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ON THE THEORY OF THE INTRABAND MECHANISM OF SINGLE-PHOTON ABSORPTION IN SEMICONDUCTORS, TAKING INTO ACCOUNT THE EFFECT OF COHERENT SATURATION

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A theoretical analysis of the frequency–temperature dependence of the single-photon absorption coefficient of polarized radiation in narrow- and wide-bandgap semiconductors is conducted, considering intraband optical transitions and including the coherent saturation effect. It is shown that with a fixed radiation frequency, the single-photon absorption coefficient initially increases with temperature, reaches a maximum, and then decreases. The position of this maximum shifts to lower frequencies for both narrow- and wide-bandgap semiconductors when the temperature dependence of the bandgap width and the effective masses of holes are taken into account. In semiconductors with a zinc-blende lattice structure, accounting for the temperature variation of band parameters leads to a reduction in the amplitude of the frequency and temperature response of the single-photon absorption coefficient. As temperature rises, the absorption threshold diminishes, an effect which is especially noticeable when using the Passler bandgap model. Each type of intraband optical transition contributes differently to the frequency, temperature, and polarization dependence of the absorption coefficient $K^{(1)}(\omega, T)$ for transitions involving the split-off band (SO) and light-hole (LH) band.
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INTRODUCTION

The absorption of light associated with optical transitions between the heavy-hole and light-hole subbands of the valence band in cubic symmetry has long been studied both theoretically and experimentally (see, for example, [1-3] and the references therein).

In studies [4-9], theoretical investigations were conducted on one- and multi-photon absorption caused by both interband and intraband optical transitions. In [8], multi-photon intraband Larmor cyclotron resonance (LCR) in *p-Ge* was examined under conditions of strong nonlinearity, where multi-photon processes contribute comparably to the absorption. In [4, 6-9], the spectral and temperature dependences of the multi-photon absorption coefficient and LCR in semiconductors with complex band structures were described. In [10, 11], saturation of the vertical optical transition rate in regions of higher intensity and nonlinear light-intensity-dependent photocurrents induced by direct optical transitions between topological surface and bulk states in three-dimensional topological insulators were observed. In [12], a microscopic theory of nonlinear edge photocurrent in graphene illuminated by terahertz radiation was developed, while in [13], single- and multi-photon interband optical transitions in monolayers of transition metal dichalcogenides were analyzed. Studies [14-17] experimentally investigated two-photon absorption of unpolarized light in *GaAs, InP, GaInAs, InSb, InAsP*.

The analysis of our calculations for the LCR coefficient (the probability of light absorption with linear and circular polarization) indicates that accounting for the effect of coherent saturation leads to a distinctive polarization dependence. Therefore, it is of interest to theoretically investigate the LCR coefficient and light absorption as a function of the angle between the wave vectors of charge carriers and photons. This is related to optical transitions from the light-hole and heavy-hole subbands to the spin-orbit split-off subband, as well as the contribution of the coherent saturation effect [5-9] to the LCR coefficient and light absorption, considering the temperature dependence of band parameters (bandgap width and effective masses of charge carriers). The present work is dedicated to studying these phenomena.

In direct-gap semiconductors with a degenerate valence band, single-photon absorption can occur not only via interband transitions but also via intraband transitions between different valence subbands. In a zinc-blende semiconductor, the top of the valence band (comprising the heavy-hole and light-hole bands, which are degenerate at $k = 0$) is split by spin–orbit coupling: a lower-lying split-off valence band is separated from the heavy/light-hole valence band by an energy Δ_{so} [13]. Here Δ_{so} (often called the spin–orbit splitting energy) denotes the energy gap between the split-off (SO) band and the top of the valence band. Intraband single-photon absorption refers to optical transitions that take place *within* the valence band, for example between the heavy-hole (HH) band and the split-off band (SO). These transitions require the presence

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of initial carriers (holes) in one of the bands; in p-type or intrinsic material at finite temperature, a certain fraction of the valence band states are empty (holes are present) allowing such absorptions to occur. Because the intraband transition energies are generally lower than the fundamental bandgap E_g, they are manifested as absorption in the infrared or far-infrared range (for instance, the HH→SO transition in GaAs with $\Delta_{so} \approx 0.34$ eV would correspond to a ~3.6μm photon).

Previous studies of one-photon absorption have mostly focused on **interband** processes and associated phenomena such as optical orientation of carriers [14] and nonlinear absorption saturation. Nonlinear light absorption in semiconductors with degenerate bands, caused by direct optical transitions between subbands of heavy and light holes, and its dependence on radiation polarization, was examined in a number of works [15]. However, the intraband single-photon absorption mechanism – especially including the effects of *coherent saturation* at high light intensities – has remained less explored. The coherent saturation effect refers to the reduction of absorption at high photon flux, due to depletion of initial-state carriers and other many-body effects that saturate the optical transition probability [16]. In the context of intraband transitions, this means that beyond a certain intensity, the absorption of additional photons is diminished because the available holes in the initial band are being exhausted (or the population distribution is driven towards equilibrium between the bands).

In this work, we develop a theoretical description of intraband single-photon absorption in direct-gap semiconductors of the zinc-blende type, explicitly including the coherent saturation effect. We consider both narrow-bandgap and wide-bandgap materials to highlight how Δ_{so} and other band parameters influence the absorption behavior. We also take into account the temperature dependence of the band structure parameters (such as E_g and effective masses), since temperature can significantly affect the absorption coefficient spectrum. Our aim is to derive analytic expressions for the polarized absorption coefficient $K^{(1)}(\omega, T)$ for intraband transitions, and to analyze how this coefficient depends on temperature, photon frequency, and light polarization in both low- and high-intensity regimes.

The polarization dependence of the probability of intraband optical transitions in A3B5 semiconductors with a degenerate valence band

It is known [2] that the absorption coefficient of N -photon light is $K^{(N)}$determined in the following form:

$$K^{(N)} = N\hbar\omega \frac{W^{(N)}}{I},, \tag{1}$$

where $W^{(N)}$ is the probability of N -photon absorption per unit volume of light, defined as [2, 5-9]. For the intraband case, we consider transitions from the HH or LH subbands to the split-off (SO) subband, whose energy dispersion is given by

$$E_{lh}(k) = \frac{\hbar^2 k^2}{2\, m_{lh}}, \quad E_{hh}(k) = \frac{\hbar^2 k^2}{2\, m_{hh}}, \quad E_{\mathrm{SO}}(k) = \Delta_{so} + \frac{\hbar^2 k^2}{2\, m_{\mathrm{SO}}}.$$

here m_{lh}, m_{hh}, and m_{SO} are the effective mass. m_{SO} is effective mass in the spin-orbit (SO) valence subband. As noted above, m_{so} is the energy gap between the top most valence edge (HH/LH) and the SO band at $k = 0$. The squared matrix elements governing these intraband transitions depend on polarization. For single-photon absorption, transitions from valence band to spin-orbit band, with relative strengths determined by angular momentum selection rules [2,5-9]. Accounting for Coherent Saturation Effects in Single-Photon Intraband Absorption To include the coherent saturation effect, we adopt the approach of Refs. [5-9],

$$W^{(N)} = \frac{2\pi}{\hbar}\sum_{n,n',\vec{k}} \left\langle \sum_{m,m'} \left| M^{(N)}_{n,m;n',m'}(\vec{k}) \right|^2 \right\rangle \left(f_{n\vec{k}} - f_{n'\vec{k}}\right)\delta\left(E_{n'\vec{k}} - E_{n\vec{k}} - N\hbar\omega\right),, \tag{2}$$

where $m, m' = \pm 1/2$ corresponds to states in the light-hole and spin-orbit split-off subbands, $m, m' = \pm 3/2$ corresponds to states in the heavy-hole subband [18, 19], $\left\langle \sum_{m,m'} \left| M^{(N)}_{n,m;n',m'}(\vec{k}) \right|^2 \right\rangle$ is the value of the squared modulus of the composite matrix element of the optical transition, averaged over the solid angles of the hole $(\vec{k})$ wave vector, for a transition from state $|n\vec{k}\rangle$ to $|n'\vec{k}\rangle$ ($|n\vec{k}\rangle \to |n'\vec{k}\rangle$), $E_{n'\vec{k}}(E_{n\vec{k}})$ and $f_{n\vec{k}}(f_{n'\vec{k}})$ are the energy and distribution function of charge carriers in the initial (or final) state, and $\vec{A}$ is the vector potential of the electromagnetic wave:

$$\vec{A}(\vec{x}, t) = A_0 \vec{e} e^{-i\omega t + i\vec{q}\vec{x}} + A_0 \vec{e}^{*} e^{i\omega t - i\vec{q}\vec{x}}, \tag{3}$$

$\hbar\omega(\hbar\vec{q})$ is the energy (momentum) of the photon, $\vec{e}$ and A_0 are the polarization vector and the amplitude of the vector potential, respectively:

$$\left(\frac{eA_0}{m_0 c}\right)^2 = \frac{2\pi e^2 I}{c\omega^2 m_0^2 n_\omega}, \tag{4}$$

I is the light intensity, $n_\omega = \frac{cq}{\omega}$ is the refractive index of the semiconductor, and the remaining terms are well-known quantities.

It should be noted that when calculating, for example, the frequency or temperature dependence of $W^{(N)}$ for both intraband and interband N-photon optical transitions, the choice of the electron-photon interaction operator, which is part of the composite matrix element of the transition, is crucial [5-9]. Depending on the chosen operator, the relative contribution of various optical transition channels, $W^{(N)}$which differ in their virtual states, may increase or decrease.

Let us analyze the optical transitions occurring from the hole subbands to the spin-orbit split-off subband (see Fig. 1), where the energy dispersion for light and heavy holes can be expressed as: $E_{lh}(\vec{k}) = \frac{\hbar^2 k^2}{(2m_{lh})}$ and $E_{hh}(\vec{k}) = \frac{\hbar^2 k^2}{(2m_{hh})}$, respectively, and for the spin-orbit split-off subband as: $E_{SO}(\vec{k}) = \Delta_{SO} + \frac{\hbar^2 k^2}{(2m_{SO})}$. Here, $m_{lh}(m_{hh})$ represents the effective mass of light (heavy) holes, and Δ_{SO} is the spin-orbit splitting energy, the numerical values of which for several semiconductors are provided in [20].

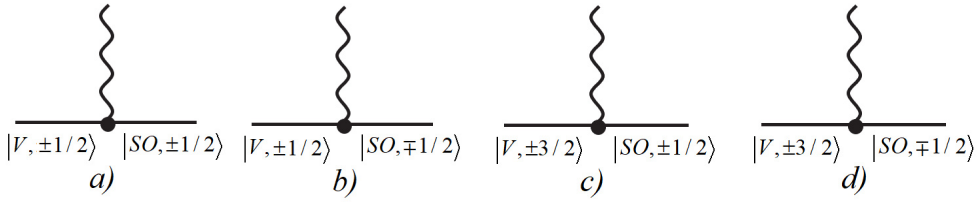

Figure 1. Feynman diagrams describing intraband optical transitions in semiconductors

It should be noted that when the photon energy satisfies the condition $\Delta_{SO} \leq \hbar\omega$, then: a) In wide-bandgap semiconductors (e.g., GaAs, where $\Delta_{SO}\langle E_g$, and E_g is the bandgap width), optical transitions from the heavy- and light-hole branches to the spin-orbit split-off subband are allowed. b) In narrow-bandgap semiconductors (e.g., InSb, where $\Delta_{SO}\rangle E_g$), optical transitions occur in two stages. First, transitions take place between the valence and conduction subbands (interband transitions) in the frequency range $E_g \leq \hbar\omega\langle\Delta_{SO}$. Subsequently, optical transitions proceed simultaneously from the heavy- and light-hole branches to the spin-orbit split-off subband (intraband transitions) as well as interband transitions in the frequency range $\hbar\omega\rangle\Delta_{SO}$. c) In intermediate-bandgap semiconductors (e.g., InAs, where $\Delta_{SO} \simeq E_g$), both intraband and interband optical transitions are allowed.

As seen from equations (1) and (2), the light absorption coefficient is determined by the squared modulus of the composite matrix element, whose polarization dependence is defined by the type of optical transitions. In particular, according to the Luttinger-Kohn Hamiltonian approximation [18, 19], the composite matrix elements for single-photon transitions $|V,\pm1/2\rangle \rightarrow |SO,\pm1/2\rangle$ a (see Fig. 1a) and $|V,\pm1/2\rangle \rightarrow |SO,\mp1/2\rangle$ (see Fig. 1b), occurring from the light-hole branch to the spin-orbit split-off subband, are defined by the relation:

$$\left|M^{(1)}_{SO,+1/2;V,+1/2} + M^{(1)}_{SO,-1/2;V,+1/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 2B^2k^2\left[\frac{9}{4}e'_-e'_+ + e'_z\frac{3}{2}(e'_+ + e'_-) + e'^2_z\right],$$

$$\left|M^{(1)}_{SO,-1/2;V,-1/2} + M^{(1)}_{SO,+1/2;V,-1/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 2B^2k^2\left[\frac{9}{4}e'^2_\perp - \frac{3}{2}(e'_+ + e'_-)e'_z + e'^2_z\right], \quad (5)$$

where $e'_\pm = e_{x'} \pm e_{y'}$, $e_{x'}, e_{y'}$, $\vec{e}$represents the projections of the polarization vector onto the Ox', Oy' axes, which are perpendicular to the wave vector of the holes $\vec{k}4B = \frac{\hbar^2 m_{lh}m_{hh}}{(m_{hh}-m_{lh})}$.

In this case, the sum of the squared moduli of the composite matrix elements is determined as:

$$\left|M^{(1)}_{SO,-1/2;V,-1/2} + M^{(1)}_{SO,+1/2;V,-1/2}\right|^2 + \left|M^{(1)}_{SO,+1/2;V,+1/2} + M^{(1)}_{SO,-1/2;V,+1/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 2B^2k^2\left(\frac{9}{2}e'^2_\perp + 2e'^2_z\right). \quad (6)$$

The composite matrix elements of single-photon transitions, $|V,\pm3/2\rangle \rightarrow |SO,\pm1/2\rangle$ i.e., optical transitions from the heavy-hole branch to the spin-orbit split-off subband (see Fig. 1c and 1d), are expressed as follows:

$$\hat{M}^{(1)}_{SO;V,hh} = \left(\frac{eA_0}{c\hbar}\right)\sqrt{\frac{3}{2}}Bk\begin{bmatrix} e'_- & 0 \\ 0 & -e'_+ \end{bmatrix}. \quad (7)$$

from which:

$$\left|M^{(1)}_{SO,\pm1/2;V,\pm3/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2\frac{3}{2}B^2\left|e'_\mp\right|^2. \quad (8)$$

It should be noted that, according to the law of energy conservation, $\frac{\hbar^2k^2}{2m_{SO}} + \Delta_{SO} - \frac{\hbar^2k^2}{2m_L} - \hbar\omega = 0$ ($L = lh$for light holes) and $L = hh$ (for heavy holes), for transitions $|V,\pm1/2\rangle \rightarrow |SO,\pm1/2\rangle$ and $|V,\pm1/2\rangle \rightarrow |SO,\mp1/2\rangle$, it is

straightforward to derive an expression for the wave vector: $k^2 = k^2_{SO,hh} = 2\mu_-^{(SO,hh)}\hbar^{-2}(\hbar\omega - \Delta_{SO})$. For transitions of type $|V,\pm1/2\rangle \to |SO,\pm1/2\rangle$ and $|V,\pm1/2\rangle \to |SO,\mp1/2\rangle$, we have $k^2 = k^2_{SO,lh} = 2\mu_-^{(SO,lh)}\hbar^{-2}(\hbar\omega - \Delta_{SO})$, where $\mu_-^{(SO,hh)} = \frac{m_{SO}m_{hh}}{(m_{SO}-m_{hh})}$, $\mu_-^{(SO,lh)} = \frac{m_{SO}m_{lh}}{m_{SO}-m_{lh}}$. Thus, it follows that the polarization dependence of the matrix element for transitions of type $|V,\pm3/2\rangle \to |SO,\pm1/2\rangle$ and $|V,\pm3/2\rangle \to |SO,\mp1/2\rangle$ is described by the quantity $|e'_-|^2 + |e'_+|^2$, while optical transitions $|V,\pm1/2\rangle \to |SO,\pm1/2\rangle$ and $|V,\pm1/2\rangle \to |SO,\mp1/2\rangle$ are characterized by the quantity $4{,}5e'^2_\perp + 2e'^2_z$. Therefore, the polarization dependence of the single-photon absorption coefficient $\left(K^{(N=1)}\right)$, as well as the probability of the considered transition $\left(W^{(N=1)}\right)$, is determined by these quantities. To calculate the spectral and temperature dependence, these quantities must be averaged over the solid angles $\vec{k}$.

It should be noted that for single-photon absorption occurring between the branches of light and heavy holes and the spin-orbit split-off subband, single-photon LCR is not observed in diamond-like semiconductors or semiconductors of the zinc blende type. To observe single-photon LCR, it is necessary to account for the contribution of the coherent saturation effect to the transition probability, which will be analyzed further.

Light Absorption Induced by Single-Photon Optical Transitions from the Heavy- and Light-Hole Branches to the Spin-Orbit Split-Off Subband

By integrating over **k** and using the density of states in the valence bands, one obtains

$$K^{(1)}(\omega) \;=\; \frac{2\pi}{\hbar}\,\frac{\hbar\omega}{I}\sum_{\mathbf{k}}\;(f^{(1)}_{\mathrm{lh},\mathbf{k}} - f^{(1)}_{\mathrm{SO},\mathbf{k}})\;|\mathbf{M}^{(1)}_{\mathrm{lh}\to\mathrm{SO}}(\mathbf{k})|^2\,\delta(E_{\mathrm{SO},\mathbf{k}} - E_{\mathrm{lh},\mathbf{k}} - \hbar\omega),$$

with analogous expressions for transitions originating from the heavy-hole subband. In wide-gap semiconductors such as GaAs, $\Delta_{so} < E_g$, so the intraband HH→SO or LH→SO transitions occur at mid-infrared frequencies. In certain narrow-gap materials (InSb) one may have $\Delta_{so} > E_g$, meaning that the SO band sits "below" the HH/LH edges but by a larger energy difference than E_g itself. Numerically, this can place the intraband transition frequency in the near-infrared or even overlapping with interband transitions.

When Δ_{so} exceeds $\mathrm{E_g}$, the calculated transition energy $\hbar\omega = \Delta_{\mathrm{so}}$ can lie in a range above the conduction-band edge, making it appear as if $\mathrm{E_{SO}}$ has become "too high." However, physically, $\mathrm{E_{SO}}$ remains part of the valence band manifold; it just so happens that $\Delta_{\mathrm{so}} > \mathrm{E_g}$ places the SO subband closer to or even above the conduction band minimum on an absolute energy scale. This does not contradict the fact that Δ_{so} is specifically the energy splitting within the valence band.

Linear-Circular Dichroism of Single-Photon Optical Transitions from the Light- and Heavy-Hole Branches to the Spin-Orbit Split-Off Subband

In this case, the probability of single-photon optical transitions is determined using the following relation (see, for example, [5-9] and the references therein):

$$W^{(1)} = \frac{2\pi}{\hbar}\left(\frac{eA_0}{m_0c}\right)^2\left\langle\sum_{n,n',\vec{k}}\left|\vec{e}\vec{p}_{nn'}(\vec{k})\right|^2\sum_{n,n',\vec{k}}\left[1+\frac{\alpha_\omega}{\hbar^2\omega^2}\left(\frac{eA_0}{m_0c}\right)^2\left|\vec{e}\vec{p}_{nn'}(\vec{k})\right|^2\right]^{-1/2}\right\rangle\times$$
$$\times\left(f_{n\vec{k}} - f_{n'\vec{k}}\right)\delta\left(E_{n'\vec{k}} - E_{n\vec{k}} - \hbar\omega\right), \tag{9}$$

where the term $\frac{\alpha_\omega}{\hbar^2\omega^2}\left(\frac{eA_0}{m_0c}\right)^2\left|\vec{e}\vec{p}_{nn'}(\vec{k})\right|^2$ arises due to the consideration of the coherent saturation effect [21], $\alpha_\omega = \frac{6\omega^2 T_n^{(1)} T_{n'}^{(1)} I}{I_0}$, $T_n^{(1)}$ is the time spent by photoexcited charge carriers in state $|n,\vec{k}\rangle$, $\vec{p}_{nn'}(\vec{k}) = m_0\hbar^{-1}\vec{\nabla}_{\vec{k}}H(\vec{k})$ is the matrix element of the momentum operator, $H(\vec{k})$ is the Hamiltonian of the charge carriers, which is described by the Luttinger-Kohn Hamiltonian for intraband single-photon optical transitions and by the Kane Hamiltonian for interband light absorption [18, 19], and $I_0 = \frac{cn_\omega\hbar^3\omega^3}{2\pi|B|}$ is a parameter that, for zinc blende semiconductors, takes on values in the range of several gigawatts/cm² [3]. In cases where it is impossible to analytically determine, for example, the polarization, frequency, or temperature dependence of multi-photon absorption or LCR, an approximation can be used where $\frac{I}{I_0} << 1$. In this approximation, the radical can be expanded into a series in terms of $\frac{I}{I_0}$, and only the first few terms of the series can be retained.

Then, substituting (7, 8) into (9), it is straightforward to determine that the angular dependence of the probability of single-photon absorption of linearly polarized light $\left(W^{(1)}_{lin}\right)$ for the first-type transitions $|V,\pm1/2\rangle \to |SO,\pm1/2\rangle$ and $|V,\pm1/2\rangle \to |SO,\mp1/2\rangle$, shown in Fig. 2a and 2b, is described as:

$$\Im_{lin}^{(2)} = (2 + 2{,}5\,sin^2\,\phi)[1 + \zeta_\omega(4 + 5\,sin^2\,\phi)]^{-1/2}, \tag{11}$$

and for second-type transitions $|V, \pm 3/2\rangle \to |SO, \pm 1/2\rangle$and $|V, \pm 3/2\rangle \to |SO, \mp 1/2\rangle$, shown in Fig. 1c and 1d, it is described as:

$$\Im_{lin}^{(1)} = \frac{2\,sin^2\,\phi}{[1+3\zeta_\omega\,sin^2\,\phi]}^{-1/2}, \tag{12}$$

where ϕ is the angle between the wave vector of the holes and the light polarization vector, $\zeta_\omega = \alpha_\omega \left(\frac{eA_0}{c\hbar}\right)^2 B^2k^2$ is the Rabi parameter, and the wave vector k, as mentioned above, depends on the light frequency and the band parameters of the semiconductor.

For circularly polarized light, the angular dependence of the probability of optical transitions $\left(W_{circ}^{(1)}\right)$ from the heavy-hole branch to the spin-orbit split-off subband is determined by the expression:

$$\Im_{circ}^{(1)} = \left\langle \frac{2\left[\frac{1}{2}(1+cos^2\,\phi')\mp P_{circ}\,cos\,\phi'\right]}{\sqrt{1+3\zeta_\omega\left[\frac{1}{2}(1+cos^2\,\phi')\mp P_{circ}\,cos\,\phi'\right]}} \right\rangle, \tag{13}$$

The angular dependence of the probability of optical transitions $\left(W_{circ}^{(2)}\right)$ from the light-hole branch to the spin-orbit split-off subband will be represented as:

$$\Im_{circ}^{(2)} = \frac{1}{2}\left\langle \frac{9\left[\frac{1}{2}(1+cos^2\,\phi')\mp P_{circ}\,cos\,\phi'\right]+2\,sin^2\phi'}{\sqrt{1+\zeta_\omega\left(9\left[\frac{1}{2}(1+cos^2\,\phi')\mp P_{circ}\,cos\,\phi'\right]+2\,sin^2\phi'\right)}} \right\rangle, \tag{14}$$

where $\phi'$is the angle between the wave vectors of the holes and the photon, and $P_{circ}$is the degree of circular polarization of the light.

From Figs. 2 and 3, it can be seen that the angular dependences of the quantities $\Im_{lin}^{(1)}$, $\Im_{lin}^{(2)}$, and $\Im_{circ}^{(2)}$, i.e., the corresponding probabilities of single-photon light absorption, exhibit oscillatory behavior. The minimum values of $\Im_{lin}^{(1)}$and $\Im_{lin}^{(2)}$, as well as $\Im_{circ}^{(1)}$ and $\Im_{circ}^{(2)}$, coincide in their angular dependence, while their maximum values depend on the type of optical transitions. Specifically: a) The probabilities of optical transitions originating from the light-hole branch (see Figs. 1a and 1b) are approximately 2.5 (for linearly polarized light) to 4.5 (for circularly polarized light) times greater than the probabilities of transitions originating from the heavy-hole branch (see Figs. 1c and 1d). b) The maximum value of the probability for second-type transitions is always greater than that for first-type transitions, regardless of the degree of polarization or the value of the Rabi parameter (ζ_ω).

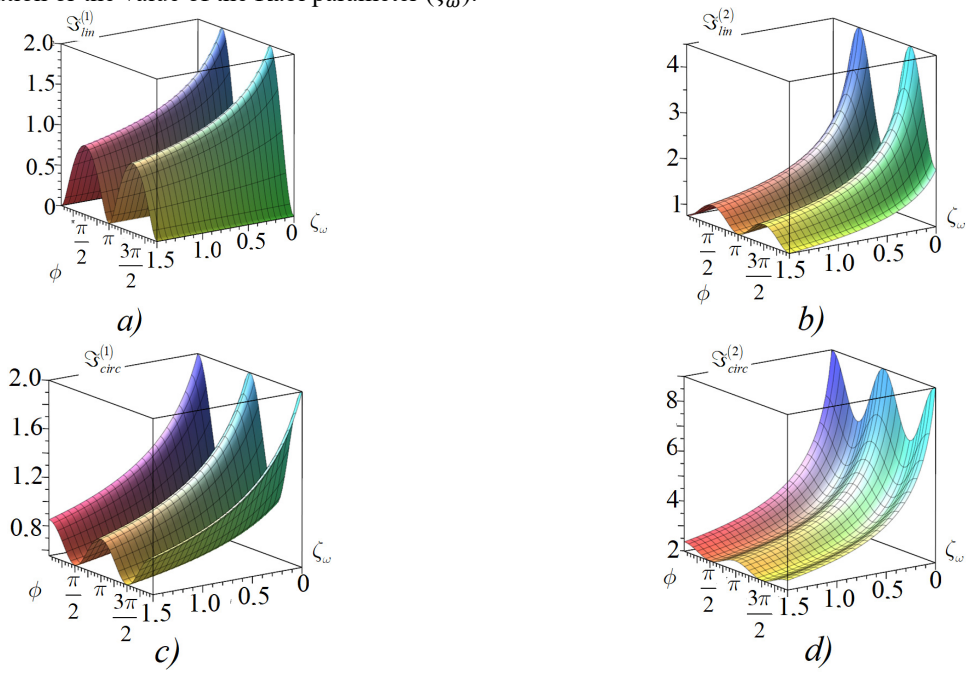

Figure 2. Graphs of the quantities $\Im_{lin}^{(1)}$ (*a*), $\Im_{lin}^{(2)}$ (*b*), $\Im_{circ}^{(1)}$_c (c), and $\Im_{circ}^{(2)}$ (d), which determine the contributions to the angular dependences and Rabi parameter dependences of the probabilities of single-photon optical transitions from the heavy-hole (a, c) and light-hole (b, d) branches to the spin-orbit split-off subband of the valence band for linearly (a, b) and circularly (c, d) polarized light

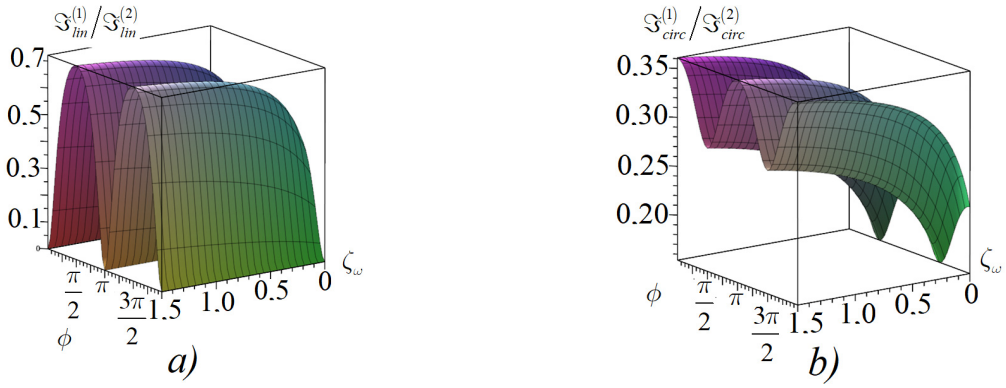

Figure 3. Graphs of the ratios $\Im_{circ}^{(1)}$ and $\Im_{circ}^{(2)}$, which allow determining the contribution of the optical transitions shown in Fig. 2 to the angular dependences and Rabi parameter dependences of the probabilities of single-photon optical transitions from the heavy- and light-hole branches to the spin-orbit split-off subband of the valence band for linearly (a) and circularly (b) polarized light.

The probabilities of optical transitions shown in Fig. 1 decrease with an increase in ζ_ω: if ζ_ω increases by 1.5 times, $\Im_{lin}^{(1)}$decreases by approximately 3.3 times, $\Im_{lin}^{(2)}$by 5 times, $\Im_{circ}^{(1)}$by 2.1 times, and $\Im_{circ}^{(2)}$by 4.5 times. It should also be noted that with increasing ζ_ω, the ratio of the probabilities of first-type optical transitions for linearly polarized light increases sharply in the range of ζ_ω $(0; 0{,}4)$values, followed by an almost imperceptible growth. For circularly polarized light, $\frac{\Im_{circ}^{(1)}}{\Im_{circ}^{(2)}}$ noticeably increases with ζ_ω across all its values.

From Fig. 3, it is evident that the primary contribution to the angular dependences and the Rabi parameter dependences of the probabilities of single-photon optical transitions from the heavy-hole (a, c) and light-hole (b, d) branches to the spin-orbit split-off subband of the valence band, for both linearly (a, b) and circularly (c, d) polarized light, is made by optical transitions involving light holes.

Thus, we have confirmed that accounting for the coherent saturation effect significantly alters the polarization dependence of the LCR coefficient.

Next, we examine the single-photon LCR coefficient, defined as the ratio $\eta = \frac{W_{lin}^{(1)}}{W_{circ}^{(1)}}$, i.e., $\eta = \frac{\Im_{lin}}{\Im_{circ}}$, as a function of the angle and the Rabi parameter, where $\eta = \eta^{(1)} + \eta^{(2)}$ $\eta^{(1)} = \frac{\Im_{lin}^{(1)}}{\Im_{circ}^{(1)}}$, and $\eta^{(2)} = \frac{\Im_{lin}^{(2)}}{\Im_{circ}^{(2)}}$ are the LCR coefficients for the first-type (Fig. 2a and 2b) and second-type (Fig. 2c and 2d) optical transitions (see Fig. 4). From Fig. 4, it is evident that both $\eta^{(1)}$ and $\eta^{(2)}$ exhibit oscillatory angular dependence, and their maximum values decrease with increasing ζ_ω, regardless of the angle between the wave vectors of the holes and the photon. It is noteworthy that the minimum value of the angular dependence of the LCR coefficient for first-type optical transitions is nonzero at $\zeta_\omega > 0$, whereas for second-type optical transitions, the minimum angular dependence $\eta^{(2)}$ equals zero across arbitrary values of ζ_ω.

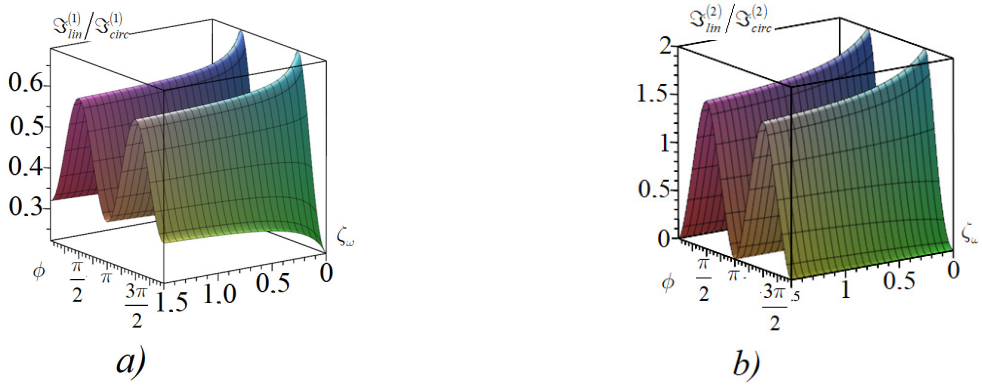

Figure 4. Dependence of the LCR coefficient on the angle and the Rabi parameter for single-photon optical transitions of the first (a) and second (b) types.

Light Absorption Induced by Single-Photon Optical Transitions from the Heavy- and Light-Hole Branches to the Spin-Orbit Split-Off Subband

The spectral, polarization, and temperature dependences of the absorption coefficient due to single-photon optical transitions from the heavy- and light-hole branches of the valence band to the spin-orbit split-off subband are determined by the following expression:

$$K^{(1)} = \frac{2\pi}{\hbar}\frac{\hbar\omega}{I}\sum_{\vec{k}}\left(f^{(1)}_{lh,\vec{k}} - f^{(1)}_{SO,\vec{k}}\right)\left|\sum_{lh,m=\pm1/2;SO,m'=\pm1/2} M^{(2)}_{lh,m;SO,m'}(\vec{k})\right|^2 \delta\left(E_{SO,\vec{k}} - E_{lh,\vec{k}} - \hbar\omega\right), \quad (15)$$

If the coherent saturation effect is taken into account [14], the following expression is obtained:

$$K^{(1)} = \frac{2\pi}{\hbar}\hbar\omega\frac{1}{I}\rho(\hbar\omega)f(T,\omega)(\langle\Re_+\rangle + \langle\Re_-\rangle), \quad (16)$$

where

$$\Re_\pm = \frac{\left|M^{(1)}_{SO,+1/2,lh,\pm1/2}(\vec{k}) + M^{(1)}_{SO,-1/2,lh,\pm1/2}(\vec{k})\right|^2}{\sqrt{1+4\frac{\alpha_\omega}{\hbar^2\omega^2}\left|M^{(1)}_{SO,+1/2,lh,\pm1/2}(\vec{k}) + M^{(1)}_{SO,-1/2,lh,\pm1/2}(\vec{k})\right|^2}}, \quad (17)$$

$\rho(\hbar\omega) = \mu_- k^{(1)}_\omega/(\pi^2\hbar^2)$ is the density of states, $k^{(1)}_\omega = (2\mu_-[\hbar\omega - \Delta_{SO}]/\hbar^2)^{1/2}$, $\left\langle\left|M^{(1)}_{n\vec{k}',n\vec{k}}\right|^2\right\rangle$ is the squared modulus of the composite matrix element $M^{(1)}_{n'\vec{k}',n\vec{k}}$ for an optical transition of type $|n\vec{k}\rangle \to |n'\vec{k}'\rangle$, averaged over the solid angles of the wave vector $\vec{k}$ $\alpha_\omega = 6\omega^2 T_1^{(1)} T_2^{(1)}\frac{I}{I_0}$, $I_0 = \frac{cn_\omega\hbar^3\omega^3}{2\pi|B|}I(\omega)$ is the light intensity (frequency), $f^{(1)}_{L\vec{k}}$ are the distribution functions of charge carriers (L=1L=1 (hh) corresponds to heavy holes, L=2L=2 (lh) to light holes, and L=SO to holes in the spin-orbit split-off subband), $E_{L\vec{k}} = -\hbar^2k^2/2m_L$ is the energy dispersion of holes in the L branch [15, 16] $e'_\pm = e_{x'} \pm e_{y'}$, $e_{x'}, e_{y'}$, $\vec{e}$ are the projections of the polarization vector onto the Ox', Oy' axes perpendicular to the wave vector $\vec{k}$ of the holes, and $\mu_-^{(SO,L)} = \frac{m_{SO}m_L}{(m_{SO}-m_L)}$ is the reduced effective mass of the holes.

In particular, for single-photon optical transitions from the light-hole branch to the spin-orbit split-off subband, the value of $\Re_\pm$ can be expressed as:

$$\Re_+ = 3\left(\frac{eA_0}{c\hbar}\right)^2 B^2k^2|e'_-|^2\left[1 + 4\frac{\alpha_\omega}{\hbar^2\omega^2}\left(\frac{eA_0}{c\hbar}\right)^2 B^2k^2 3|e'_-|^2\right]^{-1/2}, \quad (18)$$

$$\Re_- = \left(\frac{eA_0}{c\hbar}\right)^2 B^2k^2\left(9e'^2_\perp + 4e'^2_z\right)\left[1 + 4\frac{\alpha_\omega}{\hbar^2\omega^2}\left(\frac{eA_0}{c\hbar}\right)^2 B^2k^2\left(9e'^2_\perp + 4e'^2_z\right)\right]^{-1/2}, \quad (19)$$

the $4B = \frac{\hbar^2 m_{lh}m_{hh}}{(m_{hh}-m_{lh})}$.

If the contribution of the coherent saturation effect to light absorption ($\alpha_\omega = 0$) is neglected and averaging over the solid angles is performed, $\vec{k}$ from (18, 19), we obtain:

$$\left\langle\Re^{(0)}_+\right\rangle + \left\langle\Re^{(0)}_-\right\rangle = \left(\frac{eA_0}{c\hbar}\right)^2 B^2k^2\left\langle 9e'^2_\perp + 4e'^2_z\right\rangle = \frac{22}{3}\left(\frac{eA_0}{c\hbar}\right)^2 B^2k^2. \quad (20)$$

Then, (15) takes the form:

$$K^{(1)} = \frac{44\pi}{3\hbar}\left(\frac{eA_0}{c\hbar}\right)^2\frac{\hbar\omega}{I}\rho(\hbar\omega)f(\beta,\omega)B^2k^2. \quad (21)$$

Table 1. Fundamental band-structure parameters for the III–V semiconductors **GaAs, InSb, and InAs** employed in the present modelling of single-photon intraband absorption with coherent saturation.

Parameters	*GaAs*	*InSb*	*InAs*
E_g, eV	1.519	0.235	0.417
Δ_{SO}, eV	0.341	0.81	0.39
m_c/m_0	0.067	0.0135	0.026
m_{SO}/m_0	0.172	0.11	0.14
Δ_{SO}/E_g	0.24b	4.65	1.1
m_{lh}/m_0	0.09009	0.0152	0.027027
m_{hh}/m_0	0.34965	0.26316	0.33333
$\alpha_T, meV/K$	0.5405	0.32	0.276
β_T, K	204	170	93
F	-1.94	-0.23	-2.90

From Table 1, it can be seen that the reduced effective mass of holes $\mu_{-}^{(SO,hh)} = \frac{m_{SO}m_{hh}}{m_{SO}-m_{hh}}$, involved in optical transitions from the heavy-hole branch to the spin-orbit split-off subband, takes on negative values for several A3B5 semiconductors. This, in turn, results in the wave vector of charge carriers involved in such optical transitions $k_{SO,hh}^{(1\omega)} = \left[2\mu_{-}^{(SO,hh)}\hbar^{-2}(\hbar\omega - \Delta_{SO})\right]^{1/2}$ becoming an imaginary quantity. For this reason, unlike optical transitions from the light-hole branch, transitions from the heavy-hole branch to the spin-orbit split-off subband are forbidden.

Since optical transitions are allowed from the light-hole branch to the spin-orbit split-off subband of the valence band, we will further analyze the frequency and temperature dependences of the single-photon absorption coefficient. From the law of energy conservation, $\frac{\hbar^2k^2}{2m_{SO}} + \Delta_{SO} - \frac{\hbar^2k^2}{2m_L} - \hbar\omega = 0$, the wave vector is determined by the expression $k_{SO,L}^{(1\omega)} = \left[2\mu_{-}^{(SO,L)}\hbar^{-2}(\hbar\omega - \Delta_{SO})\right]^{1/2}$.

From (20) and (21), it is evident that the single-photon absorption coefficient does not depend on the degree of light polarization. Therefore, LCR is not observed in single-photon absorption. To observe it, the contribution of the coherent saturation effect to absorption must be taken into account, i.e., calculations need to be performed based on (16) and (17).

Now, we will calculate the frequency-temperature dependencies of the single-photon absorption coefficient using the following expression for the single-photon absorption coefficient, associated with optical transitions from the light hole branch to the spin-orbit split-off subband:

$$K^{(1)} = \frac{4\pi e^2}{c\omega m_0^2 n_\omega}\sum_{nn'\vec{k}}\left|\vec{e}\vec{p}_{SO,lh}(\vec{k})\right|^2\left(f_{lh,\vec{k}} - f_{SO,\vec{k}}\right)\delta\left(E_{SO}(\vec{k}) - E_{lh}(\vec{k}) - \hbar\omega\right). \tag{22}$$

Next, we assume the energy dispersion of light and heavy holes as $E_{lh}(\vec{k}) = -\hbar^2k^2/(2m_{lh})$ and $E_{hh}(\vec{k}) = -\hbar^2k^2/(2m_{hh})$, while in the spin-orbit split-off subband it is $E_{SO}(\vec{k}) = -\Delta_{SO} - \hbar^2k^2/(2m_{SO})$, where m_{lh} (m_{hh}) are the effective masses of light and heavy holes, respectively, and, Δ_{SO}- is the spin-orbit splitting energy, with numerical values for various semiconductors provided in [17]. Then, from (8), we obtain:

$$K_{SO,lh}^{(1)} = \frac{22}{3}\frac{e^2}{c\hbar n_\omega\hbar\omega}\frac{\mu_{-}}{\hbar^2}B^2\left(k_\omega^{(1)}\right)^3 f_{lh,k_\omega^{(1)}}[1 - \exp(-\hbar\omega/k_BT)]$$

or

$$K_{SO,lh}^{(1)} = \frac{11}{12}\frac{e^2}{c\hbar n_\omega}\left(\frac{m_{hh}-m_{lh}}{m_{SO}-m_{lh}}\frac{m_{SO}}{m_{lh}}\right)^2\frac{\hbar\omega-\Delta_{SO}}{\hbar\omega}\left(\frac{m_{hh}-m_{lh}}{m_{hh}}\right)^2 k_\omega^{(1)} f_{lh,k_\omega^{(1)}}\left(1 - e^{-\hbar\omega/k_BT}\right), \tag{23}$$

Where $k_\omega^{(1)} = \left[2\mu_{-}^{(SO,lh)}\hbar^{-2}(\hbar\omega - \Delta_{SO})\right]^{1/2}$, $f_{lh,k_\omega^{(1)}} = \exp\left(\frac{E_F}{k_BT}\right)\cdot\exp\left[-\frac{m_{SO}}{m_{SO}-m_{lh}}\frac{\hbar\omega-\Delta_{SO}}{k_BT}\right]$. The Fermi energy E_F is determined by the relation:

$$e^{\frac{E_F}{k_BT}} = \frac{1}{2}p\left(\frac{k_BT}{2\pi\hbar^2}\right)^{-3/2}\left(m_{hh}^{3/2} + m_{lh}^{3/2} + m_{SO}^{3/2}e^{-\frac{\Delta_{SO}}{k_BT}}\right)^{-1}, \tag{24}$$

where p is the hole concentration. Note that in our case, $\hbar\omega \gg k_BT$, so $e^{-\hbar\omega/k_BT} \ll 1$.

Thus, the frequency $(x = \hbar\omega/\Delta_{SO})$ and temperature $(y = k_BT/\Delta_{SO})$ dependencies of the single-photon absorption coefficient can be written as:

$$K_{SO,lh}^{(1)}(\omega,T) = K_0^{(1)}\frac{x-1}{x}(x-1)^{1/2}\frac{\exp\left[-\frac{m_{SO}}{m_{SO}-m_{lh}}\frac{x-1}{y}\right]}{y^{3/2}\left(m_{hh}^{3/2}+m_{lh}^{3/2}+m_{SO}^{3/2}e^{-1/y}\right)}, \tag{25}$$

where

$$K_0^{(1)} = \frac{11}{6}\frac{\pi^{3/2}e^2}{c\hbar n_\omega}\frac{(m_{hh}-m_{lh})^4}{(m_{SO}-m_{lh})^{5/2}}\frac{m_{SO}^{5/2}}{m_{lh}^{3/2}m_{hh}^2}\frac{\hbar^2p}{\Delta_{SO}}.$$

In further calculations, we assert that the temperature dependence of the bandgap width is determined by the Varshni formula [17]:

$$E_g(T) = E_g(T=0) - \gamma_T\frac{T^2}{T+T_V}, \tag{26}$$

and by the Passler formula [18]:

$$E_g(T) = E_g(T=0) - \frac{\alpha\Theta_p}{2}\left[\left(1 + \left(\frac{2T}{\Theta_p}\right)^p\right)^{1/p} - 1\right]. \tag{27}$$

Then, according to the multi-zone Kane model, the effective masses of electrons in the conduction band (m_c) and holes in the spin-orbit split-off subband (m_{SO}) depend on temperature and are expressed as:

$$m_0/m_c = \left[1 + 2F + \frac{E_P}{3}\left(E_{g0} - \frac{\alpha T}{\beta+T} + \frac{2}{3}\Delta_{SO}\right)\left(E_{g0} - \frac{\alpha T}{\beta+T}\right)^{-1}\left(E_{g0} - \frac{\alpha T}{\beta+T} + \Delta_{SO}\right)^{-1}\right], \quad (28)$$

$$m_0/m_{SO} = \left[\gamma_1 - \frac{E_P}{3}\Delta_{SO}\left(E_{g0} - \frac{\alpha T}{\beta+T}\right)^{-1}\left(E_{g0} - \frac{\alpha T}{\beta+T} + \Delta_{SO}\right)^{-1}\right], \quad (29)$$

where $E_{g0} = E_g(T=0)$. For quantitative calculations, the numerical values of the parameters γ_T, T_V, α, Θ_p, p are taken from [18].

If the numerical values of the band parameters for GaAs and InAs (see Table 1) are used, then as the temperature changes from 10 K to 300 K, the effective mass of electrons in the conduction band decreases by 0.053% and 0.051%, respectively, while the effective mass of holes in the spin-orbit split-off subband decreases by 0.01% and 0.04%, respectively, over this temperature range. At first glance, these changes appear to be very small; $\mathrm{E}_g(T)$ however, accounting for them significantly alters the frequency-temperature dependence of the absorption coefficient.

As seen from equation (8), the temperature dependence of $K_{SO,lh}^{(1)}$ is determined by the temperature dependence of $f_{lh,k_\omega^{(1)}}(\mathrm{T})$, while the frequency dependence is determined by the term $\frac{\hbar\omega-\Delta_{SO}}{\hbar\omega}k_\omega^{(1)}\rho(\hbar\omega)\exp\left(-\frac{m_{SO}}{m_{SO}-m_{lh}}\frac{\hbar\omega-\Delta_{SO}}{k_BT}\right)$. In this context, Figure 5 presents the frequency-temperature dependence of the distribution function of light holes involved in single-photon transitions in GaAs and InAs. It shows that, at a fixed frequency, the distribution function $f_{lh,k_\omega^{(1)}}$ initially increases with temperature, reaches a maximum, and then decreases. Specifically, at $\hbar\omega = 1{,}01\Delta_{SO}$ in GaAs (InAs), the function $f_{lh,k_\omega^{(1)}}$ reaches its maximum at a temperature of 90 K (60 K). Figure 5 also shows that the functions $f_{lh,k_\omega^{(1)}}(\mathrm{T}) = f_{lh,k_\omega^{(1)}}\left(\mathrm{T}, E_g(T)\right)$ and $\tilde{f}_{lh,k_\omega^{(1)}}(\mathrm{T}) = f_{lh,k_\omega^{(1)}}\left(\mathrm{T}, E_g(T)=0\right)$ differ significantly at low frequencies across all temperatures, but converge at high frequencies. Furthermore, the temperature dependence of the band parameters is prominently observed at low frequencies. The calculations do not account for the contribution of the coherent saturation effect in $f_{lh,k_\omega^{(1)}}(\mathrm{T})$ and $\tilde{f}_{lh,k_\omega^{(1)}}(\mathrm{T})$.

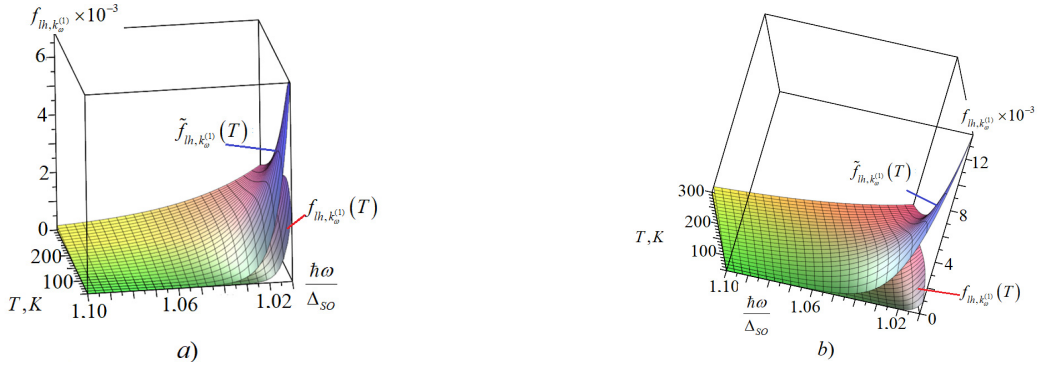

Figure 5. Frequency-temperature dependence of the distribution function of light holes $f_{lh,k_\omega^{(1)}}(\mathrm{T})$, participating in single-photon optical transitions in GaAs (a) and InAs (b) semiconductors, accounting for the temperature dependence of the bandgap width $E_g(\mathrm{T})$ and the effective mass of charge carriers using the Varshni formula, where $\tilde{f}_{lh,k_\omega^{(1)}}(\mathrm{T})$ is the distribution function of light holes at $E_g(\mathrm{T}=0)$.

The frequency-temperature dependence of the single-photon absorption coefficient $K_{SO,lh}^{(1)}(\omega,\mathrm{T})$ $\left(\widetilde{K}_{SO,lh}^{(1)}(\omega,\mathrm{T})\right)$ in InSb (a, b) and GaAs (c, d) (see Fig. 6), calculated using equation (14) with the Varshni formula (graphs a, c in Fig. 6) and the Passler formula (graphs b, d in Fig. 6), considers $\left(\widetilde{K}_{SO,lh}^{(1)}(\omega,\mathrm{T})\right)$ as the absorption coefficient, where the temperature dependence of $E_g(\mathrm{T})$ and the effective masses of holes is (or is not) accounted for. The contribution of the coherent saturation effect is not included, and the amplitude value of $\widetilde{K}_{SO,lh}^{(1)}(\omega,\mathrm{T})$ is assumed to be unity. From Fig. 6, it is evident that at a fixed frequency, $K_{SO,lh}^{(1)}(\mathrm{T})$ increases with temperature, reaches a maximum, and then decreases. This temperature behavior of $\left(\widetilde{K}_{SO,lh}^{(1)}(\omega,\mathrm{T})\right)$ corresponds to the analogous behavior of their distribution functions. Notably, in the frequency range $\Delta_{SO} \le \hbar\omega \le 1.3\Delta_{SO}$, the absorption coefficient $K_{SO,lh}^{(1)}(\omega,\mathrm{T})$ is greater than $\widetilde{K}_{SO,lh}^{(1)}(\omega,\mathrm{T})$, while at $\hbar\omega > 1.3\Delta_{SO}$, the graphs of $K_{SO,lh}^{(1)}(\omega,\mathrm{T})$ and $\widetilde{K}_{SO,lh}^{(1)}(\omega,\mathrm{T})$merge.

It should be noted that in narrow-bandgap crystals, if the dependences of $E_g(\mathrm{T})$, $m_{SO}(\mathrm{T})$, and $m_c(\mathrm{T})$ are taken into account, the dependence of $K_{SO,lh}^{(1)}(\omega,\mathrm{T})$ increases sharply (see Fig. 2). This is explained by the rapid growth of

$\left(\frac{m_{hh}-m_{lh}}{m_{SO}-m_{lh}}\right)^2\left(\frac{m_{hh}-m_{lh}}{m_{hh}}\right)^2\left(\frac{m_{SO}\cdot m_{lh}}{m_{SO}-m_{lh}}\cdot \Delta_{SO}\right)^{1/2}$ with increasing temperature (specifically, in InSb, this value increases by a factor of 10).

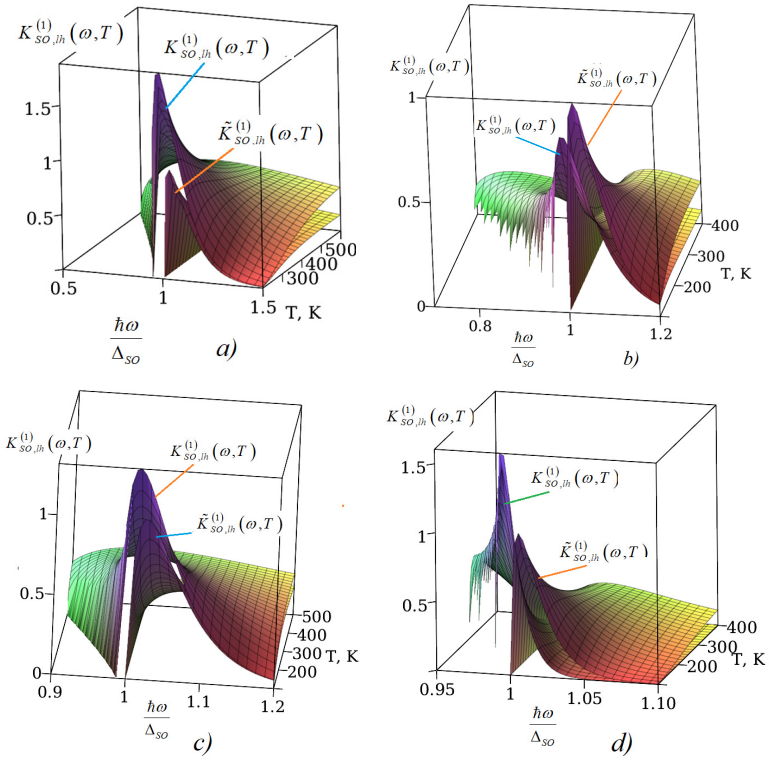

Figure 6. Frequency-temperature dependence of the single-photon absorption coefficient $K^{(1)}_{SO,lh}$ in InSb (a, b) and GaAs (c, d), where $K^{(1)}_{SO,lh}$a is calculated using the Varshni formula (graphs a, c) and the Passler formula (graphs b, d). Here, $\left(\tilde{K}^{(1)}_{SO,lh}(\omega,\mathrm{T})\right)$ represents the absorption coefficient, accounting for (or not accounting for) the temperature dependence of the bandgap width $E_g(\mathrm{T})$ and the effective masses of holes.

CONCLUSIONS

It has been shown that, when accounting for the contribution of the coherent saturation effect, the angular dependences of the probabilities of single-photon optical transitions from the heavy- and light-hole branches to the spin-orbit split-off subband of the valence band exhibit an oscillatory nature for both linearly and circularly polarized light, regardless of the Rabi parameter values (ζ_ω)

The maximum values of the angular dependence of the LCR coefficients for both first- and second-type optical transitions decrease with increasing ζ_ω, regardless of the angle between the wave vectors of the holes and the photon. The minimum value for first-type transitions is nonzero in the low ζ_ω region, while for second-type optical transitions, it is zero regardless of ζ_ω values.

The aforementioned results show that, at a fixed frequency, the single-photon absorption coefficient in GaAs and InAs semiconductors initially increases with rising temperature, reaches a maximum, and then decreases. Its maximum value, when accounting for the temperature dependence of $E_g(\mathrm{T})$, $m_{SO}(\mathrm{T})$, and $m_c(\mathrm{T})$, shifts toward lower frequencies. This shift is particularly pronounced when considering (27), both for narrow- and wide-bandgap semiconductors.

It is also noted that accounting for the temperature dependence of band parameters leads to a reduction in the frequency and temperature dependence of the single-photon absorption coefficient $K^{(1)}_{SO,lh}(\omega,\mathrm{T})$.

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ДО ТЕОРІЇ ВНУТРІШНЬОЗОННОГО МЕХАНІЗМУ ОДНОФОТОННОГО ПОГЛИНАННЯ В НАПІВПРОВІДНИКАХ З ВРАХУВАННЯМ ВПЛИВУ КОГЕРЕНТНОГО НАСИЧЕННЯ

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Проведено теоретичний аналіз частотно-температурної залежності коефіцієнта поглинання однофотонного поляризованого випромінювання у вузько- та широкозонних напівпровідниках з урахуванням внутрішньозонних оптичних переходів та ефекту когерентного насичення. Показано, що при фіксованій частоті випромінювання коефіцієнт поглинання однофотонного випромінювання спочатку зростає з температурою, досягає максимуму, а потім зменшується. Положення цього максимуму зміщується до нижчих частот як для вузько-, так і для широкозонних напівпровідників, якщо врахувати температурну залежність ширини забороненої зони та ефективних мас дірок. У напівпровідниках зі структурою ґратки цинкової суміші врахування температурної зміни параметрів зони призводить до зменшення амплітуди частотної та температурної реакції коефіцієнта поглинання однофотонного випромінювання. Зі зростанням температури поріг поглинання зменшується, що особливо помітно при використанні моделі забороненої зони Пасслера. Кожен тип внутрішньозонного оптичного переходу по-різному впливає на залежність коефіцієнта поглинання $K^{(1)}(\omega,T)$ від частоти, температури та поляризації для переходів, що включають зону відщеплення (SO) та зону легких дірок (LH).

Ключові слова: *ймовірність однофотонних переходів; коефіцієнти однофотонного поглинання та лінійно-кругового дихроїзму, ефект когерентного насичення; температурна залежність ширини забороненої зони*