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PINNING MODES OF THE STRIPE PHASES OF 2D ELECTRON SYSTEMS IN HIGHER LANDAU LEVELS

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Striking resonances, identified as pinning modes, have recently been observed in the rf spectra of the stripe phases of extremely low disorder two-dimensional electron systems with two or more filled Landau levels. We present spectra which detail the dependence of this resonance on the Landau filling factor ν, in broad ranges which include the stripe phases in the Landau levels with $N = 2, 3$ and 4.

Keywords: Stripe phase; quantum Hall; rf spectroscopy.

Two-dimensional electron systems (2DES) of low disorder, in high magnetic fields, can form a number of phases with spontaneous spatial modulation of charge density. Simplest of these phases is the Wigner crystal,[1,2] a triangular lattice of carriers found at Landau fillings ν below about 1/5 in n-type samples. Wigner crystals can also be found[3] for ν the outer edges of integer quantum Hall effects. These integer quantum Hall Wigner crystals (IQHWCs), are composed of particles or holes in the partially filled Landau level, whose filling ν^* is given by $\nu - [\nu]$, where $[\nu]$ indicates

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the greatest integer not greater than ν. For $[\nu] > 4$ the 2DES is understood, from both theory[4,5] and experiment,[6,7] to form a series of other density-modulated phases as ν^* increases. The IQHWC gives way to one or more bubble phases, which are triangular lattices of clusters of M carrier guiding centers, and then for ν^* in a range near 1/2, phases with stripes of charge density occur. The stripe phases exhibit striking anisotropy in dc transport, with respectively larger or smaller dc resistance along hard and easy directions, fixed in the GaAs host lattice.

The Wigner crystal[8] in the lowest Landau level, the IQHWC,[3] and the bubble phases[9] have been known for some time to exhibit striking resonances in their rf spectra. These electron solids are insulators due to pinning by disorder, and the resonances are understood as pinning modes, collective oscillation of pieces of the solid within the pinning potential. More recently,[10] we have observed resonances in the stripe phases, which, though strongly polarization dependent, are naturally understood as pinning modes, as well. This paper shows spectra for the stripe phase, and for the neighboring bubble phase ν ranges, for $[\nu] = 4, 6$, and 8, and so details the development of the resonance as Landau level index varied (with spin pointing up).

The experimental method, which we have used in previous work,[3,8–11] relies on metal film rf transmission lines lithographed onto the top surface of the sample, as shown in Fig. 1a. The transmission lines, of the standard coplanar waveguide type, have a straight, driven center conductor and two grounded side planes. Slots of width $W = 78$ μm, in which there is no metal film, separate the center conductor and side planes. We present data as real diagonal conductivities $\mathrm{Re}(\sigma_{jj})$, calculated from the power, P_t, transmitted through the line as $\mathrm{Re}[\sigma_{jj}(f)] = (W/2lZ_0)\ln(P_t/P_0)$, where P_0 is the power transmitted at zero σ_{jj}, $Z_0 = 50$ Ω is the characteristic impedance of the transmission line also at zero σ_{jj}, and $l \approx 4$ mm is the length of the line.

Since the polarization of the rf electric field, E_{rf}, is determined by the transmission line, two samples, taken from adjacent pieces of the wafer, were used to obtain the data: we denote σ_{xx} as taken from sample 1, in which E_{rf} is applied along the hard direction, and σ_{yy} as taken from sample 2, in which E_{rf} is along the easy direction. We determined the easy and hard directions on the wafer by looking at dc transport on yet another adjacent piece. The 2DES resides in a 30 nm GaAs quantum well (wafer 5-20-05.1) and has density 2.7×10^{11} cm^{-2}, and 0.3 K mobility 29×10^6 cm^2/Vs. Both for dc and rf measurements samples were cooled and measured without illumination, in contrast to the procedure in most dc experiments on the stripe phases. The data were taken at a sample temperature of about 35 mK, and in the low applied power limit as verified by varying the power.

Fig. 1b and Fig. 1c each show spectra taken for 81 filling factors from 4.10 to 4.90. The ν step between spectra is 0.01, and in the figure each successive spectrum is offset vertically by an increment of 6 μS. Fig. 1b shows the hard-direction conductivity $\mathrm{Re}(\sigma_{xx})$, and Fig. 1c shows the easy-direction conductivity $\mathrm{Re}(\sigma_{yy})$. For

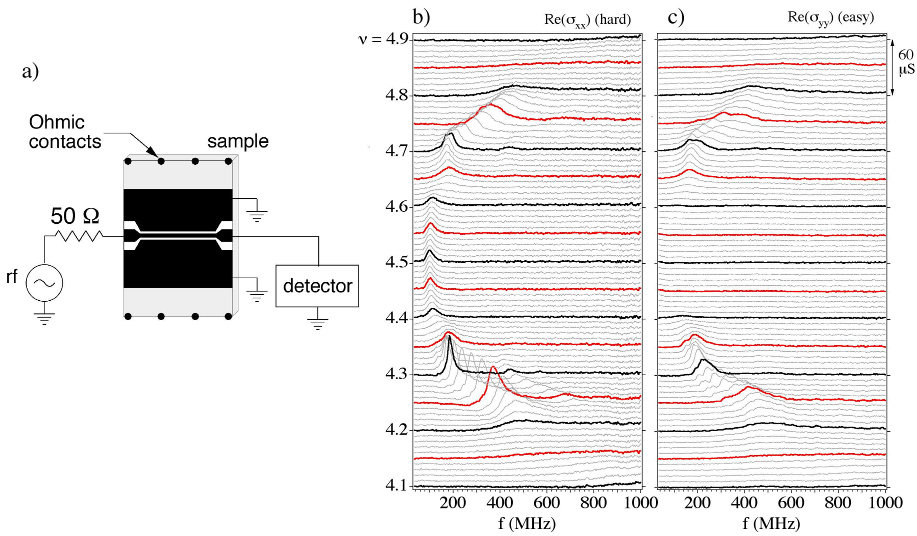

Fig. 1. a) Schematic of a sample in rf measurement set-up. The transmission line metal film is shown in black. b) Hard-direction conductivity spectra, $\mathrm{Re}(\sigma_{xx})$ vs frequency, f, measured in sample 1. c) Easy direction conductivity spectra, $\mathrm{Re}(\sigma_{yy})$ vs f, measured in sample 2. Spectra in b) and c) are shown for filling factors ν between 4.10 and 4.90 in steps of 0.01; successive spectra are vertically offset in 6 μS increments.

ν between 4.40 and 4.60, the hard- and easy-direction spectra are strikingly different, with a resonance around 100 MHz only in the hard-direction conductivity, $\mathrm{Re}(\sigma_{xx})$. This range of ν is in good agreement with theoretical predictions[12–16] for the presence of the stripe phase.

The resonance develops symmetrically about $\nu = 9/2$ ($\nu^* = 1/2$), as expected from particle-hole symmetry, so for convenience we describe the behavior of the resonance only as ν decreases from the stripe range. As ν decreases below 4.40, the easy-direction resonance turns on sharply, reaching equal peak amplitude with the hard direction resonance by $\nu = 4.37$; in this same range the peak frequency, f_{pk}, increases rapidly. At any ν for which the resonances are well-developed in both directions, the resonances in the two directions follow each other closely both in peak frequency, f_{pk}, and in peak conductivity. As ν goes from 4.38 to around 4.30, f_{pk} changes little though the peak conductivity increases, producing a distinct step or "kink" in the plot. The origin of this complicated behavior of the resonance at the edge of the stripe phase is unclear. The $M = 3$ bubble phase is a possible ground state of a disorder-free 2DES[13–15,17] in this range, as are phases containing bubble and stripe subcomponents.[18] On continuing to decrease ν, from 4.30 to 4.24, f_{pk} rapidly increases. This is in the predicted range[12,14,15,17] of the $M = 2$ bubble phase.[9] Decreasing ν below 4.24 just reduces the strength of the resonance, as described previously,[11] due to the transition to the IQHWC.

Some other peaks than the main resonance peak are present in the spectra of Fig. 1. One or two weak, higher f_{pk} peaks appear beyond the main peak where the

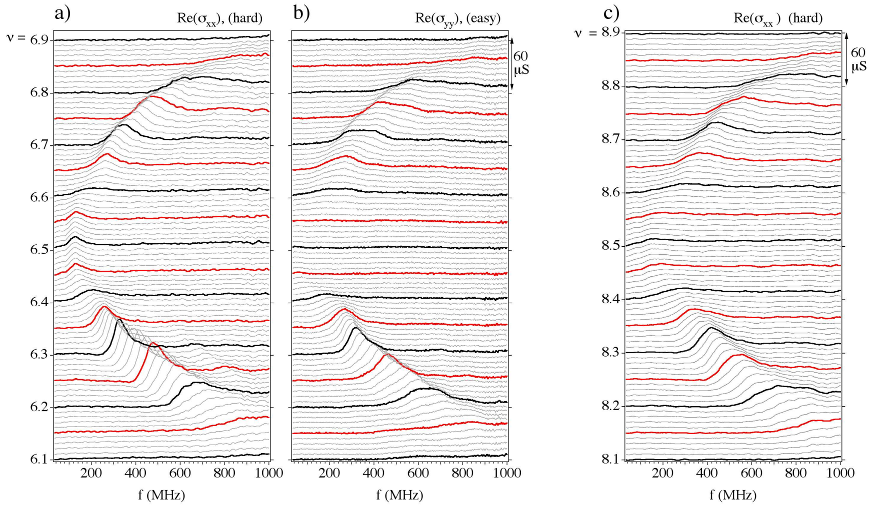

Fig. 2. a) Hard-direction conductivity spectra , Re(σ_{xx}) vs frequency, f, for filling factors ν between 6.10 and 6.90 in steps of 0.01. b) Easy-direction conductivity spectra, Re(σ_{yy}) vs f, for ν between 6.10 and 6.90 in steps of 0.01. c) Hard-direction conductivity spectra, Re(σ_{xx}) vs frequency, f, for ν between 8.10 and 8.90 in steps of 0.01.

resonance is strongest, in the ν ranges expected for the bubble phase. While the bubble phases can have "optical" excitations[15] of degrees of freedom internal to the bubbles, the predicted[15] frequency of these is $\sim$50 GHz. Instead, we interpret the higher lying peaks as due to higher spatial harmonics of E_{rf} applied by the transmission line; the dominant spatial component of E_{rf} is at wavevector π/W. Also, in the easy direction, only where the resonance is well-developed and is changing rapidly with ν, the main peak appears split. We can reasonably ascribe this splitting to small macroscopic inhomogeneity since in any spectrum with the splitting, the weaker peak lines up with the stronger peak in the spectrum from about 0.02 larger ν.

Fig. 2a and Fig. 2b show plots of many spectra in the hard and easy directions, for Landau level index $N = 3$, ν between 6.1 and 6.9. The main feature of the data for $N = 2$ is also present in this higher ν range: regions near half integer filling show a resonance in the hard direction of the stripes, but none in the easy direction. Around $\nu = 13/2$, the ν^* range of absence of the easy-direction resonance is roughly 0.43 to 0.57, narrower than around $\nu = 9/2$. A narrowing of the stripe range in ν^* is predicted theoretically[13] for increasing N. The changes of the resonances with ν^* resemble those in Fig. 1, and include the steplike structure at the edges of the stripe range, but the evolution appears smoother, and the steplike regions are less well-defined. Compared to those in Fig. 1b and c, the resonances in Fig. 2a and b at the same ν^* lie at slightly higher f_{pk}, and are broader.

Fig. 2c shows spectra measured in the hard direction, for $N = 4$, $\nu = 8.1$ to 8.9. In this range we did not take a systematic survey of spectra in the easy direction,

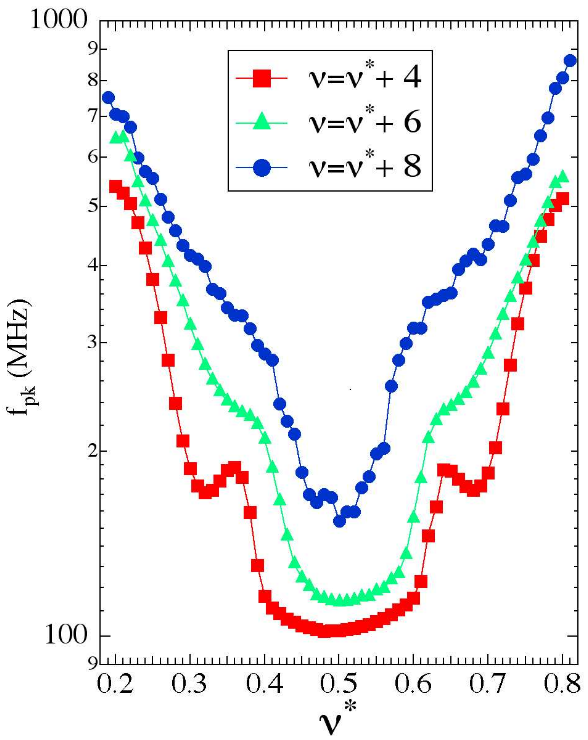

Fig. 3. Resonance peak frequency $f_{\rm pk}$, vs partial Landau level filling $\nu*$, from hard-direction conductivity data in Figs. 1 and 2.

but we verified, from $\mathrm{Re}(\sigma_{yy})$ vs magnetic field at several frequencies, that in a small range around $\nu = 8.5$ there is no easy-direction resonance. Comparing the $N = 4$ data to the $N = 3$ data shows a continuation of the trend seen in comparing $N = 2$ and $N = 3$; the resonance positions describe a still smoother curve in the plot, and the amplitude evolves gradually. The resonances are at still higher $f_{\rm pk}$ and are still broader than those for $N = 3$.

Fig. 3 shows a semilog plot of $f_{\rm pk}$ vs ν^* for the resonances in the hard-direction conductivity spectra. The data are not offset vertically. Shallow minima around $\nu^* = 1/2$ characterize the range of absence of the easy-direction resonance. As N increases these "stripe-range" minima get deeper, while the "steps" in the plots on either side of the stripe range become less clear. Relative to its value around $\nu = 9/2$, $f_{\rm pk}$ increases by only about 10% for $\nu = 13/2$ and 60% for $\nu = 17/2$.

In summary, the features of the pinning mode resonance vs ν in the $N = 2$ Landau level are largely preserved in the $N = 3$ and $N = 4$ Landau levels. Theories predict series of larger M bubble phases[13–15,17] to occur in higher Landau levels at the edges of the stripe phases, however the present experiments do not resolve more intricate variation of the resonance with ν for the larger N. Finite temperature or disorder (including density inhomogeneity) or may explain the absence of these intricate features, and the loss of sharper features in the resonance variation with ν as N increases.

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References

1. Y. E. Lozovik and V. I. Yudson, *JETP Lett.* **22**, 274 (1975); P. K. Lam and S. M. Girvin, *Phys. Rev. B* **30**, 473 (1984); D. Levesque, J. J. Weis and A. H. McDonald, *Phys. Rev. B* **30**, 1056 (1984); K. Yang, F.D.M. Haldane and E. H. Rezayi, *Phys. Rev. B* **64**, 081301 (2001).
2. M. Shayegan, in *Perspectives in Quantum Hall Effects*, ed. S. Das Sarma and A. Pinczuk, (Wiley Interscience, 1997) p. 343.
3. Y. Chen, R. M. Lewis, L. W. Engel, D. C. Tsui, P. D. Ye, L. N. Pfeiffer, and K. W. West, *Phys. Rev. Lett.* **91**, 016801 (2003).
4. M. M. Fogler, A. A. Koulakov, and B. I. Shklovskii, *Phys. Rev. Lett* **76**, 499 (1996).
5. R. Moessner and J. T. Chalker, *Phys. Rev. B* **54**, 5006 (1996).
6. M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West. *Phys. Rev. Lett.* **82**, 397 (1999).
7. R. R. Du, D. C. Tsui, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, *Solid State Commun.* **109**, 389 (1999).
8. P. D. Ye, L. W. Engel, D. C. Tsui, L. Pfeiffer, and K. W. West, *Phys. Rev. Lett.* **89**, 176802 (2002).
9. R. M. Lewis, P. D. Ye, L. W. Engel, D. C. Tsui, L. N. Pfeiffer, and K. W. West, *Phys. Rev. Lett.* **89**, 136804 (2002).
10. G. Sambandamurthy, R. M. Lewis, H. Zhu, Y. P. Chen, L. W. Engel, D. C. Tsui, L. N. Pfeiffer, and K. W. West, *Phys.Rev. Lett.* **100**, 256801 (2008).
11. R. M. Lewis, Y. Chen, L. W. Engel, D. C. Tsui, P. D. Ye, L. N. Pfeiffer, and K. W. West, *Phys. Rev. Lett* **93**, 176808 (2004).
12. N. Shibata and D. Yoshioka, *Phys. Rev. Lett.* **86**, 5755 (2001).
13. D. Yoshioka and N. Shibata. *Physica E* **12**, 43 (2002).
14. M. O. Goerbig, P. Lederer, and C. M. Smith. *Phys. Rev. B* **69**, 115327 (2004).
15. R. Côté, C. B. Doiron, J. Bourassa, and H. A. Fertig. *Phys. Rev. B* **68**, 155327 (2003).
16. A. M. Ettouhami, C. B. Doiron, F. D. Klironomos, R. Côté, and A. T. Dorsey. *Phys. Rev. Lett.* **96**, 196802 (2006).
17. A. M. Ettouhami, F. D. Klironomos, and A. T. Dorsey, *Phys. Rev. B* **73**, 165324 (2006).
18. M. M. Fogler, in *High Magnetic Fields: Applications in Condensed Matter Physics and High Magnetic Fields: Applications in Condensed Matter Physics and Spectroscopy* ed. C. Berthier, L.-P. Levy, G. Martinez, (Springer-Verlag, Berlin, 2002) p. 98.