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POLARIZATION DEPENDENCES OF SINGLE-PHOTON INTERBAND LINEAR-CIRCULAR DICHROISMS IN TETRAHEDRAL SYMMETRY CRYSTALS

Abstract. The polarization dependence of the coefficient of linear-circular dichroism of single-photon absorption of polarized radiation in crystals of tetrahedral symmetry due to optical transitions from the subbands of light and heavy holes, as well as from the spin-orbit splitting zone to the conduction band, is calculated. In this case, the contribution of the coherent saturation effect to the coefficient of single-photon linear-circular dichroism of light absorption is taken into account.

Keywords: polarization, spectral, and temperature dependence of the coefficient of single-photon absorption of light, linear-circular dichroism, crystal of tetrahedral symmetry, effect of coherent saturation of optical transitions.

Nonlinear absorption of light in a semiconductor with a degenerate valence band, which is due to direct optical transitions between heavy and light hole subbands and depends on the state of radiation polarization, was studied in [1–8]. In these papers, it is assumed that the nonlinearity in the intensity dependence of the single-photon absorption coefficient arises due to resonant absorption saturation. This saturation is due to the photoinduced change in the distribution functions of light and heavy holes in the region of momentum space near the surface corresponding $E_{hh}(\vec{k}) - E_{hl}(\vec{k}) - \hbar\omega = 0$ to the resonance condition. Here, $E_{hh}(\vec{k})\left(E_{hl}(\vec{k})\right)$ is the energy spectrum of heavy (light) holes, and ω is the frequency of light.

In [9; 10], four-photon processes in semiconductors due to optical transitions between subbands of the valence band were studied. However, interband single-photon linear-circular dichroism, as well as intraband two-photon linear-circular dichroism,

where the intermediate states are in the conduction band or in the spin-orbit splitting zone in crystals of tetrahedral symmetry, taking into account the effect of coherent saturation, remained open, to which this article is devoted.

Here we consider one- or two-photon linear-circular dichroism of the absorption of polarized radiation, taking into account the effect of coherent saturation [3; 4] in direct-gap crystals, which is due to direct optical transitions between subbands of the valence band, where we take into account the fact that intermediate states of current carriers can is located not only in the light and heavy subbands, but also in both the conduction band and the spin-orbital splitting zone. When calculating intraband single-photon light absorption, we assume that the photon energy satisfies the conditions $\hbar\omega \geq E_g$, $E_g + \Delta_{SO}$, and for intraband two-photon light absorption $2h\omega << E_g, \Delta_{co}$, where E_g is the band gap, Δ_{SO} is the spin-orbit splitting of the valence band.

In case $\hbar\omega \geq E_g$, $E_g + \Delta_{SO}$, there are two variants of interband optical transitions, the first of which satisfies the condition $E_g \leq \hbar\omega \langle E_g + \Delta_{SO}$, and in the second case the condition $\hbar\omega \geq E_g + \Delta_{SO}$ is satisfied. Therefore, in the first case, optical transitions occur between the subbands of light and heavy holes in the valence band and the conduction band, and in the second case, optical transitions occur between the spin-orbit splitting and conduction bands, which we will analyze separately.

Let the initial states be in the heavy-hole subband of the valence band, then, in the Luttinger-Kohn and Kane approximation [11; 12], the matrix element of the single-photon optical transition from the heavy-hole subband $|V, \pm 3/2\rangle$ to the conduction band $|c, \pm 1/2\rangle$, those $M^{(1)}_{\mathrm{C},\pm 1/2;\pm \mathrm{V},3/2}$, which is schematically depicted as, is determined by the relations: $M^{(1)}_{\mathrm{C},+1/2;\mathrm{V}+3/2} = \left(\frac{eA_0}{c\hbar}\right) pe'_+$, $M^{(1)}_{\mathrm{C},-1/2;\mathrm{V}-,3/2} = -i\left(\frac{eA_0}{c\hbar}\right) pe'_-$ and an optical transition of type 66 is forbidden, where $e'_\pm = e'_x \pm ie'_y$, e'_α $(\alpha = x, y, z)$ are the projections of the light polarization vector, with respect to the coordinates the Oz axis of which is directed along the wave photoexcited current carriers $(\vec{k})$, A_0 is the amplitude of the potential vector of the electromagnetic wave, p is the parameter Kane [11; 12], the rest are well-known quantities. The energy conservation law for this transition is described by $\delta\left(E_c\left(\vec{k}\right) - E_{hh}\left(\vec{k}\right) - \hbar\omega\right)$ functions, where $E_{c,\vec{k}} = \frac{\hbar^2 k^2}{2m_c} + E_g$ is the energy spectrum of electrons in the conduction band, $E_{L,\vec{k}} = \frac{\hbar^2 k^2}{2m_L}$ is the energy spectrum of holes in the subband of light $(L = lh)$ and heavy $(L = hh)$ holes.

Then the square of the modulus of these optical transitions is expressed as:

$$\left|M^{(1)}_{\mathrm{C},\pm 1/2;\mathrm{V},\pm 3/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 p^2 \left|e'_\pm\right|^2, \quad \left|M^{(1)}_{\mathrm{C},\mp 1/2;\mathrm{V},\pm 3/2}\right|^2 = 0.$$

Based on the last relations, one can obtain the polarization dependence of the probabilities of the considered optical transitions. In particular, for optical transitions of the type, the polarization dependence of the probability of a given transition, determined by the polarization dependence $\left|M^{(1)}_{\mathrm{C},\pm 1/2;\mathrm{V},\pm 3/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 p^2 \left|e'_\pm\right|^2$, has an oscillatory character for both linear and linear polarizations. In this case, the coefficient of interband linear-circular dichroism is equal to unity, i.e. linear-circular dichroism is not observed.

If the initial states are in the light hole subband of the valence band, then the matrix element of the single-photon optical transition from the light hole subband $|V, m\rangle$ $(m \pm 1/2)$ to the conduction band $|c, m'\rangle$ $(m' = \pm 1/2)$, i.e. $M^{(1)}_{\mathrm{C},\mathrm{m}';\mathrm{V},\mathrm{m}}$, which is schematically depicted as $|V, m\rangle \to |c, m'\rangle$, is defined as the ratios:

$$M^{(1)}_{c,+1/2;\mathrm{V},+1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}} pe'_-, \quad M^{(1)}_{c,-1/2;\mathrm{V},-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{-i}{\sqrt{3}} e'_+ p$$

$$M^{(1)}_{\mathrm{c},+1/2;V,-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}} e'_z p, \quad M^{(1)}_{c,+1/2;\mathrm{V},-1/2} = \left(\frac{eA_0}{c\hbar}\right) i\sqrt{\frac{2}{3}} e'_z p.$$

Then the square of the modulus of the matrix elements of the considered optical transitions is expressed as: $\left|M^{(1)}_{c,\pm 1/2;\mathrm{V},\pm 1/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{1}{3} p^2 \left|e'_\mp\right|^2$,

$\left|M^{(1)}_{c,\mp1/2;\mathrm{V},\pm1/2}\right|^2 = = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{2}{3} p^2 \left|e'_z\right|^2$. The energy conservation law of these transitions is described by the $\delta\left(E_c(\vec{k}) - E_{lh}(\vec{k}) - \hbar\omega\right)$ function. Then the wave vector of photoexcited current carriers is determined by the relation: $k^{(1\omega)}_{c,lh} = \sqrt{\frac{2\mu^{(c,lh)}_{+}}{\hbar^2}\left(\hbar\omega - E_g\right)}$, where $\mu^{(c,lh)}_{+} = = \frac{m_c m_{lh}}{m_c + m_{lh}}$ is the reduced effective mass relative to the effective mass of electrons in the conduction band and light holes.

Taking into account the polarization dependence of the matrix elements $M^{(1)}_{c,\pm1/2;\mathrm{V},\pm1/2}$ and $M^{(1)}_{c,\mp1/2;\mathrm{V},\pm1/2}$ for optical transitions of the $\left|\mathrm{V},\pm1/2\right\rangle \to \left|\mathrm{C},\pm1/2\right\rangle$ and $\left|\mathrm{V},\pm1/2\right\rangle \to \left|\mathrm{C},\mp1/2\right\rangle$ type, it is possible to determine the polarization dependence of the probability of this transition. A quantitative calculation shows that this polarization dependence of the probability of the considered optical transition for both linear and circular polarizations has an oscillatory character with respect to the angle between the polarization vectors and the wave vector of the current carriers, but with an increase in the parameter of the coherent saturation effect, the amplitude of the oscillations decreases: by 20% for linear, by 15% for circular polarization.

Above we have considered optical transitions that satisfy the conditions $E_g \le \hbar\omega \le E_g + \Delta_{SO}$ where optical transitions between the subbands of the valence band and the conduction band are allowed. Next, we determine the polarization dependence of the transition probability, where the initial states are in the spin-split band; then, the matrix elements of single-photon optical transitions from the light-hole subband $\left|V,m\right\rangle$ $(m \pm 1/2)$ to the conduction band $\left|c,m'\right\rangle$ $(m' = \pm1/2)$, $M^{(1)}_{\mathrm{C,m';V,m}}$ which are schematically depicted as $\left|V,m\right\rangle \to \left|c,m'\right\rangle$, are defined as the ratios: $M^{(1)}_{\mathrm{C},+1/2;\mathrm{SO},+1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}} pe'_z, M^{(1)}_{\mathrm{C},-1/2;\mathrm{SO},+1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}} pe'_-$ $M^{(1)}_{\mathrm{c},+1/2;V,-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}} e'_z p, M^{(1)}_{\mathrm{C},-1/2;\mathrm{SO},-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{-i}{\sqrt{3}} pe'_z$. The law of conservation of energy for these transitions is described by a $\delta\left(E_c(\vec{k}) - E_{SO}(\vec{k}) - \hbar\omega\right)$ function, where $E_{SO,\vec{k}} = \frac{\hbar^2 k^2}{2m_c} + \Delta_{SO}$ is the energy spectrum of holes in the spin-orbital splitting zone, and is the energy of the spin-orbital splitting. Whence we have $\left|M^{(1)}_{\mathrm{C},\pm1/2;\mathrm{SO},\pm1/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{1}{3} p^2 e'^2_z$, $\left|M^{(1)}_{\mathrm{C},\mp1/2;\mathrm{SO},\pm1/2}\right|^2 = = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{1}{3} p^2 e'^2_{\pm}$. In this case, the wave vector of photoexcited current carriers is defined as $k^{(1\omega)}_{c,SO} = \sqrt{\frac{2\mu^{(c,SO)}_{+}}{\hbar^2}\left(\hbar\omega - E_g - \Delta_{SO}\right)}$, $\mu^{(c,SO)}_{+}$ is the reduced effective mass with respect to the current carriers in the conduction bands and the spin of the orbital splitting.

Taking into account the polarization dependences of the squares of the moduli of the matrix elements $\left|M^{(1)}_{\mathrm{C},\pm1/2;\mathrm{SO},\pm1/2}\right|^2$ and $\left|M^{(1)}_{\mathrm{C},\mp1/2;\mathrm{SO},\pm1/2}\right|^2$ for optical transitions of the $\left|\mathrm{V},\pm1/2\right\rangle \to \left|\mathrm{C},\pm1/2\right\rangle$ and $\left|\mathrm{V},\pm1/2\right\rangle \to \left|\mathrm{C},\mp1/2\right\rangle$ type, it is possible to determine the polarization dependence of the probability of this transition. Quantitative calculations show that the polarization dependences of the probabilities of optical transitions for both linear and circular polarizations have an oscillatory character with respect to the angle between the polarization vector and the wave vector of current carriers, but the oscillations for linear polarization are approximately twice as large as those for circular polarization. For both polarizations, the oscillation amplitude decreases with increasing coherent saturation effect parameter.

Thus, we have defined the following:

1. The polarization dependence of the squares of the moduli of matrix elements for interband optical transitions for both linear and circular polarization has an oscillatory character with respect to the angle between the polarization vector and the wave vector of current carriers.

2. For a single-photon optical transition between the spin-orbit splitting zone and the conduction band, the oscillation for linear polarization is approximately twice as large as for circular polarization. For both polarizations, the oscillation amplitude decreases with increasing coherent saturation effect parameter.

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