Density of States and de Haas–van Alphen Effect in Two-Dimensional Electron Systems

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The density of states of two-dimensional electron systems in GaAs/AlGaAs single-layer and multilayer heterostructures has been determined through measurements of the high-field magnetization. Our results reveal a substantial density of states between Landau levels, even in high-mobility single quantum wells. There is no existing theoretical explanation for this anomaly.

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After more than a decade of intense study of two-dimensional electron systems[1] (2DES) the density of states (DOS) in high magnetic fields has only recently come under direct scrutiny.[2,3] Current theoretical understanding of the quantum Hall effect (QHE) makes incisive assumptions about the DOS, the distinction between localized and extended electronic states being essential.[4] The remarkable phenomena of the QHE depend directly on the different topologies of these states, vividly demonstrating the unsuitability of transport measurements for DOS determinations. The DOS at the Fermi level can, however, be obtained by measurement of a thermodynamic quantity such as magnetization or heat capacity,[3] extended and localized states contributing equally in equilibrium. Early attempts[2,5] to measure the magnetization of the 2DES were hindered by insufficient sensitivity, by low-quality samples, and, in the case of ac measurements,[5] by spurious signals arising from nonequilibrium eddy currents. In this Letter we report high-precision dc measurements of the oscillatory magnetization (de Haas–van Alphen effect) of the 2DES in homogeneous, high-mobility GaAs/AlGaAs single-layer and multilayer heterostructures. From the data we have extracted important new information about the DOS, including the Landau-level widths and their magnetic field and mobility dependences. In spite of the high quality of the samples studied, we find a significant density of states between Landau levels, in agreement with recent heat-capacity measurements but far in excess of theoretical estimates.

Ideally, the DOS of a 2DES in a large perpendicular magnetic field B consists of a sequence of sharp Landau levels separated by gaps void of electronic states. If we ignore the small spin splitting of these levels, the degeneracy of each is $2eB/h$ per unit area. At absolute zero, both the Fermi level and the magnetization exhibit a saw-tooth oscillation periodic in inverse field, with discontinuities when an integral number of Landau levels are exactly filled.[6] The magnetization oscillations are of constant amplitude $M_0 = NA\mu_B^*$, where N is the fixed 2D carrier density, A the sample area, and μ_B^* the effective Bohr magneton obtained by substitution of the carrier effective mass ($m^* = 0.0665m_0$ for GaAs). In a real 2DES, with Landau levels broadened by various mechanisms, the oscillations will be attenuated and smoothed out.[7] Measurements of the amplitude and shape of the magnetization oscillations can be used, when compared to those calculated from a model DOS, to obtain information on the underlying electronic spectrum.

Our samples are modulation-doped GaAs/AlGaAs heterostructures, grown by molecular-beam epitaxy[8] on GaAs ⟨100⟩ substrates, rotated during growth to ensure homogeneity. While each single interface contains but one 2D electron layer, the multiquantum wells consist of many, well separated, layers stacked upon one another. The carrier densities, mobilities, and other structural parameters for the samples studied are listed in Table I. The last column of the table

TABLE I. Structural and two-dimensional parameters for all three samples.

Sample	GaAs well (Å)	AlGaAs Si-doped layer[a] (Å)	Periods	Low-T mobility ($m^2/V\cdot s$)	2D density (cm^{-2})	Total 2D area (cm^2)	rms $\Delta N/N$ (%) In plane	rms $\Delta N/N$ (%) Layer to layer
1	140	400	50	8.0	5.4×10^{11}	9.9	1.1	< 1.8
2	· · ·	1000	1	28.5	3.7×10^{11}	1.5	1.0	*n/a*
3	175	450	51	3.9	5.5×10^{11}	12.6	0.8	< 2.0

[a]Including undoped spacer layers.

gives the measured rms variations in the carrier density of the samples, both within the 2D plane and perpendicular to it. To determine the transverse variation of density more than a dozen independent Shubnikov–de Haas (SdH) measurements were made on small segments (0.1×1-mm^2 bars) of the molecular-beam epitaxial wafer near each magnetization sample. An upper limit on the layer-to-layer variation of the density follows from the observed width of the low-temperature (~ 0.3 K) SdH peaks. For a single 2D layer the width of these peaks, whose magnetic field positions are proportional to carrier density, is determined by the fraction of extended states. Therefore, in a multilayer sample the peak width sets an upper limit on the density variations between layers. All three samples show a well-developed QHE at low temperature.

The magnetization measurements are performed with a recently developed torsional technique.[9] The samples are mounted on a thin fiber held perpendicular to the applied magnetic field and are oriented so that the normal to the 2D plane, along which the orbital magnetic moments must lie, is tilted away from the field direction by a small angle; this geometry is depicted in the inset to Fig. 1. The measurement consists of our slowly sweeping the field and recording, by a capacitive method, the torque on the sample. These measurements are quasi dc, limited only by the sweep rate of the field (~ 1 T in 5 min). Typical angular excursions of the sample are less than 10^{-4} and the resolution is about 5×10^{-13} J/T at 10 T.

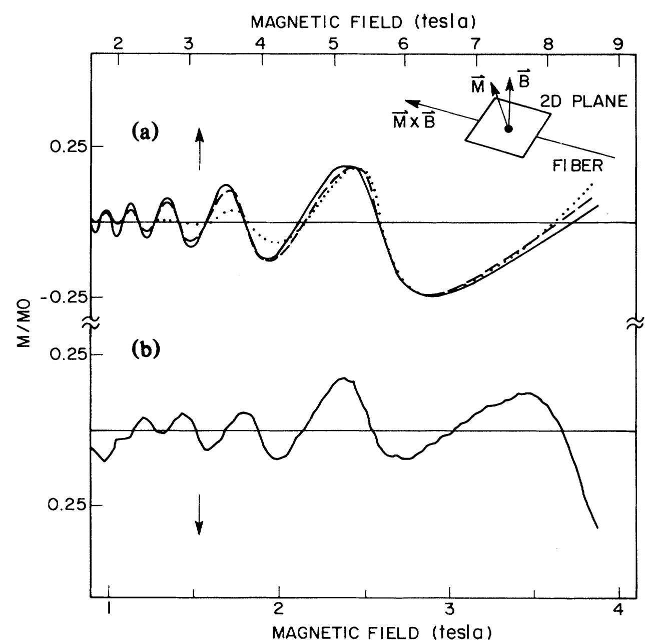

FIG. 1. Normalized magnetization for (a) sample 1 and (b) sample 2. Note different field scales. Dotted and dashed lines are fits; $\Gamma = 2.4$ meV and $\Gamma = (1\ \mathrm{meV/T^{1/2}})\sqrt{B}$, respectively. The basic geometry of the magnetization measurements is depicted at top right.

Figure 1(a) shows normalized magnetization data from sample 1, along with theoretical curves which are described below. A small, smooth background has been subtracted from the magnetometer output. In a narrow region around 5.8 T, the data represent an average of sweeps up and down in field. This was done to eliminate the effect of eddy currents[10] associated with the deep zero-resistance state in this field range ($\rho_{xx} \sim 10^{-4}\ \Omega/\square$ at 0.4 K). While the magnetization varies smoothly over the entire field range the resistivity (not shown) undergoes order-of-magnitude fluctuations as the Fermi level passes between extended and localized states. The magnetization oscillations have the correct phase and periodicity to be unambiguously identified with the de Haas–van Alphen (dHvA) effect but the amplitude and general shape indicate significantly broadened Landau levels. The lack of discontinuities suggests the absence of gaps in the DOS. Our data show no evidence of the spin contribution to the magnetization; this is not surprising given the relatively small size of the spin splittings in n-type GaAs (more than 10 times smaller than the Landau splitting, even after including g-factor enhancement effects[11]).

Figure 1(b) represents the first observation of the dHvA effect in a single layer of electrons (sample 2) by a true dc technique. A large anisotropic background magnetization, nearly linear in magnetic field, has been subtracted from the data. The magnitude and temperature dependence of this background prevent reliable determination of the 2D magnetization below 4.2 K and above 4 T. Although uncertainties in the background subtraction preclude analysis of the shape of the oscillations in Fig. 1(b), the amplitudes are well determined and can be used to gain significant information about the DOS.

Figure 2 presents a synopsis of the magnetization data on the samples listed in Table I. Here the amplitudes of the magneto-oscillations, normalized by the ideal amplitude M_0, are plotted versus magnetic field; these points provide a basis for comparison to numerical calculations. The solid lines represent theoretical envelopes for the dHvA oscillations resulting from a DOS consisting of Gaussian Landau levels:

$$D(\epsilon) = \frac{2eB}{h}\sum_{j=0}^{\infty}\frac{1}{(2\pi)^{1/2}\Gamma}\exp\left[-\frac{(\epsilon-\epsilon_j)^2}{2\Gamma^2}\right]. \quad (1)$$

In this definition Γ is the rms half-width of the levels and $\epsilon_j = (j+\frac{1}{2})e\hbar B/m^*$ is the Landau-level energy. It is clear from the figure that the observed oscillations from all three samples are considerably smaller than the ideal-gas result and require Landau-level

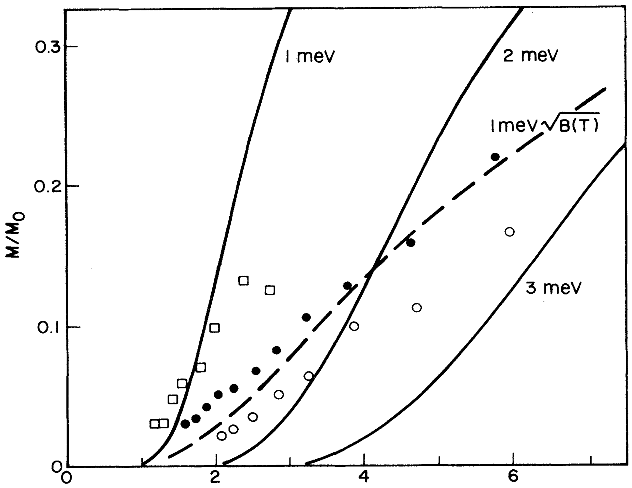

FIG. 2. Normalized dHvA oscillation amplitude vs magnetic field for all three samples: filled circles, sample 1; squares, sample 2; open circles, sample 3. The solid lines are theoretical envelopes described in text; the labels give the rms half-width of Landau levels. The dashed line is the result of assumption of a linewidth proportional to $\sqrt{B}$.

half-widths in the 1–3-meV range. It is also apparent that the model DOS with a constant Γ does not give the correct magnetic field dependence for the oscillation amplitudes. The dashed line in the figure represents a calculation in which the width Γ is assumed to vary as $\sqrt{B}$. With a prefactor of 1 $\mathrm{meV/T^{1/2}}$ the calculated magnetization oscillations are in considerably better agreement with the data for sample 1 than are any of the constant-linewidth calculations. Under the assumption of a width that is proportional to B, the resulting oscillation amplitude would be field independent and therefore give a horizontal line in Fig. 2. The dotted and dashed lines in Fig. 1(a) give the calculated results for the above DOS, for constant and $\sqrt{B}$ linewidths, respectively. The widths are adjusted to fit the oscillation amplitude around 6 T for sample 1. For the $\sqrt{B}$ fit, both the amplitude and general shape of the oscillations are reasonably approximated. Better fits to the low-field oscillations can be obtained with different line-shape functions, but discussion of such higher-order features of the DOS is not our purpose here.

For sample 2, unlike samples 1 and 3, the measurement temperature (4.2 K) contributes noticeably to the attenuation of the dHvA oscillations. The effect can be approximated by a mere increase of the effective Landau-level widths. At 2 T the observed rms half-width is 1.1 meV; removing the temperature broadening reveals a residual linewidth of about 0.9 meV, approximately 25% smaller than that observed in sample 1 at the same field. This is a modest narrowing

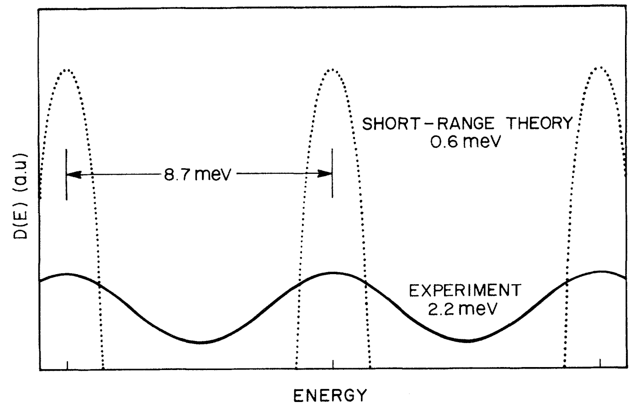

FIG. 3. Comparison of model DOS (solid line), used to fit the data from sample 1 at 5 T, with the short-range theory. At this field 8.7 meV is the Landau-level spacing. The rms half-widths of the levels are also shown.

given the almost factor-of-4 mobility difference between these two samples. It should be emphasized, however, that the link between mobility and high-field Landau-level width is highly uncertain.[12–14]

Small-scale sample inhomogeneities may present a plausible explanation for the apparently broad Landau levels. While our SdH studies rule out significant attenuation of the dHvA oscillation arising from variations of the 2D density on a gross lateral scale (~ 1 mm), as well as from layer to layer, we cannot assess smaller scale variations. Under the assumption that a local 2D density can be defined, the effect of inhomogeneities can be calculated by a simple averaging technique, the result being attenuated dHvA oscillations. We have not succeeded in generating the correct field dependence for the oscillation amplitude with such a simple model. The local-density assumption itself may be incompatible with the effect on the Landau levels of long-range potential fluctuations.[15]

At present there does not exist a coherent theoretical picture of the DOS of a 2DES in a high magnetic field. Theoretical calculations date back to times before the discovery of the QHE and are not necessarily applicable to our system. Ando and Uemura[16] derived, under various approximations, an expression for the rms width of the Landau levels assuming short-range scatterers and, while their result does give a $\sqrt{B}$ dependence for the width, the calculated magnitude is approximately 4 times smaller than our experimental results. The model DOS used to fit the data from sample 1 (at 5 T) is compared to the short-range result, appropriate to this sample, in Fig. 3. The absence of gaps in the observed DOS is striking. Given the large discrepancy between theory and experiment, it is not possible to ascertain the origin of the observed rough $\sqrt{B}$ dependence reported here.

Comparison of our results with the recent heat-capacity studies[3] shows agreement on the basic issue of the residual DOS between Landau levels but we do not find evidence for the relatively narrow structures atop a constant background cited by Gornik *et al.*[3] This discrepancy is not understood at present. The most current theoretical picture[15,17,18] reveals the DOS depending nontrivially on magnetic field and strongly upon the Landau-level filling. Neither in this work nor in the heat-capacity study were such complications included in the model DOS used for analysis. Without inclusion of such complex dependences there is no obvious way to compare the two experiments.

In summary, we have used the de Haas–van Alphen effect to determine the high-magnetic-field DOS of 2D electrons in GaAs/AlGaAs heterostructures, for both single-layer and multilayer samples. Our results give Landau-level widths which are magnetic field dependent, varying roughly as $\sqrt{B}$, but whose magnitude is about a factor of 4 larger than theoretical estimates. These widths imply a significant density of states between Landau levels, even in high-mobility ($\sim 300\,000\ \mathrm{cm^2/V\cdot s}$) single-interface structures.

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