Specific Heat of Two-Dimensional Electrons in GaAs-GaAlAs Multilayers

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(Received 15 January 1985)

We report the first observation of the magnetic-field–dependent electronic specific heat in GaAs-GaAs multilayers. With a heat-pulse technique oscillations of the sample temperature on the order of millikelvins were observed. Both intra- and inter-Landau-level contributions could be distinguished. Theoretical fits to the data reveal a density of states consisting of Gaussian peaks on a flat background.

PACS numbers: 65.40.Em, 71.25.Hc, 73.40.Lq

Electrons confined to quasi two-dimensional (2D) motion due to electric fields in heterojunctions or multilayers are known to show interesting phenomena. In particular, if an external magnetic field is applied perpendicular to the interface, the density of electronic states at high magnetic fields is then characterized by peaks in the vicinity of Landau levels and by almost zero values between them. This results in a pronounced oscillatory character of practically all physical phenomena including electrical, magnetic, and thermal properties.

In all physical properties which are measured via transport effects, pinning of the Fermi level takes place in regions of localized states which do not conduct the current.[1] However, for equilibrium properties such as the specific heat or the magnetization the difference between localized and nonlocalized states is of no importance. Therefore equilibrium properties reveal the total density of states.

Zawadzki and Lassnig[2] have recently shown that the specific heat for 2D electrons in GaAs shows a pronounced oscillatory character for a Gaussian density of states. It consists of intra- and inter-Landau-level contributions. The temperature dependence of the intralevel specific heat shows a maximum for a level width Γ to kT ratio of ~ 5.

Previously Kunzler, Hsu, and Boyle[3] have investigated temperature oscillations of oriented Bi samples as a function of the magnetic field. Oscillations of millikelvins were found at 1.3 K, indicating a change of the electronic specific heat due to a variation of the density of states in the magnetic field. Magnetothermal oscillations were employed to analyze the Landau and spin level splittings at the Fermi energy.

In this paper we report the first measurements of the magnetic-field–dependent specific heat for 2D electrons in GaAs-GaAlAs multilayers. We will show that quite conclusive results about the form of the density of states can be obtained by comparing the experimental results with calculations for different types of densities of states (Gaussian, Lorentzian, and Gaussian with constant background).

We have applied a heat-pulse technique[4–6] to determine the electronic specific heat. In this technique a short-duration heat pulse is applied at one point of the sample, increasing the sample temperature by ΔT. Thermal isolation is achieved by hanging the sample on four 5-μm-thick superconducting wires, which connect the sample with the heat bath and serve as electrical connections. The wires remain superconducting in the investigated magnetic field range. The resistance variation due to ΔT of a detector film is measured at a different point of the sample. The contributions of the electronic specific heat lead to an oscillatory resistance variation as a function of magnetic field.

The experiments were performed on two different multilayer materials: Sample 1 consisted of 172 double layers of 200-Å GaAs and 200-Å GaAlAs and residual buffer layers of 1.2-μm GaAlAs on both surfaces, grown on a semi-insulating GaAs substrate. The substrate was etched away to a total sample thickness of ~ 10 μm. The mobility at 4.2 K varied between 30 000 and 40 000 $cm^2/V\cdot s$ for different sample pieces. The density was $n_s = (6.3 \pm 0.4)\times 10^{11}$ cm^{-2}. Sample 2 consisted of 94 layers of 220-Å GaAs and 500-Å GaAlAs. The mobility at 4.2 K was $\sim 80 000$ $cm^2/V\cdot s$, and the density was $n_s = (7.7 \pm 0.3)\times 10^{11}$ cm^{-2}. Samples are prepared by polishing and etching the material down to a total sample thickness of 20 μm.

As a temperature detector a 1000- to 2000-Å-thick Au-Ge (8%-Au) film,[7] which was evaporated on the sample surface, was used. The Au-Ge films were prepared in such a way that they showed an exponential temperature dependence with the same exponent over the whole temperature range between 1.5 K and 300 K. The major advantage of these films is that they show a very small resistance change in magnetic fields up to 10 T (between 0.5% and 1%).

A second 100-Å-thick Ni-Cr film was deposited on the same sample surface as a heater. The superconducting wires were connected to the heater and detector film with small dots of silver epoxy.

The sample was mounted in an evacuated tube, which was immersed in the helium bath. The sample area varied between 2×2 mm^2 and 4×4 mm^2, the heater and detector film areas varied between 0.5×1.5 mm^2 and 1×3 mm^2. Sample size and the length of the superconducting wires produced thermal time constants τ_1 between 5 and 30 ms in the temperature range between 1.5 and 4.2 K.

The sample was heated with electric-field pulses of 0.1-ms duration. The temperature change of the sample was measured with a box-car technique at the end of the heat pulse with a gate length of ~10 μs. The time τ_1 was directly evident from the decay time of the temperature change. The application of this technique requires that the thermal relaxation time within the sample τ_2 is considerably shorter than τ_1. This requirement is fulfilled in the whole temperature range. τ_2 values in the GaAs-GaAlAs multilayer can be estimated from thermal conductivity data of GaAs to be well below 1 μs even at 1 K. The thermal conductivity of bulk GaAs ranges between 1 and 0.1 W/cm$\cdot$s at 2 K, dependent on the doping,[8] and increases with temperature. If we take into account the very low mobility transverse to the multilayers, a realistic lower limit for the thermal conductivity of the sample is 0.01 W/cm$\cdot$s. This value is still 4 orders of magnitude higher than the measured thermal conductivity of the superconducting wires which is $\sim10^{-7}$ W/cm$\cdot$s at 2 K.

As a temperature standard we use the vapor pressure of the surrounding liquid-helium bath. The temperature sensitivity of the detector film was about 1 MΩ/K at 4.2 K and ~5 MΩ/K at 2 K resulting in a maximum resolution of 0.1 mK including long-time signal averaging. The absolute temperature accuracy is ~5 to 10 mK. A sufficiently low bias current was applied to the detector film to avoid self heating. The heater film showed very little variation of resistance with temperature and magnetic field which is particularly important for measurements with the pulse method. The whole experiment is based on the assumption that only the electronic specific heat varies with magnetic field in an oscillatory manner while all other contributions remain constant.

Figure 1 shows the observed temperature change of sample 1 expressed as curves ΔR vs the magnetic field for 4.2 and 1.5 K as obtained from averaging over ten runs. The applied heat pulse raised the sample temperature at 4.2 K by 0.5 K and at 1.5 K by 0.03 K. The dashed curves ΔR_F show the background dc resistance variation of the detector film on an extended scale.

Oscillations of the sample temperature are clearly observed with a spikelike behavior for integer filling factors. The filling factor is defined by $\nu = n_s/(2eB/h)$, neglecting spin splitting, and corresponds to the number of Landau levels within the Fermi surface. An integer filling factor gives the number of fully occupied Landau levels. For comparison the dotted curve shows the oscillatory behavior of the conductivity σ_{xx} at 4.2 K of the same sample measured before being thinned down.

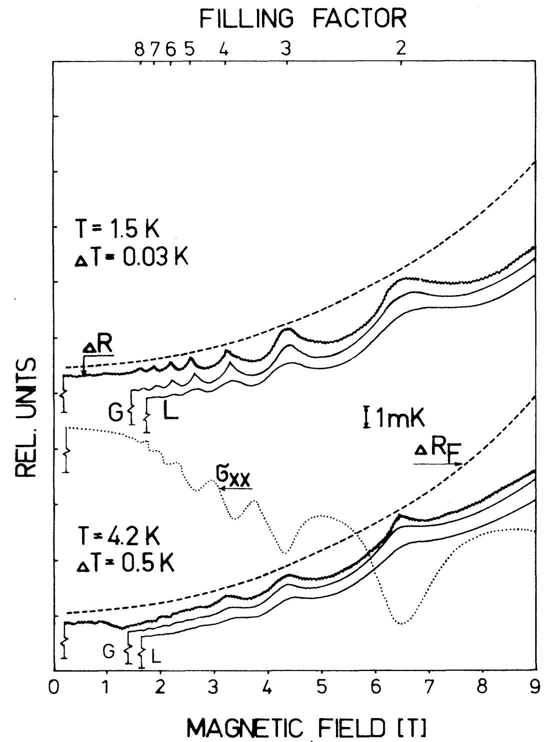

FIG. 1. Temperature change of sample 1 measured with a Au-Ge film as a function of magnetic field (curves denoted ΔR) for a heat pulse raising the sample temperature by ΔT. The dc dependence of the Au-Ge resistance is shown by curves ΔR_F. Theoretical calculations of the temperature change for a Gaussian density with a level width $\Gamma = 2.5$ meV and a background level $x = 0.25$ (curves G) and a Lorentzian density of states with $\Gamma = 2.5$ meV (curves L) are also shown but shifted for clarity.

The size of the ΔR signal is proportional to the rise in sample temperature. The data show that the sample temperature is higher for integer filling factors than for values in between, which reflects the variation of the electronic specific heat. This variation has to be considered relative to the background ΔR_F. Since the variation of the sample temperature is similar to the oscillation in σ_{xx} we can be confident that we observe the temperature change mainly due to a variation of the electronic specific heat. The oscillations which reflect only intra-Landau–level contributions for sample 1 are more pronounced with decreasing temperature and increasing magnetic field. The temperature changes are on the order of several millikelvin, which amounts to less than 1% of the total temperature change through the heat pulse at 4.2 K and to nearly 10% at 1.5 K.

A partly similar behavior is observed for sample 2 as shown in Fig. 2. For this sample, data for three different lattice temperatures are given. Additional spikes are observed for 4.2 and 5.0 K as a result of inter-Landau-level contributions. The total temperature change is smaller than for sample 1 since this sample has only 92 double layers for a total thickness of 20 μm. The interpretation of the spikes at lower magnetic fields as inter-Landau-level contributions is confirmed through their temperature dependence: The inter-Landau-level contributions are only present at higher temperatures, in agreement with the theoretical prediction.[2]

From these data we can in principle determine the form of the density of states. We have therefore performed calculations of the electronic specific heat C_{el} according to Ref. 2 using different forms of the density of states:

(a) Gaussian density of states:

$$\rho_G(\epsilon) = (\pi l^2)^{-1} \sum_n (2/\pi)^{1/2} \Gamma_G^{-1} \exp\{-[(\epsilon-\lambda_n)^2/\Gamma_G^2]\}, \tag{1}$$

where $l=(\hbar/eB)^{1/2}$ is the Landau radius, $\lambda_n = \hbar\omega_c(n+\frac{1}{2})$ is the Landau energy, and Γ_G is the broadening parameter.

(b) Lorentzian density of states:

$$\rho_L(\epsilon) = (\pi l^2)^{-1} \sum_n (\pi\Lambda_L)^{-1} \{1+[(\epsilon-\lambda_n)^2/\Gamma_L^2]\}^{-1}. \tag{2}$$

(c) Gaussian density with a constant background density:

$$\rho_{GB}(\epsilon) = \rho_G(\epsilon)(1-x) + (\pi l^2)^{-1}(x/\hbar\omega_c)\theta(\epsilon), \tag{3}$$

where x is the percentage of flat background states.

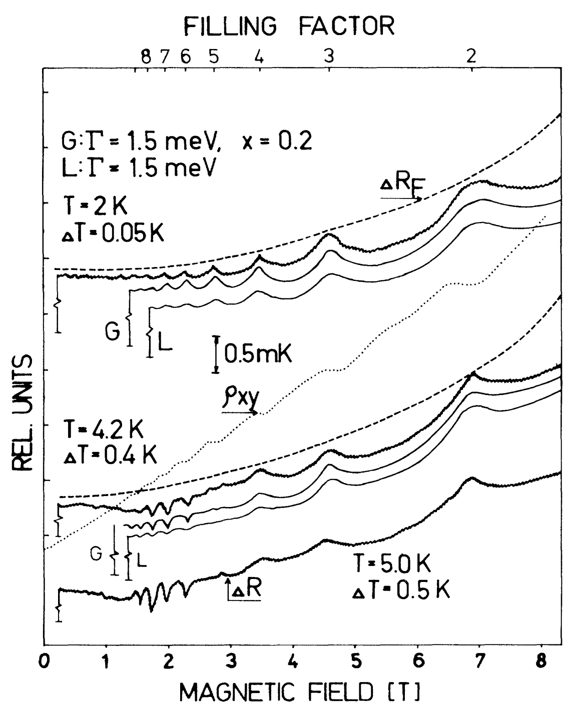

FIG. 2. Same plots as in Fig. 1 for sample 2 with $\Delta T = 0.5$ K at 5 K, $\Delta T = 0.4$ K at 4.2 K, and $\Delta T = 0.05$ K at 2 K. Theoretical curves are plotted for a Gaussian density of states with $\Gamma = 1.5$ meV and $x = 0.2$ and a Lorentzian density with $\Gamma = 1.5$ meV.

In the first step the Fermi level ζ is calculated numerically for a given electron density n_s, level width Γ, and temperature. The level width Γ is defined as the total width at half maximum. The same value is used for the different level shapes which means $\Gamma = 1.2\times\Gamma_G$ and $\Gamma = 2\times\Gamma_L$. With the determined Fermi level the electronic specific heat is calculated for a constant temperature and level width Γ as a function of magnetic field:

$$C_{el} = \int [df(\epsilon-\zeta)/dT] \rho(\epsilon)\, d\epsilon. \tag{4}$$

To compare the calculation with the experiment we have to calculate the temperature change $\Delta T(B)$ due to a change in C_{el}. A constant heat input ΔQ is applied to the sample resulting in a temperature increase ΔT, which has to be determined from the following equation:

$$\Delta Q = \tfrac{1}{4}\alpha[(T+\Delta T)^4 - T^4] + C_{el}(T,B,\Gamma)\Delta T \tag{5}$$

with $C_{lat} = \alpha T^3 = 6.21\times10^{16} kT^3$ (cm^{-3}) and $\theta_D = 344$ K.[9] The difference between $C_{el}(T+\Delta T)$ and $C_{el}(T)$ is neglected, since the temperature dependence of C_{el} is weak for the kT/Γ values considered (between 0.15 and 0.25).[2]

The calculated $\Delta T(B)$ functions for the different densities of states are plotted in Figs. 1 and 2. The curves take into account the ΔR_F background. The best fit to the data is obtained for the curves denoted G, which are shifted for clarity. Curves G in Fig. 1 are for a Gaussian level width $\Gamma = 2.5$ meV and a constant background of $x = 0.25$ [density function $\rho_{GB}(x)$]. The curves denoted L are for a Lorentzian density and the same Γ. It is directly evident that curves G agree very well with the experimental data for both temperatures but especially with the 1.5-K data. The form and

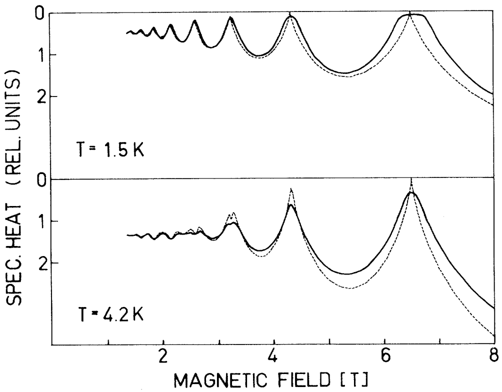

FIG. 3. Calculated electronic specific heat (inverted for comparison with the experiment) of sample 1 as a function of magnetic field for a Gaussian density of states with $\Gamma = 2.5$ meV, $x = 0.25$ (solid curves) and $x = 0$ (dashed curves) for 4.2 and 1.5 K.

the relative size of the oscillations for the Lorentzian density never fits as well as the Gaussian density.

The question of whether a pure Gaussian density ρ_G is able to explain the data can be answered from Fig. 3, where C_{el} is plotted for ρ_G with $\Gamma = 2.5$ meV and ρ_{GB} with $x = 0.25$ and $\Gamma = 2.5$ meV: It is clearly evident that the main difference is apparent at high magnetic fields where the constant background results in a flat part for integer-filling factors (solid curves). A Gaussian density ρ_G will result in a sharp spikelike behavior at high magnetic fields (dashed curves). At low magnetic fields the difference is rather small. The observed flat or rounded part of the ΔT oscillation at high magnetic fields gives a strong indication for a flat background density.

The same conclusion can be drawn from Fig. 2, where we have fitted the experimental curves for 4.2 and 2 K with a level width $\Gamma = 1.5$ meV for a Gaussian density with a background of $x = 0.2$ (denoted G) and a Lorentzian density (denoted L). From the fit at 2 K a certain amount of constant-background density is evident again. The Lorentzian density leads to too-small oscillations. At 4.2 and 5.0 K inter-Landau-level contributions at low magnetic fields are observed. Only the Gaussian density of states $\rho_{GB}(\epsilon)$ explains the size of the spikes and the behavior at 2 K at the same time.

Magnetization measurements have been performed on material similar to sample 1.[10] The rather smooth oscillations of the magnetization with field were fitted with a Gaussian density of states with $\Gamma \sim 4$ meV [if we use our definition of $\rho_G(\epsilon)$]. The samples used had a somewhat lower mobility ($\sim 20\,000$ cm^2/V·s). These results are consistent with our analysis since a smaller Γ and a constant background would lead to similar results.

In conclusion, we can state that among the theoretical models examined here, the experimental data are best explained if the form of the density of states for both materials is taken to be Gaussian with a flat background density. Sample 1 with the lower mobility has a level width of $\Gamma = 2.5$ meV and a background with $x = 0.25$, and sample 2 had a level width of $\Gamma = 1.5$ meV and a somewhat lower background with $x = 0.2$.

The origin of the density of states background is not clear. Electron density fluctuations from layer to layer and within the layers do not amount to more than 5% in our case. In Ref. 10 fluctuations of 13% were found for a similar material but a considerably larger sample. That means that the density of states resembles closely Gaussian peaks with a certain amount of rather flat background. This is consistent with results from temperature-dependent conductivity measurements in high magnetic fields which also indicate a constant background density with $x \sim 0.1$ even for high-mobility samples.[11]

This work was partly supported by the Fonds zur Föderung der Wissenschaftlichen Forschung and the Jubiläumsfonds der Österreichischen Nationalbank.

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