Topographic Mapping of the Quantum Hall Liquid using a Few-Electron Bubble

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A scanning probe technique was used to obtain a high-resolution map of the random electrostatic potential inside the quantum Hall liquid. A sharp metal tip, scanned above a semiconductor surface, sensed charges in an embedded two-dimensional electron gas. Under quantum Hall effect conditions, applying a positive voltage to the tip locally enhanced the 2D electron density and created a “bubble” of electrons in an otherwise unoccupied Landau level. As the tip scanned along the sample surface, the bubble followed underneath. The tip sensed the motions of single electrons entering or leaving the bubble in response to changes in the local 2D electrostatic potential.

Since the discovery of the integer quantum Hall effect (QHE) in a two-dimensional electron gas (2DEG), electron localization has been proposed to play a key role in the phenomenon \cite{1}. In GaAs heterostructures, the random potential responsible for localization derives mainly from randomly situated ionized donors, located between the submerged 2DEG and the sample surface. Although this picture remains widely used, it has proven difficult to quantify the random potential experimentally. Conductivity measurements, the primary tool for studying this phenomenon \cite{1}, provide only average information about the disorder. Recently developed scanning techniques hold promise for spatially resolving the behavior of semiconductor structures on nanometer scales \cite{2,3}. In particular, low compressibility strips \cite{2} with Landau level filling factor \( \nu \) close to an integer have been imaged directly in the integer Quantum Hall regime \cite{2,3}.

We present results from a new technique that images microscopic details of the disorder potential through detection of motions of single electrons within the system under study. A mobile quantum dot is created inside the 2DEG by enhancing the 2DEG density locally underneath a sharp scanned metal tip biased to attract electrons (inset Fig. 2). While scanning the tip across the sample surface we drag the dot along underneath. Comparing the single-electron charging pattern of the dot at different locations, we map the electrostatic potential directly as sensed by the 2DEG electrons. We find that the form of this potential remains mostly unchanged for different spin-split and integer Landau level fillings, which suggests that screening of the random external potential by the 2D electrons does not vary appreciably in the quantum Hall regime. Our 2DEG is formed at the GaAs/AlGaAs interface 80\( \mu \)m below the sample surface. It has an electron density of \( \approx 1.5 \times 10^{11}/cm^2 \) and mobility \( \approx 1.5 \times 10^6/cm^2/V \text{ sec} \). A metallic gate electrode, patterned in a form of a grating covers the sample surface (Fig. 1). We image a region of the surface several micrometers in size between two fingers of the gate. In the subsurface charge accumulation (SCA) method \cite{2}, a sharp scanning probe is brought close (\( \lesssim 20nm \)) to the surface of the sample. Unlike scanning tunneling microscopy, no tunneling current passes between the probe and the sample. Instead, we apply a 100 kHz AC excitation of \( \sim 3\) mV RMS to the 2DEG and to the gate. Because of the capacitance of the 2DEG to the ground and to the scanning tip, electric charge flows in and out of the 2DEG. We monitor this charging of the 2DEG by measuring the image charge induced on the scanning probe by a sensitive cryogenic amplifier.

In scanning probe measurements of semiconductor and nanoscale structures the measuring tip may, itself, strongly alter the local electron density and thus produce artifacts in images. Some researchers have taken advantage of this effect by using a scanning tip to alter the current flow in nanoscale systems \cite{2}. In previous work using SCA microscopy, we compensated the work function difference between the scanning tip and the sample to avoid the tip perturbing the sample electrostatically \cite{2}. The resulting SCA images revealed features attributed to variations of the 2DEG compressibility. In the present work, we instead purposefully apply a voltage on the scanning tip to change the electron density underneath. For magnetic fields such that the bulk Landau level filling factor is slightly less than integer, we thereby create a “bubble” of electrons in the next Landau level. The electrons in the bubble are separated from the surrounding 2DEG by an incompressible strip of integer Landau level filling. The imaged features do not display the compressibility variations inherent to the 2DEG. Instead, Coulomb blockade in the bubble determines the observed signal, and the images display a set of equipotential contours that serve as a topographic map of the
random electrostatic potential in the 2DEG. One may "read" directly the electrostatic potential by noting the positions of the contours.

We find the voltage that compensates the electric field between the tip and the sample by measuring the Kelvin signal (see Fig. 1), which is proportional to the electrostatic potential difference between the tip and the sample. With no external bias applied between them, the electrostatic potential difference equals to the work function difference between the two. We null it by applying an opposing bias to eliminate any electric field between the tip and the sample. Henceforth, we designate the tip-sample voltage as measured in deviation from this nulling voltage.

In the SCA image of a 2.5 × 2.5μm region at magnetic fields of 5.8 T, corresponding to the bulk Landau level filling factor ν = 1 (Fig. 2a), regions of high and low signal are presented as bright and dark colors, respectively. The voltage between the tip and the sample is +1 V. This corresponds to accumulation of the electrons underneath the tip. We observe a strikingly complex pattern of closed contours, reminiscent of a topographic map. The contours evolve rapidly with magnetic field, staying nested around fixed centers.

The size of the smallest feature within 2DEG resolvable by the SCA microscopy is limited by the depth of the 2DEG, d = 80nm. However, we measure separations between contours lines as small as 50nm. Therefore, we conclude that the contours do not represent charging patterns inherent to the 2DEG. Rather, the features reflect variations in the 2DEG charging induced by changes of the tip position. The periodic appearance of the contours hints that they originate from Coulomb blockade. Indeed, when we fix the tip position and vary the tip-sample voltage, the signal displays periodic oscillations. In this situation, the tip acts as a gate controlling the electron number in a quantum dot.

We explain the observed contours as follows. An electron accumulation underneath the tip forms a few-electron bubble (inset Fig. 2). As the bubble is dragged in the 2DEG plane following the tip, it experiences different local electrostatic potentials. When the potential energy for electrons is high, electrons are expelled from the bubble; when the potential energy is low, electrons are drawn into the bubble. As the tip scans across these positions of single electron transfer, the applied AC excitation causes an electron to move back and forth between the bubble and the surrounding 2DEG, producing a peak in the synchronously-detected SCA signal. Between the peaks, Coulomb blockade prevents transfer of electrons to and from the bubble, and a minimum of SCA signal is detected. As a result, SCA images display alternating contours of high and low SCA signal surrounding minima and maxima of the random electrostatic potential within the 2DEG.

The contours observed in the experiment do not intersect and have roughly the same contrast across the image. This confirms that they originate from a single bubble located underneath the tip. The fact that contours appear only on the high magnetic field side of the Quantum Hall plateau also supports this scenario. In Figure 2c, we present four images at different magnetic fields around ν = 1. For the top three images, the Landau level filling factor in the bulk of the sample is ν < 1, while underneath the tip it is ν > 1. The bubble of ν > 1 is separated from the bulk by the incompressible strip with ν = 1, (inset, Fig. 2). The strip serves as a barrier between the bulk 2DEG and the bubble and ensures charge quantization. In contrast, at the lower field side of the Quantum Hall plateau (lowest image, Fig. 2c) the filling factor is everywhere larger than 1 and a mere density enhancement forms, rather than a bubble capable of trapping single electrons.

We show the evolution of SCA images at 6 T with different tip-sample voltages in Fig. 2d. As the voltage decreases (lower images), the contours shrink and disappear around nulling voltage. Without electric field between the tip and the sample, the presence of the tip does not influence the density distribution in the 2DEG, so that the electron bubble does not form and no contour lines appear. We confirmed this statement by studying the SCA images measured at different tip heights above the surface; away from nulling voltage, the images depend strongly on changing the tip height, while at nulling voltage they stay virtually unchanged.

In some cases, submicrometer structures similar to those discussed above persist at any voltage between the tip and the sample, including the nulling voltage for the Kelvin signal. By measuring the Kelvin signal as a function of the tip height, we have found that in these cases the tip does not have a uniform workfunction over its entire surface. Most probably, this results from GaAs debris partially covering the scanning tip. As a result, an electric field exists between the probe and the sample at any tip-sample voltage, even when the averaged Kelvin signal is zero. We therefore carefully checked the cleanliness of the tip throughout the experiments reported here. Possibly, in previous work, the tip-to-sample electric field was not completely eliminated and debris on the tip resulted in a non-uniform workfunction difference between different regions of the tip and the sample. Therefore, some of the features (particularly arcs and filaments) observed in Fig. 2 of may be artifacts resulting from the tip locally perturbing the sample.

Imaging of another region of the sample at three different magnetic fields and tip-sample voltages is shown in Fig. 3. Each contour line marks a position within the 2DEG plane, where the number of electrons in the bubble changes by one. As the tip voltage decreases, the energy of the N electron state drops relative to the N + 1 electron state, and the contour line moves. Monitoring the evolution of the images at a fixed field, we observe that
contours shrink around the central locations as the voltage decreases towards nulling. We conclude that inside each contour the electron bubble has one more electron than outside. In particular, the contours surround two local minima of the potential (as sensed by electrons). Note that different contours follow the same evolution as we change the tip voltage to move one contour to a position formerly occupied by another. For example, at $B = 6.5T$ the inner contour at $+1.0V$ and the outer contour at $+0.5V$ appear indistinguishable in size and shape. This confirms our view of the bubble as an electrostatic potential probe; despite differences in bubbles created by different tip voltages, the resulting contours remain practically unchanged.

Our equipotential contours have the same meaning as topographic contours on a land map. To measure the amplitude of the electrostatic potential inside the 2DEG, we need to know the energetic separation between the single-electron contours. This information comes from measuring the width of the single electron peaks in a SCA trace taken as a function of the tip voltage at a fixed location. We fit the shape of the single electron peaks by the derivative of the Fermi distribution \[ \frac{d\nu_{1e}}{dB} \approx 2 \text{ V/T}. \] Assuming the that width of the single-electron peaks is determined by the temperature of 0.35K, we find that the Fermi energy at the bubble is changed by $\sim 2meV$ per change of the tip voltage by $1V$. Also, as we change the tip voltage by $1V$, from $+0.5V$ to $+1.5V$, at $6.6T$ the innermost contour expands to span the entire area of Figure 3. We thus conclude that the range of the random potential in this region is about $2meV$.

The contour lines observed near bulk filling factor $\nu = 1$ reappear around $\nu = 2$ (compare Fig. 2a and b). The contours observed at $\nu = 1$ display a stronger contrast, although the expected value of the exchange-enhanced spin gap ($\nu = 1$) is smaller that the cyclotron gap ($\nu = 2$). Tunneling of an electron between the interior and exterior of the bubble should be additionally suppressed close to $\nu = 1$ by the opposite spin orientation of the transferred electron in the initial and final states. This suppression of tunneling does not exist close to $\nu = 2$, and as a result the Coulomb blockade may be less pronounced in the latter case.

The contours clearly encircle the same locations at $\nu = 1$ and $\nu = 2$. The close similarity between the images indicates that we observe a fingerprint of the same random electrostatic potential at both filling factors. The random potential fluctuations extend laterally by typically $\sim 0.5-1\mu m$. This scale significantly exceeds $50nm$, the width of the spacer layer that separates 2DEG from donors. Random potential fluctuations due to remote ionized donors should have a characteristic lateral scale of about the spacer width \[ \approx \frac{\text{nm}}{\text{nm}} \]. Most probably, screening by the residual electrons left in the donor layer smoothens the potential in our sample. Note, that the size of the scanned bubble, $\sim 100nm$ (see below), in principle does not prevent observation of smaller scale potential fluctuations. Indeed, at select locations the single electron contours display very small radii of curvature, signaling steep potential bumps or dips (Fig. 3).

Figure 3 also traces the evolution of contours with magnetic field. Interestingly, the changes induced by variations of magnetic field and the tip-sample voltage are quite similar. In fact, we can compensate for the change of a contour’s size induced by magnetic field by properly tuning the tip-sample voltage (Fig. 3, images along the dashed diagonal line). The size of contours remains constant at $\nu = 1$ along lines of $\frac{d\nu_{1e}}{dB} \approx 2 \text{ V/T}$. At $\nu = 2$ the constant shapes of contours are instead preserved at $\frac{d\nu_{1e}}{dB} \approx 4 \text{ V/T}$. We can readily explain this observation by recalling that the bubble is formed on top of an integer number of completely filled (spin-split) Landau levels. When magnetic field increases, the degeneracy of these levels grows, and they can accommodate more electrons. To supply these electrons, we need to apply a larger voltage between the tip and the sample. We expect the voltage required for compensation to be roughly proportional to the number of filled Landau levels, in agreement with the experiment.

We determine the size of the bubble by measuring the periodicity of the signal with magnetic field. Adding one flux quantum per area of the bubble adds one electronic state to each filled (spin-split) Landau level, removing roughly an electron from the upper, partially filled Landau level that constitutes the bubble. We observe that as the magnetic field is changed by $\approx 0.2T$, the contours shift by one complete period. In Figure 3, the inner contour at $B = 6.4T$ coincides with the outer contour at $B = 6.6T$. For the case of Figure 2 the magnetic field period has a similar value of $\approx 0.15 T$, implying an area of $0.02\mu m^2$. This compares favorably with the square of the 2DEG depth. Because the magnetic field period does not depend on location within the image, it appears that the size of the bubble is not strongly affected by the random potential.

In conclusion, we have formed a mobile quantum dot inside the 2DEG by locally accumulating electron density underneath the scanning probe. By comparing the Coulomb blockade patterns at different locations we map the potential inside the 2DEG as sensed by the electrons. We find that the 2D electron screening of the random potential induced by external impurities changes little between different quantum Hall plateaus and within each plateau. With demonstrated single-electron sensitivity, our subsurface charge accumulation may allow understanding of a wide variety of submerged electronic structures on the nanometer scale.
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Figure 1: Sample and measurement schematics. Upper panel describes the charge accumulation (capacitance) method with an AC excitation applied to the sample and the gate. Capacitive coupling between the tip and the 2DEG induces an AC signal on the tip. Lower panel: Capacitance image of an 11 × 11 μm² region, including two “fingers” of the gate. The gate resides directly on the surface of semiconductor, while the 2DEG is buried underneath the surface. Therefore, the gate produces a larger capacitance signal. In the Kelvin probe method we vibrate the sample in the vertical direction with a frequency of 2 kHz and an amplitude of ~ 10 nm. We measure the AC charge induced on the scanning probe. It is proportional to $\frac{dC}{dV}$, where $C$ is the probe-sample capacitance, $z$ is the tip height and $V$ is the electrostatic potential difference between the tip and the sample.

Figure 2a: 2.5 × 2.5 μm SCA image at 5.8 T ($\nu \lesssim 1$) and $V_{tip} = +1$ V. b: Image of the same region at 3.0 T ($\nu \lesssim 2$). c: Magnetic field evolution of the feature at the top left corner of Fig. 2a at $V_{tip} = +1$ V. Top to bottom: 6.5, 6.1, 5.9 and 5.7 T. The features disappear when more than one spin-split Landau level is filled in the bulk ($\nu > 1$). d: Evolution of the same feature with tip voltage, 6.0 T. Top to bottom: 1.0, 0.7, 0.4 and 0.0 V. At the nulling voltage (lowest image) the tip does not influence 2DEG. Inset: schematic of the 2DEG density profile underneath the tip. Note the ring of constant density that corresponds to the incompressible strip with an integer Landau level filling factor (inset).

Figure 3: Series of 2 × 2 μm SCA images taken at a different location from Fig. 2. The changes in contour size introduced by the tip voltage and magnetic field compensate each other. See images along the diagonal dashed line. Lower panel: Schematic explanation of the changes induced in the bubble by magnetic field and the tip voltage.
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