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Properties of a ballistic quasi-one-dimensional constriction in a parallel high magnetic field

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We have investigated the magnetic properties of a ballistic quasi-one-dimensional channel, in a GaAs-$Al_xGa_{1-x}As$ heterojunction, when the magnetic field is applied in the plane of the two-dimensional electron gas. At high magnetic fields, and high applied source-drain voltage, the devices show differential conductance plateaus quantized in units of $e^2/2h$. This is a consequence of the combined effect of the electric field, which causes the number of conducting subbands to be different in the two current directions, and the Zeeman splitting of the one-dimensional subbands. When the magnetic field is parallel to the current direction, the g factor is 1.1 ± 0.1; and when the field is perpendicular to the current, the g factor is reduced.

In this paper we present results on the magnetic properties of a GaAs-$Al_xGa_{1-x}As$ heterojunction when the two-dimensional electron gas (2DEG) is confined into a quasi-one-dimensional (Q1D) channel by the action of a split gate over the $Al_xGa_{1-x}As$.[1,2] When a negative voltage is applied to the split gate, electrons are depleted from the 2DEG under the gate and a Q1D channel is defined. When the channel length is sufficiently short that electron transport is ballistic, each conducting spin-degenerate 1D subband contributes $2e^2/h$ to the differential conductance, giving rise to a series of steps as the subbands pass through the Fermi energy E_F with decreasing channel width or carrier concentration.[3,4]

The g factors of 2DEG systems have been extensively studied,[5] and in tilted field experiments[6] of a GaAs-$Al_xGa_{1-x}As$ heterojunction it is found that there is an enhancement of the g factor over its bare value by a function which is oscillatory in the applied perpendicular magnetic field. This enhancement is due to the exchange interaction that depends on the relative populations of the spin-up and spin-down states within a given Landau level.[7] In contrast, there is little work on 1D systems although Smith *et al.*[8] measured the magnetocapacitance of an array of quasi-one-dimensional wires and suggested that the g factor is anisotropic, depending on how the magnetic field is aligned in the plane of the 2DEG. The purpose of this paper is to present measurements of the nonlinear differential conductance in a high magnetic field, from which we determine the g factor in a Q1D constriction.

The spin degeneracy of the Q1D subbands in a ballistic channel can be lifted by the application of an applied magnetic field **B**, giving rise to conductance plateaus that are separated by e^2/h. However, when the applied magnetic field is perpendicular to the 2DEG there is magnetic depopulation[9,10] of the Q1D subbands, and it is easier to observe spin splitting by applying the magnetic field in the plane of the 2DEG.

Further quantization of the differential conductance ($G = dI/dV_{sd}$) can also be introduced[11,12] if a dc source-drain voltage V_{sd} is applied. This further quantization appears when the finite voltage V_{sd} is such that the number of subbands conducting in the two current directions differ by one. The quantization of the extra conductance plateaus reflects[13,14] the fraction β of the applied voltage dropped between the source and the bottleneck of the constriction. When the conductance is larger than $2e^2/h$, the fraction is measured[12,13] to be $\beta \approx \frac{1}{2}$, which agrees with theoretical predictions.[15] Therefore, the extra plateaus (half-plateaus) are approximately separated by e^2/h in the absence of a magnetic field.

In the experimental work described in this paper, the 2DEG formed at the GaAs-$Al_xGa_{1-x}As$ heterojunction possessed a mobility $\mu = 10^6$ cm^2/V sec and carrier density of 3×10^{11} cm^{-2}, after illumination with a red light-emitting diode. The split gate devices, fabricated with a lithographic width and length of 0.3 μm, were similar to those used in work we have recently reported.[11,12] The differential conductance measurements were performed in a dilution refrigerator operating at approximately 40 mK, with an available magnetic field of up to 15 T. The magnetic field **B** was always applied in the plane of the 2DEG. We denote the g factor as g_x when **B** is aligned parallel to the current **J**, and as g_y when **B** is perpendicular to **J**.

If the two mechanisms for creating conductance plateaus separated by e^2/h are independent, then at finite source-drain voltage and in a high magnetic field we expect to observe conductance plateaus quantized in units of $e^2/2h$ (which we shall call quarter-plateaus). To give evidence for the quarter-plateaus we present data, in Fig. 1(a), of the conductance versus V_{sd} in a magnetic field of 15 T parallel to the current. The bunching of the curves near values of 1.25, 1.75, and 2.25 (in units of $2e^2/h$) indicates the existence of quarter-plateaus. At higher magnetic fields we expect the quarter-plateaus to be better resolved. The existence of quarter-plateaus clearly shows that the half-plateaus observed[12] in zero magnetic field are due to spin-degenerate subbands; therefore, the half-plateaus are not the result of spin splitting[16] originating from a coupling between the electron spins and the applied electric field.

To compare with the experimental source-drain voltage data in Fig. 1(a), we present results using a model where the channel is represented by a saddle-point potential.[17] In the presence of a magnetic field **B**, and if half of the source-drain voltage V_{sd} is dropped between the contacts

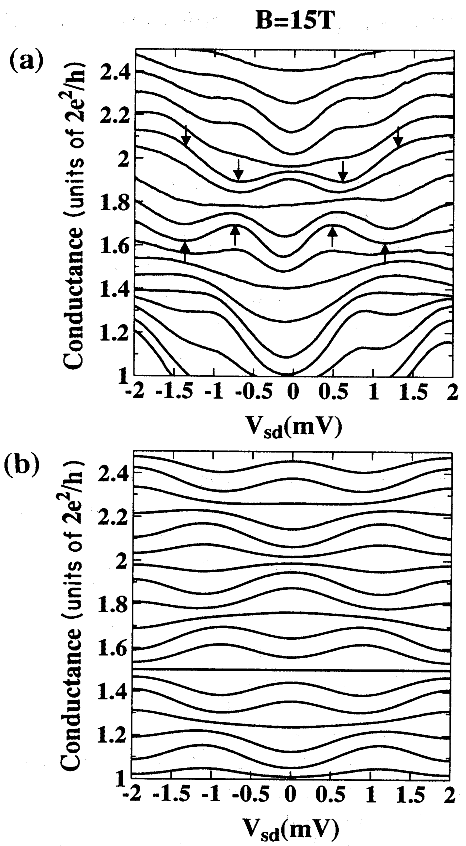

FIG. 1. (a) Experimental differential conductance vs applied source-drain voltage V_{sd} at different gate voltages in a parallel field of 15 T. The magnetic field is applied along the length of the channel. (b) The calculated differential conductance using the potential in Eq. (1), using the values $\hbar\omega_y=2$ meV, $\omega_y/\omega_x=2$, $g_x=1$, and with a parallel magnetic field $B=15$ T. Each trace is calculated at fixed E_F-U_0, which is incremented 0.3125 meV between successive traces.

and the bottleneck of the constriction, the potential energy is

$$U(x,y)=U_0-\tfrac{1}{2}m^*\omega_x^2x^2+\tfrac{1}{2}m^*\omega_y^2y^2 \pm g\mu_B SB-\tfrac{1}{2}eV_{sd}\,, \qquad (1)$$

where U_0 is the height of the potential barrier at the bottleneck, m^* is the effective mass of the electron, and ω_x describes the curvature of the inverted parabolic potential through which the electron tunnels as it traverses the constriction. In the direction transverse to electron motion the subbands have energies $(n+1/2)\hbar\omega_y$ for $B=0$. μ_B is the Bohr magneton, and $S=\frac{1}{2}$. The potential considered is two dimensional and does not include the effect of the parallel magnetic field on the subband energy spacings in the Q1D constriction. Using Eq. (1) it is possible to calculate the transmission probability[18] and the differential conductance[14] analytically. Figure 1(b) shows the results obtained using the values $\omega_y/\omega_x=2$, $\hbar\omega_y=2$ meV, and $g_x=1$. The similarity between Figs. 1(a) and 1(b) indicates that $g_x\approx 1$.

The conductance-voltage characteristics $G(V_{sd})$ can be used to obtain the subband energy spacings[19] and the spin splitting energies, and hence the g factor can be determined.[14] In Fig. 1(a) the down and up arrows mark the positions in two of the experimental traces where the Fermi energy pass through a spin-up and then through a spin-down subband. From the voltage positions of these arrows we calculate the g factor to be $g_x=1.1$.

Another method of determining the g factor is to directly compare the conductance in a magnetic field with that in an applied source-drain voltage V_{sd}. The effect of both an electric field and a magnetic field is such that the differential conductance can be regarded as an average over two different Fermi levels. The lowest trace in Fig. 2(a) shows the transconductance of the 1D channel, dG/dV_g versus gate voltage V_g, for $B=0$. The position of the $n=1$ and 2 conductance plateaus, as labeled in the figure, occurs when dG/dV_g is zero; the formation of plateaus results in structure in the transconductance. The transconductance traces that are offset in the vertical direction in Fig. 2(a) were obtained in parallel magnetic fields of 5, 10, and 15 T, with **B** applied parallel to **J** and $V_{sd}=0$. It is clear that the larger the magnetic field, the more pronounced is the splitting of the transconductance peaks. Figure 2(b) shows the zero-field transconductance of the same device with an applied source-drain voltage. Again the traces have been offset in the vertical direction, and the dashed lines are a guide to the eye that show the linear splitting of the transconductance peaks as V_{sd} is in-

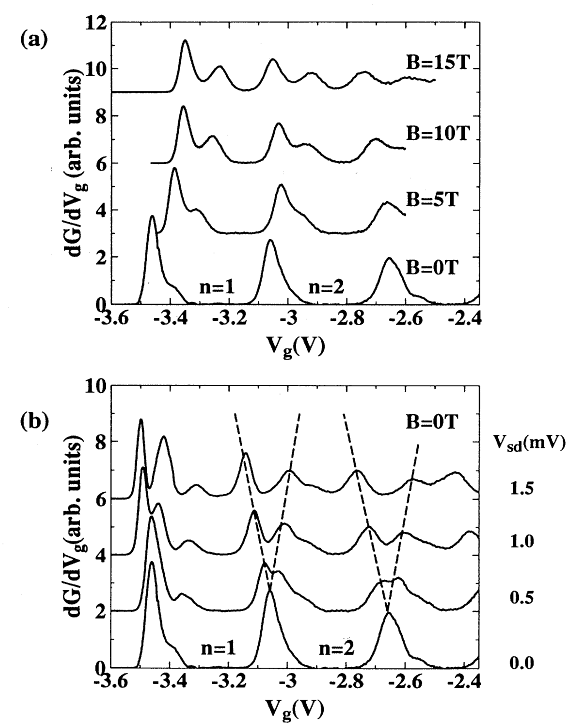

FIG. 2. (a) Traces of the transconductance dG/dV_g vs gate voltage in an applied parallel magnetic field of 0, 5, 10, and 15 T. The magnetic field is applied along the length of the channel. (b) Zero magnetic field traces of the transconductance with an applied source-drain voltage of $V_{sd}=0$, 0.5, 1.0, and 1.5 mV. As a guide to the eye, the linear splitting of the peaks are followed with dashed lines.

creased. Accurate measurements of the linear splitting of the gate voltage positions of the transconductance peaks are presented elsewhere.[12] The g factor can be calculated by finding the source-drain voltage V_{sd} at which the splitting of the transconductance peaks is equal to the Zeeman splitting in a magnetic field, that is,

$$eV_{sd}=2g\mu_B SB\ . \tag{2}$$

From Figs. 2(a) and 2(b) we calculate $g_x=1.08$ from the Zeeman splitting of the $n=2$ conductance step, and $g_x=1.04$ from the Zeeman splitting of the $n=3$ conductance step. These values of g_x are in good agreement with the value obtained from Fig. 1(a). The fact that the measured g factor is independent of subband index, and the good agreement between the theoretical and experimental curves in Fig. 1, suggests that the g factor is not a strong function of carrier density.

We have attempted measurements of the g factor g_y, when **B** is perpendicular to **J**. It was difficult to resolve the spin split transconductance peaks at 15 T; therefore, although we found that $g_x > g_y$ we could not measure the value of g_y. More detailed experiments are in progress to accurately measure this anisotropy.

In conclusion, we have measured that the voltage-induced half-plateaus for $G > 2e^2/h$ are independent from those obtained when the spin degeneracy is lifted. We have measured the electron g factor in a Q1D constriction by two methods. First, from the oscillations in the differential conductance G as a function of V_{sd} for high B. And second, by comparing the gate sweeps of the differential conductance at zero magnetic field, $G(V_g,V_{sd},B=0)$, with those at high magnetic field $G(V_g,V_{sd}=0,B)$. From the two methods we find that $g_x=1.1\pm0.1$. We stress that unlike studies of the g factors in 2DEGs, the methods used here do not require a perpendicular magnetic field.

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