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# Magnetic field effects on switching noise in a quantum point contact

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We extend a previous study of the quantum-size effect on switching noise in a $GaAs/Al_xGa_{1-x}As$ quantum point contact in zero magnetic field to the quantum Hall regime. The experimental results agree well with a model based on temporal electrostatic fluctuations of the conduction-band bottom in the point contact. A confirmation of our interpretation is obtained by a direct comparison of the noise data with measurements of the transconductance. The analysis of the data suggests that the Landé $g$ factor in a quantum point contact is enhanced with respect to the low bare $g$ factor of GaAs.

The approximate quantization in units of $2e^2/h$ of the conductance of a quantum point contact (QPC), electrostatically defined in a two-dimensional electron gas (2DEG), is a direct consequence of the one-dimensional (1D) subband structure in the point contact, combined with a nearly unit-transmission probability of the occupied subbands.[1,2] An external magnetic field lowers the number of occupied magnetoelectric subbands, and suppresses residual backscattering in the point contact.[3] At high magnetic fields, the spin degeneracy of the Landau levels is lifted, which gives rise to additional conductance plateaus at odd multiples of $e^2/h$. It is known from experiments that the spin splitting can be strongly enhanced in the case of a 2DEG in the quantum Hall regime (Landé $g$ factors up to 15).[4] This is generally attributed to the exchange interaction between electrons of opposite spin within the same Landau level.

In this paper, we present measurements on switching noise in a QPC. Previously, it has been shown[5-7] that the temporal resistance fluctuations at zero magnetic field directly reflect the 1D subband structure. Here we compare the noise measurements directly with measurements of the transconductance, confirming the model of Ref. 5, and explore the effect of the magnetic field. At weak magnetic fields, the noise intensity at even multiples of $e^2/h$ decreases with increasing $B$, due to the suppression of backscattering in a magnetic field.[8] At stronger fields we observe the formation of conductance plateaus and, consequently, minima in the noise intensity, at odd multiples of $e^2/h$, as the spin degeneracy is lifted. Our model suggests that the $g$ factor is also enhanced in a QPC, up to values of 4.

The measurements were performed at 1.4 K on a QPC defined in the 2DEG of a $GaAs/Al_xGa_{1-x}As$ heterostructure, grown by molecular-beam epitaxy. The QPC was defined by electrostatic lateral confinement of the 2DEG using a split-gate technique, which allows for the adjustment of the conductance of the point contact by means of a negative gate voltage $V_g$. The electron mobility in the 2DEG is 65 $m^2/V\,s$, corresponding to an elastic mean free path of about 6 $\mu m$. The electron density is $3.5\times10^{15}/m^2$. The number of occupied subbands in the point contact $N$ was determined from the diagonal four-terminal resistance $R_D$. In the absence of backscattering in the bulk of the sample, i.e., at minima of the Shubnikov–de Haas oscillations, $R_D$ equals $h/2e^2N$. All noise measurements at high magnetic fields were performed at these minima.

We measured the fluctuations in the longitudinal voltage $V\equiv R_L I$ across the point contact, while passing a constant current $I$ through the point contact. The longitudinal voltage was found to switch randomly between two discrete states, $V$ and $V+\Delta V$. This points to the presence of a *single* electron trap very close to the point contact.[5] Charging and decharging of the trap modulates the bottom of the conduction band of the point contact, and, for that matter, the conductance. In this paper we focus on the effect of a magnetic field on the noise intensity $\Delta R_L\equiv\Delta V/I$.

In Fig. 1, $\Delta R_L$ is plotted versus the two-terminal conductance $G$ for $B=0$, 1.83, and 2.94 T. For $B=0$ T the noise intensity is clearly suppressed for $G=2e^2/h$ and $4e^2/h$. Maxima in $\Delta R_L$ occur between these values. As can be seen in the two lower panels of the figure, a similar quantum-size effect on the noise is found, when an external magnetic field is applied perpendicular to the 2DEG. Two effects of the magnetic field can be distinguished: the minima near $G=N\times2e^2/h$ are more pronounced, and for $B=2.94$ T additional minima are seen near $G=e^2/h$ and $G=3e^2/h$.

The observed quantum-size effect on the noise is a

 

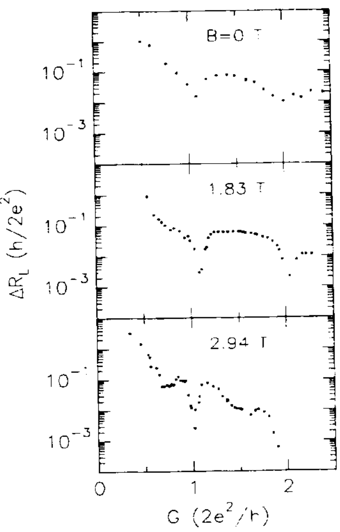


FIG. 1. The measured magnitude of the switching noise $\Delta R_L$ vs the conductance $G$ (controlled by the gate voltage) for $B=0$, 1.83, and 2.94 T.

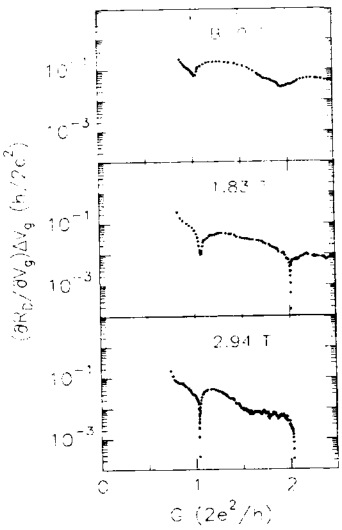


FIG. 2. The measured transconductance $(\partial R_D/\partial V_g)\Delta V_g$ of the same QPC vs the conductance $G$ for $B=0$, 1.83, and 2.94 T.

direct consequence of the existence of 1D subbands in the point contact.[5] Whenever an electron is trapped in the immediate vicinity of the point contact, the height of the potential barrier $\epsilon_0$ in the point contact is increased, as are the cutoff energies $\epsilon_n$ of the 1D subbands. A change $\Delta\epsilon_0$ in the height of the potential barrier has a minimum effect upon electron transport through the point contact when the Fermi energy $\epsilon_F$ lies exactly between two subbands, i.e., when the conductance is quantized. The noise intensity then has a minimum value. This interpretation may be verified experimentally by comparing the measured magnitude of the temporal resistance changes $\Delta R_L$ with the measured transconductance $\partial R_D/\partial V_g$. These quantities should have a very similar gate voltage and magnetic field dependence in view of the approximate equality

$$\Delta R_L=\frac{\partial R_D}{\partial \epsilon_0}\Delta\epsilon_0\approx\frac{\partial R_D}{\partial V_g}\Delta V_g \ , \tag{1}$$

which results from the fact that $V_g$ primarily affects $\epsilon_0$. In Fig. 2 we have plotted $(\partial R_D/\partial V_g)\Delta V_g$ vs $G$, where we have taken $\Delta V_g=27$ mV to obtain best agreement with $\Delta R_L$ vs $G$ from Fig. 1. Indeed, the transconductance also shows minima at $G=2e^2/h$ and $G=4e^2/h$, but more pronounced. In addition, similar to the noise data, minima are seen in the transconductance at $G=e^2/h$ and $G=3e^2/h$, due to the spin splitting.

To model our measurements, we take a gate voltage independent fluctuation $\Delta\epsilon_0$ of the potential barrier in the constriction and a unit step-function energy dependence of the transmission probability.[9] The two-terminal conductance of the point contact is given by

$$G=\frac{e^2}{h}\sum_{\sigma}\sum_{n} f(\epsilon_{n,\sigma}-\epsilon_F) \ , \tag{2}$$

with $f(\epsilon)$ the Fermi-Dirac distribution and $\epsilon_F$ the Fermi energy. We approximate the lateral confining potential in the QPC by a parabola of strength $\omega_0$, in which case

$$\epsilon_{n,\sigma}=\epsilon_0+(n-\tfrac{1}{2})\hbar\omega+\sigma g\mu_B B \ ,$$

with $\omega=(\omega_0^2+\omega_c^2)^{1/2}$, $\omega_c=eB/m$ the cyclotron frequency, $g$ the Landé $g$ factor in the point contact, $\mu_B$ the Bohr magneton, and $\sigma=\pm\frac{1}{2}$ the spin quantum number. Using $R_L=R-R_H$,[3] with $R_H$ the Hall resistance in the 2DEG, the resistance fluctuation (in the longitudinal measurement configuration) now becomes

$$\Delta R_L=-\frac{\Delta G}{G(G+\Delta G)} \ , \tag{3}$$

with

$$\Delta G=\frac{e^2}{h}\sum_{\sigma}\sum_{n}[f(\epsilon_{n,\sigma}+\Delta\epsilon_0-\epsilon_F)-f(\epsilon_{n,\sigma}-\epsilon_F)] \ . \tag{4}$$

From measurements of $R_D$ as a function of gate voltage and magnetic field, $\hbar\omega_0$ (typically 1.2 meV at $G=2e^2/h$) and $\epsilon_0$ have been obtained.

The experimental results obtained at $B=0$ T are reasonably well reproduced by the model calculations shown in Fig. 3, although the experimentally observed minima are less pronounced than those calculated. This is primarily attributed to residual backscattering in the constriction, leading to deviations from a step-function energy dependence of the transmission probability. In a magnetic field, backscattering is suppressed as demonstrated in the experiments by the sharp minima in the lower panels of Fig. 1. In the calculations, $\Delta\epsilon_0$ has been fixed at 0.12 meV, which is an averaged value for the relevant $G$ values.

The further reduction of the noise intensity at the con-

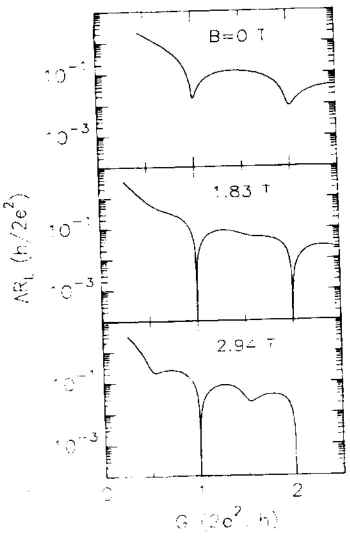


FIG. 3. The calculated magnitude of the switching noise $\Delta R_L$ vs the conductance $G$ for $B=0$, 1.83, and 2.94 T.

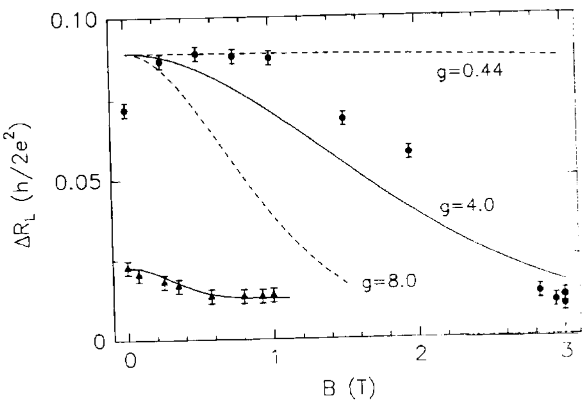


FIG. 4. The measured magnitude of the switching noise $\Delta R_L$ vs the magnetic field $B$ for $G=1.0\times 2e^2/h$ (triangles) and $G=1.5\times 2e^2/h$ (circles). The solid line is a calculation of $\Delta R_L$ vs $B$ for $g=4.0$. The dashed lines denote calculations for $g=0.44$ and 8.0.

ductance plateaus by the magnetic field is shown in Fig. 4 for $G=1.0\times 2e^2/h$. This figure also shows the magnetic field dependence of the noise intensity for $G=1.5\times 2e^2/h$. For weak fields ($B<0.5$ T) the fluctuations appear to increase with the field, whereas the noise strongly decreases for $B>1$ T. In Fig. 4 also, the model calculations of $\Delta R_L$ vs $B$ have been plotted, using $\Delta\epsilon_0=0.09$ meV. The model calculations reproduce the decrease of $\Delta R_L$ with $B$ for $G\approx 2e^2/h$. However, for both $G\approx 2e^2/h$ and $G\approx 3e^2/h$ the initial slope of the experimental data in Fig. 4 is steeper than calculated. This points to the suppression of residual impurity-related backscattering by increasing the field, an effect which is not accounted for in the model. For $G\approx 3e^2/h$, the model also reproduces the decrease of $\Delta R_L$ with the field, an effect which is attributed to the enhancement of the Landé $g$ factor. This enhancement also causes the pronounced minima of the noise intensity at $G\approx e^2/h$ and at $G\approx 3e^2/h$, as shown in the lower part of Fig. 1. We obtain a good agreement between the experimental results (Figs. 1 and 4) and the model calculations (Figs. 3 and 4) by taking $g=4.0$, which is an order of magnitude larger than the bare $g$ factor of GaAs (0.44).[10] In Fig. 4 the sensitivity of $\Delta R_L$ to the value of the $g$ factor is demonstrated by the two dashed lines corresponding to $g=0.44$ and 8.0.

The enhancement of the spin splitting is probably due to exchange interactions between electrons of opposite spin within a single hybrid magnetoelectric subband in the point contact.

In conclusion, the switching noise in a QPC is strongly governed by the subband structure in the point contact. This has been confirmed by direct comparison of the noise data with the measured transconductance. A model has been presented that satisfactorily reproduces the experimental observations, in both the ballistic and the quantum Hall regime. The magnetic field dependence of the noise also shows evidence of the magnetic suppression of backscattering at the point contact. Finally, it is found that the Landé $g$ factor in the point contact is strongly enchanced with respect to its bulk GaAs value.

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