Geometric Resonance of Composite Fermion Cyclotron Orbits with a Fictitious Magnetic Field Modulation

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In dc transport measurements of two-dimensional electron systems containing a small *charge* density modulation in one direction, resonance structure in resistance is observed near filling factor $\frac{1}{2}$. For a sufficiently well-controlled modulation amplitude, the magnetic field positions of these distinct resistance minima are consistent with values for a periodic *magnetic* modulation as predicted in a Chern-Simons fermion picture of $\nu = \frac{1}{2}$.

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An essential element of the composite fermion picture [1] of interactions in two-dimensional electron systems is the association of magnetic flux to charge. In the Chern-Simons construction utilized by Halperin, Lee, and Read [2], fictitious magnetic field is "attached" to the charge of the 2D electron system in a direction opposite to that of the applied B field. Consequently, zero effective magnetic field $\Delta B = B - B(\frac{1}{2}) = B - 2\phi n$, n the electron density and ϕ the magnetic flux quantum, is predicted at $\nu = \frac{1}{2}$ as is Fermi surface formation by the composite particles, which are themselves each an electron plus two magnetic flux quanta. This model serves to describe the experimental observations of the series of fractional quantum Hall states [3] around filling factor $\frac{1}{2}$ and the surface acoustic wave (SAW) anomalous propagation [4] directly at $\frac{1}{2}$. Further immediate support of the theory came from observation of geometric resonance of the composite particles' cyclotron orbits with SAW [5] and in antidot measurements [6]. While these experimental results collectively bolster the fundamental predictions of this mean-field theory, they do not investigate the potential breakdown of the theory: Will density perturbations on small length scales induce effects not describable by the composite fermion construction?

This question was initially addressed in experiments in which a periodic density modulation was imposed on high quality two-dimensional electron systems. Using surface acoustic waves [7] to probe the electron system conductivity, density modulations of small period λ were tuned in amplitude using periodic metal top-gates. Even small amplitude modulations ($<10\%$) showed substantial anisotropic SAW response specifically at $\nu = \frac{1}{2}$: Effects empirically similar to those that were seen for quantum Hall states were observed at $\frac{1}{2}$ for SAW propagating along the lines of the gates, but not for SAW propagating orthogonally to the gate lines. No response was seen in the dc transport for these gated, non-light-activated 2D systems. These results were subsequently explained [8] using semiclassical composite fermion theory which allowed derivation of a Boltzmann equation for the quasiparticles, within which the modulated density leads to a modulated magnetic field. As such, the model of flux associated charge was supported by these theoretical and experimental findings. In addition, this theory (and one that followed [9]) described not only the established SAW responses but stated that dc transport should demonstrate an enhanced resistivity minimum at $\frac{1}{2}$, naturally reflecting the systems' conductivity observed in the SAW experiments. These predictions were answered by dc transport measurements [10] using etched heterostructures that indeed displayed qualitatively the anisotropic response observed in SAW measurements.

An important aspect missing in both the SAW and dc transport results was evidence for geometrical resonance of the composite fermion cyclotron orbits with the periodic modulation. While such resonance structure in resistivity measurements is well established for *electrons* at small B fields in 2D, in both density modulated (electrostatic) [11] and magnetic field modulated systems [12], it was not observed in the composite fermion studies. This absence is significant because these 1D modulated systems necessarily require the charge carrier to traverse a density perturbed region of the two-dimensional electron systems (2DES): The SAW measurements and antidot measurements that have shown geometric effects either do not perturb the density or change the density in the extreme limit of excluding charge completely. Therefore, establishing resonance properties of the composite particle with the 1D modulation would demonstrate explicitly the interaction of charge-flux composite with the fictitious magnetic field of the Chern-Simons construction. These resonance structures should be seen in resistivity around $\frac{1}{2}$ in similarity to the electronic response to a modulated magnetic system [12] and as described in the results of the composite fermion Boltzmann equation analysis [8,9].

We show here results of dc transport measurements on weakly density modulated 2D heterostructures which contain clear resonance structure around $\frac{1}{2}$ filling factor. Well-formed resistance minima occur symmetrically about $\frac{1}{2}$ for sufficiently small amplitude modulation. For controlled

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modulation strength, different modulation wave vectors show the explicitly predicted resonance positions in effective magnetic field expected for a spatially modulated magnetic field $\Delta B(r) = B - 2\phi(\delta n(r) + n)$, corresponding to the imposed local electron density modulation $\delta n(r)$.

The 2D electron systems employed in this study are single interface heterostructures with the electron layer residing 2100 Å below the surface. Light exposure to a red light-emitting diode is used to promote the mobility while causing less than a 10% change in overall density. These wafers are of higher density than those studied in the earlier SAW measurements [7] of modulated systems and crucially these are exposed to light: The gated structures could not be light activated and retain small tunable density modulation.

The modulation pattern on the heterostructure is defined using e-beam lithography over an area of roughly $(0.5\ \text{mm})^2$. The periods tested ranged from 0.5 to 1.7 μm. The modulation is established in the heterostructure by etching the patterned surface using an electron cyclotron resonance etcher, which is specifically designed and controlled to expose the samples to minimal damage in proximity to the etch areas. A range of etch depths and etching parameters was tested to optimize establishment of the modulation while preserving the quality of the 2D system.

The etched area traverses the full width of a Hall bar, as shown schematically in the inset in Fig. 1. Indium contacts are diffused into the sample following the etching process roughly in the pattern shown. In total, 28 samples were fabricated with varied etch depths over the above stated modulation periods, all with only small variations in measured electron areal density.

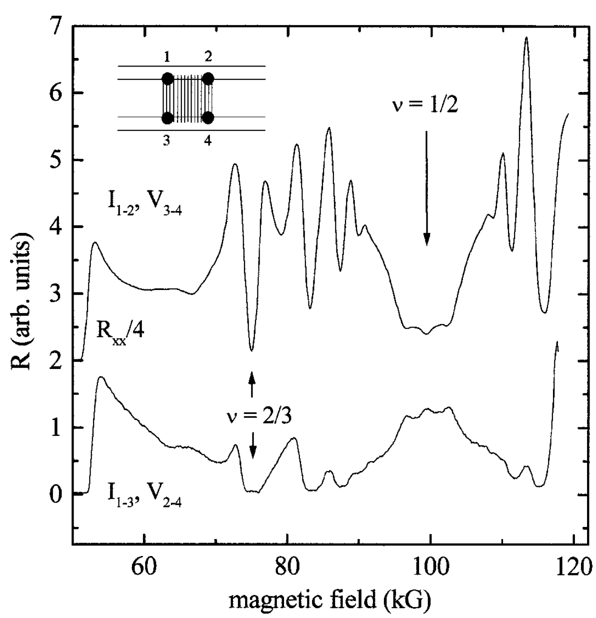

FIG. 1. dc transport configuration and magnetoresistance measurements for two orientations through a weak density modulated 2D electron system. Note the symmetrical structure at and in the vicinity of $\nu = \frac{1}{2}$. The modulation wavelength is 1.28 μm. Temperature is ~300 mK.

The results of low temperature dc transport through an etched 1D modulation are shown in Fig. 1. As seen in previous transport studies [10] and described by theory [8] for current driven across the modulation lines, an enhanced relative minimum occurs in longitudinal resistance R_{xx} at $\nu = \frac{1}{2}$. This occurs for a sufficiently small modulation period (in these studies for $\lambda < 1.5\ \mu$m). An enhanced minimum appears because the resistance at $\frac{1}{2}$ does not change substantially given that the quasiparticles can traverse the small period modulation for periods smaller than the particles' mean free path; away from $\frac{1}{2}$ the quasiparticles follow the extended equipotential lines along the imposed modulation, thus increasing the overall resistivity.

The focus of this study is the set of newly resolved structures immediately adjacent to $\frac{1}{2}$ and apparent in Fig. 1 in transport both along and orthogonal to the modulation lines. For the transport configuration $I_{1\text{-}2}$ and $V_{3\text{-}4}$ the structures are distinct local minima in R_{xx} symmetrically spaced about $\frac{1}{2}$. These structures are found to arise *asymmetrically* around $\frac{1}{2}$ for strong modulations (not shown). As the strength of the modulation is lowered (less severe etch) the minima move to smaller values of effective magnetic field and move to symmetrical positions about $\frac{1}{2}$. The strength of the modulation can be monitored by examining the commensurability oscillations of the electrons in the electrostatic modulation near $B = 0$. The measured amplitude of electron commensurability oscillations is an excellent experimental means of providing a comparative monitor of the modulation strength. Importantly, the minima structure around $\frac{1}{2}$ were found to be both symmetrical in magnetic field position and stable in magnetic field position for sufficiently small density modulations that either barely induce electron commensurability effects or show no electron commensurability. Given this restriction, the data shown in this study specifically comparing modulation periods [13] are all derived using etches that do not induce substantial electron commensurability oscillations, yet show enhanced minima at $\frac{1}{2}$.

The structures around $\frac{1}{2}$ filling factor in these lightly modulated systems are consistent with commensurability of the composite fermions cyclotron orbits with the periodic fictitious magnetic field induced by this charge density modulation. Numerical solution of semiclassical composite fermion motion in a Boltzmann equation [8] shows qualitatively the features observed near $\frac{1}{2}$, including the central minimum and the resonance structures away from $\frac{1}{2}$. The central minimum corresponds to open orbit paths of the composite fermions along the lines of the grid. The distinct minima symmetrical in effective magnetic field ΔB away from $\frac{1}{2}$ correspond to commensurability of the composite fermion cyclotron orbit with a single wavelength of the magnetic modulation. In the composite fermion model the semiclassical orbits are of radius $R_c = \hbar k_F / e\Delta B$, with the Fermi wave vector $k_F = (4\pi n)^{1/2}$, n the electron areal density. Two sources of commensurability of the charge motion are with the magnetic field modulation due to the flux associated charge of the Chern-Simons field [2], or with the electrostatic charge density modulation itself. The electrostatic and magnetic commensurability conditions relating the cyclotron radius to the modulation wavelength λ differ significantly: For electrostatic commensurability $2R_c \approx (m + \frac{1}{4})\lambda$ and for magnetic commensurability $2R_c \approx (m - \frac{1}{4})\lambda$, both where m is an index $1, 2, 3 \ldots$ stating the number of wavelengths over which the resonance occurs. In order to specifically identify the origin of these presumed geometric resonance effects a series of density modulated samples of varied wavelengths were fabricated and measured.

Figure 2 shows a series of resistance measurements around $\frac{1}{2}$ filling factor for varied modulation wavelength. For all three samples shown here the modulation strength was sufficiently weak that electron commensurability effects are not or almost not discernible. Resistance at all three wavelengths demonstrates local minima around $\nu = \frac{1}{2}$. The upper two traces are of wavelengths 0.72 and 0.54 μm, with the resonance positions in $\Delta B = B - B(\frac{1}{2})$ increasing as expected for smaller wavelength. The resonance positions predicted for magnetic commensurability are marked and are close to the observed lateral minima. The third trace also shows distinct, well-developed minima around $\frac{1}{2}$: However, this is a longer wavelength (1.28 μm) modulation than the two above traces yet shows structures at larger ΔB values. To understand how this effect fits the commensurability model a large range and number of modulation wavelengths have been studied.

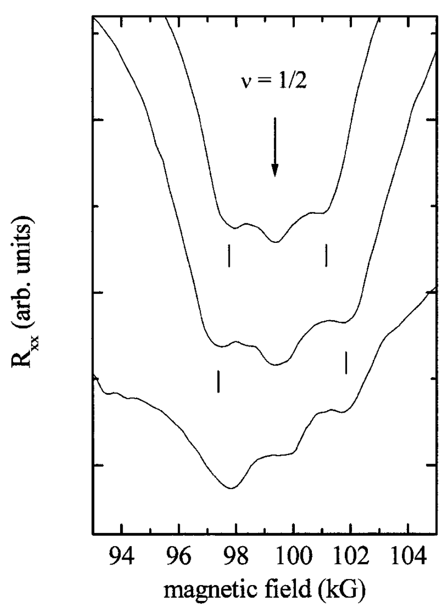

FIG. 2. Magnetotransport with current driven across the density modulation ($I_{1\text{-}2}, V_{3\text{-}4}$) for three different modulation periods focusing on filling factor $\frac{1}{2}$. The modulation periods from top to bottom are 0.74, 0.52, and 1.28 μm. Note the distinct minima around $\frac{1}{2}$ and their progression in effective magnetic field position with period. The vertical lines mark expected R_{xx} minima positions for commensurability with a magnetic field modulation. The data are offset and scaled for clarity.

Figure 3 plots resonance position versus modulation wave vector $q = 2\pi/\lambda$ for a range of wavelengths while importantly controlling the modulation strength for all data shown. Again, the data here represent modulations that do not induce discernible substantial electrostatic commensurability in the electron system near $B = 0$. Note the variation in resonance positions measured for each wave vector selected: This range is presumably due to residual variation in etch depth/modulation strength. The theoretically predicted positions for magnetic modulation are shown by the solid line in Fig. 3 with the larger wave vector data in reasonable agreement. For wavelengths larger than about 0.9 μm ($q < 7\ \mu\text{m}^{-1}$) a large departure from this magnetic commensurability line is observed. These long wavelength modulations are closer in ΔB to the predicted values for the electrostatic modulations, the line for which is shown in Fig. 3. Agreement with this line is not good.

Rather than representing electrostatic commensurability, these resonances may result from induction of higher spatial harmonics of the density modulation and consequently higher harmonics of the magnetic modulation. The lowest order, higher harmonic is a second harmonic for this type of modulation. By doubling the effective wave vector of these modulations at $q < 7\ \mu\text{m}^{-1}$, good agreement with the magnetic commensurability line is clearly shown in Fig. 3. This agreement is not only quantitatively accurate

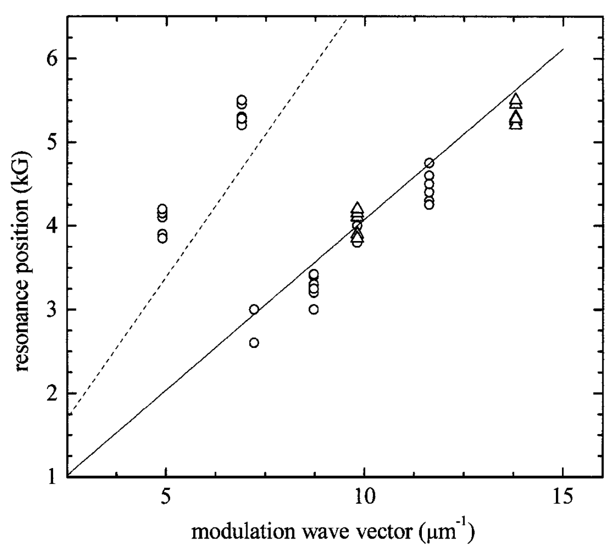

FIG. 3. Resonance positions in ΔB (resonance to resonance) versus respective density modulation wave vectors. The circles are plots of the fundamental wave vectors and the triangles are second harmonic positions of the small wave vector (<7 μm^{-1}) samples. The solid line is the theoretical position line for magnetic commensurability and the dashed line is for electrostatic commensurability.

but has a reasonable physical basis. The mean free path of the composite fermions in these heterostructures is roughly 1 μm. It is expected that any commensurability effect would be suppressed for modulation wavelengths of this order or larger. As such, these larger wavelength modulations would not demonstrate a commensurability (electrostatic or magnetic) at their fundamental spatial frequency but could at a higher harmonic. The effect of the electrostatic modulation is insignificant compared to the effect of the fictitious magnetic field modulation for the composite fermion system, and geometric resonance is shown to align with the magnetic component. More detailed calculations are required to establish that the higher harmonics can indeed be expressed as postulated here.

To summarize, distinct new resistance features are observed near $\nu = \frac{1}{2}$ in density modulated systems. Their magnetic field positions are in agreement with geometric resonance of the composite fermion cyclotron orbits with a magnetic field modulation, even for large wavelength modulations.

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