Vertical Confinement and Evolution of Reentrant Insulating Transition in the Fractional Quantum Hall Regime

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Abstract

We have observed an anomalous shift of the high field reentrant insulating phases in a two-dimensional electron system (2DES) tightly confined within a narrow GaAs/AlGaAs quantum well. Instead of the well-known transitions into the high field insulating states centered around $\nu = 1/5$, the 2DES confined within an 80Å-wide quantum well exhibits the transition at $\nu = 1/3$. Comparably large quantum lifetime of the 2DES in narrow well discounts the effect of disorder and points to confinement as the primary driving force behind the evolution of the reentrant transition.

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The prospect for a quantum Wigner crystal has driven the study of two-dimensional electron system (2DES) under the conditions of low temperature and high magnetic field. Experiments on high mobility GaAs/AlGaAs heterostructures have shown that in the limit of zero temperature the $\nu = p/(2p\pm 1)$, $p = 1, 2, 3 \ldots$ series of incompressible quantum liquid states of fractional quantum Hall effect (FQHE) terminates with a transition into a field-induced insulator at low fillings. A dramatic sequence of transitions involving a reentrant insulating phase, a $\nu = 1/m$ primary FQHE state, and the final insulating phase can be realized in the highest quality samples. Initially observed in 2DES around the $\nu = 1/5$ FQHE, the reentrant insulating phase has been also detected adjacent to the $\nu = 1/3$ FQHE state in two-dimensional hole system (2DHS). Reentrant insulating behavior is also seen in high quality silicon MOSFET and $p$-SiGe heterostructures in the integer quantum Hall regime. Because of the correlated nature of the FQHE, the insulating states above and below the FQHE states at $\nu = 1/3$ and $1/5$ are expected to be driven by electron-electron correlation rather than disorder, enhancing the likelihood of formation of a Wigner crystal. This has given impetus for various electrical, acoustic, microwave, and optical investigations of the high field insulating phases.

For an ideal, disorder-free 2DES, the ground state in the limit of zero temperature is an ordered electron crystal at small Landau level fillings. However, a positive confirmation of the Wigner crystalline order has remained controversial and somewhat elusive. This is partly due to absence of scattering experiments that can directly probe the crystalline order of the insulating phases. In addition, interpretation of various experiments in the Wigner crystalline regime is complicated by general lack of understanding of the effects of disorder in presence of strong interaction. Even the highest quality samples presently available possess non-negligible disorder at low fillings, and the competition of disorder and interaction is thought to modify the ground state of 2D systems in some fundamental way. At short distances, the ground state is conjectured to evolve into a partially ordered Wigner crystal consisting of finite-size domains that are pinned by the disorder potential. In presence of strong disorder, the ground state evolves into a disorder-driven correlated insulator called Hall insulator.

In this paper we present an unexpected observation of reentrant insulating phase around the $\nu = 1/3$ FQHE state in a two-dimensional electron system. The 2DES in question is found in a GaAs/AlGaAs quantum well whose narrow width produces a tight vertical
confinement of the electronic wave function. In spite of its relatively low mobility, we observe a clear sequence transitions to an insulator, a FQHE, and back to an insulating phase in the vicinity of $\nu = 1/3$ filling in a fashion reminiscent of the Wigner crystalline regime in high mobility $n-$ and $p$-type GaAs/AlGaAs heterostructure. Tilted magnetic field study shows that the insulating phases are found to be insensitive to the presence of parallel magnetic field. We also compare the properties of the 2DES in the NQW with a wider quantum well and the conventional heterostructure. We find that the single particle lifetime of the 2DES in NQW is comparable to other higher mobility specimen and conclude that confinement within the NQW may be responsible for the shift in the reentrant transition.

The experiment was performed using a modulation doped AlGaAs/GaAs quantum well of 80-Å in width. The density of the sample was $n = 1.1 \times 10^{11}$ cm$^{-2}$ with a low temperature mobility of $2.56 \times 10^5$ cm$^2$/V sec. The transport in narrow quantum well (NQW) is dominated by interfacial fluctuations\(^1\)
\(^9\), yielding a substantially lower mobility than comparable heterostructure samples. Samples in Hall bar and van der Pauw configurations were studied inside a dilution refrigerator with a 14 tesla superconducting magnet. Tilted-field study was performed up to 40 tesla using the hybrid magnet at the National High Magnetic Field Laboratory. A light emitting diode was used to illuminate the sample at low temperatures. Depending on the illumination conditions and the thermal cycling history, small variation in the data was detected. This, however, does not alter our conclusions.

Fig. 1 illustrates the magnetoresistance $R_{xx}$ of a NQW sample at a temperature of 35 mK. The most striking feature of the data is the sharp increase of longitudinal resistance between $\frac{1}{3} < \nu < 0.45$. Slightly after $\nu = 1/2$ $R_{xx}$ increases dramatically by more than 2 orders of magnitude, completely overwhelming other transport features. The peak resistance at $\nu = 0.38$ exceeds 900k$\Omega$ before dropping precipitously as it enters the $\nu = 1/3$ FQHE state. $R_{xx}$ subsequently diverges upon entering a high field insulating phase. The inset of Fig. 1 illustrates longitudinal and Hall resistances of the same sample under a different illumination condition. The $R_{xy}$ is quantized at $3h/e^2$ at $\nu = 1/3$, demonstrating the formation of the $\nu = 1/3$ FQHE state. The $\nu = 3/7$ FQHE state is found as a weak $R_{xx}$ minimum prior to the reentrant insulating phase.

Fig. 2 shows the temperature dependence of the insulating state at a slightly higher density ($n = 1.2 \times 10^{11}$ cm$^{-2}$). As temperature is raised, $R_{xx}$ decreases sharply with the insulating features largely disappearing above $T = 300$ mK. The inset of Fig. 2 shows an
Arrhenius plot of peak resistance at $\nu = 0.38$. The resistance at the peak is activated with an activation energy of $E_g \sim 0.26K$. At lower temperatures, there is a saturation of the resistivity. Measurement of I-V characteristics shows that the transport in the insulating regime is highly nonlinear, similar to previously observed reentrant insulating phases[2, 3, 4, 5, 6, 7, 8, 9].

Fig. 3 shows the effect of parallel magnetic field in the insulating regime above and below the $\nu = 1/3$ FQHE state. Comparison of magnetoresistance for the tilt angle of $\theta = 0^\circ$ and $\theta = 58^\circ$ at $T = 50$ mK shows that there is no appreciable change in both $\nu = 1/3$ FQHE state and the insulating states above and below $\nu = 1/3$ even though the total magnetic field was nearly double of the perpendicular magnetic field. This shows that neither the increase in the Zeeman energy nor the deformation of the wave function due to strong parallel magnetic field appears to play a large role in the insulating phase.

In Fig. 4, we explore the role of vertical confinement by comparing the transport between quantum well samples with different widths. Fig. 4a illustrates magnetoresistance of our 80Å wide NQW. Fig. 4b illustrates the magnetoresistance of a quantum well sample that is 300Å wide and possessing a mobility of $\mu = 7.8 \times 10^6 cm^2/Vs$ and a density of $n = 6.2 \times 10^{10} cm^{-2}$. In the wider quantum well specimen, magnetoresistance at 30 mK shows a well-developed sequence of FQHE states centered around $\nu = 1/2$ and $\nu = 1/4$ followed by the reentrant insulating phase prior to the $\nu = 1/5$ FQHE state. This contrasts sharply with the 80 Å-wide NQW which only exhibits a weakly developed FQHE state at $\nu = 2/3$ prior to the reentrant insulating state above $\nu = 1/3$. These results suggest strongly that narrow confinement is likely to be important in altering the properties of 2DES in the insulating regime.

The prevailing view on the high field reentrant transitions in various 2DES involves either an entry into the Wigner crystalline regime[1] or an approach based on the global phase diagram of quantum Hall effect[16]. Consideration of the former scenario follows from the importance of the electron-electron interaction in the limit of low fillings. Since the Laughlin states at $\nu = 1/m, m = 3, 5...$ occur from strong electronic correlation[26], it follows that the interaction should also play an important role in the adjacent insulating states. The reentrance is explained in terms of competition between the FQHE liquid and Wigner solid. In this point of view, the insulating phases seen in the NQW is likely to be some kind of strongly correlated ground state driven by interaction. Alternatively, the
insulating phases in NQW may occur due to some electron localization effect associated with disorder as suggested by its modest mobility. In this context, the global phase diagram picture of quantum Hall transitions is relevant as a transition from an insulator into a FQHE state at $\nu = 1/3$ is permitted.

However, in either pictures, there is no obvious explanation for the shift in the reentrant insulating transition to $\nu = 1/3$ for the 2DES in the NQW. This feature is particularly puzzling since the reentrant behavior is always found near $\nu = 1/5$ in 2DES based on GaAs/AlGaAs structures. In fact, the observed sequence of transitions in NQW resembles the reentrant insulating transitions near $\nu = 1/3$ in 2DHS in GaAs/AlGaAs heterostructure. In the reentrant insulating transitions seen in Si MOSFET and p-SiGe heterostructure, the reentrant insulating phases are found in the integer quantum Hall regime and spin is thought to play an important role. In our NQW, tilted field experiment appears to rule out the role of spin in the reentrant insulating phase.

Theoretically the transition into a Wigner crystal in 2DES is predicted for $\nu \leq 1/6.5$. In the case of 2DHS in GaAs/AlGaAs heterostructures, the stability of the insulating phases near $\nu = 1/3$ is explained in terms of increased Landau level mixing associated with its heavier effective mass ($m^*_h = 0.3m_e$) compared to that of electrons ($m^*_e = 0.067m_e$). Since the effective mass of electrons in narrow quantum wells has been shown to be comparable to heterostructures, Landau level mixing does not appear to play a significant role in NQW. As there is no universally accepted explanation for the reentrant transitions observed in various two-dimensional semiconductor systems, understanding of the shift in the reentrant behavior in the NQW is likely to be important in clarifying the nature of the associated insulating phases.

The role of disorder remains an important question as the mobility of 2DES in NQW is modest compared to other 2DES based on GaAs/AlGaAs quantum structures. However, previous experiments on GaAs/AlGaAs heterostructures with mobilities comparable to that of our NQW have not found reentrant behavior next to the $\nu = 1/3$ FQHE state. While this appears to discount the importance of disorder associated with the reentrant behavior in the NQW, interfacial roughness serves to restrict the transport in narrow quantum wells and a more quantitative measure of disorder is necessary. This is particularly important since electronic transport under magnetic field is largely determined by large angle scattering instead of the small angle scattering which dominates the zero field transport. The
single particle relaxation time, $\tau_s$, in semiconductors is consequently substantially smaller than the transport scattering time, $\tau_t$ [27, 28].

In Table I we summarize the properties of 2DES derived from 3 different GaAs/AlGaAs structures that exhibit reentrant insulating phase in the lowest Landau level. In addition to the 80Å quantum well, 2DES from a heterostructure and 300Å quantum well with mobilities that are respectively 10 and 30 times larger were compared. $\tau_t$ was deduced from zero field mobility, $\mu = e\tau_t/m^*$, and $\tau_s$ was determined from the Dingle analysis of the Shubnikov-de Haas (SDH) oscillations as suggested by Coleridge [28]. In contrast to the large differences in $\tau_t$, we found that $\tau_s$’s determined from different structures were surprisingly close. The $\tau_s$ in the high mobility 300 Å wide quantum well was 8.5 ps with the 80 Å NQW yielding a $\tau_s$ of 3.7 ps. The heterostructure sample was found to possess a $\tau_s$ comparable to other 2DES samples.

The proximity of $\tau_s$’s is also reflected in the onset of SDH oscillations, $B_{\text{onset}}$. In the insets of Fig. 4 we show the SDH oscillations for 80 Å NQW and 300 Å quantum well. A $B_{\text{onset}}$ of $\sim$ 60 mT for the NQW and $\sim$ 30mT for other samples were obtained. The comparable $\tau_s$ and $B_{\text{onset}}$ suggest that in spite of its low mobility, the electronic lifetime in NQW is not adversely affected by the tight confinement, increasing the likelihood that the reentrant behavior around $\nu = 1/3$ is driven by interaction rather than disorder. On the other hand, the larger resistivity at $\nu = 1/2$ and the absence of high order FQHE states is consistent with presence of stronger disorder in the NQW than the wider well. However, coexistence of the $\nu = 1/3$ FQHE state next to the insulating phases indicates that disorder is not enough to suppress the electron correlation in the limit of low fillings.

Since the most distinguishing characteristic of the 2DES in a NQW involves its vertical confinement, the physics of reentrance may potentially occur from a confinement-induced evolution of the Coulomb interaction. The ground state energy and the interaction parameters of 2DES depends on the finite vertical extent of the electronic wave function [29, 30]. A thicker 2DES consequently experiences a softer Coulomb potential and thereby possesses a reduced FQHE energy gap compared to a thinner 2DES. Our estimate of the thickness of electrons based on the interaction parameters in quantum wells [32] points to a substantial reduction in its thickness compared to the 2DES found in heterostructures [30]. For the 2DES in Table I we obtain a thickness of 128Å in the heterostructure specimen which contrasts sharply against the estimated thickness of 19Å and 67Å for the 80Å and 300Å quantum
wells. The role of thickness in the insulating phases in 2DES remains unknown and further theoretical investigation is necessary to clarify the effect of confinement in relation to the enhancement of \( r_s \) in the insulating regime.

In summary, we have observed a puzzling shift in the reentrant insulating phases in a 2DES confined within a NQW. The apparent shift in the reentrant transition to \( \nu = 1/3 \) cannot be reconciled in terms of disorder and points to importance of confinement. Understanding the shift in the reentrant transition may be important in uncovering the physics behind the reentrant insulating phases in the NQW as well as other two-dimensional electron and hole systems. While the confinement within a NQW is expected to produce a thinner 2DES, its effect in the high field insulating states remains to be clarified.

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TABLE I: Comparison of the properties of two-dimensional electron systems in 80Å GaAs/AlGaAs quantum well, 300Å GaAs/AlGaAs quantum well, and a GaAs/AlGaAs heterostructures. All exhibit reentrant behavior in the lowest Landau level.

| sample           | density (10^{11} cm^{-2}) | mobility, $\mu$ (cm^2/Vs) | scattering onset of single particle, $\tau_t/\tau_s$ | $\rho_{xx}$ at $\nu = 1/2$ reentrance (10^5 cm$^{-2}$) | $\tau_t$ (ps) SDH (mT) lifetime, $\tau_s$ (ps) | (kΩ/□) | $\nu$ |
|------------------|----------------------------|-----------------------------|-------------------------------------------------------|------------------------------------------------------|-----------------------------------------------|--------|-------|
| 80Å QW           | 1.1                        | $2.5 \times 10^5$           | 9.7                                                   | 61                                                   | 3.6                                           | 2.7    | 15.3  | $\nu = 1/3$ |
| 300Å QW          | 0.62                       | $7.8 \times 10^6$           | 297                                                   | 29                                                   | 8.5                                           | 35     | 0.241 | $\nu = 1/5$ |
| heterostructure  | 0.53                       | $2.5 \times 10^6$           | 95                                                    | 30                                                   | 6.7                                           | 14     | 0.741 | $\nu = 1/5$ |
FIG. 1: Longitudinal magnetoresistance of a narrow quantum well at 35 mK. Inset: longitudinal (blue) and transverse (red) magnetoresistivities of a sample with a slightly higher density. Integers and fractions indicate the Landau level filling of the two-dimensional electron system.

FIG. 2: Longitudinal magnetoresistance of a narrow quantum well at 32, 46, 60, 80, 100, 140, 210, 300 and 420 mK. Inset: Arrhenius plot of the resistivity at the peak of the reentrant insulating phase.

FIG. 4: Comparison of reentrant insulating transitions in a 80 Å (top) and 300 Å (bottom) wide quantum well with mobility of $2.5 \times 10^5 \text{cm}^2/\text{Vs}$ and $7.8 \times 10^6 \text{cm}^2/\text{Vs}$, respectively, at $T \approx 30 \text{mK}$. Insets: expanded view of the low field Shubnikov-de Haas (SDH) oscillations. While the mobilities differ by a factor of $\sim 30$, the onsets of SDH oscillations differ by a factor of $\sim 2$.

FIG. 3: Magnetoresistance vs perpendicular magnetic field for tilt angles at $\theta = 0^\circ$ (solid) and $\theta = 58^\circ$ (dashed). The measurement was performed at 50 mK.
\[ E_g = 260 \text{mK} \]
