Disorder and Interaction Effects in Quantum Wires
L. W. Smith\textsuperscript{1}, K. J. Thomas\textsuperscript{2,*}, M. Pepper\textsuperscript{3}, D. A. Ritchie\textsuperscript{1}, I. Farrer\textsuperscript{1}, J. P. Griffiths\textsuperscript{1}, G. A. C. Jones\textsuperscript{1}

\textsuperscript{1}Cavendish Laboratory, University of Cambridge, J J Thomson Avenue, Cambridge, CB3 OHE, UK
\textsuperscript{2}Dept. of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon 440-746, South Korea
\textsuperscript{3}Dept. of Electronic and Electrical Engineering, University College London, London, WC1E 7JE, UK

Abstract

We present conductance measurements of quasi-one-dimensional quantum wires affected by random disorder in a GaAs/AlGaAs heterostructure. In addition to quantised conductance plateaux, we observe structure superimposed on the conductance characteristics when the channel is wide and the density is low. Magnetic field and temperature are varied to characterize the conductance features which depend on the lateral position of the 1D channel formed in a split-gate device. Our results suggest that there is enhanced backscattering in the wide channel limit, which gives rise to quantum interference effects. When the wires are free of disorder and wide, the confinement is weak so that the mutual repulsion of the electrons forces a single row to split into two. The relationship of this topological change to the disorder in the system will be discussed.

Introduction

Quantised conductance is the most important hallmark of a clean one-dimensional (1D) electron system [1, 2]. Deviations from perfect quantization at $G = N \left(\frac{2e^2}{h}\right)T$, where $N$ is the number of transmitting modes and $T$ the transmission coefficient, can occur due to several reasons [3], the most common being scattering from disorder potentials, or imperfections in the devices resulting in $T < 1$. In split-gate devices [4], it is possible to re-establish well quantised plateaux by applying an offset voltage between the two arms of the device which laterally shifts the 1D channel away from a disorder dominated area. This technique was first shown in narrow Silicon channels [5], and Ref. [6] provides an analysis of the change in scattering as the channel is shifted. In practice, by laterally shifting the channel it is possible to check for the existence of localized impurity potentials which may give rise to spurious effects on the sample resistance. Early work on 1D channels showed that the location of a particular scattering centre affected quantised levels in a manner which depended on the parity of the quantised wavefunction [7].

In addition to deviations in the value of conductance plateaux, there can be resonance structures superimposed on the conductance trace. Close to pinch-off there could be periodic conductance oscillations due to tunnelling through a quantum dot which is unintentionally formed by an impurity potential [8]. There can also be interference effects due to electrons being backscattered by potential fluctuations. By shifting the channel sideways, the potential landscape changes, which results in a changing location of structure on the conductance trace. Applying a small perpendicular magnetic field reduces backscattering significantly, and clean characteristics can be reinstated. By increasing temperature, the resonance structures are averaged out. If the resonance is due to imperfections in the device geometry or due to static impurities, moving the channel sideways may not result in clean characteristics and the resonances will be reproducible for each cool down. This cannot be asserted for resonances due to overall potential fluctuations in the crystal, as a second cool down may change the potential landscape and the screening from the local carrier density. Thus by varying the magnetic field, temperature and spatial location of the 1D channel, combined with thermal cycling of the device, it is possible to get an overall knowledge of the origin of the various structures in a conductance measurement.
A difficulty with all these measurements is that there could be electron-electron interaction effects which give rise to deviations in the conductance. In the Luttinger liquid picture, there are disorder-induced deviations in conductance quantization, which has a power-law dependence on temperature and voltage [9, 10]. The most significant interaction effect in 1D ballistic quantum wires is the spin-related structure close to 0.7×(2e²/h), which has a distinctly different origin to that of a resonance structure. This 0.7 structure does not disappear as the channel is moved sideways, and strengthens as temperature increases (instead of thermally averaging like the disorder-related effects). The 0.7 structure occurs reproducibly in almost all ballistic 1D devices [11]. There are studies on the 0.7 structure relating it to a Kondo effect due to a quasibound state which may form in the 1D wire [12, 13, 14]. However, there are inconsistencies in this argument brought out by later work [15, 16]; for example, Sfigakis et al. [17] have specifically shown that locating a barrier at the exit regions of the 1D channel assists in the creation of a bound state and a resonance structure at 0.5(2e²/h). This structure possesses all the characteristics discussed above for a resonant structure, and shows a Kondo effect with decreasing temperature which appears additive to the 0.7.

In general, it is important to minimize the effects due to disorder in order to investigate pure electron-electron interaction effects. One of the most striking manifestations of the electron interactions is the predicted splitting of a single row of electrons into a double row in order to reduce the mutual repulsion of neighbouring electrons [18, 19]. We have recently shown that gradually reducing the lateral potential which confines the electrons in a 1D wire [20, 21] results in observation of this lateral rearrangement of electrons. In order to obtain an unambiguous identification of this effect we have taken extreme care in checking through several devices before commencing a detailed study on the row formation. This is necessary, because the formation of a double row as a ground state results in a jump from zero conductance to 4e²/h, and such behaviour can also be observed if, for example, there is a single potential spike at the centre of the channel, which unintentionally divides the wire into two halves. This was shown by fabricating split-gate devices with an additional ‘dot gate’ in the centre of the channel, by Smith et al. [22, 23].

In this paper, we investigate the potential landscape of a wide (1 µm) quantum wire, where resonances are superimposed on the conductance characteristics and change their pattern as a function of the channel position. It was found that a small perpendicular magnetic field was sufficient to remove the various structures, and increasing the temperature averages them out. The resonances disappear as the channel is moved to one side and not the other, which indicates that the origin is a disorder potential at one edge of the channel. The pattern was reproduced more or less exactly with different cool downs, indicating that the cause is a static impurity or charged defect. The current study highlights how important it is to fully characterise the devices before conclusions can be drawn about interaction effects.

Sample and Method

Our sample was fabricated from a modulation-doped GaAs/AlGaAs heterostructure. A two-dimensional electron gas (2DEG) was formed 300 nm below the surface of the wafer. The carrier density and mobility of the 2DEG, measured during the second cool down of the device are 1.5 × 10¹⁵ cm⁻² and 1.3 × 10² V⁻¹ s⁻¹, respectively. Split-gate devices with a top gate were patterned using electron-beam lithography. The top gate was 1 µm wide, and was separated from the split gates by a 200 nm layer of cross-linked polymethylmethacrylate (PMMA) [24]. The split gates were 0.4 µm long and 1 µm wide, and a schematic diagram of the device is shown in Fig. 1.
In order to study the reproducibility of conductance features, data are presented from three different cool downs of the same device. For the measurements presented in Fig. 3, the magnetic field was oriented perpendicular to the 2DEG. For another cool down (Fig. 4), the magnetic field was oriented in the plane of the 2DEG, parallel to the 1D channel. Two-terminal measurements were performed using a dilution refrigerator with a sample base temperature of 50 mK, with a 77 Hz excitation voltage of 5 µV. The device is typically operated by applying a fixed negative voltage to the split gates \((V_{sg})\), and sweeping the voltage applied to the top gate \((V_{tg})\). Thus, \(V_{sg}\) defines the 1D channel, and primarily controls the strength of the confining potential in the transverse direction. With the 1D channel defined, the density in the channel is then varied using \(V_{tg}\) [25].

Figure 1 above: Schematic diagram of the device. Three stages of e-beam lithography were required. Firstly, split gates were patterned and metalized. Following this, a 200 nm layer of PMMA was deposited, and cross-linked using the electron beam [24]. Lastly, a top gate was patterned and metalized.

Results and Discussion

In Fig. 2(a), the conductance is measured as a function of \(V_{tg}\) at different fixed \(V_{sg}\) with the offset applied to the two arms of the split gate \(\Delta V_{sg} = 0\). Between traces, \(V_{sg}\) is stepped by 50 mV, from -0.6 V on the left to -3.55 V on the right. As \(V_{sg}\) is made more negative, the electrostatic potential confining the 1D channel becomes steeper and the channel becomes narrower. Therefore, following the conductance traces from left-to-right is equivalent to moving from a weakly-confined, wider, regime to a more strongly-confined regime. The first three quantized plateaus can be clearly observed to the right of the figure in the strong-confinement regime (more negative \(V_{sg}\)). In addition to the plateaux, several trails of resonance structures can be seen, emanating from the left-hand side of the figure (weak-confinement regime), which move diagonally across to higher conductance. The resonances in general are weaker at the plateau region and stronger midway between plateaux, and appear to “form” plateaux themselves coincident with the original plateaux.

In (b), an offset \(\Delta V_{sg} = 0.5\) V is applied, which laterally shifts the 1D channel in one direction. \(V_{sg}\) is stepped from -0.6, -1.1 V on the left-hand side of the plot, to -3.3, -3.8 V on the right-hand side (voltages on both arms of the split gate are given). In this case, all features are qualitatively present as in (a), but are shifted to the right-hand side of the figure. In (c), the channel is shifted in the opposite direction
where $\Delta V_{sg} = -0.5 \text{ V}$; $V_{sg}$ is stepped from -1.1, -0.6 V on the left to -3.8, -3.3 V on the right. The channel is shifted further in the same direction in (d), where $\Delta V_{sg} = -1 \text{ V}$ is applied, and $V_{sg}$ is stepped from -1.6, -0.6 V on the left of the plot to -4, -3 V on the right.

In Figs. 2(c) and (d), it is clear that the strength of the resonances are diminishing, indicating that the channel is moving away from a disorder dominated landscape. A large offset of -1 V has produced cleaner conductance characteristics in (d); however, this has also weakened the conductance plateaux, possibly due to the decreased 1D subband spacings.

![FIGURE 3 left: COOL DOWN 2 - Conductance characteristics as a function of $V_{tg}$ and $V_{sg}$ at a fixed perpendicular magnetic field, $\Delta V_{sg} = 0$. (a) $B_{\perp} = 0$; $V_{sg}$ is stepped from -0.6 V on the left to -3.61 V on the right, in intervals of 35 mV. (b) $B_{\perp} = 0.4 \text{ T}$; $V_{sg}$ is stepped from -0.6 V on the left to -3.48 V on the right, in intervals of 30 mV, and (c) $B_{\perp} = 0.8 \text{ T}$; $V_{sg}$ is stepped from -0.6 V on the left to -3.54 V on the right, in intervals of 35 mV.](image)

Figures 3(a) to (c) show conductance data from a second cool down of the same device, where $\Delta V_{sg} = 0$. In (a), $V_{sg}$ is stepped from -0.6 V on the left to -3.61 V on the right. In this cool down, the trails of resonance features are more or less reproduced. In (b), a perpendicular magnetic field ($B_{\perp}$) of 0.4 T is applied, and $V_{sg}$ is stepped from -0.6 V to -3.48 V (left-to-right). The resonance features are suppressed quite remarkably, and the additional confinement from the magnetic field has enhanced the quality of the plateaux, particularly in the weak-confinement regime (left-hand side). It is noteworthy that the one trail of resonances which remains in (b) forms a plateau at $0.7(2e^2/h)$.

Scattering by an impurity potential is reduced by the edge states which are established in a perpendicular field. At $B_{\perp} = 0.8 \text{ T}$ [Fig. 3(c)] the plateaux show features related to the quantum Hall effect, and almost all of the resonances have disappeared. Spin splitting is weakly discernible on several traces on the left-hand side, where the confinement is weaker and the 1D subband spacings are smaller. The 0.7 structure prevails throughout the different confinement regimes, in addition a plateau appears at $e^2/h$ in Fig. 3(c), in the weak-confinement regime.

![FIGURE 4: COOL DOWN 3 - Conductance characteristics from a third cool down, in which the magnetic field is applied in the plane of the 2DEG, parallel to the 1D channel. Offset $\Delta V_{sg} = 0$. In (a), $B = 0 \text{ T}$, and $V_{tg}$ is stepped from -0.6 V on the left to -4.08 V on the right, in 60 mV intervals. In (b), $B = 7 \text{ T}$, and $V_{tg}$ is stepped from -0.6 V on the left to -4.04 V on the right, also in 60 mV intervals.](image)

Figure 4 shows data from a third cool down of the same device. At $B = 0$, the resonance trails are present with a slightly different pattern to Figs. 2(a) and 3(a). In addition to the trails, the disappearance of the first plateau (at $2e^2/h$), and a direct jump of $4e^2/h$ can be observed at $V_{tg} = -0.9 \text{ V}$, although this is less clear than...
when the conductance characteristics are clean. The jump to $4e^2/h$ marks the formation of a double row of electrons, discussed in our previous work [21]. However, without a full knowledge of the pattern of resonances that are superimposed on the conductance traces, it is difficult to attribute the disappearance of the first quantised plateau to double-row formation. At an applied in-plane magnetic field $B = 7$ T [Fig. 4(b)], the resonance trails are present though slightly suppressed, perhaps related to reduced transmission due to the shrinkage of the wavefunction from a magnetic field parallel to the channel axis. Spin splitting is hardly discernible, except in a small range of gate voltages from $V_{tg} = -0.9$ V to $-1.5$ V where there is structure at $e^2/h$. This cannot be a trail of resonance as such a trail was absent in zero field [Fig. 4(a)]. If it were a spin-split plateau, this is an indication of an absence of row formation in an in-plane magnetic field, due to disorder. All higher resonant trails are mostly unaffected, unlike the perpendicular-field case [shown in Figs. 3(b) and 3(c)]. In general it seems that the existence of the disorder is obscuring the observation of the double-row ground state.

Figure 5 shows a conductance measurement at $T = 1$ K and $\Delta V_{sg} = 0$, from the first cool down. As expected, there is an overall thermal averaging of the conductance features at this elevated temperature, and the resonant features are suppressed. A weak first plateau is visible at higher confinement strengths, along with the 0.7 structure. It is surprising that the resonance structures are stronger at higher conductance, and that those which disappear first are towards the strong-confinement regime. Generally it is expected that the structures at stronger confinement prevail with increasing temperature. The contrary nature of the data suggests that the features discussed in this paper are not due to resonant transmission of quasi-bound states in the channel, but rather are interference phenomena due to backscattering of electrons in the wide channel limit. As the channels narrows, backscattering is suppressed due to the rigid one-dimensionality. In a perpendicular magnetic field, the opposite is the case [Figs. 3(b) and 3(c)]: the resonance trails on the left-hand-side (weak confinement regime) disappear first as the edge states are further apart than in the strong-confinement regime, where there can be scattering between edge states.

Data from this same device are presented in Ref. [21], for which an offset of $-2$ V was applied to the split gate, further shifting the 1D channel. This lateral shift resulted in clean conductance characteristics across the whole confinement regime, and we conducted a detailed study on the formation of a coupled row of electrons which formed in the weak-confinement regime. Our results were confirmed by additional measurements using a similar, but disorder-free device, with no offset applied between the arms of the device [26].

**FIGURE 5: COOL DOWN 1** – These are the only results above 50mK. Conductance characteristics at $T = 1$ K, for $\Delta V_{sg} = 0$. $V_{tg}$ is swept for fixed $V_{sg}$, and $V_{tg}$ is stepped between traces from $-0.6$ V on the left to $-3.3$ V on the right. These data were obtained 8 days after the data presented in Fig. 2, therefore there is a slight drift in pinch-off characteristics, and the resonances do not occur at exactly the same gate voltages.

**Conclusion**

In conclusion, we have shown that a potential fluctuation within or near the path of a 1D channel gives rise to resonant reflections, manifested by a trail of resonances in the conductance. Moving the channel sideways by applying an offset voltage to shifted further from the impurity potential. This progressively removes the disorder and produces clean conductance characteristics. A clear observation of interaction effects leading to the formation of a double-row ground state is reduced by the presence of the disorder.
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*Email address: kalarikad@skku.edu

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