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LETTER TO THE EDITOR

Unusual conductance collapse in one-dimensional quantum structures

K J Thomas, D L Sawkey, M Pepper, W R Tribe[1], I Farrer, M Y Simmons[2] and D A Ritchie

Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

E-mail: kjt1003@cam.ac.uk and sawkey@mailaps.org

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Abstract

We report an unusual insulating state in one-dimensional quantum wires with a non-uniform confinement potential. The wires consist of a series of closely spaced split gates in high mobility GaAs/AlGaAs heterostructures. At certain combinations of wire widths, the conductance abruptly drops over three orders of magnitude, to zero on a linear scale. Two types of collapse are observed, one occurring in multi-subband wires in zero magnetic field and one in single-subband wires in an in-plane field. The conductance of the wire in the collapse region is thermally activated with an energy of the order of 1 K. At low temperatures, the conductance shows a steep rise beyond a threshold DC source–drain voltage of order 1 mV, indicative of a gap in the density of states. Magnetic depopulation measurements show a decrease in the carrier density with lowering temperature. We discuss these results in the context of many-body effects such as charge density waves and Wigner crystallization in quantum wires.

(Some figures in this article are in colour only in the electronic version)

Electron–electron interactions profoundly modify transport in one dimension. For short range interactions, a 1D system is described as a Luttinger liquid (LL) with gapless excitations [1–3]. In the presence of scattering, the conductance of an LL with repulsive interactions is predicted to vanish in a power-law fashion as temperature $T \to 0$ [4]. For long range interactions at sufficiently low densities a single-subband wire is predicted to form a 1D Wigner crystal [5, 6]. Theoretical studies also point to the existence of a charge density wave order in quantum wires [4, 5, 7]. In the case of multi-subband wires, an inter-subband charge density wave can be stabilized, which can give rise to an insulating state due to inter-subband backscattering,

[1] Present address: TeraView Ltd, Cambridge CB4 0WG, UK.
[2] Present address: School of Physics, The University of New South Wales, Sydney 2052, Australia.

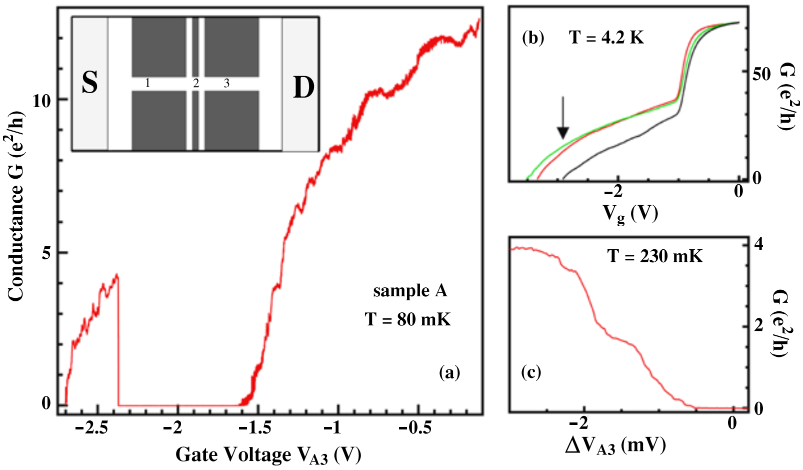

Figure 1. (a) Conductance $G(V_g)$ characteristics of sample A showing the collapse CC1 in the upward sweep of wire A3 whilst wires A1 and A2 are held at -2.91 and 0 V respectively. Inset: a schematic diagram of samples A and B, showing three split gates in series. Dimensions are given in the text. (b) $G(V_g)$ data (not corrected for series resistance) for the long wires showing definition and pinch-off characteristics: a green trace for A1, a red trace for A3 and a black trace for sweeping A1 and A3 simultaneously. (c) Detail of the collapse (abrupt drop in G) in a slow sweep showing plateau at $2e^2/h$ (in the same cooldown, but a different measurement from (a)). The x-axis origin is offset by 2.028 V.

or superconducting instabilities for Cooper scattering [8, 9]. Unlike a Luttinger liquid, such states are expected to be gapped in quantum wires at low temperatures [9].

Observation of interaction effects requires that the length L of the wire be much larger than the thermal coherence length $L_T = \hbar v_F/k_B T$, where v_F is the Fermi velocity. In shorter wires, interactions are renormalized by the non-interacting leads [10–12] and transport is broadly understood within the picture of a non-interacting electron gas, although interaction effects such as the 0.7 structure [13], enhanced g-factors [13, 14] and the high field 0.7 analogue structures [15] are still present. Fabricating clean, long 1D wires is a technological challenge [16, 17]. However, in the presence of interactions, disorder and backscattering play an important role [4, 18, 19]. Power-law behaviour in temperature and voltage, expected for a dirty Luttinger liquid, has been measured in carbon nanotubes [20] and in GaAs wires [16].

We have fabricated a long quantum wire system formed by the series addition of two or three closely spaced shorter wires defined in high mobility two-dimensional electron gases (2DEG), allowing the controlled modulation of the confining potential. By varying the widths of the wires independently, we observe a collapse in the conductance of greater than three orders of magnitude. DC bias measurements show that a gap is present in the density of states. Perpendicular magnetic field measurements show a reduction in carrier concentration as the temperature is lowered. In a parallel field the collapse is enhanced. Although there are differences, such behaviour resembles theoretical predictions of a 1D Wigner crystal [5, 6] and charge density wave order [4, 5, 7].

We present results observed for three samples. Samples A and B consist of three split gates in series, defined in a single GaAs/AlGaAs quantum well. The 2DEG formed 300 nm below the surface has a mobility $\mu = 3.4 \times 10^6$ cm^2 V^{-1} s^{-1} and density $n = 2.4 \times 10^{11}$ cm^{-2} at 1.5 K. Figure 1(a) inset shows a schematic diagram of samples A and B, which have a short wire of lithographic length $L = 0.4$ μm between two long wires of $L = 3$ μm. All wires have a width $W = 1.2\ \mu$m and the separation between adjacent wires is $S = 0.4\ \mu$m. When the gates are negatively biased, the projected dimensions of the wires in the 2DEG change due to electrostatic depletion; L increases and W and S decrease, resulting in an inhomogeneous quantum wire system longer than 7.2 μm. The results reported here do not qualitatively differ even when the central short wire is left grounded. The inhomogeneity of the potential at the junction between the long wires acts as a scattering centre or pinning source. The role of the central short wire is to modulate the potential at this region.

Sample C is defined in a single heterojunction with the 2DEG 100 nm below the surface, with $\mu = 3.6 \times 10^6$ cm^2 V^{-1} s^{-1} and $n = 3.3 \times 10^{11}$ cm^{-2} after brief illumination with a red LED. The sample (figure 4 inset) consists of a long wire of $L = 2\ \mu$m and $W = 0.8\ \mu$m between two short wires of $L = 0.3\ \mu$m and $W = 0.4\ \mu$m. The separation between the wires is 0.25 μm. Only the long wire and one of the short wires need to be defined to see the effects reported here. For all the samples, the inter-wire spacing is less than the width of the wires, implying that there is no 2DEG between the wires when defined. Standard two-terminal conductance measurements are made with the sample attached to the mixing chamber of a dilution refrigerator. The excitation voltage is $\leqslant 10\ \mu$V at a frequency of 31 Hz. The data presented here are corrected for a series resistance of 1 kΩ, unless otherwise mentioned.

Two types of conductance collapse are observed, both occurring as the width of one of the wires is swept while the others are held constant. Type 1 conductance collapses (CC1) occur in zero magnetic field and show a hysteresis in gate voltage, and type 2 (CC2) occurs only in the presence of a parallel magnetic field, but is reproducible in both directions of gate sweep.

Figure 1(a) shows a typical example of CC1 at 0.1 K, where wire 1 of sample A (A1) was fixed at −2.91 V corresponding to several occupied 1D subbands, and G is measured as a function of V_{A3}. Figure 1(b) shows the $G(V_g)$ characteristics of the two wires A1 and A3, measured independently as well as in series. The arrow indicates the voltage (−2.91 V) at which wire A1 is fixed for the measurement in figure 1(a). When A1 is biased at this voltage, the series combination of A1 and A3 together exhibits pinch-off at $V_{A3} = -2.7$ V, as shown in figure 1(a). As V_{A3} was swept towards 0 V, the two-terminal conductance $G \equiv \mathrm{d}I/\mathrm{d}V$ rose to a value close to $4e^2/h$ and abruptly collapsed to zero (within the measurement noise level) at $V_{A3} = -2.37$ V. The drop in the conductance is of more than three orders of magnitude. On continuing the voltage sweep, the conductance increases gradually from zero for $V_{A3} > -1.65$ V. In a slow sweep of V_{A3} (different measurement), shown as figure 1(c), the collapse edge shows a plateau at $2e^2/h$. At low temperatures, the zero-conductance state is stable and lasts for several days until the experiment is terminated. At higher temperatures, the conductance drops to a value above zero, but the drop is still abrupt. No such collapse has been observed in a single wire.

To highlight the reproducibility of CC1 in the up sweeps and the absence of it in the down sweeps, we show in figure 2(a) five sets of measurements taken under the same conditions. Here V_{A3} is fixed at −2.8 V and V_{A1} is swept. The conductance collapse is only observed in the up sweeps (solid curves) for $-2.5\ \mathrm{V} < V_{A1} < -1.7$ V, whereas the conductance for the down sweeps (dashed curves) remains finite, close to $3e^2/h$, for the same range of V_{A1}. The large hysteresis in the characteristics of the up and down voltage sweeps is a feature of CC1. We note that for either direction of sweep, the characteristics to the left of the collapse ($V_{A1} < -2.2$ V) in figure 2(a) are not exactly reproduced in all the traces, but to the right of the collapse ($V_{A1} > -1.7$ V) they are nearly identical. A change in pinch-off voltage accompanies a change in collapse voltage for different sweeps. Traces with a more negative pinch-off voltage have a conductance collapse at a less negative voltage and from a higher conductance value. With gate voltages fixed in the collapse region for sample B, figure 2(b) shows the reproducibility of a typical collapse state in several temperature cycles between 0.2 and 1 K.

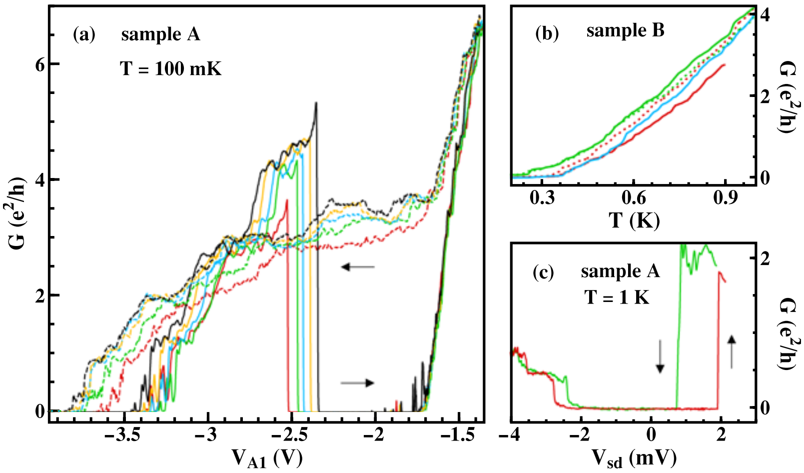

Figure 2. Five sets of up (solid curve) and down (dashed curve) sweeps showing the reproducibility of collapse CC1 in the up sweeps of $G(V_g)$. There is no collapse in the down sweeps. Wire A1 is swept whilst A3 is held constant (−2.8 V) in contrast to the case in figure 1(a). The arrows indicate the direction of sweep. For a more negative pinch-off voltage, the collapse is triggered at a less negative gate voltage and from a higher G. (b) $G(T)$ for sample B in the collapse region (with fixed gate voltages), uncorrected for series resistance, showing reproducibility in temperature sweeps. Each colour represents a temperature cycle; solid and dotted lines are for cooling and heating, respectively. (c) DC bias measurements showing hysteresis and a gap in subsequent sweeps in sample A with $V_{A1} = -1.87$ V, $V_{A2} = 0$ V and $V_{A3} = -3$ V.

Figure 2(c) shows the DC source–drain bias $G(V_{sd})$ measurements taken in the collapse region for sample A at 1 K. At $V_{sd} = 0$, the collapse state was stable at $G = 0$ for $T < 1.4$ K. As $|V_{sd}|$ increases, we observe a sudden jump in the conductance from zero to a nearly constant value, indicative of a gap in the density of states or depinning. The gap shows hysteresis and a jump to a different G value for + and $-V_{sd}$. The gap, 3–5 mV, is much greater than both the highest temperature at which any collapse is observed and the activation temperature of 5.5 K measured in this cooldown.

Transverse magnetic field measurements show that the collapse is accompanied by a reduction in the 1D carrier density with decreasing temperature. The effect of a transverse magnetic field B_z on 1D wires is to increase the energy spacing of the 1D subbands and cause them to pass progressively through the Fermi energy [21]. The energies of the magnetoelectric 1D levels are determined by the confinement provided by the gate voltages and the magnetic field. At a constant gate voltage, as in our case, magnetic depopulation causes G to decrease as $|B_z|$ is increased, with plateaus of quantized conductance appearing as the energy levels are forced through the Fermi energy. When the cyclotron diameter is greater than the wire width the levels are hybrid magnetoelectric levels, and when the cyclotron diameter is much less than the width the 1D subbands are equivalent to 2D Landau levels [21]. From the filling factor ν of Landau levels, the electron density $N_{2D} = \nu(eB_z/h)$ can be extracted. Figure 3(a) shows the magnetoconductance $G(B_z)$ at various temperatures for sample A in the collapse region with fixed gate voltages on each of the three wires. As T decreases, G at $B_z = 0$ decreases and there is a decrease in the magnetic field required to depopulate a particular subband. For example, at 4.2 K the $2e^2/h$ conductance plateau occurs at $B_z = 2$ T, but at 0.4 K the plateau shifts to 1 T, corresponding to a 50% reduction in the (2D) carrier concentration, or an equivalent drop in the Fermi energy, shown in figure 3(b).

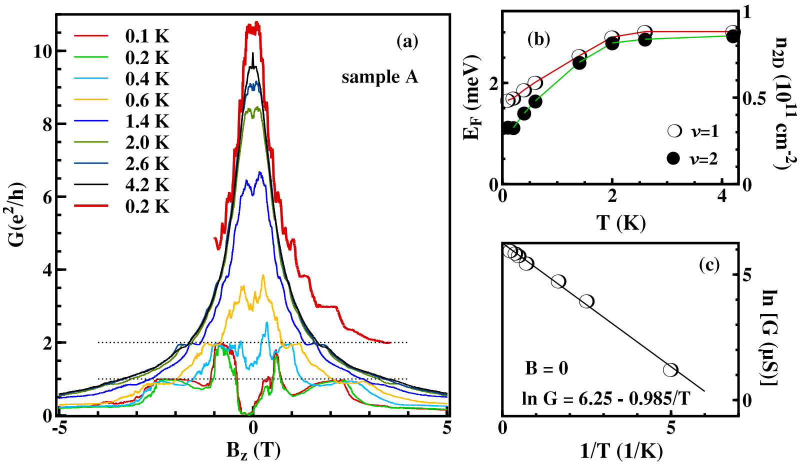

Figure 3. (a) The magnetoconductance $G(B_z)$ at various temperatures in the collapse region, at fixed gate voltages $V_{A1} = -1.55$ V, $V_{A2} = -1.66$ V and $V_{A3} = -2.7$ V taken in a different cooldown from figures 1 and 2. The thick red trace, offset vertically by e^2/h, is taken just outside the collapse (by sweeping A2 to 0 V) at 0.2 K, and shows agreement with the trace at 4.2 K in the collapse region. This indicates that the carrier density is restored on heating in the collapse regime. There is a slight asymmetry with $\pm B_z$ in the characteristics at low temperatures, and at 4.2 K a sharp peak occurs reproducibly at zero field. The data are uncorrected for series resistance. (b) The carrier density measured from the B_z positions of the filling factors $\nu = 1$ (open circles) and $\nu = 2$ (closed circles) from (a). (c) An Arrhenius plot of G at $B_z = 0$ from (a).

Starting from the collapse region, a perpendicular field of 200 mT is sufficient to restore conductance. For $T < 0.2$ K, the conductance first rises to a value close to $2e^2/h$ with increasing $|B_z|$. The thick red trace in figure 3(a) shows $G(B_z)$ measured at 0.2 K but outside the collapse region. The depopulation trace is almost identical with that measured in the collapse region at 4.2 K (black trace), indicating that the carrier density is restored on heating and showing that the drop in carrier concentration is a property solely of the long wire structure formed from the two in series. Figure 3(c) shows an Arrhenius plot of $G(B_z = 0)$ from figure 3(a), with an activation temperature of 1 K.

The second type of collapse, CC2, observed in the presence of an in-plane magnetic field, is reproducible in both directions of gate voltage sweep. Figure 4 shows five $G(V_{C1})$ traces in sample C at various in-plane magnetic fields, $B_\parallel$, applied parallel to the wires. The misalignment of the field was less than 1° out of the 2DEG plane. For this measurement V_{C2} is such that $G_{C2} = 2e^2/h$ at $B_\parallel = 0$. Strong fluctuations are present in the traces. As $B_\parallel$ increases, a small valley at $B_\parallel = 5.2$ T marked by an arrow drops to zero conductance at $B_\parallel = 12.6$ T, and the width of the collapse region increases. At $B_\parallel = 15.6$ T, the valley expands and a new region of collapse is seen at $V_{C1} \sim -0.23$ V. The conductance drop is typically e^2/h and the gate voltage width of the collapse was within $k_B T$ broadening of zero. The collapse was continuously reproduced in both sweep directions over 100 times with no appreciable change in the traces. Shifting the short wire C1 laterally has no appreciable effect. Collapse type CC1 was also observed in this sample, but reproducibility was low. It is unknown whether the reproducibility of CC2 in the up and down sweeps, in contrast to that of CC1, is associated with the lifting of the spin degeneracy of the electrons.

Traces of CC2 at different temperatures at 12.6 T are shown in figure 5. At 0.12 K the collapse is well defined, and outside the collapse region the conductance is suppressed to e^2/h. At 1.2 K strong fluctuations set in, the collapse is removed, and there is no spin-split

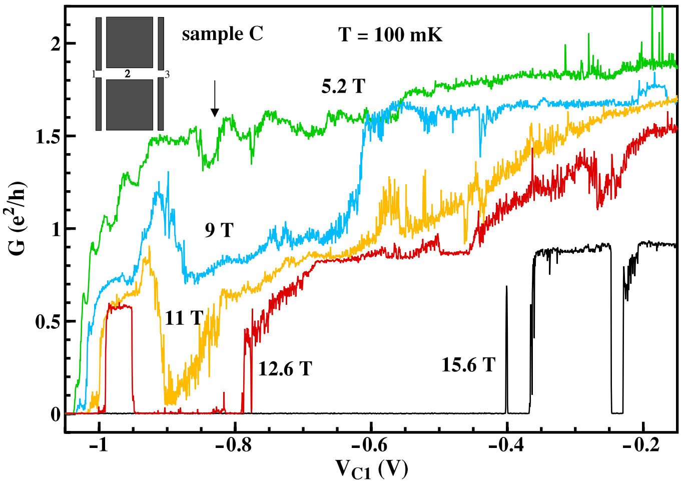

Figure 4. G at $T = 100$ mK for sample C as a function of V_{C1} at different in-plane magnetic fields, and a fixed voltage on wire C2 such that $G \approx 2e^2/h$ at $B = 0$, $V_{C1} = 0$. The conductance collapse is triggered at the region marked by the arrow. At $B_{\parallel} = 5.2$ T (green trace) there is no spin-split plateau. As $B_{\parallel}$ increases, the valley at the arrow descends to $G = 0$. The valley expands to a wider range of V_{C1} at 15.6 T, and new regions of collapse appear, for example at $V_{C1} \sim -0.23$ V. A clear spin-split plateau close to e^2/h can be observed at 12.6 T at -0.7 V $< V_{C1} < -0.45$ V. Inset: a schematic diagram of sample C (see the text for dimensions).

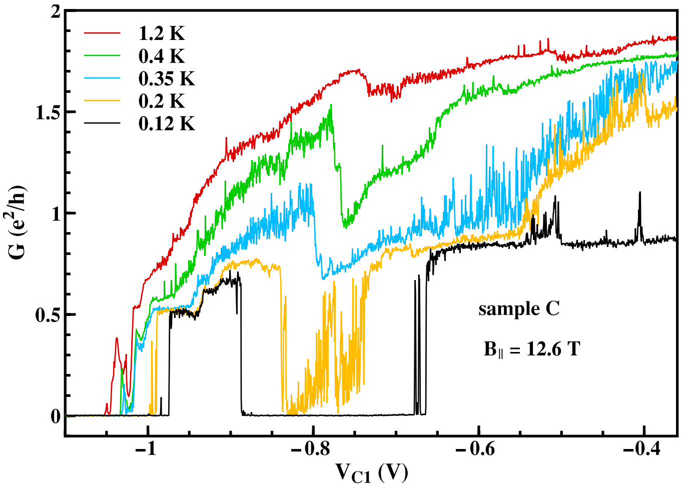

Figure 5. The temperature dependence at 12.6 T of the conductance collapse CC2. There is a small drift in the characteristics at 0.12 K from figure 4. The collapse is absent at 0.2 K, and at 0.35 K the spin-split plateau disappears and G rises showing strong fluctuations. At 1.2 K, G rises by e^2/h outside the collapse region and $1.7(e^2/h)$ in the collapse region.

plateau at e^2/h. The disappearance of the spin-split plateau and the associated rise in G at high temperatures resemble our previous observations on the 0.7 structure [22].

Various mechanisms can be responsible for small drops in conductance. Resonances, resulting from defects, impurities or modifications of the exit regions; universal conductance fluctuations [23]; and for double constrictions, anti-resonances due to mode matching [24] are possible. These mechanisms, however, cannot explain collapses of the magnitude observed here, nor the hysteresis and temperature dependences. Localization of carriers by disorder is inconsistent with figure 2(c). No anomalies were reported in previous studies of short wires in series [25, 26].

Theories exist which predict the existence of an insulating state in 1D wires. In the presence of any scattering the conductance of a Luttinger liquid is expected to vanish as a power law in temperature and voltage. The observed $G - V_{\mathrm{sd}}$ behaviour (figure 2(c)) is inconsistent with such a mechanism. An insulating state may result from the pinning of a Wigner crystal or a charge density wave by a barrier potential. The $G - V_{\mathrm{sd}}$ relation and thermally activated behaviour support such mechanisms [5]. Our 2D density immediately before the collapse is 3×10^{10} cm^{-2}. For a width of 0.3 μm, equal to the cyclotron diameter at 0.2 T, where the collapse is removed in figure 3(a), we estimate $n_{1\mathrm{D}} \approx 1 \times 10^6$ cm^{-1} or $n_{1\mathrm{D}} a_{\mathrm{B}} \sim 1$, a_{B} being the Bohr radius. At such low densities a 1D Wigner crystal [5, 6] in single-subband wires is expected, and may show a pinning energy greater than the thermal activation energy, as we observe. A trapped superconducting state [27] also cannot be excluded. For multiple subbands, an inter-subband charge density wave [9] could open a gap at the Fermi level due to inter-subband backscattering, leading to an insulating state. However, the drop in Fermi energy with temperature further suggests the formation of a state below the 1D subbands as $T \to 0$. We also note the suppression of the collapse with a small perpendicular field, which suggests that the interaction between $+k$ and $-k$ electrons is important.

In summary we have observed an unusual collapse in the conductance of serially connected 1D quantum wires. Two types of collapse are observed, both of which have the defining feature of zero conductance in a gate voltage region where a finite conductance is expected. The mechanism is unknown but may result from an inter-subband charge density wave or a 1D Wigner crystallization. Further experimental and theoretical work is necessary to understand the phenomenon.

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