Observation of Pinning Mode of Stripe Phases of 2D Systems in High Landau Levels

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We study the radio-frequency diagonal conductivities of the anisotropic stripe phases of higher Landau levels near half-integer fillings. In the hard direction, in which larger dc resistivity occurs, the spectrum exhibits a striking resonance, while in the orthogonal, easy direction, no resonance is discernible. The resonance is interpreted as a pinning mode of the stripe phase.

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In quantizing magnetic fields, and at low temperature, two-dimensional electron systems (2DES) of extremely low disorder exhibit a striking anisotropy in dc diagonal resistivity [1,2], near half-integer Landau fillings $\nu = 9/2, 11/2\ldots$ with two or more Landau levels (LLs) completely filled. The anisotropic states are understood as ‘‘stripe’’ states, in which spatial charge density modulation in the form of long, thin stripes plays a role. In addition, in ranges of ν on either side of the stripe phase, experiments showed regions of vanishing diagonal resistance and quantized Hall resistance, like the nearest integer quantum Hall effects (IQHEs), but distinct from them. These signatures of isotropic insulating behavior are due to electron solids termed ‘‘bubble phases’’ [3], which have been described as triangular lattices with clusters of M carrier guiding centers at each site, but which exhibit apparent anisotropy in the presence of a dc current [4]. For ν farther yet from half-integer filling, within the ranges of the IQHE itself, individual carriers of the partially filled LL form a triangular Wigner crystal [5,6] (IQHE-WC, or $M = 1$) similar to Wigner solid states [7–10] of low-disorder 2DES at the low ν termination of the fractional quantum Hall effect series.

As a model of other stripe states in nature, the striped phase of 2DES is of particular general interest, yet a complete microscopic picture of this phase is still lacking. The earliest theory of the striped phases [11], also incorporated a description of the bubble phase and IQHE-WC. It described the stripe phase as a unidirectional charge density wave, with charge uniformly distributed and liquidlike along the direction of stripes of width a few classical cyclotron radii. Other viewpoints of the striped phase were taken in subsequent theoretical work. Descriptions [12,13] developed by analogy with smectic or nematic liquid crystals retain the liquidlike distribution of carriers along the stripes, for the nematic over some finite distance. In contrast, in anisotropic Wigner crystal states [13–17], also referred to as ‘‘stripe crystals,’’ the carriers are arranged in a rectangular lattice and are much more closely spaced in the stripe direction, but still locked in position with respect to each other.

Disorder pins the stripe and isotropic electron solid phases, so it is of crucial importance to their phenomenology. In the isotropic solids, pinning operates in all directions, so that the electrons that form the solid are insulating. In the stripe phase, pinning is expected at least in the direction perpendicular to the stripes, resulting in ρ_{xx}, the resistivity in the hard direction, increasing as the temperature decreases. Pinning along the stripes, as well, is expected for the stripe crystal case [13–17]. Microwave spectra of isotropic electron solids [3,5,6,8–10] are known to be dominated by a striking resonance that is understood as a pinning mode [18–20], in which pieces of electron solid collectively oscillate about their pinned positions. A pinning mode is induced by disorder, so an increase in the disorder potential effectively experienced by the solid increases the frequency of the pinning mode. Pinning modes have long been known to exist in the archetypical Wigner solid found at the low ν termination of the series of fractional quantum Hall effect states, in low-disorder n-type samples [8–10]. Similar pinning modes have been found in the IQHE-WC [5] and bubble phases [3,6].

In this Letter we report rf resonances in the spectra of the stripe phases, around $\nu = 9/2$ and higher half-integer fillings. These resonances are discernible only when the rf electric field is oriented along the higher dc resistance, "hard" direction, which is nominally perpendicular to the stripes. These hard-direction resonances in the stripe phase are most naturally understood as pinning modes, since they resemble known, isotropic, pinning modes in neighboring bubble-phase regions. Comparison is made to theories [15,21] of pinning modes in the stripe phases.

As in earlier work [3,5,6,8,10], we obtained diagonal conductivities from measurements of metal transmission lines lithographed onto the samples, and coupled capacitively to the 2DES. The transmission lines, of coplanar waveguide (CPW) type have a narrow, driven centerline of lengths $l \sim 4$ mm, and grounded planes on either side separated by a slot of width $W = 78\ \mu$m. A sketch of the CPW pattern on a sample is inset in Fig. 1(a). The transmission lines apply an rf electric field *perpendicular* to their propagation direction. The CPWs are fixed on the sample surface, so we measured conductivities σ_{xx}, σ_{yy} along orthogonal host-lattice directions $[1\bar{1}0]$ and $[110]$, using two samples made from adjacent pieces of the same wafer: Sample 1 has rf electric field along the hard direction $[1\bar{1}0]$ and is used to measure σ_{xx}, while sample 2 has rf electric field, along the easy direction $[110]$ and is used to measure σ_{yy}. dc measurements on a third adjacent piece verified that x and y directions are, respectively, hard and easy. The 2DES is in a 30 nm GaAs quantum well, and has electron density, $n = 2.6 \times 10^{11}$ cm^{-2} and mobility $\mu = 2.9 \times 10^7$ cm^2/V s at 0.3 K. The samples were not illuminated at low temperature, for either the rf or the dc measurements. The data shown here were obtained at temperature $\approx$ 35 mK, and the rf power was varied to ensure the measurements were in the low-power limit.

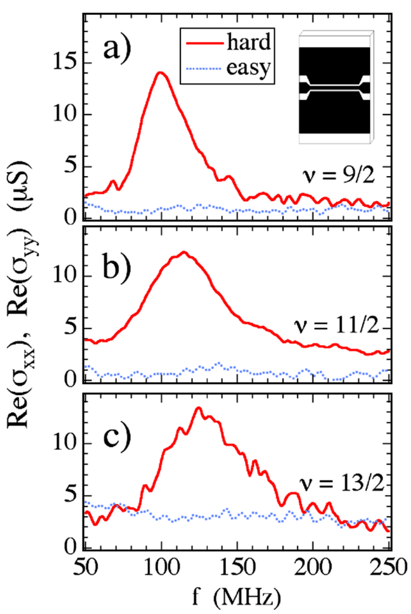

FIG. 1 (color online). Spectra of real diagonal conductivities $\mathrm{Re}(\sigma_{xx})$ (solid lines) and $\mathrm{Re}(\sigma_{yy})$ (dotted lines), vs frequency f for filling factors ν of (a) 9/2, (b) 11/2, and (c) 13/2. $\mathrm{Re}(\sigma_{xx})$ is measured in sample 1, with the rf electric field along the hard direction, and $\mathrm{Re}(\sigma_{yy})$ is measured in sample 2, with the rf electric field along the easy direction. The inset in (a) shows a schematic of a sample, with metal film that forms the transmission line shown as black.

We present real diagonal conductivities [$\mathrm{Re}(\sigma_{jj})$ where $j = x$ or y] calculated from t, the complex measured amplitude transmission coefficient of the line, normalized to conditions of vanishingly small $|\sigma_{jj}|$. The plotted conductivities are calculated as $\sigma_{jj} = -W/(Z_0 l)\ln(t)$, where $Z_0 = 50\ \Omega$ and is the characteristic impedance of the CPW calculated in the limit of vanishing σ_{jj}. This formula takes the in-plane rf electric field to be confined in the regions under the slots, which is a good approximation for small enough σ_{jj}/f. A model employing quasistatic calculation of the electric fields around the CPW in the presence of the conducting 2DES was used to check the validity of the σ_{jj} calculated in this way. This model does not allow for wave vector (q) dependence of σ_{jj}, which is thus taken to be in its low q limit.

Figure 1 shows the hard- and easy-direction real diagonal conductivity spectra, for half-integer fillings $\nu = 9/2$, $11/2$, and $13/2$, at which the stripe phases are known to exist. The hard-direction conductivity $\mathrm{Re}(\sigma_{xx})$ is from sample 1, and the easy-direction conductivity $\mathrm{Re}(\sigma_{yy})$ is from sample 2. In each spectrum a clear resonance can be seen, with the peak frequency f_{pk} increasing slightly, and the resonance becoming broader and less well developed at larger half-integer ν. In the easy direction no resonance can be seen. A weak resonance (not shown) was found in the hard direction at $\nu = 15/2$ as well.

Figure 2 shows the $\nu = 9/2$ resonance in the hard direction at various temperatures. The resonance in the hard direction disappears gradually as temperature increases, becoming invisible above $\sim$120 mK. This is about the same temperature range that was observed for the dc resistance anisotropy [1,2], consistent with the resonance being due to formation of the stripe phase. As is typical of

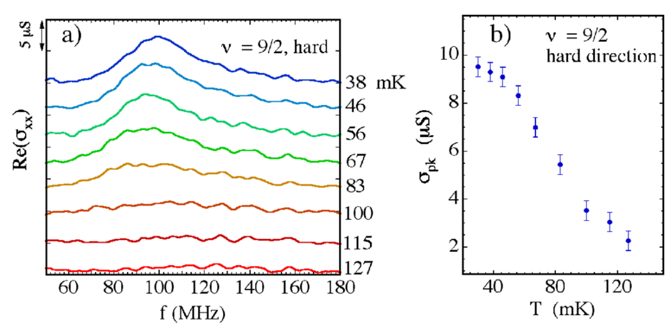

FIG. 2 (color online). (a) Spectra of hard-direction real diagonal conductivities $\mathrm{Re}(\sigma_{xx})$ at Landau filling $\nu = 9/2$, from sample 1, at temperatures marked at right. Successive spectra are offset upward by 4 μS for clarity. (b) Maximum $\mathrm{Re}(\sigma_{xx})$, σ_{pk}, vs temperature T.

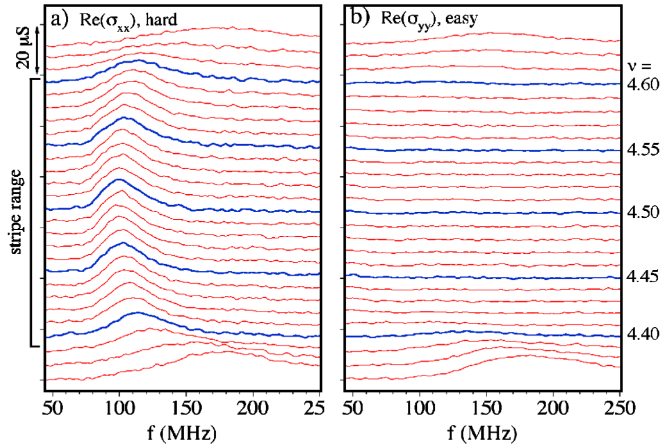

FIG. 3 (color online). Spectra, conductivity vs frequency f for many filling factors ν between 4.37 and 4.63; each succeeding trace offset upward by 5 μS: (a) Hard-direction conductivity $\mathrm{Re}(\sigma_{xx})$ measured in sample 1; (b) easy-direction conductivity $\mathrm{Re}(\sigma_{yy})$ from sample 2. Filling factors ν are marked at right. The stripe range predicted in Ref. [23] is marked at left.

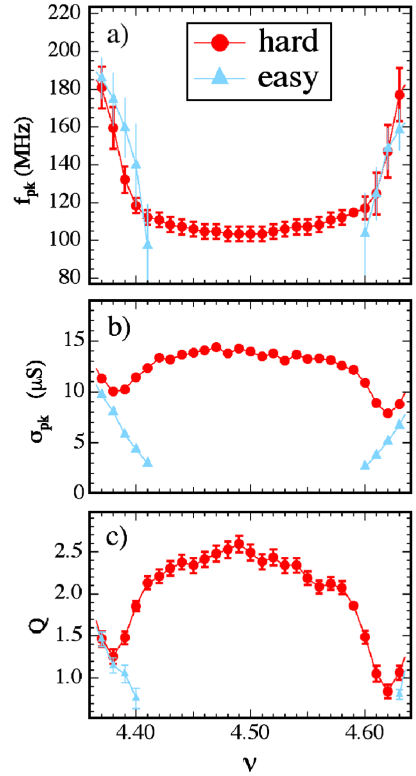

FIG. 4 (color online). Peak frequency (f_{pk}), maximum real diagonal conductivity (σ_{pk}) and quality factor Q for the resonances, vs ν, for the hard and easy directions, around $\nu = 9/2$.

pinning modes in the low ν Wigner solid range [8,22], f_{pk} is nearly independent of the temperature.

Figure 3 shows series of spectra with ν ranging from 4.37 to 4.63; the spectra are vertically offset proportional to ν. Figure 3(a) shows the hard-direction conductivity $\mathrm{Re}(\sigma_{xx})$ from sample 1, while Fig. 3(b) shows easy-direction conductivity $\mathrm{Re}(\sigma_{yy})$ from sample 2. For ν from 4.41 through 4.60, a resonance is present in the hard direction, while none can be discerned in the easy direction. This range is in reasonable agreement with theoretical predictions [16,23–25] for the occurrence of the stripe phase in the $N = 2$ LL; the predicted low ν crossover between stripe and bubble-phase ground states falls between 4.35 [24] to 4.43 [25]. As ν decreases from 4.41, or increases from 4.60, the resonance in the easy direction develops rapidly, and by $\nu = 4.37$ and 4.63, the highest and lowest ν for which spectra are shown, the spectra are nearly isotropic, so we regard these fillings as in the bubble phase.

Figure 4 shows plots vs ν of the resonance frequency (f_{pk}), the peak real diagonal conductivity (σ_{pk}), and the resonance quality factor (Q, f_{pk} divided by full width at half-maximum). We estimate errors in ν at ± 0.02 and errors in σ_{pk} as ± 0.5 μS; errors in f_{pk} and Q are as shown. At $\nu = 9/2$, the hard-direction f_{pk} vs ν exhibits a shallow minimum, while Q exhibits a weak maximum. Within most of the stripe range, from $\nu = 4.41$ to 4.59, σ_{pk}, is flat within the experimental error. For $\nu \leq 4.40$ or $\nu \geq 4.60$, the easy-direction resonance is observable: its f_{pk} agrees with that of the hard-direction resonance to within experimental error, though its σ_{pk} decreases rapidly as ν moves toward the center of the plot.

The natural interpretation of the resonance in the stripe phase is as a pinning mode. The stripe phase resonance appears to evolve out of known pinning mode resonances present in the neighboring bubble phases, which themselves succeed resonances in the IQHE-WC, as described in Ref. [6]. A resonance is present in the hard direction throughout the range from $\nu = 4.10$ to 4.90. At $\nu = 4.10$ the resonance is well understood as a pinning mode of the IQHE-WC. Increasing ν results in a transition to a bubble phase, clearly visible as a lower f_{pk} resonance [6]. As is apparent in Fig. 4(a), f_{pk} drops again at the transition from bubble phase to stripe phase. σ_{pk} changes less than 30% between the isotropic, bubble-phase resonance at $\nu = 4.63$ to the anisotropic stripe phase resonance at 9/2, strongly suggesting a similar origin of the resonances.

A number of theories [16,26–30] treat modes of the stripe phase in the absence of disorder. If the observed resonance were not a pinning mode, so that disorder did not play a role, f_{pk} would be determined by the dispersion of the mode and a fundamental wavelength $W/2$ set by the transmission line slot width, $W = 78$ μm. Particularly in treatments [28,30] based on the smectic liquid crystal, propagating modes are present only at an oblique angle to the stripes, not perpendicular or parallel to them; this would be inconsistent with our finding of the mode in the hard direction.

There have been to our knowledge only two calculations of pinning modes of the stripe phase with disorder [15,21]. Though both [15,21] predict pinning modes for rf electric field parallel to the stripes, in seeming contrast with our not observing an easy-direction resonance, the theories indicate that easy-direction pinning mode can be comparatively weak under our experimental conditions. In Ref. [15], pinning modes are found only in a state [31] that has pinning both along the stripes and perpendicular to them. The predicted pinning has about the same frequency parallel and perpendicular to the stripes, though the mode parallel to the stripes is weaker by a factor of about 4. Reference [21] obtains only the conductivity along the stripes, and predicts the easy-direction pinning mode frequency and amplitude both vanish at small wave vector q.

In weak pinning of an electron solid, the pinning mode frequency f_{pk} is larger either for increased disorder or reduced solid stiffness [18–20]. Such a reduction in solid stiffness can be realized in the low ν, lowest LL Wigner crystal, by reducing the overall sample carrier density [10], and the increase in f_{pk} is accompanied by a decrease in Q. (f_{pk} is larger for a softer solid, since the carriers effectively fall more deeply into the disorder potential, increasing the average pinning.) In this framework, the shallow minimum of f_{pk} vs ν at $9/2$, as well as the maximum in Q, is due either to a maximum of the stiffness of the stripe phase at that ν, or to a minimum in the effective disorder strength.

In summary, we have found an rf resonance that is clearly associated with the stripe phase of higher LLs, and occurs only for electric field along the hard direction. The resonance appears to evolve from known pinning modes in the bubble phases, and is similar to them, and so is naturally interpreted as a pinning mode of the stripe phase.

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