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OPTICAL ORIENTATION OF ELECTRON SPINS AND BAND SPLITTING IN DOPED SEMICONDUCTORS

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The optical orientation of the electron spins in interband absorption of circularly-polarized light in semiconductors can be used to study a number of characteristics of band splitting. The experimental results presented below illustrate the possibilities of this method for the study of the shift of the split-off valence band in doped p-GaAs, and also for the investigation of the splitting of the conduction band. This splitting, which occurs in crystals without an inversion center, should lead to additional spin relaxation. As shown by D'yakonov and Perel' [1], its rate increases rapidly with the energy of the electrons in the conduction band. At an energy $E_{h\nu}$ of the exciting-light quanta, satisfying the condition $E_{h\nu} - E_g \ll \Delta$ (E_g is the width of the forbidden band, and Δ is the spin-orbit splitting of the valence band), the spin orientation is maximal. In this case the spin relaxation corresponds to relaxation of the thermalized electrons and is characterized by a time τ^{ST}. With increasing $E_{h\nu} - E_g$, the additional relaxation due to the splitting of the conduction band can lead to a change in the type of the observed dependence of the degree ρ of the circular polarization of the recombination radiation on $E_{h\nu}$, to the extent even that the sign of the polarization may reverse.

It was found in [2] that there is a systematic discrepancy between the theoretical and experimental plots, $\rho_T(e_{h\nu})$ and $\rho_e(E_{h\nu})$, for p-GaAs with concentration 2×10^{19} cm^{-3}. It was shown in [3], however, that this discrepancy is due to the different values of τ^{ST} in the interior and on the surface of the sample. The results of [3] led to the conclusion that the spin orientation is conserved during energy and momentum relaxation of the conduction electrons in the case of a strongly-doped semiconductor. As shown in [1], scattering by impurities decreases the influence of the conduction band splitting on the spin relaxation (an effect analogous to the narrowing of the paramagnetic-resonance lines in liquids and gases). Therefore an investigation of the effective spin relaxation of non-thermalized electrons should be carried out either at lower impurity concentrations than in [2], or else at high energies.

Figure 1 shows a plot of $\rho(E_{h\nu})$ for an impurity concentration 3×10^{18} cm^{-3} in the energy interval $E_g \lesssim E_{h\nu} \lesssim E_g + 3\Delta$ at 77°K. The line width of the exciting light at the base was $\sim$20 MeV. To exclude the analyzer errors in the measurement of the weak circular-polarization signals (U_σ), the excitation was carried out both with right (σ^+) and left (σ^-) circularly polarized light. The values of $\rho(E_{h\nu})$ shown in Fig. 1 were obtained from the values of $(U_{\sigma^+} + U_{\sigma^-})/2$. At $E_{h\nu} \approx 2.02$ eV, the sign of the circular polarization reversed. A reliable criterion for the observation of the spin orientation with the aid of recombination radiation is the depolarization of this radiation in a magnetic field H. The plots of $\rho(H)$ shown in Fig. 2 were also calculated from the values of $(U_{\sigma^+} + U_{\sigma^-})/2$ at different H for three values of the wavelengths. Observation of the depolarization of the recombination radiation in

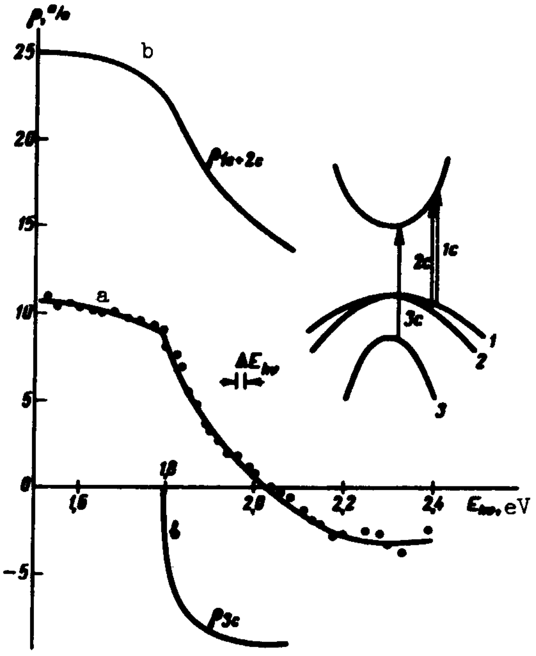

Fig. 1

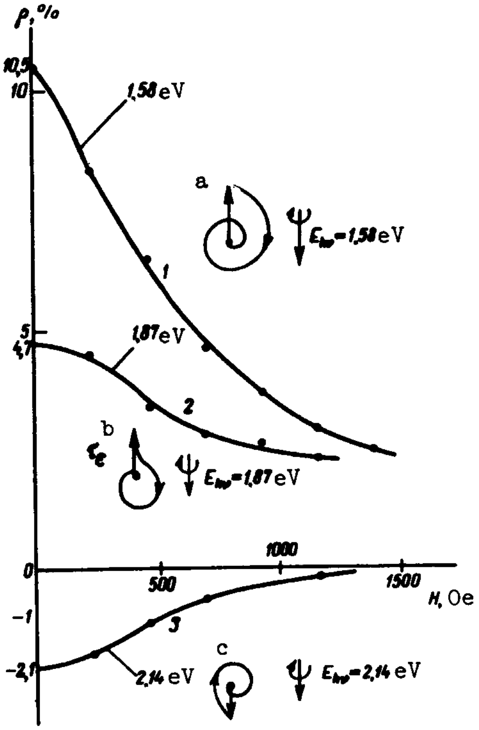

Fig. 2

Fig. 1. a - Experimental dependence of the degree of circular polarization ρ on $E_{h\nu}$, b and c - calculated $\rho(E_{h\nu})$ plots corresponding to the occurrence of orientation in transitions 1c + 2c (b) and 3c (c).

Fig. 2. Depolarization of recombination radiation in a magnetic field: 1, 2, 3 - plots of ρ(H) at $E_{h\nu}$ = 1.58, 1.87, and 2.14 eV, respectively. a, b, c - polar diagrams illustrating the change of the spin-orientation vector in space and in time upon superposition of an external magnetic field. a and c correspond to relaxation of thermalized electrons within times comparable with the period of the Larmor precession, c takes into account the rapid relaxation during a time τ_e, connected with the splitting of the conduction band, and the subsequent relaxation of the thermalized electrons.

a magnetic field (curve 3 of Fig. 2) for the section of $E_{h\nu}$ corresponding to reversal of the sign of the circular polarization on Fig. 1, makes it possible to establish reliably a "remagnetization" of the electron gas with increasing photon energy. Reversal of the sign of the circular polarization was also observed in [4], where it was interpreted in accordance with [1]. For such an interpretation, however, it is necessary to have data on the depolarization of the luminescence in a magnetic field and an analysis of the $\rho(E_{h\nu})$ dependence, since reversal of the sign of the polarization can occur regardless of the splitting of the conduction band, as a result of the considerable difference between the values of τ^{ST} in the volume and on the surface (see below).

Allowance for the different contributions of the bands of heavy (1) and light (2) holes, and also of the split-off (3) band to the resultant orientation of P makes it possible to explain the observed effect. Without allowance for the spin relaxation we have

$$P = \left(\sum_{n=1}^{3} K_n P_n\right) / \sum_{n=1}^{3} K_n ,$$

where P_n is the probability of orientation on going from the n-th band, and $K_n/\sum_{n=1}^{3} K_n$ is the normalized absorption coefficient for the n-th band. Figure 1 shows the calculated plots (b) and (c) of $\rho(E_{h\nu})$ separately for transitions leading to the creation of orientations of opposite sign. Curve (b) corresponds to the summary contribution of bands 1 and 2, while curve (c) corresponds to the contribution of band 3. In the considered energy range, the orientation determined by bands 1 and 2 predominates. However, turning on of the relaxation mechanisms that depend on the energy of the electrons in the conduction band leads to a relative decrease of the contribution of bands 1 and 2 compared with band 3, since the electron energy as a result of transitions 3c is smaller than in the case of 1c and 2c (see Fig. 1). A similar result is caused by the difference in the spatial distribution of the electrons corresponding to the transitions 1c + 2c and 3c. Since $K_1 + K_2 > K_3$, the contribution of bands 1 and 2 is larger in the near-surface layer, and that of band 3 is larger in the volume. If τ^{ST} in the volume is much larger than on the surface, then the resultant orientation can likewise reverse sign:

$$P = \sum_{n=1}^{3} [\tau_n^{ST}/(\tau_n + \tau_n^{ST})] K_n P_n \exp(-\Phi_n) / \sum_{n=1}^{3} K_n .$$

The factor $\tau_n^{ST}/(\tau_n + \tau_n^{ST})$ is determined here by the ratio of the lifetime τ_n and of the spin relaxation time τ_n^{ST} of the thermalized electrons, with allowance for their spatial distribution upon excitation from different bands. Φ_n determines the spin relaxation connected with splitting of the conduction band. According to the model of D'yakonov and Perel', $\Phi_n = (\alpha_n \varepsilon n/\varepsilon_0)^6$, where $\varepsilon_n = E_{h\nu} - E_g$ for bands 1 and 2, and $\varepsilon_n = E_{h\nu} - (E_g + \Delta)$ for band 3. $\alpha_n = 1/(1 + m_e/m_n)$, where m_e and m_n are the effective masses of the electron and of the hole in the n-th band, and ε_0 corresponds to the electron energy in the conduction band, at which P decreases by a factor e as a result of the splitting of this band. Figure 3 shows the $\rho(E_{h\nu})$ plots calculated by D'yakonov and Perel' for $\varepsilon_0 = 0.5$, 1, 2, and ∞ (in the spin-orbit splitting units $x = (E_{h\nu} - E_g)/\Delta$). The same figure shows the experimental values, multiplied by $2(\tau_{1,2} + \tau_{1,2}^{ST})/\tau_{1,2}^{ST}$ for the transition from the observed values of ρ to the calculated values of P. The factor $(\tau_{1,2} + \tau_{1,2}^{ST})/\tau_{1,2}^{ST}$ was determined for $E_{h\nu} = E_g$. No account is taken here of the variation of τ_n and τ_n^{ST} with the energy $E_{h\nu}$. At the same

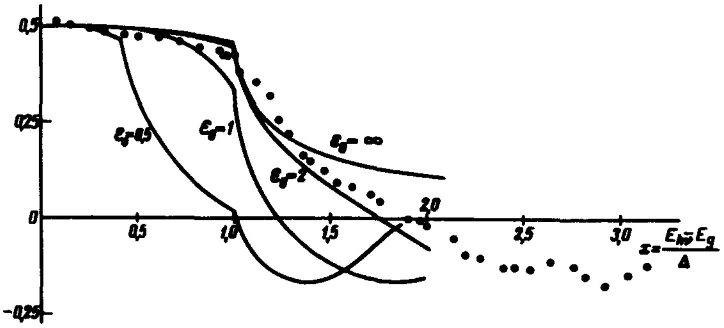

Fig. 3. Comparison of the calculated degree of orientation P at different values of the parameter ε_0 with experiment.

time, curve 2 on Fig. 2 ($E_{h\nu}$ = 1.87 eV) has a "tail" in the region of large H (up to 4 kOe), corresponding to the increased contribution of the surface region with small τ^{ST}. Curve 3 in the same figure has no such "tail," corresponding to the smaller value of K_3, namely $K_3 \approx 0.25(K_1 + K_2)$, and accordingly to the smaller contribution of the surface region. In order to verify the extent to which the influence of the surface is important, a layer of the solid solution GaAlAs was produced on the same GaAs crystal. This broad-band layer is transparent at $E_{h\nu} \lesssim E_g + 2\Delta$ and changes noticeably the characteristics of the GaAs surface, near which the spin orientation is produced. It turned out that in this case the "fan" of ρ(H) curves for different H (see [3]) became considerably narrower, and the "tails" in the region of large H have been sharply decreased. At the same time, the ρ(x) curve in the region of x from 1 all the way to the absorption edge of GaAlAs is similar to that shown in Fig. 1. In this case, a reversal of the sign of the circular polarization in the region of $E_{h\nu} \approx 2.1$ eV was also reliably established¹⁾. Thus, it can be concluded that the reversal of the sign is connected in our case with the splitting of the band, and not with surface effects. The experimental results agree with the theory at $2 \lesssim \varepsilon_0 < 3$. For a more exact determination of ε_0 it is necessary to take into account the change of τ^{ST}.

A second characteristic feature of the curve a on Fig. 1 is the presence of a kink at $E_{h\nu} = 1.79 \pm 0.02$ eV, corresponding to inclusion of the band 3. This value is smaller than the value well known for pure GaAs crystals, $E_g + \Delta = 1.85$ eV (at 77°K). This may be connected with the formation of a band of split-off acceptor states, which merge with the split-off band. The effective mass of the holes in the split-off band is approximately three times smaller than in the heavy-hole band. Therefore the formation of such a band near the split-off band should occur at lower concentrations of the acceptor impurity than is usually the case for the heavy-hole band. Thus, the method of optical orientation of the electron spins makes it possible to investigate both the mechanism of the spin relaxation of the highly-excited electrons in the conduction band, and the energy shifts of the spin-orbitally split-off band in the case of strongly doped semiconductors.

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1) More details on these experiments are contained in a paper written jointly with D.Z. Garbuzov.