Magnetization of the Fractional Quantum Hall States

I. Meinel, T. Hengstmann, D. Grundler, and D. Heitmann
Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Universität Hamburg, Jungiusstraße 11, D-20355 Hamburg, Germany

W. Wegscheider and M. Bichler
Walter Schottky Institut, Technische Universität München, Am Coulombwall, D-85748 Garching, Germany
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We observe electron magnetism originating from fractional quantum Hall states in single-layered GaAs heterojunctions. This magnetization is entirely governed by electron-electron interaction effects. The studies were performed at temperatures between 0.3 and 7 K on gated high-mobility two-dimensional electron systems. We observe oscillations in the magnetic moment at various fractional filling factors, both for $\nu < 1$ and $\nu > 1$, which persist up to 3.8 K. Most prominent features are found at filling factors $\frac{1}{3}$, $\frac{2}{3}$, $\frac{4}{5}$, and $\frac{8}{5}$. In addition, an intrinsic strongly asymmetric magnetization around $\nu = 1$ is observed. [S0031-9007(98)08279-9]

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The magnetization is one of the most fundamental properties of matter and is, besides spin and orbital magnetism, also governed by many-body effects. Many-body interaction effects can be studied advantageously in two-dimensional electron systems (2DES) as realized in a semiconductor heterostructure, which allows one to tune the 2D electron density N_S and, in a magnetic field B, the filling factor $\nu = N_S/(eB/h)$. Interaction effects lead to a renormalization of the energy states, as it is well known for the exchange enhanced spin gaps at odd filling factors and less well known also for the Landau gap at even ν [1]. A most interesting aspect, which has attracted a broad interest in the last years, is the formation of the fractional quantum Hall states (FQHS's) at filling factors p/q with p integer and q odd by electron-electron interaction [2]. As introduced in the pioneering works of Landau [3] and Peierls [4] in the early 1930s, the magnetization M of conduction electrons has to be considered as a thermodynamic quantity

$$M = -\left(\frac{\partial U}{\partial B}\right)\bigg|_{N_S}, \tag{1}$$

and should thus directly reflect the renormalization effect. U denotes the free energy and N_S is the electron density. In particular, it should give rise to a novel type of magnetization for the FQHS's which is entirely governed by the many-body interactions.

However, experiments on 2DES magnetization are rather rare and quite a challenge due to the inherent small electron number. It lasted for quite a long time until the first signature of the Landau quantum oscillatory magnetization, i.e., the de Haas–van Alphen (dHvA) effect, was experimentally proven by Eisenstein *et al.* for conduction electrons in a 2DES [5]. Only very recently, it was possible to resolve the exchange induced enhancement of the spin magnetization at odd ν [6,7]. In very high-mobility samples also the sawtooth-like magnetization [7] was proven in agreement with the 65-year old prediction [4]. Various recent theoretical [8] and experimental works [9] show that in the vicinity of FQHS's additional ground state configurations like skyrmions and spin waves exist, which are so far only partly understood, and their magnetization is not known. The physics of skyrmions and the FQHS's are often probed by activated transport [10] or optical excitation spectroscopy [11–13]. However, the former method measures the mobility gap, and within the latter technique, the evaluation has to consider carefully the initial and final state interaction of the electron-hole system which is inherently produced in optical measurements. We have performed direct magnetization experiments on single-layered high mobility $Al_{0.34}Ga_{0.66}As$-GaAs heterostructures at low density N_S. We have observed the magnetization of numerous FQHS's that persist up to higher temperatures than observed in transport measurements on the same sample. In addition, we find a strong signal of asymmetric shape in the vicinity of $\nu = 1$ which decreases with increasing temperature and decreasing N_S. Such a behavior is not present in transport or in optical measurements on $\partial U/\partial B$. This demonstrates that the direct measurement of the magnetization gives information which has not been observed in former studies.

We have investigated samples from four different wafers. The two samples with the highest mobility showed FQHS's. Here we discuss the sample which shows the richest structures. It was a single-layered $Al_{0.34}Ga_{0.66}As$-GaAs heterostructure, where a $3 \times 3.4\ \text{mm}^2$ mesa was covered by a metal gate. After illumination and for zero gate voltage the 2DES density was $0.97 \times 10^{11}\ \text{cm}^{-2}$ and the mobility $\mu = 8 \times 10^6\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ at 0.3 K. Via the gate voltage we could tune N_S down to zero. Magnetization studies at high fields up to 8 T have been performed using a very sensitive dynamic method, originally proposed by *Shoenberg*

[14]. We have applied a small modulation of the gate voltage (4–10 mV) and measured the derivative of the magnetization $\partial M/\partial N_S$ via a superconducting pickup loop surrounding the 2DES. This loop was connected to a low-noise superconducting quantum interference device (SQUID). The setup exhibits a high sensitivity ($\approx 10^{-14}$ J/T) and has been described in detail in Ref. [6]. It was calibrated to an absolute magnetic scale using a current loop of known magnetic moment instead of the 2DES. The temperature T of the sample could be varied between 0.3 and 7 K.

In Fig. 1a we present the raw SQUID-output data $\partial M/\partial N_S$ as a function of N_S for various fixed magnetic fields B. Starting from $N_S = 0$ and zero signal strength, first an onset of the magnetic signal appears and then spikelike oscillations occur. These spikes can be identified with integer filling factors. The most prominent signals are found for even $\nu = 2, 4, 6$. Smaller ones belong to the odd filling factors $\nu = 1, 3, 5$. Increasing B in Fig. 1a results in a shift of the spikes to higher N_S. If we integrate the measured signals $\partial M/\partial N_S$ with respect to N_S and extract the oscillatory part of the magnetization, we get a sawtooth-like behavior at even and odd filling factors. Examples at two different fields B are shown in Fig. 1b. This behavior is similar to what was found for the dHvA effect in other high-mobility 2DES where torque magnetometry was used. This latter technique offers the advantage of probing the magnetization directly [7]. As in Ref. [7] we also have to account for a magnetic background by subtracting a polynomial fit from the integrated data, here of second order. In agreement with theoretical predictions for the oscillatory behavior of M, the amplitude of the discontinuity at the Landau gap increases with increasing N_S, i.e., increasing filling factor ν. We point out that, while monitoring $\partial M/\partial N_S(N_S)$ in Fig. 1a, N_S is not the only parameter which is increased from left to right; at the same time, we get an improvement in electron mobility μ. From the sawtooth-like oscillations of the magnetization M in Fig. 1b we conclude that the prepared 2DES comes close to the ideal system without disorder broadening of the Landau levels. In this case the chemical potential χ exhibits a jump whenever it crosses a gap in the energy spectrum, resulting in a discontinuity in $M(B)$. Our dynamic method monitoring $\partial M/\partial N_S$ is very sensitive to abrupt changes in χ, since thermodynamic relations lead to

$$\left(\frac{\partial M}{\partial N_S}\right)\bigg|_B = \left(\frac{\partial \chi}{\partial B}\right)\bigg|_{N_S} . \tag{2}$$

From this it is obvious that spikes in Fig. 1a at $\nu = 1, 3, 5$ are smaller as compared to $\nu = 2, 4, 6$ due to the smaller energy gap between—exchange enhanced—spin-split Landau levels.

If we extend these experiments to higher magnetic fields, we find additional features. For $B = 4$ T, we observe a structure marked by the arrow in Fig. 1a which can be identified with the filling factor $\nu = \frac{5}{3}$. For $B > 6$ T, as shown in Fig. 2a, we clearly observe the $\nu = \frac{1}{3}$ and $\nu = \frac{2}{3}$ FQHS. If we integrate the $\partial M/\partial N_S$ data the same way as before for the integer filling factors, we also get a sawtooth-like behavior for the magnetization M of the fractional quantum Hall states (Fig. 2b). According to Eq. (1), this corresponds to a discontinuous change in the magnetic field dependent ground state energy at the FQHS's. The signal strength in $\partial M/\partial N_S$, representing the ground state energy change at these fractionals, is

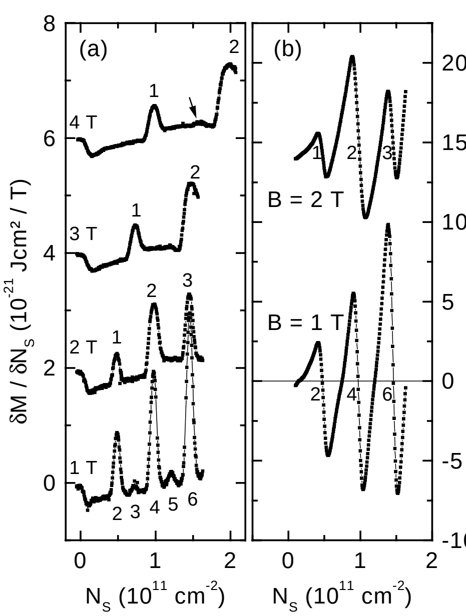

FIG. 1. (a) Measured $\partial M/\partial N_S$ as a function of the carrier density N_S for different magnetic fields at 0.3 K. Filling factors are labeled by numbers. Curves are shifted along the vertical axis for clarity, all starting from zero signal strength at $N_S = 0$. The arrow marks the FQHS $\nu = \frac{5}{3}$. (b) Sawtooth-like oscillations of the sample's magnetization, obtained by integration of the 1-T and the 2-T data in (a).

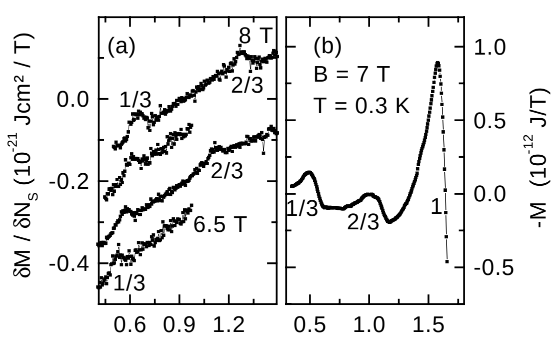

FIG. 2. High-field data on $\partial M/\partial N_S$, revealing the magnetism of the FQHS's: (a) $\frac{1}{3}$ and $\frac{2}{3}$ observed for $B \geq 6.5$ T, B is incremented by 0.5 T. Curves are offset for clarity. (b) Sawtooth-like magnetization of the fractional states, obtained from data in (a) by integration.

about a factor of 30 less than for the even integer filling factors, i.e., the Landau gap discontinuity.

If we integrate, for example, the $B = 7$ T data in the regime $N_S = 0$ to 1.5×10^{11} cm^{-2}, where the background can reliably be determined, we find for $\nu = \frac{1}{3}$ ($\frac{2}{3}$) a magnetization $\Delta M = 0.32\mu_B^*$ ($0.12\mu_B^*$) per electron. (Here, $\mu_B^* = 1.38 \times 10^{-22}$ J/T is the effective Bohr magneton for electrons in GaAs.) The estimated error, using different backgrounds, is $\pm 20\%$. In Ref. [1] for slightly different conditions ($T = 0.5$ K, $N_S = 1.5 \times 10^{11}$ cm^{-2}) a value of $\Delta M = 0.3\mu_B^*$ was calculated for $\nu = \frac{1}{3}$. Because of these different conditions one cannot absolutely compare these values, however, they are of the same order.

Interestingly, in Fig. 2 the absolute signal amplitudes at $\nu = \frac{1}{3}$ and $\frac{2}{3}$ are almost the same, though N_S differs by a factor of 2. This is in contrast to the magnetic behavior observed at the Landau and also at the exchange enhanced spin gaps, where for fixed B the signal strength always increases with increasing ν with a characteristic scaling for each type of these gaps (compare, e.g., the behavior of the odd filling factors in Fig. 1a as a function of N_S). Figure 2 indicates that in the case of the FQHS's the nature of the magnetization and the corresponding energy gap is markedly different for each of these fractionals. If we consider the absolute values per electron, we find a difference of at least a factor of 2 between the energy gaps $\Delta M \times B$ at $\nu = \frac{1}{3}$ and $\frac{2}{3}$. One reason for the reduction at $\frac{2}{3}$ might be the smaller degree of spin polarization as compared to the FQHS at $\nu = \frac{1}{3}$, which is predicted to be fully spin polarized [2]. From the values of ΔM per electron we can now calculate the corresponding thermodynamic energy gaps $\Delta M \times B$ for the FQHS's and find for $T = 0.3$ K and $B = 7$ T a value of 1.9 meV at $\nu = \frac{1}{3}$ and of 0.7 meV at $\frac{2}{3}$. From excitation spectroscopy, a smaller gap value of about 1.2 meV at 10 T was found for $\nu = \frac{1}{3}$ [13].

In order to explore the magnetization in the fractional quantum Hall regime in greater detail, we have performed a series of measurements, where we have increased the magnetic field stepwise in very small increments of 25 mT at various fixed N_S and temperatures T. Here, our technique for testing the thermodynamics on fractionals is advantageous. As expected from "classical" theories, i.e., without considering FQHS's, $\partial M/\partial N_S$ as a function of B decreases to very small signal amplitudes *between* the integer filling factors [compare curve (I) in Fig. 3a]. Therefore even very small oscillatory changes in the magnetic moment due to FQHS's can be well resolved. This is an improvement with respect to activated transport or the optical measurements where small deviations have to be discriminated on large background signals such as the longitudinal 2DES resistance or the electron-hole recombination energy. Note, that the magnetic background in our sample at N_S between 0.97 and 1.6×10^{11} cm^{-2} is near to zero (compare Fig. 1a) and is found to be constant for a fixed carrier density as a function of the magnetic field. Experimental results plotted versus $1/B$ are shown in Fig. 3. In order to identify the observed structures we have drawn the calculated positions of various possible fractionals as determined from the $1/B$ period of the peaks at integer filling factors. Local maxima emerging in $\partial M/\partial N_S$ at fractional filling factors at a base temperature of 0.3 K are found to depend critically on the carrier density in Fig. 3a. Slightly increasing N_S results in resolving features near $\frac{4}{5}$ and $\frac{2}{3}$ in addition to the earlier observed $\frac{1}{3}$. In curve (I) it is difficult to identify the exact positions at $\nu < 1$ due to the smaller signal-to-noise ratio at this low N_S. At filling factors greater than $\nu = 1$ the magnetic behavior is complicated by a shoulder which will be discussed in detail below. Starting from small N_S in Fig. 3a one observes different features in the vicinity of $\nu = \frac{9}{7}$ and $\frac{4}{3}$ merging into the shoulder with increasing N_S. Also a peak near $\nu = \frac{8}{5}$ becomes more prominent.

The observation of this magnetic shoulder for $1 < \nu < 2$ is totally unexpected. It might, at first sight, be considered as an asymmetric "broadening" of the $\nu = 1$ signal.

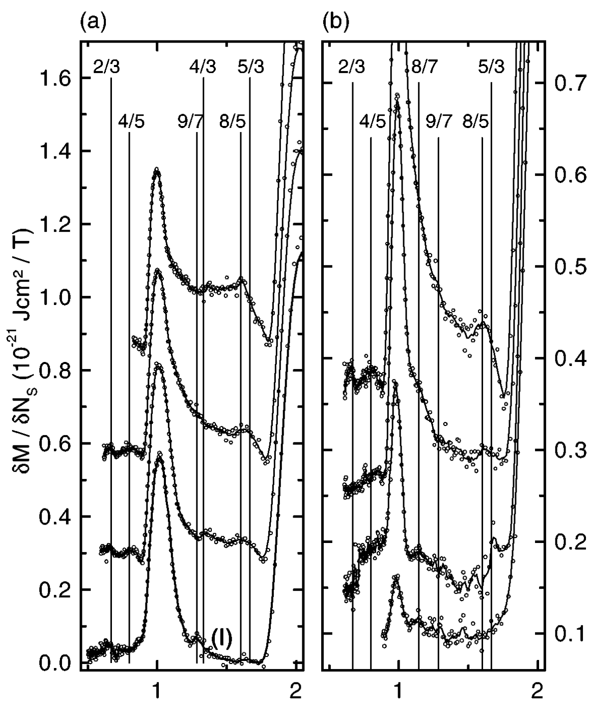

FIG. 3. (a) Magnetization $\partial M/\partial N_S$ as a function of $1/B$ at $T = 0.3$ K, measured for four different N_S, from bottom to top: (0.97, 1.08, 1.18, and 1.6) $\times 10^{11}$ cm^{-2}. Curves are offset for clarity by 0.25×10^{-21} J cm^2/T. (b) SQUID signals for $N_S = 1.18 \times 10^{11}$ cm^{-2} for different T, from bottom to top: 3.8, 2.6, 1.7, and 0.3 K. Curves are offset for clarity. In all figures the inverse magnetic field is shown in terms of $\nu = hN_S/eB$ for the different N_S. Vertical lines indicate the positions of fractionals calculated from the $1/B$ period.

That this behavior is intrinsic and of importance becomes obvious from the temperature dependence in Fig. 3b. In contrast to what might be expected intuitively, one finds that the signal at $\nu = 1$ sharpens as the temperature is *increased* from 0.3 to 2.6 K. This asymmetric behavior is considered to be an intrinsic property of a very high mobility and homogeneous 2DES since our experiments on further samples from different wafers exhibiting a somewhat lower μ but similar $N_S = 1.2 \times 10^{11}$ cm^{-2} showed $\nu = 1$ signals which were symmetric in contrast to the asymmetric shape found in our best sample. In Fig. 3b it is most striking that the magnetization of fractional states persists up to 3.8 K and that above 2 K, a new feature near $\frac{8}{7}$ is resolved when the shoulder has diminished. At these temperatures, we cannot extract the FQHS's from the transport data which we have taken under the same conditions on the sample. We note that the magnetization of the integer filling factor $\nu = 1$ could even be observed up to $T \approx 6$ K (not shown here).

In the following, we discuss the occurrence of the distinct magnetic shoulder. If we analyze the shape of the curves in detail, we find that the additional magnetization is such that it enhances the signal for $\nu > 1$, i.e., it adds a positive contribution, and that it diminishes the magnetic signal at ν very near but slightly below $\nu = 1$ with respect to an assumed symmetrical shape, i.e., as observed for higher T or smaller N_S. The origin of this additional asymmetric magnetization around $\nu = 1$ is not known at present. Of course, one is tempted to speculate that this has its origin in one of the several additional ground state configurations that are discussed in this filling factor regime, in particular skyrmions and spin waves [8]. Although experiments in agreement with theories show clear evidence for skyrmion formation [9,10,12], there are still many features under debate, in particular in what B and N_S regime they exist for a given Zeeman energy [2]. So far, there is no theoretical treatment of the contribution originating from spin waves and skyrmions to the magnetization. However, one can say that in a skyrmion-type model, one should expect a rapid spin-depolarization on either side of $\nu = 1$, whereas we see a clear magnetic asymmetry.

In conclusion, we have presented measurements in the extreme quantum limit which probe the ground state energy of a high-mobility low-dimensional electron system. By monitoring $\partial M/\partial N_S$, we have observed the magnetization of the fractional quantum Hall states. We find that it is possible to explain the present data on the oscillatory magnetization at $\frac{1}{3}$ within the model proposed in Ref. [1]. At $\frac{2}{3}$, the signal per electron is reduced as compared to $\frac{1}{3}$. This seems to be the precursor of magnetic spin depolarization in this FQHS. However, the distinct asymmetric behavior of the magnetization around $\nu = 1$ has neither been observed in experiments nor been predicted theoretically before. This demonstrates that direct measurements of the magnetization offer additional insight into the many-body electron system which is not present in activated transport or optical experiments.

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