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POLARIZATION DEPENDENCE OF SINGLE-PHOTON INTERBAND LINEAR CIRCULAR DICROISM IN A_3B_5 SEMICONDUCTORS

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Abstract

The polarization, spectral, and temperature dependences of the single-photon absorption coefficient of polarized radiation are calculated, and its linear-circular dichroism in crystals of tetrahedral symmetry is studied. In this case, the contribution to the coefficients of one-photon absorption of light from the effect of coherent saturation of optical transitions is taken into account.

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

Introduction

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 (Ivchenko, 1972; Rasulov, 1993; Ganichev, 1983; Parshin, 1987; Rasulov, 2017; Rasulov, 1996; Rasulov, 1988; Rasulov, 1993). 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 (Rasulov, 1993) multiphoton linear-circular dichroism (*LCD*) for *p-Ge* was studied in the regime of developed nonlinearity, when n-photon processes make a comparable contribution to absorption with $n=(1\div 5)$. In (Rasulov, 2016; Rasulov, 2015), 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 (Ganichev, 1983; Parshi, 1987) 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 be 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 $\hbar\omega \geq E_g$, $E_g+\Delta_{SO}$, where E_g is the band gap, Δ_{SO} is the spin-orbit splitting of the valence band.

One-photon interband linear-circular dichroism

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:

a) let the initial states be in the heavy hole subband of the valence band, then, in the Luttinger-Kohn and Kane approximation transition from $|V,\pm 3/2\rangle$ into the $|c,\pm 1/2\rangle$ conduction band, i.e. $M^{(1)}_{C,\pm 1/2;\pm V,3/2}$, which is schematically depicted as $|V,\pm 3/2\rangle \to |c,\pm 1/2\rangle$, is determined by the relations: $M^{(1)}_{C,+1/2;V+3/2}=\left(\frac{eA_0}{c\hbar}\right)pe'_+$, $M^{(1)}_{C,-1/2;V-,3/2}=-i\left(\frac{eA_0}{c\hbar}\right)pe'_-$, and an optical transition of the $|V,\pm 3/2\rangle \to |c,\mp 1/2\rangle$ type is forbidden, where $e'_\pm = e'_x \pm ie'_y$, e'_α $(\alpha = x,y,z)$-are the projections of the light polarization vector, relative 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 electromagnetic wave potential vector, p – is the Kane parameter (Ivchenko, 1989; Bir, 1972), the rest are well-known quantities. The law of conservation of energy of this transition is described by $\delta\left(E_c(\vec{k})-E_{hh}(\vec{k})-\hbar\omega\right)$ functions, where $E_c(\vec{k})=\frac{\hbar^2k^2}{2m_c}+E_g$ is the energy spectrum of electrons in the conduction band, $E_L(\vec{k})=\frac{\hbar^2k^2}{2m_L}$ is the energy spectrum of holes in the subband of light $(L=lh)$ and heavy $(L=hh)$ holes, $m_c(m_L)$ is the effective masses of current carriers in the conduction band and in the valence band, $L=lh\,(hh)$ is for subbands of light (heavy) holes.

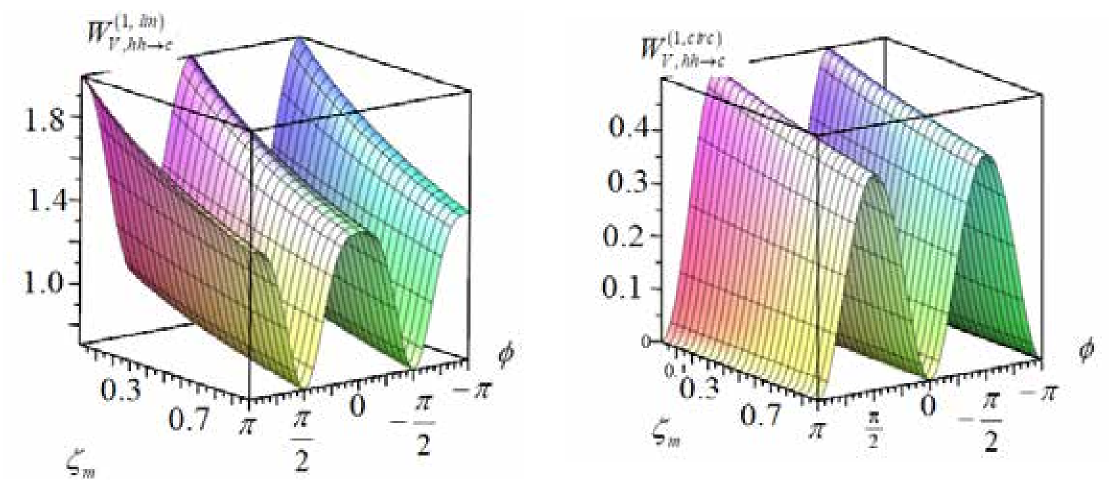
Based on the last relations, one can obtain the polarization dependence of the probabilities of the considered optical transitions. Calculations show that for optical transitions of the $|V,\pm 3/2\rangle \to |C,\pm 1/2\rangle$ type, the polarization dependence of the probability of this transition, determined by the polarization dependence $\left|M^{(1)}_{C,\pm 1/2;V,\pm 3/2}\right|^2=\left(\frac{eA_0}{c\hbar}\right)^2 p^2\left|e'_\pm\right|^2$, for both linear and circular polarizations, this dependence has an oscillatory character with respect to the angle between the polarization vector and the wave vector of current carriers. We note that, without taking into account the Rabi effect (Parshin, 1987; Rasulov, 2017; Rasulov, 1996), in this case the coefficient of interband linear-circular dichroism, defined as the ratio of the probabilities of optical transitions for linear and circular polarization, is equal to unity, i.e. linear-circular dichroism is not observed;

b) 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 $\left|V,m\right\rangle (m \pm 1/2)$ to the conduction band $\left|c,m'\right\rangle (m' = \pm 1/2)$, i.e. $M^{(1)}_{C,m';V,m}$, which is schematically depicted as $\left|V,m\right\rangle \to \left|c,m'\right\rangle$ is defined as the ratios: $M^{(1)}_{c,+1/2;V,+1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}} p_{cV} e'_-$, $M^{(1)}_{c,-1/2;V,-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{-i}{\sqrt{3}} e'_+ p_{cV}$, $M^{(1)}_{c,+1/2;V,-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}} e'_z p_{cV}$, $M^{(1)}_{c,+1/2;V,-1/2} = \left(\frac{eA_0}{c\hbar}\right) i\sqrt{\frac{2}{3}} e'_z p_{cV}$. Then the square of the modulus of the matrix elements of the considered optical transitions is expressed as: $\left|M^{(1)}_{c,\pm1/2;V,\pm1/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{1}{3} p^2_{cV} \left|e'_\mp\right|^2$, $\left|M^{(1)}_{c,\mp1/2;V,\pm1/2}\right|^2 = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{2}{3} p^2_{cV} \left|e'_z\right|^2$. 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 masses of electrons and light holes.

Figure 1. *Polarization dependence and dependence on the Rabi parameter of probability of the optical transitions type* $\left|V,hh\right\rangle \to \left|C\right\rangle$ *(a) for linear and (b) for circularly polarized light and the wave vector of the current carriers, the amplitude value of which is almost independent of the parameter of the coherent saturation effect*

a) b)



Taking into account the polarization dependence of matrix elements $M^{(1)}_{c,\pm1/2;V,\pm1/2}$ and $M^{(1)}_{c,\mp1/2;V,\pm1/2}$ for optical transitions of types $\left|V,\pm1/2\right\rangle \to \left|C,\pm1/2\right\rangle$ and $\left|V,\pm1/2\right\rangle \to$, $\to \left|C,\mp1/2\right\rangle$ it is possible to determine the polarization dependence of the probability of this transition, which is shown in (fig. 1 a). It can be seen from (fig. 1b) that the polarization dependence of the probability of the considered optical transition for both linear and circular polarizations have 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 $\zeta_\omega = 4\frac{\alpha_\omega}{\hbar^2\omega^2}\left(\frac{eA_0}{c\hbar}\right)^2 p^2_{cV}$, the amplitude of the oscillations decreases by 20% for linear, 15% for circular polarization.

Fig. 2 shows the polarization dependence of the single-photon linear-circular dichroism coefficient for type $\left|V,hh\right\rangle \to \left|C\right\rangle$ optical transitions. It can be seen from (fig. 3) that the polarization dependence of the single-photon linear-circular dichroism coefficient for the considered optical transition also has an oscillatory character with respect to the angle between the polarization vectors

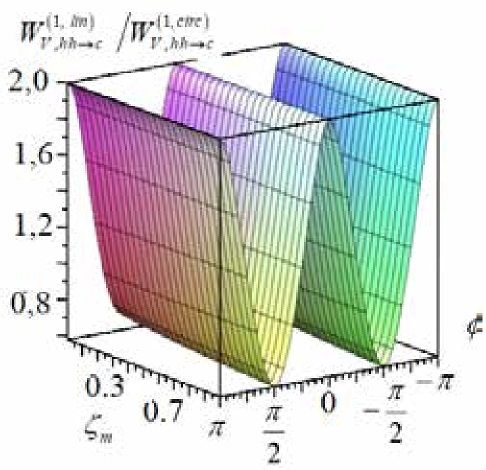
The probability of an optical transition upon absorption of linearly polarized light is about five times greater than the probability of an optical transition upon absorption of circularly polarized light. The latter is explained by the dependence of the selection rule for the considered optical transition on the degree of light polarization;

c) if the initial states are in the spin-split band, then the matrix elements of single-photon optical transitions $M^{(1)}_{C,m';SO,m}$, which are schematically depicted as $|SO,m\rangle \to |c,m'\rangle$, are defined as the relations: $M^{(1)}_{C,+1/2;SO,+1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}}p_{cV}e'_z$, $M^{(1)}_{C,-1/2;SO,+1/2} = = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}}p_{cV}e'_-$, $M^{(1)}_{c,+1/2;V,-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}}e'_z p_{cV}$, $= \left(\frac{eA_0}{c\hbar}\right)\frac{1}{\sqrt{3}}e'_z p_{cV}$, $M^{(1)}_{C,-1/2;SO,-1/2} = \left(\frac{eA_0}{c\hbar}\right)\frac{-i}{\sqrt{3}}p_{cV}e'_z$

The energy conservation law for these transitions is described by $\delta\left(E_c(\vec{k}) - E_{SO}(\vec{k}) - \hbar\omega\right)$ function, where $E_{SO}\left(\vec{k}\right) = \frac{\hbar^2 k^2}{2m_c} + \Delta_{SO}$ is the energy spectrum holes in the zone of spin orbital splitting, Δ_{SO} is the energy of spin orbital splitting.

Whence we have $\left|M^{(1)}_{C,\pm1/2;SO,\pm1/2}\right|^2 = = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{1}{3}p^2_{cV}e'^2_z$, $\left|M^{(1)}_{C,\mp1/2;SO,\pm1/2}\right|^2 = = \left(\frac{eA_0}{c\hbar}\right)^2 \frac{1}{3}p^2_{cV}e'^2_\pm$. In this case, the wave vector of photoexcited current carriers is defined as $k^{(1\omega)}_{c,SO} = \sqrt{\frac{2\mu^{(c,SO)}_+}{\hbar^2}\left(\hbar\omega - E_g - \Delta_{SO}\right)}$, $\mu^{(c,SO)}_+$ – reduced effective mass with respect to current carriers in the conduction bands and the spin of the orbital splitting.

Figure 2. *Polarization dependence and dependence on the Rabi parameter of the coefficient of single-photon linear-circular dichroism for* $|V,hh\rangle \to |C\rangle$ *type optical transitions.*



Taking into account the polarization dependences of the squares of the absolute value of matrix elements $\left|M^{(1)}_{C,\pm1/2;SO,\pm1/2}\right|^2$ and $\left|M^{(1)}_{C,\mp1/2;SO,\pm1/2}\right|^2$ for optical transitions of types $|V,\pm1/2\rangle \to |C,\pm1/2\rangle$ and $|V,\pm1/2\rangle \to \to |C,\mp1/2\rangle$, it is possible to determine the polarization dependence of the probability of this transition, taking into account the effect of coherent saturation (see fig. 3). It can be seen from (fig. 4) that the polarization dependences of the probabilities of optical transitions have an oscillatory character with respect to the angle between the polarization vector and the wave vector of current carriers, but 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.

Fig. 3 shows the complex polarization dependence of the single-photon linear-circular dichroism coefficient for type $|SO\rangle \to |C\rangle$ optical transitions. Such a non-monotonic polarization dependence is explained by the fact that the transition probability is determined not only by the distribution function of current carriers in the initial state, but also by the square of the composite matrix element corresponding to the optical transition, which is under the radical (see, for example, (Ganichev, 1983; Parshin, 1987; Rasulov, 2017)).

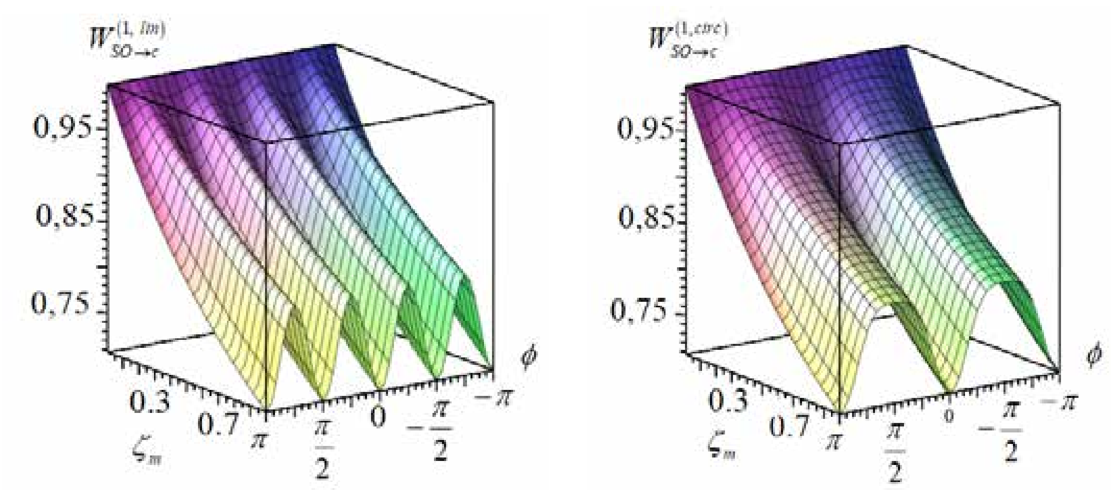
Conclusion

Thus, we have defined the following:

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

Figure 3. *Polarization dependence and dependence on the Rabi parameter of the probability of optical transitions* $|SO\rangle \rightarrow |C\rangle$ *type (a) for linear and (b) for circular polarizations of light*

a) b)



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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