

## Spin properties of low-density one-dimensional wires

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We report conductance measurements of a ballistic one-dimensional (1D) wire defined in the lower two-dimensional electron gas of a GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As double quantum well. At low temperatures there is an additional structure at  $0.7(2e^2/h)$  in the conductance, which tends to  $e^2/h$  as the electron density is decreased. We find evidence for complete spin polarization in a weakly disorderd 1D wire at zero magnetic field through the observation of a conductance plateau at  $e^2/h$ , which strengthens in an in-plane magnetic field and disappears with increasing electron density. In all cases studied, with increasing temperature structure occurs at  $0.6(2e^2/h)$ . We suggest that the 0.7 structure is a many-body spin state excited out of, either the spin-polarized electron gas at low densities, or the spin-degenerate electron gas at high densities.

One-dimensional (1D) semiconductor systems can be fabricated by a variety of techniques. Some of the best quality devices, as determined by the clarity of the quantized plateaus in the conductance characteristics, are obtained by electrostatically squeezing a two-dimensional electron gas (2DEG) at a GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As interface using a split gate defined by electron-beam lithography.<sup>1</sup> The conductance, measured as a function of the split-gate voltage, exhibits plateaus quantized at integer multiples of  $2e^2/h$ , a result that is well understood as the adiabatic transmission of spin-degenerate 1D subbands. However, after the last 1D subband has been depopulated, an additional structure in the conductance has been measured at  $0.7(2e^2/h)$ . One of the most revealing properties of this so-called 0.7 structure is its evolution into the spin-split plateau at  $e^2/h$  in a strong in-plane magnetic field. There is also an enhancement of the  $g$  factor as the 1D carrier density is reduced. Both results suggest that there is a possible spin polarization of the 1D electron gas at zero magnetic field.<sup>2</sup>

Hartree-Fock calculations<sup>3</sup> of electrons confined in a cylindrical wire show that correlation effects are weak, and that at low electron densities exchange interactions will drive a spontaneous spin polarization. A spin polarization at zero magnetic field would give an extra plateau in the conductance at  $e^2/h$  rather than  $0.7(2e^2/h)$ . To explain this discrepancy various theories<sup>4-8</sup> invoking spin have been put forward. Recent quantum Monte Carlo calculations<sup>9</sup> show that in 1D the paramagnetic state is always lower in energy than the ferromagnetic state, so it is not clear whether the Hartree-Fock calculations are in conflict with the Lieb-Mattis prediction<sup>10</sup> that there is no ferromagnetic order in a 1D system. The role of disorder in 1D systems is little understood, but it has been shown<sup>11</sup> within mean-field theory that for dimensions  $d \leq 2$  a disordered system may exhibit a partial spin polarization, even though the system without disorder is paramagnetic.

The 0.7 structure is distinctly different from the conductance plateaus measured<sup>12</sup> at multiples of  $\alpha(2e^2/h)$  in long wires fabricated by overgrowth on a cleaved edge. The renormalization of *all* the conductance plateaus by the same factor,  $\alpha \approx 0.85$ , has been interpreted<sup>13</sup> as a reduction in the transmission probability, due to poor impedance matching

between the two-dimensional (2D) contacts and the 1D wire. Wires created at the apex of a V-groove GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As heterojunction also show<sup>14</sup> renormalized conductance plateaus due to poor 1D-2D coupling. The structure at  $0.7(2e^2/h)$  occurs in addition to the usual plateaus,<sup>2,15</sup> which are correctly quantized, confirming that the source and drain reservoirs are adiabatically connected to the 1D constriction. The 0.7 structure has been observed in other GaAs-based 1D wires, such as those created by wet etching,<sup>16</sup> or by gating an undoped heterostructure.<sup>17,18</sup> Zero-field spin splitting of 1D subbands has been observed<sup>19</sup> in constrictions fabricated from PbTe, a material that has a high dielectric constant which is expected to suppress the electron-electron interactions.

In this paper we present measurements of ballistic 1D wires that remain relatively free of impurity effects at electron densities as low as  $n \approx 3 \times 10^{10} \text{ cm}^{-2}$ , equal to a 1D electron density estimated to be  $n_{1D} \approx 1.2 \times 10^7 \text{ m}^{-1}$ . This has been achieved using coupled 1D wires, where a negative voltage  $V_{sg}$  on the split gate creates two parallel wires ( $2 \times 1D$ ) out of a double quantum well system. A voltage,  $V_{mid}$ , applied to a narrow midline gate positioned in the center of the split gate, allows charge to be shifted from one wire to the other in a controllable fashion.<sup>20</sup> When only one of the two wires is conducting, the conductance characteristics show cleaner plateaus than 1D constrictions fabricated at a single heterojunction.<sup>20</sup> There is evidence of a plateau at  $e^2/h$  as the 2D electron density  $n$  is decreased, and we show how the previously measured 0.7 structure is related to this fully spin polarized state.

Two  $2 \times 1D$  samples, *A* and *B*, were fabricated from double quantum well wafers grown by molecular beam epitaxy, comprising two 150-Å-wide GaAs quantum wells separated by a 20 Å (sample *A*) or 25 Å (sample *B*) Al<sub>0.33</sub>Ga<sub>0.67</sub>As barrier. The double quantum well is doped both above and below using 2000 Å of Si-doped ( $1.2 \times 10^{17} \text{ cm}^{-3}$ ) Al<sub>0.33</sub>Ga<sub>0.67</sub>As, offset by 600 Å and 700 Å Al<sub>0.33</sub>Ga<sub>0.67</sub>As spacer layers, respectively. The electron density in each layer is approximately  $1.3 \times 10^{11} \text{ cm}^{-2}$ , with an average mobility of  $1.45 \times 10^6 \text{ cm}^2/\text{V s}$ . The wafers were processed into Hall bars with AuNiGe Ohmic contacts that connect to both 2DEG's. Split gates were defined by

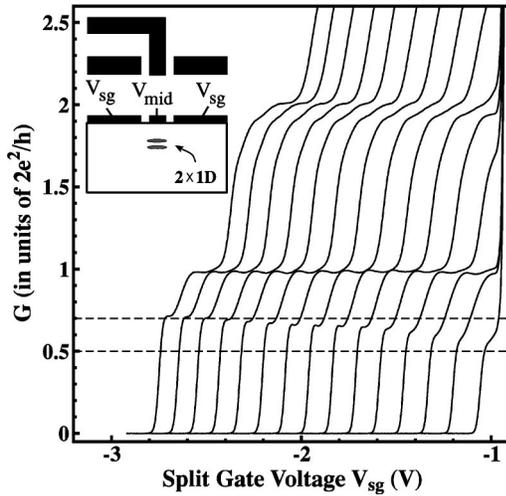


FIG. 1. Inset: Schematic plan and side views of the submicron gates used to define a  $2 \times 1D$  device in a double quantum well. Main: The conductance characteristics  $G(V_{sg})$  of sample A at  $T = 50$  mK. From left to right,  $V_{mid}$  is changed from  $-1.2$  V to  $-5.4$  V in steps of  $0.3$  V. Dashed lines are drawn at  $0.7(2e^2/h)$  and  $0.5(2e^2/h)$ .

electron-beam lithography with the pattern shown in the Fig. 1 inset. The split gates have a length of  $0.4 \mu\text{m}$  and a gap width of  $1.2 \mu\text{m}$ , and the midline gate has a width of  $0.4 \mu\text{m}$ .

Two-terminal differential conductance  $G = dI/dV$  measurements of the wires were carried out in a dilution refrigerator using standard techniques. To align the spin-degenerate plateaus at  $2e^2/h$  and  $4e^2/h$ , series resistances of  $R_s = 700 \Omega$  and  $R_s = 750 \Omega$  have been subtracted from the zero-field conductance traces of sample A and B; these  $R_s$  values are greater than the sample resistance when  $V_{sg} = 0$  V ( $345 \Omega$  and  $380 \Omega$  for samples A and B). When an in-plane magnetic field  $B_{\parallel}$  is applied parallel to the length of the split gate,  $R_s$  can become as high as  $1.5$  k $\Omega$ ; however, at a given  $B_{\parallel}$  the same resistance correction can be applied to all the traces measured at different  $V_{mid}$ . The 2D electron densities  $n$ , which we use to characterize the 1D constrictions, are measured from the number of edge states that are transmitted by the wire in the quantum Hall regime.

A previous investigation<sup>20</sup> of sample B, which is strongly coupled, showed that matching the widths and electron densities of the two wires brings them into resonance, forming symmetric and antisymmetric 1D subbands that are separated by a gap that is larger than the 2D value ( $\Delta_{SAS} = 1.4$  meV). In the measurements presented here, similar strongly coupled wires are operated away from resonance, in the regime where the top wire is pinched off. Conduction proceeds only through the lower wire, and the energy gap is unimportant.

Figure 1 shows the conductance characteristics  $G(V_{sg})$  of sample A at  $50$  mK, obtained at different electron densities as controlled by  $V_{mid}$ . From left to right the  $G(V_{sg})$  traces are measured as  $V_{mid}$  is varied from  $-1.2$  V to  $-5.4$  V in steps of  $0.3$  V. In this range of  $V_{mid}$ , the upper 1D wire is completely depopulated and the conductance, quantized in units of  $2e^2/h$ , originates from transport through the lower wire. A clear  $0.7$  structure is present in all traces, with a

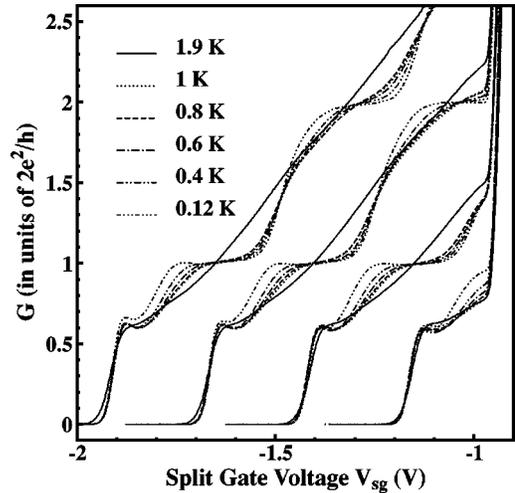


FIG. 2. Temperature dependence of  $G(V_{sg})$  characteristics of sample A on a different cooldown. The different sets of traces correspond to  $V_{mid} = 0, -1.2, -1.8,$  and  $-2.4$  V (left to right). At  $T = 2$  K structure occurs at  $0.6(2e^2/h)$  for all densities.

gradual shift of the structure to lower conductance as the electron density is lowered with a more negative  $V_{mid}$ . In previous measurements<sup>15</sup> of the  $0.7$  structure, the electron density was varied using a back gate, and the conductance of the  $0.7$  structure decreased<sup>15</sup> by  $10\%$  as the density was changed from  $1.4$  to  $1.1 \times 10^{11} \text{ cm}^{-2}$ . The lowering of the conductance structure from  $0.7(2e^2/h)$  to  $0.53(2e^2/h)$  shown in Fig. 1 occurs when the density is reduced from  $1.3 \times 10^{11} \text{ cm}^{-2}$  to  $3 \times 10^{10} \text{ cm}^{-2}$ . The midline gate has a stronger effect on the electron density in the 1D channel than a back gate, with the additional advantage that the 2D regions that constitute the source and drain are not affected by  $V_{mid}$ . More significantly, there is little degradation of the quantization or flatness of the conductance plateaus as the electron density  $n$  is decreased to  $3 \times 10^{10} \text{ cm}^{-2}$ . It is thought that the second parallel electron gas, situated only  $200 \text{ \AA}$  away, screens the electrons passing through the entrance and exit of the constriction from impurities.

Figure 2 shows the temperature dependence of the  $0.7$  structure in sample A on a second cooldown. For  $V_{mid} = 0$  V, where the density is  $n = 1.3 \times 10^{11} \text{ cm}^{-2}$ , the  $0.7$  structure drops down to  $0.6(2e^2/h)$  as the temperature is increased from  $0.12$  K to  $1.9$  K. In contrast, when the density is  $n = 3 \times 10^{10} \text{ cm}^{-2}$  at  $V_{mid} = -2.4$  V, the structure at  $0.55(2e^2/h)$  rises up to  $0.6(2e^2/h)$  as the temperature increases. Therefore, the conductance tends to  $0.6(2e^2/h)$  for temperatures greater than  $2$  K, whatever the electron density. In a strong parallel magnetic field we have observed<sup>2,15</sup> the evolution of the  $0.7$  structure to a spin-split plateau at  $e^2/h$ . If this high field state is warmed to  $2-3$  K it also moves to  $0.6(2e^2/h)$ ,<sup>21</sup> similar to the behavior at low densities seen in the right-hand side traces of Fig. 2. In both cases, the higher index plateaus do not rise with temperature, showing that there is no change in the series resistance.

On taking  $2 \times 1D$  devices to low electron densities, some samples show cleaner conductance characteristics than others. Figure 3(a) shows the  $G(V_{sg})$  characteristics for sample B at  $80$  mK, where due to impurities the conductance plateaus are not as flat as in sample A. What is most surprising

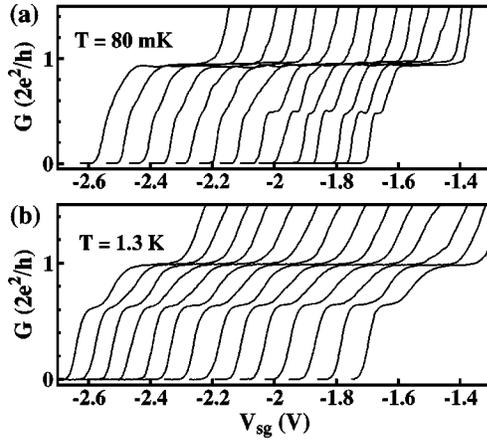


FIG. 3. Zero-field conductance characteristics  $G(V_{sg})$  of sample  $B$  at (a)  $T = 80$  mK, and (b)  $T = 1.3$  K. At both temperatures  $V_{mid}$  is decreased (left to right) from  $-0.86$  V to  $-1.0$  V, in steps of  $0.01$  V. The plateau at  $e^2/h$  measured at  $80$  mK moves to  $0.6(2e^2/h)$  at higher temperatures.

about this sample is that when the electron density is reduced below  $4 \times 10^{10} \text{ cm}^{-2}$  ( $V_{mid} < -0.94$  V) a plateau at  $e^2/h$  is observed at zero magnetic field; this has been measured on three different cooldowns. This zero-field  $e^2/h$  plateau does not originate from a  $0.7$  structure with decreasing density, as in sample  $A$ , but appears suddenly as the electron density is decreased. When the conductance measurements are repeated at  $1.3$  K, see Fig. 3(b), the  $2e^2/h$  plateau becomes cleaner and the  $e^2/h$  plateau develops into a strong structure at  $0.6(2e^2/h)$ . This high temperature structure is present in all traces in Fig. 3(b), even when there is no corresponding  $e^2/h$  plateau at  $80$  mK.

The low density  $e^2/h$  plateau in sample  $B$  has been investigated for in-plane magnetic fields  $B_{\parallel}$  up to  $16$  T. Figure 4 shows  $G(V_{sg})$  traces at  $V_{mid} = -1.06$  V as  $B_{\parallel}$  is increased in steps of  $2$  T. The zero-field  $e^2/h$  plateau strengthens and remains at  $e^2/h$  as  $B_{\parallel}$  is increased, indicating a spin splitting at  $B_{\parallel} = 0$ . Sample  $A$ , which is believed to have less impurities than sample  $B$  at the same carrier density, does not show a zero-field plateau at  $e^2/h$ . This suggests that the spontaneous spin polarization in sample  $B$  is induced by weak disorder, similar to the case studied in Ref. 11.

Our previous work<sup>2</sup> showed that the  $0.7$  structure is due to a possible spin polarization, which was accompanied by an enhancement of the  $g$  factor, both suggesting the importance of many-body interactions. Here we have shown that as the electron concentration is reduced at low temperatures, the  $0.7$  structure shifts down towards  $0.5(2e^2/h)$ , suggesting that the system is moving towards a spin polarized ground state. Whether or not such a spin polarized ground state is possible in 1D is still an open question. Lieb and Mattis have proved<sup>10</sup> that in 1D the unpolarized state is always lower in energy than the polarized state; real devices, however, are not strictly 1D because they have finite length and nonzero width. Reimann *et al.*<sup>22</sup> have predicted that in finite 1D wires there may be a spin-density wave (SDW), which could be a precursor to complete spin polarization. The SDW may give rise to localized states at the entrance and exit of the 1D wire, causing additional scattering that will reduce the con-

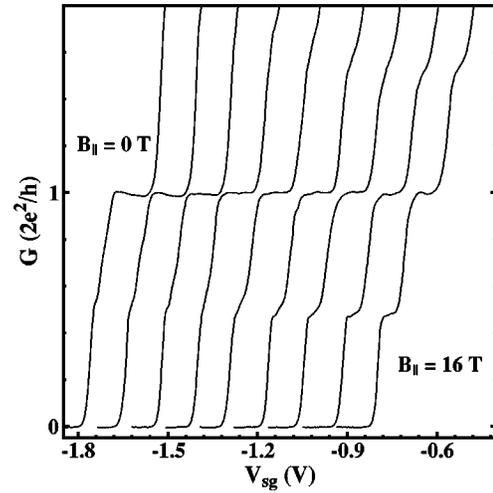


FIG. 4. Conductance characteristics  $G(V_{sg})$  of sample  $B$  at  $80$  mK and  $V_{mid} = -1.06$  V. From left to right the in-plane magnetic field  $B_{\parallel}$  is increased from  $0$  to  $16$  T in steps of  $2$  T; the plateau at  $e^2/h$  strengthens with  $B_{\parallel}$ . For clarity, successive traces have been horizontally offset by  $114$  mV. The zero-field pinch-off characteristics are slightly different from those in Fig. 3(a), as the two measurements were taken four days apart.

ductance below  $2e^2/h$ . We also report the case of a complete spin splitting at zero magnetic field, which may come about through the presence of disorder, though further clarification of this is required.

As shown by the Copenhagen group,<sup>16</sup> it appears that the  $0.7$  structure is an excited state, which at the lowest temperatures moves into the completely spin degenerate state at  $2e^2/h$ . We show here that at low temperatures the  $0.7$  structure moves into the spin polarized  $e^2/h$  state at low electron concentrations, with weak disorder, or in an external in-plane magnetic field. In all cases, the spin-split plateau at  $0.5(2e^2/h)$  moves to a slightly higher conductance, typically  $0.6(2e^2/h)$ , when the temperature is raised. At present it is not clear why there is a  $0.7$  structure rather than plateau at  $e^2/h$  at low temperatures and high densities, there may be a partial spin polarization due to a hybridization of the spin-up and spin-down state at higher temperatures.

In conclusion, we have shown that using just one of the wires in a  $2 \times 1$ D device, the electron density in the constriction can be taken to  $3 \times 10^{10} \text{ cm}^{-2}$ , without the conductance characteristics suffering so readily from impurity effects. At low electron densities the  $0.7$  structure moves towards  $0.5(2e^2/h)$  at low temperatures. We have also presented evidence for a spontaneous spin polarization, possibly brought about by weak disorder, giving rise to a plateau at  $e^2/h$ . In all cases studied, for  $T > 2$  K, structure is observed close to  $0.6(2e^2/h)$ . The temperature dependence suggests that the  $0.7$  structure is a many-body state that is excited out of the spin polarized 1D electron gas at low densities, or out of the spin-degenerate electron gas at high densities.

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