Microwave Resonance of Wigner Crystal Phase around Integer Quantum Hall States

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We have observed, by microwave absorption spectroscopy, a well defined resonance in the real part of frequency-dependent diagonal conductivity(Re[$\sigma_{xx}(f)$]) of high quality 2DES *near integer filling factors.*

Figure 1 and Figure 2 show the resonances observed around $\nu = 1$ and $\nu = 2$ respectively. The measurements were performed in a dilution refrigerator at its base temperature of 50mK, using a GaAs/AlGaAs quantum well sample with density $n = 3.0 \times 10^{11}$ cm^{-2} and mobility about 2.4×10^{7} cm^{2} V^{-1}s^{-1}. Similar resonances around $\nu = 3$ and $\nu = 4$ have also been observed on this sample, although they are significantly weaker compared to those around $\nu = 1$ and $\nu = 2$.

Fig. 1(A) displays a series of Re[$\sigma_{xx}(f)$] spectra measured at filling factors(ν) between 0.78 and 1.22. The resonance is observable for $0.84 < \nu < 0.96$ and $1.04 < \nu < 1.16$. Within either of these ν ranges, the resonance shifts to higher frequency as $\nu \to 1$ and is sharpest when ν is ~ 0.9 or 1.1. In Fig. 1(B) and (C) we plot the peak frequency ($f_{\rm pk}$) and full width at half maximum (Δf) of the resonance as functions of ν, where $f_{\rm pk}$ and Δf are extracted from Lorentzian fit of the resonance. We see $f_{\rm pk}$ monotonically increases as $\nu \to 1$ and Δf has minima at $\nu \sim 0.9$ and $\nu \sim 1.1$, where the resonance has quality factor Q (defined as $f_{\rm pk}/\Delta f$) about 3. In similar fashion to Fig. 1, we show in Fig. 2(A) a series of Re[$\sigma_{xx}(f)$] spectra at filling factors around 2 (from 1.75 to 2.25), where the resonance is observable for $1.77 < \nu < 1.92$ and $2.05 < \nu < 2.15$, and in Fig. 2(B)(C) we plot the extracted $f_{\rm pk}$ and Δf as functions of ν. In this case $f_{\rm pk}$ monotonically increases as $\nu \to 2$ and Δf is found to have minima at $\nu \sim 1.85$ and $\nu \sim 2.12$.

We have also studied the temperature(T) dependence of the resonance. With increasing T, Δf monotonically increases whereas $f_{\rm pk}$ is relative insensitive. The resonance disappears for T above ~200 mK.

We interpret the resonance as the signature of 2D Wigner crystal phase formed around integer Landau fillings, by the electrons/holes in the partially filled top Landau level with effective filling factor ν^* (where $\nu^* = \nu - K$ for filling factor ν around positive integer K) and density $n^* = (n/\nu)\nu^*$. The "pinning mode"[1], caused by such Wigner crystalline domains oscillating in impurity potential, gives rise to the observed resonance. The collective many-particle nature of this resonance is reflected by the high Q achieved and the existence of resonance at temperature several times higher than that corresponding to its resonating frequency ($hf_{\rm pk}/k_B$).

Wigner crystal has been conjectured to be the ground state of a sufficiently clean 2DES at $\nu = K + \nu^*$ for small enough ν^* and positive integer K[2], as in the case of $K = 0$ (that is, in the lowest Landau level(LLL))[3]. The LLL ($K = 0$) Wigner crystal has been supported by, for example, previous observations of similar resonance at small ν in LLL for both 2DES and 2D hole systems[4]. The feature of $f_{\rm pk}$ increasing with decreasing density also observed in these experiments, is consistent with the weak-pinning picture[5].

Our observation also indicates that the pinning of a many-particle ground state such as Wigner crystal, can be relevant for IQHE, which has traditionally been explained by a disorder induced single-particle localization mechanism.

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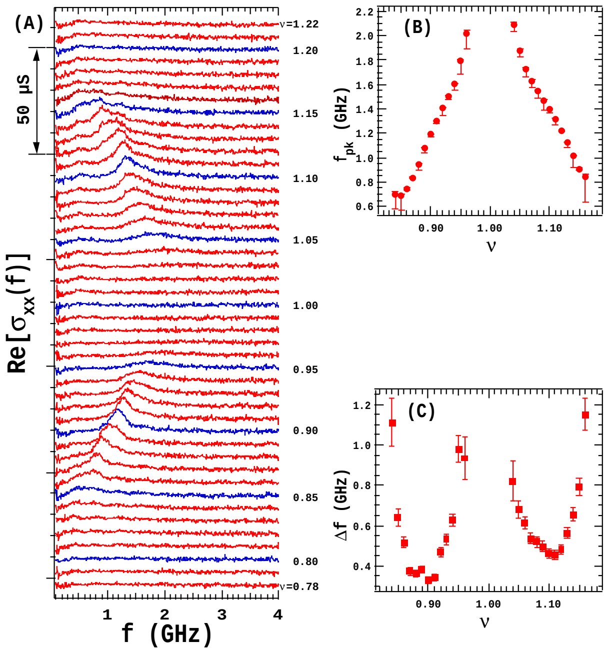

FIG. 1: **(A)** Re[$\sigma_{xx}(f)$] spectra around $\nu = 1$: from $\nu = 0.78$ (bottom trace) to $\nu = 1.22$ (top trace). Adjacent traces differ 0.01 in ν and are offset 6 μS from each other for clarity. Filling factors for selected traces are labeled at right. Measurements performed at $\sim$ 50 mK. **(B)** $f_{\rm pk}$ versus ν. **(C)** Δf versus ν.

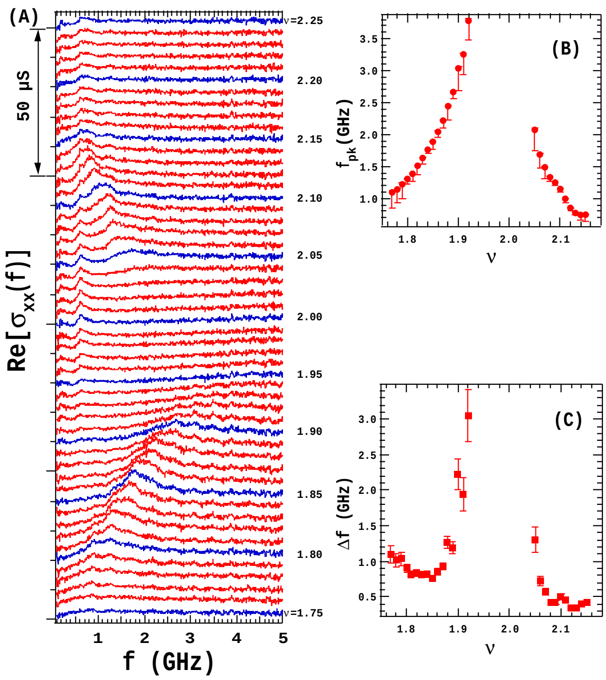

FIG. 2: **(A)** Re[$\sigma_{xx}(f)$] spectra around $\nu = 2$: from $\nu = 1.75$ (bottom trace) to $\nu = 2.25$ (top trace). Adjacent traces differ 0.01 in ν and are offset 4 μS from each other for clarity. Filling factors for selected traces are labeled at right. Measurements performed at $\sim$50 mK. (The small spike near 600 MHz in some traces is likely due to an experimental artifact). **(B)** $f_{\rm pk}$ versus ν. **(C)** Δf versus ν.