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LETTER TO THE EDITOR

Ballistic transport in one dimension: additional quantisation produced by an electric field

N K Patel†, L Martin-Moreno†, M Pepper†, R Newbury†, J E F Frost†, D A Ritchie†, G A C Jones†, J T M B Janssen‡, J Singleton‡ and J A A J Perenboom‡

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

‡ High Field Magnet Laboratory, University of Nijmegen, Toernooiveld, Nijmegen, The Netherlands

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Abstract. Experimental evidence is presented for the appearance of new plateaux in the differential conductance of a ballistic 1D channel in the high DC bias regime. In zero magnetic field, we observe steps in the differential conduction of e^2/h, as opposed to the conventional value of $2e^2/h$ for a spin-degenerate 1D subband. The new plateaux are found to be at quantised values to an accuracy of a few per cent and are described well by a model that assumes the bias is dropped symmetrically in the 1D channel. In addition, all the plateaux disappear with increasing DC voltage bias which can be explained in terms of an enhancement of the tunnelling probability. The same effects persist in a transverse magnetic field and we are able to calculate subband spacings as a function of the applied magnetic field.

Following the work of Thornton *et al* (1986) the electrostatic squeezing of a two-dimensional electron gas (2DEG) has been extensively studied in the GaAs/AlGaAs system, with lithographically defined Schottky metal gates. This process has been aided by the development of high electron mobility heterojunctions and nanoscale lithography making the ballistic regime accessible in these experiments. This has lead to the observation of quantised plateaux in conductance by Wharam *et al* (1988) and van Wees *et al* (1988). The early measurements were in the low bias regime to avoid electron heating and in more recent work (Brown *et al* 1989a, Kouwenhoven *et al* 1989) the high voltage bias response of this system has been studied where electrons are injected into the one dimensional channel giving rise to non-linear conduction. At present the theoretical predictions for this regime (Glazman and Khaetskii 1989, Castano and Kirczenow 1990) are contradictory with regards to the appearance of new plateaux. Here we present detailed results on the onset of non-linear response which agrees well with the model proposed by Glazman for the adiabatic regime.

The split gate devices used in this work were defined using standard lithographic techniques on a MBE grown GaAs/AlGaAs heterostructure of mobility $\mu > 1 \times 10^6\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ and carrier density of $3 \times 10^{11}\,\mathrm{cm^{-2}}$ after illumination. These values indicate an elastic scattering length in excess of $10\,\mu$m and a Fermi energy of 10 meV. The lithographically defined dimensions of the split gates were $0.3\,\mu$m by

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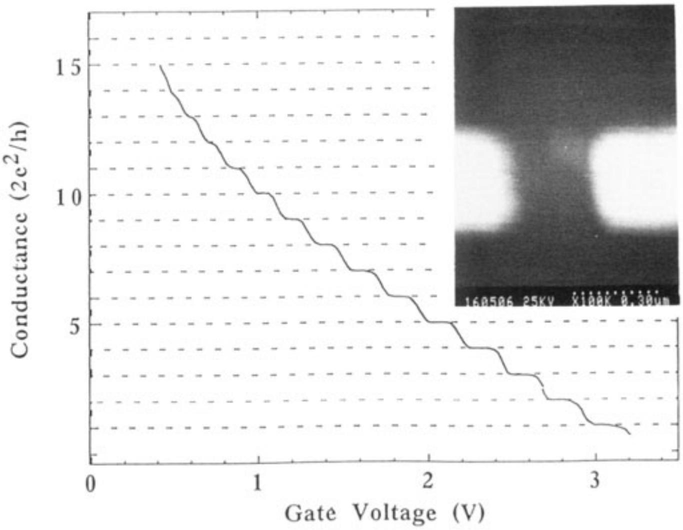

Figure 1. A plot of the conductance of the device as a function of the applied gate voltage in units of the quantised conductance at zero DC voltage bias. 15 quantised plateaux can be seen in the gate voltage sweep. The inset shows an SEM photograph of one of the devices used in this work.

0.3 μm, confirmed from SEM photographs of the split gate see inset to figure 1, which were taken after all the measurements had been performed. Four-terminal constant-current measurements of the resistance and two terminal constant voltage measurements of the conductance were used throughout. Standard lock-in techniques were utilised for all the measurements. All the samples studied showed well quantised plateaux in resistance and conductance, for a zero applied magnetic field, with up to 15 plateaux observed in the best samples. Both current biasing and voltage biasing of the split gate were conducted. Current biasing was achieved by applying a constant DC current through the sample upon which a small AC current was superimposed in order to measure the differential resistance, as a function of the applied gate voltage. Voltage biasing was achieved by adding a constant voltage to a small oscillating voltage. All measurements included were taken on a dilution refrigerator at temperatures down to 30 mK.

Figure 1 illustrates the conductance of a device as a function of the gate voltage with a low value of source–drain voltage. With increasing DC bias extra plateaux are observed in the gate voltage differential conductance characteristics of the 1D channel, as shown in figure 2. These are sample independent being found with all the devices studied. The new plateaux are half way between the normal plateaux to within an accuracy of a few per cent. The differential conductance data, at constant voltage, shows this effect clearly with the new plateaux observed down to index $n = 9$. The index n takes integer values for the normal plateaux seen at zero bias and half-integer values for the new plateaux where the conductance is defined by

$$G = (2e^2/h)n. \tag{1}$$

For the constant-current measurements the DC voltage bias is a function of the sample resistance which increases with gate voltage. This means, as the gate voltage is increased and the channel narrowed, the bias voltage across the split gate increases and we see a

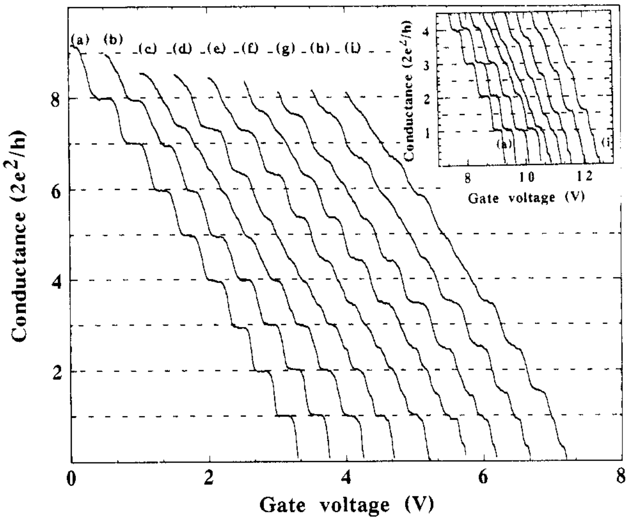

Figure 2. A plot showing the differential conductance, in quantised unit of conductance, as a function of the gate voltage for different fixed values of DC voltage bias. Successive graphs are offset horizontally by 0.2 V for clarity and increase in DC bias from 0 mV, graph (*a*) to 4 mV, graph (*i*) in intervals of 0.5 mV. Measurements were carried out at 0.5 T and 30 mK. Inset shows the same data for zero magnetic field again successive graphs are offset horizontally and the bias increases from 0 mV for graph (*a*) to 4 mV for graph (*i*).

transition from linear to non-linear conduction. The constant voltage measurements however provide a constant voltage across the split gate independent of the gate voltage, hence this is easier to analyse. All the subsequent data is shown in terms of conductance with constant source–drain voltage.

The new plateaux begin to appear at bias voltages of 1.5 mV, but calculations by Kelly (1989) and Lent *et al* (1989) suggest that this could not be due to changes in the transmission coefficient at such low biases. We will use the adiabatic model to account for the half plateaux observed. This model assumes that the confining potentials change smoothly enough along the channel for inter-subband scattering to be negligible. Then the problem of the transport through the constriction can be decoupled into a series of transport problems through 1D barriers, one for each subband. These barriers are determined by the confining potential and so will also vary smoothly.

We consider the bias voltage to be dropped equally on either side of the barrier maximum. The energy reference level is taken such that the maxima of the 1D potential barrier, denoted by E_n for the nth subband, remains unaltered by the bias. Then the DC bias V increases the chemical potential μ_L in the left hand reservoir by $eV/2$ and reduces the chemical potential μ_R in the right hand reservoir by the same amount. Consequently, taking into account spin degeneracy, the current for each one dimensional subband is given by

$$J = \frac{2e}{h}\int_{E_F - eV/2}^{E_F + eV/2} T(E)\,\mathrm{d}E \qquad (2)$$

where E_F is the chemical potential at zero bias and eV is the bias voltage. We approximate the transmission probability as one for electrons with energy above the barrier and zero

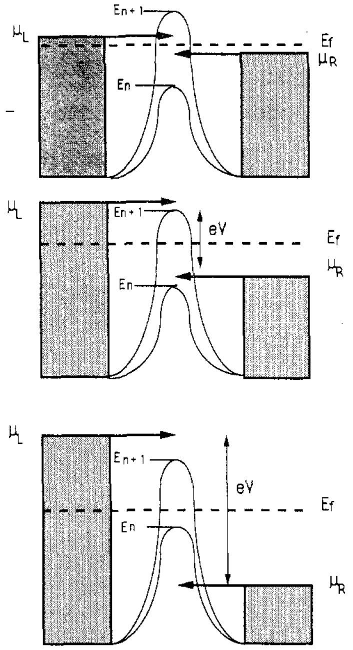

Figure 3. (*a*) Shows the low bias case where the values of chemical potentials on each side of the split gate are in the same subband. The curves represent the barriers due to the different 1D subbands with n conducting channels. Ideally when the chemical potential exceeds the top of the barrier the channel begins to conduct. (*b*) As the bias increases the chemical potentials split until we have $n + 1$ channels conducting from left to right and n channels conducting right to left. At this point the differential conductance would produce a half-integer plateau. (*c*) At even larger biases there are $n + 2$ right going channels and only n left going channels hence there are two subbands which conduct from left to right but not the other way. In this case an integer quantised conductance plateau would be observed.

for energy below. Corrections are expected to be small since smooth barriers behave almost classically (Landau and Lifshitz 1977). Applying a magnetic field reduces backscattering (Büttiker 1988) and hence further improves the approximation (Efetov 1989, Büttiker 1990).

We can now calculate the current and the differential conductance through the constriction as a function of the applied DC bias voltage. Let us first consider values of eV sufficiently small that the number of occupied subbands is unaltered, that is when μ_L and μ_R are both between E_n and E_{n+1} as shown in figure 3(*a*). Using equation (2) we can derive the current and differential conductance to be

$$J = (2e^2/h)nV \tag{3}$$

$$G = \mathrm{d}J/\mathrm{d}V = (2e^2/h)n \tag{4}$$

where n is the number of occupied 1D subbands. This is the well known result obtained previously in the limit of zero bias voltage (Wharam *et al* 1988, van Wees *et al* 1988). If we now consider the case where the bias is increased to make the chemical potential μ_L rise above E_{n+1} with μ_R still in between E_n and E_{n+1}, we have the situation shown in figure 3(*b*). The current in the $(n + 1)$ channel is then given by

$$J_{n+1} = (2e/h)(E_F + eV/2 - E_{n+1}) \tag{5}$$

with the contribution to the current coming from the other n channels still given by formula (3). Therefore the differential conductance is

$$G = (2e^2/h)(n + \tfrac{1}{2}). \tag{6}$$

Similarly it can be seen that when the bias causes the chemical potential μ_R to drop below E_n, with μ_L still in between E_n and E_{n+1}

$$G = (2e^2/h)(n - \tfrac{1}{2}) \tag{7}$$

when the bias satisfies the conditions in the above two cases, which occurs when there is one subband transporting current in only one direction, new quantised conductance plateaux are predicted. These will appear in between the normal plateaux resulting in steps in conductance of e^2/h as opposed to the usual value of $2e^2/h$.

Eventually the bias voltage will be large enough that two subbands will be transporting current in only one direction. We consider here explicitly the case in which μ_L is larger than E_{n+1} and μ_R is smaller than E_n this is depicted in figure 3(c). The current is now

$$J = \frac{2e^2}{h} nV + \frac{2e}{h}\left(E_F + \frac{eV}{2} - E_{n+1}\right) - \frac{2e}{h}\left[E_n - \left(E_F - \frac{eV}{2}\right)\right] \tag{8}$$

$$G = (2e^2/h)n. \tag{9}$$

The first term is the current for n channels as in formula (3), the second term reflects the increase in current due to the contribution of the $(n + 1)$ channel as in formula (5) and the final term is the decrease in contribution of the nth channel. The net result is a normal plateau value for the differential conductance.

The conductance as a function of gate voltage for different DC voltage bias is shown in figure 2. The data are taken at 0.5 T as the plateaux are better defined with a small magnetic field. The inset of figure 2 shows zero magnetic field data which has the same structure. The development of the new plateaux with increasing DC bias can be seen. Trace (d) clearly shows all the plateaux spaced by e^2/h. The data demonstrate experimentally the plateaux predicted by the adiabatic model at half the normal quantised conductance and these appear between all the plateaux normally observed in a 1D channel. The precise quantisation of these new plateaux also corroborates the assumption of the voltage drop being symmetrical. As the bias is further increased we would expect that over a range of gate voltages the chemical potentials are separated by at least two subbands. Nevertheless it is expected that the jumps in the differential conductance will be e^2/h unless μ_L falls below E_{n+1} at a similar gate voltage as μ_R falls below E_n so producing a jump in the differential conductance of $2e^2/h$. This effect is clear in figure 2 traces (f), (g) and (h). A third regime becomes apparent at higher values of bias where it appears that the integer plateaux may be returning.

Increasing the DC bias has the added effect of causing a smearing out of the plateaux. This effect is greatest for the higher order plateaux which start to disappear at bias values as low as 3 mV. Lower order plateaux persist longer but eventually even these disappear. In terms of the model shown in figure 3, this smearing out can be explained by an increase in the tunnelling probability and an increase in the reflection of electrons with energies above the barrier. Both of these effects will be enhanced by the increasing bias voltage as considered by Glazman *et al* (1988, 1989).

The voltage bias at which the new plateaux appear can be related, using the model described above, to the difference in energy between the chemical potential and the bottom or top of the next subband whichever is the closest. This means the regime of ohmic behaviour depends critically on the position of the chemical potential at any particular gate voltage with respect to the 1D subbands. Figure 4 shows the differential conductance taken at constant gate voltage where the DC bias voltage is swept. This clearly shows how the non-linear regime is reached at varying biases depending on the gate voltage. At a gate voltage corresponding to a plateau a high bias is required to see the onset of the non-linear conductance whereas for intermediate voltages smaller biases are required. A simple explanation for this is as follows, when a plateau at a particular gate voltage is observed, the chemical potential must lie between two subbands and to

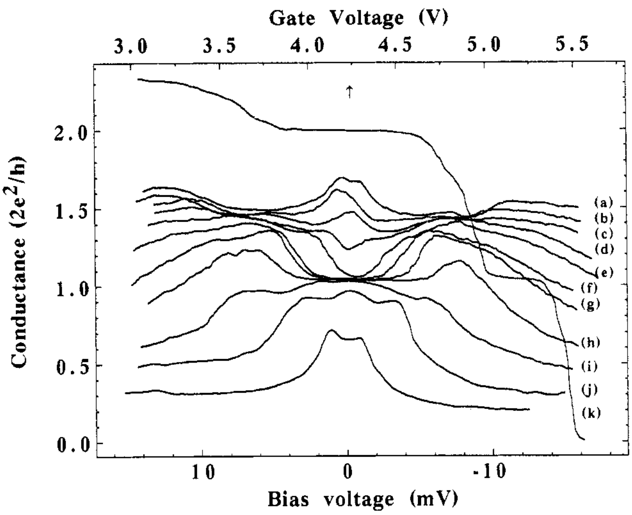

Figure 4. The upper x-axis refers to the conductance of the device as a function of the gate voltage. The series of curves show the differential conductance at fixed gate voltages with the DC bias voltage swept. The traces are separated by 50 mV increments of gate voltage; trace (a) has gate voltage 4.90 V and graph (k) 5.40 with equal increments of 50 mV. The traces are seen to converge at zero bias at a integer plateau conductance and at high biases they are seen to converge at the half-integer value of conductance.

see non-linear behaviour a bias is needed large enough to shift the chemical potential into the next subband. However away from a plateau the chemical potential is closer to the next subband and a lower bias is needed to see the same effects. The highest bias needed for the onset of non-linear response then occurs when the chemical potential is initially midway between two subbands and the bias voltage required is equal to the subband spacing. Using this criteria subband spacings were extracted. These values are of the same magnitude as data obtained by other authors (Kouwenhoven *et al* 1989, Wharam *et al* 1989). The half-integer plateaux are also evident in the data of figure 4 as well as a small asymmetry between the positive and negative bias. This is a result of the way the gate voltage is biased relative to the 2DEG which results in a effective increase of the gate voltage for positive biases and so a decrease in the conductance. Similarly negative biases lower the effective gate voltage with respect to the 2DEG and increase the conductance.

The data also shows that the new plateaux at higher index n appear at lower DC voltage biases. This reflects the fact that the higher index plateaux appear when the channel is wider at lower values of gate voltages and the 1D subbands are closer together. As the gate voltage becomes more negative the channel becomes smaller and the energies of the 1D subbands move further apart. A larger DC voltage bias is then needed to produce the new plateaux. We also need to consider how the energy levels are separated. A square well potential has subbands further apart at higher index n whereas a parabolic potential results in equally spaced values. No sign is seen in the data of an increase in the subband spacing with higher index indicating a parabolic potential is better suited than a square well potential (Wharam *et al* 1989, Berggren *et al* 1986).

A transverse magnetic field of up to 3 T was then applied to the sample. Figure 5 shows the data for 1.5 T where we see only three plateaux in the gate sweep at low bias.

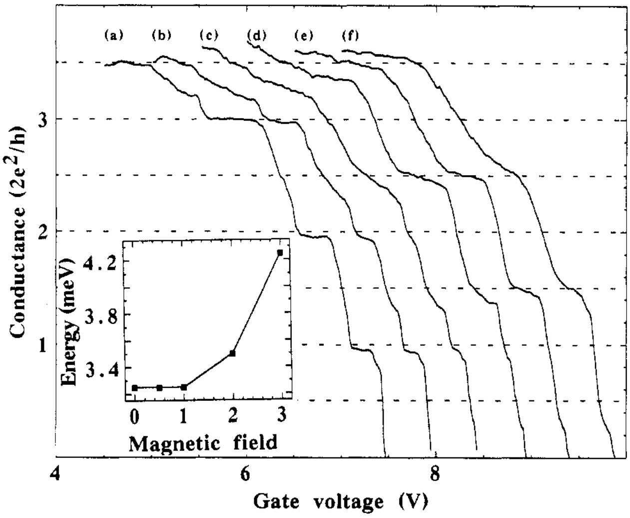

Figure 5. The differential conductance is plotted as a function of the gate voltage in a magnetic field of 1.5 T. Successive traces have an increasing DC bias with 0 mV bias for (*a*) and 5 mV for (*f*) in equal steps of 1 mV. Clear half-integer plateaux are still seen. Values of the subband spacings as a function of the magnetic field are shown in the inset. These are calculated using the DC bias sweep data where the gate voltage is kept constant.

This phenomenon is well explained by the Büttiker formalism in terms of reflection of edge states (Büttiker 1988, Brown *et al* 1989, Snell *et al* 1989). As a DC voltage bias is applied once again the half integer plateaux emerge and show the same behaviour as at zero magnetic field. Even at 3 T we still see this effect except we now need a higher bias to observe the new plateaux. This reflects the increase in subband spacing caused by the applied magnetic field. Data obtained from the bias sweep gave increasing values for the subband spacing with magnetic field. This is shown in the inset to figure 5. We will present a more detailed account of this elsewhere.

We now return to the data of figure 2 which show that as the bias is increased, the plateaux take values of $(2e^2/h)(n+\frac{1}{2})$. As mentioned earlier a jump of $2e^2/h$ could arise from an almost simultaneous change affecting the occupation of two subbands. However as this occurs for several plateaux and at different bias values a more subtle effect may be involved. Spin polarisation induced by the current has also been proposed (Edelstein 1990) which could also produce new plateaux in the conductance. This however at present cannot explain the high bias anomaly in our data.

In summary we have observed well quantised half plateaux in the high bias regime of a ballistic split gate in zero magnetic field. These are described in terms of a model incorporating the effect of bias on the chemical potentials on either side of the 1D channel in the adiabatic regime. The smearing out of the plateaux is observed and is expected to be a result of the bias enhancing the tunnelling probability and altering the transmission coefficient from the ideal values of one and zero. When a constant transverse magnetic field is applied the voltage bias response is unaltered with the half plateaux still appearing at quantised values. At the highest magnetic field of 3 T the bias required to see the half plateaux was observed to increase. Values of the subband spacing were extracted from this data and agreed with values obtained from modelling this type of structure.

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