Reentrant insulating phases in the integer quantum Hall regime

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Quantum Hall measurements are performed in a dilute high-quality GaAs two-dimensional hole system with carrier densities of (4.4–5.3) $\times 10^{10}$ cm^{-2}. With the r_s value approximately 20, the interaction effect is already strong even in the absence of magnetic field. In the integer quantum Hall regime up to 2 T, a series of reentrant insulating phases (RIPs) are observed between fillings 1, 2, 3, and 4, with peak locations periodic in $1/B$. Moreover, the RIP peaks are also characterized by a striking inductance in response to ac excitations, which is likely due to the onset of a Wigner crystal state. The multiple RIP peaks indicate a more complex phase diagram than previously perceived.

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I. INTRODUCTION

Electron-electron interaction is the source of fascinating quantum many-body states of which the Wigner crystal (WC) is a prominent example [1]. The interaction strength is measured by r_s, the ratio of Coulomb energy E_C to Fermi energy E_F, which increases with decreasing carrier density. For earlier studies of higher-density systems, large interaction is realized in the fractional quantum Hall (FQH) regime where a large magnetic field B quenches the kinetic energy down to cyclotron levels $\hbar\omega_c/2$ [2–5]. Reentrant insulating phases (RIPs) between Laughlin liquids near fillings such as 1/3 and 1/5 have been considered for the WC [2–7]. In recent years, higher-purity systems have become accessible. Carrier density can be tuned to much lower concentrations so that large r_s can be realized even in the absence of a magnetic field [8–12]. Already, there are ample examples that such strongly correlated systems deviate from the Fermi liquid [13]. Although doped samples cannot yet reach the the critical r_s value for a WC ($r_s \sim 37$ [14]), stronger interaction can be readily achieved in substantially smaller magnetic fields, even in the integer quantum Hall (IQH) regime. Whether a WC near integer fillings can be indicated by RIP-like phases is not well understood. In addition, how a strongly correlated system responds to increasing B field is another important question.

This has been investigated both theoretically and experimentally. Quantum Monte Carlo calculations suggest a connection between the high-field insulating phase, the fractional regime RIP, and the zero-field insulator [15]. Several early studies in silicon metal-oxide-semiconductor field-effect transistors attribute insulating behavior at low field to many-body insulating states [16]. However, the existence of RIPs at fillings $\nu > 1$ could not be verified in high-quality dilute GaAs systems for many years [5]. Recently, insulating behavior has been observed between fillings 1 and 2 [17], but this is not yet thoroughly investigated. Furthermore, it is not known whether transitions can occur at even higher fillings. The phase diagram for strongly interacting charges, especially dilute holes in low magnetic fields, remains an open question.

To answer these questions, we have performed experiments in p-doped GaAs two-dimensional holes at carrier concentrations (4.4–5.3) $\times 10^{10}$ cm^{-2}. Evidence for RIPs near filling factors 1, 2, 3, and 4 appears as large insulating peaks and striking inductive behavior in the magnetoresistance. The RIP locations are periodic in $1/B$ with increasing stability approaching $\nu = 1$ from higher fillings. The temperature (T) dependence reveals a metal-to-insulator transition (MIT) within the RIP. Moreover, the characteristic inductive behavior vanishes upon heating above the WC melting temperature. These observations suggest that the RIPs are WC-like states and introduce additional complexity to the phase diagram for strongly interacting charges.

II. SAMPLE CHARACTERIZATION

This study is performed using a 20 nm quantum well in p-doped ⟨100⟩ GaAs. δ doping occurs symmetrically on both sides of the well at a distance of 130 nm [Fig. 1(a)]. The entire 0.5×3 mm^2 Hall bar is self-aligned to a Cr-Au top gate 360 nm above the well. Ohmic contacts are thermally deposited 90-nm-thick AuBe (1%) film annealed at 480 °C. Contact resistance is ∼400 Ω at base temperature, determined using a combination of four-terminal and two-terminal measurements. These are checked at various field strengths and found to remain Ohmic throughout.

Hall measurements are performed in a dilution refrigerator with base temperature 15 mK. A perpendicular magnetic field is swept at the rates of $dB/dt = 1$–5 G/s. All measurements are performed using standard low-frequency techniques at $f \sim 7$ Hz. Sample excitation is in the range 1 to 10 nA to avoid heating. Each signal line is filtered by two stages of low-pass RC filters (one inside and one outside the refrigerator), each having a cutoff frequency in the low kilohertz range for low-impedance sourcing. Results have been cross-checked using a variety of filter components with C ranging from 47 pF to 10 nF and remain consistent.

Shubnikov–de Haas (SdH) oscillations appear as early as 0.06 T [Fig. 1(b)] for hole density $p = 4.4 \times 10^{10}$ cm^{-2} and mobility $\mu = 1.0 \times 10^6$ cm^2/V s. At this density, carriers occupy a degenerate heavy-hole band with an effective mass $\sim 0.42 m_0$ at 0.1 T [19]. Deep minima in the magnetoresistance and crisp Hall plateaus show the high quality of the sample.

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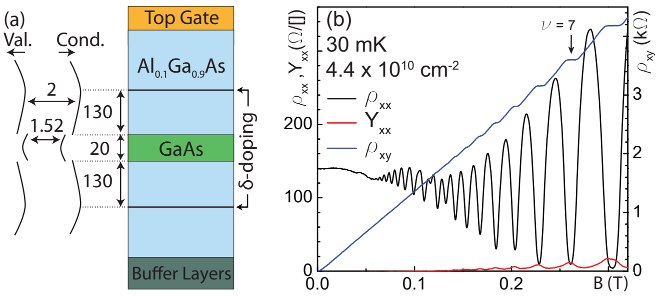

FIG. 1. (Color online) (a) Diagram of quantum well. Distances are in nanometers. Band gap energies taken from Ref. [18] are in electron volts. (b) Shubnikov–de Haas oscillations. The 0° and +90° quadrature components of the magnetoresistance, ρ_{xx} and Y_{xx}, are shown in black and red, respectively. Phase is measured relative to the driving current. Blue is used for the Hall resistance ρ_{xy}.

Here, $p = \nu B_\nu e/h$ and $\mu = 1/(pe\rho_{xx})$, where ν is the filling factor.

III. RESULTS

Figure 2(a) shows the magnetoresistance ρ_{xx} versus B for density $p = 5.1 \times 10^{10}$ cm^{-2} and $T = 50$ mK. SdH features shown in Fig. 1(b) are too small to be seen in Fig. 2(a). A striking peak (labeled P1) appears at $B = 1.77$ T between filling factors $\nu = 1$ ($B = 2.1$ T) and 2 ($B = 1.05$ T). The peak height, not shown to full scale, rises to ten times the quantum resistance h/e^2. This amplitude is similar to that of RIP peaks previously observed in the FQH regime before filling factors 1/5 and 1/3 [4,5] and is at least five times greater than that recently observed at the same filling [17]. A second peak (P2) appears at $B = 0.89$ T between fillings 2 and 3. Here also, the resistivity exhibits activated T dependence as discussed below.

Common to both P1 and P2 are large positive phase shifts (relative to the externally driven current), indicated by peaks in the +90° quadrature component of the magnetoresistance (Y_{xx}). We have performed extensive analysis to rule out electronics effects and to demonstrate that this inductive behavior arises inside the two-dimensional hole system (2DHS) only in the insulating phases. Circuit resonance is first eliminated, after which the frequency and T dependences are explored.

We note that the phase shift appears only at the insulating peaks. Resonance within the test circuit is unlikely at such low signal frequencies (~7 Hz). If this could occur, the problem would be sensitive to the sample resistance. That Y_{xx} is not a function of ρ_{xx} is evident in the comparison of the shoulder of P2 with the nearest maximum on the opposite side of the $\nu = 2$ valley. This demonstrates that unintentional coupling or resonance within the circuit is not a viable cause.

The states can be more directly probed by frequency dependence measurement. This also allows effects of the RC filters to be ascertained. The filters behave as expected, producing only a negative phase shift, and are not a possible cause. Figure 2(b) shows a characterization of the sample and filters at $B = 0$. The sample is purely resistive, showing a flat response below the cutoff frequency $f_c \sim 5$ kHz. For $f \gtrsim f_c$, the filter capacitance contributes significantly to the

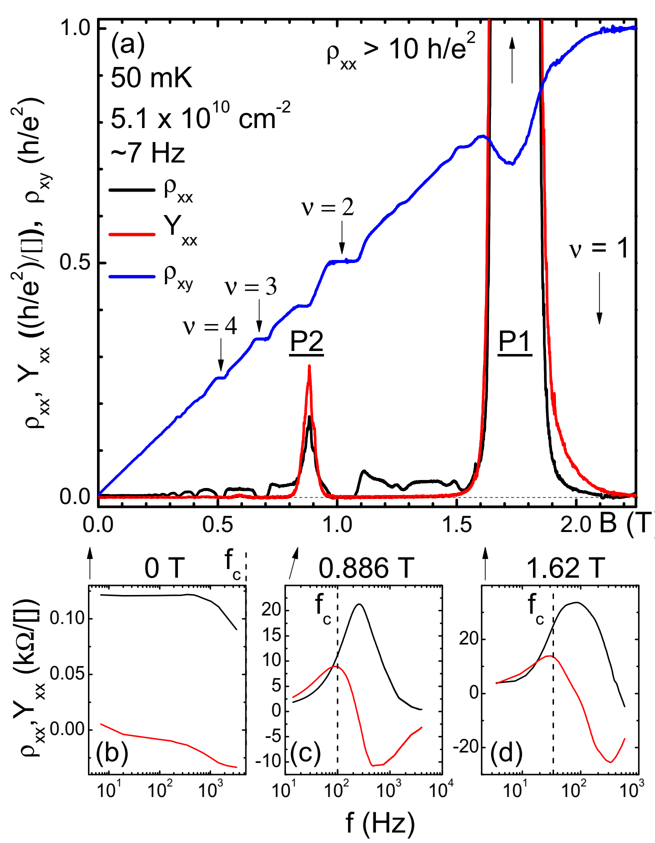

FIG. 2. (Color online) (a) Hall measurement reveals two insulating peaks in the integer regime labeled P1 and P2. At P1, ρ_{xx} reaches $10h/e^2$. For both peaks, Y_{xx} rises substantially but elsewhere is less than 10% of the total signal. (b) Magnetoresistance shows flat frequency response in zero field up to the filter cutoff frequency. (c) Inductive behavior of P2 is clearly visible below the cutoff. (d) Frequency dependence on the shoulder of P1 ($B = 1.62$ T) is similar to that at the maximum of P2. At larger sample impedance, the cutoff decreases, preventing similar measurement at the center of P1.

measured impedance, causing a negative phase shift (both ρ_{xx} and Y_{xx} appear to drop). Beyond the scale of the graph, the signal attenuates as current shunts through the capacitors to bypass the sample. In contrast, the magnetoresistance at both P1 and P2 is highly frequency dependent below f_c [Figs. 2(c) and 2(d)]. The positive slope of both ρ_{xx} and Y_{xx} and increasing impedance with rising frequency are characteristic of an inductive load. Such large inductance is a feature unique to these insulating phases.

Stronger evidence that this behavior is inherent to the 2DHS is obtained from the T-dependence of the magnetoresistance. Local heating on the sample holder alone does not affect the signal path or external electronics. Figure 3(a) shows a series of Hall measurements at slightly higher density $p = 5.3 \times 10^{10}$ cm^{-2} between fillings 2 and 3 for various temperatures up to 300 mK. The driving frequency $f \sim$ 7 Hz is chosen to be much less than f_c [see Fig. 2(c)] so that filter distortion is less than 2% over the range of impedances shown. A vertical dashed line at $B = 0.89$ T indicates the base temperature location of P2. The inset of

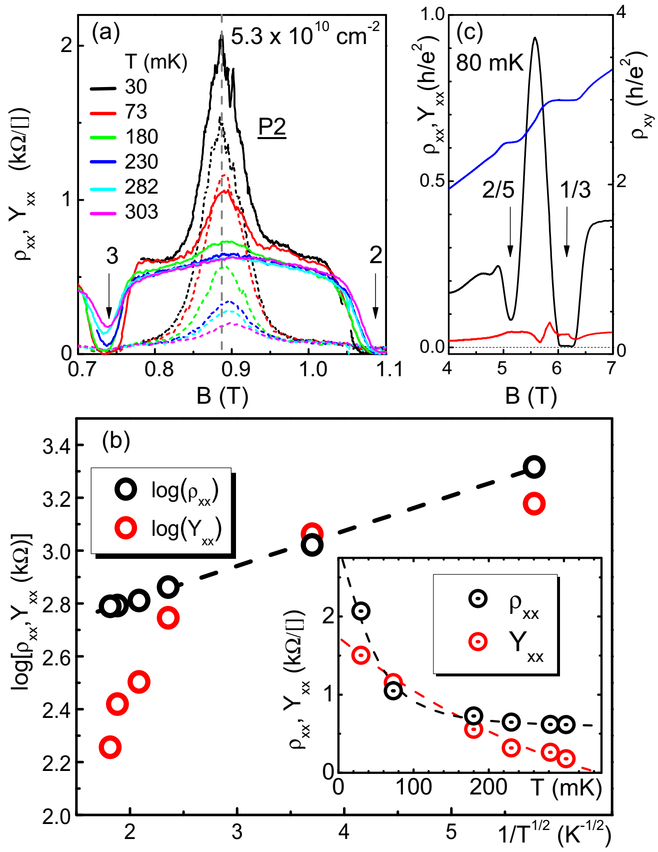

FIG. 3. (Color online) (a) A series of measurements for various temperatures (30 to 300 mK) showing both the real (solid) and imaginary (dashed) components of the magnetoresistance for fixed density at P2. A vertical dashed line appears at $B = 0.89$ T. (b) Real and imaginary components of the magnetoresistance at fixed $B = 0.89$ T plotted as a function of $T^{-1/2}$ on a semilogarithmic scale. The dotted line represents fitting to Efros-Shklovskii [20] variable-range-hopping $\rho_{xx} \propto \exp(\sqrt{T^\star/T})$ with $T^\star = 98$ mK. The inset shows both ρ_{xx} and Y_{xx} as a function of T with dotted lines as guides to the eye. (c) Hall measurement for the RIP near 1/3 at density 5.1×10^{10} cm^{-2} (the color coding is the same as that in Fig. 2).

Fig. 3(b) shows the T dependence of ρ_{xx} and Y_{xx} at this fixed value of B. From 30 to 100 mK, both signals drop rapidly. Upon further heating, ρ_{xx} changes little, but Y_{xx} continues to drop and vanishes near 350 mK. Figure 3(b) shows the activated nature of ρ_{xx}. The magnetoresistance is fitted (dashed line) to the Efros-Shklovskii variable-range-hopping model $\rho_{xx} \propto \exp(\sqrt{T^\star/T})$ describing strongly interacting systems for which a Coulomb gap appears in the density of states [20]. Although the peak height is limited by cooling capability, the activated divergence of ρ_{xx} below $T^\star = 98$ mK confirms the insulating nature of P2. Furthermore, the T dependence of Y_{xx} can arise only from changes in the 2DHS. Thus, the sample appears to undergo a temperature-driven MIT marked by the development of large inductance as T decreases. We note that this inductance appears to be distinct to the IQH-regime RIPs. Under similar conditions, Y_{xx} remains relatively small for the RIP near $\nu = 1/3$ [Fig. 3(c)].

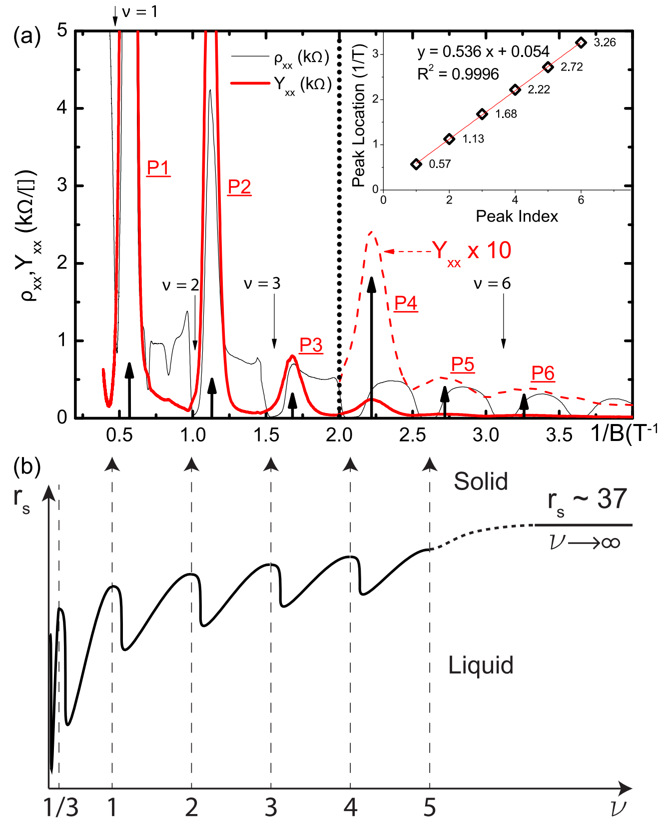

FIG. 4. (Color online) (a) Periodicity of Y_{xx} in $1/B$. To the right of the vertical dashed line, Y_{xx} has been amplified by a factor of 10 for clarity. Peaks locations are marked by upward arrows and indexed according to the closest integer filling factor. The inset shows a straight-line fit of the peak location in $1/B$ as a function of peak index. (b) Proposed phase diagram modified from Ref. [15]. Integer fillings are positioned to line up with the magnetoresistance minima in (a) as indicated by the vertical dashed arrows. A series of reentrant phases is proposed between integer fillings. Relative peak heights are qualitatively consistent with our data.

The above frequency and T dependencies indicate a common origin for insulating states P1 and P2. For both peaks, inductive behavior is the first signature to appear as T is lowered, so that Y_{xx} is a sensitive probe for identifying these unique strongly correlated RIPs. We now show, through a series of transitions visible in Y_{xx}, that P1 and P2 are connected to similar states between higher fillings. Figure 4(a) displays ρ_{xx} and Y_{xx} at $T = 50$ mK as a function of $1/B$ at lower density $p = 4.6 \times 10^{10}$ cm^{-2} for which the interaction is slightly enhanced. The Y_{xx} trace has been amplified by a factor of 10 on the right half of the graph to improve visibility (dashed red line). Positive shifts in Y_{xx} appear near each integer filling between 7 and 1, rapidly growing in height as B increases. The peaks are periodic in $1/B$, confirmed by the straight-line fit (inset) of peak location to peak index. Looking back to the lowest-density measurement in Fig. 1(b), we also see that such periodicity can extend to higher fillings. Thus, these insulating states appear to stabilize in the presence of stronger interaction. Although the peaks are approximately equal width in $1/B$, the actual peak width becomes increasingly narrow at higher fillings in low field.

IV. DISCUSSION

Since the early studies in the FQH regime, RIPs have been associated with WCs [5] or Wigner glass (WG) [21,22]. Results such as nonlinear I-V characteristics and microwave resonance seem to support this [4,6]. As theorists point out, such strongly correlated states are also expected to have a complex response to low frequencies and low-energy excitations [23,24]. In particular, inductive behavior is expected for a sliding WC [24].

In our measurement, the equivalent inductance per square is enormous, ∼10 H/□ for P2 and larger for P1, where the impedance is taken to be of the form $Z_{xx} = \rho_{xx} + i\omega L_{xx}$ so that the inductance per square is $L_{xx} = Y_{xx}/\omega$. This behavior cannot be explained in the single-particle picture where the kinetic inductance is proportional to the single-particle effective mass and is very small (on the order of 10 μH for the edge currents at integer filling) [25]. Therefore, the enormous inductance measured in these RIP phases confirms a correlated many-body effect. The exact response of a WC or WG to external ac stimulus is a complex and not well understood subject that depends upon temperature, disorder, excitation levels and frequencies, fluctuations, melting point, and the magnetic field. Although there are currently no theoretical calculations with which to compare our results, the large many-body inductance can be intuitively understood through the enhancement of the effective mass at the MIT, which has been reported in several results [26]. As shown above, the onset of inductive behavior at P2 occurs at $\frac{1}{130}E_C \sim 350$ mK, which is roughly the melting temperature for a WC [27,28]. Above the melting point, the system becomes a strongly correlated semiquantum liquid (since it is still much below the Debye temperature of ∼300 K). The diminishing collective inductance at the melting point is understood through the breakdown of long-ranged order as the interaction is overcome by rising thermal fluctuations.

The series of reentrant states suggests a more complicated phase diagram than previously expected from variational quantum Monte Carlo calculations linking the zero-field, low-field, and high-field insulating states as a single connected solid phase [15]. We propose a modified diagram [Fig. 4(b)] for the region $\nu > 1/5$ that includes more reentrant phases among higher fillings. Analogous to the quantum Hall states, these RIPs suffer from both disorder and electron scattering effects at higher Landau fillings, becoming shallower and narrower at low field. In addition, we suggest a possible distinction between RIP phases in the IQH and FQH regimes since no significant inductance appears for the RIP near filling 1/3. The correspondence between RIPs for high-density systems in the FQH regime and strongly correlated dilute systems in the IQH regime needs to be further explored.

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