J. Phys. C: Solid State Phys. **18** (1985) L783–L787. Printed in Great Britain

LETTER TO THE EDITOR

Density of states of a two-dimensional electron gas in a strong magnetic field

E Stahl[†], D Weiss[†], G Weimann[‡], K von Klitzing[§] and K Ploog[§]
[†] Physics Department, Technische Universität München, D-8046 Garching, Federal Republic of Germany
[‡] Forschungsinstitut der Deutschen Bundesport beim FTZ, D-6100 Damstadt, Federal Republic of Germany
[§] Max-Planck-Institut für Festkörperforschung, D-7000 Stuttgart 80, Federal Republic of Germany

Received 8 July 1985, in final form 29 July 1985

Abstract. We have measured the density of states in the tails of the Landau levels of GaAs–$Al_xGa_{1-x}As$ heterostructures by analysing the variation of the Fermi level position as a function of the magnetic field. The experimental data are best described by a gaussian-like density of states superimposed on a constant background density of states.

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. All calculations based on short-range potential scattering show a rapidly decaying density of states (DOS) in the tails of the Landau levels so that the minimal density of states in the middle between two Landau levels should decrease drastically with increasing magnetic field. A real energy gap with vanishing DOS is expected in very strong magnetic fields—contrary to the interpretation of our experimental data.

Already the analysis of the quantised Hall resistance of silicon MOSFETS indicated that the density of states at the centre between two Landau levels is nearly independent of magnetic field (Tausendfreund and von Klitzing 1984). Attempts to measure the DOS by analysing the capacitance of MOS structures were not very successful (Goodall *et al* 1985); but recent measurements (Gornik *et al* 1985) of the specific heat of a GaAs–GaAlAs multilayer in a magnetic field showed that the data are best described with a density of states consisting of gaussian peaks on a flat background. A direct determination of the DOS is possible if one can measure the energy of the Fermi level as a function of the filling factor of a Landau level. The filling factor can be changed either by the carrier density or the magnetic field and the positions of the Fermi energy can be deduced from an analysis of the thermally activated resistivity in the magnetic field range of the Hall plateaus (localised region). The measured activation energy is interpreted as the energy difference between the Fermi energy and the mobility edge. Since our magnetotransport measurements on GaAs–$Al_xGa_{1-x}As$ heterostructures demonstrate that up to 98% of the electrons within one Landau level are localised (Ebert *et al* 1982) and only states close to the centre of the level are extended, we assume that the mobility edge coincides with the position of the unperturbed Landau level.

For our experiments we used GaAs–$Al_xGa_{1-x}As$ heterostructures with a low-temperature mobility between 10^5 and $5.5 \times 10^5\,cm^2\,V^{-1}\,s^{-1}$. Mobilities with values as low as $1.4 \times 10^4\,cm^2\,V^{-1}\,s^{-1}$ were obtained by irradiating the devices with 1 MeV electrons. The resistivity component ρ_{xx} was measured at different magnetic field values in a temperature range $T > 3$ K where variable range hopping is unimportant (Ebert *et al* 1983). Figure 1 shows clearly that an activated resistivity is observed. The largest activation energy is observed at $B = 7.23$ T where the Fermi energy is located close to the centre between the two lowest Landau levels (filling factor $i = 2$). With increasing magnetic field the degeneracy of the Landau levels increases so that under the condition of a constant carrier density a shift of the Fermi level close to the lower Landau level is expected. The experiment shows that a variation in the magnetic field strength of 1% leads to a change in the activation energy of about 20%. Already a rough estimate shows that such a motion of the Fermi level corresponds to a density of state which is ten times smaller than the DOS without a magnetic field. From a more accurate analysis, which includes the variation of the Landau splitting with magnetic field, we can construct a density of states as shown in figure 2. The energy scale is plotted relative to the Fermi level position where the largest activation energy is observed, which corresponds approximately to the centre between two Landau levels. Measurements at the maximum of the density of states are not possible because the position of the Fermi energy can be determined only if it is located well below the mobility edge. However, from the known value for the total number of states within one Landau level, one can estimate that even for a constant DOS in the energy region where no experimental points are available, a peak density of states, larger than the density of states without a magnetic field by a factor of ten, is necessary. The unexpected result is that the density of states changes

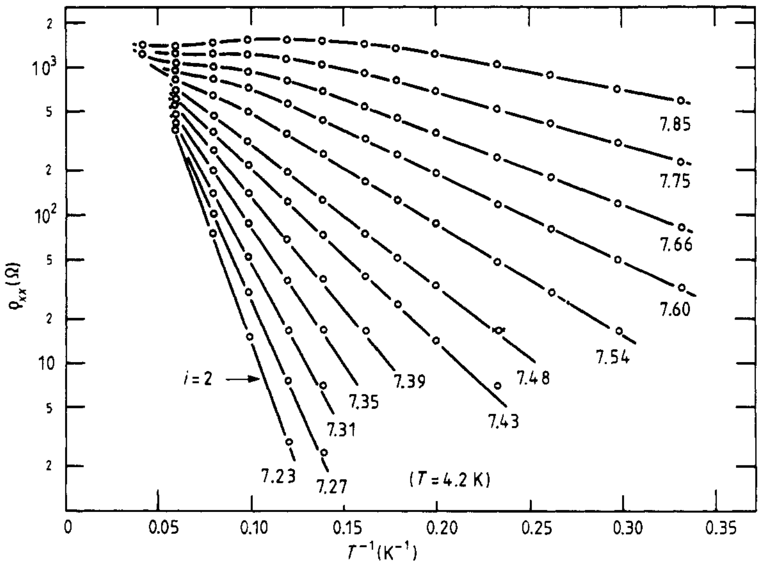

Figure 1. Temperature dependences of the resistivity ρ_{xx} of a GaAs–$Al_xGa_{1-x}As$ heterostructure at different magnetic field values (values of B are shown on curves in teslas) close to the filling factor $i = 2$. $\mu = 5.5 \times 10^5\,cm^2\,V^{-1}\,s^{-1}$.

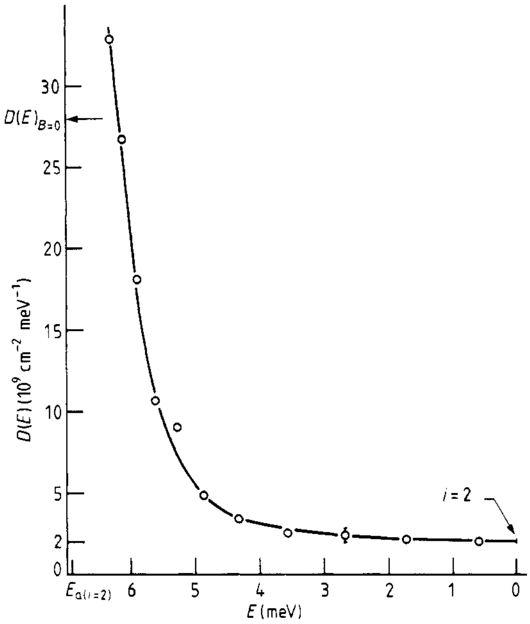

Figure 2. Density of states $D(E)$ as a function of the energy relative to the Fermi energy position where the largest activation energy is observed (corresponding to $B = 7.23$ T in figure 1). The density of states without magnetic field is marked by an arrow. $\mu = 5.5 \times 10^5\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$, i is the filling factor.

only by a factor of two within 70% of the mobility gap. Such a slowly varying density of states in the tails of the Landau levels is consistent with our experimental result that the minimal density of states is approximately identical if measured at filling factors of two and four corresponding to a variation in the energy separation by a factor of two.

The experimental DOS is best described by assuming a constant density of states in addition to the gaussian density of states of the Landau levels. The background density of states $D_{\min}$ changes with the mobility of the device and figure 3 shows a summary of $D_{\min}$ data for different samples. The decreasing density of states $D_{\min}$ with increasing

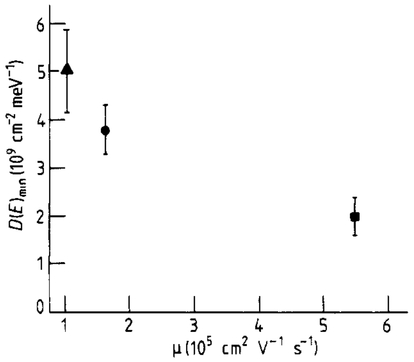

Figure 3. Background density of states $D(E)_{\min}$ as a function of the mobility of the devices. Values of N_s are: ▲, $4.2 \times 10^{11}\,\mathrm{cm^{-2}}$; ●, $3.0 \times 10^{11}\,\mathrm{cm^{-2}}$; ■, $3.5 \times 10^{11}\,\mathrm{cm^{-2}}$.

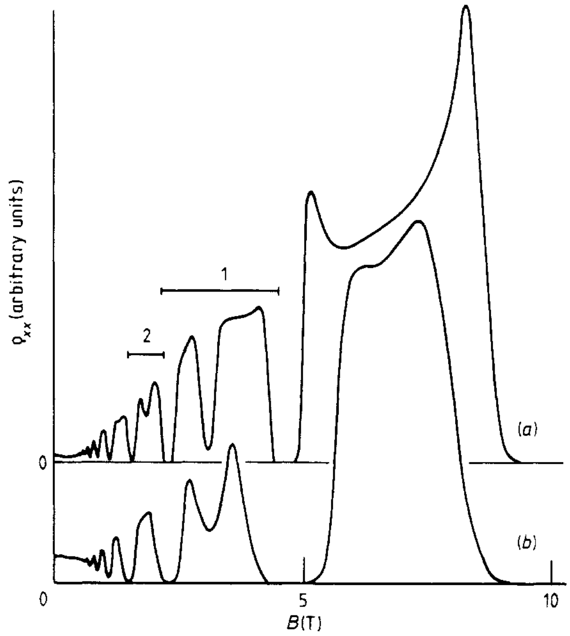

Figure 4. Resistivity ρ_{xx} as a function of the magnetic field at $T = 1.5$ K for two different heterostructures with approximately the same carrier density but different mobilities: (*a*), $\mu = 10^6\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$; (*b*), $\mu = 10^5\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$. The plateau $\rho_{xx} = 0$ around $B = 5$ T is better developed for the sample with lower mobility.

mobility gap leads to the observed reduction in the plateau width as shown in figure 4 since the Fermi energy moves more rapidly through the mobility with magnetic field if the density of states is reduced. Our method used for the direct determination of the density of states becomes inaccurate if the Fermi energy changes with temperature, if not only one Landau level contributes to the resistivity and if the prefactor in the equation for the thermally-activated resistivity is strongly temperature dependent. Computer simulations show that for the samples discussed in this publication these corrections are smaller than the error bars shown in figure 3 but become more important if one measures the density of states directly at the centre between two Landau levels where different levels contribute to the resistivity (Therefore, no experimental points are shown close to $E = 0$ in figure 2.)

One important assumption for the determination of the density of states is that the mobility edge remains fixed, independent of the temperature and the carrier density. The fact that an activated conductivity is observed within a wide range of temperature seems to indicate that a temperature-dependent mobility edge is not important. (A variation of the mobility edge linearly with temperature only gives a constant prefactor for $\rho_{\mathrm{vu}}(T)$ anyway.) A shift of the mobility edge to higher energies with increasing filling factor may be present if the Fermi energy is close to the mobility edge (Mott *et al* 1975). This correction reduces the measured density of states close to the centre of the Landau level but should be small in the energy range discussed in this paper. A detailed discussion of the experimental data on the basis of computer simulations, especially the analysis of measurements on devices with low mobilities and background density of states as high as $14 \times 10^9\,\mathrm{meV^{-1}\,cm^{-2}}$ will be published in a separate paper.

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