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Quantum Hall effect in lateral surface superlattices

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Abstract. We report magnetotransport measurements and the quantum Hall effect in lateral surface superlattices, realized in GaAs/AlGaAs high mobility heterojunctions with grid gates. We observe perturbation or destruction of the integer quantum Hall effect by a sufficiently strong periodic potential.

1. Introduction

The integer quantum Hall effect ([1, 2] and references therein) has been studied for quite some time in high mobility doped heterostructures [3]. However, the dynamics of a two-dimensional electron gas (2DEG) in the simultaneous presence of a periodic potential and a perpendicular magnetic field has long been predicted to give rise to a highly complex and variable energy level structure [4–8] which can lead to complicated transport behaviour. Advances in technology now allow us to create a high mobility 2DEG, with a superposed potential with a period much smaller than the electron mean free path, but large compared with the ordinary crystal lattice parameter [9, 10]. Lateral surface superlattices of this kind, with one-dimensional periodic potentials (gratings), have been found to exhibit new oscillations in the magnetoresistance that are periodic in the inverse of the magnetic field B [11, 12]. These have been explained in terms of the reduced Landau-level broadening that occurs when there is a commensurability between the cyclotron radius and the period of the potential and have come to be called Weiss oscillations.

However, in a two-dimensional lateral superlattice, created by a grid-gate structure, much of the predicted complicated behaviour is observed in the limit of high modulation V_0, where weakly coupled quantum dots are formed, and this results in shifts of the energy levels with magnetic field. These have been observed in magneto-capacitance measurements (MCM) [13]. In addition, lower-mobility structures have shown magnetoresistance oscillations periodic in B [14]. For superlattice potentials with weak modulation V_0, for which an anti-dot structure is created, $1/B$ oscillations

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of the longitudinal resistance, similar to those observed in grating-gate structures, suggest a quasi-one-dimensional ballistic motion of the electrons along parallel and weakly coupled channels [15]. In the regime intermediate between tightly bound dots and quasi-free motion in a lateral superlattice band structure, aperiodic structures in the MCM at low magnetic fields [16] also suggest commensurability effects associated with the magnetic flux per unit cell.

In this paper, we report high magnetic field transport properties in two-dimensional lateral superlattices, in different transport regimes. Within a single high mobility device, we can observe both the quasi-one-dimensional $1/B$ Weiss oscillations (at weak modulation, e.g. low gate-voltage amplitude) and a new effect, periodic in the density (gate voltage) near a localization threshold. In addition, we observe a break-up of the quantum Hall effect in a sufficiently strong periodic potential, associated with the break-up of the Landau level as described by Schellnhuber and Obermair [7]. We suggest a general mechanism, which is associated with localization by electron–electron scattering, for the observation of these new oscillations.

2. Experimental results

The samples are based on a GaAs/AlGaAs HEMT structure which consists of a GaAs buffer followed by 20 nm of undoped $Al_{0.3}Ga_{0.7}As$, 50 nm of $Al_{0.3}Ga_{0.7}As$ Si-doped to 10^{18} cm^{-3}, and 5 nm of undoped GaAs (figure 1(*a*)). Characterization data give a mobility of 1.0×10^6 cm^2 V^{-1} s^{-1}, after illumination at 4 K, for a carrier density $N_s = 4.7 \times 10^{11}$ cm^{-2}. A Hall-bar mesa pattern with ohmic contacts was formed (figure 1(*b*)), and a grid gate of nominal periodicity $a = 170$ nm was created on the surface by means of electron-beam lithography and subsequent lift off [8], and covered a region of 30 μm $\times$ 25 μm, including the edges of the voltage probes.

Experiments were performed at 1.4 K within a superconducting magnet, with the field oriented perpendicular to the plane of the 2DEG. Electrical measurements were made with a lock-in amplifier at 83 Hz, and the current flowing through the sample was kept in the range of 1 to 50 nA to avoid heating the sample. The grid gate was protected with a 10 MΩ resistor, and current leakage was demonstrated to remain lower than 50 pA for a negative applied gate voltage V_g more positive than -0.45 V.

The density deduced from ρ_{xy} at low field was found to have a linear relationship with the gate voltage: $\Delta N_s/\Delta V_g \simeq (5.8 \pm 0.4) \times 10^{11}$ cm^{-2} V^{-1}, consistent with the expected gate-to-channel capacitance. One effect of the grid-gate pattern is demonstrated in the magnetoresistance data of figure 1(*c*), obtained at $V_g = 0$ V. The device had previously been strongly illuminated, resulting in a modulation of the density of the 2DEG with the same period as the gate. An oscillatory phenomenon periodic in $1/B$ is clearly apparent: maxima and minima of the longitudinal magnetoresistance R_{xx} are modulated by an envelope which narrows (arrows) at $B = 1.35, 0.66, 0.95$ and 0.50 T. This is distinct from the Shubnikov–de Haas oscillation and corresponds to the earlier reported Weiss oscillations [11, 12]. The oscillation is associated with the commensurability of the cyclotron radius R_c and the period a of the structure, and is governed by the formula $2R_c = (m + \phi_0)a$, where m is an integer ($m = 0, 1$) for the maxima and a half integer ($m = \frac{1}{2}, \frac{3}{2}$) for the minima, with ϕ_0 a phase factor. With $\phi_0 = -0.25$, as found previously [11, 12], this formula is in good agreement with the observed positions of the present magnetoresistance data. In addition, the formula predicts a large broadening of the Landau level for $m = \frac{1}{2}$ at $B = 4.8$ T, and this may

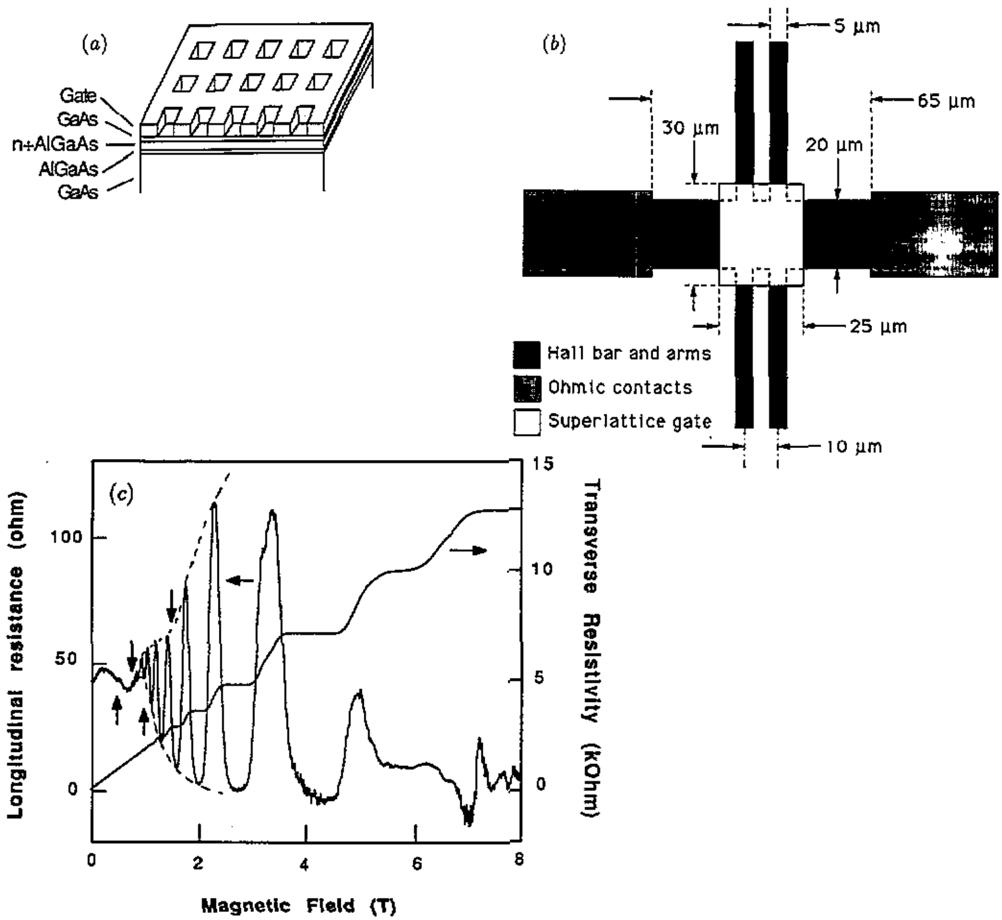

Figure 1. (*a*) Schematic cross section of a heterojunction with a grid gate structure. (*b*) Top view of device. (*c*) Measured longitudinal transverse resistivity against magnetic field at zero gate voltage and after strong illumination.

explain the unusual feature in R_{xx} around 5.0 T, although at the same magnetic field a well resolved plateau quantized at $h/3e^2$ occurs in ρ_{xy}.

Figure 2 shows the four-point longitudinal resistance R_{xx} and the Hall resistivity ρ_{xy} for several different gate voltages, for a device illuminated less strongly. This results in a lower density at $V_g = 0$ V, and a lower mobility. Consistent with the reduction of the carrier density with negative gate voltage, an increase occurs in the values of R_{xx} at the minima corresponding to the filling factor $\nu = 2, 4, 6$. We also note the progressive growth of a very slight bump around 0.8 T, corresponding approximately to $2R_c = 1.2a$, and which appears to be an unresolved signature of the low-field oscillatory phenomenon mentioned earlier. It also corresponds to the enhanced magnetoresistance reported for $2R_c = a$ [17]. Figure 3 displays, as a function of gate voltage, the minimum values of R^{ν}_{xx} attained for $\nu = 2, 4$ and 6. The value of R_{xx} at zero magnetic field and the density N_s are also indicated. For $-V_g \simeq 0.3$ V a significant increase occurs in all quantities except for the density, which is still high ($\simeq 1.6 \times 10^{11}$ cm^{-2}). For such a high carrier density, the quantum Hall effect features are usually resolved in a homogeneous 2DEG, since the screening of the disorder by

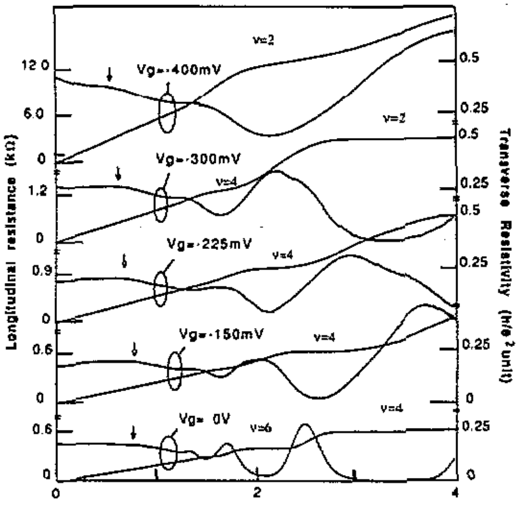

Figure 2. Longitudinal and transverse resistance against magnetic field for different gate voltages.

the gas is very effective. This strongly suggests that here the quantum Hall effect is destroyed by the modulation of the periodic potential. The R_{xx} traces also indicate a weak negative magnetoresistance at $B = 0$ T, and this can be used to estimate the inelastic mean free path l_ϕ of the carriers. Such a calculation suggests that for a gate voltage more negative than -0.32 V, $l_\phi < a$. This voltage also corresponds to a drop in mobility, and suggests the break-up of the quantum Hall effect arises from effective localization of the carriers in the quantum dots. Near this localization potential, fine structure can be seen in the transconductance. We discuss this structure in the remainder of the paper.

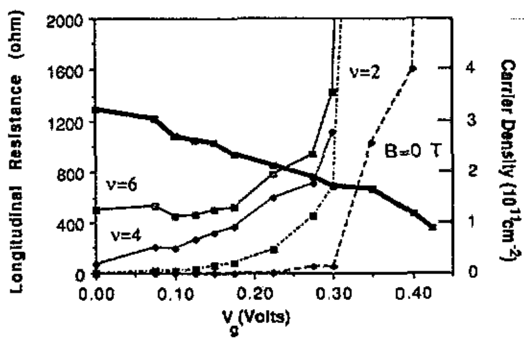

Figure 3. Replot of the values of R_{xx} corresponding to filling factors $\nu = 2, 4, 6$ (chain, dotted and full lines, respectively); the broken line indicates R_{xx} at zero magnetic field and the bold line the carrier density.

Figure 4 displays the behaviour of R_{xx} and ρ_{xy} as a function of gate voltage for a magnetic field of 4.5 T. The conditions of illumination are the same as for the results presented in figure 1, and a new series of oscillations is observed at the low density side of the quantum Hall effect plateaus. We show both the in-phase and quadrature signals (full and broken lines, respectively). For a gate voltage very near the localization

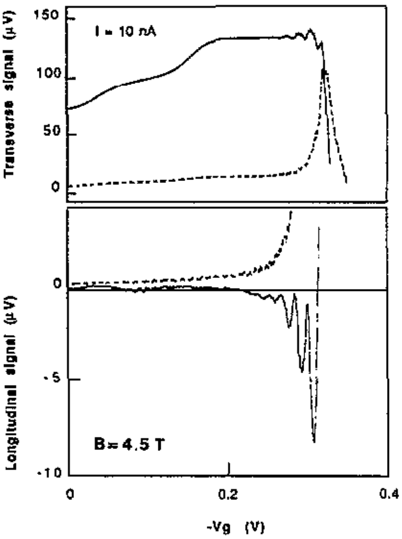

Figure 4. Longitudinal and transverse signal against gate voltage at $B = 4.5$ T and a current $I = 10$ nA. Continuous and broken lines correspond to in-phase and quadrature signals, respectively.

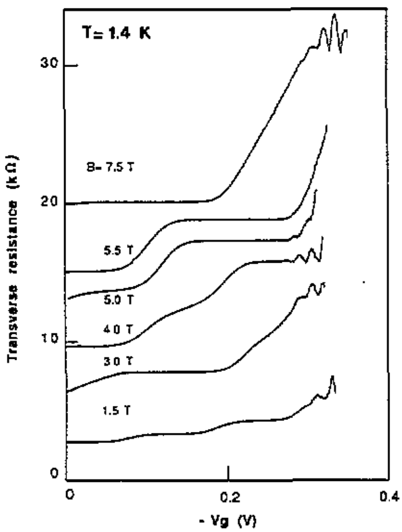

Figure 5. Modulus of transverse resistance against gate voltage for different magnetic fields. For clarity, successive curves for B above 1.5 T are offset (by 1.4, 3.3, 4.4, 6.0 and 7.6 kΩ respectively, for 3 T, 4 T, etc).

threshold, four-point measurements exhibit large phase rotation, probably due to the large increase in the two-point resistance of the partially depleted probes. As $-V_g$ is increased, successive Shubnikov–de Haas oscillations and Hall plateaus are observed, consistent with the reduction of carrier density. Just below the localization value at approximately -0.32 V, well defined oscillations develop in both R_{xx} and ρ_{xy}. Maxima of $|R_{xx}|$ correspond to maxima in ρ_{xy}. The modulus of ρ_{xy} against gate voltage is plotted in figure 5 for different magnetic fields. The oscillations are well developed for $\nu = 2, 0 \leqslant B \leqslant 4.5$ T and for $\nu = 1, B = 7.5$ T. In the region in between (5.5 T), when the localization occurs between the two quantized values (12.9 and 25.8 kΩ) of ρ_{xy}, they are visible neither in the Hall resistance nor in the longitudinal resistance. This suggests that they occur only when the Fermi level is away from the centre of the Landau levels, and near the disordered states between the levels. At a much lower magnetic field B (1.5 T), other ripples also appear near the $\nu = 4$ plateau. The regularity of the oscillations, when they occur, and their reproducibility, exclude as a possible explanation a parasitic charging of the grid gate. Furthermore, the oscillations are related to the specific grid pattern of the gate, since we do not observe them in any devices for which a planar (unpatterned) gate is used.

3. Discussion

These new oscillations cannot arise from the same effect observed by Weiss *et al* [11], since near the localization threshold, the density is evaluated to be 1.9×10^{11} cm^{-2}, which, for magnetic fields larger than 1.5 T, gives a cyclotron radius much smaller than the period of the gate. Our oscillations are found to be periodic with gate voltage, with the period almost constant at 15 mV in the whole range of the magnetic field

$1.5 \leqslant B \leqslant 7.5$ T. Using the density variation with gate voltage $\Delta N_s/\Delta V_g$ measured at low magnetic field, we get a change $\Delta N_s \simeq 8.4 \times 10^9$ cm^{-2}, or approximately two electrons per square cell per oscillation. This calculation, however, assumes a constant density of states (DOS), since changing the applied gate potential moves the Fermi energy through the DOS of the system.

Several calculations have been performed [6, 7] for the energy levels of a two-dimensional system in the simultaneous presence of a periodic potential and a high magnetic field. These have yielded very complicated energy level structures, which depend qualitatively on the magnetic field and on the lattice structure. The theoretical situation is best understood for square lattices, where two complementary regimes can be identified: In the strong-potential/weak-field regime, studied by tight-binding models, there is a fractal energy structure periodic in Φ/Φ_0, the flux per unit cell of the lattice. In the weak-lattice/strong-field regime, there is a similar fractal structure, periodic in the inverse of this quantity. The observation of the quantum Hall effect suggests that our devices are in the weak-potential regime. We can confirm this by estimating the amplitude V_0. If we assume V_0 to be equal to the Fermi level E_F at $V_g = -0.35$ V, using the DOS of a homogeneous 2DEG, $D(E) = 2.8 \times 10^{10}$ cm^{-2} meV^{-1}, we obtain $V_0 = 6.7$ mV. This is 2% of the applied gate voltage, a figure consistent with estimates based on the Laplace equation in the gate-to-2DEG region. This value is also close to the cyclotron energy. However, the characteristic force scale of the superlattice potential, $|\nabla V| \simeq 2V_0/a$, is much smaller than the scale for the magnetic force $\hbar\omega_c/l_c$ ($l_c = \sqrt{\hbar/eB}$ is the magnetic length, ω_c the cyclotron frequency) in the magnetic field range considered.

To the extent that disorder may be ignored, the band structure is periodic in Φ_0/Φ. Moreover, it is expected that the periodic potential will cause the Landau level to split into a number of broadened minibands [7]. For the range of fields studied, the DOS is approaching a field-independent structure. We have calculated such a DOS for the potential

$$V(x, y) = \tfrac{1}{4}V_0[\cos(2\pi x/a) + \cos(2\pi y/a)]$$

to first order in degenerate perturbation theory. In the $\Phi_0/\Phi \rightarrow 0$ limit, this can be performed exactly, yielding a DOS

$$g(E) = 2K(\sqrt{1-(2E/V_0)^2})/(\pi^3 l_c^2 V_0)$$

per unit area per spin, where $K(k)$ is the complete elliptic integral of the first kind of modulus k. This DOS has a weak (logarithmic) divergence at the centre of the Landau level (defined as $E = 0$), and decreases smoothly and monotonically, approaching a constant as $|E|$ approaches $\frac{1}{2}V_0$ from below, and dropping to zero for $|E| > \frac{1}{2}V_0$. For finite values of Φ/Φ_0, fine structure in the DOS can be detected only if the energy resolution is better than approximately $V_0 \times (\Phi_0/\Phi)$. Here, this value is about 250 μV, which is only a factor of two greater than the thermal noise. This structure has a much shorter period than the observed ρ_{xy} oscillations, and is likely to be smoothed by disorder (about which more later).

The conclusion is that the observed fine structure does not arise directly from the ordered-potential DOS, as the miniband-induced-modulation of the DOS is expected from the previous discussion to be too small. This is supplemented by the semiclassical picture which demonstrates that the smoothness of the DOS is not a peculiarity of the potential chosen. When the potential varies slowly ($|\nabla V| \ll \hbar\omega_c/l_c$), the Landau level consists essentially of edge states which follow the equipotential lines, with the enclosed area given by the quantization of the flux. Thus, the DOS is proportional to the real-space density of the potential energy values. This is exactly the result in our model calculation.

Therefore, the periodicity in V_g observed in the magnetoconductance extends over an energy range much wider than expected from the disorder-free Landau level linewidth, and is unlikely to be associated with commensurability or non-commensurability of the lattice spacing and cyclotron radius. Moreover, these arguments suggest that the DOS modulation by itself is not likely to be observable here. This suggests that the explanation lies with two elements that were not considered in finding the DOS: disorder and the electron–electron interaction. Disorder plays a central role in making the quantum Hall effect observable; in this regime of fields and densities, and in samples of comparable high mobilities, the electron–electron interaction has a fundamental effect on transport properties, giving rise to the fractional quantum Hall effect at lower temperature [19]. Disorder could explain the ρ_{xy} feature if some mechanism caused the degree of localization or localization length to oscillate periodically with gate voltage. One possible mechanism is provided by the electron–electron interaction.

While the nature of localized states in two dimensions is not yet completely understood, as a general rule the character of states changes dramatically as the scale W/V goes through a value on the order of unity [18]. Here V is the typical magnitude of the matrix element in a hopping formalism. In the semiclassical picture, the hops must occur between edge states circulating around adjacent extrema of the superlattice potential, and will be less than V_0. The disorder W has a magnitude proportional to the scattering potential strength and also to the density of scatterers. If there is an integer multiple of two electrons per unit cell, then we may expect the residual electrostatic repulsion to distribute the electrons among single-particle-degenerate states in a manner that yields a uniform charge density. If there is not an integer multiple of electrons per unit cell, then some excess of electrons will be distributed as scatterers over random sites in the lattice. The scattering potential has a scale on the order of 0.1 meV, given by the Coulomb energy of two electrons separated by a distance a.

As the device approaches localization at $V_g = -0.32$ V, the mobility decreases, and there is a range of gate voltages where a 0.1 meV variation in W would make a dramatic difference in the degree of localization of the states. Such a variation would lead to conductance oscillations that always occur for any magnetic field where the Fermi energy lies near the mobility edge of the Landau level DOS. The period is also predicted to correspond to a density change of approximately two electrons per unit cell. One difficulty with this argument is the case, at very high field, where the single-spin $\nu = 1$ plateau is resolved. Here the approximately 15 meV periodicity should correspond to a change of density of only one electron per unit cell, unless the superlattice potential is significantly mixing Landau levels. A possible explanation of this may be that for an odd number of electrons per unit cell, spin-flip scattering should dominate the residual electron–electron interaction. In order for the spins to be resolved, such scattering must be energetically forbidden. Thus, electron-scattering-induced disorder must be able to be neglected for odd as well as even numbers of electrons per unit cell, halving the period.

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