# Magnetization and Energy Gaps of a High-Mobility 2D Electron Gas in the Quantum Limit

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We have measured the magnetization of several single-layer, high-mobility 2D electron gas AlGaAs-GaAs heterostructures in the quantum limit. Abrupt jumps in the magnetization are observed when an integer number of Landau levels is filled. The width and the magnitude of the jumps identify incompressibility gaps in the energy spectrum of the order of the cyclotron energy, in which a small fraction of the total number of states is present. Sizable magnetization steps associated with the spin splitting are observed at odd filling factors (including $\nu = 1$) and give a measure of the exchange enhancement of the spin splitting. [S0031-9007(97)04313-5]

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In a strong magnetic field, the motion of charged particles perpendicular to the field is quantized. In two dimensions, the degeneracy $G_\phi = \phi/\phi_0$ of each energy level $\epsilon_j^{\uparrow\downarrow} = (j + 1/2)\hbar\omega_c \pm g\mu_B B$ (Landau level, LL) is given by the number of flux quanta $\phi_0 = h/e$ threaded through the sample. For a two-dimensional electron gas (2DEG) with $N$ particles, the filling factor $\nu = N/G_\phi$, which measures the number of occupied LL's, is an integer when all the available states in the $\nu$ lowest LL's are filled. At these integer values, the 2DEG is incompressible since the chemical potential $\mu$ increases *discontinuously* when, upon decreasing the magnetic field, electrons are transferred to the next LL. Simultaneously, the magnetization jumps by an amount related to the difference in chemical potential between incompressible and compressible states, which defines the incompressibility (IC) gaps. As the next LL is progressively filled, the 2DEG recovers a finite compressibility. The magnetization jumps are a consequence of the pinning of the chemical potential to a LL with degeneracy $G_\phi(B_\perp)$, determined by the magnetic field component $(B_\perp)$ perpendicular to the 2DEG. Therefore, all thermodynamic properties are anisotropic.

In the absence of disorder and interactions, the magnetization is predicted to oscillate periodically in a sawtooth pattern as a function of $\nu$: this is the two-dimensional de Haas–van Alphen effect first analyzed by Peierls [1] and revisited by Vagner [2] and Shoenberg [3] in the context of the integer quantum Hall effect (IQHE). In 2DEG samples which exhibit the IQHE, the shape of the magnetization oscillations, which probes the energy dependence of the overall density of states (DOS), is affected by disorder and interactions. Nevertheless, magnetization jumps are always expected as long as the energy spectrum retains well-defined IC gaps between compressible states.

Today, very clean single layer AlGaAs-GaAs heterostructures can have mobilities exceeding $10^6$ cm$^2$/V s and constitute an almost perfect realization of a 2DEG. However, sharp sawtooth de Haas–van Alphen oscillations have never been observed so far in such an ideal system. All earlier studies, which used relatively low mobility samples, revealed a considerable broadening and overlap of the LL's [4–6], a conclusion which has not been challenged by other thermodynamic measurements [7].

In this Letter, we report the first experimental observation of the sawtooth oscillations in the magnetization of a high mobility single layer 2DEG: the magnetization jumps at even integer $\nu$ are so sharp, that thermal broadening is observed at 4.2 K. As a function of $\nu$, the amplitude of the jumps goes through a maximum and decreases above $\nu = 4$. We also observe magnetization jumps at odd $\nu$ which give a measure of the $g$-factor enhancement.

The magnetization measurements were carried out with an ultrasensitive epoxy torque magnetometer [8] (the sensitivity $\delta M \approx 10^{-13}\ J/T$ is equivalent to $10^{10}$ Bohr magnetons at 1 T) sketched in the inset in Fig. 1, which is based on the designs in Refs. [4,5]. The angular position of a very lightweight rotor, suspended by a phosphor bronze wire, is detected by an array of capacitors between the stator and the rotor. In zero field, the 2D samples are mounted in the central rectangular space of the rotor. The normal of the 2D plane is tilted by an angle $\theta \approx 30°$ with respect to the field axis. The torquemeter is sensitive to the anisotropic 2DEG magnetization and was calibrated using a small coil mounted on the rotor with an accuracy of 10%. Since the 2D sample is isolated, the measurements were carried out at a constant number of particles.

Two series of *single layer AlGaAs-GaAs* heterostructures were studied. The "Camb" series is selectively doped, with *Si* dopants distributed in a 400 to 2000 Å thick layer recessed from the interface at a

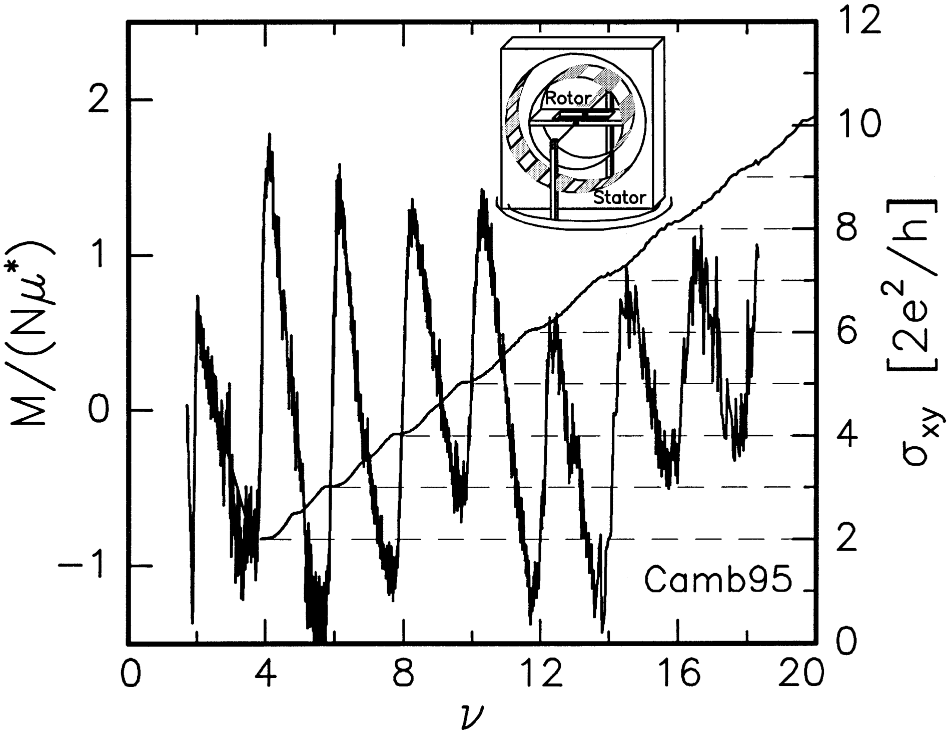

FIG. 1. Left scale: Sawtooth magnetization of sample Camb95 as a function of $\nu$; right scale: Hall conductance measured in a transport experiment on the same wafer under similar experimental conditions (after illumination). The magnetization jumps occur precisely at the center of the Hall plateaus as expected for a measurement carried out at a fixed number of particles. Inset: Schematic drawing of the torque magnetometer used in this work.

setback distance ranging from 200 to 800 Å. The "L2M" sample is Si $\delta$-doped at a setback distance of 300 Å and its substrate was thinned down to 100 $\mu$m to reduce its mass. The samples consist of $3 \times 5$ mm$^2$ AlGaAs-GaAs pieces without addenda. The carrier densities $n_{2D}$ and the mobilities $\mu_e$ were inferred from transport data using contacted samples from the same wafers.

All the magnetization data presented here were obtained after illumination with IR and red light-emitting diodes, which was essential to quench nonequilibrium currents (NEC's) induced by the electromotive force $\mathcal{E} = -d\phi/dt$ as the magnetic field is swept through integer $\nu$ [4,9]. Without illumination, the NEC's were also found to decrease with increasing sample mobilities, indicating that their size is mainly controlled by the mobility [10].

To obtain the 2DEG magnetization, a 5th order polynomial fit to the total signal was subtracted from the raw data. This fit represents the background signal, which arises mainly from the magnetic moment of the magnetometer and is about 100 times larger than the 2DEG magnetization. With this procedure, the magnetization curves are reversible and reflect the thermodynamics of the 2DEG.

The magnetization and the Hall conductance of the Camb95 sample ($n_{2D} = 4.9 \times 10^{11}$ cm$^{-2}$ and $\mu_e = 2.3 \times 10^6$ cm$^2$/V s) at a temperature of 1.2 K are plotted in Fig. 1. The magnetization curve is remarkably close to a sawtooth, where the diamagnetic steps arise at even integer $\nu$, i.e., precisely in the middle of the Hall plateaus, as expected for a measurement carried out at a constant number of particles [1–3]. The oscillation amplitude at low $\nu$ is near $2N\mu^*$, the expected value for noninteracting electrons ($\mu^* = e\hbar/2m^*$ is the orbital moment). This size of the magnetization jumps is also consistent with a recent optical determination of the 2DEG energy per particle [11].

The normalized amplitude of the magnetization jumps for different samples (L2M-200, Camb95, Camb35, and Camb55) is plotted as a function of $\nu$ in Fig. 2. For all samples, the magnitude of the jumps has a maximum around $4 < \nu < 6$, whose value is close to the saturation value for noninteracting electrons.

A rough analysis of our data can be carried out using a simplified version of the short-range scatterer DOS derived by Ando and Uemura [12]. We take the DOS to be constant within the energy range of the width $\Gamma$ of a LL, and also constant (but much smaller) in between LL's (in the IC gap). This model DOS decreases abruptly in the tails, contrary to a Gaussian DOS with a similar width, and accounts at least qualitatively for the sharp features in our data. The finite width of the magnetization jumps at $T = 1.2$ K is mainly due to the small residual density of states in the IC gaps. Using our simple model we observe that jumps occur when $\mu$ lies in the IC gap: the "width" $\delta B_M$ of the magnetization jumps at integer $\nu$ is therefore proportional to the number of gap states.

With a change in magnetic field of $\delta B$, the number of states which are swept through the Fermi level is $\nu \delta G_\phi$. Hence, the residual number of states in the IC gap is

$$N_{\text{gap}} = \nu \frac{\delta B_M}{B} G_\phi = N \frac{\delta B_M}{B} . \qquad (1)$$

To determine $\delta B_M$ we have taken the peak-to-peak difference in magnetic field of the magnetization jumps. At $\nu = 2$ (corresponding to $B = 12$ T), $\delta B_M$ is about 0.4 T for sample Camb95. We infer that only 3% of the states lie in the IC gap.

It is instructive to relate the magnetization jumps to the variations in chemical potential across the IC gap. Using the Maxwell relation $\mu_0(\partial M/\partial \mu)_H = (\partial N/\partial H)_\mu$ and the linear field dependence of $G_\phi$, we find

$$\frac{\Delta M}{N} = \frac{\Delta \mu}{B} , \qquad (2)$$

which includes all many-body effects. Using our simple model and Eq. (2) the amplitudes of the jumps are easily seen to be equal to $(\hbar\omega_c - \Gamma)/B$, a result which remains approximately true for more realistic models of the DOS. Hence, the effect of a finite width $\Gamma$ is to reduce the amplitude of the jumps. We conclude that in our experiment the LL width is small compared to the cyclotron energy, and, within our model DOS, $\Gamma$ is at most 30% of $\hbar\omega_c$ at low filling factors.

Our results show clearly that in high mobility samples the LL's are sharp and well separated for a low LL index, a conclusion which could not be drawn from previous thermodynamic measurements [4–7].

With increasing filling factor, the oscillation amplitude of sample "Camb95" is observed to decrease, which we attribute to the increasing effect of disorder on the LL width. On the other hand, the decrease in magnetization jumps observed at low filling factors, where the magnetization jumps are sharp, cannot be attributed to disorder. Several explanations can be invoked: (i) in this limit, the LL broadening and spacing [13] may be affected by many-body interactions; (ii) for long-range scatterers, one expects the LL broadening to increase when the LL index decreases [12]; (iii) a maximum of $\Delta M$ and hence of $\Delta\mu$ could indicate that the LL's are not equally spaced. This may be the case if the coupling between LL's attached to the different electric subbands of the heterojunction is enhanced in the in-plane magnetic field in the tilted-field configuration, leading to an apparent increase of the effective mass with increasing field [14].

In the Camb series, no pronounced features at odd $\nu$ (except at $\nu = 1$; see below) were observed. This may appear natural since the Zeeman energy is small compared to the cyclotron energy. However, Coulomb interactions give rise to an exchange energy and in the Hartree-Fock approximation, the energy difference $E_\uparrow - E_\downarrow$ between states with spin $\uparrow$ and $\downarrow$ in the highest LL is proportional to the difference in occupation between the $\uparrow$ and $\downarrow$ states [15–17]. This quantity can become much larger than the Zeeman energy and depends again explicitly on the sample orientation since the number of available states per unit area in a LL is $B\cos\theta/\phi_0$. As a result the torque experienced by the sample should also have sizable discontinuous jumps at odd filling factors.

In the upper panel of Fig. 3, the magnetization oscillations and the Hall resistance of the L2M-200 sample ($n_{2D} = 4 \times 10^{11}$ cm$^{-2}$, $\mu_e = 1 \times 10^6$ cm$^{-2}$/V s) at $T = 1.2$ K, are plotted as a function of $\nu$. The striking observation in this sample is that the spin splitting of the LL's is clearly resolved (both at 4.2 and at 1.2 K

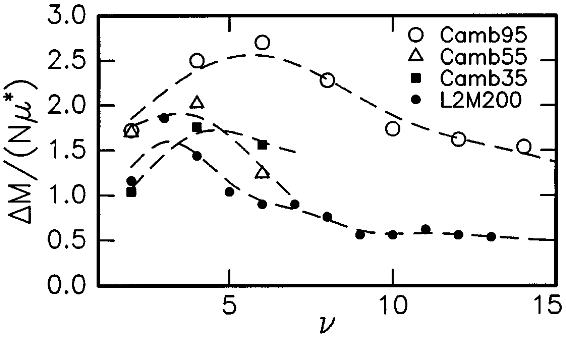

FIG. 2. Amplitude of the magnetization jumps as a function of $\nu$ for four different samples. Sample Camb55 has $n_{2D} = 3.5 \times 10^{11}$ cm$^{-2}$ and $\mu_e = 1.4 \times 10^6$ cm$^2$/V s. The other samples are described in the text. A maximum is observed between $\nu = 4$ and $\nu = 6$. These jumps are related to the jumps in chemical potential by Eq. (2).

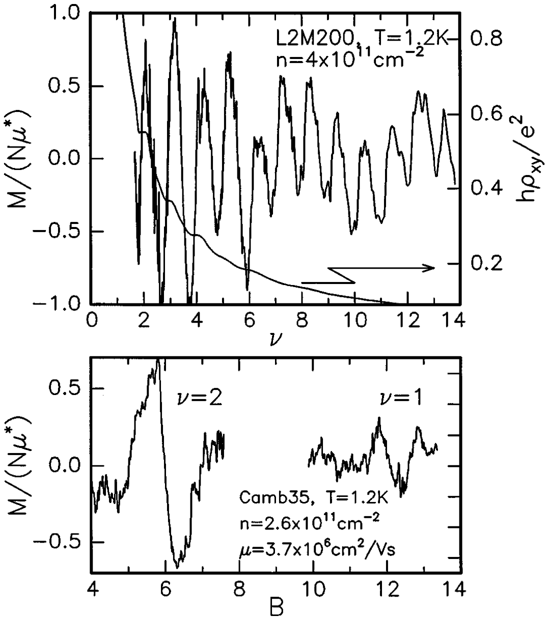

FIG. 3. Top: Plot of the magnetization oscillations observed in the L2M-200 $\delta$-doped sample and of the Hall resistance as a function of $\nu$. The spin splitting is clearly resolved, and the jumps at odd $\nu$ are of comparable size to the even ones. Bottom: Magnetization of Camb35 sample at small filling factors; a jump at $\nu = 1$ is clearly resolved.

as well as before illumination). The carrier density of this sample was not only measured using conventional transport measurements but also by a contactless torsional oscillator technique [18] relying on the NEC's mentioned before. All the experimental values for $n_{2D}$ agree to within a few percent.

The observed behavior here is qualitatively in agreement with several calculations [16,19] for the magnetization and the chemical potential of an interacting 2DEG in the presence of disorder. Nevertheless, it is a surprising result, since the transport data show only weak features at odd $\nu$ above $\nu = 5$ (Fig. 3, top panel) but the peak-to-peak magnetization amplitudes at even and odd $\nu$ are similar at least up to $\nu = 12$. Moreover, the Hall plateaus and the minima in $\rho_{xx}$ observed at odd-filling factors in the transport measurement on the Camb and L2M samples are similar, and yet the magnetization jumps at odd $\nu$'s are completely different. This demonstrates that other physical parameters besides the sample mobility are essential to the thermodynamical properties of the 2DEG at odd $\nu$'s. The long-range behavior of the disorder potential produced by the dopants may be relevant, and a systematic experimental study is needed to identify precisely the underlying physics.

Finally, we present our experimental results in the region around $\nu = 1$. In the lower panel of Fig. 3 (sample Camb35, $n_{2D} = 2.6 \times 10^{11}$ cm$^{-2}$, $\mu_e = 3.7 \times 10^6$ cm$^2$/V s), a magnetization jump at $\nu = 1$ is clearly resolved. This jump has been observed in many samples with $\mu \geq 10^6$ cm$^2$/V s, and its magnitude is always small, never exceeding 30% of the saturation value $\Delta M = 2N\mu^*$, which is consistent with optical measurements [11]. Using these values, we infer a $g$-factor enhancement of the order of 18, which is also consistent with other experimental data [7].

Although the amplitude ratio between the jump at $\nu = 1$ and the jump at $\nu = 3$ is not measured, the observation of a *small* amplitude at $\nu = 1$ could be the consequence of a reduction of the IC gap. This could simply mean that there are available many-body states at a significantly lower energy than the single spin-flip energy. Evidence for such states at $\nu = 1$ (known as Skyrmions), exists from experiment [20], but unfortunately there are at present no precise theoretical estimates for the anisotropic contribution of the Skyrmion energy to the magnetization jump.

In conclusion, our magnetization study on high mobility 2DEG's reveals a number of novel features: (a) a pronounced gap between incompressible and compressible states in which only a few percent of the total number of states are present, (b) a nonmonotonous dependence of the energy gaps between LL's, (c) a huge enhanced spin splitting of the LL's in $\delta$-doped samples, and (d) a small magnetization jump at $\nu = 1$ in very high mobility samples.

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