Microwave Resonance of the 2D Wigner Crystal around Integer Landau Fillings

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We have observed a resonance in the real part of the finite frequency diagonal conductivity using microwave absorption measurements in high quality 2D electron systems near *integer fillings.* The resonance exists in some neighborhood of filling factor around corresponding integers and is qualitatively similar to previously observed resonance of weakly pinned Wigner crystal in high B and very small filling factor regime. Data measured around both $\nu = 1$ and $\nu = 2$ are presented. We interpret the resonance as the signature of the Wigner crystal state around integer Landau levels.

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Two-dimensional electron systems (2DES)[1] subjected to perpendicular magnetic field B have been observed to display a remarkably rich array of phases in different regimes of filling factor $\nu = nh/eB$, where n is the 2D electron density. These phases include the renowned integer and fractional quantum Hall effects (QHE) [2], discovered more than two decades ago. The integer quantum Hall effect (IQHE), with ν taking integer values, has been explained by a disorder induced *one-particle* localization mechanism; whereas the fractional quantum Hall effect (FQHE), with ν being certain fractions, is strictly a many-particle phenomenon. At small ν, following the termination of FQHE series in the lowest Landau level (LLL), the ground state for a sufficiently clean system is believed to be a Wigner crystal (WC) [3,4] and disorder would pin the crystal, rendering it insulating [5]. One of the experimental supports for such Wigner crystal phase in LLL is the recent observations of sharp resonance in the real part of frequency (f) dependent diagonal conductivity $\mathrm{Re}[\sigma_{xx}(f)]$ measured by microwave absorption [6,7]. The resonance has been interpreted as caused by the pinning mode of Wigner crystal domains oscillating in the disorder potential [8,9].

In this Letter we report the observation of similar resonances around *integer* Landau fillings, which we interpret as also coming from a Wigner crystal state, formed around integer fillings by electrons/holes in the top Landau level. This also indicates that pinning of a *many-particle* ground state, such as Wigner crystal, can be relevant even for IQHE.

We have performed our study using high quality 2DES in a GaAs/AlGaAs quantum well (QW) structure grown by molecular beam epitaxy. The QW is 300 Å wide and located 2000 Å beneath the surface. The 2DES has as-cooled density $n = 3.0 \times 10^{11}$ cm^{-2} and 0.3 K mobility about 2.4×10^7 $\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$. A metal film coplanar waveguide (CPW) [10] of straight line shape was patterned onto the sample surface by photolithography. A schematic of the sample and measuring circuit is shown in the inset of Fig. 1(a). A network analyzer generates a microwave signal propagating along the CPW, which couples capacitively to the 2DES, then measures the relative power transmission P. The real part of the diagonal conductivity, $\mathrm{Re}[\sigma_{xx}]$, simply referred to as "conductivity" hereafter, can be related to P as $\mathrm{Re}[\sigma_{xx}] = -\frac{w}{2lZ_0}\ln|P/P_0|$, where $l = 2$ mm is the length of the CPW, $w = 20$ μm is its slot width, $Z_0 = 50\ \Omega$ is the

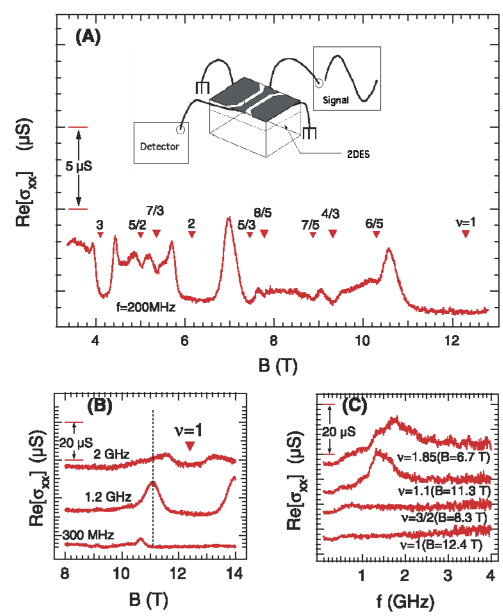

FIG. 1 (color online). (a) The B-dependent conductivity at 200 MHz and ~80 mK with a slightly elevated microwave power. Several filling factors are marked. Inset shows the schematic measurement circuit. Dark regions represent the metallic films deposited on the sample to make the CPW. (b) B-dependent conductivity around $\nu = 1$ measured at three different frequencies as labeled. Traces appropriately offset vertically for clarity. The temperature during B sweep is about 80 mK. Dotted line is a guide to the eye for the resonating behavior. (c) A few f-dependent conductivity spectra (offset for clarity) measured at ~50 mK and at various B fields labeled underneath each trace. Data in both (b) and (c) are measured with a low microwave power.

line impedance in the absence of 2DES, and P_0 is the power transmission in the limit of vanishing 2DES conductivity [10]. Normalizing P by P_0 gets rid of the nonflat f dependence of microwave attenuation not associated with the 2DES, mainly that due to the coaxial cable. While the total depletion of 2DES is not possible for our sample, $P_0(f)$ is estimated from the power transmission measured under a certain reference condition, such as at IQHE minimum, at half-filling (for example, $\nu = 3/2$), at high power, or at high temperature. Specific examples of references are given below. We have used different references to check our experimental findings and found negligible difference in the results.

In Fig. 1(a) we display an example of B-dependent conductivity measured at a fixed frequency (200 MHz) and ~80 mK. We can readily resolve such FQHE states at 6/5, 4/3, 7/5, 8/5, 5/3, 7/3, and 5/2, attesting to the high quality of the sample. Figure 1(b) shows the B-dependent conductivity measured at three different frequencies, in field range of 8 to 14 T, through $\nu = 1$. We see the peak-like "wing" (for example, the one near 11 T in the middle trace) on the side of $\nu = 1$ has a small amplitude in the 300 MHz trace (bottom), but is greatly enhanced in the 1.2 GHz trace (middle), and reduces to small amplitude again in the 2 GHz trace (top), thus displaying a resonating behavior. Such behavior is most clearly seen through the f-dependent conductivity spectrum $\mathrm{Re}[\sigma_{xx}(f)]$. Figure 1(c) shows four spectra measured at $\nu = 1$, 3/2, 1.1, and 1.85 (from bottom to top), respectively, all acquired at about 50 mK and in the low microwave power limit. The reference spectrum is taken at a much higher power at $\nu = 1$. Both spectra at $\nu = 1$ and $\nu = 3/2$ are flat within experimental tolerance and can actually be used as alternative references (P_0), giving at most a constant offset in the conductivity obtained but otherwise having little influence in the results. In contrast, the spectrum at $\nu = 1.1$ ($B = 11.3$ T) shows a strong resonance (near 1.3 GHz) of height more than 10 μS and quality factor Q [peak frequency divided by FWHM (full width at half maximum)] almost 3. Similarly, the spectrum at $\nu = 1.85$ ($B = 6.7$ T) also displays a strong resonance, near 1.7 GHz.

This resonance in f-dependent conductivity happens for ν near integers and has been observed around $\nu = 1$, 2, 3, and 4. In this Letter we focus mostly on the resonances around $\nu = 1$ and 2. The resonances around $\nu = 3$ and 4 behave similarly to those around $\nu = 1$ and 2, but are much weaker and will be treated in detail in a future publication. All data shown in Figs. 2–4 below are measured on an adjacent sample from the same wafer, at ~50 mK, and in the low power limit.

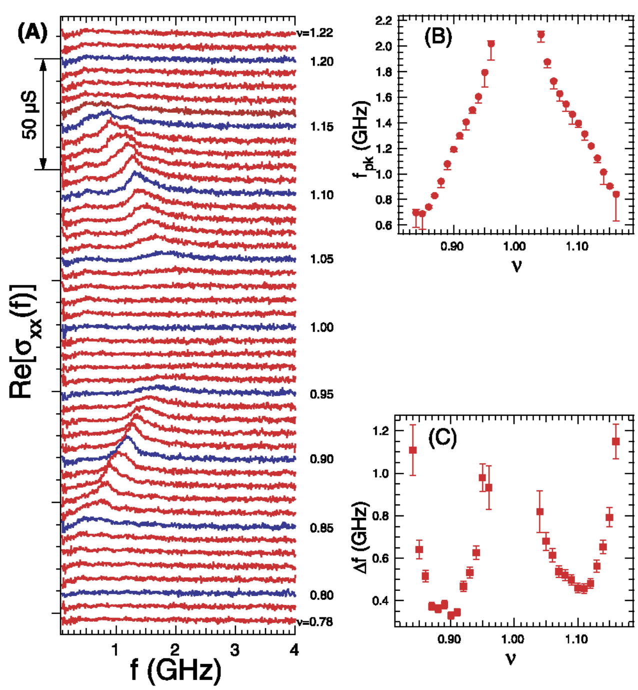

FIG. 2 (color online). (a) Frequency dependent conductivity spectra around $\nu = 1$: from $\nu = 0.78$ (bottom trace) to $\nu = 1.22$ (top trace). Adjacent traces differ by 0.01 in ν and are offset 6 μS from each other for clarity. Filling factors for selected traces are labeled at right. Measurements are performed at ~50 mK. (b) f_{pk} versus filling. (c) Δf versus filling factor.

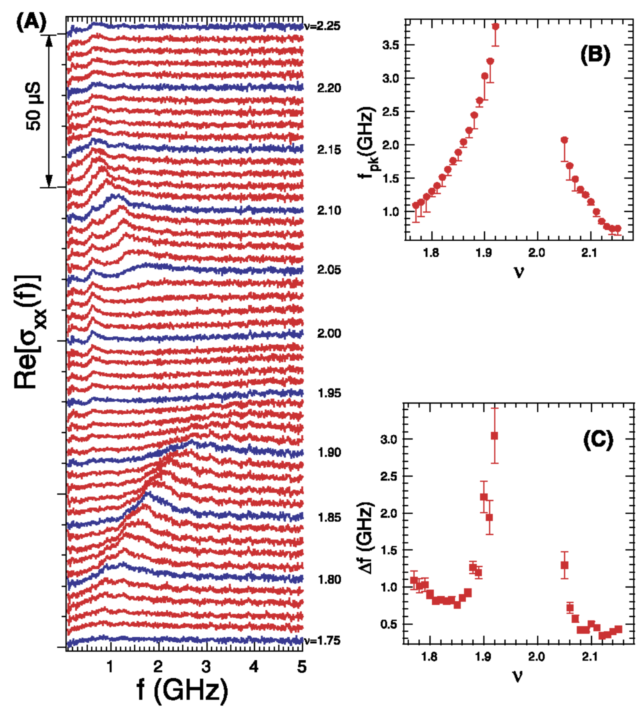

FIG. 3 (color online). (a) Frequency dependent conductivity spectra around $\nu = 2$: from $\nu = 1.75$ (bottom trace) to $\nu = 2.25$ (top trace). Adjacent traces differ 0.01 in ν and are offset 4 μS from each other for clarity. Filling factors for selected traces are labeled at right. Measurements are performed at ~50 mK. (The small spike near 600 MHz in some traces, not moving with B, is likely due to an experimental artifact). (b) f_{pk} versus ν. (c) Δf versus ν.

Figure 2(a) shows $\mathrm{Re}[\sigma_{xx}(f)]$ spectra measured at 45 filling factors ranging from 0.78 to 1.22, in equal increments of 0.01. When ν is sufficiently far from 1 (~ 0.8 and 1.2) the spectrum is flat with no resonance. A resonance starts to develop when ν is around 0.84–0.85 (for ν below 1) and 1.15–1.16 (for ν above 1) at frequencies below 1 GHz. The resonance sharpens with increasing peak frequency as ν approaches 1 (from both sides) till becoming sharpest around $\nu = 0.9$ (resonating around 1.2 GHz) and $\nu = 1.1$ (resonating around 1.4 GHz). As ν further approaches 1 the resonance weakens, but its peak frequency continues to increase; the last visible resonance is around $\nu = 0.95$–0.96 and 1.04–1.05 with frequency reaching nearly 2 GHz. In the immediate vicinity of $\nu = 1$ ($0.96 < \nu < 1.04$) the spectra are again flat. In Figs. 2(b) and 2(c) we plot the peak frequency, f_{pk}, and the full width at half maximum, Δf, of the resonance as functions of ν. Here f_{pk} and Δf are extracted by fitting the resonance to a Lorentzian: $A_0 + A_1/[A_2 + (f - f_{\mathrm{pk}})^2]$, with $\Delta f = 2\sqrt{A_2}$. While f_{pk} monotonically increases as ν moves closer to 1, Δf reaches minima when ν is about 0.1 away from 1, where the resonance has quality factor $Q = f_{\mathrm{pk}}/\Delta f$ of more than 3.

In Fig. 3(a) we display $\mathrm{Re}[\sigma_{xx}(f)]$ spectra measured at 51 filling factors between 1.75 to 2.25, again in 0.01 increments of ν. The strongest resonance on each side of $\nu = 2$ occur at $\nu \sim 1.85$(with peak frequency about 1.8 GHz) and $\nu \sim 2.12$(resonating at below 1 GHz); the peak frequency of the resonance always increases as $\nu \to 2$. The qualitative features of the resonance are similar to those around $\nu = 1$; however we notice an evident asymmetry between the two sides of $\nu = 2$, possibly related to the different wave functions in different orbital Landau levels(whereas both sides of $\nu = 1$ belong to the same orbital Landau level). The f_{pk} and Δf of the resonance are extracted as in Fig. 1 and plotted in 3(b) and 3(c) as functions of ν, respectively.

The most natural interpretation of our data is that the resonance we observe is due to a Wigner crystal phase formed around integer Landau fillings. For clean enough

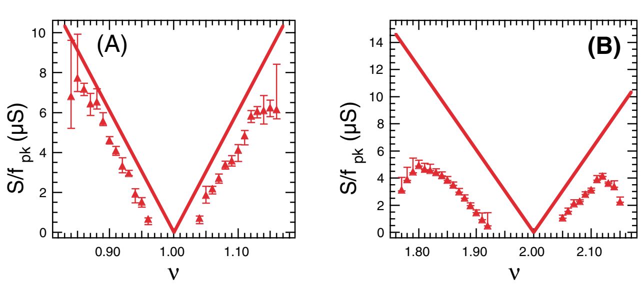

FIG. 4 (color online). (a) Oscillator strength divided by peak frequency (S/f_{pk}) as a function of filling factor, for resonance around $\nu = 1$. Thick solid line is the Fukuyama-Lee result for WC of effective filling factor $\nu^* = \nu - 1$. (b) S/f_{pk} as a function of filling factor, for resonance around $\nu = 2$. Thick solid line is the Fukuyama-Lee result for WC of effective filling factor $\nu^* = \nu - 2$. See text for details.

2DES, WC has been theoretically assumed to be the ground state of the system for filling factor $\nu = K + \nu^*$ with sufficiently small $|\nu^*|$, where K is some positive integer [11]. Such considerations are often based on the simple physical picture that electrons (or holes, for negative ν^*) in filled Landau levels can be assumed to be "inert" and the remaining electrons/holes of "effective filling factor" ν^* and density $n^* = (n/\nu)\nu^* = n\nu^*/(K + \nu^*)$ should Wigner crystallize when the size of their localized wave function (on the order of the magnetic length $l_B = \sqrt{\hbar/eB}$) becomes small compared to their average spatial separation. Because of interaction with weak disorder such a crystalline phase is pinned, rendering the top Landau level insulating, and supports a pinning mode [8] that gives rise to the observed resonance.

Our resonance is qualitatively similar to the resonance previously observed at small filling factors in the LLL Wigner crystal regime of both electrons and holes [6,7,12], as well as the recently discovered resonance from the "bubble" crystal phase in high ($\nu > 4$) Landau levels [13], all thought to be caused by the pinning mode of crystalline domains in the 2DES. The many-particle nature of such a pinning mode is reflected in several features of our observed resonance. For example, the resonance at 14 T, $\nu = 0.89$ is observed up to nearly 200 mK, much higher than $hf_{\mathrm{pk}}/k_{\mathrm{B}} \sim 50$ mK where $f_{\mathrm{pk}} \sim 1$ GHz is the resonating frequency. This rules out the pictures of individual particles trapped by disorder or individual (quasi)particle localization-delocalization transition giving rise to the resonance [14]. Furthermore, the resonance (at the lowest temperature) can have quality factor Q more than 3. The collective motion of a large region of particles can average disorder and allow such high Q [15].

Additional insights about our observed resonance in support of the pinned Wigner crystal picture can be gained by integrating the spectrum to extract the oscillator strength S [16]. Previous theory by Fukuyama and Lee [8] has calculated conductivity that predicts $S/f_{\mathrm{pk}} = |n^* e\pi/2B| = |(e^2\pi/2h)\nu^*|$ for pinned 2D WC with density n^* and effective filling factor ν^* under perpendicular B. Figures 4(a) and 4(b) display S/f_{pk} calculated for the resonance in Fig. 2 (around $\nu = 1$) and Fig. 3 (around $\nu = 2$), respectively. We see indeed the data follow a straight line over most of its range. We note here that the magnitudes of the resonance and S are found to have some significant variations (up to a factor of 2) for different cooldowns and samples (from the same wafer), but such linearlike behavior in S/f_{pk} versus ν^* is always observed.

An important feature of our resonance, as already seen in Figs. 2(b) and 3(b), is that the peak frequency of the resonance always monotonically increases with decreasing effective density n^*. This is a key character of the "weak-pinning" picture [7,12,17].

From the data presented in this paper, we notice that the observed resonance is mostly visible in a ν^* range of

$\nu_l^* < |\nu^*| < \nu_u^*$ (this range depends on the specific integer filling and even the sign of ν^*). The existence of an "upper limit," ν_u^*, analogous to the case in LLL Wigner crystal, is probably because WC is not the ground state of our 2DES at large enough ν^*. For example, away from $\nu = 1$, as $\nu \to 4/5$ or $\nu \to 6/5$, the system would enter the FQHE state, which is an incompressible liquid. This kind of "quantum melting" of the WC state would account for the observed weakening of the resonance and the drop of S/f_{pk} at large $|\nu^*|$ seen in Fig. 4. The existence of a "lower limit," ν_l^*, also corresponding to a lower limit for density $n_l^* = (n/\nu)\nu_l^*$, possibly indicates the "carriers" (electrons/holes) are individually localized by disorder for densities n^* below n_l^*. This lower limit of n^* would also imply that higher density samples may allow such resonance to be observable around higher integer fillings. Preliminary studies performed on a lower density sample (7×10^{10} cm^{-2} with mobility $\sim 5 \times 10^6$ cm^2 $\times$ V^{-1} s^{-1}) have found only relatively weak resonance around $\nu = 1$ and none around higher integer fillings.

For more disordered 2DES, theories of frequency-driven variable range hopping conduction in IQHE [18] predict a linear dependence of Re$[\sigma_{xx}]$ on frequency, which has been confirmed in recent experiments [19] on samples of mobilities up to 5×10^5 cm^2 V^{-1} s^{-1}. No resonances were seen in these experiments.

Around $\nu = 1$ a "Skyrme" crystal has been proposed [20] and there are some recent experiments hinting at its existence [21]. We note that the Skyrme crystal cannot explain our observed resonance around $\nu = 2$, where Skyrmions do not exist. Moreover, the resonance we observe shows major similarities around $\nu = 1$ and 2 in contrast to the experiments in [21], both of which showed a response in their measured quantity that has orders-of-magnitude difference between near $\nu = 1$ and 2.

In summary, we have observed a microwave resonance around integer fillings in high quality 2DES. On either side of these integer fillings ($\nu = K$), the resonance f_{pk} monotonically increases with decreasing $|\nu^*|$, whereas the resonance is strongest at certain ν away from K. We interpret the resonance as caused by the pinning mode of a Wigner crystal phase of density $n^* = (n/\nu)\nu^*$ formed by electrons/holes in the top Landau level, around the corresponding integer fillings.

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