Imaging of low-compressibility strips in the quantum Hall liquid

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Using subsurface charge accumulation scanning microscopy, we image strips of low compressibility corresponding to several integer quantum Hall filling factors. We study in detail the strips at Landau level filling factors $\nu=2$ and 4. The observed strips appear significantly wider than predicted by theory. We present a model accounting for the discrepancy by considering a disorder-induced nonzero density of states in the cyclotron gap.

Many of the key features observed in the quantum Hall effect may be explained in terms of the transport through the quasi-one-dimensional edge channels.[1] Each channel is formed where the energy of the corresponding Landau level at the edge of the sample equals the Fermi energy. Theories predict that the edge channels should be separated by narrow strips with precisely integer Landau level filling factor.[2,3] In the model, the strips arise due to the zero compressibility, i.e., $dn/d\mu=0$, of the 2DEG at the cyclotron gap in the electron density of states between two Landau levels. The formation of incompressible strips between the edge channels drastically modifies their current equilibration.[4] The microscopic structure of the strips may be directly revealed in scanning experiments.[5–7]

The recently developed technique of subsurface charge accumulation (SCA) imaging measures the local charge accumulation in a 2D system underneath a sharp scanning probe. This charge is driven by an ac excitation applied to the 2D electron gas (2DEG), embedded inside a semiconductor heterostructure. Capacitive coupling between the 2DEG and the probe permits detection of the charge accumulated in the 2DEG both in phase and 90° lagging from the excitation. This technique has proven successful in imaging local compressibility features in the 2DEG in the integer quantum Hall regime.[5] In this paper, we use SCA microscopy to study low compressibility strips formed in the presence of a smooth electron density gradient at different Landau level filling factors. The strips are formed within the bulk of the 2DEG around an induced density perturbation. The measured strip widths are a few times larger than that predicted by theory.[3] We describe how our results may be explained if we take into account a nonzero density of states in the cyclotron gap, caused by a short-range potential.

We study a standard 2DEG formed at the GaAs/$Al_xGa_{1-x}As$ interface 90 nm below the sample surface. It has an electron density of $n\approx3.5\times10^{11}$ cm^2 and mobility $\mu\approx4\times10^5$ cm^2/V sec. A uniform doping layer 60 nm wide starts 10 nm below the surface and is separated from the 2DEG by a 20 nm undoped spacer layer. To create a density gradient in the 2DEG, we locally perturb the charge distribution in the sample by applying a voltage of $+2$ to $+3.5$ V between the scanning probe and the sample for

~30 sec, when the tip is brought in close contact with the sample surface. We find that injecting the tunneling current results in an increase of the 2DEG density in a region extending laterally a few microns from the tunneling site. The electron density at the center of the perturbation is typically about 20% higher than the bulk value. After the tunneling current is switched off, this density profile does not change with time. We speculate that the local modification of the electron density is a result of electron transfer from the donor layer to the 2DEG, similar to the persistent photoconductivity effect.[8]

To determine quantitatively the extent of the perturbation, we perform Kelvin probe[9] imaging of the perturbed region. In this measurement, we mechanically vibrate the sample in the vertical direction with a frequency of 2 kHz and an amplitude of ~10 nm and measure the oscillating charge induced on the scanning probe. This charge results from the electrostatic potential difference ΔV between the probe and the sample. It is proportional to $\Delta V(dC/dz)$, where C is the probe-sample capacitance and z is their separation. We calibrate the sensitivity of this measurement to the potential difference by changing the voltage between the 2DEG and the probe and measuring the resulting change in the signal. We then place the scanning probe well outside the perturbed region and balance the Kelvin signal by applying a dc voltage between the 2DEG and the scanning probe. This procedure nulls the electric field created by the work function difference between them. The signal reappears upon placing the scanning probe above the perturbed region. Using the known sensitivity of our measurement to the potential difference, we map the electrostatic potential by scanning just above the sample surface.

The left inset of Fig. 1 shows the result of such a measurement. We choose the origin of coordinates at the center of the perturbation and fix the coordinate $y=0$. The signal is proportional to the transferred electron density and reaches its maximum of $\Delta V\sim0.5$ V near the center of the perturbed region (we ignore here a small dip in the Kelvin signal near $x=0$). We can roughly estimate the charge transfer between the 2DEG and the donor layer, which would result in such a potential difference. Taking the distance between the typical donor in the doped layer and the 2DEG $s\sim50$ nm, we arrive
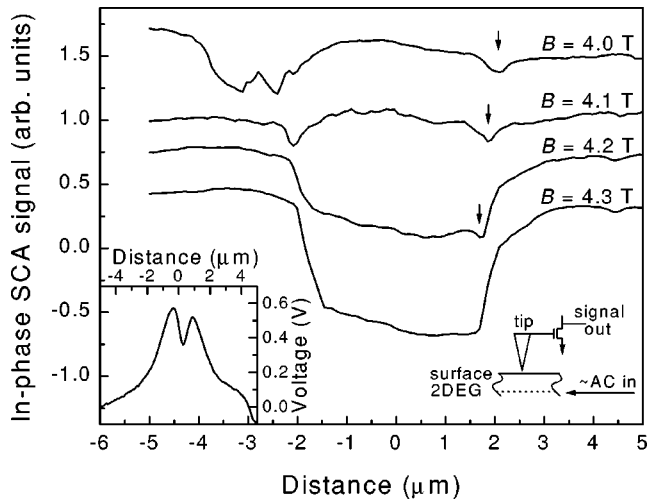
FIG. 1. The SCA measurements at different magnetic fields around $\nu=4$ across the area of enhanced density. The curves are offset for clarity. Left inset: the Kelvin probe signal. Right inset: a schematic description of the SCA technique.

FIG. 2. 13×13 μm SCA images at different magnetic fields near $\nu=2$ presented on a gray scale. The left and right images correspond to the in-phase and 90° lagging SCA signals, respectively. The measurements are performed at magnetic fields of (a) $B=8.0$ T, (b) $B=8.1$ T, and (c) $B=8.2$ T. (a) and (c) represent the limiting cases where the SCA signal is dominated by compressibility or resistivity, respectively. The data are taken at a different location than Fig. 1.

at $\Delta n=\Delta V\epsilon/4\pi es\sim5\times10^{11}/\mathrm{cm}^2$ as an estimate of the electron density transferred from the donors to the 2DEG at the center of the perturbed area. We may alternatively estimate the density enhancement from the range of magnetic fields $\Delta B\sim1$ T, where we observe the SCA anomaly at $\nu=4$ (see later in the text), as $\Delta n=\nu\Delta Be/hc\sim1\times10^{10}/\mathrm{cm}^2$. The discrepancy between the estimates probably indicates that most of the charge is transferred within the donor layer and not from the donor layer to the 2DEG. This extra charge transfer contributes to the Kelvin signal, but does not change the 2DEG density. Also, the charge could be transferred to the 2DEG from the sample surface. This would halve the result of the first estimate. At present, we cannot determine the precise charge balance within the various layers of the sample contributing to the Kelvin probe signal.

We now describe SCA imaging.[5] The technique is depicted schematically in the right inset of Fig. 1. In this measurement we apply a small ac excitation (typically 3 mV RMS in the linear response regime) at a frequency of 10–100 kHz, to an ohmic contact at the edge of the 2DEG. As a result, an electric charge flows in and out from the 2DEG. We monitor the charging of the 2DEG locally by placing a sharp scanning probe at a small distance (~10 nm) from the sample surface. The charge induced on the scanning probe is proportional to the change in the 2DEG density. We measure this charge using a sensitive cryogenic charge amplifier. The contrast in the SCA images indicates that different regions of the 2DEG charge differently, due to variations in either local compressibility or conductivity. Below, we discuss both situations.

The SCA measurement performed at zero magnetic field does not show any structure in the region of study, despite the induced density perturbation. Indeed, at zero field the 2DEG compressibility does not depend on the electron density, and its conductivity is high enough so that the sample charges fully during the excitation cycle. The situation changes when we apply a large magnetic field. The SCA images at several different magnetic fields are presented on a gray scale in Fig. 2. In magnetic fields around $B=8$ T (ν
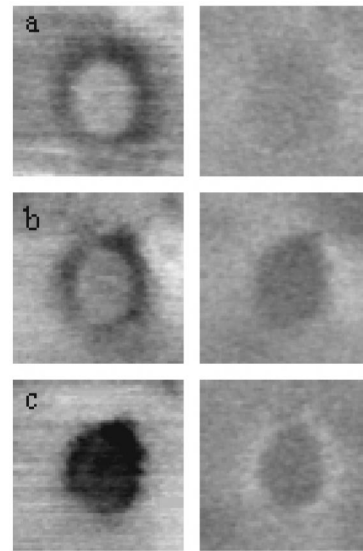
$=2$ in the bulk of the sample is reached at $B\approx7$ T) a ring feature appears in the SCA image. The magnitude of the SCA signal is higher inside and outside the ring than on the ring itself. As the field increases, the ring shrinks, moving toward the center of the perturbed area. The results of a similar SCA measurement near $\nu=4$ on a different region of the sample (prepared in the same manner) are shown in Fig. 1. Here we present only the signal measured on a single line ($y=0$) across the diameter of the ring. As in Fig. 2, we may trace the shrinkage of the ring as the field increases (see feature marked by arrows, upper curves of Fig. 1). At even higher magnetic fields the charging signal in the interior of the ring drops, forming a circular depression in the SCA signal [Fig. 1, two lower curves; Fig. 2(c)].

If the scanning probe were located just above an incompressible region, the 2DEG below would not charge and discharge with the weak ac excitation. Thus in a region of low compressibility, we detect a SCA minimum.[10] We attribute the SCA minimum (Fig. 1) at $B=4$ T to a low compressibility strip formed in the region of filling factor $\nu=4$. At higher field, $\nu=4$ corresponds to a higher electron density, causing the ring to move up the density gradient and shrink toward the center. The position of the $\nu=4$ strip shifts by ≈200 nm as we step the magnetic field by 0.1 T. At $\nu=4$, this change in magnetic field corresponds to a $1\times10^{10}/\mathrm{cm}^2$ change in the electron density. Therefore, we estimate the magnitude of the electron density gradient $dn/dx\approx5\times10^{10}/\mathrm{cm}^2\mu$m in the case of Figs. 1 and 3. The value of the density gradient depends on the specific realization of the density perturbation. In particular, in the region imaged at Fig. 2, it is five times smaller, $dn/dx\approx1\times10^{10}/\mathrm{cm}^2\mu$m.

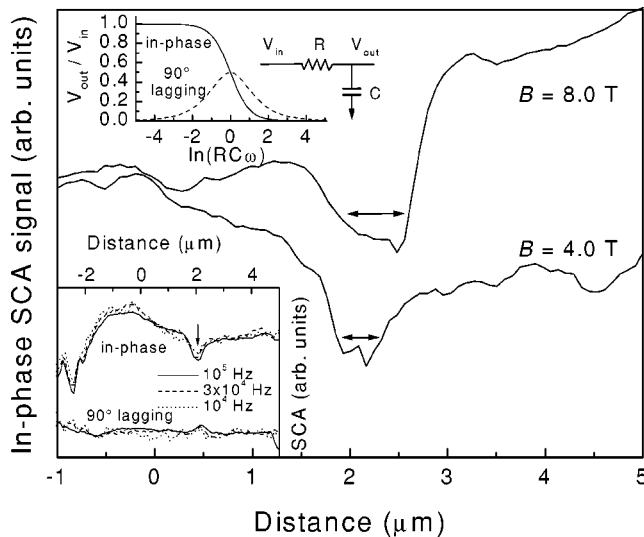A suppression of the high frequency SCA signal at a cer-

FIG. 3. The SCA signal across the $\nu=4$ and $\nu=2$ strips. The curves are offset for clarity. The data are taken at the same conditions as in Fig. 1. Lower inset: the in-phase and 90° lagging SCA signals at different frequencies around $\nu=4$. The vertical scale is the same for all frequencies. The 90° lagging signals are arbitrarily offset. Upper inset: a model diagram of the 2DEG charging.

tain region might be a result of either low compressibility or low conductivity. In the latter case, there is insufficient time to charge the region during the period of excitation. As the 2DEG longitudinal conductivity is very low in the vicinity of integer filling factors, this possibility must be examined carefully. To distinguish between the two mechanisms we study both the in-phase and 90° lagging SCA signals as a function of frequency.

A negligible phase shifted signal and no frequency dependence were observed at the conditions of Fig. 1, upper curve. This is evidenced by the upper inset of Fig. 3, where the in-phase and 90° lagging SCA signals are shown for the same conditions at frequencies of 10, 30, and 100 kHz. We therefore conclude that the observed feature reflects a suppressed 2DEG compressibility at integer filling factor. However, in some other situations we do observe a phase shifted signal. Typically, at higher magnetic fields the SCA features appear both in-phase and 90° lagging from the excitation, this demonstrating that the 2DEG does not have enough time to fully charge during the excitation cycle.

Under conditions giving rise to a phase shift, a ring-shaped feature in the 90° lagging signal accompanies the circular-shaped region of the suppressed in-phase SCA signal [Fig. 2(c)]. We interpret this pattern as resulting from incomplete charging of the interior of the circle through a poorly conducting integer ν strip around it. This situation resembles an RC circuit with a variable R (upper inset, Fig. 3). Moving the scanning probe toward the regions in the interior of the strip increases the effective resistance. This causes the measured in-phase signal to steadily decrease to zero, while the 90° lagging signal first increases from zero and then decreases back to zero level. In such circumstances, it is difficult to extract separately the conductivity and compressibility information from the signal. We have performed extensive numerical modeling allowing us to reproduce the major features observed in Fig. 1.[11]

We use the lowest curve of Fig. 1 to estimate the sensitivity of the SCA measurement. At this magnetic field the resistive strip at $\nu=4$ prevents charging of the interior region, while the exterior region charges fully.[10] This difference in signal levels between the fully charging and non-charging regions may be taken as the measure of the degree of charging, S_0. We observe that the contrast in the low compressibility strip (Fig. 1, upper curve) reaches only about $0.25\,S_0$. Partially, the amplitude of the feature is reduced due to nonlocal response of the scanning probe, which is limited by the distance between the 2DEG and the surface. We estimate the largest possible ''smearing'' from the sharpest features observed in the experiment. Taking into account the resulting response function increases the actual depth of the SCA minimum at the $\nu=4$ strip only up to $0.25\,S_0$. We conclude that the 2DEG in the $\nu=4$ strip remains partially compressible, and the large geometric capacitance causes charge to enter this region.

The SCA signal is proportional to the capacitance between the tip and the 2DEG. We crudely estimate the density of states (DOS) between Landau levels D by approximating the scanning probe and the 2DEG as a parallel plate capacitor.[12] The signal at the strip location is $S(x) \propto 1/[d + \epsilon h + \epsilon(4\pi e^2 D)^{-1}]$, where $d=90$ nm is the 2DEG depth and $h=10$ nm is the distance between the scanning probe and the surface.[13] This accounts for the 25% decrease of the signal at the strip compared to the neighboring regions, where $S(x) \propto 1/[d + \epsilon h]$. The resulting D is ~ 30 times smaller than the zero magnetic field DOS. This result agrees with the values obtained from the measurements of the DOS between Landau levels performed on bulk 2DEG samples with lateral dimensions of ~ 100 μm.[14] Our observation demonstrates that the nonzero DOS in the cyclotron gap is established on length scales smaller than the strip width.

The low compressibility strip discussed above for the filling factor $\nu=4$ reappears at filling factors $\nu=2$ and 6 (not shown). We compare the strips at $\nu=2$ and 4 in Fig. 3. Their measured widths are at least $w \sim 0.6$ μm and ~ 0.4 μm, respectively, as extracted by the eye from the flat portion of the SCA minima. These values represent conservative estimates; detailed curve fitting yields widths up to 30% greater.[11] The measured widths are significantly larger than predicted by the theory.[3] Indeed, taking $dn/dx \approx 5 \times 10^{10}/\text{cm}^2\mu$m from Fig. 1, we obtain from Eq. 20 of Ref. 3 the widths w_0 of 0.23 μm and 0.17 μm at $B=8$ T ($\nu=2$) and $B=4$ T ($\nu=4$), respectively. In Fig. 2(a) the deviation is even more pronounced: the measured width of 2 μm is four times larger than expected. We proceed now to show how this discrepancy may be qualitatively explained by considering a finite DOS localized between Landau levels.[15]

Theory predicts that magnetic field should modify the electron distribution, so that within the incompressible strip the electron density is everywhere fixed at a level corresponding to an integer Landau level filling factor.[3] This picture relies on having zero DOS in the cyclotron gap and it requires alteration if the DOS is nonzero. In particular, the resulting screening should eliminate the region of $dn/dx = 0$. Nevertheless, even in this case a low compressibility strip should be formed in the regions where the Fermi energy lies between the Landau levels and the DOS is low. If the

average DOS between the Landau levels is D, then the areal density of these states is $\sim \hbar\omega_c D$. This quantity should be equal to the span of the electron density across the strip $(dn/dx)w$. We estimate the average DOS between the Landau levels as $D\sim(dn/dx)w/\hbar\omega_c$. Taking the strip width $w\sim 0.5$ μm, we obtain an approximately tenfold suppression of the DOS as compared to the zero field value. This result concurs with our estimate based on the signal strength above. The corresponding screening radius, $\epsilon/2\pi e^2 D \sim 50$ nm is much smaller than the width of the strip. Thus, the basic assumption of Ref. 3 that the screening by the states in the cyclotron gap is negligible, does not hold in our case.

Larkin and Levitov considered the broadening of the low compressibility strip as a result of a nonzero DOS between Landau levels.[16] They found that the width of the strip is quite accurately given by $w=w_0+\Delta n/(dn/dx)$, where Δn is the areal density of electrons in the cyclotron gap. This expression shows that when $w\gg w_0$, we may approximate w by $\Delta n/(dn/dx)$, as performed above.

Efros has investigated theoretically a quantum Hall liquid in the presence of a macroscopic density gradient and random potential due to the ionized donors.[17] He predicts an areal density of electron states in the cyclotron gap of $2n_c$,

where $n_c=0.4\sqrt{C}/s$, C is the density of the ionized donors and $s=20$ nm is the spacer between them and the 2DEG. Correlations among the ionized donors are known to reduce the amplitude of the random potential, so that C should be substituted by an effective $C_0\sim 4\times10^{10}$/cm^2.[18] This gives $2n_c\approx 8\times10^{10}$/cm^2. We estimate from the experiment a close value of $w(dn/dx)\lesssim 5\times10^{10}$/cm^2. This areal density of states in the gap between Landau levels also agrees well with the one measured in a sample of a similar quality at $\nu=4$ in Fig. 3 of Ref. 19.

In summary, we have studied the 2DEG in the quantum Hall regime close to integer filling factors. In a smooth potential gradient, we observe low compressibility strips corresponding to integer Landau level filling factors. Our measurements indicate that the strips are significantly wider than predicted by theory not including a short-range disorder potential.[3] We conclude that in our sample the width of the low compressibility strips at integer filling factors is determined by a low, but nonzero density of states between the Landau levels.

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[12] The use of the parallel plate capacitor model is partly justified by an inverse proportionality of the SCA signal on the tip-sample separation h, observed for $h\lesssim 100$ nm. However, the value of h is not known precisely, and this makes the estimate of D accurate only up to an order of magnitude. Alternatively one might model the tip by a thin rod or a pointlike object. It may be shown that in these cases the contrast of the SCA signal above the low compressibility strip is determined primarily by the spatial motion of the strip in response to the ac excitation. This would result in a SCA contrast much smaller than observed in the experiment, which further justifies our use of the parallel plate approximation for the scanning tip.

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