Density of states in *n*-type inversion layers at the (100) surface of Si in a quantizing magnetic field

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A comparison was made of the experimental densities of states half-way between the Landau levels, determined by a variety of methods. The results indicated that the methods based on thermally activated measurements of the conductivity could give rise to errors in the density-of-states probably because of a shift of the mobility edge with change in the Fermi energy. It was demonstrated experimentally that for a given value of the density of states between the Landau levels the activation energy (and consequently the position of the mobility edge) could vary with the occupancy factors ($i = 4, 8, 12$). The thermodynamic density of states between the Landau levels decreased as a result of cooling. A hypothesis of nonlinear screening made it possible to explain qualitatively the observed behavior of the density of states.

INTRODUCTION

Several methods have been used to determine the density of states in a two-dimensional electron gas under the quantum Hall effect conditions; these methods utilize measurements of the transport characteristics and are based on two different phenomena. The first group of methods[1–4] is based on the activated temperature dependence of the conductivity

$$\sigma_{xx}=\sigma_0 e^{-W/k_BT} e^{-W/k_BT}\cosh(\varepsilon_F/k_BT), \qquad (1)$$

where W is the energy of the mobility edge and ε_F is the chemical potential measured from the midpoint between the Landau levels. These methods yield the activation energy and, consequently, ε_F when the electron density or, in the more general case, the occupancy factor is varied. The second group of methods[5–9] depends on the change in the contact potential due to a change in a magnetic field or in the carrier density. We can readily see that the quantities determined in experiments of the first and second types may not be identical. In fact, in the former case the determination involves the shift of the chemical potential relative to the mobility edge (which itself can shift relative to the center of a Landau level), whereas in the latter case the shift of the chemical potential is determined relative to the chemical potential of another substance. Naturally, the chemical potential of this "reference" substance is independent of the occupancy factor of the two-dimensional electron system, but nevertheless the whole ladder of the Landau levels and, consequently, the chemical potential of a two-dimensional electron gas may be shifted (or oscillate with change in the occupancy factor) relative to the chemical potential of the reference material.

Three cases of qualitlatively different behavior of the electron system in a semiconductor are presented in Fig. 1. The first case *a* corresponds to an almost ideal electron system. In this case we have $\mu + \mu_1 = \text{const}$ (where the chemical potential μ is measured from the bottom of the two-dimensional subband and μ_1 is measured from the chemical potential of the reference sample) and the thermodynamic densities of states determined in various experiments from $|\partial N_s/\partial\mu|$, $|\partial N_s/\partial(W-\varepsilon_F)|$, and $|\partial N_s/\partial\mu_1|$, are identical. (The thermodynamic density of states $D^* = \partial N_s/\partial\varepsilon_F$ should be distinguished from the density of states defined by $D = (\partial N_s/\partial\varepsilon)|_{\varepsilon=\varepsilon_F}$.)

The second case (*b*) corresponds to a symmetrically broadened Landau level. It has been shown experimentally[10–12] that the width of the level depends on the position of the chemical potential. It is also known that the position of the mobility edge on the energy axis may not coincide with the center of the Landau level (see Ref. 13 and also the results reported below). There are as yet no experimental data on a possible shift of the mobility edge due to a change in the electron density. However, there are neither any data which would demonstrate that the edge is fixed. We can expect changes in the position of the mobility edge relative to the center of the Landau level because of a change in the screening caused by a change in the occupancy factor. Then, the experimentally determined quantities $|\partial N_s/\partial(W-\varepsilon_F)|$ and $|\partial N_s/\partial\mu_1|$ are not equal even for $\mu + \mu_1 = \text{const}$.

In the third case *c* it is assumed that the potential relief is created by charges of one sign. As the screening deteriorates, the ladder of the Landau levels shifts on the energy scale[14] so that $|\partial N_s/\partial(W-\varepsilon_F)| \neq |\partial N_s/\partial\mu_1|$ applies even under the simplest conditions when the mobility edge coincides with states corresponding to the maximum density. The most general case is a combination of the variants *b* and *c*.

We can therefore expect the quantities regarded as the thermodynamic of density of states, deduced from experiments of different types, to be generally different. We determined the density of stated D_0^* in the case when the Fermi level was located half-way between the Landau levels. As shown below, the various methods can give different results even in this case.

In the present study we used two methods based on the activated temperature dependence of the conductivity:

1) determination of the activation energy for various carrier densities from the temperature dependence of the conductivity[2];

2) analysis of nonlinear characteristics in the case of filamentation of the Hall current[3];

we also used a method based on oscillations of the contact potential:

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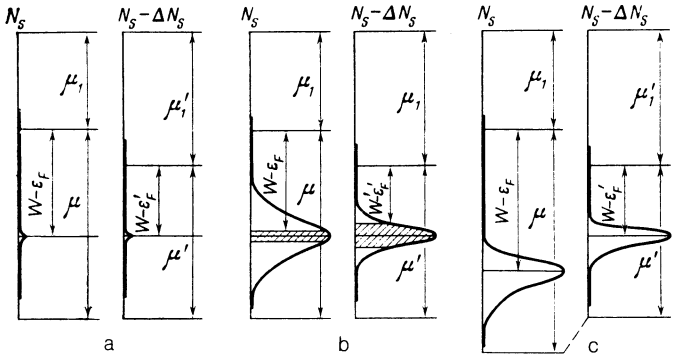

FIG. 1. Possible variants of the behavior of the electron system: a) ideal case; b) mobility edge does not coincide with the center of the Landau level; c) the concentrations of the attractive and repulsive impurities are not equal; here, μ and μ_1 are the values of the chemical potential measured relative to different origins; W and ε_F are the positions of the mobility edge and of the Fermi energy. The primes identify the same quantities after a change in the electron density N_S by an amount ΔN_S.

3) determination of the charge current in the case of low-frequency modulation of the voltage between the gate and a two-dimensional electron layer.[5-9]

At reasonable temperatures the range of validity of the activation methods is limited on one side by weak magnetic fields, whereas the third method is unsuitable in the case of low values of σ_{xx}, i.e., in the range of strong magnetic fields. (The limits of validity of this method are set by dynamic effects.) The purpose of our experiments was to investigate the density of states half-way between the Landau levels in the range of temperatures and magnetic fields where all three methods could be employed.

1. SAMPLES AND EXPERIMENTAL METHOD

Our measurements were made on four field-effect silicon transistors in which the plane of a two-dimensional electron gas coincided with the (100) plane. Two samples had the Corbino geometry. The inner diameter of the ring-shaped gate was 225 μm and the outer diameter was 675 μm. Samples Nos. 3 and 4 were Hall transistors with a rectangular gate of dimensions 250×2500 μm and 400×1200 μm. The main parameters of the investigated samples are listed in Table I. Measurements of the conductivity were made at temperatures from 4.2 to 0.3 K in magnetic fields up to 10 T.

The activation energy was determined using the dependences $\sigma_{xx}(T)$ or $\rho_{xx}(T)$ in a region where the logarithm of the measured quantity was a linear function of T^{-1}. The subsequent analysis was fully similar to that proposed in Ref. 2. An example of the experimentally determined dependence of the change in the activation energy on the electron density is demonstrated in Fig. 2. As in the preceding investigations,[2,4] the positions of the experimental points could be approximated quite accurately by a straight line with the slope governing the density of states.

Measurements of the density of states under nonlinear conditions were made using samples with the Corbino geometry. For a given current J through a sample we measured the drain–source voltage ΔU as a function of the gate potential V_g. In the case of sufficiently high currents a Hall current filament appeared and the $\Delta U(V_g)$ curve acquired a characteristic form shown in Fig. 3. Following the results of Refs. 3 and 15, the density of states D_0^* was determined (Fig. 3) from the linear part of the dependence of $\sinh[C_0\Delta U_{max}/2K_BTeD_0^*]$ on the current J. (Here, C_0 is the capacitance of an MOS structure per unit area and ΔU_{max} is identified in Fig. 3.)

The charge current J_{mod} due to modulation of the voltage across the gate by $V_g + V_{\text{mod}}$ was determined employing a bridge circuit at a frequency of 20 Hz. At each temperature and magnetic field a check was made of the linearity of the conditions and of the capacitive nature of the signal (i.e., the absence of a comparable signal in a phase rotated by $\pi/2$), and of the frequency independence of measured capacitance. For the purpose of control the modulation frequency was reduced by a factor of 3.

It is known[8] that an allowance for the contact potential yields the following expression for the density of states:

$$C^{-1}=C_0^{-1}+e^{-2}(D^*)^{-1}, \qquad (2)$$

where C is the experimentally determined "apparent" capacitance: $C=J_{\text{mod}}/\omega V_{\text{mod}}$. Since the quantity C_0^{-1} itself depends on V_g because of a change in the wave function of two-dimensional electrons due to a change in the applied field, we determined C_0^{-1} independently by measuring the charge current in the absence of a magnetic field. One should note that in this case $C^{-1}=C_0^{-1}+e^{-2}D_0^{-1}$, where $D_0=2m/\pi\hbar^2$ (m is the effective mass, of an electron). An example of an experimental curve is shown in Fig. 4.

2. COMPARISON OF THE RESULTS OBTAINED BY VARIOUS METHODS

The dependence of the minimum of the density of states on the magnetic field, determined by a variety of methods for

TABLE I.

No.	Type	μ_{max} (4,2 K), $m^2\cdot V^{-1}\cdot s^{-1}$	N_S (μ_{max}), cm^{-2}	d, Å
1	Corbino	1,9	$9\cdot10^{11}$	1370
2	Corbino	2,1	$1\cdot10^{12}$	1310
3	Hall	2,2	$5\cdot10^{11}$	2540
4	Hall	1,3	$1\cdot10^{12}$	1630

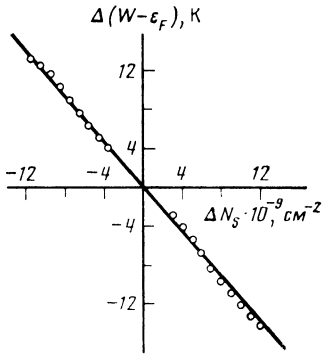

FIG. 2. Changes in the activation energy plotted as a function of the electron density. Sample No. 2, $H = 8.7$ T.

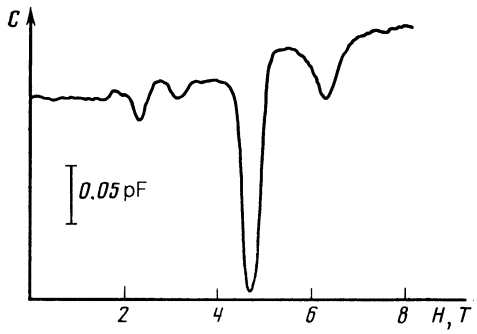

FIG. 4. Experimental dependence of the capacitance of a structure on the magnetic field at a fixed electron density.

occupancy factors $i = 4$, 8, and 12, is plotted in Fig. 5. A change from one point to another was induced by a simultaneous change of the sign of the field H and of the gate voltage in such a way that the occupancy factor remained constant (i = const) and the Fermi level ε_F was half-way between the Landau levels. Our own points, determined by the second and third methods, were obtained at $T = 1.55$ K. Moreover, we included in this figure the results obtained by other authors.[7,16] One of the results was deduced by interpolation of the data of Ref. 7, where measurements were made by the magnetocapacitance method, corresponding to the third method in our paper. The other two values were taken from Ref. 16, where measurements were made firstly by an optical method at 1.5 K and then using the activation dependence of the conductivity σ_{xx}.

It is worth noting that the densities of states measured by the same method using different samples or the same sample but with different occupancy factors were similar. Since the mobility μ^* in zero magnetic field not only varied from sample to sample, but even in the case of a single sample it was a function of the electron density, we must conclude that the density of states at the minimum cannot be some universal function of the product μ^*H.

As pointed out already in Ref. 17, the densities of states obtained by different methods are different. The methods based on thermal activation are in mutual agreement and give for D_0^* a value for differing from the results of measurements based on oscillations of the contact potential. The most probable reason for this difference is the dependence of the position of the mobility edge on the position of the Fermi level.

We can easily see that in this case the density of states deduced from thermal activation cannot be identical with the true one even in the presence of an electron-hole symmetry. (In this case the third method may give the correct value of D_0^* because any change in the position of μ results in a symmetric change in the screening and in the position of the Landau level ladder.) We shall expand W as a series in ε_F in Eq. (1):

$$\sigma_{xx} \propto \exp\left\{-\frac{W_0}{k_B T}\right\} \exp\left\{-\frac{\partial^2 W}{\partial \varepsilon_F^2}\frac{\varepsilon_F^2}{2k_B T}\right\} \mathrm{ch}\left(\frac{\varepsilon_F}{k_B T}\right). \quad (3)$$

Model calculations demonstrate that in the range of temperatures and ε_F the function usually employed in the determination of the densities of states given by Eq. (3) agrees to within 10% with the function $\exp(-W_0/k_B T)\cosh(\gamma\varepsilon_F/k_B T)$ (for a suitably selected value of γ). The experimental points could be fitted with the same degrees of success to any

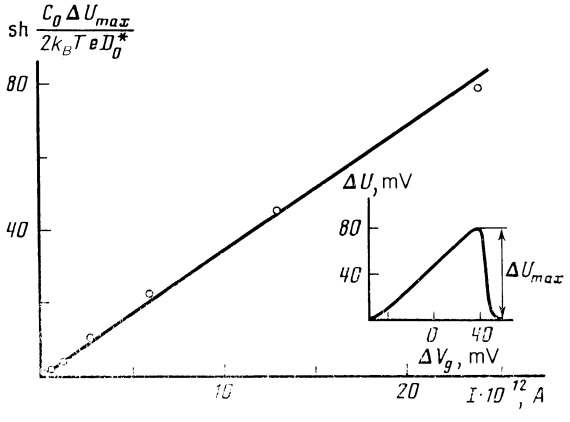

FIG. 3. Example of an analysis of the nonlinear characteristics in the case of filamentation of the Hall current. The inset shows the experimental dependence of the voltage between the drain and source on the gate voltage applied to sample No. 1.

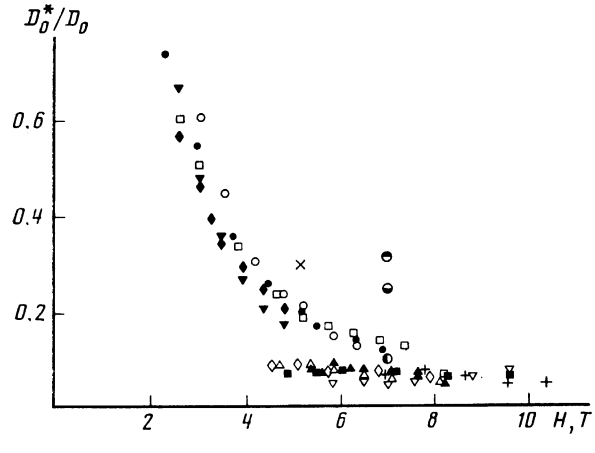

FIG. 5. Changes in the minimum density of states, measured by a variety of methods, with the applied magnetic field. Method 1: △) $i = 4$, ▲) $i = 8$ (sample No. 1); ◇) i = 4 (sample No. 3); +) $i = 4$ (sample No. 2). Method 2: ■) $i = 4$, ▽) $i = 8$ (sample No. 1). Method 3: ●) $i = 8$, ○) i = 4, □) i = 12 (sample No. 1); ▼) i = 4, ◆) i = 8 (sample No. 3); ×) $i = 4$ (sample No. 4). The point denoted by ◐ is taken from Ref. 7 and it was obtained by method 3; the point denoted by ◒ was obtained by method 1 and that denoted by ◓ was deduced from optical measurements (see Ref. 16).

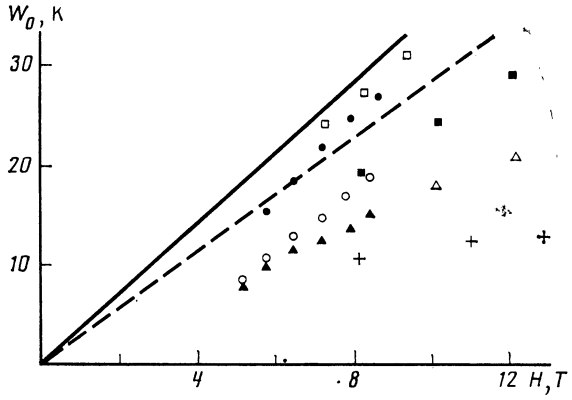

FIG. 6. Dependence of the activation energy on the magnetic field for different occupancy factors: ●) i = 4, ○) i = 8, ▲) i = 12 (sample No. 2). For comparison we included points taken from Ref. 13: □) $i = r$, ■) $i = 8$, △) i = 12, +) $i = 16$. The continuous curve corresponds to $\hbar\omega_c/2$ and the dashed curve represents the result after subtraction of the spin splitting.

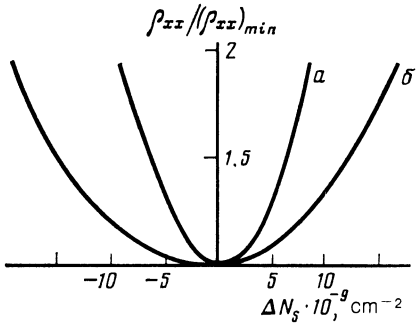

FIG. 7. Comparison of the dependences $\rho_{xx}(N_S)$ near a minimum: a) samples used in the present study; b) sample used in the study reported in Ref. 2; $H = 4.7$ T, $T = 2.1$ K.

of the dependences under discussion here. It should be remembered that $\gamma < 1$ if $\partial^2 W/\partial\varepsilon_F^2 > 0$ and $\gamma > 1$ if $\partial^2 W/\partial\varepsilon_F^2 < 0$. The reduction in the density of states compared with its true value corresponds to the second case, when the mobility edge shifts toward the Fermi level if ε_F shifts away from the midpoint between the Landau levels.

This discussion is based on the circumstance that the mobility edge may not coincide with the center of a Landau level. This was checked experimentally. Figure 6 shows the dependence of the activation energy W_0 on the applied magnetic field for various occupancy factors, each of which is an integer. It is clear from this figure that the measured value of the activation energy not only disagrees with the expected value, but the disagreement increases on increase in the occupancy factor. The least expected is the observation that the activation energy changes greatly, whereas measurements of the density of states by the activation or magnetocapacitance methods indicate constancy of any parameter of the quantum levels on going from complete filling of one Landau level to complete filling of two or three levels.

Our numerical values of the density of states are in excellent agreement with the results of Ref. 7. This reference gives the data obtained using two measurement methods. Figure 5 shows only the value of D_0^* taken from Ref. 7, because measurements under nonlinear conditions[7,18] have been made only at 2 K. Nevertheless, even in this case the density of states is in full agreement with the value obtained by us (the discrepancy between the results does not exceed 40%).

It is clear from Fig. 5 that there is a considerable difference between the results of the present study and those reported in Refs. 2 and 16. If we compare the samples from Refs. 2 and 16 with the samples listed in Table I in respect of two parameters, which are the mobility at the maximum and the electron density at which the mobility maximum is observed, it is found that the samples used in measurements on these two occasions were practically the same. However, the values determined by the sane method for the same sample differ by a factor of four. Moreover, the values of the density of states obtained in Ref. 16 by optical and activation methods are in agreement and exceed considerably the values obtained by any method in the present study. The difference is clearly due to the existence of additional long-period fluctuations in the samples used in Refs. 2 and 16. This can be demonstrated by comparing the values of $\sigma_{xx}/(\sigma_{xx})_{min}$ or $\rho_{xx}/(\rho_{xx})_{min}$ in the vicinity of one of the conductivity minima. The results of such a comparison are presented in Fig. 7. (The authors are deeply grateful to V.B. Timofeev and M.G. Gavrilov who supplied the originals of the earlier experimental records.) If we assume that the additional broadening of the curve is related to macroscopic inhomogeneities in a sample, we can estimate roughly the energy scale of such inhomogeneities. Fluctuations of the electron density were estimated at that point of the broadened curve where the change in the mobility was comparable with the mobility at the minimum. It was found from Fig. 7 that $\delta N_s \sim 4\times 10^{10}$ cm^{-2}. The density of states in a magnetic field of 4.7 T was 3×10^{13} cm$^{-2}\cdot$eV^{-1}. The corresponding scale of the energy fluctuations was 1 meV, in full agreement with 3–4 meV obtained in Ref. 16 from optical measurements.

Long-period fluctuations governing the width of the Landau level and the density of states at the minimum in Refs. 2 and 16 are essentially a constant property of the investigated samples and are most likely due to an unsatisfactory cooling procedure. In any case, broadening of the minima of the electrical conductivity or resistivity in our samples, similar to those shown in Fig. 7, can be observed by altering the cooling procedure. (Samples were usually cooled slowly and the gate was subjected to a voltage of ~ 10 V.)

3. TEMPERATURE DEPENDENCE OF THE DENSITY OF STATES

The methods based on quantum oscillations of the contact potential give the correct density of states half-way between the Landau levels if there is a complete electron-hole symmetry. However, since the wave functions of the neighboring Landau levels have different characteristic dimensions, such a symmetry of the occupancy factors corresponding to our numbers of the quantum levels is clearly disturbed. The existence of an electron-hole symmetry in an ideal two-dimensional electron system would imply also the agreement, on the carrier density scale N_S, as to the positions of the minimum of the density of states and of the conductivity minimum. In the case of real samples such a coincidence is not always observed and this may be due to a slight macroscopic inhomogeneity of the sample.

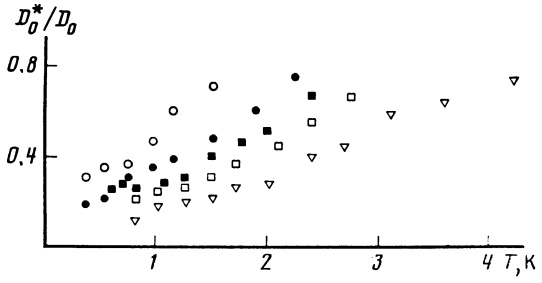

FIG. 8. Temperature dependences of the density of states measured for an occupancy factor $i = 4$ in different magnetic fields $H(T)$: ○) 2.9; ●) 3.3; ■) 3.8; □) 4.3; ▽) 4.9. Sample No. 1, method 3.

An increase in the Landau level number should reduce the differences between the screening by electrons and holes at the adjacent Landau levels, i.e., it should restore the electron-hole symmetry. Since in the case of different occupancy factors (Fig. 5) our experiments yield practically identical values of D_0^* (within the limits of the experimental error in our experiments), we could regard this situation as symmetric and determine the density of states using a method based on oscillations of the contact potential.

The temperature and magnetic-field dependences of the density of states measured by this method for an occupancy factor $i = 4$ are shown in Figs. 8–10. Similar measurements carried out for $i = 8$ gave values which agreed (within the limits of the experimental error) with those given Fig. 8. Each series of the experimental points was determined using a fixed value of the magnetic field. In the investigated range of fields and temperatures the density of states fell monotonically as a result of cooling. Our earlier nonmonotonic temperature dependences deduced from the nonlinear characteristics[19] should be attributed to a change in the quantity $\partial^2 W/\partial\varepsilon_F^2$ with temperature. In the range $T > 1.5$ K the dependence of the density of states D_0^* on the magnetic field was close to β/H^2 (Ref. 17). At lower temperatures we were unable to establish any reliable magnetic-field dependence because the results were not sufficiently accurate. The increase in the experimental error was due to the need to reduce the amplitude of modulation of the gate voltage at lower temperatures so as to avoid the nonlinear effects. The experimental series of points plotted in Fig. 8 were obtained at the minimum modulation amplitude.

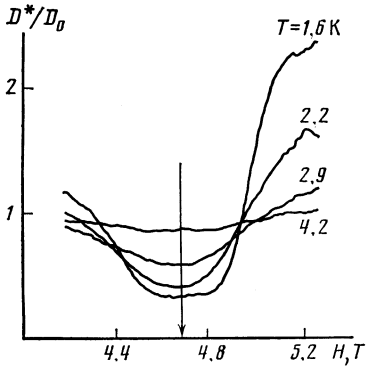

FIG. 9. Changes in the density of states with the magnetic field obtained for a constant electron density but at different temperatures ($i = 4$); method 3.

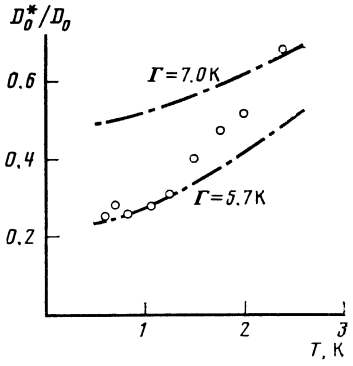

FIG. 10. Attempt to describe the dependence $D_0^*(T)$ using a temperature-independent Landau level width. The experimental points are the same as in Fig. 8 for $H = 3.8$ T.

The temperature dependence of the density of states D_0^* was not unexpected, because in the case of an occupation factor which was an integer the thermodynamic density of states can be obtained from the true density of states by averaging the latter over an interval of energies which depend on temperature:

$$D_0^* = \frac{\partial}{\partial\varepsilon_F}\int D(\varepsilon,\Gamma) f(\varepsilon,\varepsilon_F)\,d\varepsilon\,|_{\varepsilon_F=0}$$
$$= \int D(\varepsilon,\Gamma)\left(-\frac{\partial f(\varepsilon,0)}{\partial\varepsilon}\right)d\varepsilon$$
$$\approx D\left[1+\frac{\pi^2}{6}(k_B T)^2\frac{D''}{D}\right]. \qquad (4)$$

Even if D is independent of temperature, D_0^* rises monotonically as T is increased.

We shall assume that the energy dependence of the true density of states at a Landau level is a Gaussian curve[20] with a half-width Γ. If we consider only the contribution of the Landau levels nearest to ε_F without allowance for the spin and valley splittings, we obtain

$$D(\varepsilon) = \frac{D_0}{(2\pi)^{1/2}}\frac{\hbar\omega_c}{\Gamma}\left[\exp\left\{-\left(\varepsilon+\frac{\hbar\omega_c}{2}\right)^2\Big/2\Gamma^2\right\}\right.$$
$$\left.+\exp\left\{-\left(\varepsilon-\frac{\hbar\omega_c}{2}\right)^2\Big/2\Gamma^2\right\}\right], \qquad (5)$$

where ω_c is the cyclotron frequency and the energy ε is measured from the midpoint between the Landau levels. The results of calculations carried out using Eqs. (4) and (5) and a temperature-independent half-width Γ are plotted in Fig. 10. We can see that the experimental dependence $D_0^*(T)$ is considerably stronger than that predicted by the calculations and inclusion, for example, of the spin splitting weakens slightly the calculated temperature dependence of the density of states. Therefore, we can explain the observed temperature dependence $D_0^*(T)$ by postulating an increase in the Landau level width on increase in temperature.

There are at least two factors that can give rise to a temperature dependence of the Landau-level width: 1) the electron-electron interaction; 2) the temperature dependence of the screening of the potential relief.

In the former case it is convenient to consider separately the interaction with short-wavelength ($\lambda_{ph} < a$, where a is

the magnetic length) and long-wavelength ($\lambda_{ph} > a$) phonons. If $\lambda_{pb} < a$, the phonon contribution to the Landau level width can be estimated from the expression $\Gamma \sim (\hbar\omega_c \hbar/\tau)^{1/2}$ given in Ref. 20, where τ is the relaxation time in zero magnetic field. Since the frequency of the scattering by impurities is 3–4 orders of magnitude higher than the frequency of the scattering by phonons, the phonon contribution to the level width is negligible. The case of long-wavelength phonons is similar to the broadening of a Landau level because of an inhomogeneity of the electron system except that now the number of phonons and, consequently, the degree of inhomogeneity, depend strongly on temperature.

In the approximation of the deformation potential we have

$$\Gamma_{ph}^2 = \sum_{\mathbf{k},\lambda} \left(\Xi_d \operatorname{div} \mathbf{U} + \Xi_u \frac{\partial U_z}{\partial z} \right)^2 N_{\mathbf{k}}, \tag{6}$$

where Ξ_d and Ξ_u are the deformation potentials; $N_{\mathbf{k}}$ is the occupancy number of phonons; $\mathbf{k}$ is the wave vector; λ is an index which identifies the phonon polarization. In the simplest case of bulk phonons the shift is given by the expression

$$\mathbf{U}(\mathbf{r},t) = \sum_{\mathbf{k},\lambda} \left(\frac{\hbar}{2\omega\rho V} \right)^{1/2} \mathbf{e}_\lambda (a_{\mathbf{k}}^\lambda \exp\{i(\mathbf{kr} - \omega^\lambda t)\} + \text{c.c.}). \tag{7}$$

The summation carried out using Eqs. (6) and (7) over all the long-wavelength phonon modes gives

$$\begin{aligned} \Gamma_{ph}^2 &= \frac{4\pi\Xi_u^2 k_B T}{15\rho a^3 s_t^2} \left[\frac{4}{3} + \left(\frac{s_t}{s_l} \right)^2 \right] \\ &\quad + \frac{4\pi^2 Z_A^2 k_B T}{3K\rho a^3 s_R^2} \quad \text{for} \quad \frac{\hbar s_t}{a} \ll k_B T, \\ \Gamma_{ph}^2 &= \frac{\pi^2 \Xi_u^2 (k_B T)^4}{150\hbar^3 \rho s_t^5} \left[\frac{4}{3} + \left(\frac{s_t}{s_l} \right)^5 \right] \\ &\quad + \frac{\pi^3 Z_A^2 (k_B T)^4}{30K\hbar^3 \rho s_R^5} \quad \text{for} \quad \frac{\hbar s_t}{a} \gg k_B T, \end{aligned} \tag{8}$$

which includes the contributions of both bulk and surface phonons; the notation is as follows: Z_A is the deformation potential; s and s_t are the longitudinal and transverse velocities of sound; s_R is the velocity of a Rayleigh wave ($s_R \approx s_t$) and the coefficient K can be expressed in terms of the components of the attenuation of the longitudinal and transverse parts of a Rayleigh wave.[21] A calculation carried out on the basis of Eq. (8) gives a correction to the temperature dependence shown in Fig. 10, but it does not exceed 3%. Consequently, an allowance for the electron-phonon interaction cannot explain the experimental dependence $D_0^*(T)$.

We shall consider screening of the potential relief. To the best of our knowledge, there is only one treatment[22] in which the problem of screening is solved for nonzero temperatures. The solution is obtained in the form of the permittivity of an electron gas in the limit of high temperatures when $\Gamma \ll k_B T$. In this case the density of states is independent ot the Landau level width and of the nature of the potential relief. The temperature dependence of D_0^* should be exponential: $D^* \propto \exp(-\hbar\omega_c/2k_B T)$. The experiments do not confirm this behavior of the density of states, and in fact we have the opposite case $\Gamma \gtrsim k_B T$.

A phenomenological model proposed in Ref. 23 predicts a reduction in the thermodynamic density of states as a result of cooling. We tried to describe the experimental dependences on the basis of this model using two fitting parameters: the "bare" (unrenormalized) Landau level width and fluctuations of the electron density. Calculations were carried out in two variants called the μ and N_S models in Refs. 23. By way of example, the results obtained using the N_S model are plotted in Fig. 11. It is clear from this figure that the model[23] cannot describe the experimental dependence.

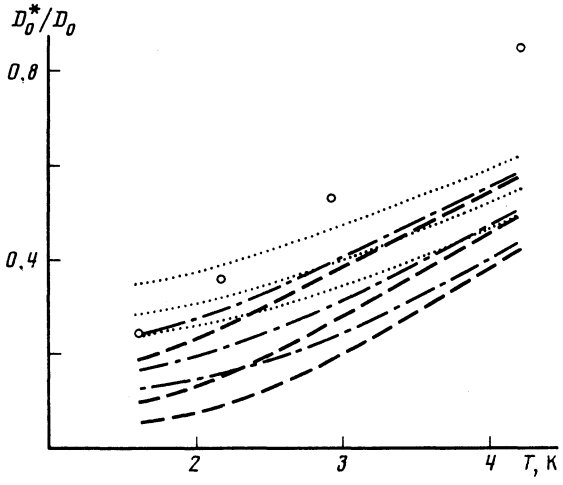

FIG. 11. Comparison of the experimental results with calculations carried out using the N_S model of Ref. 23. The calculations were carried out for Landau level half-widths Γ = 4, 5, and 6 K and for different fluctuations of the electron density: 0.5% (dashed curves); 2% (chain curves);, 5% (dotted curves). Sample No. 1.

The question arises whether, in principle, we can expect a stronger increase in the density of states than that predicted by Eq. (4). In our opinion this is possible We shall consider a model proposed in Ref. 24. In this model the Landau level width and, consequently, the position of the Fermi level are assumed to depend only on the degree of occupancy of a quantum level. We can readily see that if the number of vacant positions at a level remains constant (it is assumed that there is only one partly filled Landau level), then an increase in temperature should increase not only the chemical potential but also the level width because of deterioration in the screening of the potential relief. This effect is of special interest and we shall discuss it in greater detail. When temperature is increased, electrons are activated to those positions where the potential relief has maxima and this increases the amplitude of the fluctuation potential. We shall now estimate this increase. The additional potential V is created by electron-hole dipoles with a moment $ek_B TL_s/\Gamma_0$, where L_s is the characteristic screening length[24] and the number of dipoles is $D(\varepsilon_F)k_B TL_s^2$. Hence, we find that

$$V \propto e^2 D(\varepsilon_F)(k_B T)^2 L_c/\Gamma_0. \tag{9}$$

The concentration of such vacant positions at a level is $\delta n = e^2 N/\Gamma_0$, where Γ_0 is the level width at $T = 0$. Since the chemical potential is described by

$$\xi \propto \Gamma_0 - \frac{\pi^2}{6}(k_B T)^2 \frac{D'(\xi)}{D(\xi)} + V, \tag{10}$$

we can readily find the density of states

$$D^* = \frac{\partial}{\partial \xi}(\delta n)\,|_{\xi=\hbar\omega_c/2}$$

$$= D^*(\Gamma_0)\left[1 + \frac{\pi^2}{6}(k_B T)^2 \frac{D''}{D} + e^2 D \frac{(k_B T)^2}{\Gamma_0^2} L_c\right]. \quad (11)$$

This expression is simplified by dropping the terms containing the first derivative, since in the case of the two Landau levels we have $D'(\hbar\omega_c/2) = 0$. The first correction term on the right-hand side of Eq. (11) corresponds to that already allowed for in Eq. (4). The second correction term is of the same order of magnitude and in our opinion should explain the experimentally observed increase in the density of states on increase in temperature. Equation (11) is valid only on condition that the correction to the density of states is small compared with the density of states itself. It is clear from Fig. 8 that the experimental values of $D_0^*(T) - D_0^*(0)$ are at least of the same order as $D_0^*(0)$, so that a direct comparison of the experimental results with Eq. (11) is meaningless. Nevertheless, there is a qualitative agreement between the experimental results and those predicted by Eq. (11). In fact, as the intensity of the magnetic field is reduced, Eq. (11) predicts the expected increase in $D_0^*(0)$ and a simultaneous increase in the absolute value of the temperature-dependent correction. This is exactly the behavior observed experimentally.

It should be noted that there are ranges of the occupancy factors in which the density of states behaves nonmonotonically (Fig. 9). Cooling results initially in a fall of the density of states and then the density rises and even exceeds the initial value.

CONCLUSIONS

It follows from our experimental results that the methods based on the activated temperature dependence of the conductivity cannot be used as independent means for the determination of the thermodynamic density of states. The main reason is that the mobility edge does not coincide with the middle of the Landau level and may shift along the energy axis when the Fermi energy changes.

More reliable are the methods based on oscillations of the contact potential. The temperature dependence of the density of states determined using such oscillations can be explained by assuming a nonlinear screening. An increase in the thermodynamic density of states is then due to a reduction in the width of a single Landau level.[16]

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