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Vanishing Hall voltage in a quasi-one-dimensional GaAs-Al$_x$Ga$_{1-x}$As heterojunction

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We have measured the Hall voltage developed across a narrow, high-mobility two-dimensional electron gas of variable width. For narrow channels, the Hall voltage vanishes when the perpendicular magnetic field is reduced below a certain, critical value. If the magnetic field is kept constant as the width of the channel is reduced, the Hall voltage shows large departures from the classically expected result.

The Hall effect in narrow, high-mobility channels has recently been the subject of much interest especially since Roukes *et al.*[1] observed a vanishing Hall voltage for small magnetic fields. In their work the width of the channel was fixed in a given device and to observe systematic trends as the width was varied the authors had to look at a number of different devices. In this paper we present results from devices in which the channel width can be continuously varied electrostatically.

Electrostatic confinement of a two-dimensional electron gas (2D EG) has been used to observe 1D transport in narrow channels,[2-5] the Aharonov-Bohm effect in rings,[6] and a unique quantization of the resistance of small constrictions.[7,8] In each case reverse biasing the Schottky barrier gate on the surface of a GaAs-Al$_x$Ga$_{1-x}$As heterojunction is used to confine the 2D EG. The gate patterns are defined in polymethylmethacrylate (PMMA) resist by electron beam lithography. For ring structures and the multiprobe geometries used in this work it is convenient to use the PMMA resist as a dielectric layer to separate the gate metal from the surface of the heterojunction. The gate is biased so that it removes electrons only where the metal is in contact with the heterojunction surface, leaving a conducting channel beneath the dielectric. For the samples used in these experiments the PMMA dielectric is shaped as a Hall bar of width 1 μm, with ~ 3 μm between voltage probes. The Hall bar pattern is defined in the 2D EG for gate voltages $V_g \leq -0.6$ V. By increasing the reverse bias to the gate the width of the channel can be continuously reduced from 0.9 μm to ~ 0.1 μm (see below) until it pinches off at $V_g \sim -3.25$ V. Further details of the construction of these types of devices can be found elsewhere.[9]

Figure 1 shows R_{xx} and R_{xy} up to 12 T for a number of different gate voltages and it is evident that decreasing the gate voltage reduces the carrier concentration in the channel. For the wider channels ($V_g \sim -2.2$ V) the carrier concentration determined from the Hall voltage and the Shubnikov-de Haas oscillations agree to within the accuracy of the measurement. However, for biases $V_g < -2.2$ V the results are ambiguous because of large fluctuations in the Hall voltage.[10] Fortunately, the uncertainty is only significant (i.e., greater than 20%) for the narrowest channels ($V_g \leq -2.8$ V) and for gate voltages in the range

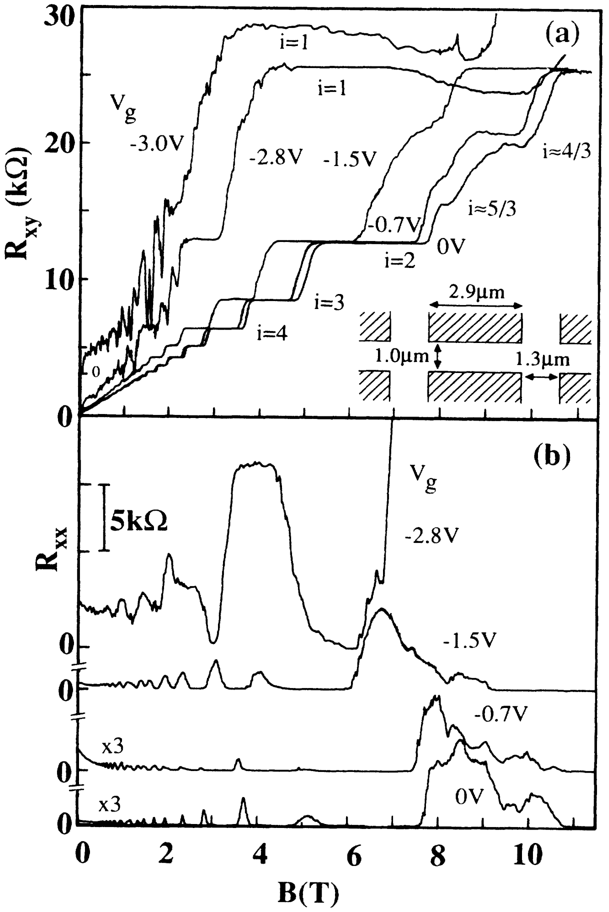

FIG. 1. (a) The Hall resistance R_{xy} for a range of gate voltages and temperature $T < 100$ mK. The filling factors, i, of the various plateaus are indicated. For the case $V_g = 0$ the narrow channel is not properly defined in the 2D EG so that R_{xx} and R_{xy} are measured across the mesa etched Hall bar which is 25 μm wide with 100 μm between voltage probes. The inset shows the geometry of the gate electrodes (shaded) which are used to confine the narrow channels. The curve for $V_g = -3.0$ V is offset for clarity. (b) The magnetoresistance corresponding to most of the Hall resistances shown in (a). The vertical axes for the lower two curves are expanded by a factor of 3, and the curves are offset as shown.

$-2.8 \leq V_g \leq -0.6$ V the carrier concentration is quite well described by the expression $n(10^{15}\ \mathrm{m}^{-2}) = 3.49 + 0.542V_g - 0.049V_g^2$.

In Fig. 1(a), along with the integer quantum Hall plateaus, we have indicated the expected positions of the $\frac{4}{3}$ and $\frac{5}{3}$ fractional plateaus. For $V_g = -0.7$ V ($w \sim 0.84$ μm, see below) there is a broad feature in R_{xy} at an approximately quantized $\frac{4}{3}$ value (with a corresponding minima in R_{xx}). This structure suggests the presence of a poorly developed fractional state which has all but disappeared for $V_g = -1.5$ V ($w \sim 0.65$ μm). We note that in our samples the reduction in mobility with carrier concentration[11] may be responsible for the disappearance of the structure[12] in R_{xy} at $\frac{4}{3}$ filling factor.

For small magnetic fields ($B < 0.1$ T) our samples show a quenching of the Hall voltage similar to that first reported by Roukes *et al.*[1] With our electrostatically defined channels it is possible to measure the Hall voltage as a function of channel width, and typical results are shown in Fig. 2 for different values of perpendicular magnetic field. The value of R_{xy} has been multiplied by the carrier concentration so that deviations from the classical result $R_{xy}n = B/e$ can be seen clearly. When the magnetic field exceeds a certain value B_t the product $R_{xy}n$ is reasonably constant about the value of B/e (top trace of Fig. 2). However, as B approaches the critical field the value of $R_{xy}n$ drops below the classical result as the width of the channel is reduced. Eventually, when $B < B_t$, the Hall voltage vanishes below a certain gate voltage and then fluctuates about a mean value of zero as the width is reduced to pinch-off. The fluctuations are strongly temperature dependent and have all but vanished for temperatures above 1.2 K. We attribute them to nonlocal effects arising from quantum interference between phase coherent electrons.[10,13] On the other hand, the vanishing Hall voltage is essentially independent of temperature up to 4.2 K.

In Fig. 3, R_{xx} and R_{xy} are shown as a function of magnetic field for the region in which quenching occurs. Even for comparatively wide channels in which the Hall voltage is not quenched ($V_g > -2.2$ V) there is still an anomalous change in the gradient at magnetic fields in the range 0.10–0.15 T. This field correlates with the field at which the large negative (or in some cases positive then negative) magnetoresistance begins to drop less rapidly. Similar anomalies have been attributed to the recovery of classical behavior when the cyclotron length, $L_c \sim \hbar k_F/eB$, is less than the channel width[14] (k_F is the Fermi wave vector). Such an interpretation is consistent with our data.

For $V_g < -2.2$ V the Hall voltage is quenched at low enough fields and fluctuates reproducibly about zero. The fluctuations are much less pronounced at higher temperatures and in Fig. 4 we show the quenched region of R_{xy} for a large number of gate voltages at a temperature of ~ 1.2 K. Each of the curves has been offset by an amount proportional to the width of the channel. The channel width cannot be readily determined from the structure of the device but can be inferred by a number of methods. In particular, Berggren, Thornton, Newson, and Pepper[4] have shown that the minima in R_{xx} depart from the usual $1/B$ periodicity at low fields and this occurs because of the presence of one-dimensional subbands. Assuming a parabolic confining potential the width of the channel can be obtained from the minima in R_{xx} and using this method

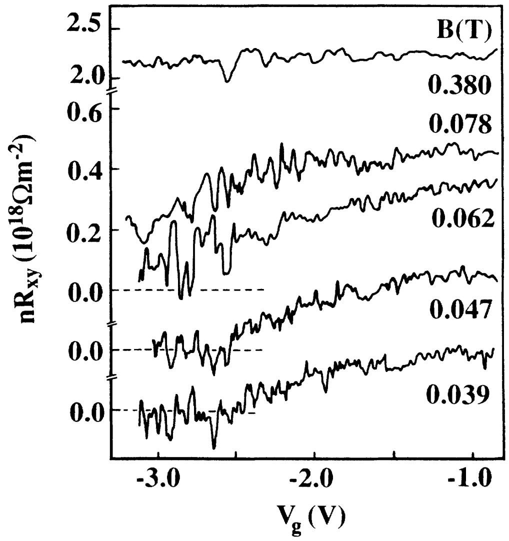

FIG. 2. The product of the Hall resistance R_{xy} and the carrier concentration n as a function of gate voltage for different values of the magnetic field. The origins of the lower two curves have been offset while the scale for the uppermost curve has been reduced by a factor of 3. ($T < 100$ mK.)

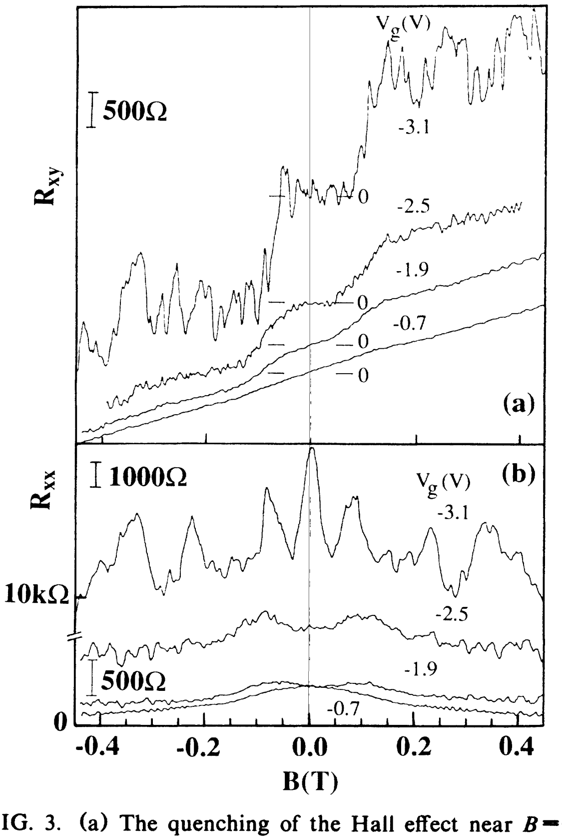

FIG. 3. (a) The quenching of the Hall effect near $B = 0$ at $T < 100$ mK and (b) the corresponding magnetoresistance for a range of gate voltages similar to those in Fig. 1.

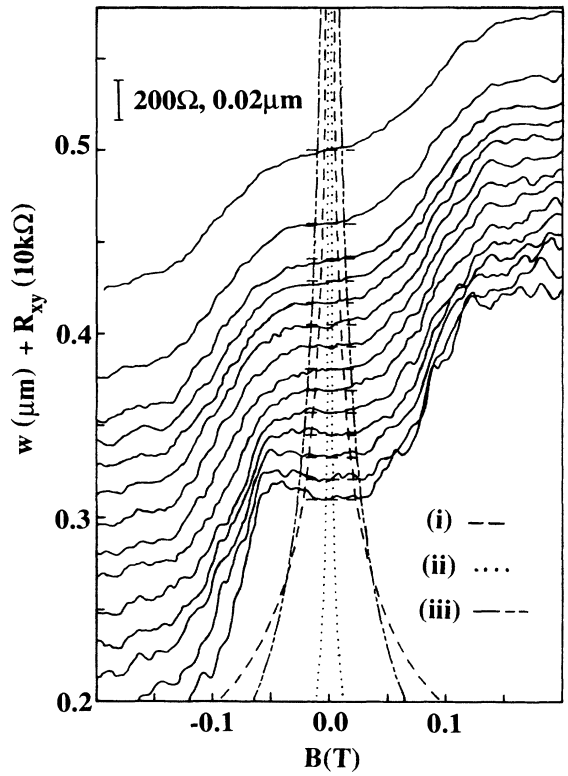

FIG. 4. The quenched region of the Hall resistance for a large number of gate voltages. The curves (measured in units of 10 kΩ) have each been offset by an amount equal to the estimated width in μm. The width in each case can be read off the vertical axis from the point at which the curve crosses the $B=0$ line. The data are presented in this fashion so that the width of the quenched region can be compared to the expressions (i) $B_t=16(h/e)k_F^{-1}w^{-3}$ which has a prefactor chosen (arbitrarily) to give better agreement than (ii) $B_t=2(h/e)k_F^{-1}w^{-3}$ (see text). For comparison we also plot (iii) $B=4(\hbar/e)w^{-2}$ obtained by equating the width to twice the magnetic length given by $(\hbar/eB)^{1/2}$.

we find that the width varies with gate voltage as $w(\mu m)=0.94+0.12V_g-0.041V_g^2$. The main problem associated with this form of analysis is the assumption of a parabolic confining potential. Numerical calculations[15] suggest that the true confining potential is somewhere between that of a square well and a parabola. The difference in width for the two types of potential is expected to be small and we note that the expression for w given above is consistent with results derived by other methods.[16,17]

Recently, Beenaker and van Houten[14] have proposed an explanation for the quenching of the Hall effect. They suggest that the suppression of edge states leads to a vanishing Hall voltage below a threshold field given by $B_t \sim 2(h/e)k_F^{-1}w^{-3}$. They were successful in fitting this expression to the results of Roukes *et al.* In Fig. 4 we plot the locus of points given by the expression for B_t using the values of $k_F=(2\pi n)^{1/2}$ and w appropriate to each gate voltage. Clearly there is a large discrepancy between the value of B_t and the region of B over which the Hall voltage in our devices can be described as quenched. The agreement is better if the expression for B_t is multiplied by a value of ~ 8. Alternatively, our estimates of the width could be too high by a factor of 2. Although this is not impossible we consider it to be highly unlikely and we will present alternative theories for the effect elsewhere.[18]

As well as explaining how the critical field depends on the width of the channel, any theory for the quenching of the Hall voltage must explain how the magnitude of R_{xy} varies with the channel width. This problem has so far not been considered theoretically. Our experimental results (Fig. 2) show that once the channel is wide enough that the Hall voltage is no longer quenched, the product nR_{xy} approaches the value B/e in an asymptotic fashion as the width is increased.

As the magnetic field is increased above the threshold value the Hall resistivity R_{xy} rises steeply from zero to form a plateaulike feature [Figs. 1(a) and 3(a)]. Indeed, Roukes *et al.*[1] have attributed this to the last quantum Hall plateau with a Hall resistance given by $R_{LP}=h/2Ne^2$ where N is the number of one-dimensional subbands present at zero field. Our results show that the Hall resistance of this feature is approximately described by the value of R_{LP} with the value N agreeing with the number of subbands expected from our estimates of the channel width. However, fluctuations and a finite slope ensure that the measured value is not accurately quantized. Further work is needed before this feature can be attributed unequivocably to the "last plateau."

In conclusion, we have measured the longitudinal and transverse resistance of a narrow 2D EG of variable width, and have observed a vanishing Hall voltage as the width of the channel is reduced provided the magnetic field is less than a threshold value B_t.

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