Physica B 175 (1991) 213–216
North-Holland

# Low-frequency noise of quantum point contacts in the ballistic and quantum Hall regime

F. Liefrink, A.J. Scholten and C. Dekker
*Faculty of Physics and Astronomy, and Debye Research Institute, University of Utrecht, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

R. Eppenga and H. van Houten
*Philips Research Laboratories, 5600 JA Eindhoven, The Netherlands*

C.T. Foxon
*Philips Research Laboratories, Redhill Surrey RH1 5HA, UK*

The low-frequency resistance noise of quantum point contacts is shown to be dominated by fluctuations in the electrostatic potential. Both in the ballistic and in the quantum Hall regime, the noise is strongly suppressed if the conductance is quantized. The suppression is enhanced by a strong magnetic field due to the absence of backscattering in the point contact. Additional minima are found in the noise as a function of the conductance due to the lifting of the spin degeneracy by the field.

Electron transport in quantum point contacts (QPCs), short constrictions defined in a GaAs/AlGaAs-heterostructure, has been studied intensively since the discovery of the quantization of their conductance in units of $2e^2/h$ [1, 2]. Due to the small electron density in the two-dimensional electron gas (2DEG), the Fermi wavelength of the electrons in these point contacts is comparable to the width of the constriction, resulting in the formation of one-dimensional (1D) subbands. The conductance quantization is a manifestation of ballistic transport: each of the subbands occupied in the QPC is transmitted with a probability close to unity. A strong magnetic field has the following effects: a smaller number of magneto-electric subbands is occupied, the spin degeneracy is lifted, and the residual backscattering in the point contact is suppressed. These are all characteristics of the quantum Hall effect regime. The study of time-averaged electron transport in QPCs [3] has recently begun to be complemented by experimental [4–6] and theoretical [7–10] work on the *kinetics* of charge transport. In this paper our earlier findings obtained in the ballistic transport regime [5] are compared with new experimental results covering the effect of a strong magnetic field on the noise characteristics.

Noise measurements were performed on a constriction defined in the 2DEG of a GaAs/AlGaAs heterostructure, which was grown by molecular beam epitaxy. The constriction was produced by electrostatic lateral confinement of the 2DEG using a split gate technique. The electron mobility in the 2DEG is 65 $m^2/Vs$, corresponding to an elastic mean free path of about 6 μm. The electron density was found to be $3.5 \times 10^{15}\ m^{-2}$. In the inset of fig. 1 the experimental set-up is shown. The number $N$ of occupied subbands in the point contact was determined from the diagonal four-terminal resistance $R_D = V_{14}/I_{23}$, which equals the two-terminal resistance $R = h/2e^2N$ [3]. We measured the fluctuations in the longitudinal voltage $V = V_{34}$,

0921-4526/91/$03.50 © 1991 – Elsevier Science Publishers B.V. (North-Holland)

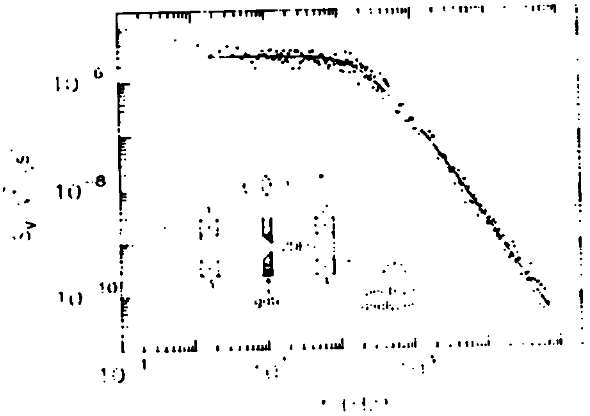

Fig. 1. Typical result for the relative excess noise spectral density $S_V(f)$ for $G = 1.5 \cdot (2e^2/h)$ at $T = 1.4$ K. Inset: schematic diagram of the experimental set-up for noise measurements.

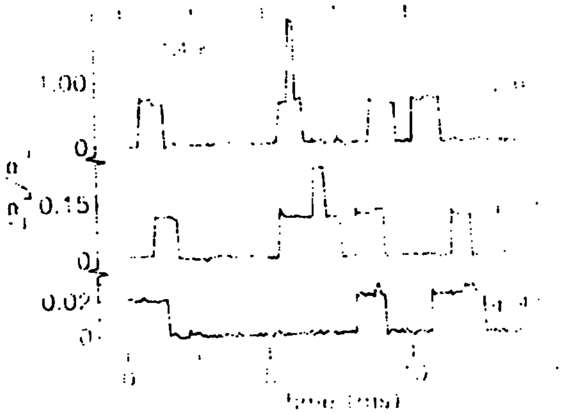

Fig. 2. Time traces of the relative change $\Delta R_L/R_L$ of the longitudinal resistance at various values of the conductance $g = (h/2e^2) \cdot G$.

while passing a constant current $I = I_{12}$ through the contacts 1 and 2. The excess (i.e. $I > 0$) noise spectral density $S_V(f)$ was obtained using a method described in ref. [11], which includes the subtraction of the instrumental and Nyquist noise. The excess noise spectral density varied quadratically with current, indicating that the voltage fluctuations originate from resistance fluctuations. We did not resolve shot noise [7–10], which has a linear current dependence. Recently, it was found that the frequency dependence of the noise spectral density is either $1/f$-like [4, 5] or Lorentzian [5]. Here we investigate an example of the latter.

A typical result for $S_V(f)$ is shown in fig. 1. The noise is found to originate from random switching of the longitudinal resistance $R_L$ ($\equiv V/I$) between two (occasionally three or four) discrete states, spending on the average a time $\tau_{low}$ in the low-resistive state $R_L$, and a time $\tau_{high}$ in the high-resistive state $R_L + \Delta R_L$. In fig. 2 some typical time traces of the resistance are shown. Such 'random telegraph signals' are known [12] to yield a Lorentzian spectral density

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

with $1/\tau_{eff} = 1/\tau_{low} + 1/\tau_{high}$ and $\Delta V \equiv I \Delta R_L$. From a measurement of $S_V(f)$ and $\Delta V$ both $\tau_{low}$ and $\tau_{high}$ can be determined. The switching of the resistance between two values can be explained by the presence of a *single* electron trap very close to the point contact. Charging and decharging of the trap modulates the electrostatic confining potential of the constriction, and thus the conductance. The times $\tau_{low}$ and $\tau_{high}$ can be identified with the capture and emission times of the trapping process. Both times depend on temperature, conductance, and magnetic field, as discussed elsewhere [5]. In this paper we focus on $\Delta V$.

In fig. 3 (upper part) $(\Delta V/V)^2$ is plotted versus the two-terminal conductance $G = 1/R$. It is clearly visible, that the effect of the switching process is suppressed whenever $G = N \times (2e^2/h)$. Maxima in $(\Delta V/V)^2$ occur right between these values. A similar quantum size effect in the noise is found in the presence of a strong external magnetic field perpendicular to the 2DEG, see fig. 4 (upper part). For the field of 2.94 T applied, the maximum number of occupied spin degenerate subbands in the constriction is limited to 2. As in the absence of an external magnetic field, minima occur whenever $G = N \times (2e^2/h)$. However, in contrast to the former case, there are additional minima at $G \approx (N + \frac{1}{2}) \times (2e^2/h)$.

The observed quantum size effect in the noise

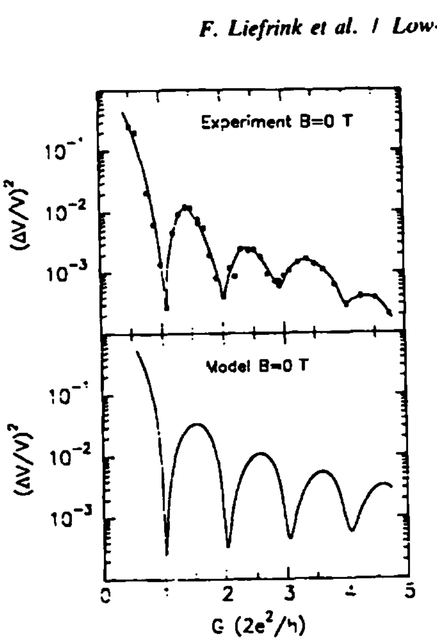


Fig. 3. $(\Delta V/V)^2$ versus $G$ for $B = 0$ T at 1.4 K. Solid curve in top figure is a guide to the eye.

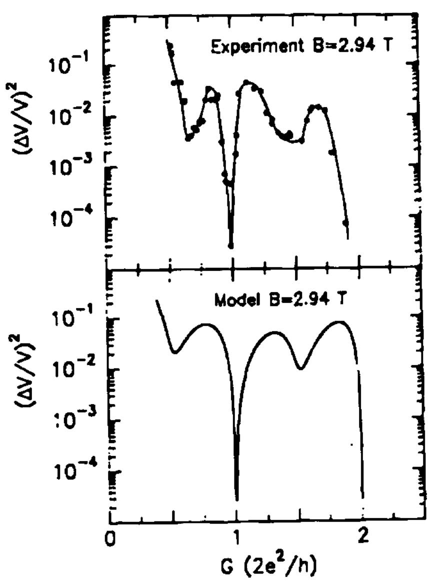


Fig. 4. $(\Delta V/V)^2$ versus $G$ for $B = 2.94$ T at 1.4 K. Solid curve in top figure is a guide to the eye.

is a direct consequence of the existence of 1D subbands in the point contact. Whenever an electron is trapped in the immediate vicinity of the point contact, the height of the potential barrier $\varepsilon_0$ in the point contact is increased, as well as the cut-off energies $\varepsilon_n$ of the 1D subbands. We model the quantum size effect on the noise at finite temperature by assuming a gate-voltage independent variation $\Delta\varepsilon_0$ of the potential barrier in the constriction, and a unit step-function energy dependence of the transmission probability [13]. The Hall conductance then is given by

$$G_H \equiv R_H^{-1} = \frac{e^2}{h} \sum_\sigma \sum_l f(\varepsilon_{l,\sigma} - \varepsilon_F) , \qquad (2)$$

with $f(\varepsilon)$ the Fermi–Dirac function, $\varepsilon_F$ the Fermi energy, and $\varepsilon_{l,\sigma} = (l - \frac{1}{2})\hbar\omega + \sigma g \mu_B B$, with $\omega_c = eB/m$, $g$ the Landé factor, $\mu_B$ the Bohr magneton, and $\sigma = \pm\frac{1}{2}$ the spin quantum number. The two-terminal conductance of the QPC is

$$G \equiv R^{-1} = \frac{e^2}{h} \sum_\sigma \sum_n f(\varepsilon_{n,\sigma} - \varepsilon_F) . \qquad (3)$$

We model the lateral confining potential in the QPC by a parabolic potential of strength $\omega_0$, in which case $\varepsilon_n = \varepsilon_0 + (n - \frac{1}{2})\hbar\omega + \sigma g \mu_B B$, with $\omega = (\omega_0^2 + \omega_c^2)^{1/2}$. The relative voltage fluctuation (in the longitudinal measurement configuration) now becomes

$$\frac{\Delta V}{V} = \frac{\Delta R_L}{R_L} = \frac{1}{R_L} \frac{\partial R_L}{\partial \varepsilon_0} \Delta\varepsilon_0 , \qquad (4)$$

with $R_L = R - R_H$ [3]. Obviously, a change $\Delta\varepsilon_0$ in the height of the potential barrier has minimal effect upon transport when $\varepsilon_F$ is right between two subbands, i.e. when the conductance is quantized. As can be seen in fig. 3 (lower part) the experimental results are well reproduced by the model calculations. In the calculations $\Delta\varepsilon_0$ has been fixed at 0.12 meV, while $\hbar\omega_0$ (typically 1.3 meV) and $\varepsilon_0$ have been obtained from measurements of $R$ as a function of gate voltage and magnetic field. The experimentally observed minima are less pronounced than those calculated from the model. This may be attributed primarily to residual backscattering in the constriction, leading to deviations from a step-function energy dependence of the transmission probability. At high conductances the calculations seem to overestimate the noise, indicating that in reality $\Delta\varepsilon_0$ depends on the gate voltage.

The present model is also valid in the presence of an external magnetic field (fig.4, lower part). Due to the suppression of backscattering by the magnetic field, the observed minima, which have also been deepened by the increased subband-splitting energy, are almost as sharp as those calculated from the model. Also reproduced by the model are the additional minima near $G = (N + \frac{1}{2}) \times (2e^2/h)$, caused by the lifting of the spin degeneracy (in the calculations an enhanced g-factor of 4 has been taken). Both in the experimental and theoretical results these minima are slightly shifted beyond the quantized values of conductance, due to the fact that the Zeeman splitting energy and the switching energy $\Delta\varepsilon_0$ are of comparable magnitude.

In conclusion, we have demonstrated a quantum size effect on the resistance noise of a quantum point contact in the ballistic and quantum Hall regime. We have shown that it is due to fluctuations in the electrostatic potential, which modulate the transmission probability of the 1D subband closest to cut-off. Systematic studies of the resistance noise of the type considered here may yield useful information on trapping and detrapping processes in relation to materials growth and processing conditions. On the other hand, it is clear that the study of the *intrinsic* kinetics of charge transport requires samples with a strongly reduced trap density.

We acknowledge J.I. Dijkhuis for discussions, F.J.M. Wollenberg for technical assistance, and C.E. Timmering for device fabrication. This work has been partly supported by the Netherlands organizations 'Fundamenteel Onderzoek der Materie (FOM)' and 'Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (NWO)'.

## References

[1] B.J. van Wees, H. van Houten, C.W.J. Beenakker, J.G. Williamson, L.P. Kouwenhoven, D. van der Marel and C.T. Foxon, Phys. Rev. Lett. 60 (1988) 848.

[2] D.A. Wharam, T.J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J.E.F. Frost, D.G. Hasko, D.C. Peacock, D.A. Ritchie and G.A.C. Jones, J. Phys. C 21 (1988) L209.

[3] C.W.J. Beenakker and H. van Houten, Solid State Phys 44 (1991) 1.

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

[5] C. Dekker, A.J. Scholten, F. Liefrink, R. Eppenga, H. van Houten and C.T. Foxon, Phys. Rev. Lett. 66 (1991) 2148.
F. Liefrink et al., to be published.

[6] G. Timp, R.E. Behringer and J.E. Cunningham, Phys Rev. B 42 (1990) 14.

[7] G.B. Lesovik, JETP Lett. 49 (1989) 592.

[8] R. Landauer, Physica D 38 (1989) 226.
R. Landauer and Th. Martin, to be published

[9] M. Büttiker, Phys. Rev. Lett. 65 (1990) 2901.

[10] C.W.J. Beenakker and H. van Houten, Phys. Rev. B submitted.

[11] F. Hofman, R.J.J. Zijlstra and J.C.M. Henning, Solid State Electron. 31, (1988) 279.

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

[13] A similar model but for a saddle point potential was recently considered by M. Büttiker, in: Granular Nanoelectronics, ed. D.K. Ferry (Plenum, New York, 1991).