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Compressibility images of the quantum Hall state

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Abstract

We have imaged the electronic compressibility of a two-dimensional electron gas in the integer quantum Hall regime. The compressibility images show quasi-insulating "incompressible" strips that separate region of electron liquid of near integer filling. The strips follow the contours of constant electron density that match exact occupancy of the Landau levels, and shift accordingly with magnetic field and electron density changes. The surface electrostatic potential distribution has an overall correlation with the compressibility patterns and the density contours marked by them and an abrupt step, at the boundaries, that provides a direct measure of the energy gap between the Landau levels.

Keywords: Quantum Hall effect; Compressibility; Scanning microscopy

The physics of mesoscopic and correlated electron systems has been for decades rich in exciting phenomena. The breaking of translation invariance, caused by boundaries, impurities and imperfections, gives rise to local variations in the electronic properties in their vicinity on length scales comparable to the electronic wavelength. The best known effects caused by such variations are: the Kondo effect; the edge states in the integer and fractional quantum Hall effect; the Anderson insulator; the proximity effect between a superconductor and a semiconductor; one-dimensional electron systems (Luttinger liquids); and interference phenomena in mesoscopic systems. Many-body effects in these systems give rise to changes or even instabilities in the electronic properties near the Fermi energy. Despite the fact that these phenomena are observed in macroscopic samples, the underlying microscopic behavior is responsible for the observed behavior. Most conventional transport and optical measurements of such systems measure quantities averaged over the entire sample. Comparison with theoretical modeling in this case is done by inferring the macroscopic behavior from various microscopic models, however, direct information on the local properties is usually lacking. In this work, we present measurements that directly probe the local behavior of the two-dimensional electron gas in the integer quantum Hall regime with sub-micron resolution [1].

The study of the 2DEG over the past decade has demonstrated that its electronic properties are com-

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pletely modified in the presence of a quantizing magnetic field [2,3]. One of the remarkable features of the quantum Hall effect (QHE) is that as the system approaches integer filling the Fermi energy moves from within the Landau level, where the density of states is large, to within the gap between Landau levels, where the density of states is low. This suggests that the electron system becomes incompressible as the filling factor approaches an integer value. The strong quantization of the density of states suggests that the system will have a novel response to spatial variations in the electron density (Fig. 1). Such variations in density exist near the boundary of a sample, where the density is forced to go down to zero, or may arise from long-range disorder. At zero magnetic field, according to Thomas Fermi's mean field theory a density gradient will be accompanied by a gradient in the electrostatic potential. A density gradient in the QHE will result in a spatial gradient of the filling factor. Away from integer filling, due to the large density of states, this density gradient will be accompanied by a very weak gradient of the electrostatic potential. However, near integer filling, this will result in an electrostatic potential step comparable to the Landau level separation (Fig. 1). The reason for this is that now the system must spatially cross over from a region where the top most Landau level is nearly full (the low-density region) to a region where this Landau level is completely filled and the next one is nearly empty (the high-density region). On the two sides of the potential step the system is fully compressible. However, at the crossover region the system becomes incompressible [4–10]. This situation resembles a p–n junction where a depletion region must form at the interface between the two materials. Using this analogy, we can estimate the spatial extent of the depletion region, a_d, in the QHE. The potential step is generated by the formation of a dipolar charged strip. The charge on the strip, $e(\partial n/\partial x)a_d$, divided by the strip capacitance, ε/a_d, must equal the voltage drop across the strip, $\eta\omega_c/e$. Therefore, the strip size is self-consistently given by $a_d = A\sqrt{\varepsilon\eta\omega_c/(e^2 dn/dx)}$ (where $A = \sqrt{2}/\pi$ from an exact calculation [7]). It is now clear that reducing the density gradient increases the width of the incompressible region.

The combination of good electrostatic sensitivity ($< 100\ \mu V/Hz^{1/2}$) (at low frequency, DC to 100 Hz,

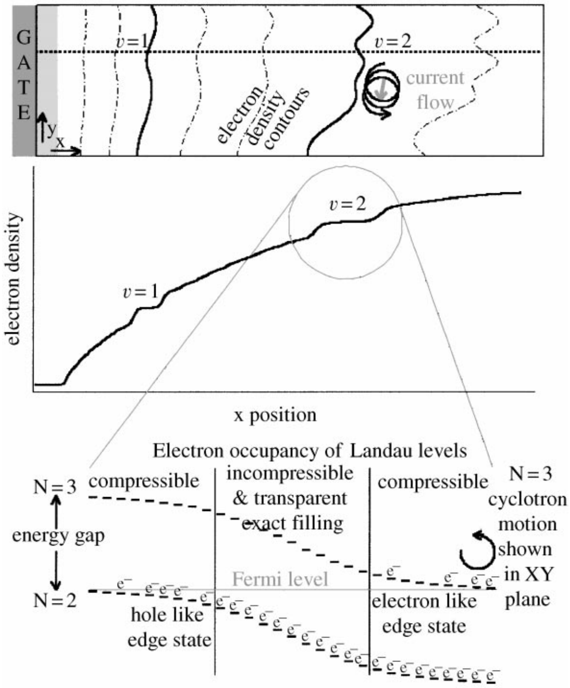

Fig. 1. Sketch of the density profile and contours of density near the edge in a somewhat non-uniform sample, with the positions of the $\nu = 1$ and $\nu = 2$ edge states and incompressible strips indicated. The edge is created by a biased gate, which induces an adjacent depleted region (orange). Insets: Regions of constant density occurring at the incompressible strips. Expanded versions of these insets (bottom) sketch how edge states, electron occupancy of Landau levels, and associated properties are expected to interrelate. An electron or "e" symbol above the dash indicates occupancy of that state. The gradual increase of electron density as one proceeds from the left to the right spans three regions: occasional vacancies for the lower Landau level, exact filling of the lower Landau level, beginning to fill the upper Landau level. In the partly occupied regions, the 2DEG is compressible, and in the fully occupied region, it is incompressible.

which minimizes resistive effects) and sub-micron resolution necessary for the present experiments is obtained by using a single-electron transistor (SET) [11,12] as a scanning electric field probe. It is fabricated on the flat, ~ 100 nm diameter tip of a tapered glass fiber, which hovers ~ 100–200 nm above the sample surface. Any change in potential under the probe modulates the current through the SET. By monitoring this current while scanning the probe in a raster pattern across the surface, one can construct "electric-field" images of the electrostatic surface

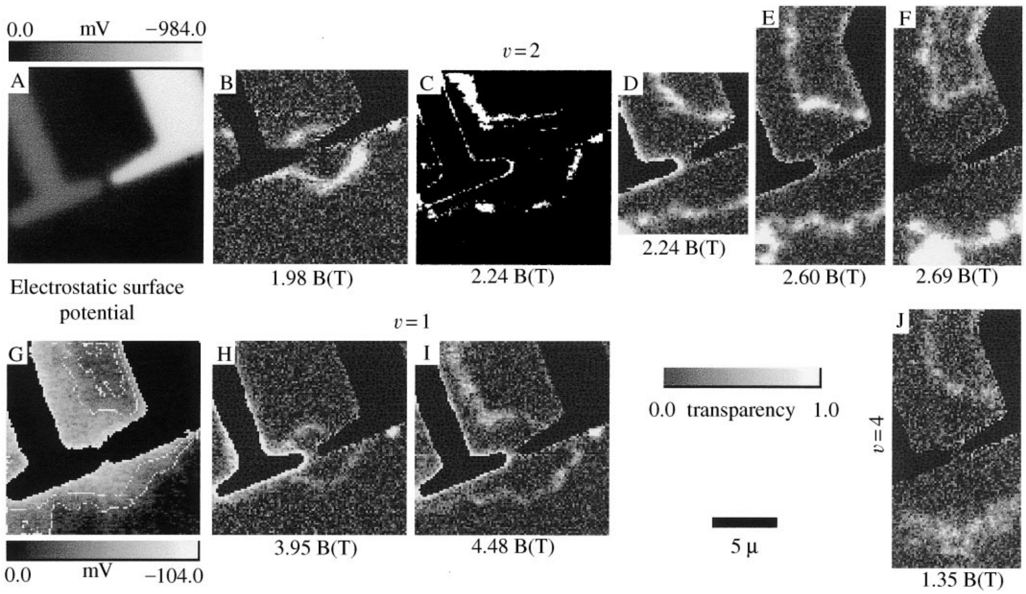

Fig. 2. (A) Typical electrostatic potential, or V_{surf}, image, on a 1.0 V scale, of the sample showing the left and right gates, for $B = 4.48$ T. Such images are obtained concurrently with each transparency image, but do not change noticeably on this scale. (B–F, H, I and J) Transparency images for different magnetic fields around filling factors of $\nu = 2, 1$, and 4. The transparency, shown in arbitrary units, is a measure of screening of the modulated back-gate voltage. (G) The electrostatic potential of Fig. 2A shown with $\sim \times 10$ higher sensitivity with two contour lines. The black masks in Fig. 2 outline the position of the gates. The weak signals seen at the gate edges in the transparency images are due to limitations of the scanning SET electronics in steep voltage gradients.

potential V_{surf}, which is a measure of the electric-field flux emanating from the surface. For the most part this is accomplished with a sample voltage feedback ($V_b = -V_{surf}$) that nulls any SET response. To extract the mV-level transparency and transport signals from the large static signals of biased surface gates (~ 1 V) and fluctuating surface and dopant charges (~ 50 meV), we use low-frequency modulation and lock-in detection schemes. For the compressibility an AC back gate voltage δV_{BG}, that is not fully screened, gives the transparency signal, $\partial V_{surf}/\partial V_{BG}$. This transparency signal is related to the compressibility κ of the 2DEG by $\partial V_{surf}/\partial V_{BG} = C/e\kappa$ where C is the capacitance between the 2DEG and the back gate [13,14]. The impedance associated with charge transport into and out of the incompressible region can become extremely large in the QHE. Therefore, special care was taken to work at sufficiently low frequencies (40 Hz) where R–C time constants are not important. In our GaAs/AlGaAs, heterojunction sample, a 2DEG forms on the GaAs side of the interface, 100 nm below the surface. Several metal gates (TiAu) are patterned on the surface. These enable us to deplete the 2DEG and to restrict current flow to specific regions. Additionally, a back gate is formed by a 1 μm thick n+layer, 5.4 μm below the 2DEG, allowing us to decrease and/or modulate the electron density. The range of density, measured locally with the SET probe, is $0.8 \rightarrow 1.2 \times 10^{11}$ cm^{-2} with a peak mobility of 4×10^6 cm^2/V s.

Fig. 2 shows images of the inverse compressibility measured in the vicinity of filling factors 1, 2, and 4. Near filling factor 2 one can clearly see an incompressible strip near the boundary of the biased gate [15]. The strip moves away from both the biased and unbiased gates as the field increases. This behavior is a direct outcome of the fact that the incompressible strip corresponds to an integer filling factor. Therefore, increasing the magnetic field will result in the motion of the incompressible strip to a correspondingly higher-density region. The incompressible strip marks a constant-density contour in the 2DEG, where higher

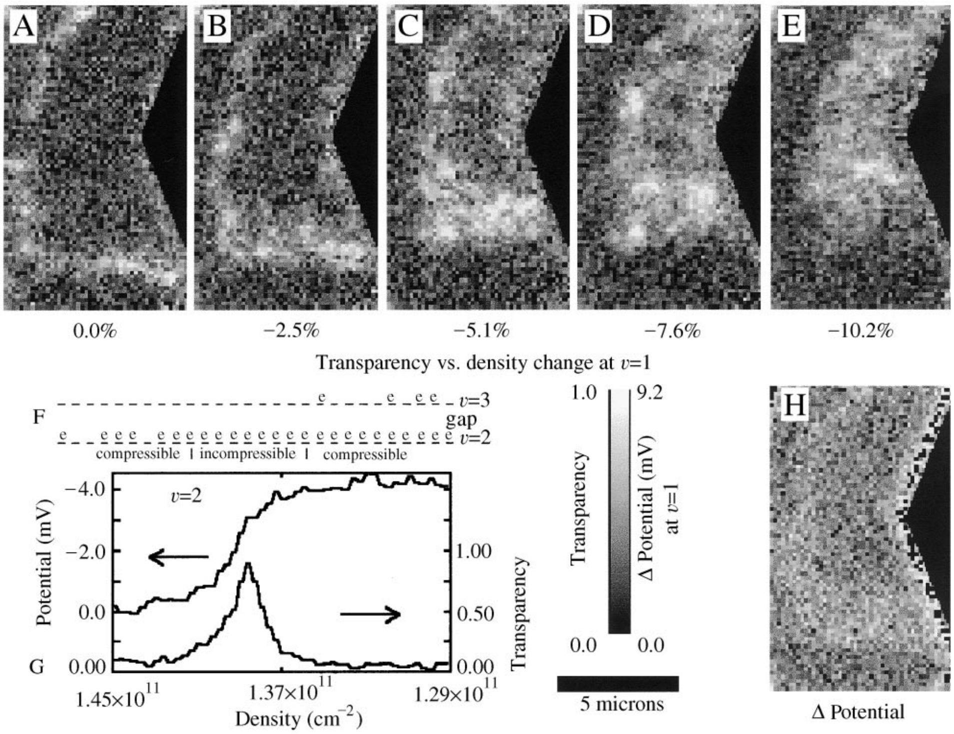

Fig. 3. (A–E) A transparency sequence at $B = 5.2$ T in which the back gate is employed to decrease the density by $\sim 1.3 \times 10^{10}$ cm^{-2}. The incompressible strips here are for $\nu = 1$. (F) A sketch showing how electrons fill the available Landau level states as in Fig. 1. It is a guide to the data of G. (G) Data showing the potential step and corresponding transparency signature created by passing a strip under the SET (held at a fixed point) by decreasing density with the back gate. (H) The difference in the surface potential of Figs. 3A and E. The brighter area corresponds to the potential step associated with the incompressible strip.

magnetic field corresponds to higher density. By monitoring its position for different magnetic fields, one can determine the density map of the 2DEG. The sequence of images for increasing magnetic field near filling factor 2 shows that although one gate is unbiased there is a slight decrease in density around it. As is apparent from the high-field images ($B = 26.00$ and 26.85 KG) the incompressible strip runs along the boundary of the biased gate until a point where it breaks away from it and propagates in the central region parallel to the unbiased gate. At the lower values of magnetic field the incompressible strip is nearly invisible near the boundary of the biased gate. At these magnetic fields the incompressible strip runs along a constant-density contour that exists very close to the biased gate. There the density gradient is strong and hence the width of the strip is too narrow to be detected. By increasing the magnetic field by a factor of 2 we should observe the $\nu = 1$ incompressible strip at exactly the same position as $\nu = 2$ strip. Similarly, we should observe the $\nu = 4$ strip by reducing the field by a factor of 2. This behavior is clearly seen in Fig. 2.

Our knowledge of the screened potential (or density) profile of the 2DEG can be used to compare it to the surface potential. Fig. 2G shows the surface potential imaged simultaneously with the compressibility images (Figs. 2B–F, H, I). Note that there is a remarkable resemblance between the shape of the incompressible features and the structure in the surface potential (Fig. 2G). This remarkable resemblance suggests that the incompressible features lay not only along constant 2DEG potential but also along constant surface potential [10]. The correlation between the surface potential and the potential in the 2DEG is found only on large length scales (greater than 0.5 μm) and forms a powerful tool, in that it allows us to study the long-range disorder scattering potential the electrons feel by simply measuring the surface potential. This measurement also suggests that the measured surface potential is in fact, to a good approximation, the potential screened by the electrons.

The incompressible strip can also be moved by varying the density using the back gate at a fixed magnetic field (Figs. 3A–E). A step in surface potential occurs at each strip, corresponding to the energy gap between the Landau levels on either side (see Fig. 1 and Fig. 3F). These steps are observed in potential images, but they are best measured by holding the SET tip fixed and passing the incompressible strip underneath it, using the back-gate voltage. Fig. 3G shows such a plot of V_{surf} versus V_{BG} for a $v = 2$ strip. The step is $\sim$ 4.5 mV, near the expected value, given by the cyclotron energy $\eta\omega_C$, of 1.7 meV/T. Across the $v = 1$ strip, at twice the field, a smaller gap $\sim$ 2 mV is measured, consistent with the expected exchange–enhanced Zeeman spin splitting energy of 0.35–0] 0.55 meV/T.

In conclusion, we have measured the local compressibility of the 2DEG in the QHE. We clearly observe the incompressible strips formed near the boundary of the sample due to a smooth density gradient. A potential step accompanies the incompressible strip. Its magnitude agrees quantitatively with the predicted one from the theory of Chklovskii et al. [7].

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