Electron transport in a non-uniform magnetic field

1995 J. Phys.: Condens. Matter 7 L307

(http://iopscience.iop.org/0953-8984/7/25/001)

J. Phys.: Condens. Matter 7 (1995) L307–L315. Printed in the UK

LETTER TO THE EDITOR

Electron transport in a non-uniform magnetic field

M L Leadbeater†, C L Foden†, T M Burke‡, J H Burroughes†, M P Grimshaw‡, D A Ritchie‡, L L Wang‡ and M Pepper†‡

† Toshiba Cambridge Research Centre Ltd, 260 Cambridge Science Park, Milton Road, Cambridge CB4 4WE, UK

‡ Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

Received 2 May 1995

Abstract. We have used MBE regrowth technology to produce a non-planar 2DEG at a GaAs/AlGaAs heterojunction grown over an etched facet. By applying a uniform magnetic field to this structure we obtain a spatially varying field component normal to the 2DEG. When the magnetic field is applied in the plane of the substrate, the resistance measured from one side of the facet to the other is found to be quantized at approximately the quantum Hall plateaux. Rotating the plane of the sample with respect to the magnetic field allows us to investigate edge state propagation and reflection in the different regions of the sample. By making the appropriate four-terminal resistance measurement we can directly determine the filling factor on the facet. In particular we study the novel situation where the transverse field component changes sign on the facet and the cyclotron orbits rotate in the opposite sense to those on the planar region.

The physics of a two-dimensional electron gas (2DEG) subjected to a uniform magnetic field forms a large part of contemporary semiconductor physics. However the more complex situation of an electron in a spatially varying field has only recently attracted attention (Dubrovin and Novikov 1980, Yoshioka and Iye 1987, Vasilopoulos and Peeters 1990, Müller 1992, Peeters and Matulatis 1993, Foden *et al* 1994, Chang and Niu 1994). One reason for this is the practical difficulty in realizing such a situation. Most current proposals have involved the use of patterned gates made out of superconductors or ferromagnets in a layer a few hundred ångströms above the plane of the 2DEG (Van Roy *et al* 1993, Kruithof and Klapwijk 1988, Geim *et al* 1990, Bending *et al* 1990, Carmona *et al* 1995, Ye *et al* 1995). Such a scheme has two disadvantages: the variation in the magnetic field is very small and dies away rapidly a short distance below the gate and the patterned gate layers will also cause strain and electrostatic variations which are in general stronger than the effects of the varying magnetic field which makes it hard to attribute effects unambiguously to the magnetic field.

The development of regrowth technology offers the potentially more fruitful approach of varying the topography of the 2DEG, as proposed by Foden *et al* (1994). We can etch a series of facets on a substrate and then grow a modulation-doped heterostructure where the electron gas at the GaAs/AlGaAs interface follows the contours of the original wafer. When we apply a uniform magnetic field (B) to such a shaped 2DEG, the angle between the field direction and the normal to the 2DEG depends on the facet and therefore will have a normal component of magnetic field which varies spatially across the sample. By varying the facet length and angle (ϕ) as well as the angle between the applied field and the normal to the substrate (θ) we can generate a wide variety of field profiles. In this letter we report the first results on a simple structure consisting of a 2DEG grown on a semi-insulating GaAs wafer which had been prepatterned with a single etched facet to form a magnetic barrier. By rotating the sample, the field component perpendicular to the facet can be larger than, smaller than, or even of the opposite sign to that on the adjacent planar region of substrate. Such a field reversal is a highly unusual situation and in principle a very large field gradient can be produced.

A (100) GaAs wafer was etched with a hydrofluoric-acid-based etchant (Meier *et al* 1987) to a depth of 1 μm, producing a 3 μm wide facet at an angle of approximately 20° to the substrate. The wafer was washed in acetone, isopropanol and Microposit resist stripper and subjected to an oxygen plasma etch to remove any residual photoresist. The wafer was then loaded into the UHV system and exposed to a hydrogen radical flux for 4 h to remove any remaining surface contamination. SIMS data showed a reduction in the oxygen levels at the surface by a factor of thirty after the *in situ* cleaning process. The wafer was then transferred under vacuum to the MBE growth chamber where the following layers were grown: 2000 Å undoped GaAs, 200 Å undoped $Al_{0.33}Ga_{0.67}As$, 400 Å $Al_{0.33}Ga_{0.67}As$ doped at 10^{18} cm^{-3}, and 100 Å undoped GaAs. A scanning electron micrograph of a cross-section through the structure is shown in figure 1. The facet is at an angle to the substrate of approximately $\phi = 20° \pm 2°$.

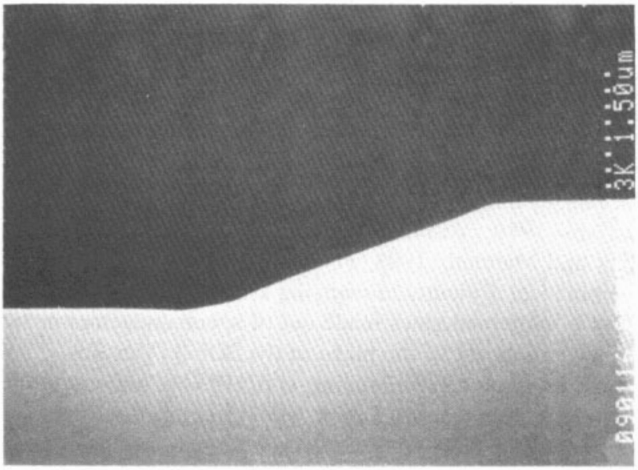

Figure 1. Scanning electron micrograph of a cross-section through the regrown structure. The facet is at an angle of 20° to the substrate.

Several sets of gated Hall bars were fabricated from this wafer using standard techniques with mesa widths of 5 μm. The Hall bars were aligned so that the etched facet passed between pairs of voltage probes 4 μm apart, i.e. the probes were within 1 μm of the top and bottom of the facet. The Hall bars also have other voltage probes which were used to measure the 2DEG in the planar regions on either side of the facet. Measurements were made at 1.4 K using conventional a.c. lock-in techniques at a frequency of 17.3 Hz with currents of between 10 and 100 nA. The samples were initially characterized by placing them with the substrate perpendicular to the magnetic field direction ($\theta = 0°$) and measuring Shubnikov–de Haas oscillations between contacts on the planar regions and across the facet.

The mobility of the regrown 2DEG was found to be 245 000 cm^2 V^{-1} s^{-1} for a carrier concentration of 4.8×10^{11} cm^{-2} after illumination. These measurements showed that the carrier density was the same on the planar regions above and below the facet.

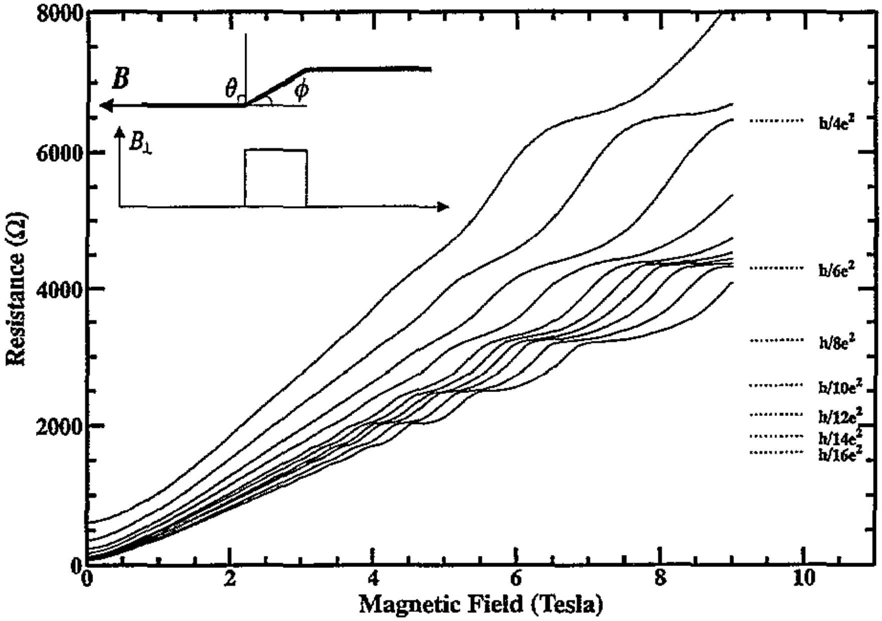

Figure 2. Magnetoresistance measured across the facet at a temperature of 1.4 K for gate voltages at 0.05 V intervals between 0.2 V (top trace) and 0.65 V (bottom trace). The magnetic field is applied in the plane of the substrate ($\theta = 90°$). The markers on the right-hand side show the expected quantized values.

With the magnetic field applied in the plane of the substrate ($\theta = \pm 90°$) there is a perpendicular component of field only on the facet. This was achieved by adjusting the sample orientation to minimize the Hall voltage on the planar region. For a total applied field of 10 T the perpendicular component on the plane was less than 5 mT and that on the facet was 3.2 T. The large in-plane component of magnetic field does not have a significant effect on the transport properties. Figure 2 shows the longitudinal magnetoresistance measured across the facet for a 5 μm wide mesa at 1.4 K at a series of gate voltages between +0.2 and 0.65 V. The magnetoquantum oscillations are periodic in $1/B$ with a series of plateaux appearing at resistances approximately given by $R = h/\nu e^2$, where ν is an even integer. One way to consider the sample in this configuration is to realize that we are injecting current from a region with no magnetic field and therefore a uniform density of states into a region where the energy is quantized in Landau levels, i.e. we can think of the planar regions of the sample as extended. high-mobility contacts to the facet. Therefore we are in effect performing a two-terminal magnetoresistance measurement on a short wide Hall bar whose dimensions are those of the etched facet and where the magnetic field is $B \sin \phi$. In such a situation it is well known that one measures both Hall and longitudinal resistance components, and rather than finding zeros at integer filling factors one obtains quantized plateaux (Fang and Stiles 1983). The reason we do not see accurate quantization of the resistance in this sample could be due to the fact that the facet Hall bar has a low aspect ratio

(0.6) and so the necessary correction to the quantized value will be very large if the Hall angle does not reach 90° (von Klitzing and Ebert 1984). The quantization is clearly worse for the higher-index Landau levels ($\nu > 10$). Another possible contribution could arise because electrons arriving in the 'contact' planar 2DEG region may travel a considerable distance before scattering (~3 μm) and therefore the full voltage drop may not appear between the two contacts closest to the facet (which are only 1 μm from the edge of the facet). This is discussed in more detail elsewhere (Leadbeater *et al* 1995). If we rotate the sample to $\theta = -70°$, the magnetic field lies in the plane of the facet so the perpendicular component is now zero on the facet and finite on the plane. We again see clearly defined plateaux in the longitudinal resistance measured *across* the facet as shown in figure 3.

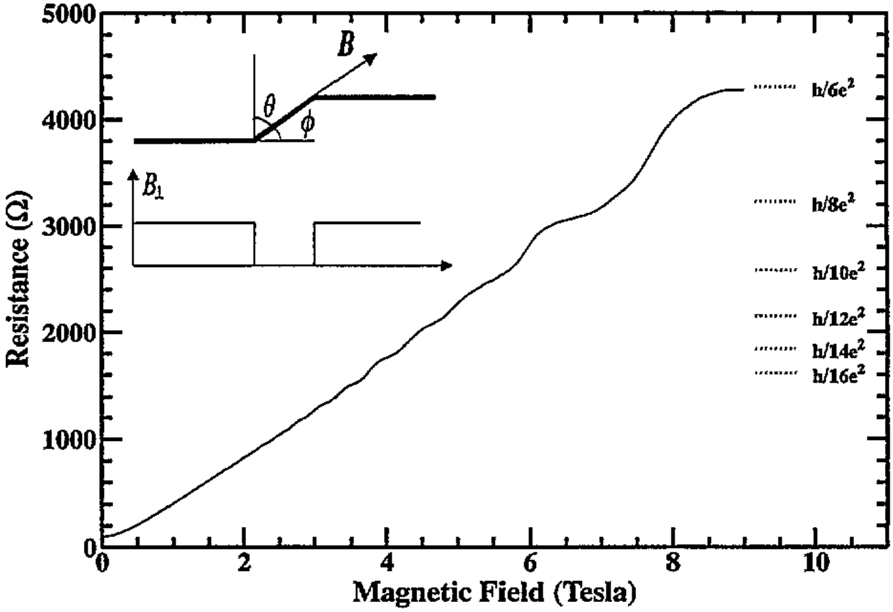

Figure 3. Magnetoresistance measured across the facet for a gate voltage of 0.5 V when the magnetic field is in the plane of the facet ($\theta = -70°$).

For a general angle we obtain magnetoresistance oscillations with different periods from measurements between probes across the facet and those on a planar region. The magneto-oscillation frequency is determined by the number density and the perpendicular component of magnetic field. The Hall voltage on the planar regions allows us to calibrate the sample orientation (θ). The best fit to the magneto-oscillation frequencies was obtained with number densities of 5.5×10^{11} cm^{-2} on the plane, 5.0×10^{11} cm^{-2} on the step, and a facet angle of $\phi = 20.2 \pm 0.5°$, in agreement with the SEM micrograph. The relatively small variation in number density shows that the use of *in situ* cleaning allows us to produce uniform growth. This is very important since we wish to be able to distinguish the effects of a change in field component from those due to a change in electron concentration.

When there is a finite component of magnetic field on both the facet and the plane of the substrate there is a different number of occupied Landau levels in each region. This situation is similar to the case of devices with an electrostatic gate covering part of the Hall bar (Haug *et al* 1988, Washburn *et al* 1988). This has been successfully described in terms of transport via edge states using the Landauer–Büttiker formula (Büttiker 1988). In this picture, the transport is governed by the electrochemical potentials (μ) of the contacts which are connected by one-dimensional states at the edge of the sample. The number of conducting channels on the plane is given by the filling factor ν_1. If the sample is tilted such that there is a higher perpendicular field component on the facet (i.e. $10° < \theta < 90°$), the number of edge states in that region is reduced to ν_2, as shown in the schematic diagram inset in figure 4. The current flows between probes 1 and 4 and the other contacts are voltage probes. If we assume that the transport is adiabatic (i.e. there is no coupling between the edge states) the four-terminal longitudinal resistance across the facet derived using the method described by Büttiker is given by

$$R_{14,23} = R_{14,65} = \left(h/e^2\right)\left(1/\nu_2 - 1/\nu_1\right) \tag{1}$$

and similarly the diagonal resistance is

$$R_{14,25} = h/\nu_2 e^2. \tag{2}$$

The other possible four-terminal resistances are $R_{14,36} = h/e^2(1/\nu_2 - 2/\nu_1)$ and $R_{14,26} = R_{14,35} = (1/\nu_1)h/e^2$. The physical result of this is that instead of measuring a zero in the longitudinal resistance across the facet at integer filling factors one observes a series of plateaux as successive edge states are reflected. It is interesting that although we do not have probes on the facet we can still measure the quantum Hall voltage on the facet by making the appropriate four-terminal measurement. The condition for observing reflection of edge states is firstly that we must have samples of sufficiently high mobility and be able to apply a large enough magnetic field to be in the edge state transport regime and secondly that we can tilt the field to an appropriate angle θ which can be found from the following equation:

$$\nu_1/\nu_2 = \cos\phi + \sin\phi\,\tan\theta. \tag{3}$$

This is harder to achieve in the magnetic system than the electrostatic case since we cannot sweep one filling factor independently of the other. However using equation (3) we can maintain a constant ratio between them.

Figure 4 shows the longitudinal ($R_{14,23}$) and diagonal ($R_{14,25}$) magnetoresistances measured across the facet and the Hall resistance on the plane ($R_{14,26}$) as a function of applied field for an angle of 77° where $\nu_1 = 3\nu_2$. The longitudinal resistance of the facet exhibits plateaux, although the measured resistances are again somewhat below the expected quantized values. There are several possible explanations for this: the sample may be incorrectly oriented so we do not have integer filling factors on both the plane and the facet at the same magnetic field, the perpendicular field may not be high enough (the longitudinal resistance on the plane does not quite go to zero), and there may also be some coupling between edge states across the facet since this is so narrow ($< 3\ \mu$m). The diagonal resistance $R_{14,25}$, on the other hand, is clearly well quantized. It is not apparent why the diagonal resistance should be much better quantized as the reasons given above for the lack of quantization across the facet would apply equally to this measurement.

The inset of figure 5 shows a schematic diagram of the edge states for the case where the filling factor on the facet is greater than that on the plane i.e. $\nu_1 < \nu_2$ for $(10° > \theta > -70°)$. If there were no coupling between edge states the longitudinal resistance would be zero; however if the additional edge states on the facet are coupled to the others, the resistance is again given by equation (1) (with ν_1 and ν_2 reversed). In this case the diagonal resistances

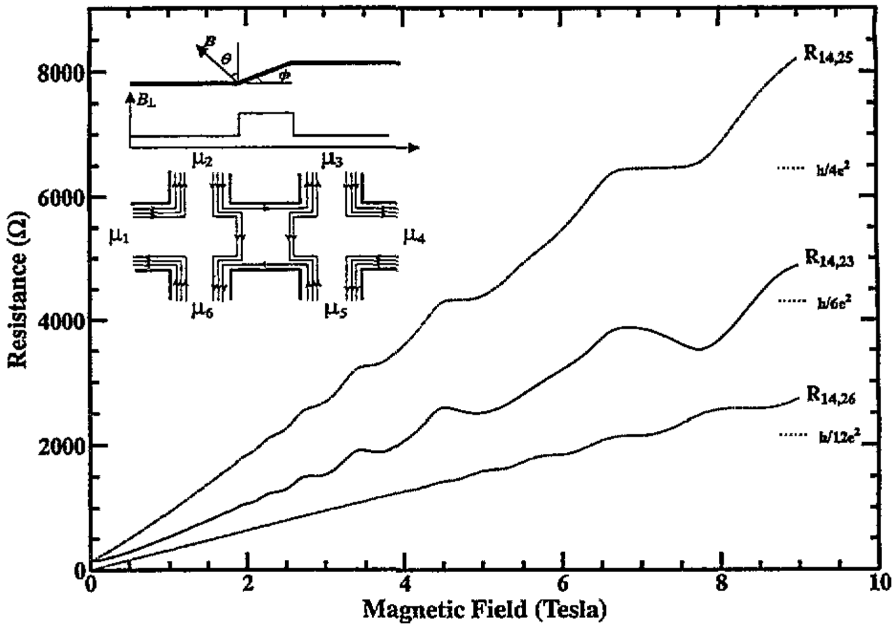

Figure 4. The longitudinal resistance $R_{14,23}$ and the diagonal resistance $R_{14,25}$ across the facet and the Hall resistance on the plane $R_{14,26}$ as a function of applied magnetic field with the field at an angle of 77° to the normal to the substrate. The perpendicular component of field is larger on the facet than on the plane. The inset shows a sketch of the orientation of the magnetic field and the variation of the perpendicular field component across the sample as well as the edge states for $\nu_1 = 3\nu_2$.

are $R_{14,25} = (2/\nu_1 - 1/\nu_2)h/e^2$ and $R_{14,36} = (1/\nu_2)h/e^2$. Figure 5 shows the longitudinal resistance of the facet $R_{14,23}$, the Hall resistance $R_{14,26}$, and the diagonal resistance $R_{14,36}$ at an angle of $\theta = -66°$ where $\nu_1 = \nu_2/3$. Plateaux are seen reasonably close to the expected values for the longitudinal resistance. This indicates that, in the region of the facet, there is strong coupling between the edge states. In this configuration the diagonal resistance is not as well quantized. It is not clear why edge states on the facet are coupled when they apparently are not on the planar regions (figure 4) or in experiments on gated samples where it has been found that there is no coupling over macroscopic distances (i.e. $> 100\ \mu$m) (Haug *et al* 1988, Komiyama *et al* 1989, Müller *et al* 1990), although it has also been argued that this decoupling only occurs for the highest-index edge states (Alphenaar *et al* 1990). One of the main differences between the electrostatically gated samples and the magnetic ones is that the transition between magnetic field regions occurs gradually over a distance of several hundreds of ångströms which may increase the probability of coupling. If there was a degree of decoupling of one or more of the edge states this would contribute to the lack of accurate quantization; however, given the fact that a number of other factors may also be responsible for this (as discussed above) we cannot with any confidence use the actual resistance values as a measure of the coupling between edge states in these samples at this point.

With the magnetically gated samples we can achieve a novel situation where we have opposite signs of field component in the different regions, as sketched in the inset to figure 6. In this case the edge states propagate in the opposite direction on the facet. Obviously this situation could not be obtained with an electrostatic gate. The longitudinal resistance would

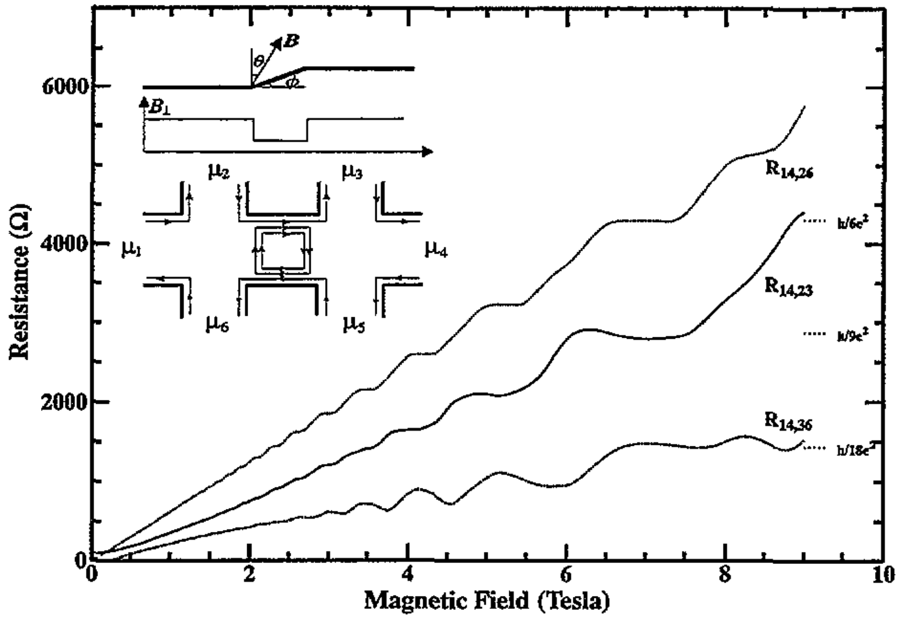

Figure 5. The longitudinal resistance $R_{14,23}$ and the diagonal resistance $R_{14,26}$ measured across the facet and the Hall resistance on the plane $R_{14,26}$ as a function of applied magnetic field with the field at an angle of -66° to the normal to the substrate. The perpendicular component of field is lower on the facet than on the plane. The inset shows a sketch of the orientation of the magnetic field and the variation of the perpendicular field component across the sample as well as the edge states for $\nu_1 = \nu_2/3$.

be infinite in the absence of coupling; if instead we assume perfect equilibration between levels on the facet and on the plane we find that the longitudinal resistance across the facet is given by

$$R_{14,23} = (h/e^2)(1/\nu_2 + 1/\nu_1) \tag{4}$$

and the diagonal resistance $R_{14,36} = -(1/\nu_2)h/e^2$. The edge states in the region where the field changes sign are the trochoidal states discussed by Müller (1992). These have a relatively large spatial extent compared to a state confined by the boundary of the sample and therefore it is quite reasonable that we find strong coupling between these states. Figure 6 shows the longitudinal, diagonal, and Hall resistances for an angle of $\theta = -86^\circ$ where $\nu_1 = 2\nu_2$. The longitudinal resistance is clearly given by the sum of the inverse filling factors rather than the difference as previously was the case.

In conclusion we have shown that by varying the topography of a 2DEG we have been able to produce a spatially non-uniform magnetic field. The resistance measured across a single facet is found to be approximately quantized. By making the appropriate four-terminal resistance measurement we are able to determine the filling factor on the facet. The deviation from accurate quantization is attributable to the very low aspect ratios of the samples studied and the degree of coupling between different edge states. It is probable that by using higher-mobility samples, lower temperatures, and higher magnetic fields the quality of the quantization would be improved. When the field is applied in the plane of the substrate, the measurement is equivalent to a two-terminal measurement of a planar 2DEG in a uniform magnetic field, with the planar regions acting as the source and drain contacts

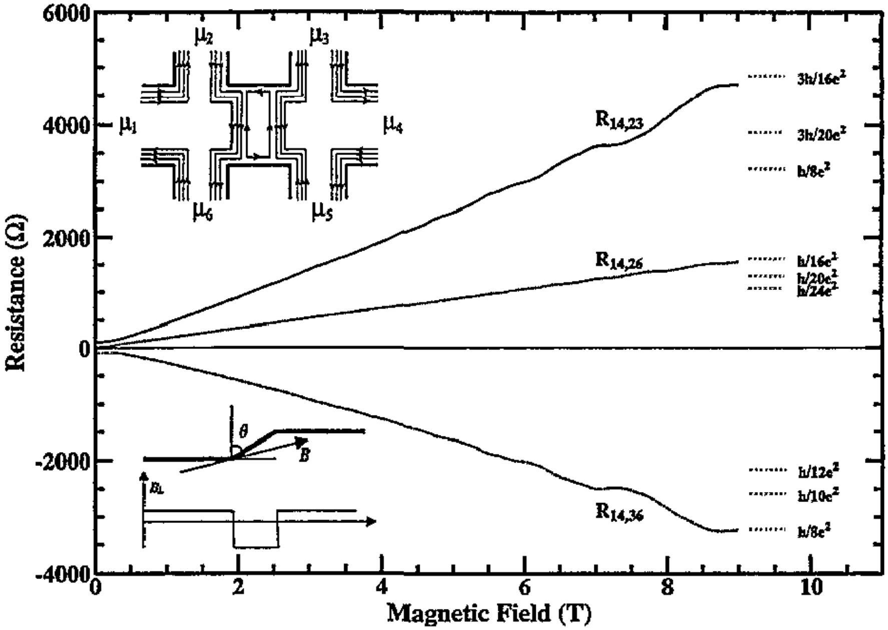

Figure 6. The longitudinal resistance $R_{14,23}$ and the diagonal resistance $R_{14,36}$ measured across the facet and the Hall resistance on the plane $_{14,26}$ as a function of applied magnetic field with the field at an angle of $-86°$ to the normal to the substrate. The normal component of the field is in opposite directions on the facet and on the plane. The inset shows the schematic orientation of the magnetic field and the variation of the perpendicular field component across the sample as well as the edge states for $\nu_1 = 2\nu_2$. Note that in this configuration the edge states on the facet circulate in the opposite direction to those on the step.

for a short and wide hall bar formed by the facet. By rotating the plane of the sample with respect to the magnetic field we are able to study the novel situation where the field component changes sign on the facet and the resistance is then found to be governed by the addition of the inverse of the filling factors.

The work in the Cavendish laboratory was supported by the EPSRC.

References

Alphenaar B W, McEuen P L, Wheeler R G and Sacks R N 1990 *Phys. Rev. Lett.* **64** 677

Bending S J, von Klitzing K and Ploog K 1990 *Phys. Rev. Lett.* **65** 1060

Büttiker M 1988 *Phys. Rev.* B **38** 9375

Carmona H A, Geim A, Nogaret A, Main P C, Foster T J, Henini M, Beaumont S P and Blamire M G 1995 *Phys. Rev. Lett.* **74** 3009

Chang M C and Niu Q 1994 *Phys. Rev.* B **50** 10 843

Dubrovin B A and Novikov S P 1980 *Sov. Phys.–JETP* **52** 511

Fang F F and Stiles P J 1983 *Phys. Rev.* B **27** 6487

Foden C L, Leadbeater M L, Burroughes J H and Pepper M 1994 *J. Phys.: Condens. Matter* **6** L127

Geim A K, Dubonos S V and Khaetskii A K 1990 *JETP Lett.* **51** 121

Haug R J, MacDonald A H, Streda P and von Klitzing K 1988 *Phys. Rev. Lett.* **61** 2797

Komiyama S, Hirai H, Sasa S and Hiyamizu S 1989 *Phys. Rev.* B **40** 12 566

Kruithof G H and Klapwijk T M 1988 *Proc. Int. Conf. on Physics of Semiconductors 19* ed W Zawadzki (Warsaw: Polish Academy of Sciences)

Leadbeater M L *et al* 1995 to be published
Meier H P, Van Giesen E, Broom R F, Walter W, Webb D J, Harder C and Jäckel H 1987 *Inst. Phys. Conf. Ser.* *91* (Bristol: Institute of Physics) p 609
Müller G, Weiss D, Koch S, von Klitzing K, Nickel H, Schlapp W and Lösch R 1990 *Phys. Rev.* B **42** 7633
Müller J E 1992 *Phys. Rev. Lett.* **68** 385
Peeters F M and Matulatis A 1993 *Phys. Rev.* B **48** 15 166
Van Roy W, Carpi E L, van Hove M, Van Esch A, Bogaerts R, De Boeck J and Borghs G 1993 *J. Magn. Magn. Mater.* **121** 197
Vasilopoulos P and Peeters F M 1990 *Superlatt. Microstruct.* **7** 393
von Klitzing K and Ebert G 1984 *Two-Dimensional Systems, Heterostructures and Superlattices* ed G Bauer, F Kuchar and H Heinrich (Berlin: Springer)
Washburn S, Fowler A B, Schmid H and Kern D 1988 *Phys. Rev. Lett.* **61** 2801
Ye P D, Weiss D, Gerhardts R R, Seeger M, von Klitzing K, Eberl K and Nickel H 1995 *Phys. Rev. Lett.* **74** 3013
Yoshioka D and Iye Y 1987 *J. Phys. Soc. Japan* **56** 448