Magnetization and dissipation measurements in the quantum Hall regime using an integrated micromechanical magnetometer

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We present low-temperature (365 mK) magnetization measurements of $40\times100\,\mu\mathrm{m}^2$ mesas of two dimensional electron gases (2DEGs) integrated into micromechanical cantilever magnetometers. Over a wide range of applied magnetic field, the cantilever resonance frequency reveals the thermodynamic magnetization of the 2DEG. Upon illumination of the sample, we observe the appearance of both cyclotron and Zeeman gaps in the density of states. We attribute this to the narrowing of the disorder-broadened Landau levels as the carrier concentration is increased. Additionally, we observe strong peaks in the dissipation of the system at small integer filling factors which we associate with eddy currents excited by the cantilever motion. [S0021-8979(00)36908-0]

Magnetization measurements of a two dimensional electron gas (2DEG) can provide information about its magnetic field dependent density of states which is not readily accessible through other techniques. Because of the importance of the quantum Hall effect in exploring the physics of two dimensional systems and in metrology, there is considerable interest in developing new experimental techniques for probing its properties with greater sensitivity and over a broader range of parameters. Here, we present the first measurements from a micromechanical oscillator containing an integrated 2DEG sample which show the presence of both cyclotron and Zeeman gaps in the thermodynamic magnetization of the 2DEG.

The main challenges in measuring the magnetization of a 2DEG are the inherently small number of electrons in the sample and the background introduced by the sample substrate. Torsional magnetometry (which is sensitive only to the anisotropic components of the magnetization) provides a promising approach to the latter problem, as the two dimensional nature of the electrons requires the orbital (and to a large degree the spin) contribution to the magnetization to be fixed normal to the sample surface. Achieving the sensitivity necessary to measure the thermodynamic magnetization of a 2DEG is a challenge in the design of torque magnetometers. In previous torsional oscillator measurements on high mobility 2DEGs, the thermodynamic magnetization was masked by nonequilibrium eddy currents excited in the sample by electromotive forces (EMFs) induced by the oscillator motion,[1] or by piezoelectric fields created by using the entire sample substrate as the torsion element.[2] Measurements using dc torque (and rf superconducting quantrum interference device)[3] techniques have been successful in observing the thermodynamic magnetization,[4–6] but can be complicated by eddy currents induced by ramping the applied field H. Even when these eddy currents can be avoided, the large size of the magnetometer required to support the sample substrate limits the sensitivity and introduces a background up to 100 times the magnetization of the 2DEG.[6,7] In addition, dc torque measurements must be performed with H applied at some appreciable angle away from the 2DEG normal (typically $\sim30°$) which can affect the spin character of the quantum Hall states. In contrast, torsional oscillator measurements can be performed with H at any angle relative to the 2DEG.

In order to address the problems of background, sensitivity, and eddy currents, we have integrated small 2DEG samples directly into micromechanical GaAs cantilevers which serve as torsional oscillators. The moment sensitivity demonstrated in similar structures[8] is orders of magnitude greater than those of magnetometers used to study 2DEGs to date. This allows us to study smaller samples, thereby reducing the EMF. As will be shown below, the background signal from the lever can be smaller than that of the 2DEG. To integrate a 2DEG into a micromechanical GaAs cantilever, an MBE-grown single heterojunction GaAs/$Al_{0.3}Ga_{0.7}As$ 2DEG (and 7000 Å GaAs/$Al_{0.8}Ga_{0.2}As$ buffer) is wet etched into $40\times100\,\mu\mathrm{m}^2$ mesas. In a second lithography step, $50\times320\,\mu\mathrm{m}^2$ cantilevers are wet etched out of an underlying 1000 Å thick GaAs epilayer so that the 2DEG mesas lie at the ends of the cantilevers. The levers are mechanically freed using a process described earlier.[8] The MBE growth structure as well SEM photo of two finished cantilevers with 2DEG mesas are shown in Fig. 1. Transport characterization of a Van der Paaw pattern wet etched into a chip from the same wafer (but not mechanically freed) shows a carrier concentration n_s and mobility μ before (after) illumination by a blue LED of $1.4\times10^{11}(3.3\times10^{11})\,\mathrm{cm}^{-2}$, and $4\times10^5(8\times10^5)\,\mathrm{cm}^2/\mathrm{V\,s}$, respectively. Because the mesa containing the 2DEG is substantially thicker than the rest of the lever (and located at the lever's end), the strain due to the bending of the lever should be concentrated well away from the mesa,

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GaAs	100 Å
$Al_{0.3}Ga_{0.7}As$	700 Å
$Al_{0.3}Ga_{0.7}As$	400 Å
GaAs	6000 Å
$Al_{0.8}Ga_{0.2}As$	1000 Å
GaAs	1000 Å
$Al_{0.8}Ga_{0.2}As$	3000 Å
SI GaAs	Substrate

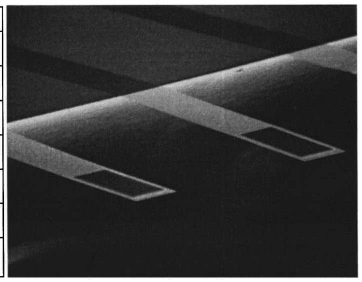

FIG. 1. Left: MBE growth structure. Si dopants are indicated by the dashed line. The 2DEG forms at the AlGaAs/GaAs interface just below the Si dopants. The cantilever is fabricated from the 1000 Å thick GaAs epilayer. The sample mesa contains all the epilayers above the cantilever (Right) SEM photo of two finished cantilevers. The levers are 320 μm long, 50 μm wide, and 0.1 μm thick. The rectangular mesas containing the 2DEG are 100 μm long and 40 μm wide.

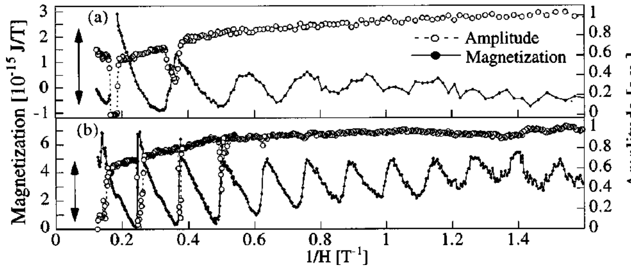

FIG. 2. (a) Magnetization M (●) of a $40\times100\ \mu m^2$ mesa of a single 2DEG at $T=365$ mK. Also shown is the amplitude of the lever oscillation (○) for a constant driving force. The jump in M at 0.18 T^{-1} occurs at $\nu=2$. (b) The same as (a) but after illumination by a blue LED. The jump in M at 0.24 T^{-1} occurs at $\nu=4$. The arrows in both (a) and (b) correspond to $2\mu^*$ per electron. The ordinate $(1/H)$ is the same for both (a) and (b).

thereby ensuring that piezoelectric fields do not disturb the 2DEG.

The cantilever is mounted in the vacuum space of a ^{3}He insert with an 8 T superconducting solenoid whose field is normal to the 2DEG (to within a few degrees). The cantilever is driven by a piezoelectric crystal and its displacement is measured with a fiber optic interferometer using a 1300 nm laser diode. This is just below the typical threshold for exciting persistent photoconductivity in the 2DEG, so as a precaution the fiber is pointed near the base of the cantilever in order to minimize the illumination of the 2DEG. Typically we couple ~5 μW of laser power into the cryostat and find that n_s (as determined by the position in H of the magnetization oscillations shown below) varies by less than a few percent over several days. At low temperature ($T<4$ K) these levers have resonance frequencies (for the lowest flexural mode) at $H=0$ of $\nu_0[0]\sim800$ Hz, and quality factors Q of ~30 000. Levers of similar dimensions with a wide variety of different integrated samples have all shown $10\,000<Q<15\,000$.[8] We attribute the increase in Q seen here to the roughly ten fold increase in the motional moment of inertia $I_{\rm eff}$ caused by the large sample mesa. This is consistent with the expected $I_{\rm eff}^{1/2}$ scaling of Q for constant intrinsic dissipation and torsional spring constant γ. We determine $\gamma=2.5\times10^{-11}$ N m/rad from the relation $2\pi\nu_0=(\gamma/I_{\rm eff})^{1/2}$,[9] where we calculate $I_{\rm eff}$ from the dimensions of the lever and mesa.

The equilibrium magnetization $M_{\rm eq}$ of a 2DEG is due to currents which circulate near the edges of the sample. These currents are generated by the combination of the confining electric field at the edges of the sample and the perpendicular magnetic field H. As H is increased, the Fermi energy E_f moves through the Landau levels (LLs) at a rate inversely proportional to the density of states at E_f. As E_f moves through a given disorder broadened LL, the degeneracy of the edge channels (and hence the circulating current) below E_f gradually increases, thereby increasing $M_{\rm eq}$. At integer filling factor $(\nu)E_f$ jumps down to the next lowest LL, depopulating the edge channels lying between the two LLs, which causes a sharp decrease in $M_{\rm eq}$. As the broadening of the LLs becomes smaller than their spacing, this decrease becomes shaper and the jump in $M_{\rm eq}$ approaches a magnitude of $-2\mu^*=-e\hbar/m^*$ per electron for even integer ν and $-g_{\rm eff}\mu_B$ for odd integer ν. This contribution to the magnetization always points normal to the 2DEG, and for odd integer ν contains the effective electronic g factor $g_{\rm eff}$. Nonequilibrium currents may also circulate in the sample, due for example to the EMF from the sample motion or from ramping H. Circulating currents (both equilibrium and nonequilibrium) provide an additional restoring torque $\tau=-MH\sin\theta$ to the lever, where M is the moment due to the circulating current and θ is the angle between H and the lever normal. For $\theta\ll1$ this torque results in a shift in ν_0 given by $\Delta\nu_0\equiv\nu_0[H]-\nu_0[0]=MH\nu_0[0]/2\gamma$. By driving the lever in a phase-locked loop (PLL), we measure ν_0 (and hence M) as a function of H.

In Fig. 2(a) we plot $M=2\Delta\nu_0\gamma/H\nu_0[0]$ as a function of $1/H$ for an unilluminated sample at $T=365$ mK. A small background linear in H and roughly half the size of the 2DEG magnetization has been subtracted. Also plotted is the amplitude of the lever oscillation for a constant drive amplitude (the maximum amplitude corresponds to ~150 nm displacement of the 2DEG). The oscillations of M are periodic in $1/H$ with an amplitude that approaches μ^* per electron at large H. The arrow in Fig. 2(a) corresponds to μ^* using a value for n_s which assumes that the magnetization jump at 0.18 T^{-1} (5.5 T) corresponds to $\nu=2$ (see below). At lower fields, the oscillations are roughly sinusoidal, but become increasingly asymmetric with increasing H. This is consistent with the LLs having a finite width in energy which becomes smaller than the cyclotron splitting only for the largest fields (note that $k_BT<\hbar\omega_c$ for $H>0.25$ T).[10] The gap in the data near 0.18 T^{-1} is caused by the substantial dissipation present near the lower integer values of ν, which at $\nu=2$ disrupts the PLL.

We note that the value of n_s determined from Van der Paaw measurements would suggest that the jump in M at 0.18 T^{-1} corresponds to $\nu=1$; however, the spin-resolved states (corresponding to odd-integer ν) only begin to become apparent after illumination of the samples, when μ is substantially increased. Assigning the jump at 0.18 T^{-1} to $\nu=2$ implies a substantial increase of n_s in the processed sample. This increase may be due to the very weak illumination of the sample by the interferometer laser or to the processing. Typically the effect of an additional nearby sur-

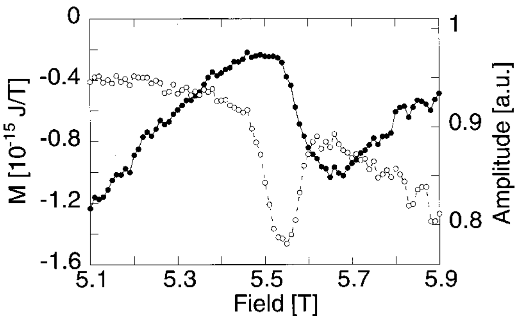

FIG. 3. Magnetization (●) and amplitude (○) of a different sample (after illumination) from the same wafer as Fig. 2, at $T=350$ mK. The jump at 5.55 T corresponds to $\nu=3$.

face (e.g., at the bottom of the lever) would be to deplete the 2DEG, though any such effect should be minimized by its large distance (~8000 Å) from the 2DEG. It is possible that the strain in the sample mesa due to the AlGaAs/GaAs lattice mismatch is released by mechanically freeing the heterostructure and may create piezoelectric fields which transfer carriers from the dopants to the 2DEG.

In Fig. 2(b), we plot M and lever amplitude for the same sample as in Fig. 2(a) after illumination by a blue LED. In this case, no background has been subtracted. The oscillations of $M[1/H]$ have sharpened into a sawtooth pattern indicative of a gap between Landau levels. The assignment of $\nu=4$ to the magnetization jump at 0.24 T^{-1} (4.1 T) corresponds to within 15% of the postillumination value for n_s from Van der Paaw measurements. In addition to magnetization jumps at even ν, a small jump at $\nu=3(0.19\,\mathrm{T}^{-1})$ and a kink at $\nu=5(0.31\,\mathrm{T}^{-1})$ are also visible. In addition to sharpening the sawtooth shape of $M[1/H]$, illuminating the sample makes the magnetization oscillations observable out to much higher ν (>30 in this sample) than in the unilluminated case.

Figure 3 shows the jump in M at $\nu=3$ ($H=5.55$T) for another sample (after illumination) from the same wafer. The upward trend of $M[H]$ represents the shoulder of the $\nu=2$ feature (not shown). By extrapolating the linear $M[H]$ on either side of the $\nu=3$ jump, we find the size of the jump to be 1.4×10^{-15} J/T, or $9.4\mu_B$ per electron. This implies $g_{\mathrm{eff}}=9.4$, an enhancement of 23 times over the bare electronic g factor in GaAs, consistent with other magnetization measurements.[6,11]

The overall character of the magnetization data described thus far is consistent with M_{eq} calculated within the single-electron picture,[10] including an enhanced g factor. However, at values of ν for which M changes sharply, the dissipation of the lever increases [visible as dips in the amplitude data in Figs. 2(a) and 2(b) and Fig. 3]. For the largest such dips, M departs from the expected behavior for M_{eq} in the form of a positive peak. For smaller dips [$\nu=4$ in Fig. 2(a) and $\nu=8$ in Fig. 2(b)], the magnetization data appears unaffected. The gradual decrease seen in the amplitude data from 0 to 8 T is observed in all the GaAs levers we have studied to date, independent of the sample, and so does not seem to be connected with the 2DEG. Peaks in the dissipation of 2DEG samples have been observed previously in torsional oscillator measurements,[1] and attributed to the presence of eddy currents excited by the oscillator motion. We have modeled these eddy current effects using the approach outlined in Refs. 12–14 and achieved qualitative agreement with the features seen here. We will present these results in a future work.[15]

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[1] P. A. Crowell, A. Madouri, M. Specht, G. Chaboussant, D. Mailly, and L. P. Lévy, Rev. Sci. Instrum. **67**, 4161 (1996).
[2] P. L. Gammel, D. J. Bishop, J. P. Eisenstein, R. P. Hall, H. L. Stormer, A. C. Gossard, and J. H. English, Surf. Sci. **196**, 417 (1988).
[3] I. Meinel, T. Hengstmann, D. Grundler, D. Heitmann, W. Wegscheider, and M. Bichler, Phys. Rev. Lett. **82**, 819 (1999).
[4] J. P. Eisenstein, H. L. Stormer, V. Naryanamurti, A. Y. Cho, A. C. Gossard, and C. W. Tu, Phys. Rev. Lett. **55**, 875 (1985).
[5] A. Potts, R. Shepard, W. G. Herrenden-Harker, M. Elliott, C. L. Jones, A. Usher, G. A. C. Jones, D. A. Ritchie, E. H. Linfield, and M. Grinshaw, J. Phys. Cond. Matter **8**, 5189 (1996).
[6] S. A. J. Wiegers, M. Specht, L. P. Lévy, M. Y. Simmons, D. A. Ritchie, A. Cavanna, B. Etienne, G. Martinez, and P. Wyder, Phys. Rev. Lett. **79**, 3238 (1997).
[7] M. Specht, Ph.D thesis, Université Joseph Fourier, 1998.
[8] J. G. E. Harris, D. D. Awschalom, F. Matsukura, H. Ohno, K. D. Maranowski, and A. C. Gossard, Appl. Phys. Lett. **75**, 1140 (1999).
[9] J. A. Sidles, J. L. Gabrini, K. J. Burland, D. Rugar, O. Züger, S. Hoen, and C. S. Yannoni, Rev. Mod. Phys. **67**, 249 (1995).
[10] D. Shoenberg, J. Low Temp. Phys. **56**, 417 (1984).
[11] S. A. J. Wiegers, M. Specht, M. Y. Simmons, D. A. Ritchie, A. Cavanna, B. Etienne, G. Martinez, and P. Wyder, Physica B **249–251**, 115 (1998).
[12] V. T. Dolgopolov, A. A. Shashkin, N. B. Zhitenev, S. I. Dorozhkin, and K. von Klitzing, Phys. Rev. B **46**, 12560 (1992).
[13] B. Jeanneret, B. D. Hall, H.-J. Bühlmann, R. Houdré, M. Ilegems, B. Jeckelmann, and U. Feller, Phys. Rev. B **51**, 9752 (1995); B. Jeanneret, B. Jeckelmann, and B. D. Hall, IEEE Trans. Instrum Meas. **48**, 301 (1999).
[14] M. E. Cage and A. Jefferey, J. Res. Natl. Inst. Stand. Technol. **101**, 733 (1996).
[15] J. G. E. Harris and D. D. Awchalom (unpublished).