Spin relaxation of holes in the split-hole band of InP and GaSb

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We report spin-orientation experiments for photoexcited holes in the spin-orbit-split valence band created by optical pumping with circularly polarized light near $\mathbf{k}=0$. The degree of circular polarization of the $E_0+\Delta_0$ luminescence, which measures directly the spin orientation of the thermalized holes, is studied as a function of the excitation energy for n-type InP (with different doping levels ranging from 5×10^{15} to 5×10^{17} cm^{-3}) and for n-type GaSb (1.8×10^{18} cm^{-3}). We observe no dependence of the polarization degree on doping in InP. The degree of polarization decreases similarly with increasing photon energy in InP and GaSb, materials with very different spin-orbit splittings. Several spin-relaxation mechanisms are discussed. The data are analyzed on the basis of the Dyakonov-Perel spin-relaxation mechanism. The effect of scattering between split-hole, light-hole, and heavy-hole bands is also considered. The Dyakonov-Perel mechanism seems to be dominant for hole excitations up to 0.5 eV above the $E_0+\Delta_0$ gap. From a fit of the experimental depolarization curves we obtain reasonable momentum relaxation times for holes of the order of 100–200 fs in InP and 200–300 fs in GaSb.

I. INTRODUCTION

Optical orientation of electron spins is a powerful method for investigating relaxation processes in semiconductors (for a review, see Ref. 1). Optical pumping with linearly polarized light has also shown to yield spin-polarized photoelectrons in GaAs.[2] This effect has found application in spin-polarized electron sources.[3]

Most of the past investigations have dealt with the study of conduction-band electrons in p-type materials.[4] Work on hot-electron luminescence above the direct gap E_0 in GaAs (Ref. 5—7) and InP (Refs. 8 and 9), or on the polarization analysis of the band-to-band luminescence,[5,10] was carried out in order to analyze the various energy, momentum, and spin-relaxation mechanisms for electrons. This work was stimulated by theoretical studies of spin-relaxation processes by Elliott and Yafet,[11,12] Dyakonov and Perel,[6,13,14] and Bir et al.[15] In these experiments the spins of conduction electrons are oriented by pumping with circularly polarized light. The dependence of the various spin-relaxation mechanisms on temperature and doping has been used to distinguish between them.[16–18] Using the Hanle effect,[19] i.e., the spin depolarization of electrons subject to a transverse magnetic field, quantitative values have been obtained for the spin relaxation times of electrons in the conduction band.[20–22] The effect of the different valence bands on the optical orientation of electron spins in the conduction band of p-type GaAs has been studied by varying the energy of the exciting light and observing the degree of polarization of the E_0 luminescence.[23,24] In dilute magnetic semiconductors (Cd$_{1-x}$Mn$_x$Se, Cd$_{1-x}$Mn$_x$Te) ultrafast spin relaxation of electrons has been observed by picosecond luminescence studies ($\tau_s\approx20$ ps).[25] The nuclear spins of the Mn^{2+} atoms ($S=\frac{5}{2}$) induce an internal magnetic field which leads to a spin relaxation somewhat similar to the Dyakonov-Perel mechanism.

Little work has been done on n-type materials,[21,22,26,27] especially on the above-gap luminescence which occurs in them near $E_0+\Delta_0$, the spin-orbit-split component of the direct gap.[28] The corresponding valence state has equivalent angular momentum $J=\frac{1}{2}$ and thus will be treated here as a spin or pseudospin doublet. This spin can be fully oriented: the luminescence at $E_0+\Delta_0$ is then 100% circularly polarized. Recently, a preliminary report on the dependence of the polarization degree of the $E_0+\Delta_0$ luminescence on the excitation energy of GaAs has appeared.[29,30] For holes created $9\hbar\Omega_{LO}$ above the $E_0+\Delta_0$ gap in the split-hole band a spin polarization is still observed after thermalization. The spin loss is attributed to scattering processes between the split-hole and light- and heavy-hole bands. The Dyakonov-Perel mechanism[13,14] is thought to be less important.

We have studied the dependence of the degree of circular polarization as a function of the exciting laser frequency in n-type InP and GaSb. Band-mixing and spin-orbit-splitting effects can be judged by comparing the measurements of InP [valence-band splitting $\Delta_0=0.11$ eV (Ref. 31)] with those of GaSb [$\Delta_0=0.75$ eV (Refs. 32 and 33)]. Four InP samples with different doping levels (between 5×10^{15} and 5×10^{17} cm^{-3}) were investigated. Within this range, no effects of doping were found. For InP the spin depolarization can be interpreted with the mechanism proposed by Dyakonov and Perel.[13,14] For GaSb, however, inter-valence-band scattering should produce a depolarization stronger than observed. This suggests that indirect transitions may be important in determining the observed polarized luminescence.

Section II of this paper is devoted to the theory of spin orientation as related to the $E_0+\Delta_0$ luminescence. After the description of experimental details (Sec. III) and results (Sec. IV), several possible spin-relaxation mechanisms are discussed in Sec. V. Two of them (Dyakonov-Perel and inter-valence-band scattering) are argued to be important for our samples. A detailed analysis of both mechanisms yields information about their relative impor-

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tance and provides values of momentum relaxation times. These results are compared to the scattering times obtained by subpicosecond spectroscopy.[34]

II. SPIN ORIENTATION AND POLARIZED LUMINESCENCE

The band structure of InP and GaSb at the Γ point can be characterized by two sets of bands; the conduction band c (Γ_6) which is twofold degenerate (spin) and the valence band v, composed of four subbands. The heavy-(hh) and light-hole (lh) bands, belonging to the Γ_8 irreducible representation, are together fourfold degenerate at Γ, while the split-hole (sh) band (Γ_7) is only twofold degenerate.[35,36]

The wave functions of an electron state around the Γ_6 c-band state can be written as[37-39]

$$| c \rangle = | \mathbf{k}, m \rangle = e^{i\mathbf{k}\cdot\mathbf{r}} | S, m \rangle, \quad m = \pm \tfrac{1}{2} \tag{1}$$

with the Bloch amplitudes

$$| S, \tfrac{1}{2} \rangle = iS\uparrow \quad \text{and} \quad | S, -\tfrac{1}{2} \rangle = iS\downarrow . \tag{2}$$

Here, S denotes the spatial part of the s-type Bloch amplitude, invariant under the symmetry transformations of the crystal (Γ_1), and $m = \pm\tfrac{1}{2}$ is the spin projection along an *arbitrary* quantization direction (if one neglects the spin splitting of these states to be discussed below). The wave function of an electron state in the sh band can be written[39]

$$| \text{sh} \rangle = | \mathbf{k}, M \rangle = e^{i\mathbf{k}\cdot\mathbf{r}} \sum_{\mu} D^{(1/2)}_{\mu,M}(\phi,\theta,\psi) | \tfrac{1}{2},\mu \rangle , \tag{3}$$

with

$$| \tfrac{1}{2},\tfrac{1}{2} \rangle = -\frac{1}{\sqrt{3}} [(X+iY)\downarrow + Z\uparrow] \tag{4a}$$

and

$$| \tfrac{1}{2},-\tfrac{1}{2} \rangle = \frac{1}{\sqrt{3}} [+(X-iY)\uparrow - Z\downarrow] . \tag{4b}$$

Here, $M = \pm\tfrac{1}{2}$ is the projection of the angular momentum along $\mathbf{k}$, μ is the eigenvalue of the angular-momentum operator J_z, while ϕ, θ, and ψ are the Eulerian angles of the vector $\mathbf{k}$ with respect to a fixed coordinate system. ψ is an arbitrary phase angle, and $D^{(1/2)}$ denotes the finite rotation matrix for the angular momentum $J = \tfrac{1}{2}$. The spatial wave functions X, Y, Z transform as the coordinates x, y, z.

A spin-orientation experiment for holes in the sh band can be separated into three steps:

(i) The creation of spin-polarized holes in the sh band by optical pumping with circularly polarized light.

(ii) Relaxation of the holes in the sh band in energy, momentum, and spin (thermalization).

(iii) Recombination of electrons (majority carriers) at the bottom of the c band (n-type material) with holes near the top of the sh band upon emission of circularly polarized light.

The dipole selection rules for sh-c transitions near $\mathbf{k}=0$ require that for right-hand circularly polarized light (photon angular momentum l along the linear momentum $\mathbf{k}$

equal $+1$) the $| \tfrac{1}{2}, -\tfrac{1}{2} \rangle$ sh state be coupled to the $| S,\tfrac{1}{2} \rangle$ c state (quantization direction $\equiv$ direction of propagation of light), whereas for left-hand circularly polarized light ($l = -1$) the $| \tfrac{1}{2},\tfrac{1}{2} \rangle$ state must couple to the $| S, -\tfrac{1}{2} \rangle$ state only.[13,14,39,40] Thus, pumping with circularly polarized light excites electrons from the sh band into the c band and orients the spin along the photon angular momentum, whereas a hole is left in the sh band with opposite spin. Thus, for excitation in the sh band near the Γ point, *complete* spin orientation of split-off holes by optical pumping with circularly polarized light should be obtained. Band mixing through $\mathbf{k}\cdot\mathbf{p}$ terms between the sh and lh bands for $\mathbf{k}\neq 0$ reduces the average spin of holes created in the sh band by excitation with circularly polarized light (we label it then $\pm\tfrac{1}{2}S_{0,3}$). Assuming isotropic bands, one obtains an expression for the degree of spin orientation $S_{0,3}$ at the creation point:[13,39]

$$S_{0,3}(\hbar\omega_L) = -\frac{1}{4} \frac{(1+b)(g-6x+9b-5)}{-bg+6x-b-3} , \tag{5}$$

with

$$b = \frac{4}{3} \frac{m_c^{-1} + 3m_{\text{lh}}^{-1}/4 + m_{\text{hh}}^{-1}/4}{m_{\text{lh}}^{-1} - m_{\text{hh}}^{-1}} , \tag{6a}$$

$$g = [36x^2 - 12x(b+3) + (3b+1)^2]^{1/2} , \tag{6b}$$

and

$$x = \frac{\hbar\omega_L - E_0}{\Delta_0} . \tag{6c}$$

In Eqs. (5)–(6c) the excitation energy is $\hbar\omega_L$, and m_c, m_{lh}, and m_{hh} are the effective masses of the c, lh, and hh bands, respectively. For excitation at the Γ point ($\hbar\omega_L = E_0 + \Delta_0$, $x=1$), $S_{0,3}=1$, whereas for $\hbar\omega_L = E_0 + 2\Delta_0$ ($x=2$), $S_{0,3}=0.5$. The function $S_{0,3}$ is quite sensitive to the spin-orbit splitting, thus revealing that the spin orientation at the $E_0 + \Delta_0$ gap is entirely due to spin-orbit interaction: for $\Delta_0 \to 0$ or $x \to \infty$, $S_{0,3}$ tends to zero.

If the photoexcited holes in the sh band relax to the top of the band in energy and linear momentum but not in angular momentum (spin), the luminescence at $E_0 + \Delta_0$ produced by their recombination with majority electrons (n-type sample) should be determined by the band mixing between the sh and the lh bands. Thus, the degree of circular polarization of the luminescence at $E_0 + \Delta_0$, defined as[41,39]

$$P_c = \frac{I_+ - I_-}{I_+ + I_-} , \tag{7}$$

where I_+ (I_-) denotes the intensity of the luminescence polarized like (opposite to) the exciting laser light, should hold:

$$0 \le P_c \le S_{0,3}(\hbar\omega_L) , \tag{8}$$

with $P_c = S_{0,3}$ if no spin relaxation occurs. Comparison of the dependence of the spin orientation of holes on the excitation energy with the loss of spin orientation due to band mixing ($S_{0,3}$) should thus reveal whether additional spin-relaxation mechanisms for holes are present or not.

Linearly polarized light produces a linear combination of the two spin orientations, which will quickly lose their phase coherence due to linear momentum relaxation.[40,42] Thus in this case no angular-momentum alignment is possible for holes in the sh band. The degree of linear polarization, defined as[42]

$$P_l = \frac{I_{||} - I_\perp}{I_{||} + I_\perp} , \qquad (9)$$

where $I_{||}$ ($I_\perp$) denotes the intensity of the luminescence with polarizer and analyzer parallel (crossed) to each other, should vanish for the $E_0 + \Delta_0$ luminescence.

III. EXPERIMENT

We measured the dependence of the degree of circular polarization on the frequency of the exciting light for the luminescence near $E_0 + \Delta_0$ in InP and GaSb. To check the selection rule $P_l = 0$ [Eq. (9)], we also performed measurements with linearly polarized light. The n-type InP samples studied were sulfur-doped, covering a free-electron range $n \simeq N_d = 5 \times 10^{15}$ to 5×10^{17} cm^{-3}. One sample ($n = 5 \times 10^{15}$ cm^{-3}) was cut with a (001) surface from bulk material obtained from G. Müller (Universität Erlangen—Nürnberg). The other samples, supplied by K. Benz (Universität Stuttgart), were epitaxial layers ($d = 1.5 - 7.8$ μm) grown on semi-insulating InP:Fe(001) substrates by chemical-vapor deposition (CVD). In GaSb the $E_0 + \Delta_0$ luminescence is weaker and the experiments could only be comfortably performed on a Te-doped sample (Czochralski grown) with $n \simeq N_d = 1.8 \times 10^{18}$ cm^{-3} cut from bulk material.

The luminescence measurements were carried out with the discrete lines of a Kr$^+$ laser and with a cw dye laser. The dye LD700 (Lambda Physik, Göttingen) was pumped with all red lines of a Kr$^+$ laser (4.5 W) and lased in the energy range 1.5—1.7 eV, close to the $E_0 + \Delta_0$ gaps of InP [1.52 eV (Ref. 31)] and GaSb [1.57 eV (Ref. 32)]. Since the $E_0 + \Delta_0$ luminescence is rather weak (about 10^8 times weaker than the edge luminescence in InP at 10 K), the laser power incident on the sample was as high as 100—200 mW. The laser beam was focused onto the sample with a cylindrical lens to keep the power density below 10 W/cm^2.

To improve the degree of linear polarization of the dye laser light from about 95% to more than 99%, we used a quartz Glan-Thompson polarizer. As a linear analyzer we chose a polarization foil. Two superachromatic $\lambda/4$ plates (Halle, Berlin) served as circular-polarization converters of the linearly polarized light.[43] These plates are composed of three pairs of plates made of quartz and MgF$_2$ which are glued between parallel plates of Suprasil. Within the (310—1100)-nm range the wavelength shift amounts to ($\lambda/4$)$\pm 2\%$. The $\lambda/4$ plates were put behind the linear polarizer (in front of the linear analyzer) in order to obtain a circular polarizer (analyzer).

The luminescence was detected either with a Spex 0.8 m monochromator, equipped with a standard RCA 31034 GaAs photomultiplier, or with a Jarrell-Ash 1-m double monochromator, equipped with a Varian VPM-164A In-Ga-As-P photomultiplier cooled down to 200 K. The

latter detector covers a range down to 1.1 eV (1100 nm), also allowing measurements of the E_0 luminescence in InP [$\simeq 1.42$ eV (Refs. 31 and 44)]. The experiments were performed in a helium-flow cryostat at about 10 K under nearly normal incidence (external angle of incidence 15°) on the sample. To check the experimental setup, we determined the degree of circular and linear polarization of the reflected laser light to be $P_c = (94 \pm 3)\%$ and $P_l = (98 \pm 2)\%$. These values determine the minimum detectable polarization ($\simeq 5\%$).

IV. RESULTS

Figure 1 shows the luminescence spectra obtained on InP ($n = 1.7 \times 10^{17}$ cm^{-3}) with circularly polarized light for two different laser energies. At $\hbar\omega_L = 1.551$ eV the luminescence has $P_c > 0.9$, whereas the polarization is completely lost ($P_c = 0$) at $\hbar\omega_L = 1.833$ eV. The intensity of the luminescence decreases by a factor of 30 from $\hbar\omega_L = 1.551$ eV to $\hbar\omega_L = 1.833$ eV. No shift of the luminescence frequency with $\hbar\omega_L$ is observed. It occurs
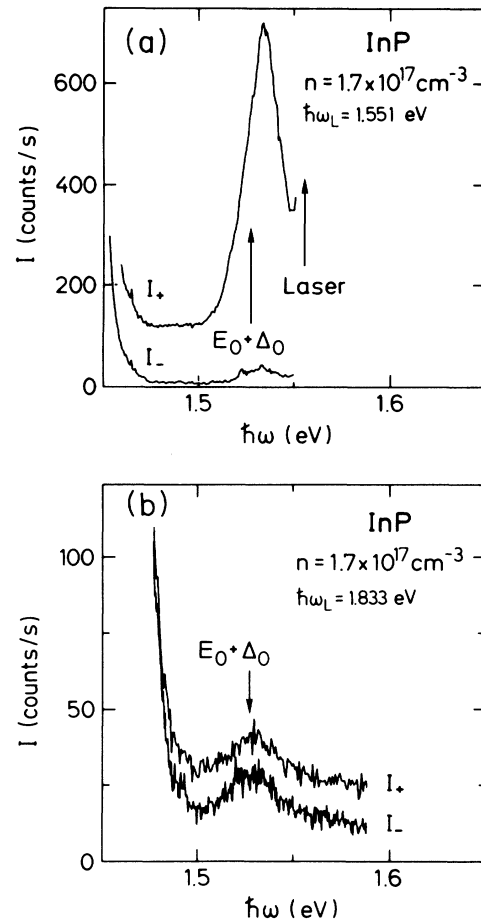
FIG. 1. Luminescence spectra of InP ($n = 1.7 \times 10^{17}$ cm^{-3}) obtained near $E_0 + \Delta_0$ with circularly polarized light at two different laser energies, (a) $\hbar\omega_L = 1.551$ eV and (b) $\hbar\omega_L = 1.833$ eV. (The upper curve I_+ has been shifted vertically with respect to the lower curve I_-.)

very close to reported values of the $E_0 + \Delta_0$ gap [1.527 eV (Ref. 31)] independently of n. Only for the highest doped sample ($n = 4.7 \times 10^{17}$ cm^{-3}) the peak is 5 meV higher than for the other samples.

Figure 2 displays P_c as a function of $\hbar\omega_L$ (lower horizontal scale). The upper scale gives the kinetic energy ε_0 of the hole in the sh band at the creation point (assuming direct transitions) in units of the LO-phonon energy $\hbar\Omega_{LO}$. The polarization degree P_c decreases monotonically from more than 90% to zero and does not show any concentration dependence within the range $n = 5 \times 10^{15}$ to 5×10^{17} cm^{-3}. The function $S_{0,3}$, calculated according to Eqs. (5) and (6) with the band-structure parameters given in Table I, represents the upper limit for P_c expected from the band mixing of the sh and lh states. The function $S_{0,3} e^{-\phi(\varepsilon_0)}$ is a fit with the predictions of the Dyakonov-Perel spin-relaxation mechanism (see Sec. V).

The total intensity I ($= I_+ + I_-$ or $I_\parallel + I_\perp$) of the luminescence depends on the doping level and the excitation energy as displayed in Fig. 3. The higher the doping level, the higher the luminescence intensity. From 1.5 to 1.9 eV the intensity decreases by a factor of 30 and becomes constant as P_c approaches zero. Over the entire excitation range no linear polarization of the $E_0 + \Delta_0$ luminescence is observed.

The luminescence spectra of GaSb reveal a more complicated behavior. Figure 4 depicts such spectra in the I_+ configuration for four values of $\hbar\omega_L$. The line shapes of Fig. 4 depend on the excitation energy between 1.65 and 1.72 eV, whereas for $\hbar\omega_L \geq 1.72$ eV no appreciable change is seen. For $\hbar\omega_L < 1.65$ eV almost no $E_0 + \Delta_0$ luminescence is observed. At $\hbar\omega_L = 1.653$ eV a weak feature is seen at the $E_0 + \Delta_0$ gap [1.565 eV (Refs. 32 and 33)] and a shoulder begins to develop at the low-energy scale of the laser frequency. At $\hbar\omega_L = 1.699$ eV this shoulder becomes the dominant structure, shifting slightly with increasing $\hbar\omega_L$. Finally, it disappears at $\hbar\omega_L = 1.722$ eV, leaving behind a broad structure between 1.55 and 1.70 eV. Be-
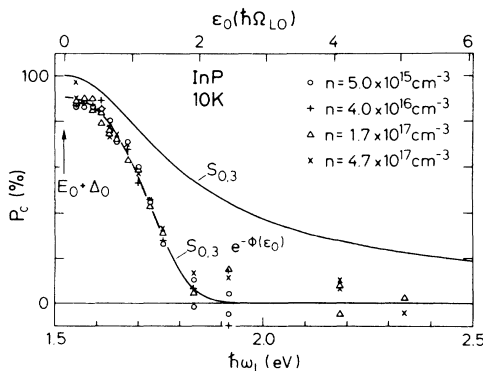

FIG. 3. Total intensity I ($= I_+ + I_-$ or $I_\parallel + I_\perp$) for the $E_0 + \Delta_0$ luminescence in InP as a function of the laser energy $\hbar\omega_L$. The intensity has been normalized with respect to the incident power.

fore its disappearance, the shoulder has its peak (and its upper edge) 100 meV (130 meV) above the gap. The luminescence is fully circularly polarized up to 1.70 eV (Fig. 5) and then the degree of polarization decreases monotonically to 0%. No linear polarization is observed over the whole excitation range. This luminescence must still be due to the $E_0 + \Delta_0$ gap because of its circular polarization, but it probably includes nonvertical transitions.[53,54] A shift of the luminescence peak of about 100 meV with respect to the $E_0 + \Delta_0$ gap would be consistent with nonvertical transitions of electrons near the Fermi energy of the c band with thermalized holes in the sh band for $n = 1.8 \times 10^{18}$ cm^{-3}. In this regard one must

FIG. 2 Degree of circular polarization P_c as a function of the excitation energy for four InP samples with different doping levels ($n = 5 \times 10^{15}$ to 5×10^{17} cm^{-3}). The lower scale on the x axis displays the energy $\hbar\omega_L$ of exciting laser light, the upper scale the kinetic energy ε_0 of the hole at the creation point. The functions $S_{0,3}$ and $S_{0,3} e^{-\phi(\varepsilon_0)}$ have been calculated according to Eqs. (5), (6), and (26a).
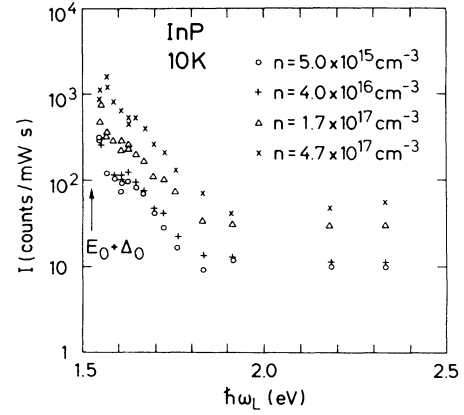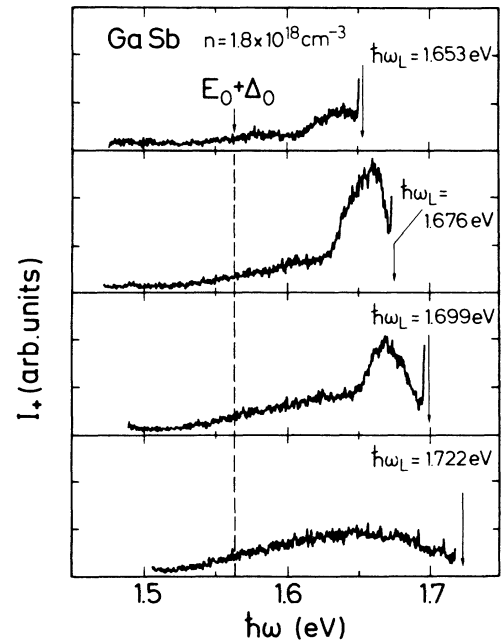

FIG. 4. Luminescence spectra of GaSb ($n = 1.8 \times 10^{18}$ cm^{-3}) obtained near $E_0 + \Delta_0$ with circularly polarized light in the I_+ configuration at four different laser energies. The intensity scale has been normalized with respect to the laser power.
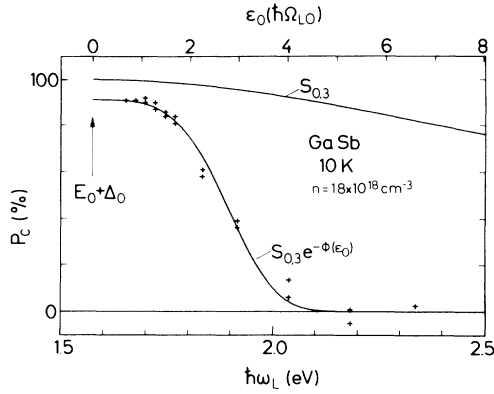
FIG. 5. Degree of circular polarization P_c as a function of the energy $\hbar\omega_L$ of the exciting laser light (lower scale) and of the kinetic energy ε_0 of the hole at the creation point (upper scale) for GaSb. The functions $S_{0,3}$ and $S_{0,3}e^{-\phi(\varepsilon_0)}$ correspond to calculations from Eqs. (5), (6), and (26a).

keep in mind that the L minima in GaSb occur about 100 meV higher than the Γ minimum[55,56] and that for $n \geq 7 \times 10^{17}$ cm^{-3} free electrons should also be present at the L point of the Brillouin zone.[57] The high-energy edge of the luminescence, 130 meV above the $E_0 + \Delta_0$ gap, may correspond to vertical transitions of electrons near the Fermi level with incompletely thermalized holes in the sh band ($m_{\mathrm{sh}}/m_c \approx 3$). Nonvertical *excitation* of holes in the sh band, from sh states near Γ, cannot be completely discarded. This mechanism would explain the complete spin orientation of the holes as a consequence of the lack of energy and momentum relaxation before recombination.

The function $S_{0,3}$ in Fig. 5 has been calculated with Eqs. (5) and (6) using the band-structure parameters of Table I. Note that the band mixing is much lower in GaSb than in InP, as expected from the corresponding spin-orbit splittings [$\Delta_0 \approx 100$ meV in InP (Ref. 31) and $\Delta_0 \approx 750$ meV in GaSb (Refs. 32 and 33)] Nevertheless, the spin orientation is completely lost for excitations 0.5 eV above the gap. The curve $S_{0,3}e^{-\phi(\varepsilon_0)}$ represents a fit

TABLE I. Parameters used for theoretical calculations.

	InP	GaSb
m_c	$0.077m$ [a]	$0.041m$ [g]
m_{hh}	$0.60m$ [b]	$0.36m$ [h]
m_{lh}	$0.12m$ [c]	$0.047m$ [i]
m_{sh}	$0.21m$ [c]	$0.13m$ [h]
E_0 (eV)	1.42 [c]	0.82 [j]
Δ_0 (eV)	0.105 [c]	0.745 [k]
$\hbar\Omega_{\mathrm{LO}}$ (meV)	43 [d]	29 [d]
C_F (eV cm$^{1/2}$)	3×10^{-5} [e]	1×10^{-5} [e]
$\gamma_{\mathrm{k \cdot p}}$ (eV Å^3)	-100 [f]	85 [f]
γ_{LMTO} (eV Å^3)	-100 [f]	58 [f]

[a]Reference 45.
[b]Reference 46.
[c]Reference 31.
[d]Reference 47.
[e]See Eq. (25) and Ref. 48.
[f]Reference 49.
[g]Reference 50.
[h]Reference 51
[i]Reference 52.
[j]Reference 32.
[k]References 32 and 33.

based on the Dyakonov-Perel spin-relaxation mechanism (see Sec. V). Figure 6 displays the intensity of the $E_0 + \Delta_0$ luminescence in GaSb as a function of the excitation energy. Note that, in contrast to Fig. 3, this intensity decreases only by less than a factor of 3 over the excitation energy range. This fact may be due to the importance of nonvertical transitions in the excitation and/or recombination process.

V. THEORY OF SPIN RELAXATION AND DISCUSSION

Comparison of the calculated $S_{0,3}$ curves with experimental data of Figs. 2 and 5 shows that band mixing is not the only spin-relaxation mechanism for holes in the sh band. The spin-orbit splitting Δ_0 does not seem to be very relevant for spin relaxation since the loss of spin orientation is similar in InP [$\Delta_0 = 0.1$ eV (Ref. 31)] and GaSb [$\Delta_0 = 0.8$ eV (Refs. 32 and 33)]. Several spin-relaxation mechanisms have been proposed. The Dyakonov-Perel mechanism[13,14,39,58] (DP) is based on the spin splitting of band states proportional to k^3 that is found in noncentrosymmetric crystals (left-hand panel of Fig. 7). These terms can be derived in third-order perturbation theory by $\mathbf{k} \cdot \mathbf{p}$ interaction, including the v or c bands and also a higher conduction band (Γ_7, Γ_8).[59,60] They are equivalent to the effect of a $\mathbf{k}$-dependent internal magnetic field. The spin relaxation can be regarded as the precession of the spin around this "magnetic field."

In dilute magnetic semiconductors, such as $\mathrm{Cd}_{1-x}\mathrm{Mn}_x\mathrm{Se}$ and $\mathrm{Cd}_{1-x}\mathrm{Mn}_x\mathrm{Te}$, a spin relaxation of electrons occurs through spin exchange of free-carrier spins with the Mn^{2+} spins ($S = \frac{5}{2}$) via the hyperfine interaction.[28] In heavily doped materials ($p, n \geq 10^{18}$ cm^{-3}) the exchange interaction between free carriers contributes an additional relaxation as proposed by Bir et al. (BAP).[15,58] An efficient spin-relaxation mechanism has also been proposed by Elliott and Yafet[11,12,58] (EY) for materials with small direct gaps, large spin-orbit splittings, and high hole concentrations. It is based on the reabsorption of recombination radiation with simultaneous creation of electron-hole pairs.

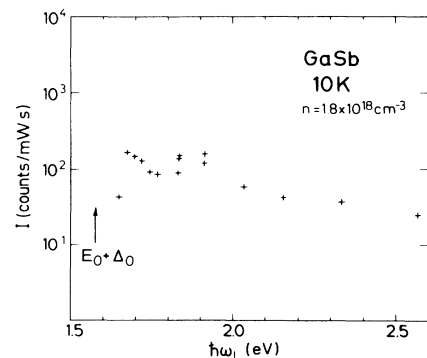Intervalence-band scattering processes of holes between

FIG. 6. Total intensity I ($= I_+ + I_-$ or $I_\parallel + I_\perp$) of the $E_0 + \Delta_0$ luminescence in GaSb as a function of the laser energy $\hbar\omega_L$. The intensity has been normalized with respect to the incident power.
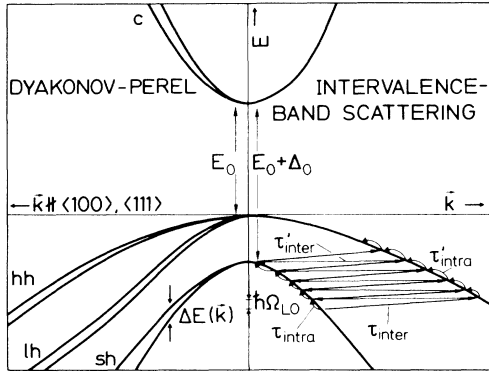
FIG. 7. Illustration of the Dyakonov-Perel mechanism (left-hand panel) and of the spin relaxation via inter-valence-band scattering (right-hand panel).

the sh and lh,hh bands and back to the sh band (right-hand panel Fig. 7) can also contribute to spin depolarization.[29,30] Since energy and momentum relaxation of holes is most efficient for scattering by LO phonons under our experimental conditions,[61−63] this mechanism should become important for kinetic energies of the holes greater than 2LO-phonon energies.

The EY and BAP mechanisms can be discarded in our experiments, since no doping dependence of the spin depolarization is observed in InP and the hole concentrations in the sh band are low, even under steady-state excitation conditions. We will thus discuss the DP and backscattering mechanisms in more detail. In order to obtain the dependence of the degree of circular polarization as a function of the excitation energy, we have to determine the degree of spin orientation of thermalized holes at the top of the sh band.

The Dyakonov-Perel Hamiltonian can be written as[14]

$$H'(\mathbf{k}) = \hbar\sigma \cdot \mathbf{\Omega}(\mathbf{k}) , \tag{10}$$

where the "precession frequency" is

$$\mathbf{\Omega}(\mathbf{k}) = \frac{\gamma}{\hbar}\mathbf{\kappa}(\mathbf{k}) . \tag{11}$$

The vector

$$\mathbf{\kappa} = (k_x(k_y^2 - k_z^2), k_y(k_z^2 - k_x^2), k_z(k_x^2 - k_y^2))$$

is perpendicular to the $\mathbf{k}$ vector and vanishes in the $\langle 111 \rangle$ and $\langle 100 \rangle$ directions. The coefficient γ for the sh band can be obtained via third-order $\mathbf{k} \cdot \mathbf{p}$ perturbation theory involving the Γ_7, Γ_8 valence bands and the Γ_6 and Γ_7, Γ_8 conduction bands. Values of γ calculated with the $\mathbf{k} \cdot \mathbf{p}$ theory and the self-consistent linear muffin-tin-orbitals method[64] (LMTO) are shown in Table I for InP and GaSb.

The DP Hamiltonian results in a spin splitting of the sh state at $\mathbf{k} \neq 0$, except for the $\langle 111 \rangle$ and $\langle 100 \rangle$ directions (left-hand panel of Fig. 6). The energy splitting between the spin-up "↑" and spin-down "↓" states for $\mathbf{k}$ in the $\langle 110 \rangle$ directions amounts to

$$\Delta E = \gamma k^3 = 2\hbar |\mathbf{\Omega}| . \tag{12}$$

↑ and ↓ refer to the [$\bar{1}$10] direction for $\mathbf{k} \| [110]$; the corresponding spin splitting can be attributed to an equivalent magnetic field along [$\bar{1}$10]. The spin depolarization is thus produced by the precession of the spin in that magnetic field. The average steady-state spin polarization along the i direction $\overline{S_i}$ is found by solving the corresponding Boltzmann equation and averaging over all possible directions of $\mathbf{k}$,

$$\overline{S_i} = \langle S_i \rangle_\mathbf{k} . \tag{13}$$

This procedure is simplified by assuming that the momentum scattering time within the sh band is much shorter than the spin lifetime in this band. Under these conditions the DP Hamiltonian of Eq. (10) can be treated as a small perturbation. After some tedious but straightforward algebraic manipulations, one finds[58]

$$\left|\frac{\partial \overline{S_i}}{\partial t}\right|_{DP} = -4\frac{\tau_p}{\gamma_3}[\overline{S_i}(\overline{\Omega_j^2} + \overline{\Omega_k^2}) - \overline{S_j}(\overline{\Omega_j\Omega_i}) - \overline{S_k}(\overline{\Omega_k\Omega_i})] \tag{14a}$$

$$= -\frac{\overline{S_i}}{\tau_{s,ii}} + \frac{\overline{S_j}}{\tau_{s,ij}} + \frac{\overline{S_k}}{\tau_{s,ik}} . \tag{14b}$$

The first term in Eq. (14b) describes the relaxation of the mean spin $\overline{S_i}$ along the i direction, the other two the spin scattering from the j,k to the i direction. These terms can be estimated to be small compared with the first one. γ_3 is a geometrical factor which depends on the scattering mechanism.[39] From Eqs. (14a) and (14b) one finds, for the spin-relaxation time τ_s,

$$\frac{1}{\tau_s} = \frac{8}{3}\frac{\tau_p}{\gamma_3}(\overline{\Omega_x^2} + \overline{\Omega_y^2} + \overline{\Omega_z^2}) = \frac{8}{3}\frac{\tau_p}{\gamma_3}\overline{\Omega^2} . \tag{15}$$

Equation (15) can be decomposed into two factors.[58] The factor $\tau_p(\frac{2}{3}\overline{\Omega^2})^{1/2}$ can be interpreted as the "precession angle" between two momentum-changing collisions. For large $\tau_p(\frac{2}{3}\overline{\Omega^2})^{1/2}$ the spin component perpendicular to $\mathbf{k}$ is lost within the time τ_p.[13] If $\tau_p(\frac{2}{3}\overline{\Omega^2})^{1/2}$ is small, however, Eq. (15), which implies motional narrowing, applies. A spin orientation is maintained although momentum and energy are relaxed. The spin-relaxation time can be calculated as a function of the energy ε of the hole in the sh band bearing in mind that $\overline{\kappa_i^2} = \frac{4}{105}k^6$ [Eqs. (11) and (15)] and using $\varepsilon = \hbar^2 k^2/2m_{sh}$, where m_{sh} is the effective mass of the whole in the sh band. Equation (15) then becomes[58]

$$\frac{1}{\tau_s} = \frac{2.44}{\gamma_3}\frac{\gamma^2}{\hbar^8}m_{sh}^3\tau_p\varepsilon^3 . \tag{16}$$

The DP spin-relaxation time *increases* with decreasing τ_p and lower kinetic energy of the split-off holes.

In order to obtain the degree of circular polarization of the $E_0 + \Delta_0$ luminescence as a function of the excitation energy, one has to determine the spin polarization P_c of a hole thermalized to the top of the sh band that was created with a kinetic energy ε_0 in the sh band. The DP spin-relaxation time as a function of the kinetic energy of the hole is given by Eq. (16). At the top of the split-off band the spin relaxation of holes due to the DP mechanism is negligible since the k^3 terms which are important for this

process vanish at the Γ point. On the other hand, holes near the $E_0 + \Delta_0$ gap that are scattered, i.e., by LO phonons to other bands, are lost to the split-off band and relax rapidly to the E_0 gap. In order to evaluate the total effect of the DP Hamiltonian during thermalization, one has to integrate over the time needed to thermalize the sh hole from an initial energy ε_0. One finds[13]

$$P_c \big|_{\varepsilon=\varepsilon_0} = S_{0,3} e^{-\phi(\varepsilon_0)} \tag{17}$$

with the attenuation "constant" $\phi(\varepsilon_0)$ defined as

$$\phi \big|_{\varepsilon=\varepsilon_0} = \int_0^{t_0} \frac{dt}{\tau_s} . \tag{18}$$

$S_{0,3}$ is the function given by Eqs. (5) and (6), which takes the reduced spin orientation of the holes at the creation point into account. The integration over time can be replaced by an integration over energy using the energy relaxation time τ_ε:[13]

$$\frac{d\varepsilon}{dt} = -\frac{\varepsilon}{\tau_\varepsilon} . \tag{19}$$

Thus, Eq. (18) becomes

$$\phi \big|_{\varepsilon=\varepsilon_0} = \int_0^{\varepsilon_0} d\varepsilon \frac{1}{\varepsilon} \frac{\tau_\varepsilon}{\tau_s} . \tag{20}$$

This integration can be carried out analytically if we assume a dependence of τ_ε/τ_s on energy $\tau_\varepsilon/\tau_s \propto \varepsilon^\nu$, where the constant ν should be different for different scattering processes. One finds[13]

$$\phi \big|_{\varepsilon=\varepsilon_0} = \frac{1}{\nu} \left[\frac{\tau_\varepsilon}{\tau_s} \right] \bigg|_{\varepsilon=\varepsilon_0} . \tag{21}$$

The most important mechanism for energy and momentum relaxation of holes in GaAs is scattering by LO phonons via the Fröhlich interaction.[61-63] In this case the energy relaxation time can be related to the momentum relaxation time $\tau_{p,\text{LO}}$ for inelastic scattering by LO phonons [see Eq. (19)]:

$$\tau_\varepsilon = \frac{\varepsilon}{\hbar\Omega_{\text{LO}}} \tau_{p,\text{LO}} . \tag{22}$$

The total momentum relaxation time τ_p, however, should be lower than $\tau_{p,\text{LO}}$, since it also include elastic scattering by ionized impurities, quasielastic scattering by acoustic phonons, and inelastic carrier-carrier scattering.[65-67] From Eqs. (16), (21), and (22) it follows that

$$\phi = \frac{2.44}{\nu\gamma_3} \frac{\gamma^2}{\hbar^9\Omega_{\text{LO}}} m_{\text{sh}}^3 (\tau_p \tau_{p,\text{LO}}) \bigg|_{\varepsilon=\varepsilon_0} \varepsilon_0^4 . \tag{23}$$

For our purpose we will at first neglect the difference between τ_p and $\tau_{p,\text{LO}}$, replacing it by an average value $\overline{\tau}_p$. Equation (23) contains the energy dependence of ϕ in the prefactor $1/\nu$, in ε_0^4, and in the product $\overline{\tau}_p^2$. The numerical factor γ_3 is independent of energy, and for scattering by LO phonons it amounts to $\frac{11}{6}$.[66,67,58] The usual expression for the momentum relaxation time for LO-phonon scattering, valid in the limit of small LO-phonon energies or high hole kinetic energies, is[68-70]

$$\frac{1}{\tau_{p,\text{LO}}} = \frac{C_F^2}{2\pi\hbar^2} \left[\frac{m_{\text{sh}}}{2\varepsilon} \right]^{1/2} \ln\left| \frac{1+b}{1-b} \right| , \tag{24}$$

with $b = \text{Re}(1 - \hbar\Omega_{\text{LO}}/\varepsilon)^{1/2}$.

The Fröhlich constant C_F is defined as

$$C_F = \{ 2\pi e^2 [\epsilon^{-1}(\infty) - \epsilon^{-1}(0)] \hbar\Omega_{\text{LO}} \}^{1/2} , \tag{25}$$

where e is the elementary charge, $\epsilon(\infty)$ and $\epsilon(0)$ are the high- (rf) and low-frequency (ir) dielectric constants. In the limit of low kinetic energies ε ($\varepsilon \rightarrow 0$) the divergence in the logarithm of Eq. (24) compensates for the $\sqrt{\varepsilon}$ behavior of the momentum relaxation time. For holes of low kinetic energy $\overline{\tau}_p = \text{const}$, whereas at higher energies a $\sqrt{\varepsilon}$ behavior is found. Replacing Eq. (24) in Eq. (23) yields $\phi \propto \varepsilon_0^\nu$ with $\nu \simeq 4$ for $\varepsilon_0 \rightarrow 0$ and $\nu \simeq 5$ for larger ε_0. Thus, in the case of pure scattering by LO phonons, ϕ can be written as

$$\phi = \begin{cases} 0.332 \dfrac{\gamma^2}{\hbar^9\Omega_{\text{LO}}} m_{\text{sh}}^3 \overline{\tau}_p^2 \varepsilon_0^4 = B_4 \varepsilon_0^4, & \overline{\tau}_p = \text{const} \tag{26a} \\[2em] 0.266 \dfrac{\gamma^2}{\hbar^9\Omega_{\text{LO}}} m_{\text{sh}}^3 \dfrac{\overline{\tau}_p^2}{\varepsilon_0} \varepsilon_0^5 = B_5 \varepsilon_0^5, & \overline{\tau}_p \propto \sqrt{\varepsilon} . \tag{26b} \end{cases}$$

Equations (26), together with Eq. (17), describe the dependence of the spin orientation of holes at the top of the sh band on the excitation energy found for the DP mechanism. They suggest a fitting procedure for the experimental data of Figs. 2 and 5. The only fitting parameter, B_4 or B_5, is independent of the excitation energy and is related to fundamental band-structure parameters such as γ and m_{sh}. Our basic assumption lies in the energy dependence of the momentum relaxation time $\overline{\tau}_p$. The best fits for the experimental data on InP and GaSb are indeed obtained for ν between 4 and 5. The fits shown in Figs. 2 and 5 assume a ε_0^4 law for ϕ [Eq. (26a)]. For these fits the function P_c of Eq. (17) has been multiplied by 0.9: this prefactor accounts for possible losses of polarization in the experimental setup. The parameters B_4 or B_5 obtained from the fit [InP: $B_4 = (45\pm5)\times10^3$ eV^{-4}, $B_5 = (70\pm10)\times10^4$ eV^{-5}; GaSb: $B_4 = (20\pm5)\times10^3$ eV^{-4}, $B_5 = (25\pm5)\times10^4$ eV^{-5}] have been used to determine the mean momentum relaxation times $\overline{\tau}_p$ [Eq. (26)].

Tables II and III compare the momentum relaxation times calculated from Eq. (24) with those obtained by the two different fitting procedures [Eqs. (26a) and (26b)]. We chose for InP $\gamma = -100$ eV Å^3 as obtained by the k·p theory and also the LMTO method.[49] In the case of GaSb two different values are used for γ, since the value obtained by the k·p method (85 eV Å^3) is 40% higher than that from the LMTO method (58 eV Å^3).[49] In addition, Tables II and III list the values for the precession angle $\tau_{p,\text{LO}}(\frac{2}{3}\Omega^2)^{1/2}$. The comparison of both types of fits, according to Eq. (26), reveals that in the region where the degree of circular polarization is measured accurately [$\hbar\omega_L - (E_0 + \Delta_0) \leq 0.5$ eV] the different fitting procedures yield comparable momentum relaxation times $\overline{\tau}_p$. The result does not depend appreciably on whether an ε_0^4 or ε_0^5 dependence is taken for the ratio τ_ε/τ_s. The momentum

TABLE II. Calculated scattering times for InP at the spin-orbit-split valence band. The data labeled $\tau_{p,\text{LO}}$ (fs) were calculated from Eq. (24). Those labeled $\bar{\tau}_p(\nu=4)$ and $\bar{\tau}_p(\nu=5)$ were obtained from the fit to depolarization data (Fig. 2) as described in the text. This table also lists the precession angle $\tau_{p,\text{LO}}(\frac{2}{3}\overline{\Omega^2})^{1/2}$.

$\hbar\omega_L - E_0 + \Delta_0$ (eV)	ε_0 (meV)	$\tau_{p,\text{LO}}$ (fs)	$\tau_{p,\text{LO}}(\frac{2}{3}\overline{\Omega^2})^{1/2}$	$\bar{\tau}_p(\nu=4)$ (fs)	$\bar{\tau}_p(\nu=5)$ (fs)
0.2	53	92	0.38	109	111
0.5	133	63	1.02	109	176
0.7	187	63	1.73	109	209
1.0	266	66	3.05	109	249

relaxation time so determined lies around 100—200 fs for InP and 200—300 fs for GaSb. The values of τ_p calculated with Eq. (24) are a factor of 2 too low in InP and too high in GaSb. The agreement is, however, acceptable if one considers that the relaxation-time approximation is not valid at low kinetic energies of the hole in the sh band.[70] The discrepancy between calculated and fitted values can be slightly improved for a highly doped material if one considers, in addition, elastic scattering by ionized impurities.[65–67] However, since no dependence of the spin depolarization on doping was observed in InP, this modification can only be applied to GaSb pending a determination of the dependence on doping of P_c. A decrease of the total momentum relaxation time due to acoustic-phonon scattering may affect both materials.

The momentum relaxation time for Coulomb scattering can be calculated for a screened Coulomb potential $V(r) = -Ze/[\epsilon(0)r]e^{-r/L}$. The result is[70]

$$\frac{1}{\tau_{p,C}} = \frac{n_I Z^2 e^4}{(2m_{\text{sh}})^{1/2}\epsilon^2(0)\pi}$$
$$\times \epsilon^{-3/2}\left[\ln(4L^2k^2+1) - \frac{4L^2k^2}{4L^2k^2+1}\right]. \quad (27)$$

Here, n_I denotes the ionized-impurity concentration, Z the ionic charge, ε the kinetic energy of the hole, k its wave vector, and L the screening length of the Coulomb potential which can be approximated by the Fermi-Thomas screening length[71] or the mean distance between two impurities in highly doped material, whichever is smaller. $n_I = 1.8 \times 10^{18}$ cm^{-3} yields $L = 51$ Å. The elastic momentum scattering time $\tau_{p,C}$ increases from 1.36 to 8.57 ps for $\hbar\omega_L - (E_0 + \Delta_0) = 0.2$—1.0 eV due to the elec-

trostatic nature of the interaction. At excitation 0.2 eV above the the the gap the total momentum scattering time decreases from 465 to 347 fs, which is in slightly better agreement with the value obtained from the fit. The total momentum scattering time can further be decreased by inelastic hole-hole or hole-electron scattering, which are known to be important for highly doped materials.[62] The momentum scattering times $\tau_{p,\text{LO}}$ listed in Table II for InP and in Table III for GaSb are close to the electron—LO-phonon scattering time given in Ref. 34 for GaAs: $\tau_{p,\text{LO}} = 165$ fs. This value can be scaled to estimate the corresponding hole scattering time considering only the effective-mass factor of Eq. (24). One obtains $\tau_{p,\text{LO}} \approx 255$ fs for holes in the split-off band of GaAs.

The LO-phonon scattering time for holes in the split-off band at the same kinetic energy ε (measured in units of the LO-phonon energy) should not differ much from GaAs to GaSb or InP, since the scaling factor in Eq. (24), $m_{\text{sh}}/\hbar\Omega_{\text{LO}}$, varies only slightly [(4.4—4.8)m/eV] for these materials.

Tables II and III reveal that the "precession angle" $\tau_{p,\text{LO}}(\frac{2}{3}\overline{\Omega^2})^{1/2}$ lie between 0.3 and 15 rad. It is evident that the excitation experiments were performed neither in the "motional-narrowing" limit nor in the limit of spin relaxation with momentum relaxation (a spin orientation is still observed after momentum relaxation). The "precession angle" is small in the region where the degree of circular polarization is considerable [$\hbar\omega_L - (E_0 + \Delta_0) \leq 0.5$ eV]. In this region the DP mechanism should operate. The formalism developed above assumes a spin splitting of the sh band proportional to k^3 [Eq. (12)]. This should be only valid very close to the center of the Brillouin zone.[60] A k·p calculation shows, however, that the decrease in γ with increasing k for InP and GaSb is not

TABLE III. Calculated scattering times for GaSb at the spin-orbit-split valence band. The data labeled $\tau_{p,\text{LO}}$ (fs) were calculated from Eq. (24). Those labeled $\bar{\tau}_p(\nu=4)$ and $\bar{\tau}_p(\nu=5)$ were obtained from a fit to the depolarization data (Fig. 5) as described in the text. The table also lists the precession angle $\tau_{p,\text{LO}}(\frac{2}{3}\overline{\Omega^2})^{1/2}$.

$\hbar\omega_L - E_0 + \Delta_0$ (eV)	ε_0 (meV)	$\tau_{p,\text{LO}}$ (fs)	$\gamma_{\text{LMTO}} = 58$ eV Å^3			$\gamma_{\text{k·p}} = 85$ eV Å^3		
			$\tau_{p,\text{LO}}(\frac{2}{3}\overline{\Omega^2})^{1/2}$	$\bar{\tau}_p(\nu=4)$ (fs)	$\bar{\tau}_p(\nu=5)$ (fs)	$\tau_{p,\text{LO}}(\frac{2}{3}\overline{\Omega^2})^{1/2}$	$\bar{\tau}_p(\nu=4)$ (fs)	$\bar{\tau}_p(\nu=5)$ (fs)
0.2	46	465	1.12	213	185	1.64	146	126
0.5	120	413	3.93	213	293	5.77	146	200
0.7	167	424	6.62	213	345	9.70	146	235
1.0	240	455	12.22	213	413	18.02	146	283

drastic in the region of interest here.[49] The theory should be adequate for excitations up to 0.5 eV above the gap, but it should be modified for higher $\hbar\omega_L$. This poses no problem since the spin orientation is completely lost, within error, for excitations 0.5 eV above the gap (Figs. 2 and 5).

Short momentum relaxation times, such as those found in GaSb, can be simulated with the DP theory if part of the spin depolarization at $E_0 + \Delta_0$ is due to an additional spin-relaxation mechanism. In Ref. 30 it has been shown that, when the kinetic energy of the holes in the split-off band at the creation point ε_0 corresponds to several LO-phonon energies, the distribution of carriers in the split-off band near the Γ point consists predominantly of holes which are transfered to the lh and hh subbands after excitation and then return to the split-off band. We will discuss this inter-valence-band scattering mechanism with a simple model of sh$\rightarrow$(lh,hh) interband transitions, thus neglecting the contribution from holes created directly in the lh or hh bands. If a significant part of the spin-depolarized holes near $E_0 + \Delta_0$ were directly created in the lh or hh band, we would expect, at least, a strong depolarization in Figs. 2 and 5 already at $\varepsilon_0 = \hbar\Omega_{LO}$, which is not observed experimentally. Holes once scattered outside the sh band lose their spin orientation rapidly in the lh and hh bands due to the heavy mixing of angular momentum in the lh and hh bands and elastic scattering. When they are backscattered into the sh band, their spins are entirely depolarized. We only consider LO-phonon scattering, intraband (τ_{intra}) and interband (τ_{inter}), into the hh band, because of the higher density of states of the hh band as compared to the lh band (right-hand panel of Fig. 6). This mechanism is expected to be more efficient for GaSb than for InP because of the larger spin-orbit splitting. It explains qualitatively the decrease of the luminescence intensity with increasing $\hbar\omega_L$ by the loss of holes in the sh

band during relaxation (in InP, this is not the case for GaSb; see Figs. 3 and 6). Constant luminescence intensity and zero polarization degree means that each hole seen in the radiative recombination at $E_0 + \Delta_0$ has at least once been scattered outside the sh band during thermalization.

The basic assumptions of the model can be sketched as follows. The sh holes are intraband scattered ($\tau_{\text{intra}}, \tau'_{\text{intra}}$) via the Fröhlich interaction (the primes are used for scattering times with the initial state in the hh band). At each point, the holes can be interband scattered with the relative probability $\tau_{\text{intra}}/\tau_{\text{inter}}$ ($\tau'_{\text{intra}}/\tau'_{\text{inter}}$). Deformation-potential scattering [dominant in GaSb (Ref. 72)] is taken into account for the interband scattering only. The degree of spin orientation of holes at $E_0 + \Delta_0$ for kinetic excitation energies ε_0 greater than 2LO-phonon energies can be written as

$$P_c = S_{0,3}(\varepsilon_0) \frac{1}{1 + A(\tau_{\text{intra}}/\tau_{\text{inter}}, \tau'_{\text{intra}}/\tau'_{\text{inter}})} , \qquad (28)$$

where $S_{0,3}$ is given by Eqs. (5) and (6) and A denotes the relative amount of spin-depolarized holes to spin-polarized ones. The $\tau'_{\text{inter}}/\tau_{\text{inter}}$ ratio for deformation-potential scattering is assumed to be constant in the energy range under consideration given by the ratio of density-of-states effective masses ($m_{\text{hh}}^{3/2}/m_{\text{sh}}^{3/2}$). In our model we assume the ratio $\tau'_{\text{intra}}/\tau_{\text{intra}}$ to be equal to $m_{\text{sh}}^{1/2}/m_{\text{hh}}^{1/2}$ according to Eq. (24). The energy dependence of the scattering times is neglected over the small energy scale investigated ($\varepsilon_0 \lesssim 6\hbar\Omega_{LO}$). Taking into account the energy dependence of these parameters would introduce a factor less than $\sqrt{3}$ from $\varepsilon_0 = 2\hbar\Omega_{LO}$ to $6\hbar\Omega_{LO}$, which is neglected for the simplicity of the model. Under these assumptions, simple algebra yields a geometrical series for A which can be summed to give

$$P_c = S_{0,3}(\varepsilon_0) \frac{1}{1 + (m_{\text{sh}}^2/m_{\text{hh}}^2)(\tau_{\text{intra}}/\tau_{\text{inter}})[(1 + \tau_{\text{intra}}/\tau_{\text{inter}})^{n-1} - 1]} , \qquad (29)$$

where the number of phonons

$$n = \frac{\varepsilon_0}{\hbar\Omega_{LO}} \geq 2 .$$

This result is a very sensitive function of the ratio of the intraband and interband scattering times.

Figures 8 and 9 show calculations with Eq. (29) for InP and GaSb with different ratios $\tau_{\text{intra}}/\tau_{\text{inter}}$. Under the assumptions described above, interband scattering by LO phonons will only be important for $\varepsilon_0 \geq 2\hbar\Omega_{LO}$. For $\tau_{\text{intra}} \ll \tau_{\text{inter}}$ no depolarization due to inter-valence-band scattering occurs, whereas for $\tau_{\text{intra}} \gg \tau_{\text{inter}}$ the spin orientation is immediately lost at $2\hbar\Omega_{LO}$. Backscattering processes may become important for excitations more than 0.3 eV above the gap. In InP the spin orientation is almost lost at this point, but in GaSb scattering processes may present an additional depolarization mechanism. An interband scattering time of 40 fs, as obtained from the broadening of the $E_0 + \Delta_0$ gap of GaSb [8 meV (Ref. 33)], would yield too strong a spin depolarization, as shown by

the curve for $\tau_{\text{intra}} = 10\tau_{\text{inter}}$ in Fig. 9. Thus inter-valence-band scattering processes would destroy, in the case of GaSb, the good agreement found for the DP mechanism. They actually would probably lead, for $\varepsilon_0 \geq 2\hbar\Omega_{LO}$, to P_c much smaller than observed experimentally. Although a more careful analysis of the interband processes may remove some of these difficulties, one may also consider this result, and those of Fig. 6, as suggesting that some holes are produced near Γ for all values of $\hbar\omega_L$ (nondirect transitions involving possibly impurity levels).

VI. CONCLUSIONS

We have shown that luminescence excitation experiments with circularly polarized light on n-type III-V semiconductors can yield information about spin-relaxation mechanisms for holes. In the case of the sh band of InP and GaSb the spin relaxation is consistent with the predictions of the DP mechanism if one assumes dominant scattering of holes by LO phonons via the Fröhlich interaction. The agreement between the energy
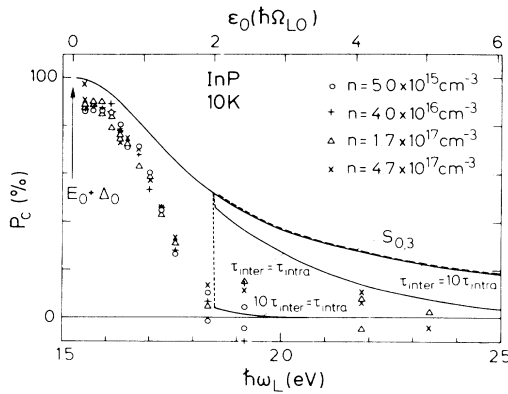
FIG. 8. Degree of circular polarization P_c as a function of the excitation energy for InP. The calculated curves consider inter-valence-band scattering processes for three different ratios of scattering times according to Eqs. (5), (6), and (29).

FIG. 9. Degree of circular polarization P_c as a function of the excitation energy for GaSb. The calculated curves take inter-valence-band processes for three different ratios of scattering times into account [Eqs. (5), (6), and (29)].

and momentum relaxation times obtained from the DP fit of the polarization data and the calculations for scattering by LO phonons is reasonable. The effect of inter-valence-subband scattering are also considered. It should not alter our conclusions in the case of InP. In the case of GaSb, however, because of the large spin-orbit splitting Δ_0, a strong interband contribution to the spin depolarization, which is not observed experimentally, is expected. The exact reason for the failure to observe this contribution is not known. This, and other anomalies, suggest that for our GaSb samples the excitation mechanism may
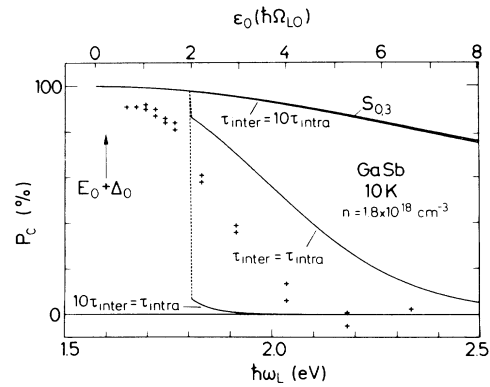
not be **k** conserving, but may involve impurity-induced, nondirect directions, leaving the holes near the top sh band.

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