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LETTER TO THE EDITOR

Observation of Aharonov–Bohm oscillations in a narrow two-dimensional electron gas

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Abstract. We have observed Aharonov–Bohm oscillations using a split gate GaAs–AlGaAs heterojunction FET of the type used to demonstrate the quantised, one-dimensional, ballistic resistance. The periodicity of the Aharonov–Bohm oscillations allowed extraction of the channel area and, hence, by using values of width derived from magnetic depopulation data, the channel length could be determined. It is found that the effective channel length increases as the area, and width, decreases in agreement with a simple model based on the depletion approximation.

The use of the split-gate technique for the control of the width of the conducting channel of the GaAs–AlGaAs heterojunction has resulted in the observation of one-dimensional transport [1] and associated 1D quantisation [2]. If the conducting channel is sufficiently short that transport is ballistic, then the resistance is quantised [3, 4] with the total value $h/2e^2i$ reflecting the number of occupied 1D sub-bands, i.

In addition, because the phase coherence and elastic scattering lengths are large compared with sample size, related structures can be used for the investigation of electron transport in coupled, quantum, systems [5, 6].

In this Letter we present results on the observation of Aharonov–Bohm oscillations [7] in the conductance of a split-gate structure and show that the periodicity of the oscillations can be used to provide information on the channel geometry.

Electron beam lithography was used to define a short, narrow, split-gate structure on the surface of a high-mobility heterostructure, the mobility at liquid helium temperatures being in excess of 150 $m^2\,V^{-1}\,s^{-1}$. The lithographically defined width of the channel was 350 nm; however, the effective channel width could be decreased continuously to pinch-off via the application of a negative bias to the split gate. The lithographically defined length of the channel was 250 nm which is expected to increase with the change in the channel width. In the absence of a transverse magnetic field the quantised ballistic resistance was observed; sixteen plateaux were clearly resolved as the width of the narrow channel was varied.

In the presence of a transverse magnetic field the additional magnetic quantisation leads to the formation of hybrid magneto-electric sub-bands. As the magnetic field is increased there is a smooth transition between these hybrid levels and the purely magnetic Landau levels. The depopulation of the hybrid magneto-electric sub-bands

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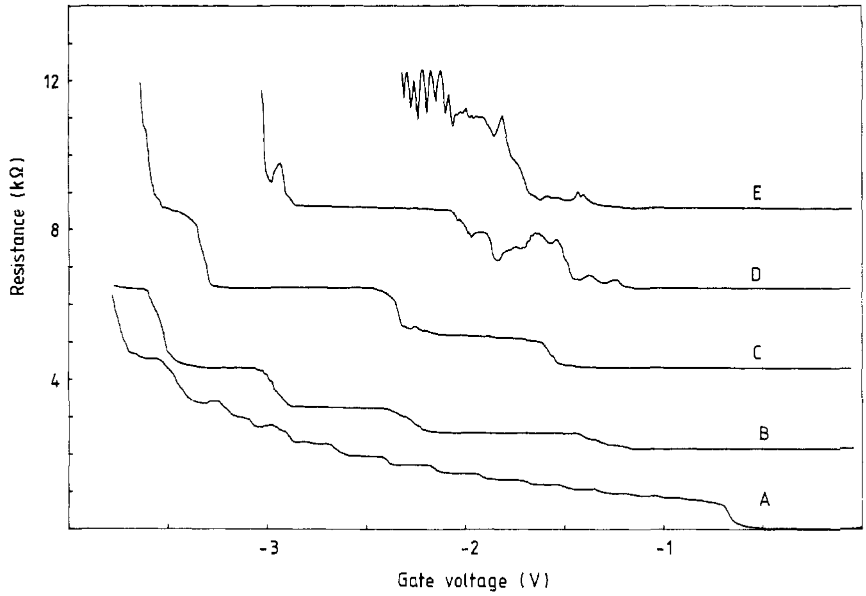

Figure 1. Gate characteristics: the two-terminal resistance is displayed as a function of voltage applied to the split gate for the following values of magnetic field (in T((A) 0; (B) 1; (C) 2; (D) 3; (E) 4. There is a clear progression from the quantised ballistic resistance through magnetic depopulation to the broad quantum Hall plateaux with intervening Aharonov–Bohm oscillations.

has been modelled in a number of papers [2, 8, 9]. In figure 1 the resistance measured between probes located near opposite ends of a channel defined by split gates is plotted as a function of the applied gate voltage for a variety of different magnetic fields at 0.1 K. The resistance was calculated from the voltage between the probes for a constant current of 10^{-8} A. As the magnetic field is increased, the sub-bands pass through the Fermi energy for smaller values of negative bias, i.e. increasing the magnetic field results in a particular sub-band passing through the Fermi energy at an increased width. Following on from the magnetic depopulation, when the field exceeds about 1.5 T additional plateaux start to form, corresponding to the spin-split levels found in the quantum Hall regime. Above 2.5 T there is clear evidence of structure in the regions between plateaux, which for fields in excess of 3.5 T shows marked oscillatory behaviour. The periodic oscillations were found up to the highest magnetic fields used, 6.5 T, and were always between, and not on, the quantised plateaux.

In figure 2 the same resistance measurement is presented as a function of the applied transverse field for different gate voltages. For fields in excess of 3 T there is clear evidence of oscillatory behaviour modulated by significant background structure in the regions between plateaux. Furthermore there is a marked change, ≃25%, in the period of oscillation between $V_g = -1.5$ V and $V_g = -2.5$ V, which corresponds to a change in the area enclosing the flux producing the Aharonov–Bohm oscillation. Assuming the oscillations to correspond to a flux quantisation of h/e, the defined loop areas can be extracted as a function of the channel width, W, which, in turn, can be calculated from the magnetic depopulation data [8]. These data are presented in table 1.

We also include in table 1 the length, L, of the channel obtained by dividing the Aharonov–Bohm area by the width obtained from analysis of the magnetic depo-

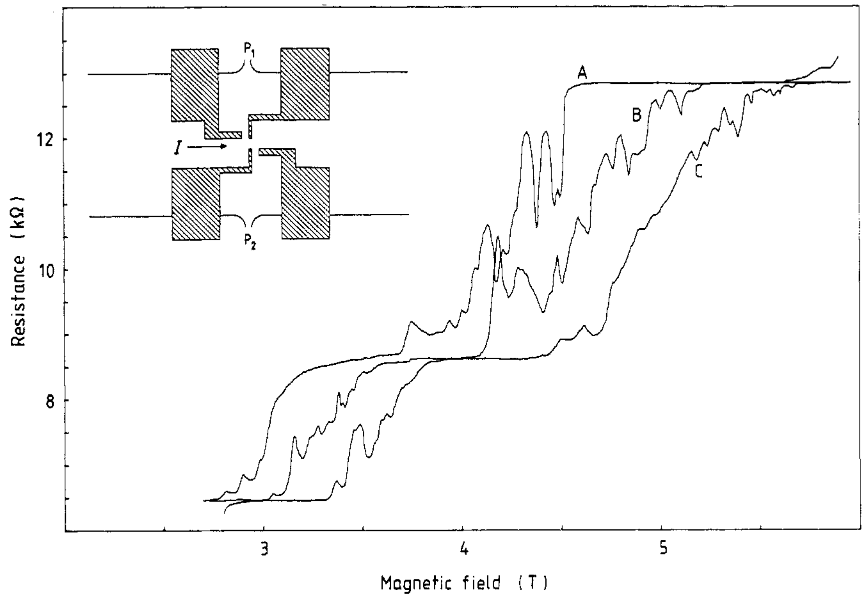

Figure 2. Magnetoresisistance: the two-terminal resistance measured between the probes P$_1$ and P$_2$ as a function of the values of gate bias displayed in table 1. The values of the gate voltage (in V) are (A) −2.5; (B) −2.0; (C) −1.5. Inset we display the metallisation pattern (shaded) on the outlined etched heterojunction mesa. The probes P$_1$ and P$_2$ which measure the voltage on either side of the narrow channel are indicated, as is the current I.

Table 1. Parameters as follows: V_g, gate voltage; W, width derived from the depopulation data; ΔB, Aharonov–Bohm periodicity; A, area derived from the oscillations, assuming h/e periodicity; L, length calculated from A/W; $W + L$, the value obtained by addition of W and L.

V_g (V)	−1.5	−2.0	−2.5
W (m)	2.5×10^{-7}	1.6×10^{-7}	1.3×10^{-7}
ΔB (T)	0.056	0.066	0.070
A (m^2)	7.0×10^{-14}	5.9×10^{-14}	5.6×10^{-14}
L (m) = A/W	2.8×10^{-7}	3.7×10^{-7}	4.3×10^{-7}
W (m) + L (m)	5.3×10^{-7}	5.3×10^{-7}	5.6×10^{-7}

pulation. It is seen that L increases as the channel becomes increasingly narrow, and is always greater than the lithographically defined length of 2.5×10^{-7} m. This increase is in accord with a simple depletion approximation model, as will now be shown.

If the channel width for zero applied voltage is W_0, then the effective channel width W is given by

$$W = W_0 - 2d$$

where d is the depletion region on each side originating from the voltage applied to the split gate. The depletion regions will add, approximately, a distance d onto both the entrance and exit of the channel. The channel length, L, is now given by

$$L = L_0 + 2d$$

where L_0 is the channel length with zero voltage applied to the gate.

Thus we find that $W + L = W_0 + L_0$, i.e. a constant value. the table shows that the experimentally determined value of $W + L$ is reasonably constant with change in gate voltage. The values of W_0 and L_0 are obtained by taking the lithographically defined values and are 3.5×10^{-7} m and 2.5×10^{-7} giving $W_0 + L_0 = 6 \times 10^{-7}$ m. The small discrepancy between this value and that experimentally determined may be due to the difference between L_0 for zero gate voltage and the lithographically defined length.

The results clearly suggest that, like edge current scattering in the quantum Hall regime of other device structures [10], the effect arises from interference between waves derived from a common source, one of which is reflected at the entrance to the channel, the other being transmitted but then reflected back by a change in potential at the exit. The formation of a closed loop by such a scattering of the edge states will only occur between the quantised plateaux, as is observed. Aharonov–Bohm oscillations, of much larger amplitude than found here, have been reported by van Loosdrecht and co-workers [11] using a split-gate device. However, these authors found that the periodicity did not change as the width of the channel was varied by a gate voltage; in addition, an asymmetry was found in the magnitude of the oscillations upon reversal of the magnetic field. As they suggest, such an eventuality may arise from a particular channel configuration resulting in the effective area remaining unchanged with a change in gate voltage. However, in the light of the results presented here, it is very possible that strong impurity scattering within, or close to, the channel is responsible for the enhanced amplitude of their oscillations as well as giving a constant area of flux containment.

In the context of this Letter it is significant that theory has suggested [12, 13] that resonant behaviour will lead to non-zero reflection coefficients, as each sub-band depopulates, due to the change in potential at the entrance to, and exit from, the channel. It is worth pointing out that the measurement probes will enhance reflection, so leading to the effect reported here. We do not find, at the present time, Aharonov–Bohm oscillations in conventional split-gate devices as used in earlier work [4, 6].

We found that for negative biases in excess of −2.5 V the oscillations disappear. In the presence of a magnetic field the conduction of electrons in the narrow channel will be in the edge states, and, in order for a well defined loop area to exist, edge states on opposite sides of the channel must be spatially separated. This will not be the case when the width becomes comparable with the cyclotron length, as also observed by van Loosdrecht and co-workers [11].

In conclusion, a periodic Aharonov–Bohm oscillation has been observed in the magnetoresistance of a short split-gate device whose periodicity gives information on the voltage dependence of area of the narrow channel. The effective area is in agreement with the predictions of a simple depletion approximation model. Our observation of Aharonov–Bohm oscillations in a quantum dot with periodicity determined by the area of the dot was first predicted by Sivan and Impy [14, 15].

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