A Laterally Modulated 2D Electron System in the Extreme Quantum Limit

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We report on magnetotransport of a two-dimensional electron system (2DES), located 32 nm below the surface, with a surface superlattice gate structure of periodicity 39 nm imposing a periodic modulation of its potential. For low Landau level fillings ν, the diagonal resistivity displays a rich pattern of fluctuations, even though the disorder dominates over the periodic modulation. Theoretical arguments based on the combined effects of the long-wavelength, strong disorder and the short-wavelength, weak periodic modulation present in the 2DES qualitatively explain the data.

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Two-dimensional electron systems (2DESs) subjected to both an artificial periodic modulation and a quantizing, perpendicular magnetic field B are expected to exhibit remarkable behavior arising from the interplay of the period of the modulation and the magnetic length, and the relative strengths of the periodic modulation, cyclotron energy (hωc), and disorder potential. When the periodic modulation’s strength is weak compared to hωc, each of the highly degenerate Landau levels (LLs) evolve into an energy spectrum with recursive effects of the periodic modulation within a single, resolved periodic potential, so that the butterfly’s larger energy gaps remain open. Then, one may probe directly the effects of the periodic modulation within a single, resolved LL. In particular, maxima and minima are expected in the low-temperature (T) diagonal resistivity ρxx as B is swept at fixed density n through a LL, i.e. as the Fermi level (EF) moves through the subbands and subgaps of the butterfly. Yet, for realistic disorder-broadened LLs, new physics can occur, due to the competition between the strengths of the disorder and the periodic modulation.

Here we present low-T magnetotransport measurements in a GaAs/AlGaAs 2DES, at a distance of 32 nm below the surface, whose potential is modulated via a surface gate with triangular symmetry and a periodicity of 39 nm, the smallest periodicity yet reported. Moreover, our data are taken in the extreme quantum limit, i.e. at low LL fillings ν where the integer quantum Hall effect is observed. Despite the high quality of the 2DES and its close proximity to the modulating gate, the disorder induced by doping impurities, located at a distance of ≈20 nm, is much larger than the periodic potential. Naively, one may expect that in this regime where the periodic potential is only a small perturbation, it should play no significant role in the transport properties of the system. Surprisingly, our results reveal that the small periodic potential does play a large role. Experimentally, we observe that the lowest spin-down LL is significantly broadened and ρxx at low ν exhibits a rich fluctuation pattern. Our theoretical arguments, based on the combined effects of the weak, short-wavelength periodic potential and the strong, long-wavelength disorder, qualitatively explain the data. The results highlight the importance of the very different length scales of the disorder and the periodic potentials in determining transport through the 2DES: because there are large areas of the sample where the disorder potential is very flat, the periodic potential plays the dominant role locally – this is one of the rare cases in physics where a small perturbation has a significant and non-trivial effect.

The sample studied here was grown by molecular beam epitaxy, and consists of a GaAs/Al0.3Ga0.7As heterostructure with a 2DES (n ≈ 3 × 1011 cm⁻²) at a distance d = 32 nm below the surface. The Si dopant atoms were deposited at a distance of about 12 nm below the surface. The low-T mobility, prior to and after the patterning, is about 3 × 10⁵ cm²/Vs. Experiments were performed on 20 μm-wide Hall bars fabricated by standard photolithography and wet etching. The distance between the probes used to measure the resistivity was 20 μm. The resistivity coefficients were measured by probe pairs located in different regions of the Hall bar, yielding qualitatively similar results. The 2DES is placed in a periodic potential created by a top gate realized by means of a diblock copolymer nanolithography technique. First, a self-assembled layer of hexagonally-ordered polyisoprene nano-domains (spheres with center-
external gate bias, a rich structure is present in the
right inset to Fig. 1(a). Even without applying an
a

(2) Compared to the data taken in the unpatterned sam-
ple, the Landau band splits into
to-center distance a) contained in a polystyrene matrix
was formed on the sample’s surface. After the removal
of the polisoprene spheres a polystyrene mask ≈ 15 nm-


trace for (a) the patterned sample at V_g = 0 V and (b) unpatterned sample at indicated



FIG. 1: (color online) \( \rho_{xx} \) vs \( \nu \) traces for (a) the patterned sample at \( V_g = 0 \) V and (b) unpatterned sample at indicated
temperatures. The top magnetic field scale is for the data of



FIG. 2: \( \rho_{xx} \) vs \( \nu \) at \( T = 0.05 \) K and various \( V_g \) (n). Curves for \( V_g = 0, 75, \) and \( 200 \) mV have been shifted for clarity.

ple and has an extended tail on the low-\( \nu \) side. To bet-

ter illustrate the observed asymmetry for the patterned
sample, we display in the insets to Fig. 1 the \( \sigma_{xx}, \sigma_{xy} \)
flow diagram. We note that both the \( \rho_{xx} \) fluctua-
tions and the asymmetry are reproducible with repeating



The central result of our experimental work is shown in
Fig. 1 where \( \rho_{xx} \) is displayed in the filling factor range
1.1 < \( \nu \) < 1.8 at various temperatures for the patterned
and unpatterned samples. Several features of the data are



FIG. 2. \( \rho_{xx} \) vs \( \nu \) at \( T = 0.05 \) K and various \( V_g \) (n). Curves
for \( V_g = 0, 75, \) and \( 200 \) mV have been shifted for clarity.












has a fractal structure of its own. Simple arguments show that the total number of states per unit area in each of the upper \( m \) main subbands is \( n_0 = 1/A \), whereas the lowest main subband contains the rest of \((\Phi/(m\Phi_0)-1)n_0\) states of the LL. The three subgaps shown as yellow regions in Fig. 3 are the most robust against disorder: if disorder is small, one expects to see minima in \( \rho_{xx} \) when \( E_F \) is inside these subgaps \((\rho_{xx} \propto \sigma_{xx}, \text{Fig. 2})\). For a given \( n \) we find the magnetic field \( B_i \) at which \( E_F \) is inside each of the main subgaps of the spin-down lowest LL to be \( B_i = \Phi_0/2 (n + in_0) \). For \( n = 2.92 \times 10^{11} \text{ cm}^{-2} \) \((V_y = 0\) in Fig. 1), \( E_F \) should cross the main subgaps at \( B_1 = 7.6 \text{ T}, B_2 = 9.2 \text{ T}, \) and \( B_3 = 10.7 \text{ T} (\nu = 1.59, 1.31, \text{ and } 1.13) \). Figs. 1 and 2 show that the low-\( T \) \( \rho_{xx} \) vanishes for all \( \nu \lesssim 1.3 \) and \( \nu \gtrsim 1.6 \), suggesting that all states, except for a few in the second highest subband, are fully localized. The same conclusion is reached if the analysis is repeated for an attractive potential \( V_1 < 0 \), for which the Hofstadter structure of Fig. 3 is inverted.

These observations indicate that disorder plays an important role. From the measured low-\( T \) mobility we estimate the width of the disorder-broadened LLs at \( 0.24 \times (B[T])^{1/2} \text{ meV} \). For \( B = 10 \text{ T} \) it is \( \approx 0.7 \text{ meV} \), much larger than \( V_1 = 0.1 \text{ meV}/V \times V_y (V) \) inferred from the exponentially decaying solution of the Laplace equation. Although the modulation amplitude is not precisely known, in our sample it likely remains smaller than the disorder. Since the main subgaps are filled in by disorder, the features in \( \rho_{xx} (\sigma_{xx}) \) cannot be attributed to \( E_F \) crossing the smaller gaps inside the second subband (from \( B_1 \) to \( B_2 \)); these smaller gaps must also be filled in by disorder. Hence, an interpretation of our data based on the naive Hofstadter butterfly is inappropriate.

In order to understand the origin of the \( \rho_{xx} \) features, we must analyze the new regime of a small periodic modulation and large disorder. Slowly-varying disorder (expected in high-mobility, remotely-doped samples such as ours) can be treated in semiclassical terms, with wavefunctions following the equipotentials of the disorder. The LLs are broadened, with all high (low) energy states being localized near maxima (minima) of the disorder potential. Current-carrying extended states correspond to equipotential contours percolated across the sample and are found in a so-called critical region at the center of the Landau band. The effect of a supplementary weak periodic potential is illustrated in Fig. 4, where we plot equipotential contours of the total 2DES potential.

The disorder potential is a sum of screened Coulomb potentials from doping impurities located 20 nm from the 2DES. The amplitude of both disorder and the periodic potentials are close to experimental estimations. Instead of smooth trajectories, the equipotential contours now have a fractured nature, with many little “bubbles” around minima of the periodic potential on the flat areas of the disorder potential. Since the lattice constant \( a \) is comparable to the magnetic length, quantum mechanical tunneling spreads the electronic wave-functions over these flat regions, and considerably helps their percolation throughout the sample. This picture is in qualitative agreement with the results of Figs. 1 and 2, which show that \( \rho_{xx} \) of the patterned sample is considerably enhanced with increasing \( T \) on the low-\( \nu \) side, suggesting transport through temperature-activated hopping between nearby states, absent in the unpatterned sample.

This picture also offers a possible explanation for the detailed peak and valley structure observed in our magne-
The disorder potential is 0.7 meV. Consider the area enclosed in the rectangle drawn in Fig. 4, which is almost disorder-free (it has very little underlying disorder variation). Wave-functions across such flat regions correspond to those of finite-area Hofstadter butterflies, with appropriate boundary conditions. For the appropriate energy range, \( E_F \) is either inside a subband or a gap of such local Hofstadter structures. If \( E_F \) is inside a subband, wave-functions span the flat region and help enhance the percolation. When \( E_F \) is inside a gap, there are no states supported by the flat region and hence, no current can flow across it. Such flat regions act as switches which are turned on or off as \( E_F \) is changed, helping or hindering the current flow through the sample. When one or more switches are off, there are fewer paths for the current to be carried across the sample, and a valley is expected in \( \sigma_{xx} \) (\( \rho_{xx} \)).

Finally, the appearance of the fluctuation pattern preponderantly on the low-\( \nu \) side (see Fig. 2) is a direct consequence of the particle-hole asymmetry of the triangular potential. For LL filling factors \( 1 < \nu < 3/2 \) (3/2 < \( \nu \) < 2), percolation between wave-functions localized around minima (maxima) of the disorder is helped by the “bubbles” centered on the minima (maxima) of the periodic potential (see inset to Fig. 4). When attractive, the triangular potential has deep minima on a triangular pattern, and shallow maxima on a displaced honey-comb pattern (notice that there are almost no honey-comb arranged “bubbles” in Fig. 4). For 3/2 < \( \nu \) < 2, the shallow maxima of the periodic potential are not as effective in enhancing percolation, and \( \sigma_{xx} \) (\( \rho_{xx} \)) in the modulated sample is similar to that of the unpatterned sample.

These semi-classical arguments are supported by preliminary computations of \( \sigma_{xx} \), shown in Fig. 5, based on the Kubo-Landauer formalism [14]. The calculation is done for a given realization of a slowly-varying disorder potential and for a fixed value of \( B \). As \( n \) is varied from 2.6 to 3.4 \( \times 10^{11} \) cm\(^{-2} \), \( E_F \) sweeps through the disorder broadened LL. In Fig. 5(a), the peak-to-peak amplitude of the periodic modulation – 9\( \nu \) for the triangular superlattice – is somewhat larger than disorder’s strength. Well-defined subbands start to separate and evolve towards the Hofstadter butterfly structure expected in the limit where disorder becomes negligible compared to the periodic modulation. In the opposite limit of no periodic modulation [Fig. 5(c)], we observe a narrow, smooth peak when \( E_F \) is inside the critical region of percolated states (not centered at \( E = 0 \) because the disorder potential is not particle-hole symmetric). For a periodic modulation weaker or comparable to the disorder strength [Fig. 5(b)], a pattern of peaks and valleys emerges, as the periodic potential influences the percolation inside and near the critical region. Efforts to improve the description of the disorder potential are under way, so that quantitative comparisons with the experiment become possible.

To conclude, our work extends the rich problem of modulated 2DESs in quantizing magnetic fields to a new regime of long-wavelength, strong disorder and short-wavelength, weak periodic potential, and uncovers yet more interesting physics.

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