Evidence for Two Different Solid Phases of Two Dimensional Electrons in High Magnetic Fields

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We have performed RF spectroscopy on very high quality two dimensional electron systems in the high magnetic field insulating phase, usually associated with a Wigner solid (WS) pinned by disorder. We have found two different resonances in the frequency dependent real diagonal conductivity spectrum and we interpret them as coming from two different pinned solid phases (labeled as “WS-A” and “WS-B”). The resonance of WS-A is observable for Landau level filling \(\nu<2/9\) (but absent around the \(\nu=1/5\) fractional quantum Hall effect (FQHE)); it then crosses over for \(\nu<0.18\) to the different WS-B resonance which dominates the spectrum at \(\nu<0.125\). Moreover, WS-A resonance is found to show dispersion with respect to the size of transmission line, indicating that WS-A has a large correlation length (exceeding \(\sim 100 \mu m\)); in contrast no such behavior is found for WS-B. We suggest that quantum correlations such as those responsible for FQHE may play an important role in giving rise to such different solids.

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In 1934, Wigner proposed that electrons can crystallize into a solid when their (Coulomb) interaction energy dominates over their kinetic energy. In two dimensions, it is expected that formation of such Wigner solid (WS) can be facilitated by a sufficiently strong perpendicular magnetic field (\(B\)). On the other hand, a two dimensional electron system (2DES) with areal density \(n\) can condense into quantum Hall (QHE) states with dissipation-free transport at a series of integer or fractional Landau filling factors \(\nu=(h/e)(n/B)\), where \(h/e\) is the Dirac flux quantum. Calculations predicted the transition from fractional QHE series (which are incompressible quantum liquids) to WS to occur around the transition from fractional QHE series (which are incompressible quantum liquids) to WS to occur around the transition from fractional QHE series (which are incompressible quantum liquids) to WS.

In our experiments, we have measured even lower disorder 2DES and observed two different resonances in different regimes of HBIP, with one resonance crossing over to the other as \(\nu\) is reduced (by increasing \(B\)). We interpret the two resonances as coming from two different solid phases pinned by disorder.

The 2DES samples we have used are fabricated from two very high quality GaAs/AlGaAs/GaAs quantum well (QW) wafers grown by molecular beam epitaxy. Data from three samples will be presented. Sample 1 contains a 50nm-wide QW with \(n=6.8\times 10^{11}\text{cm}^{-2}\) and mobility \(\mu \sim 10^{7}\text{cm}^2/\text{Vs}\). Sample 2a and 2b are from the other wafer, each containing a 65nm-wide QW with \(n=5.1 \times 10^{10}\text{cm}^{-2}\) and \(\mu \sim 8 \times 10^{6}\text{cm}^2/\text{Vs}\).

We have deposited on the surface of each sample a metal film coplanar waveguide (CPW) similar to the ones used in previous experiments measuring microwave conductivity of 2DES. A typical measurement circuit is shown schematically in Fig. (A) and a magnified (not to scale) local cross section of the sample near the CPW is shown in Fig. (B). A network analyzer generates and detects the RF signal, which propagates along the CPW and couples capacitively to the 2DES. The CPW confines the electric field (\(E\)) mainly in each slot region of width \(w\) (shown in Fig. (B)), giving \(E\) a step function profile (neglecting edge effects related to the 2DES), and therefore introducing a finite wavevector through the dominant Fourier component \(q \sim \pi/w\). The relative power absorption (\(P\)) by the 2DES is measured. Under conditions of sufficiently high \(f\) and low 2DES conductivity, no reflections at ends of CPW, and when 2DES is in its long wave length limit \(l_0=2\), \(P = \exp((2lZ_0/w)\text{Re}(\sigma_{xx}))\), where \(l\) is the to-
Measurements are done in the low RF power limit, by dilution refrigerator and placed in a perpendicular magnetic field so that resonance “B” dominates the spectrum and “A” continues to evolve but eventually weakens. By 33 mT, the resonance “B” becomes dominant and “A” nearly disappears. From 22.9T to 33T, the resonance “B” becomes dominant and “A” nearly disappears. By 33 mT, resonance “B” becomes dominant and “A” nearly disappears. From 22.9T to 33T, the resonance “B” becomes dominant and “A” nearly disappears. By 33 mT, “B” becomes dominant and “A” nearly disappears. From 22.9T to 33T, “B” becomes dominant and “A” nearly disappears. By 33 mT, “B” becomes dominant and “A” nearly disappears.

We have also observed higher lying but relatively weak resonances such as the one labeled as peak “2” in the figure. They show qualitative similarities with “A” (for example, the dependence on magnetic field) but do not appear to fit simple harmonics of “A’. Details of them will be discussed in a future publication.

FIG. 1: (A) Scheme of microwave circuit typically used in our experiment. Sample size is ~3×5 mm. Dark regions on sample surface represent metal films deposited to make the CPW. The dimensions of the CPW can vary, but have been carefully designed to match the 50Ω characteristic impedance. (B) Magnified (not to scale) local cross section of sample with CPW, where w is the width of each slot region. The 2DES resides in a symmetric AlGaAs/GaAs/AlGaAs QW and is 0.4-0.5 µm under the surface. Sample substrate is GaAs.

FIG. 2: Sample 1: Re[σxx(f)] spectra measured at various B, in increasing order from B=18.6T (bottom) to 33T (top). Adjacent traces are offset for 3µS from each other for clarity. Magnetic fields (and selected ν’s) are labeled at right. Measurements were performed at T ~60 mK. From left to right, the long dashed, dotted, dot-dashed, and short dashed lines are guides to the eye, corresponding to peaks “B”, “C”, “A” and “2” respectively, as explained in the text.

A striking difference between resonances “A” and “B” is seen by comparing Fig. 2(A) to 2(B), which shows the spectra measured at five representative magnetic fields using sample 2b. Sample 2b was cut from the same wafer with sample 2a and only differs in the slot width (w) of the CPW. Both samples show similar resonances “A” and “B”, with similar ν range of crossover. However, going from w=30 µm (sample 2a) to 60 µm (sample 2b), we notice that fpk of resonance “A” shifts to lower value while fpk of resonance “B” is not affected; this is true...
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even when resonances “A” and “B” coexist (for example, in the spectrum at 14T). Since \( w \) introduces a finite wavevector in the measurement, we are apparently sensing the dispersion \( f_A(q) \) of resonance “A” using samples with varying \( w \).

Our data thus reveal two distinct regimes in the HPBIB characterized by two different resonances (“A” and “B”): one at \( 2/9 < \nu < 0.18 \) (except for a narrow range around \( \nu = 1/5 \) where only resonance “A” has been observed; and another at \( \nu < 0.125 \) (down to the smallest \( \nu \) we have accessed) where the rather different resonance “B” dominates [13]. We interpret the two regimes as corresponding to two different (pinned) solid phases, hereafter referred to as “WS-A” and “WS-B” respectively, each being the preferred ground state in the respective \( \nu \) range. Because of interaction with disorder, either solid is pinned (thus insulating), and can support a similar pinning mode [3, 10, 11, 12, 13] that gives rise to the observed resonance. The \( f_{\text{pk}} \) of our resonances are nearly an order of magnitude lower than what previous experiments [3] observed [21], probably due to significantly reduced pinning disorder in our samples.

The striking crossover behavior, which we do not observe for \( T \) above \( \sim 130 \) mK [21], is consistent with a magnetic field induced phase transition from WS-A to WS-B and with coexistence of the two phases (at low \( T \)) in the transition regime \( (0.18 > \nu > 0.125) \), suggesting such transition would be first order. The intermediate peak “C” disappears at \( \sim 100 \) mK, leaving only peaks “A” and “B” present in the spectra. Though peak “C”, like “A” and “B”, is reproducible in different cooldowns of the same sample; we have sometimes noticed other delicate features that appear to depend on the way the sample is cooled (for example, peak “B” sometimes briefly splits near \( \nu = 0.125 \) before dominating the spectra at lower \( \nu \)’s). Such complicated behavior may reflect some delicate competition between multiple or intermediate phases in the transition regime.

The apparent crossover from WS-A to WS-B is mainly controlled by Landau level filling \( \nu = n h / e B = 2 (l_B / r)^2 \), where the magnetic length \( l_B = \sqrt{h / e B} \) (which measures the size of electron wavefunction) and the mean separation between electrons \( r = 1/\sqrt{\pi n} \). This rules out the crossover being caused by interplay of \( l_B \) with, for example, some disorder length scale [13] or as some \( n \)-induced transition, but rather points out the important role played by many-electron quantum correlations, dependent on \( l_B / r \).

The dispersion behavior of resonance “A” as seen in Fig. 3 requires WS-A must have a correlation length larger than \( w \) of the CPW; otherwise the pinned solid is effectively subjected to a uniform electric field, therefore can not couple to the finite \( q \) introduced by \( w \). Preliminary measurements on another sample with \( w = 80 \) \( \mu \)m show that resonance “A” continues to shift to lower \( f \), implying a correlation length in WS-A at least on the order of \( \sim 100 \) \( \mu \)m, which is two orders of magnitude larger than what the simple estimate used in [8] for a classical WS would give.

It has been thought that correlations responsible for FQHE can still be relevant [22, 23, 24, 25] even in HBIP. More specifically, theories [23, 24, 27] have considered different types of “correlated” WS ("cWS") made of “composite fermions” or “composite bosons”, the quasiparticles (electrons bound with even or odd number (\( m \)) of flux quanta respectively) proposed to largely encapsu-
late the FQHE correlations\cite{16}. In this notation, a CWS would be a WS made of “bare” electrons, corresponding to the original case proposed in \cite{2}. The theories \cite{23, 24, 25} have predicted a series of first order phase transitions among these different types of CWS as preferred ground states in different regimes of HBIP, thus offering an attractive interpretation for the different phases we observed as these different solids. So far, different theories \cite{23, 24, 25} have favored, for example near $\nu=1/5$ (corresponding to our WS-A), different types of CWS’s; and a detailed calculation of the dynamical responses of different CWS’s pinned by disorder is not yet available to allow for a direct comparison with our observed resonances. Although caution should be taken in comparing these theories (for ideal 2DES) to experiments on realistic samples, some predictions seem to be consistent with our observations. For example, \cite{24}CWS (favored in \cite{24}) is in remarkable agreement with our phenomenological value below which WS-B resonance dominates. Some other predictions, however, seem to be at odds with our observations. For example, \cite{23}WS (favored in \cite{23}) is predicted to significantly soften as $\nu$ approaches 1/5; for a weakly pinned solid \cite{24, 25, 26} this would result in increasing $f_{pk}$ of the resonance, which is not the case we have observed. Generally, it is expected that even modest disorder may have significant influences on the various CWS phases \cite{24}, for example, it may stabilize one CWS against another, consistent with the fact that previous microwave experiments \cite{8} on a heterojunction sample with lower mobility ($\sim 5 \times 10^6$ cm$^2$/Vs) than our QW samples have observed only one resonance in HBIP.

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\bibitem{18} Details of this resonance in the so called “reentrant insulating phase” (RIP \cite{6}, for $1/5<\nu<2/9$) and near the transition to $\nu=1/5$ and $2/9$ FQHE liquids will be presented elsewhere.
\bibitem{19} Preliminary data from sample 2a with a relatively low as-casted density ($4.6 \times 10^{10}$ cm$^{-2}$) and up to 33T shows resonance “B” to continuously evolve down to $\nu\sim 0.06$. No other resonances are observed in the spectrum at such small $\nu$.
\bibitem{20} Previous experiments \cite{8} found $f_{pk}\sim 1$ GHz or higher. Our samples show nearly flat spectrum at such high $f$.
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