Solid State Communications, Vol.58,No.1, pp.5-7, 1986.
Printed in Great Britain.
0038-1098/86 $3.00 + .00
Pergamon Press Ltd.

DENSITY OF STATES OF GaAs-AlGaAs-HETEROSTRUCTURES DEDUCED FROM TEMPERATURE DEPENDENT MAGNETOCAPACITANCE MEASUREMENTS

V. Mosser*, D. Weiss, K. v. Klitzing, K. Ploog and G. Weimann+

Max-Planck-Institut fur Festkorperforschung, Heisenbergstr. 1, D-7000 Stuttgart 80, F R G

(Received November 21, 1985 by M. Cardona)

We have analyzed the density of states of a two dimensional electron gas in a GaAs-AlGaAs hetereostructure by measuring the magnetocapacitance in magnetic fields up to 6 Tesla at temperatures below 10 K. The experimental data are well described by a Gaussian-like density of states where the linewidth Γ is proportional to $\sqrt{B}$.

Introduction

The energy spectrum of a two-dimensional electron gas in a strong magnetic field consists in the ideal case of discrete Landau levels with a degeneracy corresponding to the number of flux quanta within the area of the sample. Scattering processes lead to a broadening of the energy levels. Several attempts [2-4,6,8] have been made to determine the real shape of the density of states (DOS).

The analysis of the quantized Hall resistance of silicon MOSFETs indicates that the density of states at midpoint between two Landau levels is nearly independent of magnetic field [1]. Gornik et al. [2] measured the specific heat of a GaAs-AlGaAs multilayer and found that the data are best described by a Gaussian-like density of states superimposed on a constant background. Temperature dependent measurements of the resistivity in the regime of the Hall plateaus [3] confirmed the existence of a flat, mobility dependent background between Landau levels, but this method is restricted to measurements in the tails of the Landau levels. Eisenstein et al. [4] fitted their magnetization data with a Gaussian DOS. They found a magnetic-field dependent Landau level width varying roughly as $\sqrt{B}$ but with a magnitude about four times larger than predicted by the theory based on short-range potential scattering [5].

Capacitance measurements seem to be a straightforward method to obtain information about the DOS [6]. Varying the magnetic field, changes in the DOS are reflected by oscillations of the magnetocapacitance. Recently Smith et al. [6] tried to deduce the DOS from capacitance measurements. They analyzed mainly the minima of the oscillations at 1.3 K, but this method failed at magnetic fields larger than 1.6 Tesla. Moreover, they found a remarkable discrepancy between the theoretical and experimental values of the maxima in the DOS.

Measurements at higher temperatures and careful interpretation of the data not only at the capacitance minima but also at the maxima, allow an extension of the analysis to higher magnetic fields.

Theoretical background

The capacitance of a system consisting of a metal-insulator (with ionized impurties)-semiconductor sandwich (e.g. Au-AlGaAs-GaAs-heterostructure) depends not only on the thickness of the insulator but also on the DOS at the semiconductor side and on parameters of the material. The calculation of the capacitance is based on a solution of the Poisson equation which yields (Fig. 1) [7]

$$V_G = K + \frac{E_F}{e} + \frac{eL_A}{\epsilon_1} n_s \qquad (1)$$

L_A is the thickness of the AlGaAs layer, ϵ_1 is the dielectric constant of the insulator, and K takes into account fixed charges in the AlGaAs layer and barrier heights at both interfaces. At low temperatures, carriers in both materials are frozen out, so that K is a constant. V_G is the gate voltage, n_s denotes the carrier density in the channel and e is the elementary charge. Eq. (1) can be rewritten as

$$eV_G = \frac{e^2L_A}{\epsilon_1} n_s + E_0 + (E_F - E_0) + eK \qquad (2)$$

Differentiating Eq. (2) with respect to n_s within the variational approximations of Stern [8], which take into account the n_s dependence of the subband edge E_0, one obtains for the capacitance

$$\frac{1}{C} = \frac{1}{C_A} + \frac{\gamma z_0}{\epsilon_s} + \frac{1}{e^2 \frac{dn_s}{d(E_F - E_0)}} \qquad (3)$$

where C is the measured differential capacitance at a given magnetic field, C_A is the capacitance of the insulating AlGaAs layer, ϵ_s is the dielectric constant of GaAs, z_0 is the average position of the electrons in the channel, γ is a constant numerical factor between 0.5 and 0.7, and $dn_s/d(E_F-E_0)$ is the thermodynamic DOS at the Fermi level, in the following denoted as $dn_s/d\mu$. The first two terms on the right hand side of Eq. (3) are assumed to be constant in a magnetic field, and thus changes in the capacitance are directly related to changes in the thermodynamic DOS of the 2DEG. At T=0 the total inverse capacitance in a magnetic field can be expressed as

$$\frac{1}{C} = \frac{1}{C_0} - \frac{1}{e^2 D_0} + \frac{1}{e^2 D} \qquad (4)$$

where C_0 denotes the value of the total capacitance at B=0, D is the DOS at the Fermi level in the presence of a magnetic field and D_0 is the DOS within the lowest subband, equal to 2.9×10^{10} $cm^{-2}meV^{-1}$ in the absence of a magnetic field. At finite temperatures D has to be replaced by $dn_s/d\mu$.

Permanent address
* Physik Dept. E16, TU Munchen
D-8046 Garching

+ Forschungsinstitut der Deutschen Pundespost beim FTZ, D-6100 Darmstadt

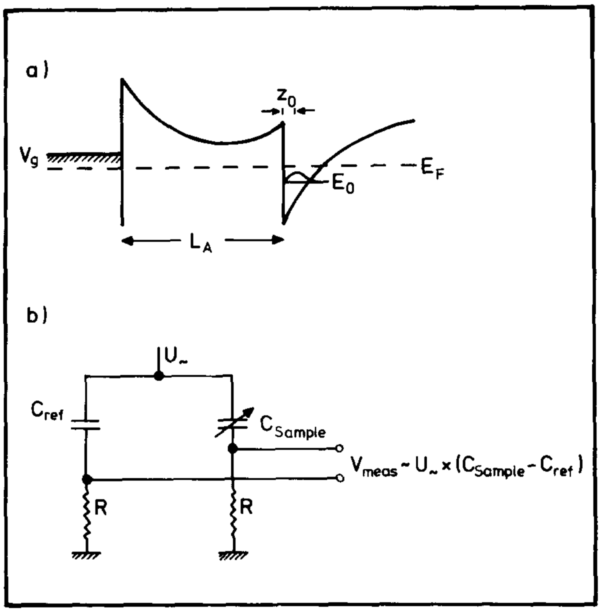

Fig. 1 Schematic diagram of the conduction band edge (a) for a gated modulation doped GaAs-AlGaAs heterostructure showing the quantities used in the derivations and schematic experimental set-up (b)

Experimental results

The sample used in this study was a gated (gate area 0.8 mm^2, evaporated gold) GaAs-AlGaAs heterostructure with a Hall geometry. For capacitance measurements all the Hall contacts were short-circuited and acted as a channel contact. The carrier density at $V_G=0$, as given by the periodicity of the capacitance oscillations was $n_s = 2.25 \times 10^{11} cm^{-2}$ in agreement with Shubnikov-de Haas and low field Hall data and the mobility was 190,000 cm^2/Vs.

The signal was obtained by measuring the voltage drops at the sample and a high precision Boonton capacitance decade. This arrangement allows both a precise determination of the phase and the absolute value of the signal (see Fig. 1). The frequency chosen for the measurements was 223 Hz. Measurements between 22.3 Hz and 446 Hz showed no change in the signal. The modulation amplitude was 5 mV, which corresponds to a modulation of $\Delta n_s \approx 4 \times 10^9 cm^{-2}$. Further reduction of this amplitude showed no change in the signal. At each temperature the real part of the signal was monitored, and we checked that the signal was always purely capacitive for $C > C(B=0)$, even in the case of very low temperatures (T= 1.64 K) and high magnetic fields. Warming up and cooling down of the sample introduced no change in the signal. The temperature was stabilized in the presence of a magnetic field by a capacitance temperature controller and measured at B=0 with a calibrated carbon-glass resistor. Temperatures below 4 2 K were achieved by reducing the vapour pressure of the surrounding liquid-helium-bath

The experimental results were compared with calculations of C(B) assuming a Gaussian plus a constant background DOS D_{UG}

$$D(E) = A \cdot \frac{B}{\Gamma} \cdot \sum_j \exp\left\{\frac{-(E-(j+\frac{1}{2})\hbar\omega_c)^2}{2\Gamma^2}\right\} + D_{UG} \quad (5)$$

where the constant A is determined by the number of electrons in one Landau level, Γ is the broadening parameter of the Gaussian distribution, and ω_c the cyclotron frequency. For a given electron density n_s (assumed to be constant in the investigated temperature and magnetic field range), magnetic field B, temperature T, and DOS D(E) the position of the Fermi level μ is determined by solving numerically the equation

$$n_s = \int_0^\infty D(E)\, f(E-\mu) dE \qquad (6)$$

Then

$$\frac{dn_s}{d\mu} = \int_0^\infty D(E) \frac{df(E-\mu)}{d\mu} dE \qquad (7)$$

is calculated numerically, too. All energies are taken relative to the subband edge E_0. With the temperature dependent form of Eq. (4) and Eq. (7) one obtains C(B). Spin splitting, which is small compared to the cyclotron energy for GaAs, is neglected in the calculation.

Some further considerations are necessary to fit the data using the expressions above. The minima and maxima of the measured capacitance are connected to minima and maxima in the DOS in the two-dimensional electron gas A minimum is obtained when the Fermi level is between two Landau levels. Additional calculations, assuming a Gaussian distribution of the electron density n_s, show that inhomogeneities strongly influence the minima but not the maxima of the capacitance at sufficient high magnetic fields (> 1 Tesla). Furthermore at low temperatures the capacitance signal is no longer purely capacitive, if the Fermi level position is between two Landau levels ($\sigma_{xx} \approx 0$). For this reason, it is advisable to concentrate on the maxima of the measured capacitance to fit the data.

Fig. 2 shows the capacitance data at different temperatures. Also shown is the fit to these data assuming a linewidth $\Gamma = 0.3\sqrt{B[T]}$[meV] and a background of 3 $6 \times 10^9 cm^{-2} meV^{-1}$. The value of the constant background is obtained from temperature dependent resistivity measurements in the regime of the Hall plateaus carried out on the same material [9]. At all investigated temperatures the calculated maxima of the magnetocapacitance are in excellent agreement with the experimental ones up to 5 Tesla. A fit of the experimental data with a magnetic field independent linewidth or a linewidth which differs from the assumed value by more than 10 % was not possible. It should be mentioned that the assumption of a vanishing background D_{UG} broadens Γ only by about 10 % The depths of the measured minima at low temperatures are smaller than the calculated ones as long as resistivity effects in the channel are negligible (low B-field). This is attributed to inhomogeneities. Their influence decreases with increasing temperature. At higher magnetic fields the capacitance signal at the minima is governed by the small conductivity σ_{xx} which becomes less important at higher temperatures Therefore the fit works well for minima and maxima of magnetocapacitance at higher temperatures. The difference between experiment and calculation if only one Landau level is filled cannot be explained yet.

Actually not the carrier density n_s but the electrochemical potential is kept constant during experiments. As the variation of n_s only influences the width of the maxima and minima and not the absolute value of the magnetocapacitance minima and maxima, the assumption of a constant carrier density seems applicable to fit the data. This will be discussed in more detail in a further publication.

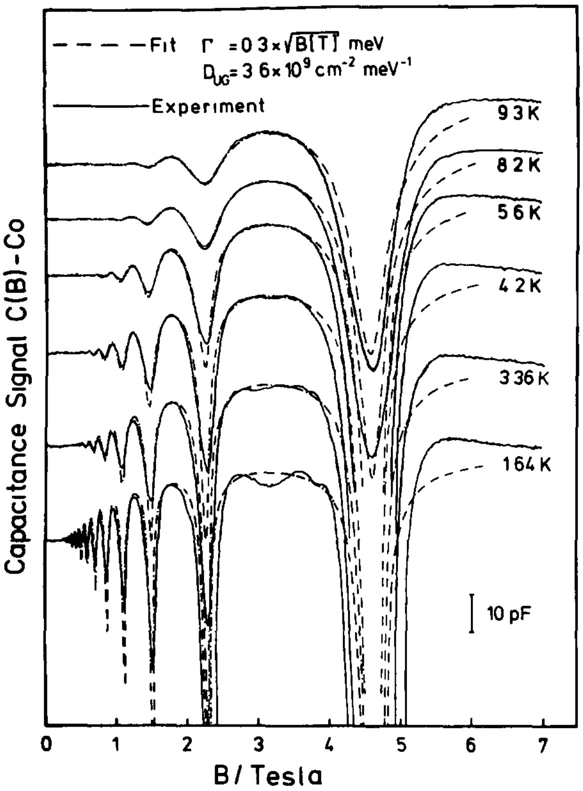

Fig. 2 Measured magnetocapacitance and corresponding fit assuming a Gaussian DOS with a broadening parameter $\Gamma = 0.3\sqrt{B[T]}$[meV] superimposed on a constant background DOS $D_{UG} = 3.6 \times 10^9 cm^{-2} meV^{-1}$. For the sake of clarity the curves are shifted vertically

Assuming a Gaussian DOS with a linewidth $\Gamma = 0.3\sqrt{B[T]}$[meV] and a superimposed constant background of $3.6 \times 10^9 cm^{-2} meV^{-1}$ we are able to fit the magnetocapacitance data in the whole temperature range 1.64 K<T<9.3 K for a sample showing a mobility of 190,000 cm^2/Vs. The result is summarized in Fig. 3, where the experimentally deduced DOS is compared with the self-consistent Born approximation (SCBA), assuming short-range scatterers [5].

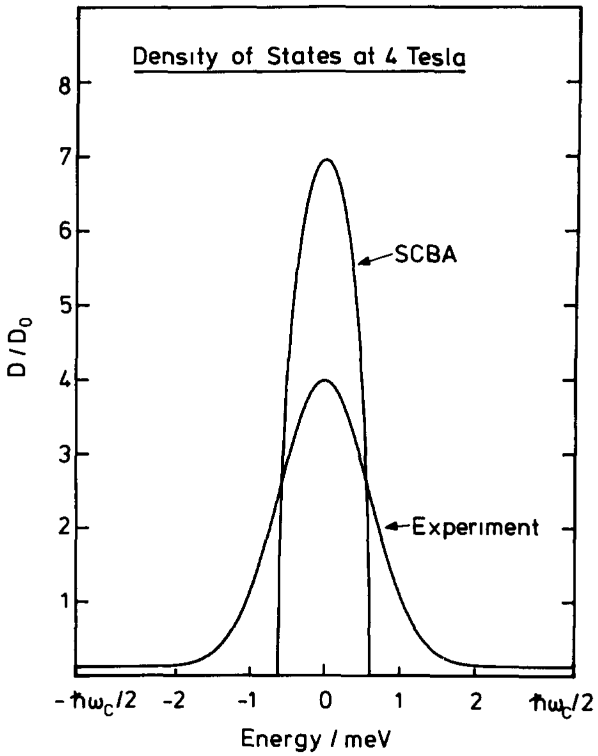

Fig. 3 Comparison of the experimentally deduced DOS with the theoretical curve based on the self consistent Born approximation (SCBA), assuming short-range scatterers

Summary

By measuring the magnetocapacitance in the temperature range from 1.64 K to 9.3 K in magnetic fields up to 6.2 Tesla we have shown that maxima in the DOS are directly related to maxima in the capacitance. The good agreement between theory and experiment not only at one temperature but also in the whole temperature range confirms strongly our model. As the method is sensitive to maxima in the DOS, magnetocapacitance measurements and temperature measurements of the resistivity in the regime of the Hall plateaus - a method which is used for the determination of the DOS in the tails of the Landau levels - are complementary methods.

Acknowledgement

One of us (V.M.) wishes to thank the Humboldt Foundation for its support.

References

1. B. Tausendfreund and K. v. Klitzing, Surf. Sci. 142, 220 (1984)
2. E. Gornik, R. Lassnig, G. Strasser, H.L. Stormer, A.C. Gossard, and W. Wiegmann, Phys. Rev. Lett. 54, 1820 (1985)
3. E. Stahl, D. Weiss, G. Weimann, K. v. Klitzing, and K. Ploog, J. Phys C18, L783 (1985)
4. J.P. Eisenstein, H.L. Stormer, V. Narayanamurti, A.Y. Cho, and A.C. Gossard, Yamada Conf. XIII on Electronic Properties of Two-Dimensional Systems (1985), p. 292
5. T. Ando, Y. Uemura, J. Phys. Soc. Jap. 36, 959 (1974)
6. T.P. Smith, B.b. Goldberg, P.J. Stiles, and M. Heiblum, Phys. Rev. B32, 2696 (1985)
7. D. Delagebeaudeuf, N.T. Linh, IEEE Trans. ED-29, 955 (1982)
8. F. Stern, Phys. Rev. B5, 4891 (1972)
9. D. Weiss, E. Stahl, G. Weimann, K. Ploog, and K. v. Klitzing, Yamada Conf. XIII on Electronic Properties of Two-Dimensional Systems (1985), p. 307