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LETTER TO THE EDITOR

Resonant magneto-transport through a lateral quantum box in a semiconductor heterostructure

R J Brown, C G Smith, M Pepper, M J Kelly†, R Newbury, H Ahmed, D G Hasko, J E F Frost, D C Peacock†, D A Ritchie and G A C Jones
Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

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Abstract. We have investigated magneto-transport through a lateral quantum box defined by a patterned Schottky barrier on a GaAs–AlGaAs heterojunction. As the size of the box, and the reflecting barrier potential, are varied, edge states are successively reflected with a consequent change in the value of the plateaux of resistance.

Superimposed on a plateau are modulations of resistance having both electrical and magnetic origin. Resonant transport, with an increase in transmission ratio to unity, (corresponding to oscillations in resistance at, or above, the plateaux values), occurs when an integer number of wavelengths fit into the box perimeter and are rapidly modulated by flux quantisation of the Aharonov–Bohm type.

In addition, resonance can arise when an incident wave tunnels through the barriers via a circulating, trapped, edge current. This behaviour brings in an extra mode of current and causes the resistance to drop below the value of a plateau in contrast to the previously mentioned resonance arising from transport above the barrier.

The electrostatic squeezing of a two-dimensional electron gas (2DEG) in a AlGaAs–GaAs heterojunction has been exploited extensively for the investigation of one dimensional quantum transport since its introduction by Thornton *et al* [1]. In previous work [2] we used a modification of a split gate device to form a lateral quantum box, which could be used to alter the transmission of the system and produce peaks in resistance above those due to the quantised, one-dimensional (1D), ballistic resistance. We now report on the use of such a structure for the investigation of resonance effects in magneto-transport. Two areas of work recently described in the literature are relevant to this Letter. The first is the observation of a quantised Hall Resistance of two dissimilar 2D electron gases in series, produced, for example, by a narrow gate over part of a heterojunction [3, 4]. The total two-terminal resistance is (h/e^2) $[1/(i-j) - 1/i]$ where i and $i-j$ are the number of edge current channels in the two quantum Hall resistors, i.e. j channels are reflected at the junction. As the bulk Landau levels are localised the resistance is determined by the number of conducting edge channels. The second area of relevance is both theoretical and experimental work on Aharonov–Bohm oscillations in a narrow but uniform, 2D electron gas. In the presence of a sufficiently high magnetic field, edge currents are established that follow the contours of the sample [5]. A particularly significant feature of edge current transport is that, as the two directions of motion are separated, backscattering can only occur at the entrance and exit of the sample where

† Also at GEC Hirst Research Centre, East Lane, Wembley HA9 7PP, UK.

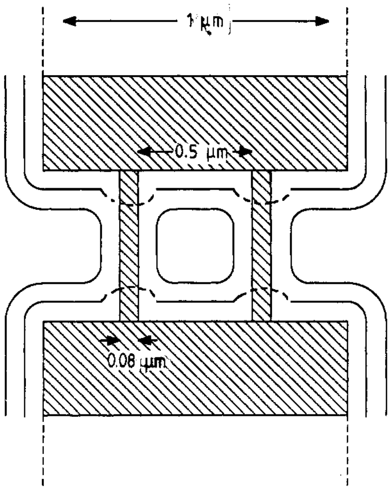

Figure 1. A plan view of the device used to define a lateral quantum box. The hatched area is the gold/palladium metallisation and the contours correspond to the equipotentials.

the edge currents flowing in opposite directions are closest together. If a wave can be back-scattered at the exit, by tunnelling across to the edge current flowing in the opposite direction, a circulating current can be established [6, 7]. The change in phase of the electron wave as it circulates will give rise to interference as in a conventional ring structure. Recent experiments have confirmed that Aharonov–Bohm oscillations can be displayed by a narrow, but uniform, electron gas in which the periodicity of the oscillations varied in the expected manner with the channel area [8, 9]. The dependence on area is a definite requirement in establishing that circulating edge currents are responsible for the oscillations and that scattering from an impurity, or defect, is not creating a 'quasi-ring' situation. In our earlier work [8] on this topic it was noted that the existence of a potential on either side of the narrow channel enhanced the process of the reflection of edge currents giving rise to the oscillations. As we had previously found that reflection effects and associated resonant structure were greatly enhanced in a lateral quantum box [2] so it was decided to investigate the magnetoresistance of this structure.

The heterojunction used in the experiment was of a typical high-electron-mobility transistor type, consisting of a semi-insulating GaAs substrate on which is grown (by molecular beam epitaxy) a superlattice buffer ((AlAs 2.5 nm, GaAs 2.5 nm) × 20), 1 μm nominally undoped GaAs, 20 nm undoped AlGaAs, 40 nm AlGaAs Si doped at 10^{18} cm^{-3}, followed by a 10 nm undoped GaAs capping layer. The 2DEG at the GaAs–$Al_{0.37}Ga_{0.63}As$ interface had a carrier concentration of 2.75 10^{11} cm^{-2} and an electron mobility of 98 m^2 V^{-1} s^{-1} both measured at 4 K in the dark. The box was created by a patterned Schottky barrier on top of the heterojunction. The barrier structure was defined using electron beam patterning of PMMA resist followed by lift-off of 50 nm of gold–palladium. The system is illustrated in figure 1 and consists of a 1D channel with two fine line barriers across it. The region enclosed by the split gate and the fine lines is the lateral quantum box. In figure 1 we sketch the equipotentials associated with electron states in our structure. We note that because of capacitive edge effects, the thin lines are less effective in depleting the electron gas underneath them than are the wide gates. This implies a range of gate bias within which the narrow 1D channel is defined but the barrier height under the centre regions of the fine wires is less than the Fermi energy [10, 11].

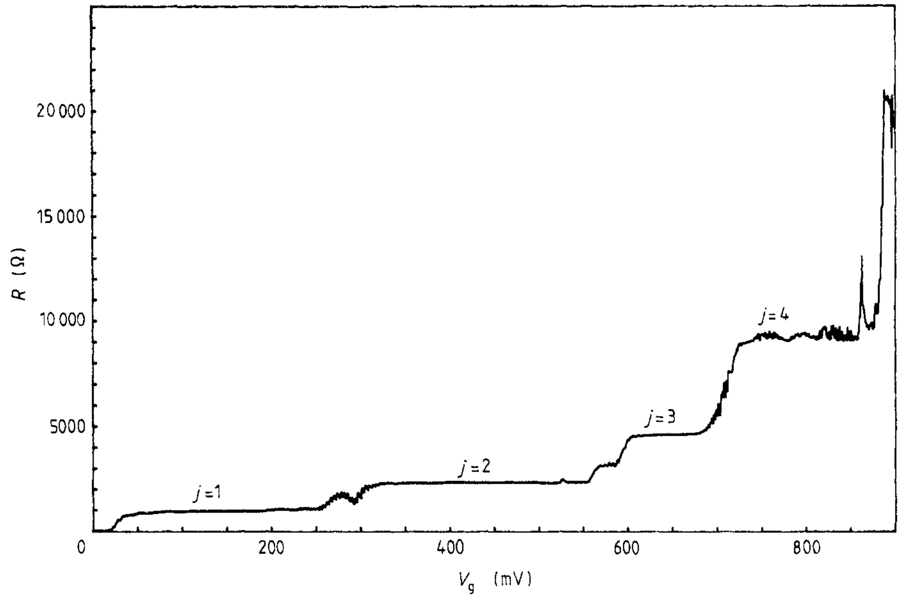

Figure 2. The magnetoresistance (at 2 T) of the quantum box as the gate voltage is swept negative (temperature ~0.1 K).

Increasing the negative gate voltage results in a decrease in the area of the box as well as an increase in the barrier potential and a decrease in the width of the entrance and exit regions.

Transport measurements were carried out at a fixed magnetic field as the gate voltage was varied. The results reported here were carried out mainly at 2 T corresponding to $\omega_c\tau \sim 200$ (ω_c = cyclotron frequency, τ = elastic scattering time). The observed Landau levels were spin split. In the quantised plateaux regions the current is carried by edge states associated with each bulk Landau level. Such edge states flow along equipotentials and are shown schematically in figure 1; they are seen to follow the contours of the depletion region, and, in particular, it is possible to exclude particular edge states from flowing into the central region by making the barrier potential increasingly negative, thus forming a lateral quantum box. We note that if the conditions are such that electrons are transmitted by tunnelling through the closed edge state then the resistance drops. On the other hand, if classically allowed electron transport across the barrier into the dot is inhibited, the resistance rises.

In figure 2 we show typical data obtained from a two-terminal magnetoresistance measurement as the gate voltage is swept negative (using standard phase-sensitive detection techniques and a constant current of 10^{-9} A). The usual four current and voltage probes were used situated approximately 100 μm away from the quantum box. In figures 3 and 4 we show specific regions of voltage sweep in greater detail. It is seen that the major features are well defined plateaux in resistance and two oscillation periods, both of which correspond to an increase in resistance, as well as a smaller number of oscillations corresponding to a decrease in resistance.

The plateaux can be explained relatively easily using the Buttiker [12] analysis of reflected Landau levels in a similar manner to that adopted in [3] and [4]. With our values of magnetic field and carrier density, a total of six spin-split Landau levels are occupied.

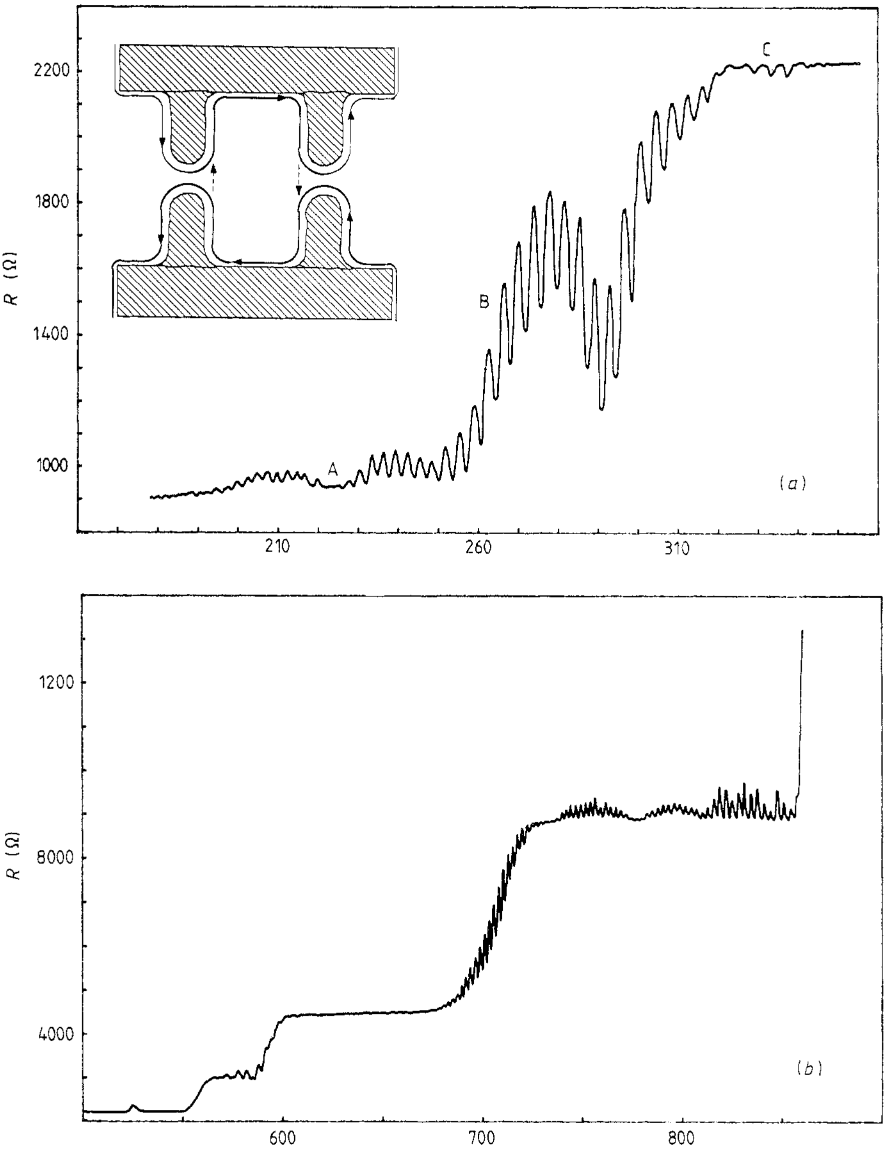

Figure 3. (*a*) Details of the magnetoresistance between $V_g = -160$ mV and $V_g = -360$ mV (i.e. between the $j = 1$ and $j = 2$ plateaux). Regions A and C are discussed in the text, region B corresponds to the Aharonov–Bohm-like oscillations superimposed on the resistance rise between plateaux. Inset: the full curve shows the relevant edge state for our discussion, with the broken section indicating tunnelling segments for an enclosed edge state. (*b*) Further details of the magnetoresistance between $V_G = -500$ mV and $V_G = -900$ mV (i.e. between the $j = 3$ and $j = 4$ plateaux).

As the gate potential is increased and successive edge states are repelled from the quantum box, resistance plateaux appear of value

$$R_{xx} = (h/e^2)\, j/i(i-j) \tag{1}$$

where $i = 6$ is the number of incident Landau levels, and j is the number of reflected

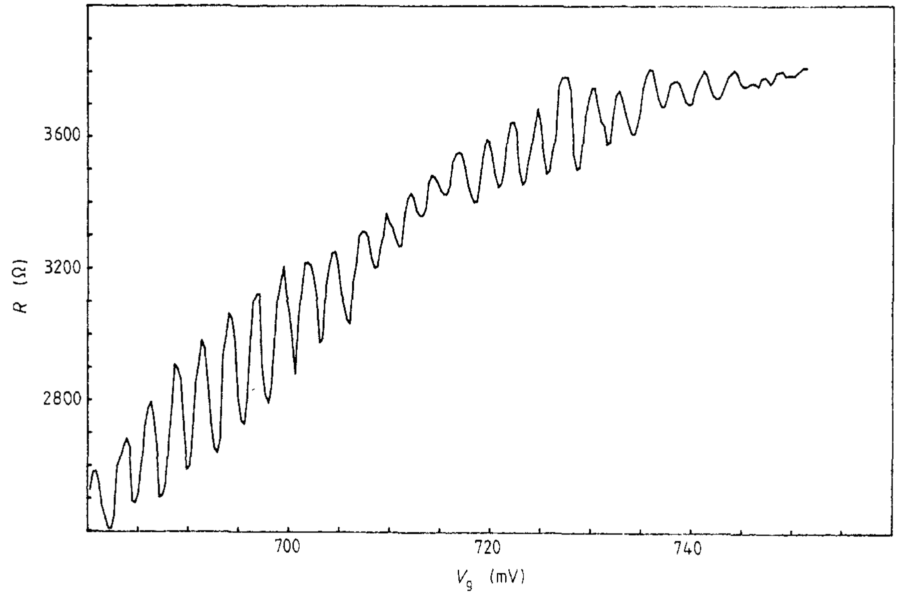

Figure 4. Modulated magnetoresistance oscillations (from a $B = 2.56$ T measurement) and in the gate voltage range corresponding to the $j = 2$ and $j = 3$ plateaux.

levels, as indicated in figure 2 (the $j = 5$ level has been observed but is off scale). In general we obtain agreement with equation (1) to well within experimental error, and we have repeated this exercise successfully at other values of magnetic fields of up to 5 T.

We suggest that the higher-frequency oscillations are of Aharonov–Bohm type occurring when the flux through the box changes by one flux quantum due to the change in box area. We now calculate the expected periodicity. The channel width W in a split gate structure has been shown to be given by [13]

$$W \simeq C(V_0 - V) \tag{2}$$

except very close to pinch-off, where C is a constant depending on carrier concentration, V_0 is the pinch-off voltage and V is the applied voltage. The Aharonov–Bohm period for small changes of V is given in terms of a change of area, A, by

$$\mathrm{d}A = \phi_0/B \tag{3}$$

where $\mathrm{d}A$ is the change in area, B is the magnetic field and ϕ_0 is the flux quantum. Utilising equation (2), and neglecting small corrections near the entrance and exit to the quantum box, we write $A = W^2$ and the period ΔV is given by

$$\Delta V = \phi_0/2BC^2(V - V_0). \tag{4}$$

An approximate value of C, bearing in mind the limitations of the above approach, can be obtained by noting that a gate voltage (V_0) of -2 V pinches off a channel of width $\sim 10^{-4}$ cm, giving a value of 5×10^{-5} cm^{-1} V for C. Inspection of the results of figure 2 shows the periodicity of the Aharonov–Bohm oscillations increasing from about 2.5 mV to 4 mV in reasonable agreement with equation (4) which predicts a slower increase from 2.5 mV. Similarly the results of figure 3 are also in reasonable agreement with the predictions of equation (4). The experimentally determined periodicities will not necessarily increase smoothly as successive edge currents are excluded from the box, as, due to their different energies, and associated equipotentials, the relative areas enclosing the flux will differ.

We assign the low-frequency modulation to a resonance in edge-state transmission which occurs when an integer number of wavelengths fit around the perimeter of the box. In this case, the weakly reflected and incident waves are in phase so causing the normal resonance situation where a high-intensity internal wave develops and the transmission of the entire system tends to unity (see inset to figure 3(*a*)). This results in the resistance falling to the plateau value (marked A in figure 3(*a*)). The increase in resistance away from resonance is due to destructive interference between the reflected wave and the incident wave, and so is a measure of the reflectivities of the barriers. This whole effect is, of course, modulated by the effects of flux containment.

The resonance just described occurs when $n\lambda = 4W$ or $n\lambda = 4C(V_0 - V)$, hence the period ΔV is equal to $\lambda/4C = 25$ mV if we use a Fermi wavelength of the edge states of about 500 Å (which follows from $E_F \sim 10$ meV for the 2DEG) and the ratio of this modulation to that due to the flux change is about 10 : 1, in very reasonable agreement with the experimental results, over the entire voltage range, which are between 11 : 1 and 13 : 1. We note that the effective transport wavelength of the edge states will be somewhat greater than the value of the Fermi wavelength used here, so improving the agreement with experiment.

Turning to a consideration of the results, we see that the dominant effect arises from the modulated increase in resistance, signifying an oscillatory variation in transmission. The effect arises from reflection at the well defined electrostatic potential barriers at the entrance to, and the exit from, the box. At resonance the transmission of the entire system goes to unity and a plateau value of resistance is found. Experimentally the modulation produced by the ratio of perimeter to wavelength is stronger than that produced by the flux quantisation. This behaviour is close to that predicted for weak coupling between a ring and leads [14], and the periodic variation in the density of states causes the following behaviour:

$$T = \frac{T_{RES}(h/2\tau)^2}{(E_F - E_n(\phi))^2 + (h/2\tau)^2} \tag{5}$$

where E_F is the Fermi energy, T is the value of the transmission probability, E_F lies between two bands $E_n(\phi)$ and $E_{n+1}(\phi)$ arising from the absence of scattering in the presence of magnetic flux, and τ is the lifetime of each edge state in its magnetically imposed loop. In the weak coupling limit an integer number of flux quanta produce $E_F = E_n(\phi)$, and then $T = T_{RES}$, which goes to unity when an integer number of wavelengths fit into the perimeter, P, of the box. Following the general approach of Jain and Kivelson [15], the overall transmission T can be expressed in the form, valid for small departures from unity,

$$T = (1 - b\sin^2\theta)(1 - a\sin^2\alpha).$$

Here $\theta = \pi Pl/\lambda$; $\alpha = \pi W^2Bm/\phi_0$ where l and m are integers, $a, b \ll 1$ and increase with the reflectivity of the barriers. (In this analysis we consider only the lowest energy transmitted edge state.) For the first two periods shown on the $j = 4$ plateau in figure 3(*b*) the resistance has a minimum value which varies as $\sin^2\theta$ added to which are the rapidly fluctuating $\sin^2\alpha$ spikes. However, it is not clear why the weak rather than the strong coupling situation is found when the barrier potential is less than the edge-state energy. As the coupling decreases and the potential is near the energy of the particular edge state, for example the third modulation of figure 3(*b*), the Aharonov–Bohm type of oscillations become larger and can cause T to reach unity. However, a wavelength modulation is still apparent, as are harmonics at $-V_g \geqslant 800$ mV in figure 3(*b*). Possibly the increase in confinement gives rise to a greater wavefunction overlap at the point where the incident wave enters the box, the net effect being to give rise to a very strong resonance and unity T, whereas for less overlap the net effect is a weaker modulation of the density of states. We note that due to the finite extent of the edge state into the box, flux containment at the edge will give rise to dephasing and a consequent reduction in amplitude of the oscillations.

Both figures 3(*a*) and 3(*b*) show the oscillations obtained when increasing the potential causes the resistance to rise between plateaux as an edge state is excluded from the box. It is clear that both modulation frequencies are present and the overall change in transmission is very large. It is to be noted in figure 3(*a*), (at the higher end of the range of gate voltage, marked C), that when the state is classically excluded weak oscillations are observed which correspond to a decrease in resistance below the plateau value. These arise from a resonance that occurs when the incident wave tunnels through the barriers via the circulating, enclosed-edge current in the dot and have been investigated by other authors [9]. Resonance occurs at the standing wave condition and the increase in current brings the resistance below the plateau value.

Thus, in summary, we have shown that the lateral quantum box can be used for the investigation of resonance phenomena in magneto-transport. The edge currents set up by a magnetic field can be successively excluded by increasing the barrier potential. Overlap between the incident wave and a weak, internal, reflected wave give rise to variations in transmission. Two types of resonance are found, one of electrical origin when an integral number of wavelengths can be accommodated around the perimeter, and one that depends on the magnetic flux. These effects arise from the passage of an incident wave over the reflecting barrier into the box. When the wave is classically excluded, and the resistance moves to the next plateau, resonance occurs under the same conditions but is weaker and now the resistance drops below the plateau value as a classically excluded edge state is partially transmitted.

Although the theoretical framework of these effects are clear, a detailed understanding of both the dependence of frequency modulation on barrier potential and the lineshape are lacking.

We note the presence of resonance-like 'bumps' in resistance on otherwise flat quantised plateaux (see figure 3(*b*), $-V_g = 525$ mV for illustration). These are clearly of mesoscopic origin but as yet we have no detailed explanation of them.

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References

[1] Thornton T J, Pepper M, Ahmed H, Andrews D and Davies G J 1986 *Phys. Rev. Lett.* **56** 1198

[2] Smith C G, Pepper M, Ahmed H, Frost J E F, Hasko D G, Peacock D C, Ritchie D A and Jones G A C 1988 *J. Phys. C: Solid State Phys.* **21** L893
[3] Haug R J, MacDonald A H, Streda P and von Klitzing K 1988 *Phys. Rev. Lett.* **61** 2797
[4] Washburn S, Fowler A B, Schmid H and Kern D 1988 *Phys. Rev. Lett.* **51** 2801
[5] Halperin B I 1982 *Phys. Rev.* B **25** 2185
[6] Sivan U, Imry Y and Hartzstein C 1989 *Phys. Rev.* B **39** 1242
[7] Sivan U and Imry Y 1989 *Phys. Rev. Lett.* **61** 1001
[8] Wharam D A, Pepper M, Newbury R, Ahmed H, Hasko D G, Peacock D C, Frost J E F, Ritchie D A and Jones G A C 1989 *J. Phys. Condens. Matter* **1** 3369
[9] Van Wees B J, Kouwenhoven L P, Harmans C J P M, Williamson J G, Timmering C E, Broekaart M E I, Foxon C T and Harris J J 1989 *Phys. Rev. Lett.* **62** 2523
[10] Thornton T J, Pepper M, Ahmed H, Andrews D and Davies C J 1986 *Electron. Lett.* **22** 247
[11] Schmid H, Rishton S A, Kern D P, Washburn S, Webb R A, Kleinsauer A, Chang T H P and Fowler A B 1988 *J. Vac. Sci. Technol.* B **6** 122
[12] Büttiker M 1988 *Phys. Rev.* B **38** 9375
[13] Wharam D A, Ekenburg U, Pepper M, Hasko D G, Ahmed H, Frost J E F, Ritchie D A, Peacock D C and Jones G A C 1989 *Phys. Rev.* B **39** 6283
[14] Büttiker M, Imry Y and Azbel M Ya 1984 *Phys. Rev.* A **30** 1982
[15] Jain J K and Kivelson S 1988 *Phys. Rev.* B **37** 4111