PHYSICAL REVIEW B VOLUME 33, NUMBER 2 15 JANUARY 1986

Floating-gate technique applied to two-dimensional systems

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(Received 26 August 1985)

We report a new technique of using a floating-gate capacitive structure to measure the electrochemical potential difference between a reference conductor and the material in question as a function of some external parameter. It is illustrated by measurements on two two-dimensional systems: Si metal-oxide-semiconductor structures and (Ga,Al)As:GaAs heterostructures.

INTRODUCTION

A new technique using a floating-gate structure to measure the electrochemical potential difference (EPD) between two conducting systems is illustrated by measurements as a function of magnetic field for two two-dimensional electron-gas (2DEG) systems; Si (MOS) metal-oxide-semiconductor inversion layers and (Ga,Al)As:GaAs heterolayers.[1] We observe both thermodynamic and hysteretic behavior.

Since the discovery of the effect of the magnetic field on a 2DEG at low temperatures,[2] there has been a great deal of interest and work in elucidating the properties of such systems. The discovery of the integer[3] and fractional[4] quantum Hall effect led to further questions of the effect of strong magnetic fields on 2DEG's. Recent work to determine the density of states (DOS), such as low-frequency capacitance,[5] specific heat,[6] and de Haas–van Alphen studies[7–9] has resulted in quantitative statements on the DOS of specific samples.

EXPERIMENTAL DETAILS

The experimental technique can be viewed in its simplest form as a capacitor structure formed from two conductive planes or "plates." One of the conductors is the sample, while the other serves as a reference plate of known properties. If a perfect voltmeter is connected to the capacitor and the magnetic field is varied, the measured changes in the emf will reflect the difference of the responses of the two conductors. If the response of the reference plate to the magnetic field is known or slowly varying, then any rapid structure that is observed can be attributed to interactions of the magnetic field with the sample plate.

The Si samples are large-area MOS structures with a source but no drain contact. The low-temperature mobility of these samples is typically 15 000 $cm^2/V\,s$. The potential measurement was made between the gate and the source contact. The gate is heavily doped poly-Si and hence serves as the "reference" plate, while the 2D inversion layer, which is contacted by the source, serves as the sample plate.

The (Ga,Al)As:GaAs samples are conventional heterostructure devices, with the addition of a "capacitive" contact dot located on the surface of the heterostructure. This dot serves as the reference plate, and hence the potential is measured between this contact dot and an Ohmic contact to the 2DEG. The density of these samples is approximately 2.9×10^{11} cm^{-2}, with a low-temperature mobility of 350 000 $cm^2/V\,s$.

The measurement apparatus consists of a differential amplifier which is located in the sample chamber in order to minimize the potential signal losses from leads extending outside the Dewar. The important considerations for this amplifier are its input impedence and power dissipation. The present amplifier was constructed from commerical n-channel metal-oxide-semiconductor field-effect transistors (MOSFET's) arranged in a standard differential stage configuration. The input capacitance is less than 2 pF and the input resistance is greater than 10^{15} Ω. A schematic of the measurement system is shown in the inset of Fig. 1. In the case of the Si MOS system, the charge on the gate and hence the inversion layer density are fixed at some gate bias point. The magnetic field is then swept and the resulting variations in the gate potential with respect to the source are measured. An identical Si "buck-out" sample was used outside of the magnetic field in order to remain within the dynamic range of the amplifier. In the (Ga,Al)As:GaAs heterostructure system, the bias point is already fixed by the substrate doping level.

The accuracy and resolution of the experiment can be affected by several parameters. The most important requirement is to minimize charge loss, both from leakage in the sample and measurement circuit, and from the input bias currents required to drive the amplifier. Any leakage of

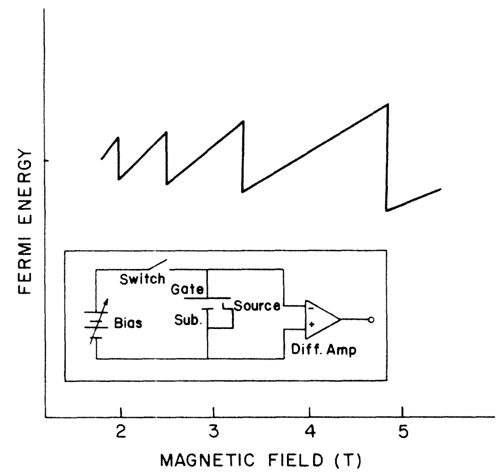

FIG. 1. Fermi energy as a function of magnetic field for a two-dimensional electron gas in a magnetic field, ignoring spin. Abrupt changes occur at Landau level transitions. Inset: Schematic of the experimental apparatus used to study Si MOS systems. The gate is charged to some bias point, the switch is then opened and gate "floated" (i.e., charge is fixed). Variations in the potential difference between gate and source are then measured at the output of the differential amplifier.

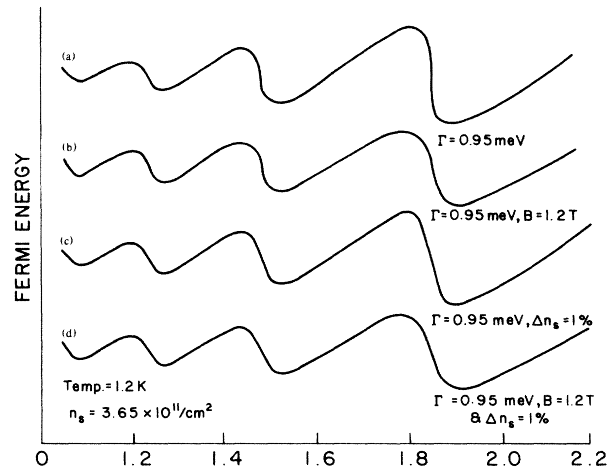

FIG. 2. Results of calculations for a GaAs heterostructure, demonstrating the effects caused by modifying the delta-function density of states: (a) assuming uniform Gaussian broadening, (b) as a function $\sqrt{B}$ broadening, (c) for inhomogeneous broadening, and (d) for a combination of $\sqrt{B}$ and inhomogeneous broadening.

charge from the sample either through connections or through the amplifier will affect the measurement. Therefore, extremely high impedences must be maintained up to the input stage of the amplifier. Bias currents are minimized by making the capacitance of the sample large relative to the input capacitance of the amplifier. The ratio of the capacitance of the samples to that of the input of the amplifier exceeds 100/1.

Leakage for a MOS structure is certainly a more severe problem than for a heterostructure. The major EPD is the gate voltage, of the order of volts, while the signal change versus the magnetic field is of the order of meV. The leakage rate is at least proportional to the potential difference, and so there is a multiplicative factor of thousands in the error due to leakage. The importance of the leakage rate is evident from the background slope of the measured EPD when slowly sweeping the magnetic field. A further signature is the change in the carrier density over time. The density measured by the oscillation period changed by about 8% over 3 h. This rate, coupled with the known capacitance, gives a total leakage resistance of about $10^{15}\ \Omega$. The case for the heterostructure is different in that the leakage problem only reduces the magnitude of the signal, and does not add a signal proportional to the EPD. It does not lead to an integrated loss of carriers as a function of time as in the Si case. Although capable of detecting changes in the EPD of the order of microvolts, our detection system may be off by a scale factor of 2.

RESULTS

A brief discussion of the expected results is appropriate prior to examining the actual data. In the absence of scattering in a magnetic field the density of states can be described by delta functions at energies at $E=(i+\frac{1}{2})\hbar\omega_c$, where i = integer and $\hbar\omega_c$ is the Landau energy. As the magnetic field is swept up, the degeneracy of each level increases, hence the Fermi level will remain in a given level until it is emptied and then drop to the next lower level. The free energy of the system therefore will change slowly within a level and abruptly between levels as shown in Fig. 1. The floating-gate experiment measures the electrochemical potential of the 2DEG relative to the reference plate (gate), and thus is a direct probe of the change in Fermi energy. Broadening of the delta functions due to scattering and inhomogeneities will tend to soften the transitions and steplike oscillations in the potential similar to those shown in Fig. 2 are expected.

The initial results from the Si sample are shown in Fig. 3. The data exhibit the expected characteristics, with clear

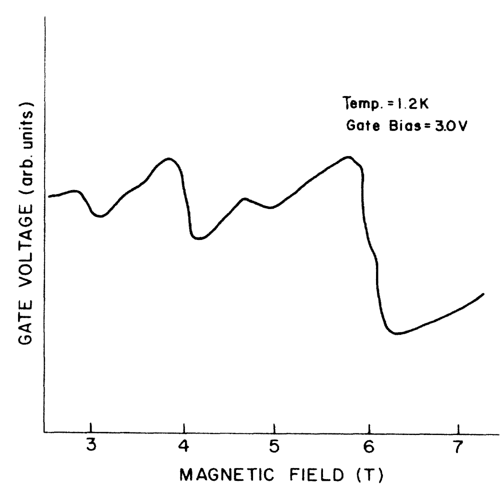

FIG. 3. Typical results of floating-gate measurement of EPD for Si MOS systems. Structure at high fields is due to spin splitting.

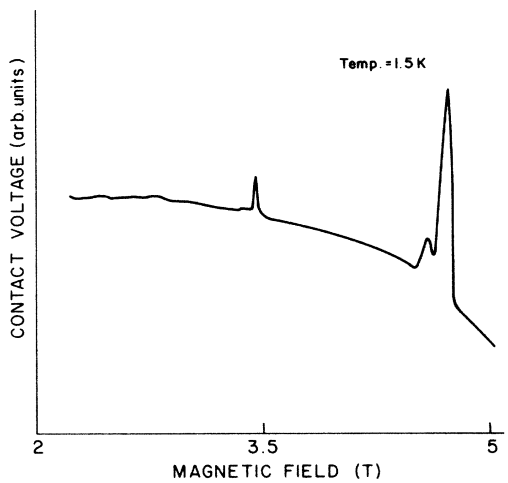

FIG. 4. Typical results of floating-gate measurement of EPD for GaAs heterostructure. Low-field structure is thermodynamic and similar to Si, while the large spikes at high fields are due to increasing the field.

steplike structure at the major Landau level transitions, and spin levels are visible at higher fields. The relevant parameters are given in the figure. At the fields and gate voltage used, we did not resolve any effects due to valley splitting, but would expect to do so at higher fields. A number of interesting features can be observed in these data. The gate potential calculated from the period of the oscillations agrees with the initial biasing value for the sample. Within the temperature range of the measurements, 1.2 to 4.2 K, we see no marked changes in the structure.

Data from the (Ga,Al)As:GaAs sample are shown in Fig. 4. The general characteristic of these data is similar to those of Si, however, additional structure is seen in the region between adjacent levels. This structure consists of large "spikes" whose amplitude is typically many times larger than the associated Landau-level step. As shown, the sign of the spike depends on the direction of the field sweep. A similar structure can just be resolved in the $i=8$ transition of the Si data. Structure was observed in Si MOS structures previously.[10]

ANALYSIS

The data fall into two main catagories, the expected variation that is thermodynamic in nature, and the history-dependent variations. We concentrate our analysis on the MOS data as they are more extensive and illustrative of the thermodynamic behavior.

As seen in Figs. 3 and 4, the drops in the electrochemical potential are not vertical as a function of the magnetic field. This indicates that there is a nonzero density of states between Landau levels. While not attempting a full analysis in this preliminary report, we wish to illustrate the effects of different kinds of broadening of the density of states on the variations in EPD. It should be noted that the measured potential variations are the properties of an interacting system, and do not necessarily correspond to those of a noninteracting system which we use in the following discussion.

A Gaussian model density of states with a broadening parameter Γ is used to calculate the electrochemical potential as a function of magnetic field. Integrating the product of the Fermi function and the model DOS with respect to energy up to a constant number of carriers yields the electrochemical potential and number of states for a given magnetic field. The inclusion of broadening due to inhomogeneity was achieved through a Gaussian distribution of density. Self-consistent calculation of the many-body enhanced Landé g factor gave no marked change in the results.

Figure 2 exhibits the results of a calculation for a heterostructure for the cases of magnetic-field-independent broadening with $\Gamma=0.95$ meV [Fig. 2(a)], $\sqrt{B}$ broadening with $\Gamma=0.95$ meV at 1.2 T [Fig. 2(b)], inhomogeneous broadening with $\Gamma=0.95$ meV and a 1% Gaussian distribution in carrier density [Fig. 2(c)], and the combined effect of $\sqrt{B}$ broadening in Fig. 2(b) and inhomogeneous broadening in Fig. 2(c) [Fig. 2(d)]. It can be seen that both kinds of additional broadening have the effect of making the drop between levels less steep at high fields, which is similar to the data in Figs. 3 and 4. It should be noted that the addition of a constant background to the calculation yields a linear increase in the EP as a function of magnetic field and cannot account for the data. The field range over which the drop in EP occurs divided by the field in the middle of the drop is relatively constant at higher fields, and is about $\frac{1}{20}$ to $\frac{1}{10}$. The ratio of the slopes in and between Landau levels gives, approximately, the inverse ratio of the density of states.

The additional structure in Fig. 4 centered around the magnetic field values where the Fermi energy is in between Landau levels is hysteretic, and is absent at low fields and high temperatures. As the field is increased and/or the temperature is decreased, the spike structure emerges. Its size depends on the above, but its sign depends on whether the field was increasing or decreasing. As the field is increased further or the temperature is lowered, the size increases, reaching voltages of almost 100 meV. It is only at the highest fields and the lower temperatures that the spikes are not the mirror image of each other. It appears that there is a contribution that is of comparable magnitude to the usual spikes but independent of the direction of the swept field. The stability of all these spikes is such that, on occasion, stopping the field sweep and sitting on the spike for periods approaching 10^5 s results in little change. However, if the field is swept in the other direction, the EPD "rapidly" switches to the reverse spike. It is possible to sweep slowly enough that a path is traversed between the two. If the field is held constant while on this path, then either spike can be traced by sweeping the field in the appropriate direction.

The likely explanation for these spikes is just the eddy currents induced in the sample from the time-varying magnetic field. These persist over long periods of time when the samples are in the quantum Hall regime. The eddy currents would travel around the system's "center," and result in an EPD between the outside and the inside approximately equal to the current, I, times the Hall resistance. The sign of the difference would depend on the direction of current. Our circulating currents were at least as high as 10^{-6} A. Evidently the breakdown of the quantum Hall effect at higher electric fields causes a rapid decay at higher current levels.

CONCLUSIONS

We have demonstrated that the floating-gate technique permits measurement of the variation of the electrochemical potential relative to a reference when some external parameter such as the magnetic field is varied. It is nonperturbative in that the perturbation may be made as small as is desired, and should be widely applicable. We have illustrated the technique with preliminary data for two-dimensional electron gases in both Si MOS structures and in (Ga,Al)As:GaAs heterostructures as a function of magnetic field. We see evidence of a measurable density of states between Landau levels at high magnetic fields that suggest inhomogeneities and perhaps $\sqrt{B}$ broadening must be included with the approximate magnitudes used in the calculations. We expect that this type of experiment will be very effective in studying the long-time constants associated with the decay of currents in the quantum Hall regime.

ACKNOWLEDGMENTS

We wish to acknowledge the National Science Foundation for its support through Grant No. 8314397 and the Central Facilities of the Material Research Laboratory which were utilized.

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