Energy spectrum of the ground state of donors in germanium with allowance for spin

N. S. Averkiev, B. L. Gel'mont, V. G. Golubev, V. I. Ovanov-Omskiĭ, and G. I. Kropotov

A. F. Ioffe Physicotechnical Institute, USSR Academy of Sciences

(Submitted 12 March 1982)
Zh. Eksp. Teor. Fiz. **83**, 1409–1417 (October 1982)

We investigate the energy spectrum of an electron bound to a shallow donor in germanium, and its dependence on the magnetic field H. A spin-induced fine structure of the lines of donor photoexcitation from the ground state into the excited states $3p_{+1}$ and $2p_{+1}$ of Sb and P impurities is experimentally observed. Theoretical calculations of the spectrum of the ground state of the Sb donor are carried out for $\mathbf{H}\|[111]$ with allowance for the diamagnetic shift, the valley-orbit interaction, and the influence of the electron spin. The spin splitting of the ground state leads to the appearance of eight different levels, the spacing between which is in general not a monotonic function of H. The probabilities of optical transitions of electrons from the ground state to excited p states of the donor are calculated. The calculated positions and intensities of the spectral lines agree with experiment.

PACS numbers: 71.55.Dp

1. INTRODUCTION

The short-range component of the impurity-atom potential in a semiconductor leads to a shift and splitting of the electron energy levels, which are degenerate in the effective-mass approximation. The shift and splitting depend on the chemical nature of the impurity (chemical shift) and on its spatial position in the unit cell. An investigation of the chemical shift makes possible a high-precision chemical analysis of extremely small amounts of impurities in crystals. Especially instructive from this point of view is an investigation of optical transitions from the ground state of an electron bound to an impurity. The reason is that the chemical shift is largest for the ground state, for which the wave function is a maximum in the central cell occupied by the impurity atom.

In a magentic field, owing to the shrinking of the wave function of the electron in a direction perpendicular to the field, the difference between chemical shifts of different impurities increases, thereby improving substantially the resolution of the impurity-analysis method. The most effective method of analyzing the chemical composition of the impurity is therefore an investigation of optical transitions from the ground state of an impurity in a magnetic field.

The problem of investigating the energy structure of the ground state of an impurity in semiconductors in a magnetic field is of interest also in the sense that magnetic fields turn out to be effectively stronger than in atomic spectroscopy. Owing to the high dielectric constant and the small effective mass it is possible to achieve in semiconductors magnetic fields such that the diamagnetic shift and the spin splitting are comparable, as a result of which the ground state has a complicated multiplet structure. In the absence of spin splitting, the energy of all the levels would increase monotonically (in absolute value) with increasing magnetic field. In magnetic fields in which the spin splitting becomes comparable with the chemical shift, however, level crossing takes place. This leads to a nonmonotonic dependence of the level energy on the magnetic field.

Germanium is one of the most thoroughly investigated semiconductors that can be produced with a specified impurity composition and in which the band parameters, the wave functions, and the electron levels at the impurity are known with high accuracy.[1] Germanium is therefore the most suitable object for the investigation of the multiplet structure of the ground state of an impurity in a magnetic field. The paramagnetic and Raman resonances of electrons bound on P and As donors have been observed for the ground state in Ref. 2. Transitions from the ground $1s$ state and the $2s$ state were investigated in Refs. 3 and 4, but no spin structure of the energy spectrum was observed.

The present paper is devoted to a theoretical and experimental investigation of the fine structure, produced in a magnetic field, of the ground structure of an electron on a donor of group V in germanium. We have observed for the first time ever the ground-state multiplet structure due to the electron spin. According to our calculation, allowance for the spin leads to a nonmonotonic dependence of the distances between the levels on the magnetic field. This means that when the magnetic field is changed the terms first move apart, then come together, and then move apart again. Selection rules are obtained for the transitions between the ground and excited states; these selection rules were investigated with the aid of the spectra of the photoconductivity produced by photothermal ionization[5] of the donors in the magnetic field. To obtain high-resolution spectra we used one of the variants of the method of photoelectric spectroscopy of impurities in semiconductors, proposed by Kogan and Lifshitz.[5] The line spectra of the photoconductivity were recorded at a fixed frequency of submillimeter gas lasers by scanning the magnetic field. When the magnetic field is scanned, at the instant when the energy of the optical transition of the electron between the bound state on the impurity center coincides with the laser-emission photon energy, resonant photoexcitation of the impurity atoms takes place. As a result of the subsequent phonon absorption, the electron turns out to be in the conduction band and a sharp peak

 0038-5646/82/100811-05$04.00

appears in the photoconductivity spectrum (photothermal ionization).

In Sec. 2 we calculate theoretically the dependence of the ground-state energy levels on the intensity of a magnetic field, applied in the [111] direction, for which the experiment is performed. In Sec. 3 the experimental procedure is described. In Sec. 4 we give the experimental results and their discussion.

2. ENERGY OF THE GROUND STATE OF THE ELECTRON BOUND ON A SHALLOW DONOR

The mnima of the conduction band of germanium are located at the edge of the Brillouin zone at the L points. In the effective-mass approximation the ground state of an electron localized on a donor is eightfold degenerate when the electron spin is taken into account. The valley-orbit interaction due to the short-wave component of the impurity potential shifts the energy levels and lifts the degeneracy partially. Thus, the ground state is split into a sixfold degenerate (representations Γ_7 and Γ_8 of the T_d point group) and a doubly degenerate (representation Γ_6) terms. The splitting depends on the type of impurity.

In a magnetic field, the level degeneracy is lifted. A variational calculation of the energy levels in germanium for symmetrical directions of the magnetic field **H** along the [100] and [111] crystallographic axes was carried out in Ref. 1 without allowance for the spin splitting. If we disregard the valley-orbit interaction, the ground state splits in the **H**‖[111] geometry into two levels connected respectively with one ellipsoid (A) oriented along the magnetic-field direction, and with three ellipsoids (B) at an angle to **H**. The energy of these levels and the distance between them increase monotonically with increasing H. The valley-orbit interaction lifts the degeneracy of the level connected with the B ellipsoids. Thus, without allowance for the spin, three levels would be produced in a magnetic field from the two levels at $H=0$. The spin splitting can lead to the appearance of eight different levels, and the distance between them is in the general case no longer a monotonic function of H.

In the effective-mass approximation the Hamiltonian of an electron bound to a shallow donor takes near the point of the minimum of the conduction band the form

$$\hat{\mathcal{H}}=\frac{1}{2m_{\parallel}}\left(\hat{p}_z-\frac{e}{c}A_z\right)^2+\frac{1}{2m_{\perp}}\left[\left(\hat{p}_x-\frac{e}{c}A_x\right)^2+\left(\hat{p}_y-\frac{e}{c}A_y\right)^2\right]-\frac{e^2}{\varkappa r}+\frac{1}{2}\mu_B[(g_{\parallel}-g_{\perp})\hat{s}_zH_z+g_{\perp}(\hat{\mathbf{s}}\mathbf{H})], \tag{1}$$

where $m_{\parallel}$ and $m_{\perp}$ are the longitudinal and transverse masses of the electron, $g_{\parallel}$ and $g_{\perp}$ are the longitudinal and transverse g factor, c is the speed of light, e is the charge, $\varkappa$ is the dielectric constant, μ_B is the Bohr magneton, **A** is the vector potential, $\mathbf{H}=\operatorname{curl}\mathbf{A}$, $\hat{\mathbf{p}}$ is the momentum operator, r is the distance from the impurity center to the electron, and s is the spin operator. The z axis is directed along the ellipsoid axis. The symmetry of the g factor is determined by the group of the wave vector at the Brillouin-zone point corresponding to the minimum energy, and is analogous to the symmetry of the effective-mass tensor. In this approximation, the wave function is the product of a smooth function Φ, which is the solution of the Schrödinger equation $\hat{\mathcal{H}}\Phi=E\Phi$ and of the Bloch function $\psi_{[ikl]}$ corresponding to the given extremum [ikl] of the conduction band. The symbols i, k, and l can take on values 1 or $\bar{1}$. In Ref. 1 are given the results of a variational calculation of the dependence of the ground state of the energy of an electron bound to a shallow donor in germanium on the magnetic field intensity for two directions of **H**, [100] and [111]. Without allowance for the spin and the valley-orbit interaction, in a magnetic field **H**‖[111], the ground state splits into two. In the case when the electron is in the A valley, the energy E_A depends more strongly on H than the enrgy E_B in any of the principal equivalent B-valleys.

The mutually orthogonal wave functions of the electron are of the form

$$\begin{aligned}\varphi_1&=\Phi_A\psi_A, \quad \varphi_2=\frac{1}{\sqrt{3}}(\psi_{[11\bar{1}]}+\psi_{[1\bar{1}1]}+\psi_{[\bar{1}11]})\Phi_B,\\ \varphi_3&=\frac{1}{\sqrt{3}}(\psi_{[11\bar{1}]}+\varepsilon_3\psi_{[1\bar{1}1]}+\varepsilon_3^2\psi_{[\bar{1}11]})\Phi_B,\\ \varphi_4&=\frac{1}{\sqrt{3}}(\psi_{[11\bar{1}]}+\varepsilon_3^2\psi_{[1\bar{1}1]}+\varepsilon_3\psi_{[\bar{1}11]})\Phi_B,\end{aligned} \tag{2}$$

where $\psi_A=\psi_{[111]}$ and $\varepsilon_3=\exp(2\pi i/3)$. Multiplying by the spin functions $|\uparrow\rangle$ and $|\downarrow\rangle$, we obtain eight functions for the ground state of the electron. To determine the level splitting due to the short-range potential and to the action of the magnetic field on the spin, it is necessary to calculate the matrix elements of the total Hamiltonian on the wave functions (2). In a magnetic field **H**‖[111] there are four different matrix elements that characterize the chemical shift:

$$\begin{aligned}\Delta V_1&=\Phi_A^2(0)\int\psi_A^*V(\mathbf{r})\psi_A\,d^3r,\\ \Delta V_3&=\Phi_A(0)\Phi_B(0)\int\psi_A^*V(\mathbf{r})\psi_B\,d^3r,\\ \Delta V_2&=\Phi_B^2(0)\int\psi_B^*V(\mathbf{r})\psi_B d^3r,\\ \Delta V_4&=\Phi_B^2(0)\int\psi^*_{[1\bar{1}1]}V(\mathbf{r})\psi_{[11\bar{1}]}d^3r.\end{aligned} \tag{3}$$

Here $V(\mathbf{r})$ is the short-range potential and ψ_B is a Bloch function belonging to any of the B ellipsoids. The short-range potential mixes the states pertaining to the different valleys, therefore the matrix that determines the possible values of the electron energy has a dimensionality 8×8 at an arbitrary direction of the magnetic field. At **H**‖[1$\bar{1}$1], however, it breaks up into two 3×3 matrices and into one 2×2 matrix. The wave functions of the first three levels are superpositions of the functions $\varphi_1|\uparrow\rangle$, $\varphi_2|\uparrow\rangle$, and $\varphi_4|\downarrow\rangle$. The energies of these levels are determined by the eigenvalues of the matrix

$$\mathcal{H}_1 = \begin{vmatrix} E_A + \Delta V_1 + {}^1/_2 g_\parallel \mu_B H & \sqrt{3}\,\Delta V_3 & 0 \\ \sqrt{3}\,\Delta V_3 & E_B + \Delta V_2 + 2\Delta V_4 + {}^1/_2 \bar{g}\mu_B H & \lambda\mu_B H \\ 0 & \lambda\mu_B H & E_B + \Delta V_2 - \Delta V_4 - {}^1/_2 \bar{g}\mu_B H \end{vmatrix}, \tag{4}$$

where $\bar{g} = (g_\parallel + 8g_\perp)/9$; $\lambda = \sqrt{2}(g_\perp - g_\parallel)/9$; E_A and E_B are the eigenvalues of the Hamiltonian (1) without allowance for the spin. Their dependence on H was calculated in Ref. 1. The matrix $\mathcal{H}_2$, constructed on the functions $\varphi_1|\downarrow\rangle$, $\varphi_2|\downarrow\rangle$, and $\varphi_3|\uparrow\rangle$, differs from the matrix $\mathcal{H}_1$ in that the following substitutions have been made: $g_\parallel, g_\perp \to -g_\parallel, -g_\perp$. Finally, the matrix $\mathcal{H}_3$ constructed on the functions $\varphi_3|\downarrow\rangle$ and $\varphi_4|\uparrow\rangle$ takes the form

$$\mathcal{H}_3 = \begin{vmatrix} E_B + \Delta V_2 - \Delta V_4 - {}^1/_2 \mu_B \bar{g} H & \lambda\mu_B H \\ \lambda\mu_B H & E_B + \Delta V_2 - \Delta V_4 + {}^1/_2 \mu_B \bar{g} H \end{vmatrix} \tag{5}$$

Its eigenvalues are

$$E = E_B + \Delta V_2 - \Delta V_4 \pm {}^1/_2 \mu_B H [\bar{g}^2 + 4\lambda^2]^{1/2}. \tag{6}$$

We have calculated numerically the dependence of the level energy on the magnetic field for the case when the impurity is Sb (Fig. 1). At $H = 0$ we have for this impurity $\Delta V_1 = \Delta V_2 = -0.69$ meV and $\Delta V_3 = \Delta V_4 = -0.088$ meV. The values of E_A, E_B, $\Phi_A(0)$, and $\Phi_B(0)$ were taken from Ref. 1. The values $g_\parallel = 0.9$ and $g_\perp = 1.92$ are given in Ref. 6. The levels E_1^-, E_2^-, and E_3^- are the eigenvalues of the matrix $\mathcal{H}_1$, the levels E_1^+, E_2^+, and E_3^+ of the matrix $\mathcal{H}_2$, and the levels E_4^* and E_4^{**} of the matrix $\mathcal{H}_3$. A characteristic feature of the dependence of the splitting of the energy levels is the presence of level anticrossing regions at $\gamma \sim 0.5$ and $\gamma \sim 1.0$. The minimum distance between the terms is determined by the parameter λ and amounts to 0.051 meV for the levels E_1^- and E_3^- and 0.025 meV for E_2^+ and E_3^+. Here

$$\gamma = \hbar\omega_c/2R, \quad \omega_c = eH/m_\perp c, \quad R = m_\perp e^4/2\hbar^2\varkappa^2,$$

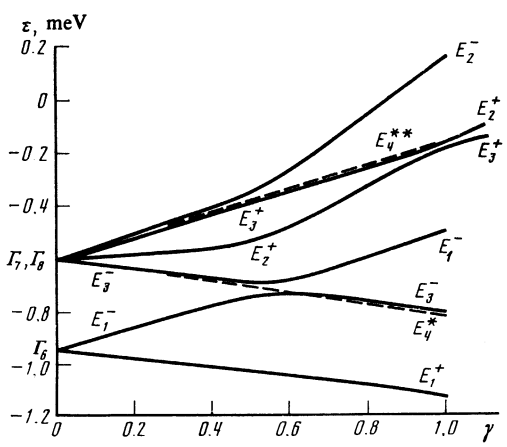

FIG. 1. Energy structure of the ground state of an electron bound to an Sb donor in a magnetic filed (the level energy is reckoned from the energy of the ground state of the donor in the effective mass approximation, $E_0 = 9.052$ meV, Ref. 1). Dashed--levels from which transitions are forbidden.

$R = 4.35$ meV [1].

For arsenic and phosphorus impurities the valley-orbit splitting in a zero magnetic field ($4\Delta V_3$) is respectively 4.23 and 2.83 meV (Ref. 5). In this case the mixing of the states Γ_7 and Γ_8 with Γ_6 in magnetic fields $\gamma \sim 1$ can be neglected. The splitting of the lower state Γ_6 is determined by a g factor equal to $(g_\parallel + 2g_\perp)/3$. The energy spectrum for these impurities was calculated in Ref. 7.

We investigated experimentally the transitions from the ground state to the excited stae of p-type in the valley A. In this situation, transitions from the states E_4^* and E_4^{**} are forbidden, from the states E_1^-, E_2^-, and E_3^- are allowed into the state $p|\uparrow\rangle$, and from the states E_1^+, E_2^+, and E_3^+ they are allowed into $p|\downarrow\rangle$. Figure 2 shows the relative intensities W of these transitions at equal population of all eight levels of the ground state.

3. EXPERIMENTAL PROCEDURE

Electron transitions between ground and excited states of donors in germanium were investigated with a submillimeter laser magnetospectrometer. Submillimeter cw gas-discharge D_2O and H_2O lasers have high monochromaticity and a sufficient power level (1–10 mW) to ensure in this experiment a high resolution and sensitivity. The spectrometer resolution is determined by the inhomogeneity of the magnetic field within the sample and amounts to $\sim 10^{-3}$ meV.

We investigated the photoconductivity spectra due to the photothermal ionization of the donors in the magnetic field at $T = 4.2$ K. The photoresponse was registered at the fixed frequencies of the submillimeter lasers with the superconducting solenoid magnetic field swept up to 65 kOe. The spectra were measured in accordance with standard lock-in detection scheme at the frequency of the radiation amplitude

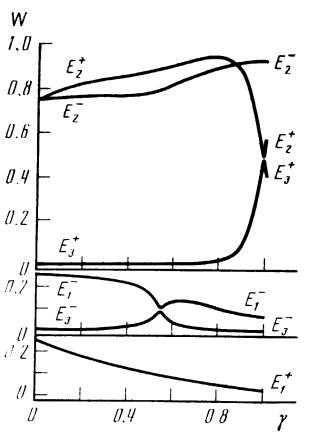

FIG. 2. Dependences of the probabilities of transitions from the ground state into excited p states on the magnetic field.

modulation, which was effected by a mechanical chopper at a frequency 750 Hz.

We investigated n-Ge doped with antimony to a donor density $N_d \sim 10^{13}$ cm^{-3} and with phosphorus to a density $\sim 10^{14}$ cm^{-3}, with a compensation $K = N_d/N_A \leqslant 0.1$. The germanium samples were parallelipipeds measuring $8\times4\times2$ mm.

The magnetic field was applied perpendicular to the radiation propagation direction (Voigt geometry) and parallel to the [111] axis of the crystals. The sample orientation in the magnetic field was with the aid of an adjustment device accurate to $\sim 30'$. The electric field in the sample was chosen weaker than the field of the impact ionization of the impurity and amounted to several V/cm.

The population of the impurity states was determined by the equilibrium and nonequilibrium carriers generated by the unmodulated background radiation from the warm parts of the cryostat. To prevent modulated background radiation a cooled filter of crystalline quartz was placed in the optical channel ahead of the sample. The measurements were made also with additional interband excitation of the electrons from an incandescent lamp in those cases when this led to narrowing of the spectral line as a result of charge exchange of the impurities. The unmodulated radiation of the interband additional illumination was applied to the target through the same metallic optical waveguide as the submillimeter radiation.

A study of the energy structure of the ground state of the donor was made by observing the transitions to the excited states, due to the ellipsoid A. In the case of possible disorientation of the sample, the ellipsoids of group B become nonequivalent and additional peaks appear in the spectrum. This phenomenon, which hinders the identification of the spectral lines, does not appear for ellipsoid A.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows sections of the photoconductivity spectrum of a Ge(Sb) sample. In addition, Fig. 3a (curve 3) shows by way of example the line of transition into the excited state $3p_{+1}$ of the phosphorus in the photoconductivity spectrum of the Ge (P) sample. In phosphorus-doped germanium, the valley-orbital splitting of the donor ground state is 2.83 meV. The triplet state $1s$ of the phosphorus at $T = 4.2$ K is not populated, therefore the optical excitation of the donor comes only from the singlet state. This circumstance is the reason why the photoexcitation spectra of antimony and phosphorus differ in Fig. 3. The doublet structure of the transition from the ground singlet state of the phosphorus into the excited p state is due to the difference between their spin splitting.

To identify the experimental peaks in the photoconductivity spectra we use the theoretical values of the level energies of the ground state with the calculated values of the intensity of the transitions from the given levels. Figure 4 illustrates method chosen to identify the spectral lines. The transitions between the ground and excited states of antimony, shown in these figures, correspond to the photoconductivity spectra in Fig. 3. In magnetic fields, in which transitions are observed, the energy of the emission photon is added to the energies of the chosen levels of the ground state and levels of the $3p_{+1}$ and $2p_{+1}$ states are constructed. When recording the photoconductivity spectrum by scanning the magnetic field, the first to appear in the spectrum are the lines of the transitions having the highest energy in the given magnetic field. Let us identify the peaks of curve 1 of Fig. 3a. As seen from Fig. 4a, the highest energy in the group of transitions into the $3p_{+1}$ state is possessed by transitions from the levels E_1^+ and E_1^-. The absence of splitting of the line of the $E_1 \rightarrow 3p_{+1}$ transition at $H \approx 10$ kOe is evidence that the spin splittings of the $3p_{+1}$ and E_1 states are close in this field region. Next in energy is the low-intensity transition from the level E_3^-. It is the first in the group of four spectral lines corresponding to transitions from the triplet state. The lowest energy is possessed by the weak transition from the level E_3^+, which should be the last observed in terms of the magnetic field. The central peaks in this group correspond to the most intense transitions from the levels E_2^- and E_2^+, the order of which is determined by the relation between the spin splittings of the excited states and of the E_2 state. In the identification assumed by us, which ensures good agreement between experiment and the theoretical calculations, the spin splititng of the excited $3p_{+1}$ and $2p_{+1}$ states turns out to be larger in the region of the experimentally investigated fields than the distance $E_2^- - E_2^+$. Therefore the identified order of the transitions is the same as indicated in Fig. 4. However, the distance, in terms of the magnetic field, between the corresponding experimental peaks decreases with increasing H, and in the field region $\gamma \sim 0.9$–1.0 the transitions from the levels E_2^+ and E_2^- will have identical energies. The doublet structure of the line is transformed into a singlet structure. In strong fields, the distance $E_2^- - E_2^+$ should exceed the spin splitting of the excited

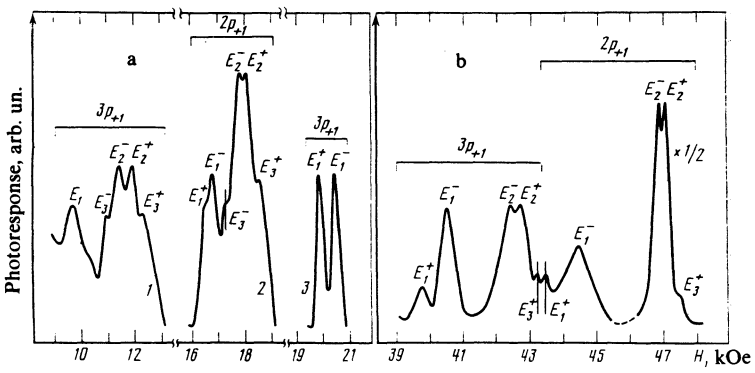

FIG. 3. Dependence of the photoresponse on the magnetic field. a) Curves 1 and 2—Ge(Sb) ($N_d = 1\times10^{13}$ cm^{-3}, $K = 0.08$; $\hbar\omega = 10.45$ meV); 3 — Ge(P) ($N_d = 1.9\times10^{14}$ cm^{-3}, $K = 0.01$; $\hbar\omega = 14.71$ meV); b) Ge(Sb); $\hbar\omega = 14.71$ meV. The markings of the peaks corresponds to the initial and final states of the electron upon photoexcitation of the donors by laser radiation.

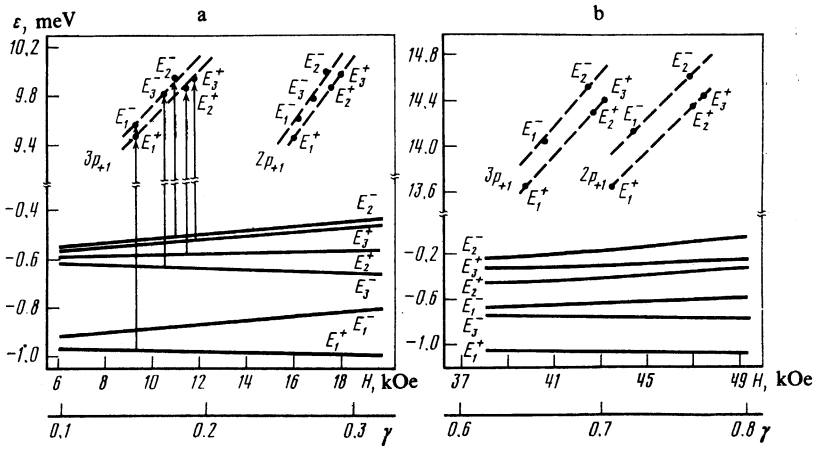

FIG. 4. Dependences of the level energies of the ground and excited states on the magnetic field of Ge(Sb): a) $\hbar\omega = 10.45$ meV; b) $\hbar\omega = 14.71$ meV. Solid lines—theory. The symbols next to the points correspond to the initial level of the transition. The arrows are shown for only one group of transitions.

states, and the sequence of the transitions is changed.

The identification was carried out in the same manner also for the other groups of transitions, and in any region of magnetic fields the transitions from the 1*s* levels with indices " + " and " − " proceed, in accordance with the selection rules, respectively to the levels $p_{+1}|\downarrow\rangle$ and $p_{+1}|\uparrow\rangle$, thereby confirming the correctness of the identification.

We note some singularities in the evolution of the position and intensity of the spectral lines in a magnetic field. The singlet structure of the line of the transition from the state E_1 is transformed into a doublet whose component separation increases with increasing magnetic field (see Fig. 3). When the [111] crystallographic axis of the sample is rotated relative to the magnetic field, the singlet of the line $E_1 \rightarrow 3p_{+1}$ ($H \sim 10$ kOe) broadens in accord with the different dependence of the spin splitting of the E_1 and p states on the field direction.

In the analysis of the correspondence between the experimentally observed peak intensities (Fig. 3) and the calculated transition probabilities (Fig. 2) account must be taken of the equilibrium population of the impurity states, a population determined by the sample temperature, and the presence of a constantly present additional experimental background impurity illumination that alters substantially the equilibrium population. The intensity of the excitation lines of the donors is also influenced by the change of the probability of the thermal ionization of the final p states in the magnetic field. The frequently employed interband excitation of the electrons has also led to a change in the ratio of the line intensity. Despite the indicated circumstances, it is possible to establish a good correspondence between the experimental and theoretical data.

The group of transitions from the ground state into a definite p state of antimony in the photoconductivity spectra consists of at most six peaks. This agrees with the theoretical calculations, in which the transitions into the p states are allowed from six levels: E_1^+, E_1^-, E_2^+, E_2^-, E_3^+ and E_3^-. The forbidden transitions from the levels E_4^* and E_4^{**} were not observed in experiment. In each group of transitions, the most intense are transitions from the levels E_2^+ and E_2^-, and their relative magnitude increases in a magnetic field $\gamma \sim 0.8$ (Fig. 3). Next in intensity are transitions from the levels E_1^+ and E_1^-. The intensity of the lines of the transitions from the level E_1^- is higher in the entire range of investigated fields than from the level E_1^+. In a magentic field $\gamma \sim 0.67$–0.75 their ratio increases (Fig. 3b).

The observed differences between the calculated and experimental line intensities are connected with transitions from the state E_3. The intensities of the transitions $E_3^- \rightarrow 3p_{+1}|\uparrow\rangle$, $2p_{+1}|\uparrow\rangle$ and $E_3^+ \rightarrow 3p_{+1}|\downarrow\rangle$, $2p_{+1}|\downarrow\rangle$ in fields $\gamma \sim 0.2$–0.3 turned out to be larger than the calculated ones. The transitions $E_3^- \rightarrow 3p_{+1}|\uparrow\rangle$, $2p_{+1}|\uparrow\rangle$ in fields $\gamma \sim 0.65$–0.7 could not be observed, whereas the peaks corresponding to the transitions $E_3^+ \rightarrow 3p_{+1}|\downarrow\rangle$, $2p_{+1}|\downarrow\rangle$ at $\gamma \sim 0.7$–0.8 are present in the photoconductivity spectra.

The performed identification of the experimental data enables us to determine the magnitude of the spin splitting of the excited $3p_{+1}$ and $2p_{+1}$ states of the antimony donor in a magnetic field. It was proposed that in the magnetic-field intervals ~ 2.5–4 kOe, in which the groups of transitions from the ground state are concentrated, the energies of the spin-split levels $3p_{+1}$ and $2p_{+1}$ states depend linearly on the field. The energy distances Δ_H between the spin components of the excited states turned out to depend on the field like $\Delta_H = g_{\parallel}\mu_B H + \delta$. Here δ determines the splitting between the twofold degenerate states ($p_{+1}|\uparrow\rangle, p_{-1}|\downarrow\rangle$) and ($p_{+1}|\downarrow\rangle$, $p_{-1}|\uparrow\rangle$) in a zero magnetic field, with account taken of the corrections to the effective-mass method on account of the other bands. The quantity δ differs from zero only for p-type states and its order of magnitude is E_p^2/E_g; E_p is the energy of the p level and E_g is the width of the forbidden band.[8] The value of δ determined from experiment is ~ 0.05 meV.

Thus, the good agreement between experiment and theory allows us to regard the structure of the ground state of the antimony donor in germanium and its dependence on the magnetic field to be finally established.

[1]N. Lee, D. M. Larsen, and B. Lax, J. Phys. Chem. Solids **34**, 1817 (1973).
[2]E. M. Gershenzon, N. M. Pevin, I. T. Semenov, and M. S. Fogel'son, Fiz. Tekh. Poluprov. **10**, 1749 (1976) [Sov. Phys. Semicond. **10**, 1039 (1976)].
[3]K. Horii and Y. Nisida, J. Phys. Soc. Japan **31**, 783 (1971).
[4]E. M. Gershenzon, G. N. Gol'tsman, and A. I. Elant'ev, Zh. Eksp. Teor. Fiz. **72**, 1062 (1977) [Sov. Phys. JETP **45**, 555 (1977)].
[5]Sh. M. Kogan and T. M. Lifshitz, Phys. Stat. Sol. (a) **39**, 11 (1977).
[6]R. E. Pontinen and T. M. Sanders, Phys. Rev. Lett. **5**, 311 (1960).
[7]R. People and P. A. Wolf, Phys. Rev. (B) **24**, 4635 (1981).
[8]G. L. Bir and G. E. Pikus, Symmetry and Strain-Induced Effects in Semiconductors, Wiley, 1975 (Russ. orig. Nauka, 1972, p. 358).

Translated by J. G. Adashko