Pinning mode resonances of 2D electron stripe phases: Effect of in-plane magnetic field

Han Zhu, 1, 2 G. Sambandamurthy, 2, 3 L. W. Engel, 2 D. C. Tsui, 3 L. N. Pfeiffer, 4 and K. W. West 4

1 Department of Physics, Princeton University, Princeton, NJ 08544, USA
2 National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA
3 Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA
4 Bell Laboratories, Alcatel-Lucent Technologies, Murray Hill, NJ 07974, USA

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We study the anisotropic pinning-mode resonances in the rf conductivity spectra of the stripe phase of 2D electron systems (2DES) around Landau level filling 9/2, in the presence of an in-plane magnetic field, B_{ip}. The polarization along which the resonance is observed switches as B_{ip} is applied, consistent with the reorientation of the stripes. The resonance frequency, a measure of the pinning interaction between the 2DES and disorder, increases with B_{ip}. The magnitude of this increase indicates that disorder interaction is playing an important role in determining the stripe orientation.

Many systems in nature exhibit phases with spontaneous spatial modulation of charge density in a stripe pattern. Such stripe phases exist in extremely low disorder two-dimensional electron systems (2DES) hosted in GaAs in high magnetic field, for Landau level fillings near ν = 9/2, 11/2, 13/2, ... . The stripe phases are manifested in dc transport by strong anisotropy in dc transport below about 150 mK, with smaller and larger diagonal resistivities respectively along orthogonal “easy” and “hard” directions that are fixed in the semiconductor host lattice. Early theoretical work on 2DES near these fillings predicted the stripe phases even before the experiments, and described them as unidirectional charge density waves. Later theoretical pictures were based on analogy with liquid crystals, and included quantum Hall smectics as well as quantum Hall nematic states, with local smectic order but long range orientational order. Yet another proposed state for the stripes, is a highly anisotropic rectangular lattice, which is referred to as the “stripe crystal”.

Much of the detailed understanding of the stripe phases stems from their sensitivity to in-plane magnetic field, B_{ip}, which studies of DC transport have shown can interchange the hard and easy axes in the sample. This switching is naturally interpreted as reorientation of the stripes, with B_{ip} acting as a symmetry-breaking field to overcome the native anisotropy of the sample. For most of the samples surveyed, switching for B_{ip} applied in the original (i.e. B_{ip} = 0) easy direction. In accord with this finding, theory that considered the effect of B_{ip} on the wave function in the direction (z) perpendicular to the 2D plane in a finite-thickness, disorder-free 2DES, presents an anisotropy energy E_A, a per electron energy difference between stripe orientations perpendicular and parallel to B_{ip}. The theory, which considers the stripes as a unidirectional charge density wave, indicates that E_A favors the stripes being perpendicular to B_{ip}. Not addressed in that theoretical framework are experimental results for B_{ip} applied perpendicular to the original B_{ip} = 0 easy axis, which show dc resistances along the sample axes can approach each other near the switching point, and even cross over in some cases, leaving the axis of lower dc resistance parallel to B_{ip}.

Recent work has shown that the stripe phase has a striking signature in its rf spectrum. A resonance is present in its diagonal conductivity along the hard direction, nominally perpendicular to the stripes, while the spectrum is essentially flat in the easy direction, parallel to them. This resonance is understood as a pinning mode, a collective oscillation of correlated pieces of the electronic phase within the potential of pinning impurities. Pinning modes of the stripe phase have also been studied theoretically. Similar resonances have been observed in many high-magnetic-field electron solids, including the Wigner crystal phases found at the high magnetic field termination of the fractional quantum Hall series and at the outer edges of integer quantum Hall plateaus, and also the bubble phases, which exist in regions of ν immediately adjacent to the stripes. Besides the value of the resonances as a signature of particular phases, the pinning modes serve to characterize the disorder that produces them. Importantly for this work, their peak frequency is a measure of the average potential energy of a carrier in the pinning disorder.

In this paper we examine the dependence of the pinning resonances of the stripe phases on B_{ip}. We find B_{ip} to switch the axis along which the resonance is observed, much as it switches the hard and easy axes in the dc transport experiments. Switching occurs for B_{ip} applied along either the original hard or original easy axis. For B_{ip} near the switching point, resonances appear for polarizations in both directions, suggesting that coexisting, perpendicularly oriented domains are present as the switching occurs. A unique feature of the present experiments is the information on
pinning strength provided by the measured resonance frequency, \(f_{pk}\), which we find increases vs \(B_{ip}\), at different rates depending on the axis in which \(B_{ip}\) is applied. We find that the change due to \(B_{ip}\) of the average binding energy of carriers in the disorder potential is comparable to theoretically predicted \([20, 21]\) \(B_{ip}\)-induced anisotropy energy. The results imply that the disorder-carrier interaction is \(B_{ip}\)-dependent, and plays an important role in determining stripe orientation, even when significant \(B_{ip}\) is applied.

The sample wafer is a 30 nm GaAs/Al\(_x\)Ga\(_{1-x}\)As quantum well, with density \(2.7 \times 10^{11}/\text{cm}^2\) and mobility \(29 \times 10^6\text{cm}^2/V\text{s}\) at 0.3 K. As in earlier work \([22, 23, 26, 28]\), we evaporated a coplanar wave guide (CPW) transmission line onto the sample surface. The CPW consists of a driven, straight center line separated from grounded planes on either side by a slot of width \(w = 78 \mu\text{m}\). The line has length \(l \sim 4 \text{ mm}\), and its characteristic impedance \(Z_0 = 50\Omega\) when the 2DES conductivity is small. From the absorption of the signal by the 2DES, the real part of the 2DES diagonal conductivity in direction \(j\) calculated as \(\text{Re}(\sigma_{jj}(f)) = (\nu/2!Z_0)\ln(P_t/P_0)\), where \(P_t\) is the transmitted power, normalized by \(P_0\), the power transmitted at zero \(\sigma_{jj}\). At the measuring frequencies the rf electric field produced by the CPW is well-polarized perpendicular to the propagation direction. In order to measure conductivities \(\sigma_{xx}\) and \(\sigma_{yy}\) along orthogonal crystal axes of the sample, we present data from two adjacent pieces of the same wafer, and patterned CPW’s along perpendicular axes. \(\hat{x}\) denotes the GaAs crystal axis [110], which for the present samples is the DC “hard” direction at \(\nu = 9/2\) in zero \(B_{ip}\). \(\hat{y}\) is the crystal axis [110], the zero-\(B_{ip}\) DC “easy” direction. Sample 1 has \(E_{rf}\) along \(\hat{x}\); sample 2 has \(E_{rf}\) along \(\hat{y}\).

We applied \(B_{ip}\) by tilting the sample in a rotator with low-loss, broadband, flexible transmission lines. The temperature of all measurements reported here is around 40 mK. The rotation angle \(\theta\) is calculated from the magnetic fields of prominent quantum Hall states. From perpendicular field \(B_\perp\), \(B_{ip} = B_\perp \tan \theta\). \(B_{ip}\) can also be directed to be along either \(\hat{x}\) or \(\hat{y}\) (in separate cool-down’s), so we present data from a total of four combinations of \(E_{rf}\) and \(B_{ip}\) directions.

Fig. 1 shows spectra of the real diagonal conductivities, \(\text{Re}(\sigma_{xx})\) and \(\text{Re}(\sigma_{yy})\), at filling factor \(\nu = 9/2\), as \(B_{ip}\) applied along \(\hat{y}\), parallel to the stripe orientation at zero \(B_{ip}\). For reference, Fig. 1a shows spectra taken with \(B_{ip} = 0\), taken for the same samples and cooldowns used for \(B_{ip} > 0\) in the rest of Fig. 1; a 90 MHz resonance is present in the spectrum of \(\text{Re}(\sigma_{xx})\), for which \(E_{rf}\) is polarized in the hard direction, but there is no resonance in \(\text{Re}(\sigma_{yy})\), for which \(E_{rf}\) is polarized in the easy direction. Application of \(B_{ip} \approx 0.51\ T\), as shown in Fig. 1b, does not switch the axis on which the resonance is observed; the resonance remains visible only in \(\text{Re}(\sigma_{xx})\), with the peak conductivity, \(\sigma_{pk}\), and peak frequency, \(f_{pk}\), increased.

![FIG. 1: Frequency spectra of real conductivities \(\text{Re}(\sigma_{xx})\) (solid lines) and \(\text{Re}(\sigma_{yy})\) (dashed lines), for \(B_{ip}\) along \(\hat{y}\) and increasing from (a) to (d). \(\sigma_{xx}\) is measured in sample 1, and \(\sigma_{yy}\) in sample 2. The nominal stripe orientation at zero \(B_{ip}\) is sketched as inset.](image-url)
In the narrow, transitional one-polarization resonance, there are crossover ranges in which the switching of the polarizations is shown in panel 3a for $B_{ip}$ along $\hat{y}$ and in panel 3b for $B_{ip}$ along $\hat{x}$. In both panels there are distinct ranges of $B_{ip}$ in which a resonance is present exclusively in $\text{Re}(\sigma_{xx})$ or $\text{Re}(\sigma_{yy})$. Separating these ranges of one-polarization resonance, there are crossover ranges in which peaks can be observed in both $\text{Re}(\sigma_{xx})$ or $\text{Re}(\sigma_{yy})$. This reinforces the description in which $B_{ip}$, applied on either axis, can be thought of as switching the resonance from $\text{Re}(\sigma_{xx})$ to $\text{Re}(\sigma_{yy})$. This switching of the polarization of the resonance is most naturally interpreted as a reorientation of the stripes, by analogy with the $B_{ip}$ induced switching of the hard and easy axes observed in dc transport studies [12, 13, 14, 15, 16, 17, 18].

FIG. 2: Frequency spectra of real conductivities $\text{Re}(\sigma_{xx})$ (solid lines) and $\text{Re}(\sigma_{yy})$ (dashed lines), for increasing $B_{ip}$ along $\hat{x}$ from (a) to (d). The inset shows the nominal stripe orientation at zero $B_{ip}$.

Fig. 3 presents plots of the resonance peak conductivity $\sigma_{pk}$ and frequency, $f_{pk}$, vs $B_{ip}$. $\sigma_{pk}$ from both polarizations is shown in panel 3a for $B_{ip}$ along $\hat{x}$ and in panel 3b for $B_{ip}$ along $\hat{y}$. In both panels there are distinct ranges of $B_{ip}$ in which a resonance is present exclusively in $\text{Re}(\sigma_{xx})$ or $\text{Re}(\sigma_{yy})$. Separating these ranges of one-polarization resonance, there are crossover ranges in which peaks can be observed in both $\text{Re}(\sigma_{xx})$ or $\text{Re}(\sigma_{yy})$. This reinforces the description in which $B_{ip}$, applied on either axis, can be thought of as switching the resonance from $\text{Re}(\sigma_{xx})$ to $\text{Re}(\sigma_{yy})$. This switching of the polarization of the resonance is most naturally interpreted as a reorientation of the stripes, by analogy with the $B_{ip}$ induced switching of the hard and easy axes observed in dc transport studies [12, 13, 14, 15, 16, 17, 18].

FIG. 3: (a): In-plane field $B_{ip}$ along $\hat{x}$, the resonance amplitudes in $\text{Re}(\sigma_{xx})$ (solid triangles) and $\text{Re}(\sigma_{yy})$ (solid circles), as functions of the magnitude of $B_{ip}$. (b): For $B_{ip}$ along $\hat{y}$, the resonance amplitudes in $\text{Re}(\sigma_{xx})$ (open triangles) and $\text{Re}(\sigma_{yy})$ (open circles), as functions of $B_{ip}$. (c): The resonance peak frequencies vs $B_{ip}$, with the same symbols as in (a) and (b). The inset shows the nominal stripe orientation at zero $B_{ip}$. The table at right shows $\Delta$, the per-carrier pinning energy difference between stripes parallel and perpendicular to $B_{ip}$; magnitudes and directions of $B_{ip}$ at which $\Delta$ is assessed appear in the left column.
anisotropy energy $E_A$ as a function of $B_{ip}$ for a given sample vertical ($z$) confinement. To affect $f_{pk}$, $B_{ip}$ must modify the effect of disorder, again by modifying the carrier wave function including $z$ dependence. If the disorder relevant to pinning is due to interface roughness, as conjectured by Fertig [30] for the Wigner crystal, $B_{ip}$ could increase pinning by increasing wave function amplitude at the quantum well interfaces. Such an effect can be inferred from the wave functions in a quantum well in higher Landau levels, in the presence of $B_{ip}$, as presented in ref. [21].

The change in $f_{pk}$ on applying $B_{ip}$ is large enough to be comparable to the calculated $E_A$ [14, 20], implying that a disorder interaction, specifically pinning energy, plays an important role in determining the orientation (or other parameters) of the stripe state. For the transitional $B_{ip}$'s, at which resonances are present in both $\sigma_{xx}$ and $\sigma_{yy}$ pinning energy anisotropy $\Delta$, due to $B_{ip}$ is directly obtained as the difference of $f_{pk}$ measured with $E_{rf}$ perpendicular and parallel to $B_{ip}$; taking the resonances to be occurring when $E_{rf}$ is polarized perpendicular to the stripes, $\Delta = h[f_{pk}(\text{stripes}||B_{ip}) - f_{pk}(\text{stripes} \perp B_{ip})]$. The table next to Fig. 3c presents the $\Delta$ and $B_{ip}$ values. For comparison, $E_A$, calculated [14] for the same carrier density and quantum well thickness as in the present sample, is about 6 mK per carrier at $B_{ip}=0.8$ T. The pinning energy tends to stabilize the orientation of the stripes parallel to $B_{ip}$, and so is competing with $E_A$, which for our sample favors the stripes perpendicular to $B_{ip}$. Interplay of this type may explain the complex switching behavior we observed, with pinning energy driving the switching of the resonant polarization when $B_{ip}$ is applied perpendicular to the original stripe direction. More generally, dependence of the carrier-disorder interaction on $B_{ip}$ may explain some of sample-dependent behavior of the stripe states that has been noted in dc transport experiments [15].

To summarize, our studies of the stripe phase in $B_{ip}$ indicate that disorder in the stripe phase, as measured by $f_{pk}$, increases with $B_{ip}$. The presence of resonances in both polarizations around the $B_{ip}$ of the apparent switching of the stripe direction indicates there are likely coexisting regions of perpendicularly oriented stripes at the transition.

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