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LETTER TO THE EDITOR

Ballistic transport through the fluctuation potential: strong one-dimensional quantization in two-dimensional GaAs/AlGaAs structures

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Abstract. We have observed the $2e^2/h$ conductance quantization with varying electron concentration in GaAs–GaAlAs heterostructures with *continuous* (i.e. with no split) gates. The effect of the 1D quantization in 2D structures is explained as being due to the ballistic transport through an *intrinsic* constriction formed by random potential fluctuations in the short conducting channel. The separation between 1D subbands, up to 18 meV, is larger than that revealed so far in split-gated structures allowing the conductance quantization to be tracked up to 50 K.

The quantization of the conductance in units of $2e^2/h$ has been observed in high-mobility GaAs/AlGaAs heterostructures with split gates when the electron concentration was varied by varying the gate voltage [1, 2]. The origin of this effect lies in the ballistic motion of one-dimensional electrons through a narrow constriction formed by the split gate. Over the last few years this phenomenon has been intensively studied both theoretically and experimentally [3]. One objective of these investigations has been to increase the separation between one-dimensional energy subbands and thus observe the quantization at higher temperatures. To maximize the subband separation the width of the constriction must be as small as possible, and for a given split width there is also an optimal depth for the 2DEG [4]. In split-gated structures optimized in this way the maximum separation between 1D subbands observed so far is about 10 meV [5–7] and the highest temperature at which the quantization has been seen is 30 K. Recently it has become clear that in addition to the electrostatic profile of the split-gate constriction, the potential fluctuations due to randomness in the distribution of ionized donors in the GaAlAs layer may also strongly affect the manifestation of the conductance quantization [8–10]. The role of the fluctuations is most significant near the conduction threshold where the electron concentration is too small to provide effective screening. Large fluctuations can interrupt the conducting path in a split-gated structure which makes it difficult to resolve the conductance quantization in long channels [8]. In this study we investigate the opposite case of very short channels. In addition, our GaAs/AlGaAs structures do not have split gates. However, near the conduction threshold, the large-scale fluctuations divide the 2DEG into a set of 1D channels. If the

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electron mobility along these channels is high enough the conductance is determined by the ballistic motion of electrons through the intrinsic constrictions formed by the fluctuation potential.

To study this conductance regime we used MBE-grown structures consisting of a 50 nm thick n-GaAlAs layer ($N_d \approx 10^{18}$ cm^{-3}) and an undoped 1 μm thick GaAs layer on an i-GaAs substrate. To increase the fluctuations we have decreased the thickness of the undoped spacer in the GaAlAs to 2 nm. The uniform gate has a short length L = 150 nm in the direction of the current and a large width W = 200 μm. Such a large W/L-ratio was expected to help a single 1D path running along the deepest potential valley to dominate the total conductance. At small positive gate voltage $V_{g0} = 0.1$ V the electron concentration n_0 of the homogeneous 2DEG is calculated from the period of the Shubnikov–de Haas oscillations and is equal to $\sim 8 \times 10^{11}$cm^{-2}. The corresponding value of electron mobility is then 5×10^4cm^2 V^{-1} s^{-1}. This means that the mean free path in the undepleted 2DEG is about 0.8 μm and is much larger than the channel length under the gate. The two-terminal conductance has been measured in the temperature range from 4.2 K to 70 K using the lock-in technique with an AC excitation voltage of 300 μV at the frequency of 12 Hz.

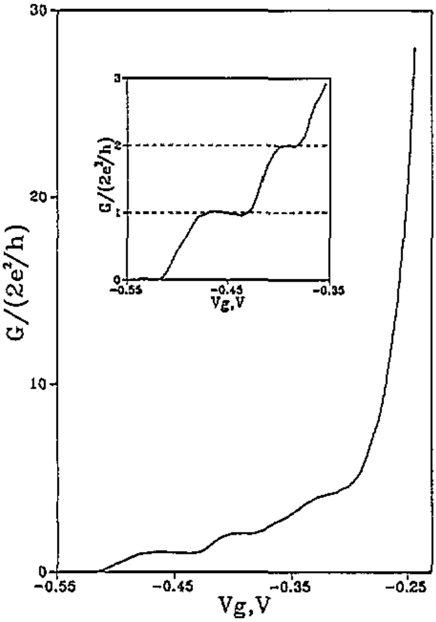

Figure 1. The differential conductance as a function of the gate voltage, sample H1. Inset: quantized conductance near the threshold.

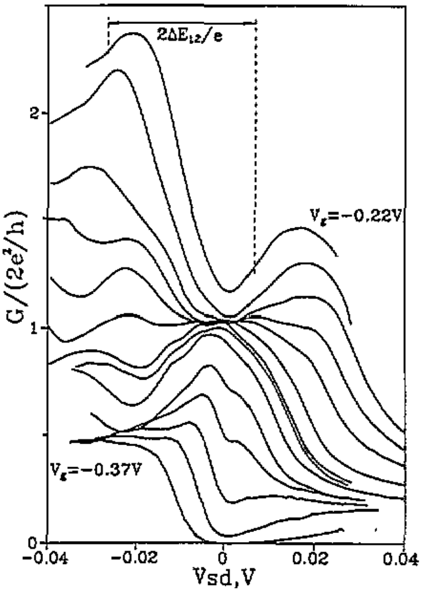

Figure 2. The differential conductance as a function of the source–drain bias at T = 4.2 K, with the indication of the separation between the two subbands; sample H04. In successive traces the gate voltage is incremented by 10 mV.

Samples H1, H03 and H04 described below have been fabricated from the same wafer and are nominally identical. Figure 1 shows an example of the conductance–gate voltage dependence at T = 4.2 K. Instead of a smooth curve, which would be normally expected for a 2D channel, two steps of height $2e^2/h$ are clearly seen. We have studied fifteen samples altogether and ten have shown from one to three conductance steps followed by a rapid increase of conductance with further increase of V_g. Five samples have exhibited more complicated $G(V_g)$-dependence than a simple step-like characteristic. This dependence is similar to mesoscopic conductance fluctuations near the conduction threshold in GaAs MESFETs [11, 12].

To analyse the shape of the intrinsic constriction we have applied the methods developed before for the split-gate structures [13–15]. The potential near the saddle point is considered as parabolic:

$$U(x, y) = U_0 - \tfrac{1}{2}m\omega_x^2 x^2 + \tfrac{1}{2}m\omega_y^2 y^2 \qquad (1)$$

where x and y are the directions along and perpendicular to the current respectively and m is the effective mass. The energy separation between 1D subbands has been obtained directly by differential conductance–gate voltage measurements with DC bias applied along the channel, as in [14, 15]. Figure 2 shows the differential conductance as a function of the source–drain voltage at different V_g for the sample with the largest subband separation. The separation δE_{12} between the bottom of the first and the second subbands corresponds to the bias eV_{sd} at which the semi-integer quantization, $\mathrm{d}I/\mathrm{d}V = 2(N - 1/2)e^2/h$ ($N = 1, 2, \ldots$), arises instead of the integer quantization $\mathrm{d}I/\mathrm{d}V = 2Ne^2/h$ which is found at zero bias. More precisely, $\delta E_{12} = e(V_1 - V_2)/2$, where $V_{1(2)}$ is the positive (negative) source–drain voltage at which the second derivative $\mathrm{d}^2I/\mathrm{d}V^2$ has its maximum value [15]. The value $\delta E_{12} \approx 18$ meV has been obtained by both methods, and is almost twice as large as that in the best split-gate structures [7]. The classical turning-point width of the intrinsic constriction at the bottom of the first and the second subbands, $\delta y = 2\hbar((2N-1)/m\delta E_{12})^{1/2}$, is then $\delta y_1 \approx 16$ nm and $\delta y_2 \approx 28$ nm.

The value $\hbar\omega_y = \delta E_{12}$ characterizes the constriction in the direction perpendicular to the current. For different samples from the same wafer this value varies from 10 to 18 meV. The comparison of this value with the V_g-separation of the two steps gives the value of $\mathrm{d}E_F/\mathrm{d}eV_g \sim 0.2$ which is the rate of the constriction potential shift with varying gate voltage relative to the Fermi energy. The steepness of a step in the $G(V_g)$-dependence is determined by the transmission coefficient $T_N(E_F)$ for the Nth subband, which in turn depends on the potential curvature in the direction of the current. Here we will obtain the value of $\hbar\omega_x$ and analyse the evolution of the step shape with increasing temperature and magnetic field supposing that the two conductance steps correspond to the same constriction. According to [13]

$$T_N = 1/(1 + \exp(-\pi\varepsilon_N)) \qquad (2)$$

where ε_N is the ratio of the electron energy (measured from the bottom of the Nth subband) to the energy $\hbar\omega_x$:

$$\varepsilon_N = 2[E_F - \hbar\omega_y(N - \tfrac{1}{2}) - U_0]/\hbar\omega_x. \qquad (3)$$

The perpendicular magnetic field gives rise to the cyclotron motion with frequency $\omega_c = eB/mc$, which changes the energy ε_N in the following manner:

$$\varepsilon_N(H) = [E_F - U_2(N - \tfrac{1}{2}) - U_0]/U_1 \qquad (4)$$

where $U_1 = [\hbar/(2\sqrt{2})][(\Omega^4 + 4\omega_x^2\omega_y^2)^{1/2} - \Omega^2]^{1/2}$, $U_2 = [\hbar/\sqrt{2}][(\Omega^4 + 4\omega_x^2\omega_y^2)^{1/2} + \Omega^2]^{1/2}$ and $\Omega^2 = \omega_c^2 + \omega_y^2 - \omega_x^2$. This corresponds to the sharpening of a step and the increase of the separation between the steps. Finite temperature smears the steps in accordance with the expression

$$G(\varepsilon_{\mathrm{F}}, H, T) = (2e^2/h) \int_{-\infty}^{\infty} T_N(\varepsilon, H)(-\mathrm{d}f(\varepsilon_{\mathrm{F}}, \varepsilon)/\mathrm{d}\varepsilon)\,\mathrm{d}\varepsilon \tag{5}$$

where $f = \{1+\exp[(\varepsilon-\varepsilon_{\mathrm{F}})/kT]\}^{-1}$. At $T = 0$ and $H = 0$ the maximum value of $\partial G/\partial E_{\mathrm{F}}$ at ε_N=0 is equal to $(e^2/2\hbar)\hbar\omega_x$, i.e. it is determined by the curvature of the constriction potential in the x-direction [13]. The value of ω_x is obtained from the experimental value of $\partial G/\partial V_{\mathrm{g}}$ at the lowest temperature taking into account that $\partial G/\partial V_{\mathrm{g}} = (\partial G/\partial E_{\mathrm{F}})(\partial E_{\mathrm{F}}/\partial V_{\mathrm{g}})$ and using the value for $\partial E_{\mathrm{F}}/\partial V_{\mathrm{g}}$ calculated above. The parameters $\hbar\omega_x$ and $\hbar\omega_y$ obtained ($\hbar\omega_x$ is typically half the value of $\hbar\omega_y$) are then used in the analysis of the $G(V_{\mathrm{g}})$-dependence at different T and H with the threshold gate voltage as an adjustable parameter. Figure 3 and figure 4 demonstrate a good agreement between the experimental data and expression (5) for the case of two 1D subbands in an intrinsic constriction. The fact that the smearing of the steps is successfully described as being only due to the temperature smearing of the Fermi function means that the mobility variation in our temperature range does not affect the ballistic propagation of electrons.

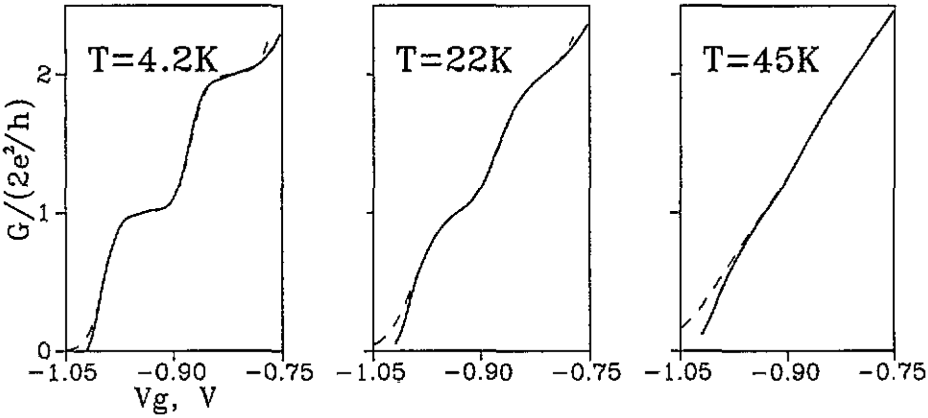

Figure 3. The differential conductance as a function of the gate voltage at different temperatures; sample H03. Dotted line: theory (5) with $\hbar\omega_y = 15$ meV and $\hbar\omega_x = 8.1$ meV.

Such a description of the conductance steps as being due to the same constriction is applied to all the samples that we have studied which have two steps in the $G(V_{\mathrm{g}})$-dependence. We have also observed the superposition of two 1D channels when three conductance steps were seen. In this case the shift of the first two steps with magnetic field can be described by theory while the third step moved much more slowly than would be expected if it had its origin in the same 1D channel.

The general behaviour of $G(V_{\mathrm{g}})$-dependences is in agreement with the idea of non-linear screening of the random potential from ionized donors by two-dimensional electrons [16, 8, 9] which arises at small electron concentrations. In this case the RMS amplitude of the long-ranged fluctuations γ and their correlation length R strongly increase with the decrease of electron concentration, $\gamma(n) \approx e^2 N_{\mathrm{d}}/\chi n$, where χ is the dielectric constant, and $R \approx N_{\mathrm{d}}/n^2$ [16]. However, when the increasing R becomes comparable with the distance

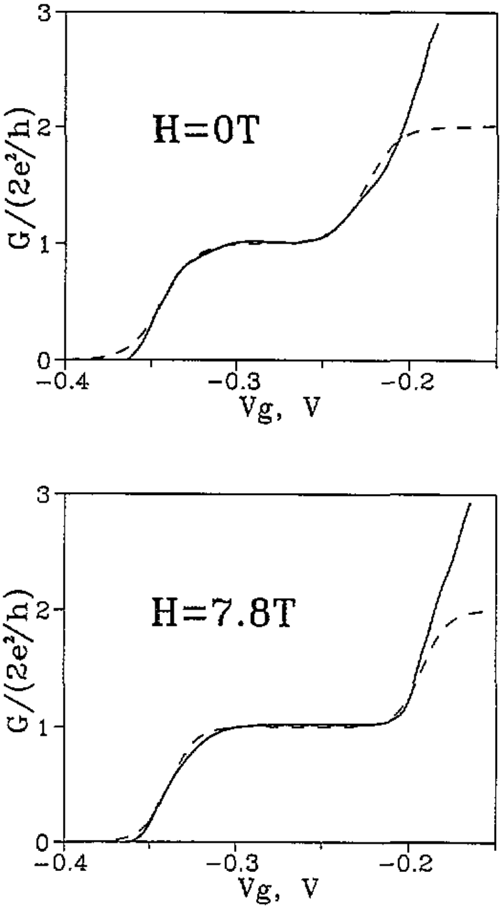

Figure 4. The differential conductance as a function of the gate voltage at different values of the magnetic field at $T = 4.2$ K; sample H04. Dotted line: theory (5) with $\hbar\omega_y = 18$ meV and $\hbar\omega_x = 9$ meV.

t between the 2DEG and the gate, the amplitude of the fluctuations becomes independent of the electron concentration as the screening is now determined by the metallic gate. This can explain why one path can dominate the total conductance over a V_g-range of about 200 mV corresponding to the two steps in the $G(V_g)$-dependence (figure 1). The rapid increase of the conductance after the steps occurs at the stage when with rising concentration the electron screening becomes important and the decrease in γ results in the merging of many 1D paths into a 2D sheet of electrons. The estimation of the electron concentration at which R is equal to the distance from the 2DEG to the gate ($t = 500$ Å) gives $n_c \approx 4 \times 10^{11}\,\mathrm{cm}^{-2}$. We can estimate the corresponding value of V_{gc} suggesting the linear relation between n and V_g

$$n(V_g) - n_0 = (C/e)(V_g - V_{g0}) \tag{6}$$

where $C=\chi/4\pi t$. For the sample H1 we thus have obtained $V_{gc} \approx -0.25$ V, which is very close to the region of the rapid conductance increase in figure 1.

The conductance quantization in an intrinsic path could be destroyed by the scattering inside this path imposed by the potential fluctuations [9]. The fact that we see very pronounced quantization is due to the short length of the channel in our structures, which is comparable to the correlation length of the fluctuations $R \sim t$ in the region of the steps.

In conclusion, the observed 1D conductance quantization in the 2D system is due to a single 'natural' constriction formed by the fluctuation potential. The analysis of the step-like $G(V_g)$-dependence at different temperatures and magnetic fields shows that the intrinsic constrictions are significantly narrower than that in conventional split-gate structures. Direct evaluation of the fluctuation potential parameters can be a useful application of the study of the ballistic electron propagation through intrinsic constrictions.

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