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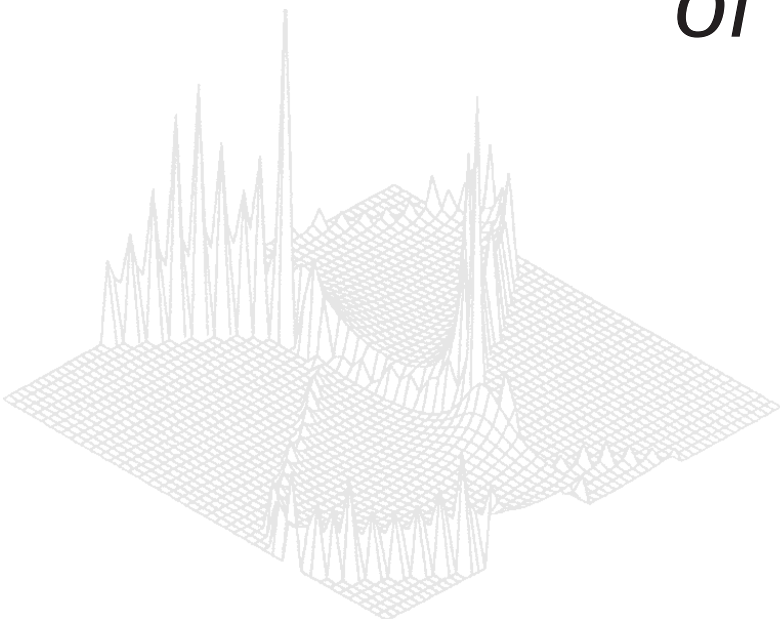

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Many-body Spin Interactions in Semiconductor Quantum Wires*

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Abstract

Zero length quantum wires (or point contacts) exhibit unexplained conductance structure close to $0.7 \times 2e^2/h$ in the absence of an applied magnetic field. We have studied the density- and temperature-dependent conductance of ultra-low-disorder GaAs/AlGaAs quantum wires with nominal lengths $l = 0$ and 2 μ*m*, fabricated from structures free of the disorder associated with modulation doping. In a direct comparision we observe structure near $0.7 \times 2e^2/h$ for $l = 0$, whereas the $l = 2$ μ*m* wires show structure evolving with increasing electron density to $0.5 \times 2e^2/h$ in *zero* magnetic field, the value expected for an ideal spin-split sub-band. Our results suggest the dominant mechanism through which electrons interact can be strongly affected by the length of the 1D region.

A one-dimensional (1D) quantum wire may be produced by constricting a two-dimensional electron gas (2DEG) formed at the GaAs/AlGaAs interface in a semiconductor heterojunction. Quantum wires have been used extensively to study ballistic transport in one dimension where the conductance is quantised in units of $2e^2/h$ (Wharam *et al.* 1988; van Wees *et al.* 1988). This result is well explained by considering the allowed energies of a non-interacting electron gas confined to 1D, where the factor of 2 is due to spin degeneracy. Electron interaction effects in 1D have been considered for some time, involving models (Luttinger 1963) which go beyond the conventional Fermi liquid picture. Such correlated electron models have been applied to quantum wire systems (Kane and Fischer 1992) and recent experimental studies (Tarucha *et al.* 1995; Yacoby *et al.* 1996) have investigated their predictions. Although recent theories have considered the effect of weak disorder on correlation effects (Maslov 1995), it is generally accepted that low-disorder nanostructures are necessary for such investigations.

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Low-disorder quantum point contacts (which are quantum wires of length $l = 0$) formed in GaAs/AlGaAs heterostructures (and recently other material systems) exhibit unexplained conductance structure close to $0.7 \times 2e^2/h$ in the absence of a magnetic field (Thomas *et al.* 1996, 1998; Kane *et al.* 1998; Kristensen *et al.* 1998; Tscheuschner and Wiek 1996). Studies by Thomas *et al.* (1996) suggest that the structure is a manifestation of electron–electron interactions involving spin. The continuous evolution of the $0.7 \times 2e^2/h$ structure into a Zeeman spin–split conductance plateau with the application of an in-plane magnetic field, together with enhancement of the g-factor for lower 1D channels, is consistent with this interpretation (Thomas *et al.* 1996).

In this paper we present transport data for 1D systems free from the disorder associated with modulation doped heterostructures, including strong evidence for spin related many-body effects in long 1D regions. We find conductance structure comparable to that of Thomas *et al.* in our zero length wires, while our 2 μm quantum wire exhibits plateau-like structure near $0.5 \times 2e^2/h$ in a zero magnetic field, the value expected for an ideal spin-split level.

Our results are suggestive of an interpretation in which spin splitting in a zero magnetic field is only fully resolved in long 1D regions, perhaps above a critical length scale. This does not explain why structure in short constrictions consistently occurs near $0.7 \times 2e^2/h$. A clue may be found in recent theories (Flambaum and Kuchiev 1999; Rejec *et al.* 1999) which consider the possibility of a feature at $0.75 \times 2e^2/h$ due to a splitting between the one singlet and three triplet states where electron pairs (attractive interaction) dominate transport. As the length of the 1D region is increased it has been suggested (Flambaum and Kuchiev 1999) that the dominant many-body interaction can alter and, if spontaneous spin polarisation occurs, a principal feature at $0.5 \times 2e^2/h$ would be observed, perhaps with some remanent weak structure close to $0.75 \times 2e^2/h$.

The study of correlated electron states requires devices with ultra-low disorder since such states are expected to be easily destroyed by disorder and may be masked by other effects associated with localisation. We have developed a novel GaAs/AlGaAs layer structure (see Fig. 1) that avoids the major random potential present in conventional HEMT devices by using epitaxially grown gates to produce an enhancement mode FET (Kane *et al.* 1995). These devices are advantageous for the study of 1D interacting systems because they eliminate the need for a dopant layer in the AlGaAs adjacent to the 2DEG, thus greatly reducing disorder while allowing the electron density in the 2DEG to be varied over a large range. The electron mobility in the 2DEG is typically $4-6 \times 10^6\ \mathrm{cm^2\,V^{-1}s^{-1}}$ at 4.2 K and increases further at lower temperatures. At 100 mK the 2D ballistic mean free paths exceed 160 μ*m* (Facer *et al.* 1999) which is greater than our sam-

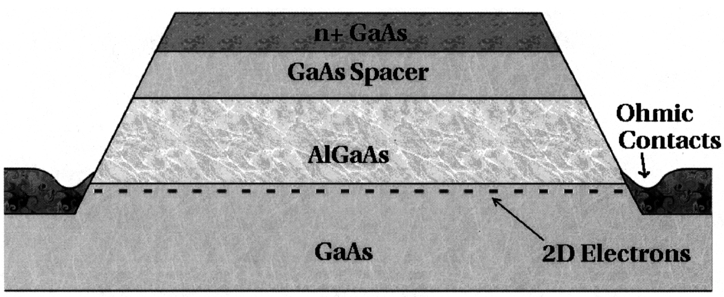


Fig. 1. Cross-sectional schematic of the enhancement mode field effect transistor (FET) used as the basis for fabrication of our ultra-low disorder quantum wires.

ple dimensions. These devices are comparable with the highest mobility electron systems yet produced. Ballistic conductance plateaus have been demonstrated in quantum wires up to 5 μm in length, with the data exhibiting more than 15 plateaus (Kane *et al.* 1998).

To investigate the sensitivity of many-body effects to the length of the 1D region, we have measured the conductance of quantum wires of nominal length $l = 0$, 2 μm and 5 μm. The devices were patterned from ultra-high mobility heterostructures, consisting of a 75 nm layer of $Al_{0.3}Ga_{0.7}As$ on top of GaAs to produce the 2DEG interface. A 25 nm GaAs spacer separated the epitaxial conducting top gate from the AlGaAs (refer to Fig. 1). NiAuGe ohmic contacts were made to the 2DEG using a self-aligned technique. Electron beam lithography and shallow wet etching were used to selectively remove the top gate to form the quantum wires (Fig. 2). The top gate was sectioned into three separately controllable gates. The centre (top gate) was biased positively relative to the contacts to induce a 2DEG at the GaAs/AlGaAs interface. This positive bias V_T determined the carrier density in the 2DEG reservoirs which was tunable from $0.6 - 6 \times 10^{11}$ cm^{-2} corresponding to $V_T = 0.05$ V to 0.8 V. A negative voltage V_s was then applied to the side gates to produce electrostatic 1D confinement in addition to the geometric confinement already present (see Fig. 2).

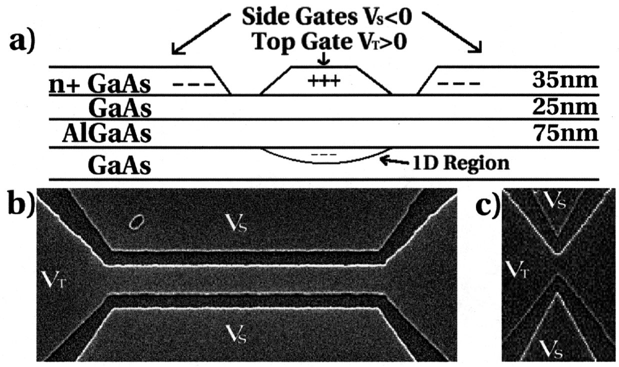


Fig. 2. (a) Cross-sectional schematic of a quantum wire, showing the positively biased top gate and the side gates biased negatively. (b) SEM micrograph of a quantum wire with length $l = 5$ μm. (c) SEM micrograph of a quantum wire with length $l = 0$.

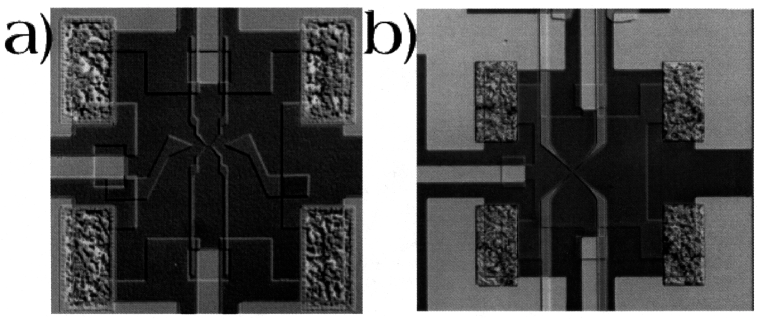


Fig. 3. Optical photographs of the patterned heterostructures showing ohmic contacts (mottled regions) and gate contacts (lighter regions). The square region is 100 μm each side. (a) A 5 μm quantum wire. (b) A 1 μm quantum wire.

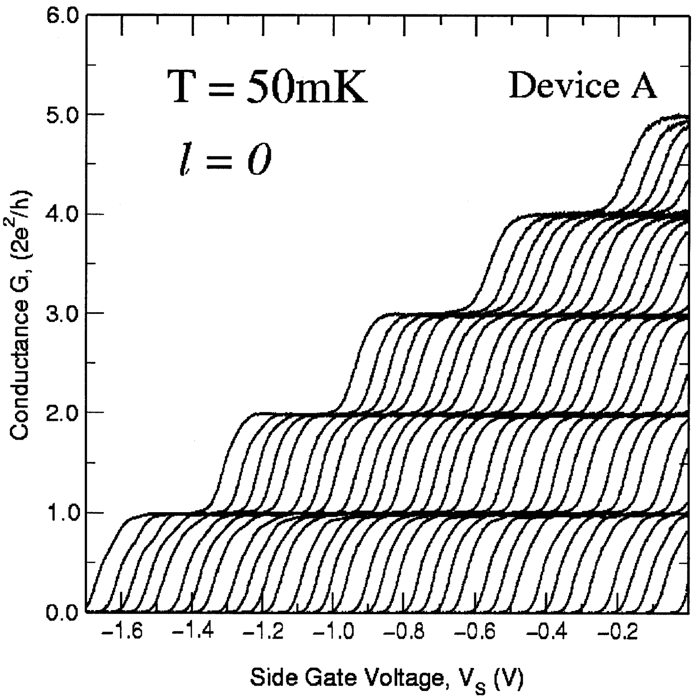
Low frequency four-terminal conductance measurements were made with an excitation voltage below 10 μV using two lock-in amplifiers to monitor both current and voltage. We stress that the results presented here are raw data as no equivalent series resistance has been subtracted and no attempt has been made to adjust the plateau heights to fit with quantised units of $2e^2/h$.

The conductance G of a zero-length quantum wire is shown in Fig. 4 as a function of the side gate voltage V_s at a temperature $T = 50$ mK. Data were taken at a series of top gate voltages corresponding to different 1D densities. The 1D electron density n_{1D} may be controlled using *both* the top and side gates to vary the shape of the potential well perpendicular to the channel. When both the top and side gates are strongly (*weakly*) biased positive and negative respectively the confining potential is steep (*shallow*), leading to a large (*small*) 1D sub-band spacing and a corresponding high (*low*) 1D electron density. In this way it is possible to maintain a constant 1D occupancy, and hence conductance, while varying n_{1D} .

For $G < 2e^2/h$ (top Fig. 4) an additional feature is observed close to $0.7 \times 2e^2/h$, as seen by others (Thomas *et al.* 1996, 1998; Kane *et al.* 1998; Kristensen *et al.* 1998; Tscheuschner and Wiek 1996). A similar feature is also observed in a second identical quantum wire with length $l = 0$ (bottom Fig. 4) although here the conductance structure is much weaker despite the fact that both these $l = 0$ quantum wires were fabricated from the same material and measurements were carried out in the same cool down. As with other workers we find that this feature is robust to cryogenic cycling, indicating that it is unlikely to be related to an impurity state. Although the data for device A in Fig. 4 imply an small enhancement of the 0.7 structure with increasing n_{1D}, the trend is not fully monotonic and is less so for the second $l = 0$ wire measured (device B in Fig. 4). Fig. 5 shows the temperature dependence of the conductance for the wire length $l = 0$ exhibiting the strongest feature near $0.7 \times 2e^2/h$ (device B). The temperature measurements in the top panel of Fig. 5 were made with an average electron density ($n_{2D} \approx 3 \times 10^{11}$ cm^{-2}, $V_T = 0.4$ V). Similar behaviour with temperature is seen at high and low electron densities in both of the zero length quantum wires studied (see the bottom panel in Fig. 5). This temperature dependence deviates from the expected single particle result with little thermal smearing below $0.7 \times 2e^2/h$. Such puzzling behaviour is consistent with measurements made by others (Thomas *et al.* 1996; Kristensen *et al.* 1998).

The results in Fig. 4 demonstrate that these epitaxially gated nanostructures produce ultra-low disorder quantum wires for $l = 0$ which exhibit the $0.7 \times 2e^2/h$ conductance feature comparable with the strongest so far observed. When we extend to longer quantum wires, new and unexpected results are seen.

Fig. 6 shows the conductance G of a quantum wire with $l = 2$ μm as a function of side gate voltage V_s . The density n_{1D} increases from right to left as the confining potential is steepened. Data were obtained at temperatures of $T = 1$ K (top) and $T = 50$ mK (bottom). Clear conductance quantisation is seen near integer multiples of $2e^2/h$ with up to 15 plateaus evident, indicating ballistic transport along the full length of the 2 μm wire, as previously reported (Kane *et al.* 1998). The data collected at $T = 1$ K show a clear plateau-like feature which becomes more pronounced and evolves downwards in G towards $0.5 \times 2e^2/h$ as V_T is increased. A much weaker inflection is also present near $0.7 \times 2e^2/h$ across the full density range. Further evidence of many-body phenomena is seen evolving in the range $1.5 - 1.7 \times 2e^2/h$ where the structure is strong enough to resemble the conductance feature seen near $0.7 \times 2e^2/h$ in quantum wires with $l = 0$. Very weak inflections are also observed near $2.7 \times 2e^2/h$ on some traces.



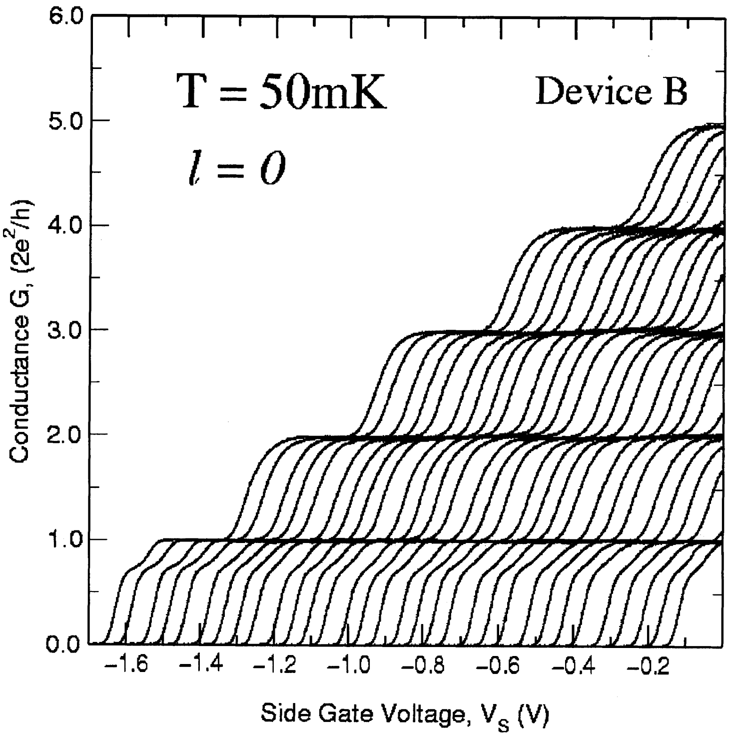


Fig. 4. Conductance measurements of two $l = 0$ quantum wires as a function of side gate voltage for increasing top gate voltages. For device A (*top*) $V_T = 170 - 306$ mV (right to left) in steps of 4 mV. For device B (*bottom*) $V_T = 172 - 300$ mV (*right to left*) in steps of 4 mV. The temperature was 50 mK.

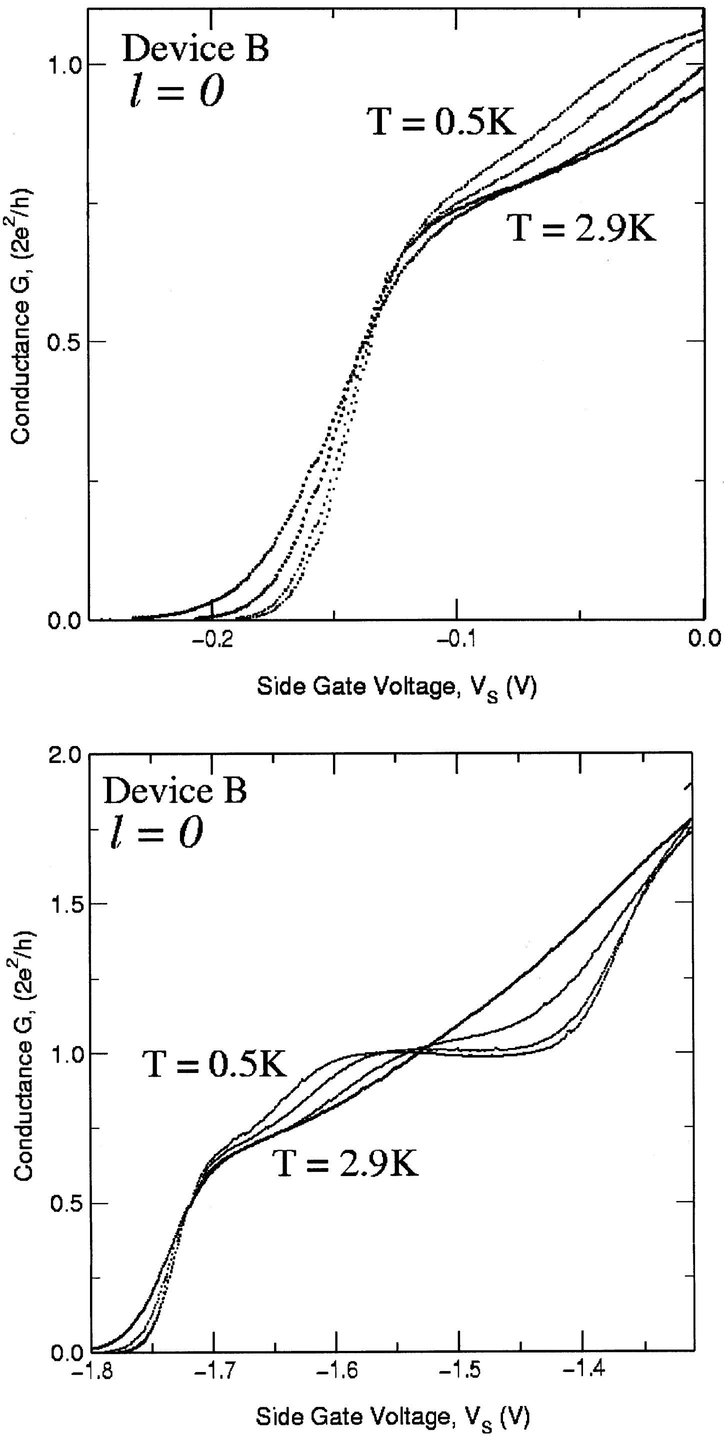


Fig. 5. Temperature dependence of conductance for device B ($l = 0$ quantum wire) as a function of side gate voltage. The top gate voltage is $V_T = 0.4$ V (*top*) and $V_T = 0.17$ V (*bottom*). The curves are for temperatures 0.5, 1.0, 1.5 and 2.9 K.

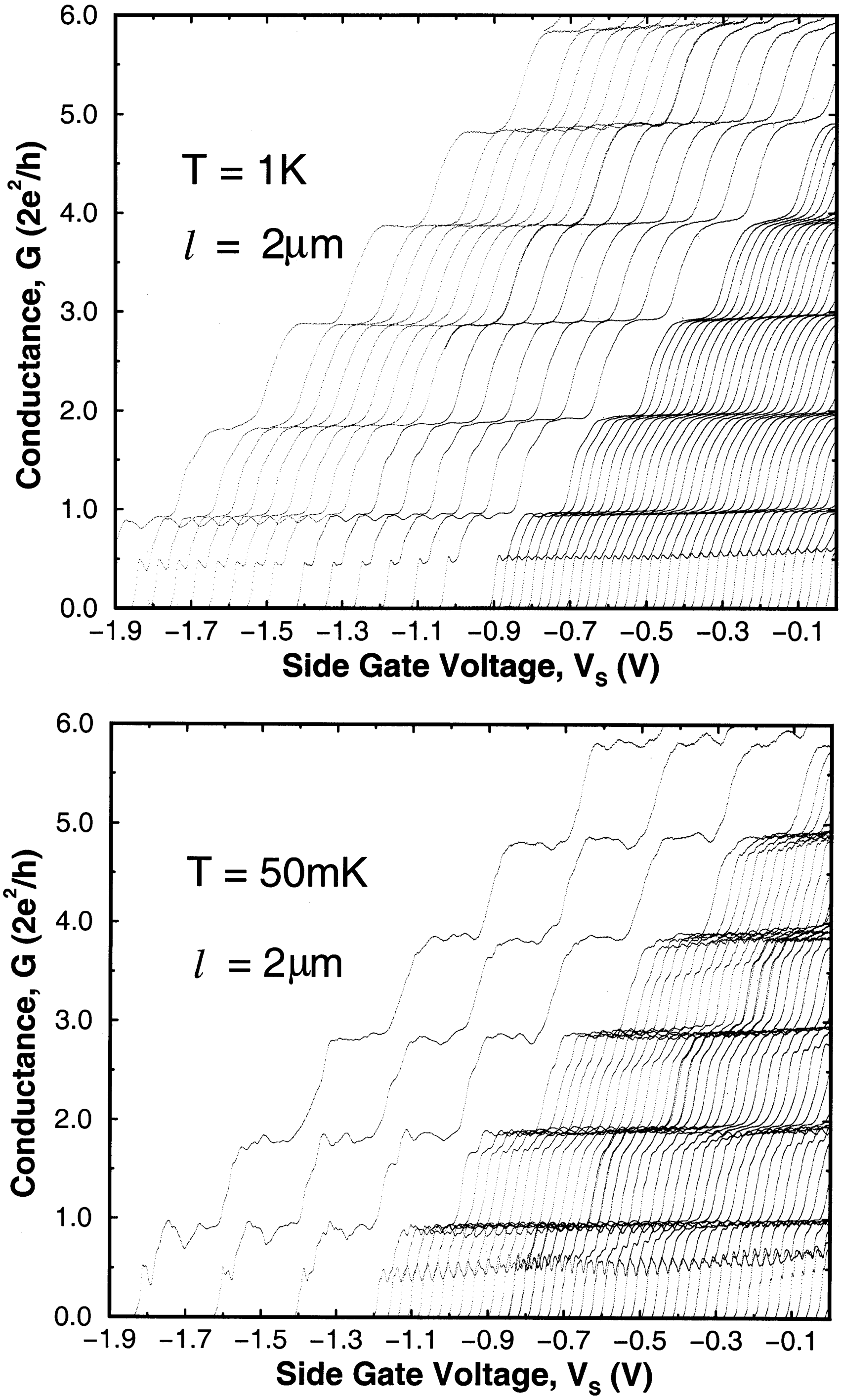


Fig. 6. Conductance of a $2\ \mu m$ quantum wire as a function of side gate voltage for top gate voltages $V_T = 300 - 620$ mV (right to left). The data in the top panel wasobtained close to 1 K and the data in the bottom panel was obtained at approximately 50 mK.

Conductance measurements of quantum wires with $l = 5$ μ*m* exhibit similar plateau-like features near $0.5 \times 2e^2/h$ to wires with $l = 2$ μ*m*, as noted in our previous work (Kane *et al.* 1998). However, for $l = 5$ μ*m* the weak disorder which is present leads to a distortion of the conductance plateaus, making interpretation more difficult and here we focus on wires with $l = 2$ μ*m* where the single particle plateaus are as clear as those seen in $l = 0$ devices. As the 2 μ*m* wire is cooled to $T = 50$ mK the feature near $0.5 \times 2e^2/h$ remains; however, rich evolving structure is also revealed. Conductance inflections occur below each of the integer plateaus (within e^2/h) which predominantly evolve downwards in G with increasing n_{1D}. One explanation within a single-particle picture is weak disorder, leading to interference of electron waves along the quantum wire. However, against this, the strongest features survive at $T = 1$ K and are reminiscent of the $0.7 \times 2e^2/h$ feature seen in low-disorder $l = 0$ wires, implying instead a many-body origin.

Fig. 7 details the evolution of the conductance features seen in quantum wires of length $l = 0$ and 2 μ*m* with varying n_{1D}. We define the position of the feature seen in $l = 0$ devices near $0.7 \times 2e^2/h$ as the conductance G at which dG/dV_s is a local minimum. In a similar manner, for the $l = 2$ μ*m* quantum wire we define the position of the plateau-like feature as the first local minimum in the dG/dV_s curve for $T = 1$K.

Note that the plateau at $2e^2/h$ remains almost constant for the $l = 0$ wire but for $l = 2$ μ*m* the plateau falls in G (by up to 8%) as n_{1D} is increased. Suppression of plateaus below the ideal quantised values has been observed in previous studies on quantum wires

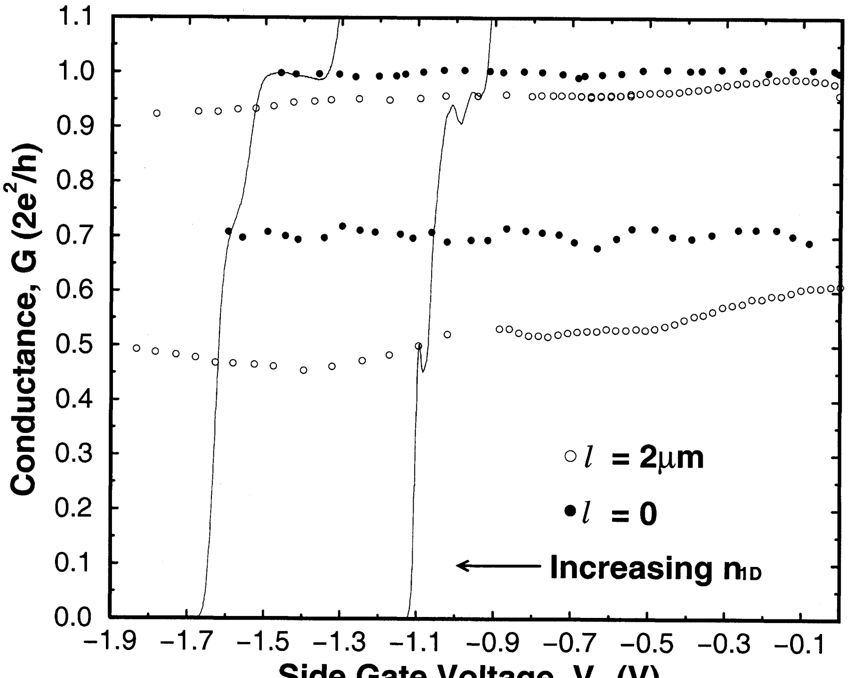


Fig. 7. Evolution of the conductance features seen in $l = 0$ and 2 μ*m* quantum wires as a function of n_{1D}. The evolution of the corresponding plateauat $2e^2/h$ is also shown. Single conductance traces are included forboth devices to facilitate interpretation. Open circles are 2 μ*m* data and closed circles are $l = 0$ data (device B).

(Tarucha *et al.* 1995; Yacoby *et al.* 1996; Kane *et al.* 1998), and considered theoretically in a number of many-body treatments (Kane and Fischer 1992; Maslov 1995). In our case the suppression cannot be explained by a simple increase of the effective series resistance associated with the 2D contact regions, since the 2D sheet resistance decreases with increasing V_T. Abrupt coupling of the 2D reservoirs to the low density 1D region could result in a reduction of the transmission coefficient as the 2D electron density is increased. We note that the density mismatch is larger for the longer wire, since the top-gate voltage threshold for conduction is almost twice as large for $l = 2$ μ*m* as for $l = 0$.

Turning now to the non-integer plateaus we see that the feature near $0.7 \times 2e^2/h$ in $l = 0$ devices becomes slightly more *pronounced* with increasing n_{1D} (Fig. 2) but the variation in conductance is small. This is in contrast to the plateau-like feature seen in the $l = 2$ μ*m* wire data, which evolves towards $0.5 \times 2e^2/h$ with increasing n_{1D}. It is significant that if the single particle plateau for $l = 2$ μ*m* is normalised to equal $2e^2/h$ then this feature still evolves downwards in G, but never falls below $0.5 \times 2e^2/h$, the position expected for a spin-split 1D plateau.

Conductance data suggestive of many-body effects in 1D have now been observed in a variety of high mobility structures including split-gated HEMTs (Thomas *et al.* 1996), gate metallised structures (Kristensen *et al.* 1998) and our undoped enhancement mode FETs considered here. Some evidence for this effect has also been seen in low mobility quantum wires based on ion-beam defined GaAs transistors (Tscheuschner and Wiek 1996) and other material systems such as GaInAs/InP (Ramvall *et al.* 1997) and n-PbTe (Grabecki *et al.* 1999). The diverse number of experimental systems that have been examined would seem to establish the feature as an intrinsic property of a 1D correlated system. In particular the temperature dependence, described as *activated* by Kristensen *et al.* (1998) and detailed in our $l = 0$ wires, remains consistent between devices of different design (Thomas *et al.* 1996; Kristensen *et al.* 1998). Some important exceptions do exist, however, as in measurements of narrow wires by Yacoby *et al.* (1996) and Tarucha *et al.* (1995) where there appears to be no *strong* feature present even though clear quantisation is seen. The absence of the feature in Yacoby *et al.* (1996) may be associated with a large 1D sub-band spacing made possible in that case due to a novel epitaxial confinement technique.

The most commonly invoked explanation for additional conductance structure near $0.7 \times 2e^2/h$ has been some form of spontaneous spin polarisation mediated through the exchange interaction, as detailed in Gold and Calmels (1996) and Wang and Berggren (1996). The possibility of a ferromagnetic instability below a critical electron concentration has also been considered (Byczuk and Dietl 1998). It has so far remained a mystery as to why measurements show structure near $0.7 \times 2e^2/h$, rather than at $0.5 \times 2e^2/h$, the value expected for a fully spin-polarised 1D level. The fact that we see structure near $0.7 \times 2e^2/h$ in $l = 0$ wires and structure evolving towards $0.5 \times 2e^2/h$ in longer wires (with $l = 2$ μ*m* and $l = 5$ μ*m*—see Kane *et al.* 1998) leads to a possible scenario in which spin-splitting is only fully resolved in wires above some critical length scale. The additional structure we observe near $1.7 \times 2e^2/h$, and in higher sub-bands below 1 K, also suggests that many-body effects become enhanced in longer 1D regions. We note that conductance anomalies in higher sub-bands have been predicted (Wang and Berggren 1996).

An alternative explanation has been argued in two recent theories (Flambaum and Kuchiev 1999; Rejec *et al.* 1999) that consider a scenario in which two (or more) body processes dominate. In the proposed case where electron pairs dominate transport and $l = 0$, the three triplet states are lower in energy than the one singlet state, leading to a plateau at (slightly less than) $0.75 \times 2e^2/h$, since the triplet states are transmitted (with transmission coefficient not precisely 1), while the singlet is reflected by the constriction. In our $l = 2$ μm wire, although the dominant feature below $2e^2/h$ occurs near $0.5 \times 2e^2/h$, there is additional weaker structure in the vicinity of $0.75 \times 2e^2/h$ which is still noticeable at $T = 1$ K (see Fig. 3). Whereas this could be due to the onset of spontaneous polarisation for $l > 0$ and increasing n_{1D}, this observation could also be compatible with 1D Wigner crystallisation (dominant repulsive interaction) providing the Landau–Buttiker framework can be extended to this regime (Flambaum and Kuchiev 1999).

In conclusion, we have studied ultra-low disorder quantum wires utilising a novel GaAs/AlGaAs layer structure which avoids the random impurity potential associated with modulation doping, making these devices ideal for the study of electron correlations in 1D. In common with other workers we find structure near $0.7 \times 2e^2/h$ in wires with $l = 0$, whereas in longer wires the dominant structure evolves towards $0.5 \times 2e^2/h$ at high 1D carrier concentrations. It is not possible to be conclusive as to whether these effects are related to a many-electron spin polarisation, or to a more complex explanation (for example 1D Wigner crystallisation). However, it is clear that both the length over which interactions occur and the 1D density play an important role in determining the effect of these mechanisms upon electrical transport.

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