dc Transport of Composite Fermions in Weak Periodic Potentials

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dc transport through one- and two-dimensional periodic modulations of density has been investigated near half filling of the lowest Landau level. For both geometries, the modulation, which is rather weak for electrons at small magnetic fields, triggers an unexpectedly strong response for composite fermions. The dramatic effect observed in 1D gratings is best described as a large positive magnetoresistance emanating from the half filled state. 2D gratings display four peaks similar to dimensional resonances observed in antidot arrays despite the small modulation amplitude. [S0031-9007(98)06145-6]

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The similarity in the Hall and longitudinal magnetoresistivity of a high mobility two-dimensional electron system (2DES) as one moves away from zero magnetic field and half filling of the lowest Landau level, spurred Jain to conceive the concept of the composite fermion (CF), an electron-vortex compound, as a candidate unifying picture of the integral (IQHE) and fractional (FQHE) quantum Hall effects [1]. Within this model, the appearance of dissipationless incompressible quantum fluids at fractional fillings $\nu = p/(2p \pm 1)$, where p is an integer, was interpreted as the integer quantum Hall effect of CFs. Excitation gaps due to the electron-electron interaction became Landau quantization gaps and other concepts of the IQHE were transposed onto those of the FQHE. Moreover, this model gave the first hint that the up to then enigmatic half filled state might be metallic. Halperin, Lee, and Read investigated this state by converting it into a mathematically equivalent one, using the Chern-Simons gauge field theory [2]. Resorting to a mean-field approximation, they were left with the picture of a sea of weakly interacting quasiparticles (electron-flux tube compounds, hereafter also referred to as CFs), carrying charge e and moving in the apparent absence of the external magnetic field $B_{1/2}$. Away from half filling, they are subjected to an effective magnetic field $B_{\mathrm{eff}} = B - B_{1/2}$ and execute semiclassical circular orbits. This appealing analogy with electrons near zero external magnetic field served as a catalyst for experiments seeking to confirm the existence of a Fermi surface. Geometries, previously explored for electrons around $B = 0$, were deployed with considerable success to buttress the CF model by demonstrating the semiclassical ballistic motion with a cyclotron radius set by the effective magnetic field rather than the externally applied magnetic field [3–5].

Dimensional resonances in antidot lattices provided some of the most compelling evidence [3]. Yet, the observation of analogous commensurability effects in weakly modulated structures in dc transport, the aim of this work, has remained illusive so far. Such systems form an interesting paradigm for the study of the amplified sensitivity of CFs via the fictitious magnetic field to local density variations. The spatially dependent density distribution is accompanied with a spatially dependent effective magnetic field. Moreover, they may shed new light on the role of gauge field fluctuations and may provide the clearest demonstration of flux attachment since the commensurability condition for electrostatic and magnetic modulation is shifted in phase [6]. A local density disturbance of 1% suffices to produce a modulation amplitude of the effective magnetic field of 1% $\times B_{1/2}$ or more than 0.1 T for typical samples. It is without counterpart for electrons at small external magnetic fields for which the regime of magnetic modulation of comparable magnitude is more difficult to access [7,8]. This work is also related to recent surface acoustic wave (SAW) measurements performed on a 2DES that is subjected to a periodic 1D density grating either parallel or perpendicular to the SAW propagation direction [9]. A large peak in the velocity attenuation with a SAW wavelength insensitive width was observed for the perpendicular orientation (wave vector of the modulation perpendicular to that of the SAW) only. dc transport revealed no new features for this orientation (contact configuration B in Ref. [9] for which the current flows perpendicular to the stripes). Contrary to their findings, we measure an astonishingly strong response in dc transport. Equally unanticipated, systems with 2D weak modulation display dimensional resonances normally associated with antidot lattices for which the electrostatic potential near the antidots exceeds the Fermi energy. Thus, both geometries, 1D and 2D gratings, induce anomalously large effects for composite fermions despite rather small modulation amplitudes.

The experiment was conducted on a set of two high mobility $GaAs/Al_xGa_{1-x}As$ heterostructures (A-B). The samples were shaped into Hall bar geometries using standard photolithographic techniques and alloyed In contact pads. Prior to electron-beam lithography and after illumination with a red light emitting diode (LED), the areal density n_e and electron mobility μ at zero magnetic field and 50 mK were, respectively, 1.81×10^{11} cm^{-2} and 11.3×10^6 cm^2/V s (A), and 1.36×10^{11} cm^{-2} and 8.3×10^6 cm^2/V s (B). The resistivity at the half filled Landau level equaled $270\Omega/\square$ (A) and $360\Omega/\square$ (B), corresponding to a CF mean-free path of approximately 1.4 μm. The 1D and 2D gratings were imposed by electron-beam lithography and a subsequent shallow reactive ion etch (RIE).

The inset of Fig. 1 depicts the longitudinal resistivity ρ_{xx} at small external magnetic fields for 1D weak modulation perpendicular to the current direction ($\perp$). From this data, the modulation amplitude can be estimated in two different ways. The imposed modulation along the x direction lifts the degeneracy of the Landau levels with respect to the x coordinate of the guiding center and broadens them into bands with an oscillating width as the magnetic field is varied [10]. The dispersion of the Landau bands gives rise to an extra contribution to the conductivity, in addition to the usual scattering conductivity, referred to as the band conductivity. The nonzero group velocity in the y direction enhances σ_{yy} manifested in an increase of ρ_{xx} in experiment. The band conductivity also has a classical analog [11]. The scattering conductivity is of quantum mechanical nature and changes in accordance with the modified density of states. Although ρ_{xx} in the modulated geometry is affected by both, the additional band conductivity contribution overwhelms. At flat band condition when the cyclotron diameter, $2R_c$, equals $a(\lambda - 1/4)$ (λ is an integer and a is the periodicity), the orbits described by the electrons average away the effect of the periodic potential. For these values of the magnetic field the bandwidth reduces to zero and the band conductivity vanishes. The resulting oscillatory part of the longitudinal resistivity fits well [10]

$$\frac{\Delta \rho_{xx}}{\rho_0} = \left(\frac{V_0}{E_F}\right)^2 \frac{l_e^2}{aR_c} \cos^2\!\left(2\pi \frac{R_c}{a} - \frac{\pi}{4}\right). \qquad (1)$$

In this expression, ρ_0 is the zero field longitudinal resistivity, l_e the electron mean-free path, V_0 the modulation amplitude, and E_{F} is the Fermi energy. Commensurability oscillations up to $\lambda = 8$ can be discerned in the inset of Fig. 1. From their amplitude we deduce a modulation strength V_0 of 84 μeV or 0.9% of the electron Fermi energy with the aid of Eq. (1). Alternatively, V_0 may be estimated from the positive magnetoresistance at very small B (see inset of Fig. 1). It saturates at $B \approx 5$ mT. Experimental data are best described by the model of classical magnetic breakdown [12]. As long as the force exerted by the sinusoidal potential in the x direction exceeds the Lorentz force, closed orbits and open trajectories in the y direction coexist. The latter enhance ρ_{xx} until a critical magnetic field for which open orbits cease to exist, $B_0 = 2\pi V_0/eav_{\mathrm{F}}$, is surpassed, where v_{F} equals the Fermi velocity. This expression yields the same value, $0.009E_{\mathrm{F}}$, of the modulation amplitude.

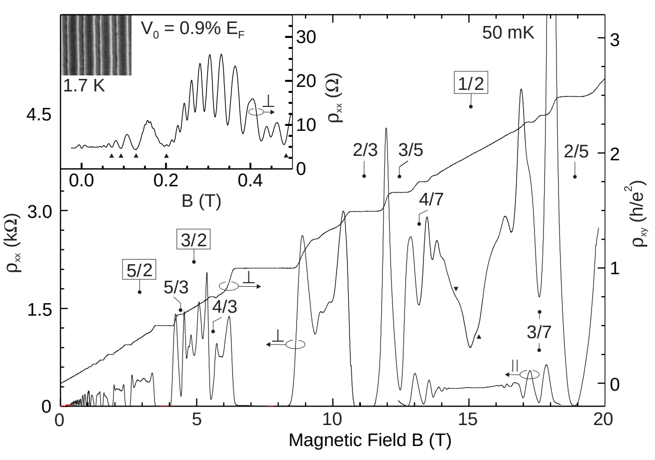

FIG. 1. Longitudinal magnetoresistivity ρ_{xx} as a function of the external magnetic field for 1D weak modulation perpendicular ($\perp$) and parallel ($\parallel$) to the current direction. The gratings have a period of 400 nm. Data for the parallel orientation ($\parallel$) in the vicinity of $\nu = 1/2$ show no structure on this scale [13]. The Hall resistivity ρ_{xy} is depicted for the perpendicular orientation ($\perp$) only. The top inset shows the classical commensurability oscillations with minima (triangles) whenever $2R_c = a(\lambda - 1/4)$ for the perpendicular electrostatic modulation at small external magnetic fields. The modulation strength V_0 equals approximately 0.9% of the electron Fermi energy. Arrows mark shoulders, discussed in the text.

Bearing in mind the mean field expression for the effective magnetic field, such a density modulation produces a spatially dependent effective magnetic field with an amplitude $B_{\mathrm{m,eff}}$ equal to $0.9\% \times B_{1/2}$ or 0.135 T. Even though a mixture of electrostatic and magnetic modulation is therefore inevitable for the composite fermion regime, the magnetic modulation component is expected to dominate. A striking positive magnetoresistance develops from $\nu = 1/2$ as $|B_{\mathrm{eff}}|$ is increased in the experiment of Fig. 1($\perp$) for which the current flows perpendicular to the etched stripes. Figure 2 compares data obtained from an additional set of four different gratings with periods $a = 600$, 700, 800, and 900 nm, all consistently displaying a marked dip upon approaching the half filled Landau level. It is entirely absent for the parallel orientation [see Fig. 1($\parallel$)] [13]. It is tempting to draw on the analogy with electrons subjected to a one-dimensional periodic magnetic stray field $B_m(x)$ produced by a ferromagnetic metallic grating [8] orthogonal to the current direction. The resulting magnetic commensurability oscillations are accompanied with a strong low field positive magnetoresistance as one moves away from zero external magnetic field. The phenomenon has been ascribed to open snake orbits [8], wiggling electron trajectories along a $B_m(x) = 0$ borderline [14]. Analogous to the open orbits of the classical magnetic breakdown mechanism described earlier, they promote the conductivity along the direction of the ferromagnetic stripes and raise the magnetoresistance

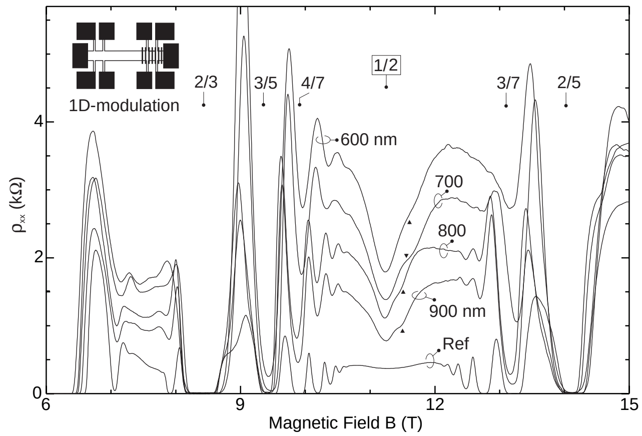

FIG. 2. The magnetoresistivity ρ_{xx} versus magnetic field for 1D weak modulation perpendicular to the current direction with grating periodicities of 600, 700, 800, and 900 nm. The etched stripe width is kept constant at approximately 110 nm. Estimated modulation strengths from low field data (not shown) are of the order of 1%. A reference measurement on an unpatterned section of a Hall bar has been included. Arrows mark shoulders, discussed in the text.

ρ_{xx}. The latter attains a maximum when the external applied magnetic field reaches the modulation amplitude for which such open orbits no longer survive. Thus, the magnetic field position of this maximum is a measure of the modulation amplitude [8]. Near half filling, the experiment displays a positive magnetoresistance that extends up to much larger values of $|B_{\rm eff}|$ than the modulation amplitude of the order of 0.1 T and would suggest local density disturbances of up to 10%. Clearly some ingredients are missing to form a consistent model, unless our implicit assumption, that the strength of the density perturbation taken from the low field data can be transferred to the high field regime, is incorrect. The physical mechanism that would account for such a tendency towards a charge instability remains, however, unclear.

The implementation of the 1D modulation has been achieved by performing a shallow etch of a grating pattern and by illumination after cooling down the sample. In the work of Willett *et al.* [9], the periodic structure is induced by a metallic gate and no illumination is required. While at zero field the electron effects are similar, the correlated system at $\nu = 1/2$ can in principle be strongly influenced by screening due to the metallic gate and the density "smoothing" due to illumination. The different results obtained in dc transport for both systems suggests that they may be sensitive to the details of the perturbation being used [15]. Willett and coworkers were unable to assign an explanation for the effect of the modulation on the SAW propagation velocity [9]. They point out the phenomenological similarity of the velocity attenuation at $\nu = 1/2$ with that of any of the incompressible quantum Hall states. If indeed a quantum Hall state is formed at $\nu = 1/2$, it would imply the unlikely scenario that the system is incompressible in one direction and compressible in the other (since signals were only observed for one orientation of the grating) [9]. We can exclude the interpretation based on a quantum Hall like state in our dc transport experiment for the orthogonal orientation, since the resistivity increases exactly at $\nu = 1/2$. The Hall resistance, displayed in Fig. 1 for a 400 nm-grating, also shows no sign pointing in this direction. Von Oppen and co-workers [16] have put forward an alternative scenario to understand the SAW measurements by solving the Boltzmann equation in the framework of the semiclassical composite fermion theory. In addition, they predict signatures in dc transport induced by the 1D-modulation in qualitative agreement with the data presented here [16]. The crux that awaits clarification is whether this model not only yields a similar shape but also a comparable magnitude of the response for realistic parameters.

The shoulder structures, indicated by solid triangles in Figs. 1 and 2, have not been identified, although they might be precursors of geometric resonances. Even though it is justified to view a 1% density modulation as weak, the corresponding effective magnetic field modulation is rather strong. If in addition a tendency towards a charge instability further amplifies the modulation strength, the absence of clear commensurability effects should not come as a surprise. We suggest that a further reduction of the density modulation is crucial to observe and understand such effects in the 1D geometry.

Figure 3 displays ρ_{xx} in the fractional regime obtained on a shallow etched 600 nm 2D lattice [17] and compares it to an unpatterned section of the Hall geometry. All fractions are retained and the resistivity at half filling merely increases by 40% exemplifying the small disturbance introduced by the 2D array. Since both sample preparation and

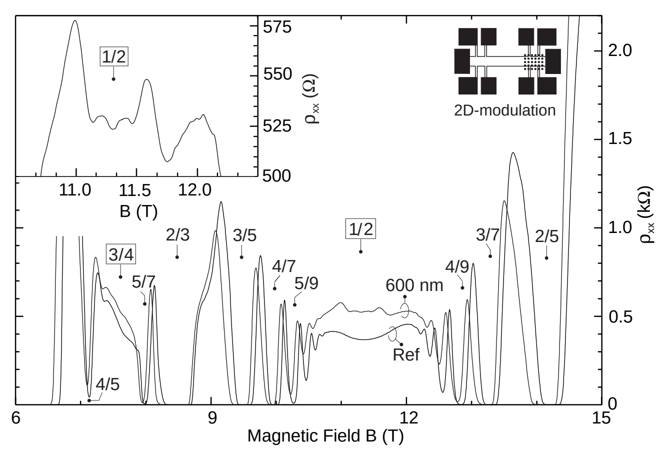

FIG. 3. The longitudinal magnetoresistivity ρ_{xx} for 2D weak modulation imposed by a shallow RIE etch. The array has a period a of 600 nm. The inset displays an enlargement of the data and reveals four distinct peaks symmetrically arranged our $\nu = 1/2$. The fifth peak at 12 T is attributed to the background resistance and also appears in the reference curve.

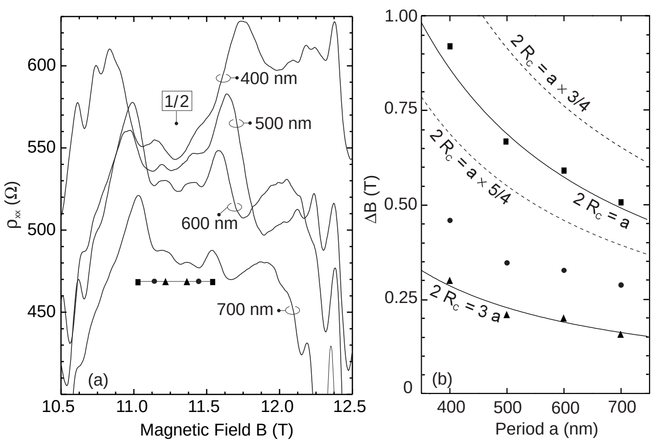

FIG. 4. (a) The magnetoresistivity ρ_{xx} for weakly 2D modulated systems around half filling with periods of 400, 500, 600, and 700 nm. (b) The primary peak-to-peak (rectangles), secondary peak-to-peak (triangles) and minimum-to-minimum (circles) separation as a function of the periodicity. The resonant matching conditions at which extrema are anticipated in the longitudinal resistivity for electrostatic modulation (primary minimum at $2R_c = a \times 3/4$), magnetic modulation (primary minimum at $2R_c = a \times 5/4$), and an antidot potential (primary maximum at $2R_c = a$, secondary maximum for a soft potential at $2R_c = 3a$) are also shown.

the illumination procedure are identical to the 1D gratings, we conjecture local density reductions of approximately 1% or local variations in the effective magnetic field of the order of 0.1 T.

At high magnetic fields, in an enlargement depicted in the inset of Fig. 3, four distinct peaks, symmetrically arranged around $\nu = 1/2$, can be resolved. The additional peak at higher magnetic field (12 T) is associated with the background resistance and also shows up in the reference measurement. The scaling behavior with lattice constant of the extrema has been investigated in Fig. 4 for a set of four different lattices. The magnetic field intervals separating the primary and secondary peaks and the minima have been correlated with the resonant matching conditions at which extrema are anticipated in the longitudinal resistivity for weak electrostatic and magnetic modulation and an antidot potential [Fig. 4(b)]. Quite astonishingly in view of the 1% modulation, the data for the primary peak persuasively follow the $2R_c = a$ trace, normally associated with the fundamental peak in antidot lattices [18]. Even the location of the secondary maxima (although prone to a larger error bar in determining its precise position) is well described by the condition $2R_c = 3a$ related with deformed cyclotron orbits encircling four "*antidots*" in a soft potential [19]. Whether a mixture of strong 2D-magnetic modulation (≈0.1 T) combined with weak electrostatic modulation may account for antidotlike features still needs to be addressed theoretically, even for electrons at small magnetic fields. In conclusion, the—for electrons at small magnetic fields—rather weak periodic potentials (whether 1D or 2D) produce an unexpectedly strong modulation for composite fermions.

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