Magnetoacoustic investigation of the electron structure of gallium under pressure

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The effect of hydrostatic pressures up to 8 kbar on various extremal cross sections of the Fermi surface of gallium is investigated. A magnetoacoustic measurement technique using high pressure is described. The results are interpreted within the framework of the Reed model. The band structure of gallium is calculated by the local pseudopotential technique along certain symmetric directions for pressures between 1 bar and 10 kbar. The rate of the shift of the band extrema near the Fermi level is determined in the indicated pressure range. The results of the calculations are compared qualitatively with the experimental data.

1. INTRODUCTION

Gallium belongs to the IIIb group of metals and crystallizes in an orthorhombic structure (D_{2h}) with four atoms per unit cell. The allocation of the atoms, the unit cell and the Brillouin zone of Ga were described in[1]. Thanks to a random ratio of the lattice constants, the Brillouin zone for Ga represents an almost true hexagonal prism, as a consequence of which the Fermi surface in the single-wave approximation manifests a pseudopotential symmetry in the $k_y k_z$ plane.[2] The extensive experimental information pertaining to the Fermi surface of Ga does not, however, contradict this feature of the specified approximation.

A model of the Fermi surface of Ga that is more consistent with the experimental data has been proposed by Reed, using the method of local semi-empirical pseudopotential for calculation of the energy bands. Spin-orbit effects have not been taken into account here.[3] The shape of this surface in one octant of the Brillouin zone is shown in Fig. 1.

The qualitative agreement between the theoretical representations and the experimental results is rather good, but part of the experimental data, which refer basically to very small portions of the Fermi surface, do not find their explanation in the Reed model.[4,5] The galvanomagnetic measurements of Stark and Kimball[6] also indicate certain lack of correspondence in this model. Gallium is one of the few non-transition metals in which there have been practically no attempts to date to study the effect of uniform deformation on its energy spectrum. The hydrostatic pressure is very convenient for a test of the different model representations. In particular, the use of the pressure dependence of the frequencies of the quantum oscillations of kinetic and thermodynamic quantities allows us, within the framework of the pseudopotential theory, to interpret the cause of the observed oscillations more definitively.

Thus, in spite of the fact that by now many theoretical and experimental researches have been completed which were devoted to the study of the Fermi surface of Ga (at a normal volume of the unit cell), isolated details still remain unclear, and an experimental setup for the study of the pressure dependence of the parameters of the energy spectrum of the carriers in Ga is of interest. As previously,[7] we use here a magnetoacoustic method and a high-pressure techniques.

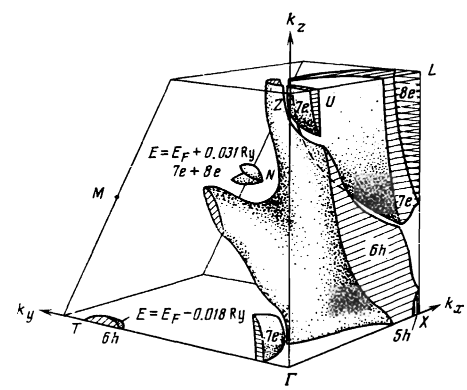

FIG. 1. Shape of the Fermi surface of Ga in one octant of the Brillouin zone, according to the Reed model.

2. METHOD OF MEASUREMENT

For the magnetoacoustic investigations at high pressures, we used the well-known pulse method for the recording of the ultrasonic absorption in the frequency range 30—300 MHz. Generation and reception of the ultrasonic waves of longitudinal polarization was accomplished by a reflection method with a single X-cut quartz piezopickup of thickness 0.1 mm, working on its odd harmonics. The reflection method requires a single reliable acoustic binding of the investigated sample to the piezoelectric transducer, which is especially important in acoustic measurements at high pressures and low temperatures. To make the acoustic contact (binding) of the quartz with the sample we used GKZh-94 oil or plasticized epoxy glue on a base of ED-6 resin.

The uniform deformation was produced in cold worked radially expanded chamber of beryllium bronze by the fixed pressure method, suggested by Itskevich et al.[8] The modified part of the chamber construction for magnetoacoustic measurements is shown in Fig. 2. The basic dimensions of the chamber are: diameter of the working channel 8 mm, external diameter of the chamber 24 mm, general length of the chamber 160 mm. A feature of this chamber is the use of integrated construction of the shutter together with a locking nut and high-frequency joint, which facilitates the assembly and the adjustment of the acoustic contact with the sample. For supplying the pressure to the sample, we used pentane with an oil cushion at the piston.[9]

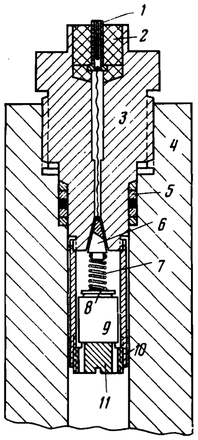

FIG. 2. Modified part of the high-pressure chamber: 1—contact pin, 2—insulator, 3—shutter, 4—body of the bomb, 5—sealing ring, 6—conical electrical conductor, 7—spring, 8—piezoelectric transducer, 9—sample, 10—collar of the acoustic head, 11—compressed sample.

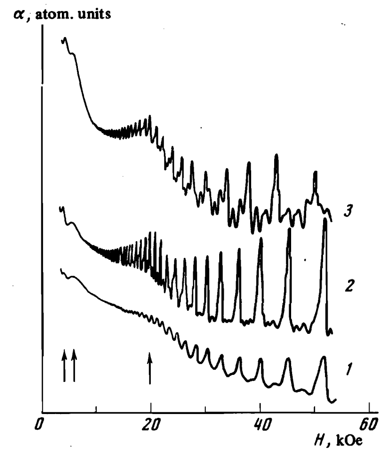

FIG. 3

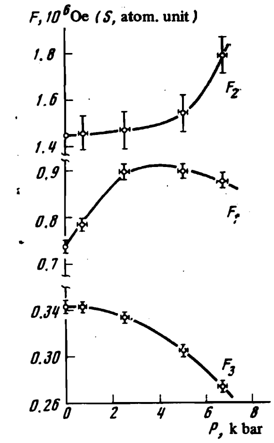

FIG. 4

FIG. 3. Dependence of the sound absorption coefficient α for the frequency f = 200 MHz on the magnetic field in the geometry q||H||b: 1—P = 1 bar, T = 4.2°K, 2—P = bar, T = 1.65°K, 3—P = 6.3 kbar, T = 1.65°K

FIG. 4. Change of the oscillation frequencies under pressure, observed for q||H||b.

Irreversible reduction of the amplitude of the magnetoacoustic oscillations because of the insufficient hydrostatic character of the pentane at low temperatures was practically not observed in durations of the temperature cycles, from room to helium temperatures and return, of not less than 10 hr. The value of the pressure was measured by a tin manometer by means of the change in the temperature of the superconducting transition by the induction method. It must be noted that the pressure in the chamber was increased at temperatures below 0°C to prevent melting of the single crystals of gallium as a consequence of the heating of the transmitting medium. This is connected with the low temperature of melting of gallium and its decrease with increase in the applied pressure.[10]

Single crystal samples of Ga of various crystallographic orientations, with a diameter of 6 mm and thickness 4—5 mm, were cut by the electric spark method out of a large single-crystal ingot of initial purity 99.99996%[1)] with subsequent lapping to plane-parallelism on slabs with diamond paste and etching of the damaged layer. The normals to the end surfaces coincided with the principal crystallographic directions a, b, c with an accuracy to within ±0.5°.

The magnetoacoustic investigations in Ga were carried out at temperatures of 1.6—4.2 K in a magnetic field of a superconducting solenoid up to 55 kOe in a geometry in which the magnetic field H was parallel to the direction of propagation of the sound q (q is the wave vector of the sound).

3. RESULTS OF MEASUREMENTS

The interesting dependence of the sound absorption coefficient, obtained for the direction q ∥ H ∥ b, is shown in Fig. 3. At a pressure of P = 1 bar, quantum oscillations in the ultrasonic absorption were recorded with frequencies $F_1 = 0.725 \times 10^6$ Oe, $F_2 = 1.45 \times 10^6$ Oe, and giant quantum oscillations of the sound absorption with $F_3 = 0.342 \times 10^6$ Oe, and also some oscillations of an unknown nature shown in Fig. 3 by the arrows; these were periodic in the reciprocal of the magnetic field with frequency $F_4 = 1.7 \times 10^4$ Oe. The measured frequencies F_1 and F_3 refer to the extremal cross sections of the $7e^U$ electron surface and the $6h^T$ hole surface according to the Reed model.[3] The frequency F_4 was observed by Condon[4] and Reed tentatively assigned it to the fifth hole band localized at the point X ($5h^X$). The frequency F_2 does not have an interpretation in the Reed model, although a branch of points

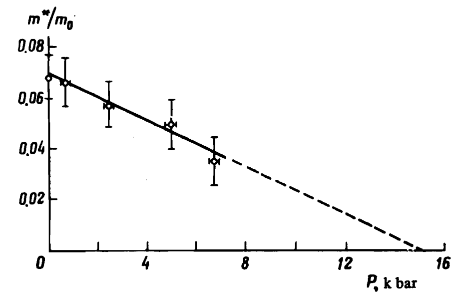

FIG. 5. Pressure dependence of the cyclotron mass of the carriers of the $6h^T$ band for H||b.

close to it was observed in[4] on the angular dependence of the quantum oscillations of the magnetic susceptibility.

The pressure dependences of the cross sectional areas of these surfaces are shown in Fig. 4. No pressure effect was noted for the frequency F_4 because of the very smeared-out maxima of the sound absorption. Figure 5 shows the pressure dependence of the cyclotron mass of the carriers of the hole band $6h^T$, obtained from the temperature dependence of the oscillations in the range of magnetic fields H = 10—15 kOe. Measurements of the amplitude of the oscillations were carried out for the temperatures 1.65 and 3.3 K; 2.1 and 4.2 K at fixed pressure. The effective mass was determined from the expression[11]

$$m^* = \frac{e\hbar H_n}{2\pi^2 ckT_2} \operatorname{Arch} \frac{A(T_2, H_n)}{A(T_1, H_n)}, \quad T_1 = 2T_2 \tag{1}$$

(A is the amplitude of the oscillations in relative units, c the velocity of light, e the charge on the electron, $\hbar \cdot 2\pi$-Planck's constant, k the Boltzmann constant) and, at a pressure P = 1 bar, $m^* = (0.07 \pm 0.015) m_0$, where m_0 is the mass of the free electron. On the basis of linear extrapolation of the $m^*(P)$ dependence, we can assume that the effective mass of the carriers of the $6h^T$ band tends to zero at P ~ 15 kbar.

For an explanation of the nature of the origin of the frequency F_4, additional investigations were carried out on the frequency dependence of the oscillations at P = 1 bar. The oscillating dependence of the sound absorption on the magnetic field for a sound frequency f = 30 MHz did not differ from that for a frequency of 200 MHz, which is shown in Fig. 3. This fact shows that the oscillations with frequency F_4 are not resonance oscillations or other effects that depend on the sound wavelength.

The frequency dependence of the width of the peaks in giant quantum oscillations allows us to estimate the relaxation time of the carriers of the $6h^T$ band. Gurevich and coworkers[12] have shown that the necessary and sufficient condition for neglect of the collision broadening in comparison with the temperature broadening of the peaks of the giant quantum oscillations is of the form

$$B=(2kT/m^*)^{1/2}q\tau\gg 1. \quad (2)$$

With decrease in the frequency of the ultrasound, the peaks of the giant quantum oscillations begin to broaden when the condition (2) ceases to be satisfied. The lowest frequency of the ultrasonic oscillations used in our experiment was 30 MHz. Significant broadening of the peaks of the giant quantum oscillations was not observed at this frequency. One can estimate the relaxation time of the carriers of the $6h^T$ band by using the relation (2). The estimate yields $\tau \geq 4 \times 10^{-9}$ sec, if we take $B \approx 5$, T = 1.65 K and $m^* = 0.07m_0$.

In the geometry of the experiment, **q** ∥ **H** ∥ c, less complicated oscillating dependences were recorded for the ultrasonic absorption. A P = 1 bar, the frequencies of the quantum oscillations were measured: the predominant frequencies of the beats were $F_5 = 0.22 \times 10^6$ Oe and $F_6 = 0.2 \times 10^6$ Oe; $F_7 = 0.78 \times 10^6$ Oe, $F_8 = 23 \times 10^6$ Oe, $F_9 = 12 \times 10^6$ Oe. All these frequencies were observed in the de Haas—van Alphen effect[4,13] and interpreted in the Reed model as oscillations of the extremal cross sections of the electron bands $8e^N$, $7e^T$, $7e^L$, respectively and of the orbit, due to magnetic breakdown at the central cross sections $7e^L$ and $8e^L$ bands and denoted by Reed as $(\frac{1}{2}7e + \frac{1}{2}8e)^L$.

Figure 6 shows the change in the areas of the cross sections of these bands for uniform compression of the crystalline lattice. It should be noted that the behavior of the cross sections $7e^T$ (frequency F_7) and $8e^N$ (F_5 and F_6) bands have a non-monotonic dependence. With increase in the pressure, the areas of the cross sections first increase, and then decrease. The various logarithmic derivatives corresponding to this are shown in the table as a function of the pressure range. The beats between the quantum oscillations of frequencies F_5 and F_6 from the surface $8e^N$ disappear with increase in the pressure. Evidently, these two neighboring cross sections degenerate into a single extremal cross section. The amplitude of the magnetic breakdown oscillations (frequency F_9) with increase in pressure from zero to 6 kbar reaches a significant value for a magnetic field that is smaller by about 10 kOe.

For the case **q** ∥ **H** ∥ a, for uniform compression up to 8 kbar, quantum oscillations with a frequency $F_{10} = 0.875 \times 10^6$ Oe from the band $7e^T$, giant quantum oscillations $F_{11} = 0.505 \times 10^6$ Oe from the hole band $6h^T$ and resonance oscillations in small magnetic field from the "butterfly" cross section $7e^L$, on which the value of $\partial S/\partial k_x$ reaches an extremum, were studied in a wide range of magnetic fields. For normal pressure, the frequency of the resonance oscillations $F_{12} = 1.37 \times 10^3$ Oe (f = 200 MHz).

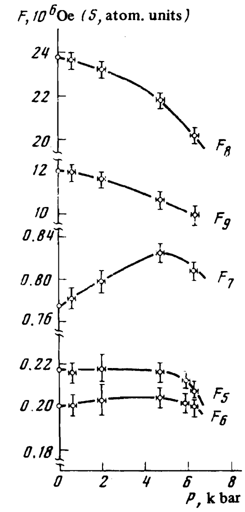

FIG. 6. Change under pressure of the oscillation frequencies observed in the geometry q∥H∥c.

In the determination of the absolute value of the cyclotron mass m* in[7], an inaccuracy has crept into reduction of the temperature dependence of the oscillation amplitudes. The effective mass m* was determined from the slope of the dependence of ln(A/T) on T, where A is the amplitude of oscillations, which is not valid, in view of the fact that the studied oscillations, beginning with magnetic fields of 15—20 Oe, have the nature of giant quantum oscillations. The more accurate value of the cyclotron mass is equal to $m^* = (0.11 \pm 0.02)m_0$. The value of the logarithmic derivatives of the oscillation frequencies with respect to the pressure was calculated from the simple relation

$$d\ln F/dP = \Delta F/F_0\Delta P, \quad (3)$$

where $\Delta F = F_P - F_0$, F_P is the frequency at the pressure P and F_0 the frequency in the absence of pressure. The values of the logarithmic derivatives of the experimental frequencies, averaged over the indicated range of pressures, are given in the table.

4. CALCULATION OF THE BAND STRUCTURE OF Ga UNDER PRESSURE

For the calculation of the band structure, we used the local semi-empirical pseudopotential method without account of spin-orbit effects. The form factor of the pseudopotential for Ga at normal pressure has the form[3]

Frequency	Cross section	H∥	$F\cdot 10^6$ Oe	Experimental: $\frac{d\ln F}{dP}$, k bar^{-1}	Experimental: $\frac{d\ln m^*}{dP}$, k bar^{-1}	Pressure range k bar	Calculated: $\frac{dE_{extr}}{dP}$, m Ry/k bar
F_1	$7e^U$	b	0.735±0.015	+0.05±0.02 −0.01±0.005	— —	0÷4 4—7	0.7 0.7
F_2	—	b	1.45±0.10	+0.02±0.01	—	0—8	—
F_3	$6h^T$	b	0.343±0.003	−0.03±0.005	−0.08±0.04	0÷8	0.9 $6h^T$ 1.45 $9e^T$
F_4	$5h^X$	b	0.017±0.006	—	—	0÷8	0.8
F_5	$8e^N$	c	0.22±0.01	+0.001±0.001 −0.01±0.005	—	0—4 4÷7	—
F_6	$8e^N$	c	0.20±0.01	+0.001±0.001 −0.01±0.005	—	0—4 4÷7	— —
F_7	$7e^T$	c	0.78±0.01	+0.01±0.005 −0.01±0.01	—	0—5 5—7	0.85 0.85
F_8	$7e^L$	c	23±2	−0.025±0.008	—	0—8	1.1
F_9	$(\frac{1}{2}7e+\frac{1}{2}8e)^L$	c	12±1	−0.025±0.008	—	0—8	1.1
F_{10}	$7e^T$	a	0.875±0.010	−0.008±0.002	—	0—8	0.85
F_{11}	$6h^T$	a	0.505±0.005	−0.03±0.005	−0.08±0.04	0—8	0.9 $6h^T$ 1.45 $9e^T$
F_{12}	$7e^L$ $(dS/dk_x)_{extr}$	a	0.00137±0.0006	−0.003±0.0015	—	0—8	1.1

$$U_0(Q)=0.72(Q-0.85)(1.5-Q)[1+0.1(1.15-Q)] \quad \text{at} \quad Q\leqslant 1.5$$
$$U_0(Q)=0 \quad \text{at} \quad Q>1.5 \tag{4}$$

Here $Q = n/2k_F$, n is the wave vector of the reciprocal lattice, k_F the radius of the Fermi sphere. We use atomic units, i.e., $\hbar^2/2m = 1$, and the energy is given in Rydbergs.

Depending on the location of the point in the Brillouin zone, from 85 to 100 plane waves were taken into account in the secular equation. The matrix of the secular equation was contracted by the Löwdin method to a matrix of 20—30 order. The number of vectors was so chosen that symmetry degeneracy was avoided. The band structure was determined in different directions for pressures from 1 bar to 10 kbar. The coefficients of linear compressibility for Ga are equal to[14]

$$\chi_a=0.59\cdot10^{-3}\ \text{kbar}^{-1},\ \chi_b=0.72\cdot10^{-3}\ \text{kbar}^{-1},\ \chi_c=0.4\cdot10^{-3}\ \text{kbar}^{-1}.$$

The same parameters have been used as in[3].

If we neglect the nonlocality of the pseudopotential in the case of screening, then the local form factor of Ga under pressure, $U_P(Q)$, is expressed in terms of the form factor (4) in the following fashion:

$$U_P(Q)=\frac{\Omega_0}{\Omega_P}U_0(Q)\frac{\varepsilon_0(Q)}{\varepsilon_P(Q)}, \tag{5}$$

where Ω_0 and Ω_P are the atomic volumes for normal and high pressures, $\epsilon_0(Q)$ and $\epsilon_P(Q)$ are the corresponding dielectric permittivities of the free electrons in the Hartree approximation:

$$\varepsilon(Q)=1+\frac{1}{2\pi k_F Q^2}\left[\left(\frac{1-Q^2}{2Q}\right)\ln\left|\frac{1+Q}{1-Q}\right|+1\right]. \tag{6}$$

Such an approximation is achievable if we neglect the corrections to the form factor (5) of the order ΔU:

$$|\Delta U/U|\leqslant((\Omega_P-\Omega_0)/\Omega_0)^2. \tag{7}$$

Change in the Fermi energy of Ga under pressure was determined in the free electron model and turned out to be equal to $dE_F/dP = 0.9$m Ry/kbar. The perturbation-theory corrections to this quantity are insignificant and can be neglected. The calculations yield linear dimensions of the separate parts of the Fermi surface along the principal crystallographic directions and the velocity of displacement of the energy extrema (E_{extr}) near the Fermi surface for different values of the volume of the unit cell. The results of the calculation are given in the table and in Fig. 7.

5. DISCUSSION OF THE RESULTS

The change in the parameters S and m* of the electronic structure under pressure within the approximation of almost free electrons is given by the simple relations:[15]

$$\frac{d\ln S}{dP}=-\frac{2}{3}\chi, \tag{8}$$

$$\frac{d\ln m^*}{dP}=\frac{1}{2}\frac{d\ln S}{dP}-\frac{1}{3}\chi, \tag{9}$$

where $\chi = V^{-1}(dV/dP)_T$, χ is the isothermal compressibility, V the volume of the sample, An increase in all cross sections at the range $d \ln D/dP = +1.14\times10^{-3}$ kbar^{-1} should occur upon neglect of some anisotropy of the compressibility under pressure.

The data of the experiment under pressure for the investigated cross-sections do not agree with the approximation of the almost free electron (except $7e^U$,

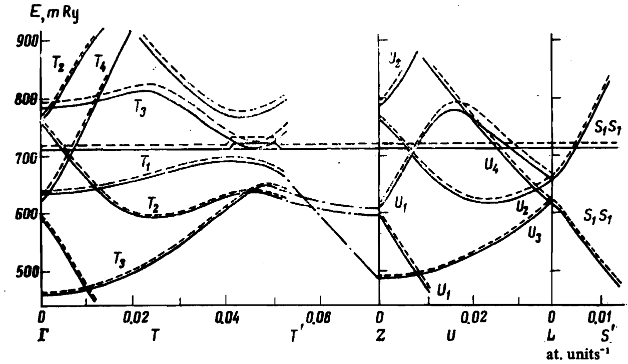

FIG. 7. Band structure of Ga along certain symmetric directions: solid curve P = 0, dashed curve, P = 10 k bar. For the extremum $9e^T$, the increase in the level of the chemical potential E_F by 11 mRy is shown. The designations of the terms and directions are the same as in [3].

$7e^T$ and $8e^N$ bands, for which the sign of the logarithmic derivatives coincide in a certain pressure range). Change in the mass for the hole band $6h^T$ is also not described by the expression (9). Account of the changes in the cross sectional areas under uniform compression of the crystalline lattice by the pseudopotential method was not performed by us. However, the difference in the quantities $dE_{extr}/dP - dE_F/dP$, given in the table, makes it possible to compare the experimental results with the local semiempirical pseudopotential calculation.

Attention should be directed to the behavior of the hole band $6h^T$ and electron band $9e^T$ close to extrema on the ΓT line of the Brillouin zone (Fig. 7). Calculation predicts identical displacement, under pressure, of the extremum $6h^T$ and of the level of the chemical potential E_F, which means a small change in the cross sectional area of the $6h^T$ band from the change in the lattice parameters given in the experiment. However experiment indicates a large value of $d \ln S/dP$ for the cross section $6h^T$. In the local semiempirical pseudopotential model for small pieces of the Fermi surface, one can consider nonlocal effects by the method of unknown constant contributions to the Fermi level. The value and the sign of the contribution will depend on the position of these portions of the Fermi surface in the Brillouin zone. Thus, the surface $6h^T$ is obtained in the Reed model by lowering of the Fermi energy near the point T of the Brillouin zone by 18 mRy. On the other hand, there is an electronic extremum $9e^T$ where agreement of the model linear dimensions in k_y and k_x with the experimental values[5,13]. The velocity of displacement of the extremum is $dE_{extr}/dP = 1.45$ mRy/kbar for the $9e^T$ cross section and the electron transition can take place for a calculated pressure $P_c \sim 18$ kbar, which agrees with the possible experimental value $P_c \sim 15$ kbar.

A strong change under pressure of the cyclotron mass m* of the carriers for the $6h^T$ band (Fig. 5) indicates that the dispersion law of this band is close to linear. From these considerations, the closed piece of the constant-energy surface, interpreted by Reed as the $6h^T$ band, is tentatively assigned to the extremum of the ninth band, $9e^T$. However, the final solution of this problem depends on the result of an experiment in which the sign of the change carriers of this band can be determined.

The nonmonotonic behavior of $S(P)$, observed for the energy bands $7e^U$, $7s^T$ and $8e^N$, is not confirmed in our calculation. The reason for such a type of dependence for $S(P)$ in Ga is unclear. We only note that the nonomontonic dependence of $S(P)$ has been observed in other materials with a relatively simple shape of the Fermi surface, for example, in antimony.[16]

The behavior of the extremal orbits of the constant-energy surface of the butterfly $7e^L$ and the corresponding magnetic breakdown cross section $(\frac{1}{2}7e = \frac{1}{2}8e)^L$ for a magnetic field $H \parallel c$ is identical in sign with the local semiempirical pseudopotential calculation. It is surprising that the experimental value $d \ln S/dP = 0.025\ \text{kbar}^{-1}$ for the $7e^L$ cross section is not small for such large surfaces.

It follows from the results of the experiment that the value of the energy gap decreases monotonically, preventing the formation of the orbit $(\frac{1}{2}7e + \frac{1}{2}8e)^L$ in the plane of the extremal cross sections $k_z = k_c$.

The insignificant decrease of the quantity $(\partial S/\partial k_x)_{extr}$ with increase in the external pressure on the butterfly $7e^L$ for $H \parallel a$ can be understood as some decrease in the anisotropy of the given constant-energy portion under pressure.

Attention is drawn to the $5h^X$ band (the frequency F_4 in our experiment and the δ frequency in[4]). The independence of the oscillation frequencies of the sound wavelength shows that these are quantum oscillations of the sound absorption from a very small piece of the surface, the maximum area of which is about $\frac{1}{30}$th of the minimum cross section of the $6h^T$ band. According to experiment, the condition

$$ql(\hbar\omega_c/\varepsilon_F)^{1/2} \gg 1 \quad (10)$$

(l is the mean free path, ω_c is the cyclotron frequency of the carriers, ϵ_F is the Fermi energy) which is necessary for the existence of giant quantum oscillations of the sound absorption,[12] is satisfied for the carriers of the $6h^T$ band in the investigated Ga samples (Fig. 3). Condition (10) is even better satisfied for carriers of the energy band $5h^X$, since $\epsilon_F(5h^X) \ll \epsilon_F(6h^T)$ and $m^*(5h^X) \sim (\frac{1}{3})m^*(6h^T)$.[4] The maximum oscillations of the sound absorption F_4 (shown by arrows in Fig. 3) are very diffuse and the presence of giant quantum oscillations from carriers of this band is not at all evident.

The second feature of these oscillations is the following. Usually, the effect of pressure is very important for small constant-energy surfaces. Calculation by the method of local, semiempirical pseudopotential also proves the strong change in the $5h^X$ band under pressure. According to the calculation, vanishing of this surface should take place at a pressure $P_c \lesssim 3$ kbar if we identify this band with the frequency δ of[4] and the frequency F_4 in our experiment. The independence (or weak dependence) of the oscillations of F_4 on the pressure denies their belonging (and also for the frequency δ) to the $5h^X$ band and, evidently is a more reliable interpretation of this band with the data shown in Fig. 9 of ref. 5.

Thus, the behavior under pressure of certain cross sections of the energy bands of Ga has been investigated, excluding the multiply-connected hole surface of the monster in the sixth band. Depending on the cross sectional area and the cyclotron mass of the carriers of the $6h^T$ (or $9e^T$) bands and from a calculation of the band structure under pressure, a conclusion has been drawn that this portion of the surface vanishes under pressure. According to theory (see[17]), the electron transition should be reflected in the superconducting transition temperature T_c. The scatter of the experimental points and the large scale jump in pressure in the researches of[18] possibly obscure this feature of T_c.

More precise determination of the parameters of the pseudopotential should be made for clarification of the specific shape of the surface at the point N of the Brillouin zone (the reason for the beating of the frequencies F_5 and F_6 on the "cigar" $8e^N$ is not clear) the origin of the small frequency F_4 (corresponding to the frequency[4]) and frequency F_2. Therefore, a further study of the electron structure of Ga is necessary.

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