spectral density $S_V(0)/V^2$ vs G at 1.40 K. Data for QPC No. 1 denote the $1/f$ noise, $S_V(100\ \text{Hz})/V^2$, while for QPC No. 2 the Lorentzian plateau value, $S_V(0)/V^2$, is given. Arrows denote upper bounds. Solid lines are guides to the eye. Bottom figure: $(\partial G/\partial \varepsilon_F)^2/G^2$ vs G, calculated from Eq. (1).

direct observation in the time domain of discrete resistance switching. A model is presented which is able to account for the variety of effects observed, and the kinetics of one single electron trap is studied in detail.

Two nominally identical QPCs were produced by electrostatic lateral confinement of the 2DEG of a GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructure using a split-gate technique.[1] At 1.40 K, the bulk 2DEG carrier density is $3.5\times10^{15}/m^2$, and the mobility amounts to 65 m^2/Vs corresponding to a mean free path of about 6 μm. Both QPCs clearly exhibit the conductance quantization (not shown here). From the thermal smearing of the plateaus, the 1D subband splitting energy $\Delta\varepsilon$ is estimated to be 1.3 meV. The QPC was biased with a dc current I from 1 to 100 nA chosen such that eV was less than $\Delta\varepsilon$ as well as k_BT, with V the applied voltage, k_B Boltzmann's constant, and T the temperature. The excess ($I>0$) voltage-noise spectral density S_V was obtained with the method described in Ref. 4, which, among other corrections, involves subtraction of the Nyquist noise. S_V was found to exhibit a quadratic dependence on the bias current, which establishes the nature of the fluctuations to be genuine resistance fluctuations. Predicted noise contributions with a linear I dependence[5] were not found at the current levels and bandwidth (0.1 Hz–100 kHz) used.

A primary result is contained in Fig. 1, which shows the relative excess-noise spectral density as a function of the conductance, tuned with the gate voltage. Both QPCs manifest a drastic dependence on G: Sharp minima occur for $G=n(2e^2/h)$ with n an integer, i.e., *at* the plateaus in G where the Fermi energy ε_F is right between the bottom energies ε_n of two 1D subbands, whereas maxima are observed for $G=(n+\frac{1}{2})(2e^2/h)$, i.e., between the plateaus in G, where $\varepsilon_F\approx\varepsilon_{n+1}$. Note that S_V/V^2 differs typically by more than an order of magnitude between minima and maxima. This quantum size effect on the noise is attributed to fluctuations in the transmission probability for the subband which is closest to cutoff. Although in reality the transmission probability fluctuates in a complicated way, we model the fluctuations at finite T by fluctuations in the effective number of transmitted channels, or, equivalently, in $\varepsilon_F-\varepsilon_0$. Arbitrarily choosing ε_0 fixed, and ε_F fluctuating about a time-averaged value $\bar{\varepsilon}_F$, the relative voltage-noise spectral density for a QPC with idealized step-function transmission probability is straightforwardly calculated to equal

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

$$\frac{\partial G}{\partial\varepsilon_F}=\frac{2e^2}{h}\frac{1}{k_BT}\sum_n f(\varepsilon_n-\bar{\varepsilon}_F)[1-f(\varepsilon_n-\bar{\varepsilon}_F)], \tag{1b}$$

with $f(\varepsilon)$ the Fermi-Dirac distribution at temperature T and S_{ε_F} the spectral density of the fluctuations of ε_F. Note that $\partial G/\partial\varepsilon_F$ is evaluated at $\varepsilon_F=\bar{\varepsilon}_F$. The universality of the quantum size effect is due to the fact that, *irrespective of the spectral dependence of* S_{ε_F}, the G dependence of S_V/V^2 is contained in the $(\partial G/\partial\varepsilon_F)^2/G^2$ term. In other words, any temporal fluctuation in the confining potential will have the strongest effect upon transport at the occupancy thresholds of the 1D subbands, where $\partial G/\partial\varepsilon_F$ is largest. The bottom part of Fig. 1 shows the calculated G dependence which compares remarkably well to the experimental noise data: At low temperatures ($k_BT\ll\Delta\varepsilon$) maxima are observed for $G\approx(n+\frac{1}{2})(2e^2/h)$, whereas at integer $G/(2e^2/h)$, in which case both subbands n and $n+1$ contribute equally, the intensity is exponentially suppressed. Furthermore, the overall decrease with G is reproduced. In the calculations $\Delta\varepsilon$ is fixed at 1.3 meV. The origin of the fluctuations in $\varepsilon_F-\varepsilon_0$ will be extracted from the experimental results presented below. The simple model contained in Eq. (1) provides a satisfactory account of the experimentally observed quantum size effect on the noise.

The frequency dependence of S_V/V^2 appears to be surprisingly different for both QPCs; see Fig. 2. For QPC No. 1, S_V/V^2 comprises a $1/f$-noise contribution, together with some additional intensity at low frequencies ($f<100$ Hz). This functional dependence is quite similar for the entire range of I, T, and G investigated. In the remainder of the paper, we therefore concentrate on the $1/f$ contribution for this QPC. At high temperatures ($T>15$ K) the frequency dependence for QPC No. 2 (cf. the spectrum for 26 K in Fig. 2) is very similar to that of QPC No. 1, i.e., $1/f$-like. However, upon lowering the temperature a Lorentzian term, $S_V(0)/(1+4\pi^2f^2\tau^2)$, arises with such an intensity as to rapidly overwhelm all other noise contributions (cf. the spectra for 13 and 2 K in Fig. 2).

How can these striking differences between noise spectra of two nominally identical QPCs be accounted for?

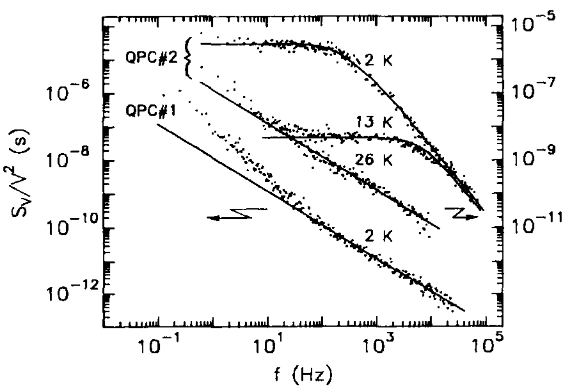

FIG. 2. Typical examples of excess-noise spectra for $G=1.5(2e^2/h)$. Solid lines denote fits by Lorentzian or $1/f$ contributions.

A clue is found in the examination of the resistance directly in the time domain. Whereas for QPC No. 1 a continuous noise signal is found, QPC No. 2 shows discrete resistance switching.[6] As seen in Fig. 3, the conductance randomly switches between two (occasionally three or four) discrete values, spending on the average a time $\tau_{\rm high}$ in the high-resistive state and $\tau_{\rm low}$ in the low-resistive state. The latter state appears to be preferred: A typical ratio is $\tau_{\rm low}/\tau_{\rm high} \sim 8$. At 1.4 K, our lowest temperature, the amplitude ΔG of these conductance changes is close to e^2/h, and accordingly amounts to a very substantial fraction (up to 70%) of the average conductance G. At high temperatures, $T > 15$ K, switching effects are no longer observed. The results for QPC No. 2 may be straightforwardly interpreted as a consequence of the presence of a *single* electron trap located in the immediate vicinity of the point contact. Charging and decharging of the trap then locally modulates the electrostatic confining potential, and, consequently, the conductance of the quantum point contact. The significant low-temperature magnitude of the switching effect is due to the variation of ~ 1 of the transmission probability of the subband closest to cutoff, which is most sensitive to changes in the electrostatic potential. The times $\tau_{\rm high}$ and $\tau_{\rm low}$, which may be identified with capture and emission times, exhibit a slow monotonic increase with G, without any structure with a $2e^2/h$ periodicity, indicating that the nature of the trapping kinetics is virtually unchanged. Thus, it is only the modulation of the potential which brings about the quantum size effect, in support of Eq. (1). "Random telegraph signals," such as in Fig. 3, have been shown[7] to yield a Lorentzian contribution to the noise spectral density, i.e.,

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

$$1/\tau_{\rm eff} = 1/\tau_{\rm low} + 1/\tau_{\rm high}. \quad \text{(2b)}$$

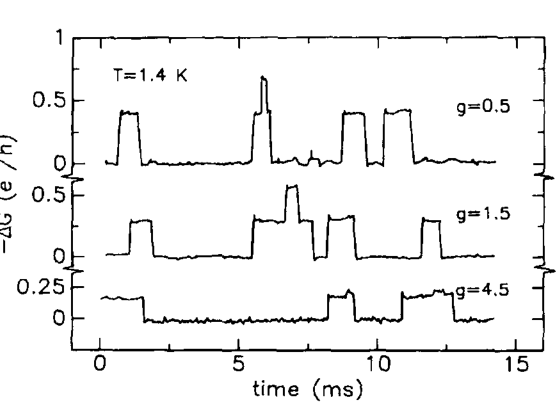

FIG. 3. Typical time traces of the conductance in QPC No. 2 at various values of $g \equiv G/(2e^2/h)$.

Indeed, the low-temperature noise spectra for QPC No. 2 match Eq. (2) excellently upon insertion of ΔG, $\tau_{\rm low}$, and $\tau_{\rm high}$ from the corresponding time traces, demonstrating that an unambiguous identification of the major source of low-frequency noise in QPC No. 2 has been achieved. In order to make a connection with Eq. (1a), we note that, since ε_0 and the electrostatic potential are intimately related, the fluctuations in $\varepsilon_F - \varepsilon_0$ similarly involve discrete switching, so that S_{ε_F} has a Lorentzian dependence as in Eq. (2).

Further support for this picture is found from the temperature dependence. In Fig. 4, the Lorentzian-plateau value for QPC No. 2 is seen to decrease somewhat with T up to 8 K for $G = 1.5(2e^2/h)$, but, by contrast, to increase with T for $G = 1.0(2e^2/h)$. For $T > 8$ K, the noise intensity in both cases decreases by orders of magnitude due to a drastic shortening of $\tau_{\rm high}$ from 1 to 10^{-3} ms. At these temperatures $\tau_{\rm high}$ exhibits thermally activated behavior, i.e., $\tau_{\rm high} = \tau_0 \exp(E_a/k_B T)$, whereas $\tau_{\rm low}$ is constant (8 ms) throughout the entire temperature range. Fits for $T > 11$ K yield the activation energy $E_a = 11 \pm 1$ meV and attempt time τ_0 of order 10^{-9} s. Surprisingly, the thermally activated behavior is *not* found over the entire temperature range: Below 11 K, $\tau_{\rm high}$ rather abruptly levels off to become constant (1 ms) below 8 K. The likely explanation is that at low T the dominant mechanism is a direct tunneling of the electrons through the potential barrier. Then, the effective

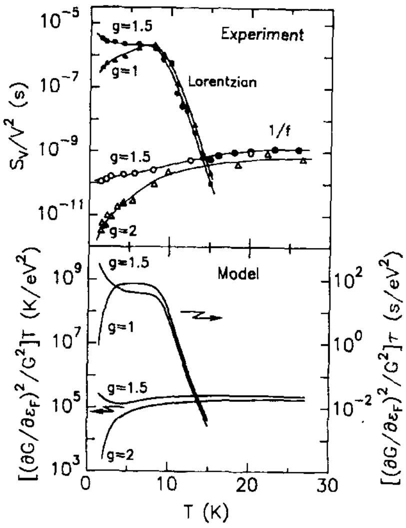

FIG. 4. Top figure: Temperature dependence of S_V/V^2 for QPC No. 1 (open symbols) and QPC No. 2 (solid symbols) at various values of $g \equiv G/(2e^2/h)$. Lorentzian-plateau values $S_V(0)/V^2$ are given for QPC No. 2, and $1/f$ contributions $S_V(100\ {\rm Hz})/V^2$ for both devices. Solid lines are guides to the eye. Bottom figure: Temperature dependence of $[(\partial G/\partial \varepsilon_F)^2/G^2]\tau$ and $[(\partial G/\partial \varepsilon_F)^2/G^2]T$, as explained in the text.

rate should be given by $\tau_a^{-1}+\tau_t^{-1}$, with τ_a^{-1} the thermally activated rate and τ_t^{-1} a temperature-independent tunneling rate. Indeed, this fits the data excellently. In order to arrive at the calculated temperature dependence of the fluctuations for QPC No. 2 (bottom part of Fig. 4), we multiply the $(\partial G/\partial \varepsilon_F)^2/G^2$ term of Eq. (1a) by the experimental values of $\tau=\tau_{\rm eff}^2/(\tau_{\rm low}+\tau_{\rm high})$, since, for a Lorentzian dependence, $S_{\varepsilon_F}(0)$ is linear in τ, cf. Eq. (2). Then, the rapid decrease at high T is obtained. The low-T limits of Eq. (1b) yield a $1/T^2$ decrease of $(\partial G/\partial \varepsilon_F)^2/G^2$ with T for $G=(n+\frac{1}{2})\times(2e^2/h)$, but a $(1/T^2)\exp(-\Delta\varepsilon/k_BT)$ increase for $G=n(2e^2/h)$. Both features qualitatively reproduce the experimental results.

It thus appears that the Lorentzian part of the noise characteristics of QPC No. 2 is well understood. How do these results relate to the $1/f$-like noise found both for QPC No. 2 above 15 K and for QPC No. 1 within the entire temperature range (see Fig. 4)? It is well known[6,8] that an ensemble of microscopic fluctuating entities, each contributing a Lorentzian term to the noise, together with an appropriate distribution of time constants, yields a $1/f$ spectrum. It is therefore plausible to envisage the $1/f$-like spectrum to originate from trapping processes at a number of electron traps which are positioned further away, in other words, not so strategically in the immediate proximity of the point contact as the particular trap in QPC No. 2. Dutta and Horn have shown[8] that for the case of thermally activated processes with an approximately uniform distribution of barrier heights, the $1/f$ spectral density is linear in T. Adopting this result, we arrive from Eq. (1) at $[(\partial G/\partial \varepsilon_F)^2/G^2]T$ as the relevant variable for the temperature dependence. As seen from Fig. 4, the calculated result again compares favorably to the experimental data, showing the correct trends for the G values considered. The strikingly dissimilar T dependences of both QPCs are thus accounted for. The remaining deviations are probably due to a nonconstant distribution of barrier heights,[8] as well as to the nonideality of the QPCs.

In summary, the quantum size effect seen in the conductance dependence of the noise and the surprisingly nonuniversal temperature and frequency dependences are all manifestations of temporal fluctuations in the electrostatic potential which primarily affect the transmission probability of the 1D subband closest to cutoff. The observation of spontaneous resistance switching has demonstrated the origin of the potential fluctuations as trapping processes involving localized electron traps. A theoretical model has been presented which accounts qualitatively for the main features observed experimentally.

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[1]For a comprehensive review, see H. van Houten, C. W. J. Beenakker, and B. J. van Wees, in *Semiconductors and Semimetals*, edited by M. A. Reed (Academic, New York, 1990).

[2]B. J. van Wees *et al.*, Phys. Rev. Lett. **60**, 848 (1988); D. A. Wharam *et al.*, J. Phys. C **21**, L209 (1988).

[3]Y. P. Li, D. C. Tsui, J. J. Heremans, J. A. Simmons, and G. W. Weimann, Appl. Phys. Lett. **57**, 774 (1990).

[4]F. Hofman *et al.*, Solid-State Electron. **31**, 279 (1988).

[5]G. B. Lesovik, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 513 (1989) [JETP Lett. **49**, 592 (1989)]; M. Büttiker, Phys. Rev. Lett. **65**, 2901 (1990).

[6]Discrete resistance switching has previously been observed in the low-temperature conductance of ultrasmall devices belonging to quite different transport regimes; see, for instance, K. S. Ralls *et al.*, Phys. Rev. Lett. **52**, 228 (1984); M. J. Uren *et al.*, Appl. Phys. Lett. **47**, 1195 (1985); C. T. Rogers and R. A. Buhrman, Phys. Rev. Lett. **53**, 1272 (1984); **55**, 859 (1985); R. T. Wakai and D. J. van Harlingen, Appl. Phys. Lett. **49**, 593 (1986).

[7]S. Machlup, J. Appl. Phys. **25**, 341 (1954).

[8]P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).