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Many-body spin-related phenomena in ultra low-disorder quantum wires

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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/Al_xGa_{1-x}As quantum wires with nominal lengths $l=0$, 0.5, and 2 μm, fabricated from structures free of the disorder associated with modulation doping. In a direct comparison in *zero* magnetic field we observe structure near $0.7\times 2e^2/h$ for $l=0$, whereas the $l=2$ μm wires show structure evolving with increasing electron density to $0.5\times 2e^2/h$, the value expected for an ideal spin-split subband. For intermediate lengths ($l=0.5$ μm) the feature at $0.7\times 2e^2/h$ evolves to $0.55\times 2e^2/h$ with increasing density. Our results suggest the dominant mechanism through which electrons interact can be strongly affected by the length of the one-dimensional region.

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Quantum wires have been used extensively to study ballistic transport in one dimension (1D) where the conductance is quantized in units of $2e^2/h$.[1,2] This result is well explained by considering the allowed energies of a noninteracting 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[3] which go beyond the conventional Fermi liquid picture. Such correlated electron models have been applied to quantum wire systems[4] and recent experimental studies[5,6] have investigated their predictions. Although recent theories have considered the effect of weak disorder on correlation effects,[7] it is generally accepted that low-disorder nanostructures are necessary for such investigations.

Low-disorder quantum point contacts (which are quantum wires of length $l=0$) formed in GaAs/Al_xGa_{1-x}As heterostructures exhibit unexplained conductance structure close to $0.7\times 2e^2/h$ in the absence of a magnetic field.[8–12] Studies by Thomas *et al.*[8] 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.[8]

In this paper we present transport data for 1D systems free from the disorder associated with modulation doped heterostructures, including evidence for spin-related many-body effects in long 1D regions. We find conductance structure comparable to Thomas' in our zero length wires, while our 2-μm quantum wire exhibits plateaulike structure near $0.5 \times 2e^2/h$ in zero magnetic field, the value expected for an ideal spin-split level. Further, for wires of intermediate length ($l=0.5$ μm) we find a pronounced feature at $0.7 \times 2e^2/h$ that evolves *continuously* to $0.55\times 2e^2/h$ with increasing 1D electron density.

Theories involving electron-correlation effects have been developed recently to explain why experiments predominantly show a feature at $0.7\times 2e^2/h$, rather than at $0.5 \times 2e^2/h$ expected for simple spin-splitting. These include models which involve two-electron spin singlet/triplet pairing[13,14] or Fermi-pinning at a spontaneously spin-split subband.[15] Our data, together with recent results obtained by Thomas *et al.*,[16] indicate that the ideal value of $0.5\times 2e^2/h$ can also occur, either above a certain length scale, or beyond some critical carrier density or potential profile, thereby lending strength to an interpretation in terms of spin polarization.

The study of correlated electron states requires devices with ultralow-disorder since such states are expected to be easily destroyed by disorder and may be masked by other effects associated with localization. We have developed a GaAs/Al_xGa_{1-x}As layer structure which avoids the major random potential present in conventional High Electron Mobility Transistors (HEMTs) devices by using epitaxially grown gates to produce an enhancement mode Field Effect Transistor (FET).[17] These devices are advantageous for the study of 1D interacting systems because they eliminate the need for a dopant layer in the Al_xGa_{1-x}As 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$\times 10^6$ 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 μm (Ref. 18) which is greater than our sample 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.[10]

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 $l=0$, 0.5 μm, 2 μm and 5 μm. l is defined in the device schematic shown in the inset of Fig. 3. The devices were patterned from ultra-high-

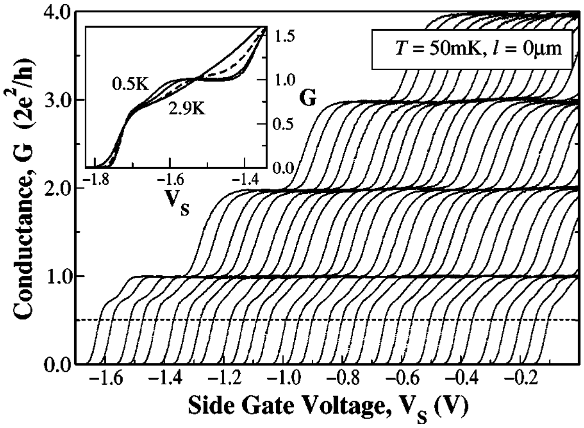

FIG. 1. Conductance of a $l=0$ quantum wire as a function of side gate voltage for top gate voltages, $V_T=172$ mV–300 mV (right to left) in steps of 4 mV. Inset: Temperature dependence of the conductance at $V_T=0.4$ V for $T=0.5$, 1.0, 1.5, and 2.9 K.

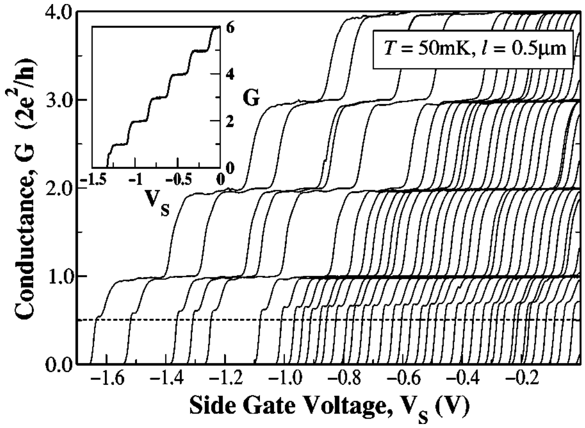

FIG. 2. Conductance of a $l=0.5$ μm quantum wire as a function of side gate voltage for $V_T=560$ mV–1500 mV (right to left). Inset: Conductance as a function of side gate voltage for $V_T=1.5$ V.

mobility heterostructures, comprising 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 $Al_{1.0}Ga_{0.7}As$. 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. This device structure is described in detail in Ref. 10. The epitaxial top layer was sectioned into three separately controllable gates (see inset to Fig. 3). The center (top gate) was biased positively relative to the contacts to induce a 2DEG at the GaAs/$Al_xGa_{1-x}As$ interface. This positive bias V_T determined the carrier density in the 2DEG reservoirs which was typically tunable from $0.6–6\times10^{11}$ cm^{-2}. 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.

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 quantized units of $2e^2/h$.

The conductance G of a zero-length quantum wire is shown in Fig. 1 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 subband 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}. We have confirmed this by measuring the 1D subband energy spacing using a DC source-drain technique.[19]

For $G<2e^2/h$ an additional feature is observed close to $0.7\times2e^2/h$, as seen by others.[8–12] A similar feature is also observed in a second identical quantum wire with length $l=0$ (not shown). 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 in Fig. 1 imply a 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. The inset of Fig. 1 shows the temperature dependence of the conductance for the wire with length $l=0$. Similar behavior with temperature is seen at high and low electron densities in both of the zero length quantum wires studied. This temperature dependence deviates from the expected single particle result with little thermal smearing below $0.7\times2e^2/h$. Such puzzling behavior is consistent with measurements made by others.[8,11]

The results in Fig. 1 demonstrate that these epitaxially gated nanostructures produce ultra low-disorder quantum wires for $l=0$ which exhibit the $0.7\times2e^2/h$ conductance feature comparable with the strongest so far observed. When we extend to longer quantum wires, new and unexpected results are seen.

Figure 2 shows the conductance G of a quantum wire with $l=0.5$ μm as a function of V_S. The density n_{1D} increases from right to left as the confining potential is steepened, in a manner analagous with Fig. 1. Unlike the data in Fig. 1, the conductance feature below the first plateau begins at $0.7\times2e^2/h$ and evolves *continuously* downwards with increasing n_{1D} to $0.55\times2e^2/h$ in the range of gate voltages shown. It is difficult to determine whether the position of the feature might continue to evolve if larger gate voltages were applied.[20] We note that the data presented in Fig. 2 (also see inset) are clean and free of features due to length resonances and other effects associated with disorder. Further, the temperature dependence of the conductance feature (not shown) is very similar to that seen for the $l=0$ device.

Figure 3 shows the conductance G of a quantum wire with $l=2$ μm. Data were obtained at temperatures $T=1$ K and $T=50$ mK. Clear conductance quantization is seen near integer multiples of $2e^2/h$ with up to 15 platueas evident, indicating ballistic transport along the full length of the 2 μm wire, as previously reported.[10] The data collected at $T=1$ K

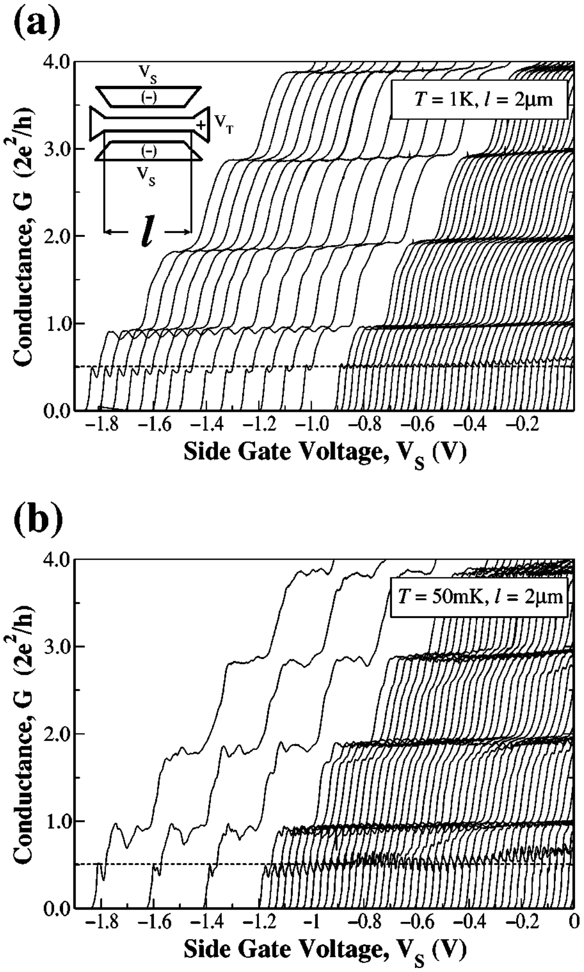

FIG. 3. Conductance of a $l=2$ μm quantum wire as a function of side gate voltage for $V_T=300$ mV–620 mV (right to left). The data in (a) were obtained at 1 K and in (b) at 50 mK. The inset to (a) is a schematic of the device. Electrical conduction occurs below the middle region (top gate), which is biased positively with voltage V_T. The side gates are biased negatively with voltage V_S. l is the characteristic length of the 1D region.

show a clear plateaulike feature below $2e^2/h$ which becomes more pronounced and evolves downwards in G towards $0.5\times 2e^2/h$ as $n_{1\text{D}}$ is increased. A much weaker inflection is also present near $0.7\times 2e^2/h$ on some traces. Further evidence of many-body phenomena is seen evolving in the range 1.5–$1.7\times 2e^2/h$.

Conductance measurements of quantum wires with $l=5$ μm exhibit similar plateaulike features near $0.5\times 2e^2/h$ to wires with $l=2$ μm, as noted in our previous work.[10] However, for $l=5$ μm 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 $l \leqslant 2\mu$m where the single-particle plateaus at $T=1$ K are as clear as those seen in $l=0$ devices.

As the 2 μm 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 $n_{1\text{D}}$. One explanation within a single-particle picture is weak disorder, leading to interference of electron waves along the quantum wire. However, against this, remnants of the strongest features survive at $T=1$ K, in particular the feature below $2\times 2e^2/h$ is reminiscent of the $0.7\times 2e^2/h$ feature seen in low-disorder $l=0$ wires, implying a possible many-body origin.

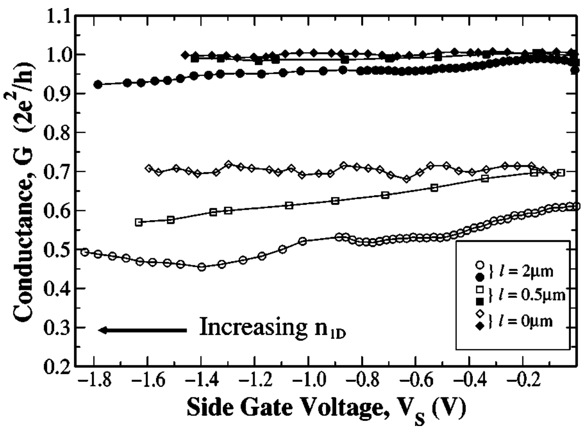

FIG. 4. Evolution of the conductance features (open symbols) seen in $l=0$, 0.5, and 2 μm quantum wires as a function of V_S. The evolution of the corresponding $n=1$ plateau near $2e^2/h$ is also shown (solid symbols).

Figure 4 details the evolution of the conductance features seen in quantum wires of length $l=0$, 0.5 μm, and 2 μm with varying V_S (and hence $n_{1\text{D}}$). We define the position of the feature seen in $l=0$ and 0.5 μm devices at 0.6–$0.7\times 2e^2/h$ as the conductance G at which dG/dV_s is a local minimum. In a similar manner, for the $l=2$ μm quantum wire we define the position of the plateaulike 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 $l=0$ and 0.5 μm, but for $l=2$ μm the plateau falls in G (by up to 8%) as $n_{1\text{D}}$ is increased. Suppression of plateaus below the ideal quantized values has been observed in previous studies on quantum wires,[5,6,10] and considered theoretically in a number of many-body treatments.[4,7] 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.[21]

Turning now to the noninteger plateaus we see that the feature near $0.7\times 2e^2/h$ in $l=0$ devices becomes slightly more *pronounced* with increasing $n_{1\text{D}}$ (Fig. 1) but the variation in conductance is small. This is in contrast to the plateaulike features seen in the $l=0.5$ μm and $l=2$ μm wire data, which both evolve downward towards $0.5\times 2e^2/h$ with increasing $n_{1\text{D}}$. In the case of the $l=2$ μm wire we note that if the $n=1$ plateau is normalized 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,[8] gate metallized structures,[11] and the 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[12] and other material systems such as GaInAs/InP (Ref. 22) and *n*-PbTe.[23] 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* in Ref. 11 and confirmed in our $l=0$ data (Fig. 1 inset) and $l=0.5$ μm wires (not shown), remains consistent between devices of different design. Some important exceptions do exist, however, as in measurements of narrow wires by Yacoby *et al.*[6] and Tarucha *et al.*[5] there appears to be no *strong* feature present even though clear quantization is seen. The absence of the feature in Ref. 6 may be associated with a large 1D subband spacing made possible in that case due to an 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 polarization mediated through the exchange interaction.[24,25] The possibility of a ferromagnetic instability below a critical electron concentration has also been considered.[26] Despite recent theoretical studies[13–15] it is still unclear why measurements show structure near $0.7\times 2e^2/h$, rather than $0.5\times 2e^2/h$, the value expected for a fully spin-polarized 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 $l=0.5$ μm, 2 μm, and 5 μm (Ref. 10)] leads to a possible scenario in which spin-splitting is only fully resolved in wires above some critical length scale or 1D density. The additional structure we observe in $l=2$ μm devices near $1.7\times 2e^2/h$, and in higher sub-bands below 1 K, also suggest that many-body effects become enhanced in longer 1D regions.[27]

Very recently Thomas *et al.*[16] have reported 1D conductance measurements in double quantum well structures. Their results show that for $l=0.4$ μm devices the feature at $0.7\times 2e^2/h$ evolves to $0.5\times 2e^2/h$ with *decreasing* 1D density indicating that the 0.7 feature may evolve as a function of n_{1D} or potential profile. We note that the devices studied in Ref. 16 may share a similar confining potential with our devices, since strong gate biases are required in both cases to force the conductance feature to evolve downwards to $0.5\times 2e^2/h$.

In conclusion, we have studied ultra low-disorder quantum wires utilizing a GaAs/$Al_xGa_{1-x}As$ 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. Without further investigations on many samples it is not possible to definitively rule out disorder-related backscattering as leading to the length dependent results we observe. In spite of this, our data show a consistent trend with varying length on five different samples and, taken together with the recent results in Ref. 16, indicate that both the length over which interactions occur and the 1D density play an important role in determining the effect of correlation mechanisms upon electrical transport.

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