Surface Science 170 (1986) 285–291
North-Holland, Amsterdam

DENSITY OF STATES IN LANDAU LEVEL TAILS OF GaAs–Al$_x$Ga$_{1-x}$As HETEROSTRUCTURES

D. WEISS * and E. STAHL
Physik-Department, Technische Universität München, D-8046 Garching, Fed. Rep. of Germany

G. WEIMANN
Forschungsinstitut der Deutschen Bundespost beim FTZ, D-6100 Darmstadt, Fed. Rep. of Germany

and

K. PLOOG and K. VON KLITZING
Max-Planck-Institut für Festkörperforschung, D-7000 Stuttgart 80, Fed. Rep. of Germany

Received 22 July 1985; accepted for publication 13 September 1985

From an analysis of the thermally activated resistivity as a function of the magnetic field in the quantum Hall regime we deduced the position of the Fermi energy in the mobility gap as a function of the filling factor and therefore the density of states. The measured density of states is best described by a Gaussian like profile superimposed on a constant background.

1. Introduction

Magnetotransport measurements on heterostructures at low temperatures are usually dominated by magnetic field regions where the Hall resistivity ρ_{xy} adopts a quantized value and the longitudinal resistivity ρ_{xx} is vanishingly small. The origin of these plateaus is attributed to a position of the Fermi energy within a mobility gap. The density of localized states in the mobility gap is unimportant for a discussion of transport data at zero temperature but must be known if variable range hopping [1] (which includes the density of states at the Fermi energy) plays a role or if thermodynamic properties are studied (specific heat [2], De Haas–Van Alphen effect [3]). Moreover, all transport theories include information about the density of states (DOS), and a microscopic theory of the quantum Hall effect or the longitudinal resistivity

---

* Present address: Max-Planck-Institut für Festkörperforschung, D-7000 Stuttgart 80, Fed. Rep. of Germany.

should give first of all a correct answer for the density of states. The existing theories are usually based on the assumption that short range scatterers dominate. The self-consistent Born approximation leads to an elliptic lineshape for the DOS with a linewidth Γ depending on the mobility μ and the magnetic field B [4]:

$$D(E)=\frac{eB}{h}\sum_n\left[1-\left(\frac{E-E_n}{\Gamma}\right)^2\right]^{1/2}, \tag{1}$$

$$\Gamma\sim(B/\mu)^{1/2}. \tag{2}$$

On the basis of these equations one expects that for a typical GaAs heterostructure with $\mu = 200{,}000\ \mathrm{cm^2\ V^{-1}\ s^{-1}}$ and a magnetic field of 5 T, about 80% of the energy distance between Landau levels is a real energy gap. Higher order approximations show that an exponentially decaying DOS is expected for energies $E-E_n$ larger than the linewidth of the Landau levels, so that a real energy gap with vanishing density of states may be not present, but the DOS at the center between two Landau levels should decrease drastically if the magnetic field (energy separation between adjacent Landau levels) is increased.

However, screening effects (which depend on the density of states at the Fermi energy E_F) modify the broadening of the Landau levels [5], so that Γ depends on the position of E_F. The following discussion is based on a picture which does not include many-body effects. The notation "density of states" in this paper is used to characterize the electronic properties within a single particle picture.

2. Experimental results and discussion

We have analyzed the resistivity ρ_{xx} in a strong magnetic field as a function of the temperature for GaAs-$Al_xGa_{1-x}As$ heterostructures with mobilities $14{,}000 < \mu < 550{,}000\ \mathrm{cm^2\ V^{-1}\ s^{-1}}$ and carrier densities $1.4\times10^{11} < n < 4.2\times10^{11}\ \mathrm{cm^{-2}}$. The devices have Hall geometry with a typical length of about 3 mm, a width of about 0.4 mm and a distance between potential probes of 0.5 mm. The device current was kept below 1 μA where electron heating is negligibly small. The filling factor of the Landau levels is changed by varying the magnetic field B. At finite temperatures, well-developed minima $\rho_{xx}^{\min}$ are observed in the resistivity at magnetic field values close to integer filling factors $i = nh/eB$. The temperature dependence of $\rho_{xx}^{\min}$ for $2 < T < 20$ K is usually dominated by an exponential term corresponding to

$$\rho_{xx}^{\min}\sim\exp(-E_a/kT). \tag{3}$$

Measured activation energies E_a at different magnetic field values are

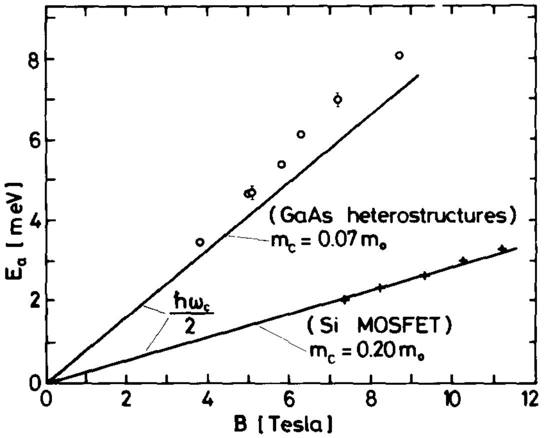

Fig. 1. Measured activation energies E_a in the resistivity at a filling factor corresponding to a fully occupied lowest Landau level as a function of the magnetic field B. The solid lines correspond to half of the cyclotron energy.

shown in fig. 1 for both GaAs heterostructures and silicon MOSFETs. The filling factor corresponds always to a fully occupied lowest Landau level which means $i = 2$ for GaAs heterostructures (each experimental point corresponds to another sample) and $i = 4$ for silicon (100) MOSFETs (the carrier density is changed proportional to the magnetic field by varying the gate voltage). The experimental points demonstrate that the activation energy E_a seems to be related to half of the cyclotron energy which corresponds to the energy separation between the Fermi energy E_F and the center of the Landau level E_n. This result looks similar to measurements on amorphous systems where a thermally activated conductivity is observed with an activation energy corresponding to the energy difference between the Fermi energy and the mobility edge of the conduction or valence band. In analogy, the mobility edge of the Landau levels is located at the center of the Landau levels in agreement with calculations of the localization length [6] and percolation theories [7].

The model in which the temperature dependence of the resistivity in the plateau region (not only at integer filling factor) is dominated by a term

$$\rho_{xx} \sim \sum_n \exp\left(-\frac{|E_n - E_F|}{kT}\right) \tag{4}$$

forms the basis for a determination of the Fermi level position as a function of the filling factor and therefore for a direct measurement of the density of localized states.

The motion of the Landau levels relative to the Fermi energy (reduction in the activation energy $E_a = |E_n - E_F|$) if the filling factor of a Landau level is varied is clearly visible in fig. 2. From $B = 7.19$ T ($i = 2$) to $B = 7.39$ T

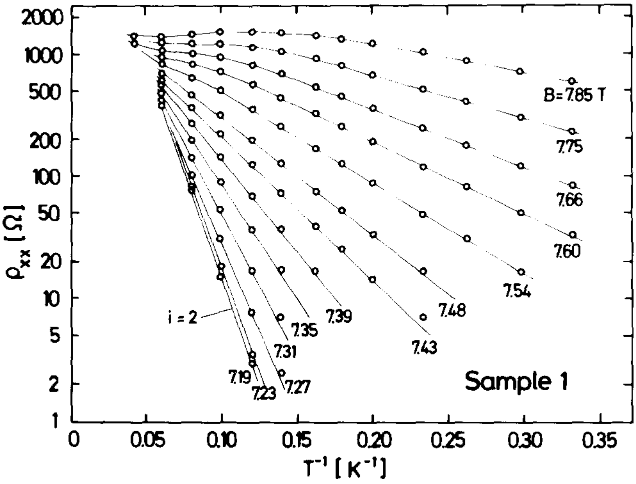

Fig. 2. Temperature dependence of the resistivity ρ_{xx} at different magnetic fields close to a filling factor $i = 2$.

($i = 1.95$) a reduction in the activation energy of about $\Delta E = 4$ meV is observed. Since a filling factor change of 0.05 at this magnetic field corresponds to a density variation of $\Delta n = 9 \times 10^9$ cm^{-2}, a mean value for the density of states of about $D(E) = \Delta n/\Delta E \approx 2 \times 10^9$ cm^{-2} meV^{-1} can be deduced. Fig. 3 shows a typical result for $D(E)$ as a function of the energy relative to the center of the plateau region. The maximum close to $E = 0$ in fig. 3 is an artifact since for the Fermi energy close to $E = 0$ *two* Landau levels contribute to the thermally activated conductivity, which complicates the analysis of the experimental data. If the Fermi energy is shifted out of the

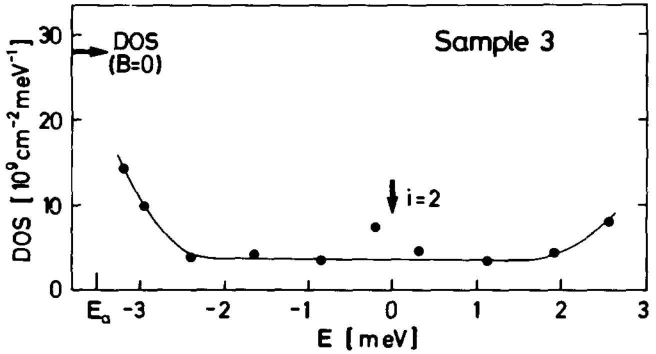

Fig. 3. Density of states as a function of energy. $E = 0$ corresponds to the center between two Landau levels.

Table 1
Sample parameters

Sample	n (cm^{-2})	μ ($cm^2\ V^{-1}\ s^{-1}$)	i	D^{min} ($cm^{-2}\ meV^{-1}$)
1	3.5×10^{11}	550,000	2	$2\ \times10^9$
1	3.5×10^{11}	550,000	4	$2\ \times10^9$
2	1.4×10^{11}	400,000	2	$2\ \times10^9$
3	1.8×10^{11}	190,000	2	3.6×10^9
4	3.0×10^{11}	170,000	2	3.8×10^9
5	4.2×10^{11}	105,000	2	$5\ \times10^9$
5	4.2×10^{11}	105,000	4	$5\ \times10^9$
6	1.7×10^{11}	14,000	2	$14\ \times10^9$

symmetry point between two Landau levels by more than the thermal energy kT, the contribution of the Landau level with the higher activation energy becomes unimportant.

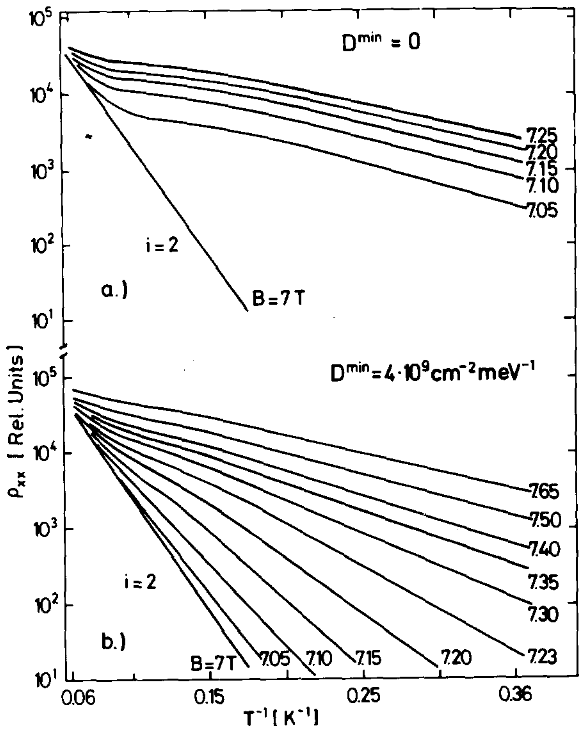

Fig. 4. Calculated resistivity ρ_{xx} as a function of temperature (eq. (4)) at different magnetic field values. The Gaussian linewidth is $\Gamma = 0.25\sqrt{B}$ (T) meV for both the upper and lower curves but different background densities D^{min} are assumed.

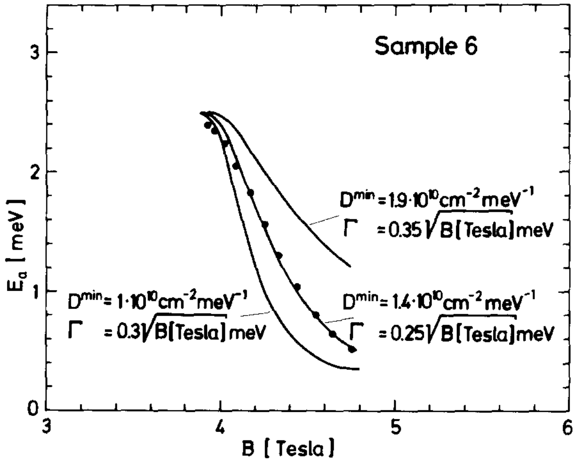

Fig. 5. Measured activation energies as a function of the magnetic field compared with activation energies deduced from calculated curves (eq. (5)) using different combinations of background density of states D^{min} and Gaussian linewidth Γ.

The experimental result that the density of states is constant within 50% of the energy between Landau levels is typical for all samples investigated. Some samples show an asymmetry of the DOS relative to integer filling factor with a stronger increase at the high energy side.

Measurements of the DOS at filling factors $i = 2$ and $i = 4$ for one and the same sample show that the minimal density of states is nearly independent of the filling factor and therefore of the energy separation between Landau levels. This result is consistent with an energy independent background DOS in the tails of the levels. The value of the background density of states D^{min} depends on the mobility of the sample. A reduction of the mobility by a factor of 40 leads to an increase of D^{min} by a factor of 7. The corresponding data are summarized in table 1.

Calculations of ρ_{xx} on the basis of eq. (4) demonstrate that the finite density of states D^{min} in the mobility gap influences strongly the result. Fig. 4 shows such calculations with and without a background DOS of 4×10^9 cm^{-2} meV^{-1}. The linewidth of the Gaussian DOS is $\Gamma = 0.25\sqrt{B}$(T) meV. A reconstruction of the DOS by deducing "activation energies" from fig. 4b in the temperature range of the experiments demonstrates that the constant background DOS is reproduced within 20%. However, the determination of the DOS close to the center of the Landau level becomes inaccurate, since a strongly varying DOS at the Fermi energy leads to a temperature dependent E_F. Moreover, a temperature dependent prefactor in front of the exponential term in eq. (4) becomes important if the activation energy is small. From our computer simulations $\rho_{xx}(T)$, we got the result that the experimental data are best described with a temperature dependent prefactor corresponding to

$$\rho_{xx}=\frac{\text{const.}}{T}\sum_n \exp\left(-\frac{|E_n-E_F|}{kT}\right). \tag{5}$$

The determination of $D^{\min}$ is within the uncertainty of 20% not influenced by the prefactor.

Fig. 5 summarizes the data obtained for our heterostructure with a mobility of only 14,000 $\text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ at $T=4.2$ K. This low mobility is obtained by irradiating a high mobility sample ($\mu=550{,}000$ $\text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$) with 1 MeV electrons. The measured "activation energy" is plotted as a function of the magnetic field. The same dependence is obtained from calculated ρ_{xx} curves (eq. (5)) with a background DOS of 14×10^9 $\text{cm}^{-2}\ \text{meV}^{-1}$ in addition to a Gaussian line shape with $\Gamma=0.25\sqrt{B}$ (T) meV.

It should be noted that the "point-by-point" construction of the DOS discussed in this paper becomes incorrect in the energy region where the DOS change drastically with energy, so that computer simulations are necessary for a determination of the DOS close to the center of the Landau levels.

References

[1] G. Ebert, K. von Klitzing, C. Probst, E. Schuberth, K. Ploog and G. Weimann, Solid State Commun. 45 (1983) 625.

[2] E. Gornik, R. Lassnig, G. Strasser, H.L. Störmer, A.C. Gossard and W. Wiegmann, Phys. Rev. Letters 54 (1985) 1820.

[3] J.P. Eisenstein, H.L. Störmer, V. Narayanamurti, A.Y. Cho and A.C. Gossard, Surface Sci. 170 (1986) 271.

[4] For a review, see: T. Ando, A.B. Fowler and F. Stern, Rev. Mod. Phys. 54 (1982) 427.

[5] T. Ando and Y. Murayama, J. Phys. Soc. Japan 54 (1985) 1519.

[6] T. Ando, J. Phys. Soc. Japan 53 (1984) 3101.

[7] S.A. Trugman, Phys. Rev. B27 (1983) 7539.