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SPIN-CYCLOTRON RESONANCE IN *n*-TYPE INDIUM ANTIMONIDE AT LOW TEMPERATURES

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An interpretation of known experimental data on magnetic resonance measurements in tellurium-doped n-type indium antimonide crystals with compensation ratio $K \approx 0.1$ of tellurium (hydrogen-like donors) by zinc (hydrogen-like acceptors) at 10 MHz frequency in a quantizing external magnetic field with induction from 0.17 to 1.70 T at liquid-helium temperature is proposed. It is revealed that the observed resonance is caused by the absorption of energy quanta of radio-frequency (10 MHz) radiation by c-band electrons. The electron transition between adjacent Landau levels is mediated by the electric component of the radio wave, while transitions between Zeeman sublevels are driven by its magnetic component. The number of absorbed radio-frequency quanta at resonance increases from $3.9{\cdot}10^4$ to $1.6{\cdot}10^5$ with c-band electron concentrations from $6{\cdot}10^{15}$ to $5{\cdot}10^{18}$ cm^{-3} at an approximately constant compensation ratio. Calculations show that the width of the magnetic resonance lines (from peak to peak of the first derivative of the radio-wave absorption signal with respect to the external magnetic field) is determined by fluctuations in the potential energy of electrons in the crystals due to their doping and compensation.

Keywords: *n-type indium antimonide, low temperatures, absorption of radio waves, spin-cyclotron magnetic resonance.*

Introduction. Semiconducting InSb crystals do not have a center of symmetry and are characterized by covalent and ionic interatomic bonding and strong spin–orbit coupling [1]. Spin-inversion of a *c*-band electron in such crystals situated in an external constant (stationary) magnetic field is due to the action of not only the magnetic but also of the electric component of the electromagnetic wave. However, a stationary external magnetic field and the magnetic component of the wave field can affect the orbital motion of electrons, which leads to the *g*-factor being independent of the *c*-band electron quasi-wave vector **k**. The manifestation of these features in electron spin resonance is called combined resonance [2].

An interpretation of results of room-temperature magnetic resonance measurements at fixed frequency $f = \omega/2\pi = 10$ MHz (spin–phonon resonance model) in *n*-type indium antimonide crystals doped with tellurium and slightly compensated with zinc was proposed [3, 4]. According to the model [3], a *c*-band electron absorbs a transverse optical (TO) phonon of the InSb crystalline matrix from the Brillouin zone center and a quantum of radio-wave energy of frequency 10 MHz under the magnetic resonance recording conditions [4]. This leads to an electron transition to a higher Landau level with spin inversion (this transition of a *c*-band electron is shown as a vertical arrow in Fig. 1).

Let us compare the concentrations of optical phonons in an InSb crystal at absolute temperatures 4.2 and 300 K. Because the average energy of an optical phonon $\hbar\langle\omega_{op}\rangle$ is practically the same for the three optical branches, the average concentration of optical phonons is [7]

$$\langle N_{op}\rangle \approx \frac{3N_{InSb}}{\exp\,(\hbar\langle\omega_{op}\rangle/k_B T) - 1}\ , \tag{1}$$

where $N_{InSb} \approx 2.9{\cdot}10^{22}$ cm^{-3} is the total concentration of In and Sb atoms in a crystal of the stoichiometric composition; $\hbar = h/2\pi$, the reduced Planck constant; $\hbar\langle\omega_{op}\rangle = 22.9$ meV, the average energy of an optical phonon [8]; k_B, the Boltzmann constant; and $\hbar\langle\omega_{op}\rangle/k_B \approx 266$ K.

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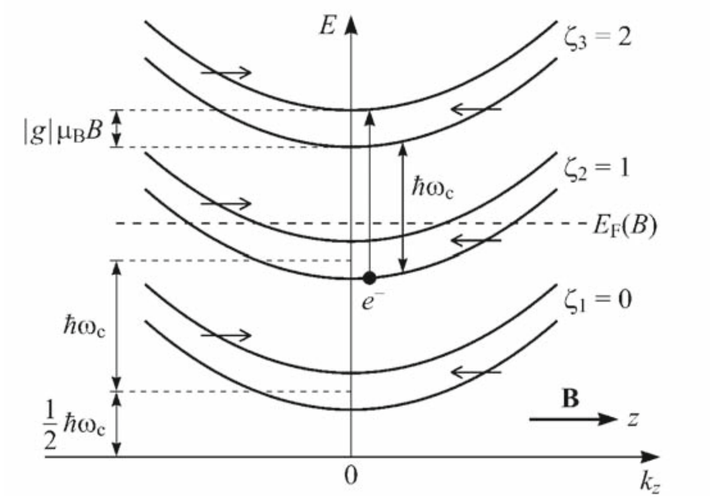

Fig. 1. Energy levels E of a c-band electron of degenerate n-InSb:Te,Zn as a function of the projection k_z of its quasi-wave vector on the direction of induction **B** of an external stationary homogeneous magnetic field [3]. The vertical arrow shows transition of an electron (e^-) between Landau levels and Zeeman sublevels with spin inversion; E, c-band electron energy; $E_F(B)$, Fermi level (depends on magnetic induction B of external constant field and is situated in the c-band at absolute temperature $T = 4.2$ K [5]); whole numbers $\zeta_1 < \zeta_2 < \zeta_3$ enumerate the three Landau levels; k_z, projection of electron quasi-wave vector on the z axis; μ_B, Bohr magnetron; ω_c, cyclotron angular frequency; the black dot (and symbol e^-) denote an electron in the c-band, arrows on parabolas show the orientation of the spin relative to the direction of magnetic field force lines: to the right, with the field; to the left, against the field (because the c-band electron g-factor $g \approx -51.31$ at $T = 1.4$ K for electron concentration $n \approx 10^{15}$ cm^{-3} [6]).

According to Eq. (1), the concentration of optical phonons at $T = 4.2$ K is $\langle N_{op}\rangle \approx 3\cdot10^{-5}$ cm^{-3}; at 300 K, $\langle N_{op}\rangle \approx 6\cdot10^{22}$ cm^{-3}, i.e., optical phonons are practically absent in an InSb crystal at $T \approx 4.2$ K. Therefore, the results of the model [3] cannot be used directly for liquid-He temperatures.

Let us find the average concentration of acoustic phonons in crystalline InSb (with a concentration of its own atoms $N_{InSb} \approx 2.9\cdot10^{22}$ cm^{-3}) in thermodynamic equilibrium at $T = 4.2$ K. The concentration of phonons is considered to be independent of the external magnetic field. For temperature T much less than the Debye temperature T_D ($T_D = 203$ K for InSb [8]), the average concentration of all acoustic phonons (longitudinal LA and two types of transverse 2TA) can be estimated as before [7] as $\langle N_{ac}\rangle \approx 21.6N_{InSb}(T/T_D)^3$. In particular, $\langle N_{ac}\rangle \approx 1.5\cdot10^{18}$ cm^{-3} for $T = 4.2$ K. The average energy of an acoustic phonon for $T << T_D$ $\langle E_{ac}\rangle = \hbar\langle\omega_{ac}\rangle \approx (\pi^4/36)k_BT$ [9]. We obtain $\langle E_{ac}\rangle \approx 0.98$ meV for liquid-He temperature 4.2 K. Because the quantity $\langle E_{ac}\rangle$ is greater than the thermal ionization energy (<0.7 meV) of Te atoms in n-InSb crystals, all atoms of this hydrogen-like donor dopant are ionized for $B = 0$ at liquid-He temperature [1, 8].

Magnetic resonance in n-InSb:Te,Zn crystals was measured on a nuclear magnetic resonance radiospectrometer at operating frequency $f = \omega/2\pi = 10$ MHz in a magnetic field with induction $B < 1.7$ T and modulation frequency of this field of 70 Hz [4, 10]. A total of six nonmagnetic samples (number $j = 1, 2, \ldots, 6$) of approximately the same shape and volume (~30 mm^3) with c-band electron concentrations from $n_1 = 6\cdot10^{15}$ cm^{-3} (sample 1) to $n_6 = 5\cdot10^{18}$ cm^{-3} (sample 6) were studied. The samples were oriented so that the scanning constant external magnetic field induction vector **B** (field **B** is also designated $\mathbf{B}_0$ in radiospectroscopy) was directed along the crystallographic [211] direction. Figure 2a shows magnetic $\mathbf{H}_1 \propto \cos(\omega t)$ and electric $\mathbf{E}_1$ radio-wave components that were variable over time t. Component $\mathbf{H}_1$ caused electron spin reorientation (transition between Zeeman split energy levels). Component $\mathbf{E}_1 \propto \cos(\omega t + \varphi)$ had phase shift φ relative to component $\mathbf{H}_1$ because of the high low-temperature electrical conductivity of the samples [11, 12]. Radio-wave component $\mathbf{E}_1$ contained a component orthogonal to vector **B**. Therefore, cyclotron absorption of radio waves by c-band electrons was

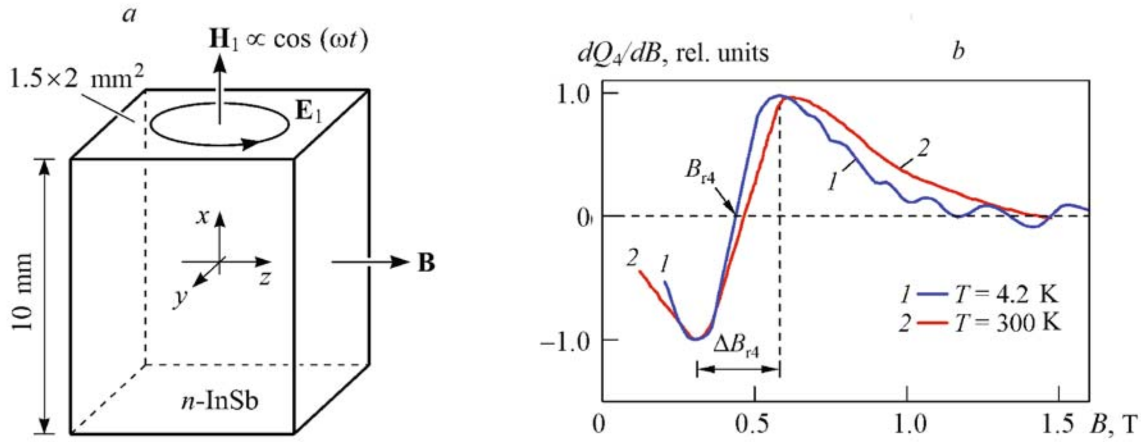

Fig. 2. Sample of crystalline n-InSb of typical dimensions; arrows show direction of scanning constant magnetic field $\mathbf{B}$ (along the z axis), magnetic $\mathbf{H}_1$ (along the x axis), and electric $\mathbf{E}_1$ components (in the yz plane) of a radio wave with frequency $\omega/2\pi$ = 10 MHz (a); experimental first-derivative signal from gain coil resonator Q_4 loaded with sample 4 with electron concentration $n_4 = 1 \cdot 10^{17}$ cm^{-3} for induction of spin-polarizing magnetic field B at 4.2 and 300 K (from the literature [4, 10]).

possible. Note that the density of c-band electron states in this magnetic field had maxima at electron energies coinciding with the position of Zeeman (spin) sublevels of Landau levels [13–15]. Therefore, transitions between Landau levels would be resonant if the initial and final c-band electron states were close to the bottom of the Landau parabola, i.e., on average a direct (vertical) transition in the "single-electron energy E-projection of quasi-wave vector k_z" diagram occurred near the center of the Brillouin zone for $\langle k_z \rangle \approx 0$ (Fig. 1).

The aim of the present work was to describe the physical picture of magnetic resonant absorption of radio waves with frequency 10 MHz by c-band electrons in n-InSb:Te,Zn crystals and to calculate the dependence of the magnetic resonance line widths on electron concentration at liquid-He temperature.

Auxiliary Equations. Let us evaluate the dependences of the effective mass of a c-band electron $m_j = m(n_j)$; the electron g-factor $g_j = g(n_j)$; and the electron drift motion $\mu_j = \mu(n_j)$ on electron concentration n_j in the jth sample at $T = 4.2$ K.

The dependence of the effective mass of a c-band electron $m(n_j)$ (from literature data [8] at $T = 77$ K) on the electron concentration n_j is written as [16]

$$m_j = m(n_j) \approx m_{\mathrm{nd}}[1 + 2.6 \cdot 10^{-2} (n_j/n_{\mathrm{m}})^{0.3}] , \tag{2}$$

where $m_{\mathrm{nd}} = 0.0136 m_0$ is the effective mass of the c-band electron density of states in a non-doped InSb crystal [8]; m_0, the electron mass in a vacuum; and $n_{\mathrm{m}} = 3.1 \cdot 10^{12}$ cm^{-3}, a fitting parameter.

The dependence of the electron g-factor $g(n_j)$ on n_j (in cm^{-3}) at cryogenic temperatures is approximated as [3]:

$$g_j = g(n_j) \approx 191 - 35.3 \ \log (n_j) + 1.283 \log^2 (n_j) < 0 . \tag{3}$$

Note that Eqs. (2) and (3) implicitly include the dependence on Landau levels with numbers ζ_{i} and ζ_{f} (the index i is before the transition of the electron between levels; index f, after the transition) because the chemical potential (Fermi level) $E_{\mathrm{F}}(B)$ at low temperatures exists in the c-band. The higher the concentration of c-band electrons is, the higher the Fermi level is situated in the c-band and, consequently, the lower the Landau levels are situated below the Fermi level (Fig. 1).

The chemical potential $E_{\mathrm{F}j}$ of c-band electrons without an external magnetic field ($B = 0$) as follows [12, 16]:

$$E_{Fj} \ \approx \ \varepsilon_{Fj} \left[1 - \frac{\pi^2}{12} \left(\frac{k_{\mathrm{B}} T}{\varepsilon_{Fj}} \right)^2 \right] > \ 3 k_{\mathrm{B}} T \ , \tag{4}$$

where $\varepsilon_{Fj} = \hbar^2(3\pi^2 n_j)^{2/3}/2m_j$ is the Fermi energy at the zero absolute temperature limit for electrons ($E = 0$ calculated from the bottom of the c-band; Fig. 1).

It follows from Eq. (4) that the chemical potential E_{Fj} for all previously studied n-InSb:Te,Zn samples [4, 10] at $T = 4.2$ K ($3k_BT = 1$ meV) was situated in the c-band; $E_{F1} = 14$ meV for $n_1 = 6\cdot10^{15}$ cm^{-3} and $E_{F6} = 542$ meV for $n_6 = 5\cdot10^{18}$ cm^{-3}. According to the literature [17], note that all samples were found on the metallic side of the insulator–metal concentration phase transition (Mott transition).

The experimental data for the Hall and drift mobility of c-band electrons $\mu_j = \mu(n_j)$ of InSb for $T = 77$ K that were previously obtained [8, 16] could be approximated as

$$\mu_j = e\langle\tau_j\rangle/m_j \approx \mu_{\mathrm{lat}}[1 + (n_j/n_\mu)^{0.43}]^{-1} , \tag{5}$$

where e is the elementary charge; $\langle\tau_j\rangle$, the average relaxation time of a quasi-pulse of a c-band electron; $\mu_{\mathrm{lat}} = 1.2\cdot10^6$ cm^2/V·s, the electron mobility limited by their scattering on crystal matrix phonons [1]; $n_\mu = 1.0\cdot10^{14}$ cm^{-3}, a fitting parameter.

The condition for observing cyclotron resonance (for $B = B_{rj}$) has the form

$$\omega_{crj}\langle\tau_j\rangle = \mu_j B_{rj} > 1 ,$$

where $\omega_{crj} = eB_{rj}/m_j$ is the cyclotron angular frequency of a c-band electron with magnetic resonance.

The condition $\mu_j B_{rj} > 1$ was fulfilled in the previous experiments [4, 10] according to Eqs. (2) and (5): $\mu_1 B_{r1} = 3.0$ for $n_1 = 6\cdot10^{15}$ cm^{-3} and $\mu_6 B_{r6} = 1.8$ for $n_6 = 5\cdot10^{18}$ cm^{-3}. Thus, an external magnetic field with induction 0.17–1.7 T is quantizing ($\hbar\omega_c >> k_BT$) for the studied n-type InSb crystals at $T = 4.2$ K.

Basic Equations. Let us examine spin-cyclotron absorption simultaneously of radio waves and an acoustic phonon by a c-band electron in n-type InSb at low temperatures.

The condition on a quasi-wave vector of phonons that can participate in forming a magnetic resonance signal is imposed by the law of conservation of the z-component of the electron quasi-wave vector [12, 18]:

$$k_{2z} = k_{1z} \pm q_z = k_{1z} \pm q \cos\theta , \tag{6}$$

where k_{2z} and k_{1z} are projections of c-band electron quasi-wave vectors in the direction of induction vector $\mathbf{B}$ after (index 2) and before (index 1) absorption (+) or emission (–) by an electron of an acoustic phonon; $q_z = q\cos\theta$, the z-component of quasi-wave vector $|\mathbf{q}| = (q_x^2 + q_y^2 + q_z^2)^{1/2}$ of a phonon; and θ, the angle between the direction of the phonon wave vector $\mathbf{q}$ and the z axis (Fig. 1).

If phonons move at arbitrary angles θ relative to the movement of electrons along the direction of induction $\mathbf{B}$ of the scanning magnetic field, then the distribution density of the angle between the electron wave vector and the phonon according to the literature [19, 20] is $\sin(\theta)/2$, where θ varies from 0 to π. Averaging Eq. (6) over angle θ gives

$$\langle k_{2z}\rangle = \langle k_{1z}\rangle \pm \frac{q}{2}\int_0^\pi \cos\theta\,\sin\theta\,d\theta = \langle k_{1z}\rangle \pm \langle q_z\rangle = \langle k_{1z}\rangle , \tag{7}$$

where $\langle q_z\rangle = 0$.

The approximation [Eq. (7)] is supported by previous work [21], i.e., the transverse (relative to vector $\mathbf{B}$) component of the quasi-wave vector of a TO-phonon is small, i.e., $\langle q_z\rangle \approx 0$, near the resonant absorption by an electron with an average quasi-wave vector $\langle k_z\rangle$ of a TO-phonon and an ultrasound energy quantum leading to electron spin inversion [22].

Spin-cyclotron absorption corresponds on average to the vertical transition [Eq. (7)] shown by the arrow in Fig. 1, which consists of a transition only between adjacent Landau levels (with conservation of spin orientation) $\hbar\omega_c$ with a subsequent transition between Zeeman sublevels (with a change in spin orientation relative to the external field induction vector) $|g|\mu_B B$. The difference between Landau level numbers ζ_f and ζ_i is $\zeta_f - \zeta_i = 1$; $\zeta = 0, 1, 2, \dots$.

Cyclotron absorption of radio waves (transition of an electron between Landau levels) occurs if 1) the average free path length of a c-band electron is longer than the average cyclotron (Larmor) radius of its orbit and 2) the condition $\omega_{cr}\langle\tau_j\rangle > 1$ is fulfilled. A transition between Zeeman sublevels with a change of spin orientation occurs when the upper sublevel is free and has spin orientation opposite to that occupied by an electron in the lower sublevel.

Let us consider that a spin-cyclotron transition occurs upon absorption by an electron of $N_{\mathrm{r}}^{(\mathrm{sc})}$ energy quanta of the radio-frequency measuring signal with frequency $f = \omega/2\pi$. We have for a sample with number j considering the change of c-band electron total energy E in a resonant magnetic field ($B = B_{\mathrm{r}j}$) upon absorption by it of radio-frequency field energy quanta:

$$\left(\hbar\,\frac{e}{m_j} + |\,g_j|\,\mu_{\mathrm{B}}\right)B_{\mathrm{r}j} \;=\; N_{\mathrm{r}j}^{(\mathrm{sc})}\hbar\omega\ , \tag{8}$$

where $eB_{\mathrm{r}j}/m_j = \omega_{\mathrm{cr}j}$ is the c-band electron cyclotron angular frequency in the jth sample with electron concentration n_j with magnetic resonance ($B = B_{\mathrm{r}j}$); $m_j = m(n_j)$, the effective electron mass according to Eq. (2); $|g_j|\mu_{\mathrm{B}}B_{\mathrm{r}j}$, the Zeeman splitting energy of each Landau level; $|g_j|$, the electron g-factor modulus according to Eq. (3); $N_{\mathrm{r}j}^{(\mathrm{sc})}$, a free parameter, the number of absorbed radio-wave energy quanta (i.e., radio photons) with spin-cyclotron resonance; $\hbar\omega$, an energy quantum of a signal (i.e., detecting magnetic resonance) radio wave with frequency $f = \omega/2\pi = 10$ MHz.

It follows from Eq. (8) that the observed resonant absorption of electromagnetic radiation of frequency 10 MHz by an n-InSb crystal in a constant magnetic field at liquid-He temperature (Fig. 2b) is due to absorption of $N_{\mathrm{r}j}^{(\mathrm{sc})}$ energy quanta $\hbar\omega \approx 4{\cdot}10^{-5}$ meV. The leads to a transition of a c-band electron between adjacent Landau levels with spin inversion. The higher the frequency $\omega/2\pi = f$ of the measuring signal is, the greater the induction $B_{\mathrm{r}j}$ at which the resonance center line is recorded is. This agreed with the experiment [10].

The transition of a c-band electron simultaneously between Landau levels and Zeeman sublevels (effect of a constant magnetic field) occurs according to Eq. (7) on average without a change in the z-component of quasi-wave vector **k**. The c-band electron energy during this resonant transition changes according to Eq. (8), in which $N_{\mathrm{r}}^{(\mathrm{sc})} > 1$ is a free parameter; ω_{cr} and $g < 0$ depend on the electron concentration. Finally, the average value of the z-component of a phonon quasi-wave vector $\langle q_z\rangle$ must be equal to zero, which agrees with the previous calculations [21, 23], for resonant absorption by c-band electrons of a radio wave with frequency $f = 10$ MHz.

According to Eq. (1), optical phonons are absent in n-InSb:Te,Zn crystals at 4.2 K. Therefore, magnetophonon absorption, i.e., the transition of a c-band electron between Landau levels upon absorption of an optical phonon without spin inversion, is not observed at low temperatures (in contrast to cyclotron-phonon resonance, which does not weaken with decreasing temperature [24]). Magnetophonon absorption in n-InSb crystals is observed in the range 63–119 K, which manifests as an oscillatory nature of the change in the longitudinal and transverse components of the electrical resistance in a magnetic field [25]. Therefore, the oscillations observed at liquid-He temperature (Fig. 2b) are not explained by magnetophonon resonance. The range of external magnetic fields 0.17–1.7 T for n-InSb crystals at 4.2 K is quantizing, i.e., the observed oscillations of the magnetic resonance signal are related to the singular nature of the densities of initial and final c-band electron states at the bottom of the Landau levels (Shubnikov–de Haas oscillations [10]). Also, crossing of Landau levels with the Fermi level is characteristic of Shubnikov–de Haas oscillations. Note that the observation of a two-phonon (LO + TA) magnetic resonance in an InSb crystal with a c-band electron concentration of $1.5{\cdot}10^{16}$ cm^{-3} at 4.2 K was reported [26]. However, nonequilibrium phonons in the InSb crystal appeared under the influence of IR radiation in the range 15–25 μm (83–50 meV) [26], in contrast to the experiments examined by us [4, 10].

The dependences [Eqs. (2) and (3)] of effective mass $m_j = m(n_j)$ and the electron g-factor $g_j = g(n_j)$ on the electron concentration n_j must be considered to calculate the number of absorbed quanta $N_{\mathrm{r}j}^{(\mathrm{sc})}$ during spin-cyclotron resonance using Eq. (8).

Results and Discussion. Table 1 presents results for the number of absorbed quanta $N_{\mathrm{r}j}^{(\mathrm{sc})}$ of energy $\hbar\omega$ during spin-cyclotron resonance for magnetic induction equal to the experimentally observed position of the center line of radio emission absorption ($B = B_{\mathrm{r}j}$).

A comparison of the measured $B_{\mathrm{r}4}$ values at room and liquid-He temperatures for an n-InSb:Te,Zn sample with c-band electron concentration $n_4 = 1{\cdot}10^{17}$ cm^{-3} showed a slight shift of the line with increasing temperature to larger $B_{\mathrm{r}4}$ values and an increase in its width at half-height (the interval $\Delta B_{\mathrm{r}4}$ between the maximum and minimum dQ_4/dB in Fig. 2b). The presumed positions of the line centers $B_{\mathrm{r}j}^{(\mathrm{e})}$ and their widths $\Delta B_{\mathrm{r}j}^{(\mathrm{e})}$ for the remaining samples at $T = 4.2$ K are obtained by calculating the percentage of the shift (Table 1).

Table 1 gives the $B_{\mathrm{r}j}^{(\mathrm{t})}$ and $\Delta B_{\mathrm{r}j}^{(\mathrm{t})}$ values calculated by multiplying $B_{\mathrm{r}j}^{(\mathrm{e})}$ and $\Delta B_{\mathrm{r}j}^{(\mathrm{e})}$ by the ratio of experimental $B_{\mathrm{r}j}^{(\mathrm{e})}$ and $\Delta B_{\mathrm{r}j}^{(\mathrm{e})}$ values at $T = 4.2$ K to the corresponding $B_{\mathrm{r}j}^{(\mathrm{e})}$ and $\Delta B_{\mathrm{r}j}^{(\mathrm{e})}$ values at $T = 300$ K for sample 4, for which experimental

TABLE 1. Experimental and Calculated Magnetic Resonance Parameters of Six Samples of n-InSb:Te,Zn at $T = 4.2$ K

j	n_j, cm^{-3}	$B_{rj}^{(e)}$, T	$\hbar\omega_{crj}^{(t)}$, meV	$g_j^{(t)}\mu_B B_{rj}^{(t)}$, meV	$N_{rj}^{(sc)}/10^4$	$\Delta B_{rj}^{(e)}/\Delta B_{r1}^{(e)}$	$\Delta B_{rj}^{(t)}/\Delta B_{r1}^{(t)}$
1	$6.0\cdot10^{15}$	0.17	1.16	0.46	3.9	1.0	1.0
2	$1.0\cdot10^{16}$	0.20	1.32	0.53	4.5	1.3	1.2
3	$5.8\cdot10^{16}$	0.36	2.05	0.84	7.0	1.9	2.1
4	$1.0\cdot10^{17}$	0.44	2.36	0.98	8.1	2.4	2.6
5	$9.0\cdot10^{17}$	0.94	3.75	1.59	13.0	4.8	5.3
6	$5.0\cdot10^{18}$	1.60	4.71	1.90	16.0	10.5	9.4

Note: j, sample number; n_j, c-band electron concentration; $B_{rj}^{(e)}$, experimental magnetic induction at resonance for jth sample; $\hbar\omega_{crj}^{(t)}$, theoretical energy of electron cyclotron motion, where cyclotron angular frequency $\omega_{crj}^{(t)} = eB_{rj}^{(t)}/m_j$ is calculated with magnetic resonance ($B = B_{rj}^{(t)} = B_{rj}^{(e)}$) considering Eq. (2); $N_{rj}^{(sc)}$, number of absorbed quanta with frequency 10 MHz estimated from Eq. (8); $\Delta B_{rj}^{(e)}/\Delta B_{r1}^{(e)}$, ratio of experimental absorption line width of the jth sample at $T = 4.2$ K to the absorption line width of the 1st sample $\Delta B_{r1}^{(e)} = 0.12$ T; $\Delta B_{rj}^{(t)}/\Delta B_{r1}^{(t)}$, theoretical ratio of width calculated from Eq. (10). The values of $B_{rj}^{(e)}$ and $\Delta B_{rj}^{(e)}$ at $T = 300$ K were taken from the literature [3].

data for $B_{rj}^{(e)}$ and $\Delta B_{rj}^{(e)}$ are available at 4.2 and 300 K. The ratio $B_{r4}^{(e)}$ ($T = 4.2$ K)/ $B_{r4}^{(e)}$ ($T = 300$ K) = 0.94 for sample 4. The ratio of the line widths of the magnetic resonance $\Delta B_{r4}^{(e)}$ ($T = 4.2$ K)/ $\Delta B_{r4}^{(e)}$ ($T = 300$ K) ≈ 0.9.

Let us consider as before [3] that the width of the magnetic resonance signal is due to the mean-square fluctuation of the electron electrostatic potential energy $W(n_j)$ [27, 28]:

$$W(n_j) \approx 0.685 \frac{e^2}{4\pi\varepsilon_r\varepsilon_0} (1-K)^{1/6} n_j^{1/3} , \tag{9}$$

where $\varepsilon_r = 16.8$ is the low-frequency relative dielectric constant of the InSb crystalline matrix [8]; $\varepsilon_0 = 8.854$ pF/m, the electric constant; $K \approx 0.1$, the compensation ratio of Te by Zn for samples 1–6; $n_j = (1-K)N_j$, the concentration of c-band electrons; N_j, the concentration of Te atoms as H-like donors in the jth sample, all in charge state (+1); KN_j, the concentration of H-like acceptors (Zn atoms), all in charge state (–1). The dopant charge states are given in units of elementary charge e.

Fluctuations of c-band electron potential energy are responsible for the coexistence of vertical and nonvertical transitions between adjacent Landau levels in the single-electron energy–spatial-coordinate diagram [29] and, consequently, determine the inhomogeneous line broadening of the spin-cyclotron magnetic resonance. Then, according to the literature [3], we obtain for all samples for the ratio of the line width (from peak to peak; Fig. 2b) in the jth sample to that in sample 1, $\Delta B_{rj}^{(t)}/\Delta B_{r1}^{(t)}$, considering Eq. (9) and for $K \approx 0.1$

$$\frac{\Delta B_{rj}^{(t)}}{\Delta B_{r1}^{(t)}} \approx \frac{W(n_j)}{W(n_1)} = \left(\frac{n_j}{n_1}\right)^{1/3} , \tag{10}$$

where $W(n_j)$ are the mean-square fluctuations of c-band electron potential energy in the jth sample [Eq. (9)]. Calculations using Eq. (10) agreed with the experiment (Table 1).

Conclusions. A spin-cyclotron resonance model was proposed to interpret known magnetic resonance measurements in n-InSb:Te,Zn crystals at liquid-He temperature ($T = 4.2$ K). According to this model, a c-band electron absorbs $N_r^{(sc)}$ quanta of radio-frequency radiation energy (frequency $f = \omega/2\pi = 10$ MHz; quantum energy $hf \approx 4\cdot10^{-5}$ meV), which leads to a transition of the electron to a higher Landau level with spin inversion (rise with inversion). The spin inversion of the electron is caused by the magnetic component of the radio wave; the transition of the electron between Landau levels, by the electric component. Absorption of energy quanta (from $3.9\cdot10^4$ to $1.6\cdot10^5$) of radio-frequency radiation upon increasing the c-band electron concentration from $6\cdot10^{15}$ to $5\cdot10^{18}$ cm^{-3} is necessary to observe the law of energy conservation during the transition of a c-band electron between adjacent Landau levels with spin inversion.

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REFERENCES

1. M. Levinshtein, S. Rumyantsev, and M. Shur (Eds.), *Handbook Series on Semiconductor Parameters*, Vol. 1, World Scientific, Singapore (1996).
2. E. I. Rashba, *Sov. Phys. Usp.*, **7**, No. 6, 823–836 (1965).
3. N. A. Poklonski, A. N. Dzeraviaha, and S. A. Vyrko, *J. Appl. Spectrosc.*, **87**, No. 4, 652–661 (2020)]
4. M. V. Kondrat′ev, M. V. Kondrat′ev, *Sov. Phys. Semicond.*, **20**, No. 8, 932–933 (1986).
5. H. Kahlert and G. Bauer, *Phys. Rev. B: Solid State*, **7**, No. 6, 2670–2682 (1973).
6. G. Bemski, *Phys. Rev. Lett.*, **4**, No. 2, 62–64 (1960).
7. N. A. Poklonskii, S. A. Vyrko, and S. L. Podenok, *Statistical Physics of Semiconductors* [in Russian], KomKniga, Moscow (2005).
8. O. Madelung, *Semiconductors: Data Handbook*, Springer, Berlin (2004).
9. N. A. Poklonski, A. N. Dzeraviaha, S. A. Vyrko, A. G. Zabrodskii, A. I. Veinger, and P. V. Semenikhin, *AIP Adv.*, **11**, No. 5, Article ID 055016 (1–9) (2021).
10. M. V. Kondrat′ev, *Sov. Phys. Solid State*, **19**, No. 2, 357–358 (1977).
11. M. Dressel and G. Gruner, *Electrodynamics of Solids. Optical Properties of Electrons in Matter*, Cambridge University Press, Cambridge (2003).
12. D. Jena, *Quantum Physics of Semiconductor Materials and Devices*, Oxford University Press, Oxford (2022).
13. N. B. Brandt and S. M. Chudinov, *Sov. Phys. Usp.*, **25**, No. 7, 518–529 (1982).
14. J. Hajdu and G. Landwehr, in: *Strong and Ultrastrong Magnetic Fields and Their Applications*, F. Herlach (Ed.), Springer, Berlin (1985), pp. 17–112.
15. Yu. A. Firsov, V. L. Gurevich, R. V. Parfeniev, and I. M. Tsidil′kovskii, in: *Landau Level Spectroscopy (Modern Problems in Condensed Matter Science, 27.2)*, G. Landwehr and E. I. Rashba (Eds.), North-Holland, Amsterdam (1991), pp. 1181–1302.
16. N. A. Poklonski, S. A. Vyrko, and A. N. Dzeraviaha, *Semiconductors*, **52**, No. 6, 692–701 (2018).
17. N. A. Poklonski, S. A. Vyrko, and A. G. Zabrodskii, *Phys. Solid State*, **46**, No. 6, 1101–1106 (2004).
18. B. K. Ridley, *Quantum Processes in Semiconductors*, Oxford University Press, Oxford (2013).
19. A. M. Mathai and H. J. Haubold, *Probability and Statistics: A Course for Physicists and Engineers*, De Gruyter, Berlin (2018).
20. T. L. Agekyan, *Probability Theory for Astronomers and Physicists* [in Russian], Nauka, Moscow (1974).
21. V. A. Margulis, *Sov. Phys. Solid State*, **23**, No. 3, 515–516 (1981).
22. S. T. Pavlov and Yu. A. Firsov, *Sov. Phys. Solid State*, **7**, No. 9, 2131–2140 (1965).
23. R. V. Parfen′ev, G. I. Kharus, I. M. Tsidil′kovskii, and S. S. Shalyt, *Sov. Phys. Usp.*, **17**, No. 1, 1–19 (1974).
24. F. G. Bass and I. B. Levinson, *Sov. Phys. − JETP*, **22**, No. 3, 635–642 (1966).
25. Yu. A. Firsov, V. L. Gurevich, R. V. Parfeniev, and S. S. Shalyt, *Phys. Rev. Lett.*, **12**, No. 24, 660–662 (1964).
26. V. I. Ivanov-Omskii, B. T. Kolomiets, and E. M. Sheregii, *Sov. Phys. JETP Lett.*, **18**, No. 6, 199–200 (1973).
27. N. A. Poklonski, S. A. Vyrko, A. I. Kovalev, and A. N. Dzeraviaha, *J. Phys. Commun.*, **2**, No. 1, Article ID 015013, 1–14 (2018).
28. N. A. Poklonskii, S. A. Vyrko, and A. N. Derevyago, *Zh. BGU, Fiz.*, No. 2, 28–41 (2020).
29. N. A. Poklonskii and S. A. Vyrko, *J. Appl. Spectrosc.*, **69**, No. 3, 434–443 (2002).