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Recent results in microwave and rf spectroscopy of two-dimensional electron solids

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Abstract. The paper presents data on the bubble phase of two-dimensional electron systems in higher Landau levels, as an example of the application of broadband microwave and rf spectroscopy to the study of electron solids.

1. INTRODUCTION

Over the last few years, our broadband microwave spectroscopic studies [1–7] of two-dimensional electron systems (2DES) in extremely high quality samples have yielded a number of results on high magnetic field (B) electron solids. Such solids are necessarily pinned by disorder, and they exhibit striking rf or microwave resonances, due to "pinning modes," in which regions of solid oscillate about their pinned positions.

When multiple Landau levels are occupied, a high mobility 2DES can arrange itself into a series of electron solid or anisotropic stripe phases, depending on the filling ν^* of the partially filled, "top" Landau level, beneath which completely filled Landau levels exist. ($\nu^* = \nu - [\nu]$, where $[\nu]$ is the greatest integer not greater than ν.) The stripe phase, which at least on a small enough length scale can be described as a unidirectional charge density wave [8–10], occurs in the center of the Landau level, around $\nu^* = 1/2$. Moving toward the edges of the Landau level, the stripes break up into "bubble phases," which are lattices of clusters (bubbles) of M electron guiding centers. Near the edges of the Landau level, in the region of the integer quantum Hall effect, individual electrons (or for $\nu^* > 1/2$, holes) in the top Landau level form a lattice, which we call the integer quantum Hall Wigner crystal (IQHWC).

We have recently observed pinning resonances in the bubble [3] and IQHWC [2] phases. This paper will focus in particular on the bubble phases, and will present some more recent data than that previously published. Evidence for coexistence [6] of the bubble phase and the IQHWC around $\nu = 4$ will be described.

2. EXPERIMENTAL METHOD

Fig. 1 shows a schematic of the method we use for broadband measurements of the 2DES diagonal conductivity. A standard, planar type of microwave transmission line is fabricated on the top surface of a sample, and is capacitively coupled to the 2DES, a fraction of a μm beneath. The data will be presented as $\mathrm{Re}(\sigma_{xx})$, calculated from the appropriately normalized power P, transmitted through the line, as $\mathrm{Re}(\sigma_{xx}) = -W|\ln(P)|/2Z_0L$, where W is the width between center conductor and side plane (as shown in Fig. 1b), Z_0 is the characteristic impedance of the line in the case of vanishing σ_{xx}, and L is the length of the line. The data are measured in the low power limit, in which decreasing the applied power does not affect the measured conductivity.

The data presented here came from samples made from a GaAs/AlGaAs wafer containing a 300 Å quantum well, with typical density $n = 3.0 \times 10^{11}$ cm^{-2} and 300 mK mobility $\mu = 2.4 \times 10^7$ cm^2 V^{-1} s^{-1}.

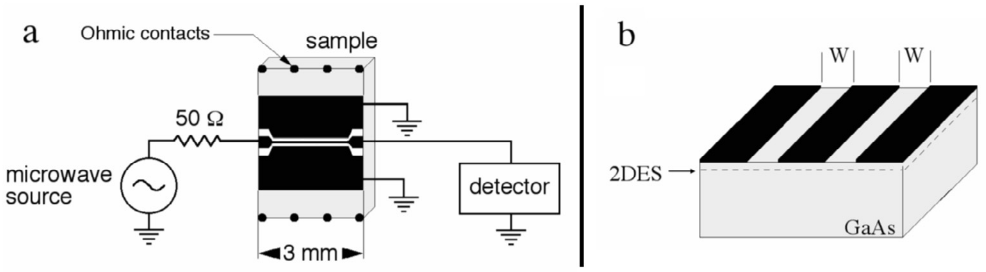

Figure 1. *a.* Schematic of measurement setup. The coplanar waveguide transmission line is fabricated on the top of a sample. The metal film that forms the transmission line is shown as black. The metal side planes are grounded, while the narrow center conductor is driven. Under the conditions of the measurement in-plane microwave electric field at the 2DES is mainly confined to the regions under the slots between center conductor and ground planes. In addition to straight transmission lines like the one shown, we routinely use meandering transmission lines, which, when the 2DES is isotropic, simply produce more absorpion than the straight lines. *b.* Magnified cutaway view of a sample near the transmission line (not to scale). Typically, width of the slot between center conductor and ground planes is $W = 30\,\mu$m.

3. RESONANCES IN THE BUBBLE PHASES

Fig. 2 shows recent data on Re(σ_{xx}) vs magnetic field, B, at frequency $f = 500$ MHz and temperature about 50 mK. As in dc traces of diagonal resistivity ρ_{xx}, taken in similar samples (see for example [11, 12]), clear minima are present due to integer quantum Hall effect (IQHE) at $\nu = 3, 4, 5, 6, 7,$ and

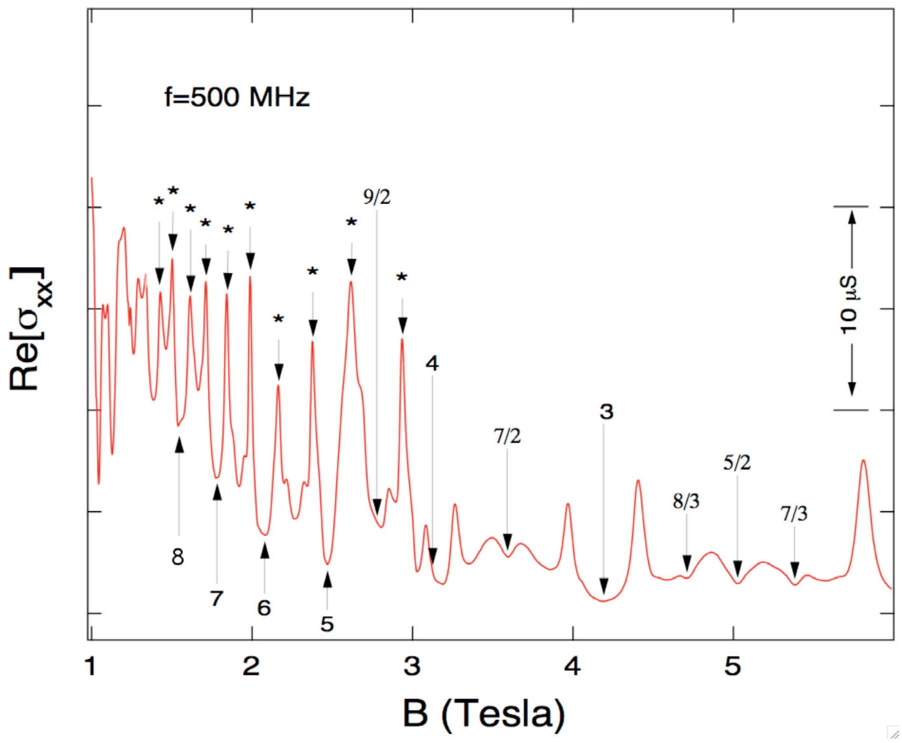

Figure 2. The real diagonal conductivity, Re(σ_{xx}) vs magnetic field B at $T \approx 50$ mK. Peaks due to bubble phase resonances are marked with "$*$".

to the fractional quantum Hall effect (FQHE) at $7/3$, $5/2$, $8/3$, and $7/2$. The bubble phase is identified with the "reentrant integer quantum Hall effect" (RIQHE) in dc transport [11–13]. In the RIQHE there is vanishing dc diagonal resistivity and dc Hall resistance quantized like that of the nearby IQHE. In contrast, the 500 MHz data in Fig. 2 shows sharp peaks around $1/4$ and $3/4$ filled Landau levels, where the bubble phases are expected and the RIQHE is observed in dc [11–13]. These peaks are due to the resonance in the spectrum of the bubble phases, and depend strongly on f. The resonance is strong evidence in support of the interpretation of the RIQHE as due to an electron solid, capable of supporting a pinning mode. Though the rest of this paper concentrates on the range of ν between 4 and 5, the peaks due to the bubble phase resonances are clearly visible in Fig. 2, out to $\nu \approx 8 + 3/4$.

Fig. 3 shows previously unpublished data. It combines many spectra, $\mathrm{Re}(\sigma_{xx})$ vs f, taken for ν between 4.1 and 4.55; the gray scale represents $\mathrm{Re}(\sigma_{xx})$. Contours have been added at intervals of 1 μS for $\mathrm{Re}(\sigma_{xx}) > 3$ μS. The transmission line was oriented so the electric field was along the expected hard direction, that of larger dc diagonal resistance in the anisotropic stripe phase. A similar resonance, ascribable to a bubble phase of holes in the top Landau level with occupation, appears for ν from 4.64 to 4.80. The ν ranges in which we see the resonance are in excellent agreement with theoretical predictions [8, 14, 15] for the ν range of an $M = 2$ bubble phase. The decrease of the peak frequency as $\nu^* = 1/2$ is approached is typical [16] of pinning modes in the lowest Landau level , whose f_{pk} decreases with increasing carrier density n. It is a consequence of the carriers more closely associating themselves with impurities when the density (and hence the crystal stiffness) is reduced, so that the average pinning energy and f_{pk} increase. The carrier density relevant to the bubble phase is that in the top Landau level

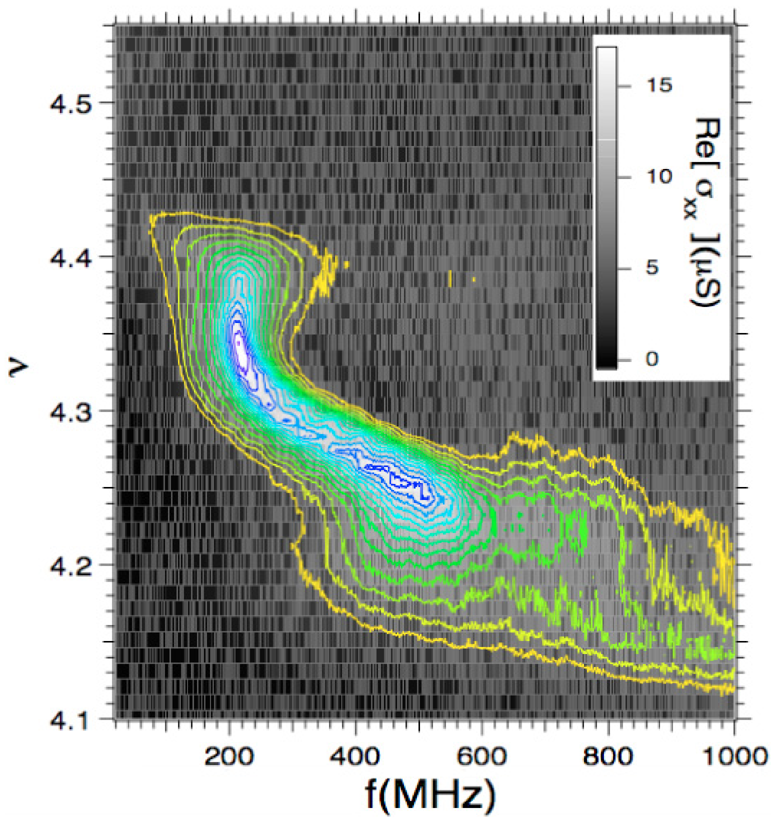

Figure 3. A grayscale plot of $\mathrm{Re}[\sigma_{xx}(\mathrm{f})]$ for ν between 4.1 and 4.55, at $\approx$ 35 mK. Contour lines at intervals of 1 μS (starting at 3 μS) are superimposed.

$n^* = n\nu^*/\nu$, which increases as $\nu^* = 1/2$ is approached. Near the ν range of the striped phase, the decrease of f_{pk} with ν^* appears to saturate around $\nu = 4.32$, and $f_{pk} \approx 200$ MHz. This saturation is likely related to stripe formation, and qualitatively resembles calculations [17] of spectra within a pinned stripe phase.

4. COEXISTENCE OF BUBBLE PHASE AND IQHWC

Fig. 4a shows spectra measured near $\nu = 4$ [6]. While the spectrum is flat just at $\nu = 4$, prominent resonances appear at both higher and lower ν. For $\nu < 4$, there is a single resonance in the range of ν between 3.80 and 4.18, whose f_{pk} increases as $\nu = 4$ is approached. We ascribe this resonance to the pinning mode [2, 4] of the IQHWC of holes in the third excited Landau level. The density of these carriers decreases as $\nu = 4$ is approached, so the increase of f_{pk} is explanable again as the typical behavior of a pinning mode as carrier density is reduced [16]. The interpretation of the resonance as a pinning mode of holes is bolstered [2, 4] by similar behavior around the integer quantum Hall effects near ν =1,2, and 3, and by quantitative analysis of the integrated intensity of the resonance vs ν^*.

For $\nu > 4$ the situation is more complex. An IQHWC pinning mode of electrons emerges first as ν is increased from 4, and appears alone for between $\nu \approx 4.05$ (where $f_{pk} \approx 2.4$ GHz) and $\nu \approx 4.18$. Starting at $\nu \approx 4.18$ and continuing through $\nu \approx 4.25$, a second resonance grows rapidly in the low f shoulder of the IQHWC resonance; this is identified as the bubble resonance, and it dominates the spectrum for $\nu \geq 4.25$. Hence resonances characteristic of the two phases are both present, indicating that the two phases are coexisting in different regions of the sample. The f_{pk} for the two resonances are obtained by fits of the spectra to a pair of Lorentzians, and are plotted vs ν in Fig. 4b.

The coexistence is consistent with theoretical predictions that the transition between the IQHWC and bubble phases are first order [9, 15, 18]. The filling $\nu = 4.22 \pm 0.02$, at which there are equal densities of carriers calculated from the intensities of each resonance likewise is within error of calculated values [14, 15, 18] for the transition between the two phases. That there is a clear transition, between two phases, as marked by the double peak, is a confirmation of the overall picture with a distinct IQHWC and bubble phase. Information on M, the number of electron guiding centers per bubble, can be obtained within the context of a model in ref. [15], which calculates the effect of M on the crystal shear modulus and hence

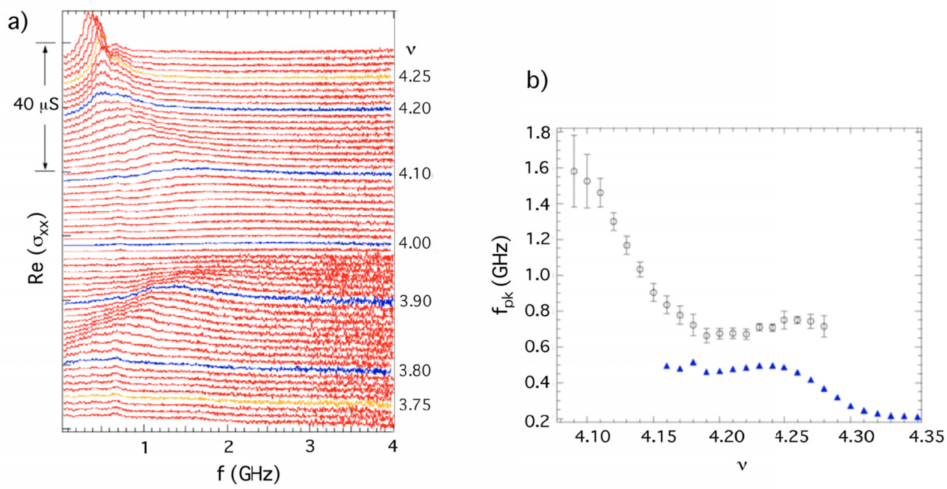

Figure 4. a) Re(σ_{xx}) versus f for ν between 3.70 and 4.29, offset vertically proportional to ν. Temperature $\approx$ 35 mK. The spectra between 4.00 and 4.29 are less noisy due to increased averaging. b) Resonance frequencies f_{pk} for the bubble (closed triangles) and IQHWC peaks (open circles).

on f_{pk}. For a fixed disorder potential, f_{pk} is found to go as $M^{-1/2}$. The ratio of peak frequencies for the bubble and IQHWC is in good agreement with the predicted value, $1/\sqrt{2}$, for a transition from IQHWC ($M = 1$) to an $M = 2$ bubble phase.

5. CONCLUSION

Our recent results [1–7], as well as the data presented here on the bubble phase, demonstrate that broadband rf and microwave, transmission line-based spectroscopy is of value for probing the properties and phase transitions of electron solids in 2DES.

Acknowledgements

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