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Distribution of the quantized Hall potential in GaAs-$Al_xGa_{1-x}As$ heterostructures

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We report measurements of the Hall potential distribution in the interior of the two-dimensional electron gas in GaAs-Al_xAs heterostructures. In the quantized Hall regime, our data provide direct evidence for the existence of extended states in the bulk of a two-dimensional system. Bunching of the potential distribution is observed as a function of the quantizing magnetic field and is attributed to the presence of density gradients as the dominant macroscopic inhomogeneities.

In the quantized Hall effect, the distribution of the Hall potential in the interior of the sample remains an important but unresolved problem. Two physical pictures are presently available. One is based on the existence of extended states at the edges of the sample.[1] The Hall current is believed to be primarily the net difference between two oppositely directed currents carried by these edge states. In the absence of electron-electron interactions, all the current would flow along the edges[2] and no potential drop would be expected in the interior of the sample. The other is a semiclassical, percolation picture, wherein the Hall current is described as the flow of an incompressible fluid of charge carriers around potential barriers.[3-6] Kazarinov and Luryi[5] pictured the current-carrying states as electronic waves propagating along the equipotential lines, like light waves in optical fibers, extending through the entire length of the sample. These extended states exist in the bulk of the two-dimensional (2D) electron system and the Hall potential is distributed throughout the sample.

Fang and Stiles[7] have recently carried out an extensive study of the potentials in the quantized Hall regime, at the periphery of the sample. They find that the sample edges form equipotential lines; one of which is at the quantized Hall voltage, the other at the ground potential. In order to obtain information on the potential distribution in the interior of the sample, we have studied in detail the potential distribution inside several samples, in the well-quantized regimes. Our data indicate that the Hall potential is distributed throughout the interior of the sample, consistent with the semiclassical percolation picture. They provide, for the first time, direct evidence that current-carrying extended states indeed exist in the bulk of the 2D electron system. The Hall current is able to flow around the Ohmic metal contacts placed in the sample interor, while maintaining a quantized Hall voltage across the sample. In the well-quantized regime, the interior Ohmic contacts show extremely high source impedance. This experimental fact suggests that near each contact, the 2D electrons flow almost completely along closed, constant potential lines surrounding the contact. Excitation of current flow across them to charge or discharge the contact becomes increasingly more difficult as temperature T decreases and is impossible at $T=0$. In all our samples, the crystal-growth processes invariably give rise to density variations, usually in the form of a gradient along a well-defined direction. It is found that this type of macroscopic inhomogeneity, though dominant in determining the flow pattern of the Hall current in the sample, does not disturb the quantization of the Hall resistance.

Both conventional Hall bridge and Corbino-type geometries are used in our measurements. The samples are typical modulation-doped GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructures[8] grown by molecular-beam epitaxy (MBE). They are single-interface structures with a 2D electron density $n=3.9\times10^{11}$ cm^{-2} and a mobility $\mu=5.9\times10^4$ cm^2/V sec at 4.2 K.

In order to measure the potential distribution in the interior of a sample, several indium dots, each ~50 μm in diameter, are evenly placed inside the sample, along a line perpendicular to the direction of the Hall current. The detailed configuration for a Hall bridge is shown in the inset of Fig. 1. Ohmic contacts to the 2D electrons are formed by alloying the In dots at 400 °C in a hydrogen atmosphere. Subsequently, the electrical contacts are carefully tested to ensure Ohmic behavior. In view of the high source impedance, mentioned above for contacts in the interior of the sample in the quantized regime, great care was taken to assure that there were no spurious contributions in our measurements. One consequence of this high source impedance is the long-time constant in the measurement. We optimized it by choosing samples with densities to have the $i=2$ quantized Hall plateau (i.e., the plateau at $\rho_{xy}=h/2e^2$ $=12.90$ kΩ) close to $B=8$ T. In such samples, the diagonal conductivity σ_{xx} is sufficiently small to warrant quantization of the Hall resistance to better than one part in 10^5, but not so small as to give rise to a time constant in excess of 5 min and to make the influence of stray capacitance appreciable. We use an electrometer (Keithley 642) with an input impedance of 10^{16} Ω to avoid loading down the source voltage. During measurement, the total Hall voltage across a Hall bridge is always monitored with a digital voltmeter to make sure it retains the quantized value. Furthermore, the potential at an interior contact is measured from both edges of the Hall bridge, at separate times, to check for consistency.

In Fig. 1, we show the variation of the internal potentials as a function of magnetic field B, measured at different interior contacts with respect to one edge of the sample. In contrast to a smooth change over a plateau region, which

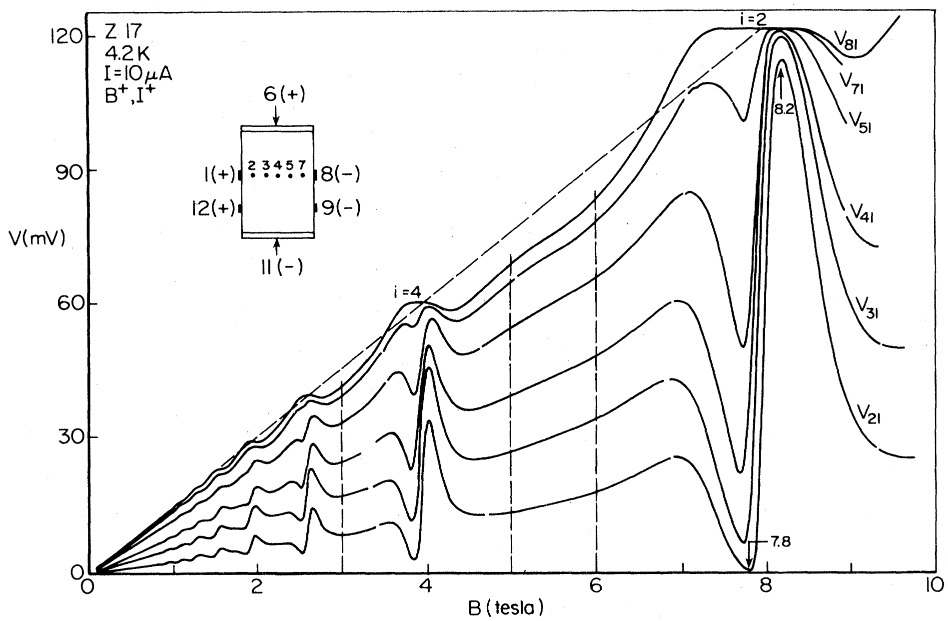

FIG. 1. The potentials as a function of B measured at different interior contacts with respect to contact No. 1 on one edge of the sample. The quantized plateau corresponding to $\rho_{xy} = h/2e^2 = 12.90$ kΩ is labeled by $i = 2$ and the dashed line indicates the expected Hall voltage in the classical limit. The sample configuration and the contact arrangement are shown in the inset.

one might expect, the internal potentials vary tremendously with magnetic field. This kind of change is more pronounced in the $i = 2$ plateau, within which the total Hall voltage across the sample remains constant to better than one part in 10^4. The complementary potential drop between different interior contacts and the opposite edge is separately measured, and shown in Fig. 2. Within our experimental error of 1%, any two complementary potentials add up to the total quantized Hall voltage. Therefore, we are confident that our results show minimal influence from impedance problems. Our results for $B \lesssim 5$ T are very similar to the results obtained by Sichel, Sample, and Salerno.[9] At these low magnetic fields, the quantized Hall plateaus are not sufficiently well developed to allow unambiguous conclusions. The normalized potential distribution across the sample is plotted in Fig. 3 for several magnetic fields. Outside the quantized regions, for $B = 3$, 5, and 6 T, a fairly uniform distribution is obtained. Within the $i = 2$ plateau,

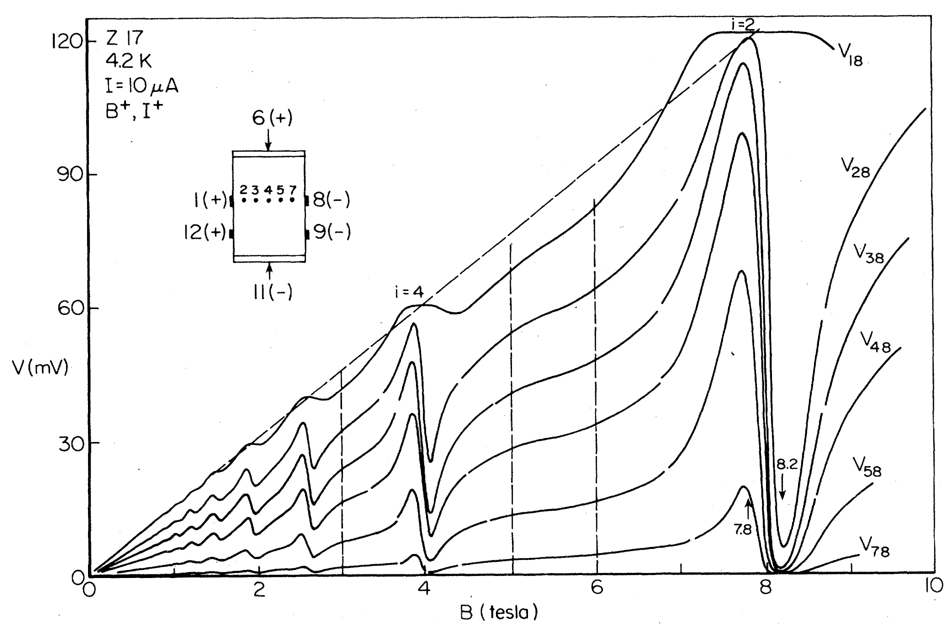

FIG. 2. The potentials measured at different interior contacts with respect to contact No. 8 on the opposite edge of the sample.

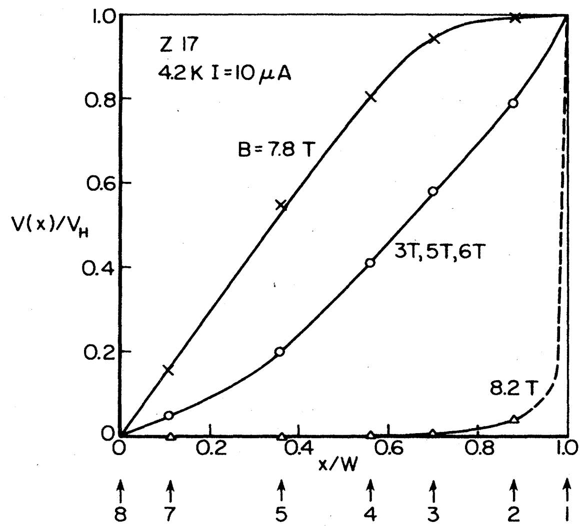

FIG. 3. Potentials measured an x with respect to contact No. 8 on one edge of the sample at several values of B. W is the width of the sample and V_H is the total Hall voltage. The arrows indicate the position of the labeled contacts at which the data are taken.

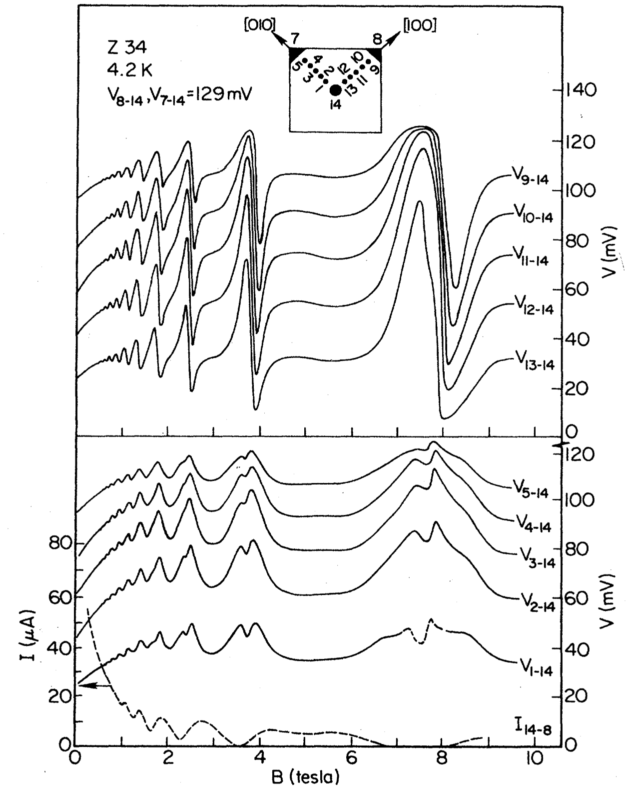

FIG. 4. The potentials as a function of B measured at different interior contacts with respect to the center contact No. 14, of a Corbino-type sample. The inset shows the contact arrangement.

at $B = 8.2$ T, the Hall potential drops almost its total value within one tenth of the width of the Hall bridge, near one edge of the sample. This field of 8.2 T is higher than the field at the plateau center, $B_c = 7.8$ T, when the lowest two Landau levels are completely filled. Below B_c most of the potential drop occurs at the opposite edge. At the central field, 7.8 T, the Hall potential is distributed almost uniformly throughout the bulk of the sample. We have verified that the observed bunching effect in the distribution always occurs at a given edge at a given field, regardless of the polarity of the current or the polarity of the applied magnetic field. Similar results have been obtained in samples made from different crystals.

Our present understanding of this dramatic bunching effect is based on the presence of a gradient in the 2D electron density of the sample in the direction of the Hall field. Such density gradients have already been found in similarly grown crystals.[10] Within the quantized region, the diagonal resistivity ρ_{xx} is known to increase exponentially, over several orders of magnitude,[11] as the magnetic field deviates from the central field of the plateau. In other words, when the local 2D electron density and the magnetic field are well matched so as to satisfy the filling condition $n = ieB/h$ (where i is the Landau level index, e the electron charge, and h the Planck constant), ρ_{xx} is minimal. The Hall current, always seeking the path of minimal resistance, will bunch in this region of the sample. This observation explains qualitatively the bunching, as well as the switching of the potential drop from one edge of the sample to the other, as the magnetic field is increased. In order to substantiate this explanation, we have carried out an experiment measuring the potential distribution in a Corbino-type geometry (Fig. 4). In the direction the density gradient is expected, the bunching effect is reproduced. In the perpendicular direction, in which the gradient across the sample is expected to be absent or minimal, no bunching is observed at any magnetic field and the potential is always distributed throughout the interior of the sample.

In summary, our results demonstrate that the Hall potential is distributed into the bulk of the sample, whether inside or outside of the quantized plateau region. This conclusion is clearly supported by the data in Fig. 3 ($B = 7.8$ T) and the additional measurements made on a Corbino-type sample. Our experiments indicate that in the quantized regions extended electrons can manage to go around any dissipative region where ρ_{xx} is large, in a manner reminiscent of supercurrents in type-II superconductors.

Because of the presence of density gradients on our samples, the effective width, over which the Hall potential drops, is much narrower than the geometrical width of the samples. However, the Hall voltage does not depend on this effective width. The existence of density inhomogeneities may give rise to significant changes in the internal potential distribution, but it does not perturb the quantization of the Hall resistance. The physical picture emerging from our experiments is similar to that of Kazarinov and Luryi,[5] wherein the extended states carrying the Hall current are visualized as electron waves propagating along the equipotential lines extending through the entire length of the sample. The Hall potential distribution is dominated by various macroscopic inhomogeneities, and will never be like the distribution calculated in their absence.

Note added in proof. We learned after the submission of this paper that similar results have been obtained by G. Ebert, K. v. Klitzing, and G. Weimann [J. Phys. C (to be published)].

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