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Magnetotransport in a nonplanar two-dimensional electron gas

M. L. Leadbeater, C. L. Foden, J. H. Burroughes, and M. Pepper*
Toshiba Cambridge Research Centre Ltd., 260 Cambridge Science Park, Milton Road, Cambridge CB4 4WE, United Kingdom

T. M. Burke, L. L. Wang, M. P. Grimshaw, and D. A. Ritchie
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 OHE, United Kingdom

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We investigate the magnetoresistance of a nonplanar two-dimensional electron gas (2DEG) fabricated by growth of a GaAs/(AlGa)As heterojunction on a wafer prepatterned with facets at 20° to the substrate. Applying a uniform magnetic field (B) produces a spatially nonuniform component of field perpendicular to the 2DEG. With the field in the plane of the substrate, the resistance measured across an etched facet shows oscillations that are periodic in $1/B$. This measurement is equivalent to a two-terminal measurement on a planar Hall bar in a uniform field. Magnetoquantum oscillations are also observed between voltage probes on planar regions of the sample located directly adjacent to the facet where there is no perpendicular field component. These are interpreted as being due to current propagating out from the corners of the facet along the edges of the mesa in a similar fashion to the current in a conventional planar Hall bar, which enters and leaves from diagonally opposite corners. In samples with an even number of facets the symmetry of the magnetoresistance is reversed, consistent with this interpretation.

The development of regrowth technology using *in situ* cleaning techniques means that we can now investigate the effects of varying the *topography* of an electron gas in addition to varying the dimensionality.[1] We produce a shaped two-dimensional electron gas (2DEG) by etching a series of facets on the starting wafer, cleaning in a hydrogen plasma, and then growing a remotely doped GaAs/$Al_xGa_{1-x}As$ heterojunction. The electron gas is confined to a sheet at the interface between the GaAs and $Al_xGa_{1-x}As$ layers but this interface is no longer planar. The use of *in situ* cleaning with a hydrogen plasma enables us to produce a uniform electron gas on the etched and unetched regions.

If we apply a uniform magnetic field to this nonplanar 2DEG, the perpendicular component of the field varies with position, depending on the angle (θ) between the field and the normal to the facet. This offers a flexible technique to investigate the physics of electron motion in a nonuniform field.[2–6] Alternative techniques rely on the deposition and patterning of layers of superconductors or ferromagnets.[7–10] These have the disadvantage that they produce only a relatively small modulation in the applied field and there are comparable effects due to the strain induced by the patterned gate. Using the regrowth technique we have complete control over the shape of the 2DEG and, by varying the strength and direction of the applied field, can produce a field modulation of several tesla, and achieve the situation of reversing the sign of the perpendicular field component on neighboring facets.

A (100)GaAs wafer was etched to produce a 3-μm-long facet at an angle of 20° to the substrate. Following an *in situ* cleaning with a hydrogen radical flux the wafer was transferred under vacuum to the molecular-beam-epitaxy growth chamber where a modulation-doped heterostructure was grown 2000 Å from the original interface. Details of the cleaning procedure and growth are given elsewhere.[11] Hall bars with width 40 μm were fabricated using standard techniques. The etched facet is situated between voltage probes 10 μm apart. Other pairs of voltage probes on either side of the facet were used to measure the 2DEG in the planar regions alone. A schematic diagram of the Hall bar is given in Fig. 1; the probes are numbered for ease of reference. The current is passed between probes 1 and 8 in all cases. Four-terminal resistance measurements were made at 1.4 K using conventional ac lock-in techniques with a constant current in the range 10–500 nA. No dependence on the magnitude of the current was found within this range. The samples were initially measured with the substrate perpendicular to the magnetic-field direction ($\theta=0°$). Figure 2 (lower trace) shows a typical Shubnikov–de Haas trace for the longitudinal magnetoresistance measured across the facet (voltage probes 4 and 5). The data show well-defined zeros at integer filling factors. The mobility of the regrown 2DEG was 245 000 $cm^2/V\,s$ at 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. This demonstrates the importance of the

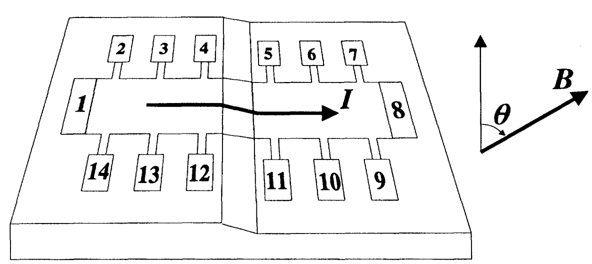

FIG. 1. Schematic diagram of the Hall bar showing the relationship between the etched facet and the voltage probes. The facet is at an angle of 20° to the substrate. The magnetic field is applied at an angle θ to the normal to the substrate. In all measurements the current flows between probes 1 and 8.

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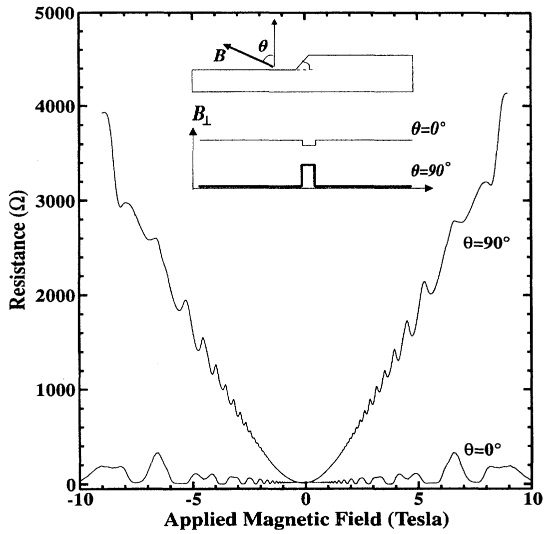

FIG. 2. Magnetoresistance measurement across a single facet (voltage probes 4 and 5) with the magnetic field applied perpendicular to the substrate ($\theta = 0°$) and in the plane of the substrate ($\theta = 90°$) at a temperature of 1.4 K. The current is between probes 1 and 8. The inset sketches the variation of the perpendicular field component across the sample.

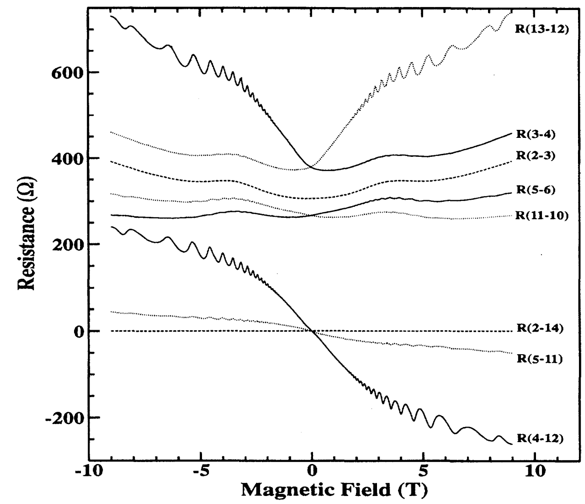

FIG. 3. Four-terminal resistance measured using pairs of voltage probes on the planar regions of the sample plotted against magnetic field for $\theta = 90°$. The perpendicular component of magnetic field is zero in these regions. Note the strong asymmetry with the sign of the applied field. The current flows between probes 1 and 8.

in situ cleaning as samples that did not undergo this process showed much greater nonuniformity.

With the magnetic field (B) applied in the plane of the substrate ($\theta = 90°$), only the facet experiences a perpendicular component of field. This is confirmed by the fact that the Hall voltage measured on a planar region of the sample well away from the facet was zero. Figure 2 (upper trace) shows the magnetoresistance measured across the facet (voltage probes 4 and 5, current probes 1 and 8). A series of magneto-oscillations are observed that are periodic in $1/B$. The resistance across the facet increases from 13 Ω at $B = 0$ T to 4135 Ω at 9 T, a ratio of 320. This positive magnetoresistance persists to high temperatures ($T > 100$ K), indicating that it is of classical origin. In this configuration, we can think of the planar regions of the sample as high-mobility leads connecting the facet to the voltage probes and we are in effect performing a two-terminal magnetoresistance measurement on a short wide Hall bar (aspect ratio 0.075) where both Hall and longitudinal resistance components are measured, and instead of zeros at integer filling factors, quantized plateaus are observed.[12] The reason we do not see quantized plateaus in this sample could be the low aspect ratio. Samples with a higher aspect ratio have been shown to give better quantization.[11]

If we measure the resistance between voltage probes on the planar regions, there is no perpendicular component of magnetic field in this orientation and we would not expect to see any field dependence. However, we find that for probes directly adjacent to the facet there is a strong magnetoresistance that depends on the direction of the applied magnetic field. Figure 3 shows the four-terminal magnetoresistance between voltage probes on planar regions adjacent to the facet. The top two curves show the resistance for probes above the facet on the left (12-13) and right (3-4) of the Hall bar and the center two curves show the equivalent pairs (10-11) and (5-6) for the region immediately below the facet. Again the current is passed between probes 1 and 8. A pronounced asymmetry with field direction is shown in all four traces. Pairs of probes on opposite sides of the mesa and opposite sides of the facet show the same symmetry with applied field direction, i.e., the voltage measured between probes 5 and 6 and between 11 and 10 is high when that between 3 and 4 and between 13 and 12 is low. The fact that the asymmetry is larger for the probes situated in the region above the facet may be because the facet is not exactly equidistant from the pairs of voltage probes. We also observe magneto-oscillations imposed on the positive background magnetoresistance that have the same periodicity as those measured directly across the facet (see Fig. 2). Figure 3 also plots the longitudinal magnetoresistance measured between two voltage probes well away (>50 μm) from the facet (probes 2-3). This resistance is symmetric in field and no magneto-oscillations are observed. There is a broad peak at 4 T in this curve that was not observed in Hall bars that did not cross an etched facet. The origin of this feature is not presently understood. We also measure a voltage between Hall probes that are close to the facet (i.e., 4-12 and 5-11) but not between those which are well removed from the facet (probes 2-14). The periodicity of the magneto-oscillations in the Hall voltage again matches that of those in the longitudinal magnetoresistance. These are plotted as the lower three traces in Fig. 3.

These data are remarkable because we see magneto-oscillations in a region that does not experience a perpendicular magnetic field. The periodicity of the oscillations matches that of the measurement directly across the facet and therefore must be associated with the magnetic field on the facet. They cannot be accounted for by the residual perpendicular field (<5 mT) or by the parallel field as there would be no asymmetry with the sign of the field. We can understand these results by again considering the facet to be a Hall bar and the planar regions to be large leads connected to the

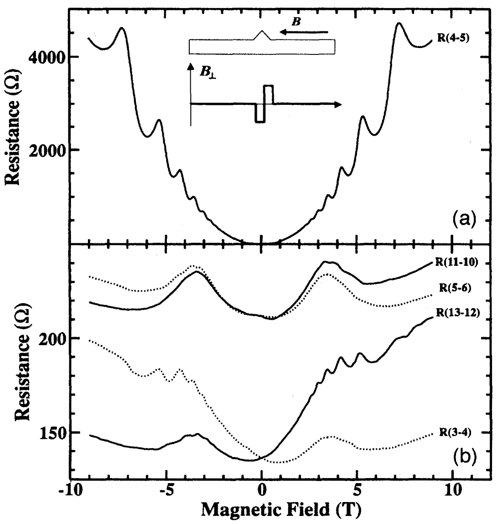

FIG. 4. Four-terminal magnetoresistance for a sample with an etched ridge when the field is applied in the plane of the substrate ($\theta = 90°$). (a) Resistance measured across the ridge and (b) resistance measured using voltage probes on the planar regions directly adjacent to the ridge.

probes. When current is injected into a Hall bar it enters through a small area at one corner and exits through the diagonally opposite corner. We observe different resistances on opposite sides of the Hall bar, which implies that the injected current is propagating along one side of the mesa. The electrons injected from the facet into the zero perpendicular field region travel a considerable distance before they equilibrate with the rest of the 2DEG, i.e., contact to the facet is made some characteristic scattering length away from the edge of the facet. If the distance between a voltage probe and the facet is less than this length, the potential measured is influenced by the magnetic field on the facet. When the magnetic-field direction is reversed, current flows from the opposite pair of corners of the Hall bar, which explains the asymmetry of the magnetoresistance. The distance at which the magneto-oscillations die out depends on the amount of scattering in the system and therefore on the sample temperature and mobility. Normally the contacts to a semiconductor system are highly disordered; in contrast, here we have a system with extremely high mobility contacts. An asymmetry in the magnetoresistance was seen even in the case where the voltage probes were 80 μm from the facet.

We have also measured samples with a 2DEG regrown over an etched ridge. The ridge is 1 μm wide and etched to a depth of 1500 Å. Figure 4(a) shows the resistance across the ridge (probes 4-5) with the magnetic field in the plane of the substrate. The frequency of the magneto-oscillations across the ridge differs from that of the single-facet sample. The etch depth for a ridge is less than the depth of the regrown material (2700 Å), which may produce some planarization during regrowth. There is a threshold at $B = 0.7$ T, above which the resistance increases rapidly. The cyclotron radius at the threshold field is approximately half the length of the facet, i.e., until the cyclotron orbit can fit within the facet, Landau levels do not form and the magnetoresistance is suppressed. For the single-facet devices the equivalent field is less than 100 mT and no threshold was observed.

If we measure the four-terminal resistance using a pair of voltage probes on the planar region adjacent to the ridge we can again see magneto-oscillations although there is no perpendicular field. Figure 4(b) plots these oscillations for pairs of probes on different sides of the mesa both above the ridge (3-4 and 13-12) and below the ridge (5-6 and 11-10). The current flows between probes 1 and 8. The symmetry is between pairs on the *same* side of the Hall bar, i.e., 3-4 and 5-6 are high in the positive field direction when 13-12 and 11-10 are low, whereas for single-facet devices diagonally opposite pairs of probes were matched. We consider a ridge to consist of two Hall bars in series with alternating signs of magnetic field; the current enters a corner of the first facet on (say) the right-hand side of the mesa and exits from a corner of the second facet on the same side of the mesa. This confirms our picture of the facet as a Hall bar surrounded by large contact regions where there is no magnetic field. At the apex of the ridge the perpendicular field component changes sign. This situation has been modeled by Müller[5] who predicted the appearance of one-dimensional states confined to the apex of the ridge. In the present measurements we do not see effects that we can assign to these states.

In conclusion, we have produced a nonuniform perpendicular component of magnetic field in a 2DEG grown over a prepatterned substrate. By rotating the direction of the applied field we can produce a situation where there is a perpendicular component of magnetic field in only one small region of the sample. Magneto-oscillations are observed in the resistance measured across the facet as well as in regions of the sample where the perpendicular field is zero. These are due to current being injected from the corners of the etched facet in the same way that the current in a conventional Hall bar enters and leaves through diagonally opposite points. This nonequilibrium current then propagates a considerable distance through the planar 2DEG lead without undergoing scattering and hence the planar region is influenced by the magnetic-field component on the facet. The magnetoresistance between probes adjacent to the facet is strongly asymmetric with respect to the sign of the applied field. In samples with an even number of facets the symmetry of the magnetoresistance is reversed, i.e., pairs of probes on the same side of the Hall bar show similar behavior, whereas for an odd number of facets diagonally opposite pairs are matched. The technique of regrowth on a prepatterned substrate is generally applicable for the production of a wide variety of magnetic-field profiles, in particular, we can produce field components of opposite signs on neighboring facets.

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*Also at Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom.

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