Possible Spin Polarization in a One-Dimensional Electron Gas

K. J. Thomas, J. T. Nicholls, M. Y. Simmons, M. Pepper, D. R. Mace, and D. A. Ritchie
Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE, United Kingdom
(Received 4 March 1996)

In zero magnetic field, conductance measurements of clean one-dimensional (1D) constrictions defined in GaAs/AlGaAs heterostructures show up to 26 quantized ballistic plateaus, as well as a structure close to $0.7(2e^2/h)$. In an in-plane magnetic field all the 1D subbands show linear Zeeman splitting, and in the wide channel limit the g factor is $|g| = 0.4$, close to that of bulk GaAs. For the last subband, spin splitting originates from the structure at $0.7(2e^2/h)$, indicating spin polarization at $B = 0$. The measured enhancement of the g factor as the subbands are depopulated suggests that the "0.7 structure" is induced by electron-electron interactions. [S0031-9007(96)00520-0]

PACS numbers: 71.70.Ej, 71.18.+y, 73.20.Dx, 73.40.Kp

The application of a negative voltage to lithographically defined gates over a GaAs-AlGaAs heterostructure allows the underlying two-dimensional electron gas (2DEG) to be electrostatically squeezed into a particular shape [1]. This has allowed the study of one-dimensional transport phenomena [2], where, if the mean free path is larger than the effective channel length, it is possible to observe ballistic one-dimensional (1D) conductance plateaus [3,4].

Interaction effects may be significant in a clean one-dimensional single-mode electron gas, giving rise, for example, to new crystal [5,6] and liquid states [7]. For long-range $1/r$ interactions between electrons a 1D Wigner crystal is expected [5] to occur when the 1D carrier density is much less than the $(\text{Bohr radius})^{-1}$. For short-range interactions a clean 1D system may be modeled as a Tomonaga-Luttinger (TL) liquid, where it is predicted [8] that the conductance will be renormalized to $G = K(2e^2/h)$, with a parameter $K > 1$ for attractive interactions, $K < 1$ for repulsive interactions, and $K = 1$ for a noninteracting electron gas. Other theories [9–11] suggest that conductance renormalization will not occur because the measured contact resistance is determined by the noninteracting electrons that are injected into the wire.

With the exception of recent results [12], phenomena observed at zero magnetic field in clean 1D GaAs wires have been interpreted within a single-electron picture. Using a modified TL liquid theory [13] that accounts for disorder scattering, Tarucha, Honda, and Saku [12] measured an interaction parameter $K \approx 0.7$ from temperature studies of wires longer than 2 μm. However, this is not supported by the presence of a renormalized conductance quantization. Experimentally, residual impurity scattering and weak resonance effects make it difficult to interpret small changes in G as interaction effects.

In this paper we present two pieces of experimental evidence that suggest that interaction effects are important in clean split-gate devices. First, as the number of 1D subbands decreases, we have measured an enhancement of the in-plane electron g factor over its bulk GaAs value. Second, in zero magnetic field we have observed reproducible structure at approximately $0.7(2e^2/h)$. We show that this *0.7 structure* is an intrinsic property of a 1D channel at low densities, and that its origin could be related to spin.

Previously from measurements [14] of the transconductance dG/dV_g we have determined $g_{\|}$, the in-plane g factor when the magnetic field $\vec{B}$ is applied parallel to the current $\vec{j}$ through a ballistic 1D constriction. A zero in dG/dV_g corresponds to a conductance plateau, whereas a peak corresponds to the step region between plateaus. The magnitude (but not the sign) of $g_{\|}$ was determined from a comparison of the splitting of a transconductance peak in an in-plane magnetic field with that induced by an applied source-drain voltage V_{sd}. When the gate voltage separation of given peaks in dG/dV_g of the two measurements are the same, the g factor is determined by equating the two energy scales [14],

$$eV_{\text{sd}} = 2g\mu_B BS\,, \tag{1}$$

where μ_B is the Bohr magneton and $S = 1/2$. When two and three 1D subbands are occupied, the measured [14] $g_{\|}$ factors were 1.08 and 1.04, respectively. In this earlier experiment it was not possible to measure $g_{\perp}$ (in-plane magnetic field $\vec{B}$ applied perpendicular to $\vec{j}$).

We have investigated ballistic 1D constrictions defined in high mobility 2DEGs, formed at a modulation-doped $GaAs/Al_{0.33}Ga_{0.67}As$ heterostructure grown on a (100) GaAs substrate. Sample A (Figs. 1 and 2) is a split-gate device of lithographic width $W = 0.75$ μm and length $L = 0.4$ μm, defined above a 2DEG of depth 2770 Å, which after illumination with a red light-emitting diode has a carrier density of $n_s = 1.8 \times 10^{11}$ cm^{-2} and a low-temperature mobility of $\mu = 4.5 \times 10^6$ cm^2/V s. Sample B (Figs. 3 and 4) is a device with $W = 0.95$ μm and $L = 0.4$ μm, defined above a 2DEG of depth 3170 Å, which has $n_s = 1.4 \times 10^{11}$ cm^{-2} and $\mu = 3.5 \times 10^6$ cm^2/V s after illumination. Similar 1D constrictions have shown [15] an absence of resonant structures on the quantized conductance plateaus, demonstrating the lack of potential fluctuations within the 1D constriction. The 1D subband structure was also probed [15] using a source-drain voltage of up to $V_{\text{sd}} = 4$ mV. For all subbands

0031-9007/96/77(1)/135(4)$10.00

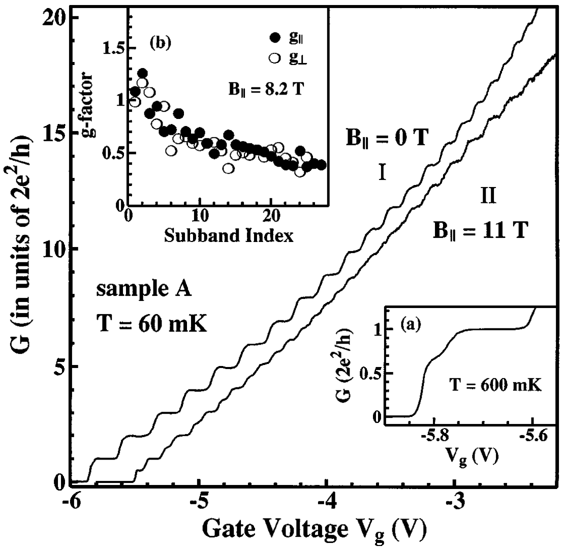

FIG. 1. (I) Gate voltage $G(V_g)$ characteristics showing 20 conductance plateaus quantized in units of $2e^2/h$. (II) The gate characteristics (offset by 0.3 V for clarity) in a magnetic field of 11 T. Insets: (a) detail of the structure at $0.7(2e^2/h)$; (b) the in-plane g factors as a function of subband index, as obtained from the Zeeman splitting at 8.2 T.

the splitting of the transconductance peaks was linear in $V_{\rm sd}$, indicating that $V_{\rm sd}$ does not perturb the electrostatic confinement potential within the constriction. We shall rely on this result when we use Eq. (1) to measure both $g_\parallel$ and $g_\perp$ for all 26 1D subbands.

Low temperature measurements of the two-terminal conductance, $G(V_g) = dI/dV$, were performed using an excitation voltage of 10 μV at a frequency of 71 Hz. Measurements in an in-plane magnetic field were carried out

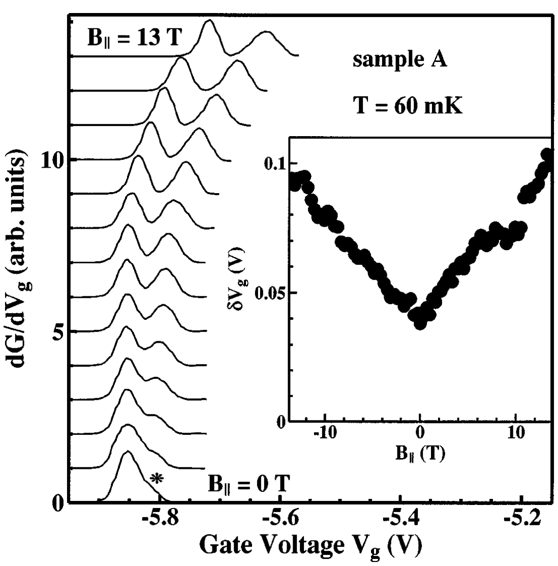

FIG. 2. Transconductance traces dG/dV_g of the transition between $G = 0$ and $2e^2/h$ as a function of $B_\parallel$. The traces have been vertically offset for clarity. The inset shows the gate voltage splitting δV_g of the transconductance peak positions as a function of $B_\parallel$.

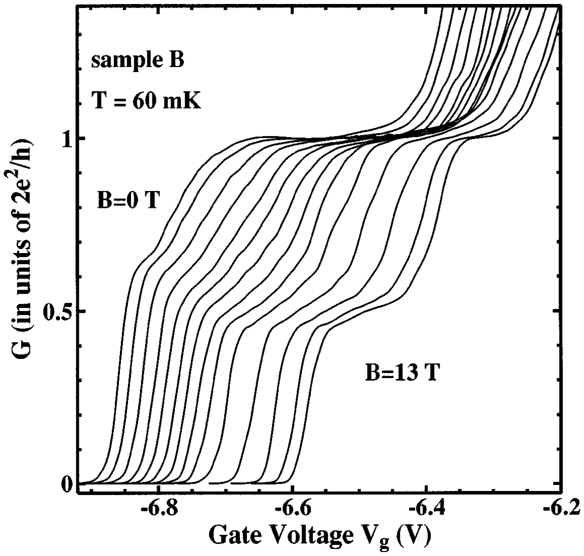

FIG. 3. The evolution of the structure at $0.7(2e^2/h)$ into a step at e^2/h in a parallel magnetic field $B_\parallel = 0 - 13$ T, in steps of 1 T. For clarity, successive traces have been horizontally offset by 0.015 V.

with the field applied either parallel ($B_\parallel$) or perpendicular ($B_\perp$) to the current j through the constriction. The results presented here are qualitatively the same for both field orientations. To check for an out-of-plane magnetic field component due to misalignment, we monitored the Hall voltage; from such measurements we were able to align the samples to better than 1°. All the results presented in this paper were reproducible on different sample cooldowns, and have been observed in a variety of devices fabricated on different wafers. The bulk 2DEG resistance changes with B, and so conductance sweeps have been corrected by choosing a series resistance (typically less than

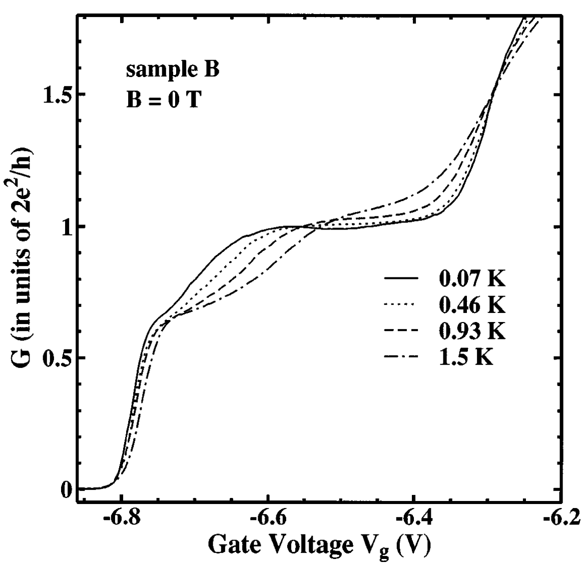

FIG. 4. Temperature dependence of the *0.7 structure* compared to the quantized plateau at $2e^2/h$.

$2\,\mathrm{k}\Omega$) that will match the last spin-degenerate plateau to the quantized value of $2e^2/h$.

Trace I in Fig. 1 shows the gate characteristics $G(V_g)$ of sample A in zero magnetic field. With decreasing gate voltage V_g the constriction is narrowed, and a conductance step of $2e^2/h$ is observed each time a spin-degenerate 1D subband is depopulated [3,4]. In addition to the last plateau at $2e^2/h$, trace I shows a weak structure close to $0.7(2e^2/h)$; inset (a) in Fig. 1 shows the detail of this *0.7 structure* at 600 mK. We have observed this feature in many 1D constrictions and previously we have commented [16] on this reproducible structure, both in our devices and in others.

We shall first present the magnetic field properties of the higher conductance plateaus, where the application of a magnetic field in the plane of the 2DEG lifts the spin degeneracy of the 1D subbands [3]. Trace II in Fig. 1 shows the gate characteristics obtained in a parallel field of $B_{\parallel} = 11$ T. For $V_g < -4$ V, additional spin-split plateaus are interleaved between those observed at $B_{\parallel} = 0$. For $V_g > -4$ V the Zeeman energy is comparable to the subband spacings, and both sets of spin-split plateaus cannot be easily resolved. Inset (b) of Fig. 1 shows $g_{\parallel}$ and $g_{\perp}$ for all 26 subbands, measured using Eq. (1) at 8.2 T; similar results were obtained at 12 T. Three features are clear: First, there is little in-plane anisotropy of the g factor. Second, when the constriction is very wide $g_{\parallel} \approx g_{\perp} \approx 0.4$, close to the value $|g| = 0.44$ of bulk GaAs [17]. Third, as the subband index decreases, $g_{\parallel}$ and $g_{\perp}$ increase.

When the channel is just defined, it is wide with a carrier density equal to that of the bulk 2DEG and the electrostatic confinement which can be described by a square-well potential. In this limit the channel can be considered to be more 2D than 1D, and the measurement of a g factor close to that of bulk GaAs provides compelling evidence for the validity of the energy splitting technique [14]. As V_g is made more negative the constriction narrows, the confinement potential becomes more rounded, the carrier density within the channel is reduced, and, for the last few occupied subbands, the anisotropy of the confinement within the channel can be described by a saddle-point potential [18]. We, however, observe little anisotropy of the in-plane g factor as the number of subbands is reduced, and we believe that electron-electron interactions are responsible for the enhancement of $g_{\parallel}$ and $g_{\perp}$. This interpretation is in contrast to that [19] in much narrower (<100 Å) 1D wires, where $\vec{k} \cdot \vec{p}$ theory can account for the measured in-plane anisotropy of the g factor.

In Figs. 2 and 3 we present transconductance (dG/dV_g) and conductance traces that show the behavior of the *0.7 structure* in a strong in-plane magnetic field. Figure 2 shows transconductance data obtained by numerical differentiation of conductance sweeps $G(V_g)$ measured in fields of $B_{\parallel} = 0$ to 13 T. Because of the presence of the *0.7 structure* at $B_{\parallel} = 0$, there is a satellite peak, marked with a star, on the right hand side of the main transconductance peak that accompanies the transition from $G = 0$ to $2e^2/h$. As $B_{\parallel}$ is increased in steps of 1 T, the satellite peak grows in intensity and the two peaks separate. At $B_{\parallel} = 13$ T the two peaks have roughly equal integrated areas, and the zero between the two transconductance peaks corresponds to the spin-split conductance plateau at e^2/h. As a function of $B_{\parallel}$ there is a parabolic shift of both transconductance peaks to more positive gate voltage; this is also observed for higher 1D subbands and can be attributed to a diamagnetic shift of the bottom of the 2D subband edge [20]. Similar parabolic variations of the position of spin-up and spin-down Coulomb blockade peaks have been observed in a quantum dot device [21].

The Fig. 2 inset shows the gate voltage separation δV_g of these two transconductance peaks in positive and negative $B_{\parallel}$. The splitting δV_g is linear in $B_{\parallel}$, and the value $\delta V_g = 0.035$ V at $B_{\parallel} = 0$ which can be interpreted as a zero-field spin splitting with an estimated energy of $\Delta E \approx 1$ meV. We measure both ΔE and the g factors of the $n = 1$ subband from the relation $eV_{\mathrm{sd}} = 2g_{\parallel}\mu_B BS + \Delta E$, rather than Eq. (1). We have also measured linear Zeeman splittings of the higher 1D subbands.

Figure 3 shows more clearly, in conductance, the evolution of the *0.7 structure* as $B_{\parallel}$ is increased in steps of 1 T. The left hand trace at $B_{\parallel} = 0$ T shows a clear structure close to $0.7(2e^2/h)$, which by 9 T has shifted down to e^2/h. Figure 3 also shows that the structure at $0.7(2e^2/h)$ is not replicated at $0.7(e^2/h)$ when the spin degeneracy is removed at high $B_{\parallel}$, evidence that the *0.7 structure* is not a transmission effect.

Figure 4 shows the temperature dependence of the last conductance step. As the temperature is increased from 0.07 to 1.5 K the definition of the plateau at $2e^2/h$ becomes weaker, whereas the *0.7 structure* strengthens and becomes flatter. The *0.7 structure* is observable even at 4.2 K (not shown) when all the quantized plateaus have disappeared. At present, we are unable to explain this unusual temperature behavior, though it might imply that the *0.7 structure* is more sensitive to localization than the 1D plateaus. The behavior also provides evidence that the *0.7 structure* is not due to an impurity, for example, Coulomb charging would be important if there was "puddling" of the electrons close to pinch-off, but such effects would show a weakening with increasing temperature. Further evidence for the absence of impurity effects comes from measurements where the channel is laterally shifted by $\pm 0.04\ \mu$m (using the technique described in Ref. [22]); there is little movement of the *0.7 structure* and no degradation of the higher index quantized conductance plateaus.

Because of the lack of inversion symmetry and the presence of interface electric fields, zero-field spin splitting can be present in GaAs/AlGaAs heterostructures. Such mechanisms will simply lift the spin degeneracy of the subbands, and for the last subband this will give rise to a spin-split plateau at $0.5(2e^2/h)$ rather than at $0.7(2e^2/h)$. However, it is expected [23] that the energy splitting will be too small ($\sim 10^{-2}$ K) to be important in our devices.

In conclusion, we have measured the in-plane g factors for the 26 subbands in a very clean 1D constriction. In the wide channel limit we have demonstrated a transport technique to measure the g factor of bulk GaAs. There is little anisotropy of the g factors in the constriction, and the enhancement of $g_{\parallel}$ and $g_{\perp}$ as the subband index decreases is indicative that many-body effects are important as the constriction becomes narrower. We have presented evidence that the *0.7 structure* is seen in high mobility 1D electron gases, and is not related to impurities. We cannot explain the origin of this new structure, though in a strong in-plane magnetic field we have shown that the *0.7 structure* evolves into the spin-split plateau at e^2/h; therefore, we speculate that there is a possible spin polarization of the 1D electron gas in zero magnetic field.

We acknowledge useful discussions with K.-F. Berggren and A. V. Khaetskii. We thank the Engineering and Physical Sciences Research Council (UK) for supporting this work. K. J. T. acknowledges support from the Association of Commonwealth Universities, J. T. N. acknowledges support from the Isaac Newton Trust, and D. A. R. acknowledges support from Toshiba Cambridge Research Centre.

[1] T. J. Thornton *et al.*, Phys. Rev. Lett. **56**, 1198 (1986).
[2] For a review, see C. W. J. Beenakker and H. van Houten, in *Solid State Physics*, edited by H. Ehrenreich and D. Turnbull (Academic Press, New York, 1991).
[3] D. A. Wharam *et al.*, J. Phys. C **21**, L209 (1988).
[4] B. J. van Wees *et al.*, Phys. Rev. Lett. **60**, 848 (1988).
[5] L. I. Glazman, I. M. Ruzin, and B. I. Shklovskii, Phys. Rev. B **45**, 8454 (1992).
[6] H. J. Schulz, Phys. Rev. Lett. **71**, 1864 (1993).
[7] F. D. M. Haldane, J. Phys. Condens. Matter **14**, 2585 (1981).
[8] C. L. Kane and M. P. A. Fisher, Phys. Rev. B **46**, 15 233 (1992).
[9] D. L. Maslov and M. Stone, Phys. Rev. B **52**, 5539 (1995).
[10] I. Safi and H. J. Schulz, Phys. Rev. B **52**, 17 040 (1995).
[11] V. V. Ponomarenko, Phys. Rev. B **52**, 8666 (1995).
[12] S. Tarucha, T. Honda, and T. Saku, Solid State Commun. **94**, 413 (1995).
[13] M. Ogata and H. Fukuyama, Phys. Rev. Lett. **73**, 468 (1994).
[14] N. K. Patel *et al.*, Phys. Rev. B **44**, 10 973 (1991).
[15] K. J. Thomas *et al.*, Appl. Phys. Lett. **67**, 109 (1995).
[16] N. K. Patel *et al.*, Phys. Rev. B **44**, 13 549 (1991).
[17] A. M. White, I. Hinchliffe, P. J. Dean, and P. D. Greene, Solid State Commun. **10**, 497 (1972).
[18] L. Martín-Moreno, J. T. Nicholls, N. K. Patel, and M. Pepper, J. Phys. Condens. Matter **4**, 1323 (1992).
[19] M. Oestreich *et al.*, Europhys. Lett. **31**, 399 (1995).
[20] F. Stern, Phys. Rev. Lett. **21**, 1687 (1968).
[21] J. Weis, R. J. Haug, K. von Klitzing, and K. Ploog, Surf. Sci. **305**, 664 (1994).
[22] J. G. Williamson *et al.*, Phys. Rev. B **42**, 7675 (1990).
[23] L. I. Glazman and A. V. Khaetskii, J. Phys. Condens. Matter **1**, 5005 (1989).