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Direct measurement of the density of states of a two-dimensional electron gas

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We present a direct measurement of the density of states of a two-dimensional electron gas in a quantizing magnetic field. By measuring the magnetocapacitance of modulation-doped GaAs-(AlGa)As heterostructures at low frequencies, we have observed quantum oscillations resulting from changes in the density of states alone.

The density of states (DOS) of a two-dimensional electron gas (2DEG) in a magnetic field is central to the understanding of weak-field properties such as transport and strong-field phenomena such as the quantized Hall effect[1] and the fractionally quantized Hall effect.[2]

The DOS of an ideal 2DEG in a normal magnetic field at zero temperature is characterized by a series of delta functions or Landau levels. Impurities, defects, and inhomogeneities in semiconductors broaden these levels and create localized states. Measurements of transport and optical properties of a 2DEG yield information concerning the DOS, but are complicated by other factors that are not easily treated. The magnetization[3,4] and specific heat[5] can in principle yield the DOS, but to date inhomogeneities have obscured determination of the underlying DOS. The capacitance of a 2DEG is also directly related to the DOS. Capacitance measurements are the most straightforward, and small-area single-layer samples can be used. In addition, by changing the frequency of measurement, carrier concentration, device geometry, and device construction, particular aspects of the DOS such as the time required to access localized states can be investigated. By choosing samples with the appropriate boundary conditions and developing an accurate model incorporating resistance effects, future studies may provide important information about the DOS in the fractionally quantized regime or reveal the precise role of scattering in a 2DEG.

The first observations of quantum oscillations in the capacitance of a 2DEG were made by Kaplit and Zemel[6] and Voshchenkov and Zemel.[7] Shortly thereafter Stern[8] proposed a one-dimensional diffusion model for the capacitance of inversion layers at low temperatures. He indicated that the DOS of a 2DEG could be observed directly at low frequencies, where changes in the in-plane conductivity are negligible when compared to changes in the capacitive impedance. Since then others[9–12] have studied the capacitance of a 2DEG and confirmed the general features of the model. In previous studies the magnetic field strengths required to resolve the Landau levels were such that the magnetoresistance dominated the effective (measured) capacitance of the system. This led some workers to conclude incorrectly that the density of states could never be extracted from capacitance measurements.[12] The development of high-mobility, high-homogeneity semiconductor heterostructures has reduced the magnetic field strength requirements for observation of quantum oscillations in the capacitance. The product of the cyclotron frequency and the zero-field scattering time ($\omega_c\tau$) must be greater than unity, but the Landau-level separation must be small to reduce conductivity effects. Because the relationship between the measured capacitance C_{meas} and the conductivity of a 2DEG is complicated and highly dependent upon boundary conditions, direct observation of the DOS is best accomplished at low frequencies, where the conductivity can be ignored.

We report the results of capacitance measurements in high-mobility GaAs-(AlGa)As heterostructures in the regime where the conditions for observation of the DOS are met. This confirms for the first time that the DOS of a 2DEG is directly related to the capacitance.

Following the approach of Stern,[8,13] the total capacitance C_t consists of the series capacitance of the (AlGa)As barrier layer C_b and the channel C_c. The devices used in this study have no Ohmic contacts to the 2DEG, so changes in the carrier concentration of the heavily doped (AlGa)As portion of the barrier layer can be ignored at low temperatures. Thus, C_t is given by

$$\frac{1}{C_t}=\frac{1}{C_b}+\left(\frac{dQ}{d\phi}\right)^{-1} ,$$

where Q is the total charge in the channel and ϕ is the band bending as shown in Fig. 1.

If a simple variational approximation is used which ignores image effects, many-body effects, penetration of the wave function into the barrier,[14] and nonparabolicity of the band structure, the channel capacitance is given by

$$\frac{A}{C_c}=\frac{\gamma z_0}{\epsilon_0\kappa_c}+\frac{1}{e^2 dn/d\mu} ,$$

where A is the area of the capacitor, z_0 is the average position of the electrons in the channel, γ is a numerical constant between 0.5 and 0.7, κ_c is the relative dielectric constant of the channel material, and $dn/d\mu$ is the thermodynamic DOS at the Fermi energy.

Although these approximations can strongly affect the calculated subband energy, they do not change z_0 (Refs. 15–17) significantly. In addition, because the carrier concentration is constant, they do not change the fundamental relationship between the capacitance and the DOS.

z_0 does not change appreciably in experiments where the

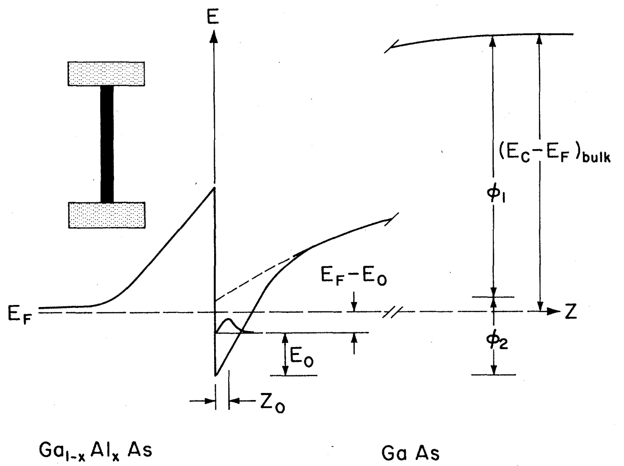

FIG. 1. Schematic diagram of the conduction-band edge for a modulation-doped GaAs-(AlGa)As heterojunction showing the quantities used in the derivation of the relationship between the measured capacitance and the density of states. An outline of the sample geometry is also shown.

magnetic field is varied. Thus, the first two terms are essentially constant and changes in the capacitance are directly related to changes in the DOS of the 2DEG. The DOS is then related to the total capacitance by the following:

$$\frac{1}{e^2 dn/d\mu}=\frac{A}{C_t}-\frac{A}{C_b}-\frac{\gamma z_0}{\epsilon_0 \kappa_c} .$$

When conductivity effects can be neglected, C_t can be replaced by C_{meas}.

The devices used in this study were fabricated by etching a mesa in the geometry shown in Fig. 1 and evaporating aluminum over the large-area pads at each end of the device. The pads were 990 microns by 330 microns and the channel was 1660 microns long and 166 microns wide. This type of capacitance measurement was first proposed by Binet[18] for contactless capacitance measurements on epitaxial surface layers. It is employed in this study because it simplifies device fabrication, reduces the effects of current flow into the corners of Ohmic contacts in the quantized Hall regime, and does not couple the 2DEG to the undepleted donors in the barrier layer. The carrier concentration and mobility are 3.6×10^{11} cm^{-2} and 3.5×10^{5} cm^2 V^{-1}s^{-1}, respectively.

The magnitude and phase of the measured capacitance at 20 Hz are shown in Fig. 2. Measurements were made using applied voltages sufficiently small (5 mV) that further reduction did not influence the measured signal. Above 0.5 T quantum oscillations are observed in the measured capacitance. This is close to the minimum field strength at which quantum oscillations in the conductivity are seen (0.4 T). The latter indicates that the homogeneity of the 2DEG is better than 1%. Above 1.65 T the magnetoresistance of the 2DEG begins to influence the measured capacitance of the 2DEG appreciably. This is indicated by the changes in the phase angle of the measured signal. We have defined the phase angle such that it is zero if the signal arises from a purely capacitive impedance. In the Stern model, decreasing

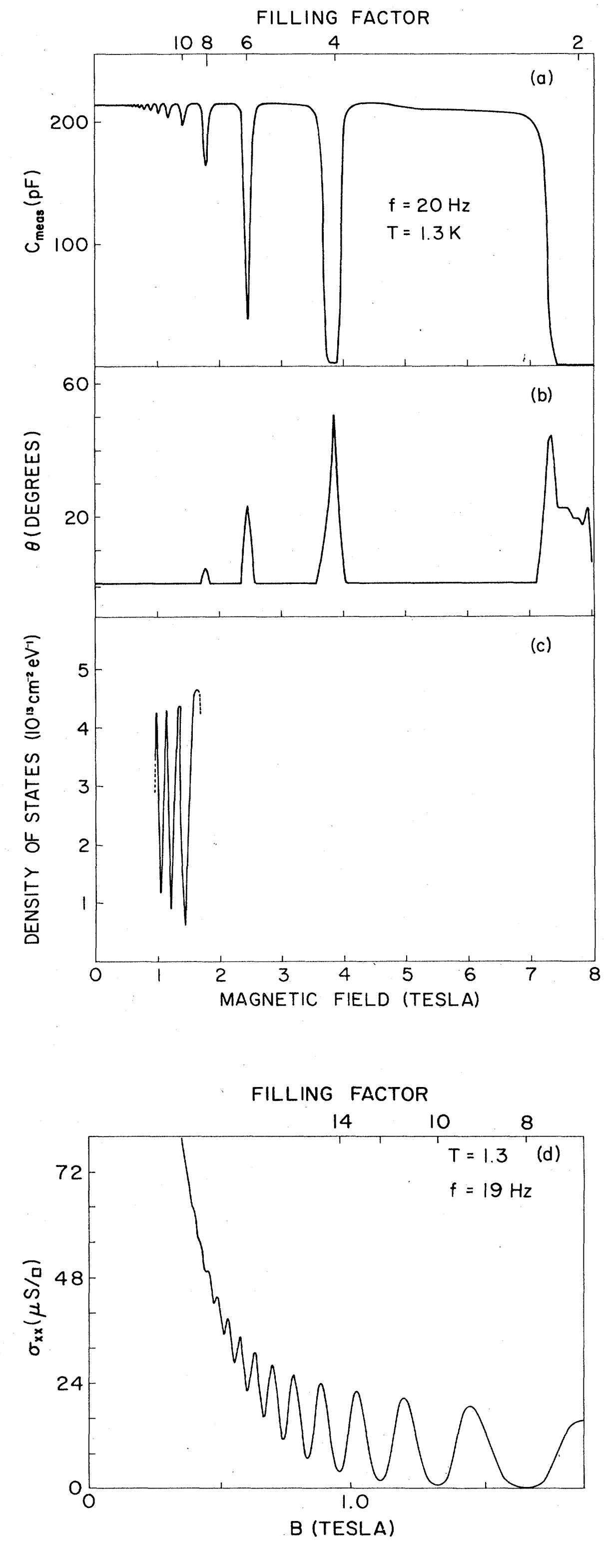

FIG. 2. (a) The magnitude and (b) phase angle of the measured capacitance vs magnetic field. The phase angle is defined so that a purely capacitive signal has a phase angle of 0° and a purely resistive signal has a phase angle of 90°. (c) The density of states determined from the measured capacitance. (d) The conductivity of a circular geometry device fabricated from the same material.

the frequency reduces resistance effects. When the measurement frequency is reduced from 20 to 10 Hz the signal is more noisy, but within experimental accuracy there is no change in the shape or size of the minima in the measured capacitance. This indicates that we are accessing the same states at these two frequencies. At 200 Hz resistivity effects are more important, resulting in larger changes in the phase angle and measured capacitance for a given magnetic field strength.

The measured capacitance also shows the expected temperature dependence. At 4.2 K the magnitudes of the dips in the measured capacitance at filling factors ν of 6, 8, and 10 are approximately 10%, 20%, and 30% of their values at 1.3 K. The change in the phase angle is also much smaller due to the increase in the conductivity minima. At 4.2 K the phase angle does not change detectably for $\nu \geqslant 8$. The conductivity at this temperature was about an order of magnitude larger than at 1.3 K. The conductivity for a device fabricated on the same material is shown in Fig. 2(d). The ratio of the diagonal and off-diagonal resistivity is approximately 1/1000 for $\nu = 10$, and a well-developed ρ_{xy} plateau is observed in Hall bar devices.

The difference between C_b and C_{meas} cannot be measured directly, but the model predicts that a 10% drop in the measured capacitance corresponds to an 80% reduction in the density of states from its zero-field value. The model also predicts that the maximum capacitance will increase by about 2% as magnetic field strength increases. This is observed and confirms our estimates for C_b. When the difference between C_b and C_{meas} is small, the measured DOS is not reliably determined unless greater precision is achieved. Therefore, we fit the data with a capacitance calculated from a model density of states having the following form:

$$D(E) = \frac{1}{2\pi l^2} \sum_{N,s} \frac{1}{\Gamma} \sqrt{2/\pi} \exp\left[-2\frac{(E - E_{N,s})^2}{\Gamma^2}\right] ,$$

where l is the magnetic length, Γ is the broadening parameter, and $E_{N,s}$ is the Landau-level energy.

Integrating the product of the Fermi function and the model DOS with respect to energy to a constant number of carriers yields the Fermi energy and hence the number of states for a given magnetic field. Additional temperature corrections are less than 10% and are not included. The magnetic field is then varied and the resultant DOS is used to generate a capacitance. The general features of the DOS versus magnetic field are cusplike dips between Landau levels, which become very sharp and deep for a broadening parameter $\Gamma < 0.9$ meV. We find that neither broadening due to Γ independent of B (scattering-time approximation) nor to Γ as a function of $\sqrt{B}$ give the correct percentage change in the dips of the capacitance between Landau levels or sufficiently widen structure to fit the data.

Consequently, we introduce broadening due to inhomogeneity into the model by including in the calculation a Gaussian distribution of density in the sample. Even small (less than 1%) inhomogeneity rounds the cusps and raises and equalizes the magnitude of the dips between Landau levels. The effect is stronger at larger magnetic fields (smaller filling factors), where the cusps are sharper and deeper.

By combining Γ broadening and sample inhomogeneity, we approximate the data for ν equals 10, 12, and 14 reasonably well. Figure 3(a) shows the capacitance data and the fit with $\Gamma = 0.95$ meV and inhomogeneity $\langle \Delta n_S \rangle = 0.5\%$. Figure 3(b) shows the measured DOS and fit using the same parameters. The percentage change in the capacitance between Landau levels and the uncertainty in the data allow us to put lower and upper limits on Γ of 0.9 to 1.0 meV and on sample inhomogeneity of 0.4 to 0.8% if a Gaussian form for the density of states is assumed. Γ is much larger than predicted from either the scattering-time approximation ($\Gamma = 0.3$ meV) or the self-consistent Born approximation for the case of short-range scatterers ($\Gamma = 0.3$ meV). It is important to emphasize that although a Gaussian form for the Landau levels is the most widely accepted starting point and hence is used in this work, the measured DOS should not necessarily have a Gaussian form. Lee[19] has emphasized the distinction between the thermodynamic density of states $dn/d\mu$ which is being measured in this experiment and the single-particle density of states which has a Gaussian form in some perturbation expansions.[20]

Finally, the change in C_{meas} at $\nu = 8$ is much larger than

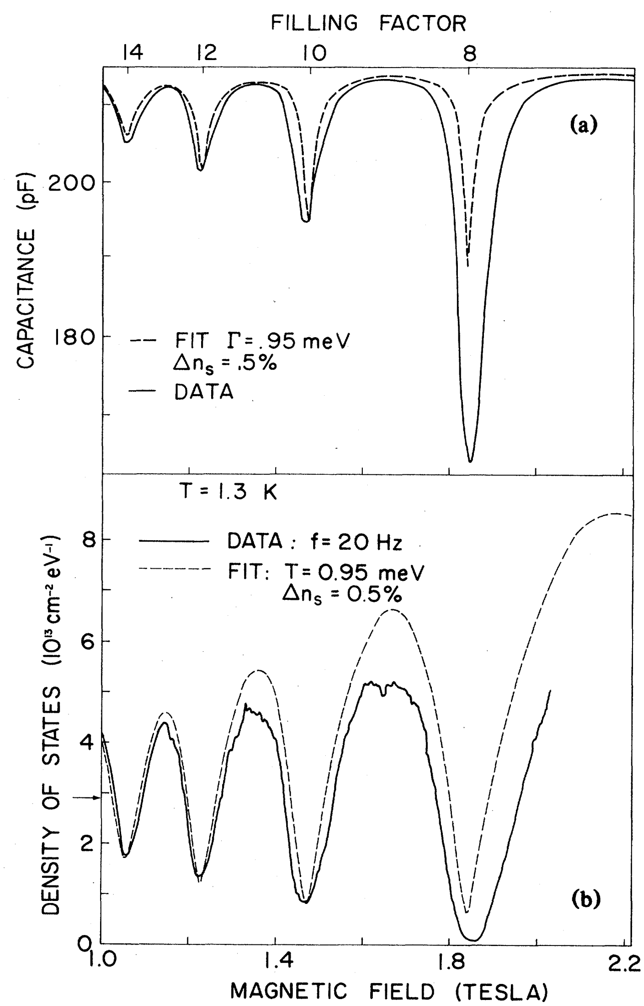

FIG. 3. The measured and calculated capacitance (a) and density of states (b) vs magnetic field. The dashed line is the approximation for $\nu = 10$, 12, and 14, based on a model using Gaussian Landau levels. The arrow indicates the zero-magnetic-field density of states.

the change in the calculated capacitance (see Fig. 3), indicating that resistivity effects are easily identified and that even small changes in the phase angle cannot be ignored.

In summary, we have reported magnetocapacitive measurements of the DOS for Landau levels in a 2DEG. We have approximated this DOS with a Gaussian shape function with a broadening of 0.95 meV independent of magnetic field strength. We also find, by modeling, that inhomogeneity strongly affects the measured DOS and must be included in the data analysis.

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