ELECTRONICS


THE LINEAR-CIRCULAR DICHROISM OF INTERBAND SINGLE-PHOTON ABSORPTION OF LIGHT IN CRYSTALS

Rustam Rasulov
Professor
of Fergana State University,
Republic of Uzbekistan, Fergana
E-mail: r_rasulov51@mail.ru

Makhliyo Mamatova
Doctoral student
of Fergana State University
Republic of Uzbekistan, Fergana

Umida Isomaddinova
Teacher
of the Kokand State Pedagogical Institute
Republic of Uzbekistan, Kokand

Nurillo Kodirov
Doctoral student
of Fergana State University.
Republic of Uzbekistan, Fergana

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.
АННОТАЦИЯ

Рассчитаны поляризационная, спектральная и температурная зависимости коэффициента однофотонного поглощения поляризованного излучения и исследован его линейно-циркулярный дихроизм в кристаллах тетраэдрической симметрии. При этом учтен вклад в коэффициенты однофотонного поглощения света эффект коherentного насыщения оптических переходов.

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

Ключевые слова: поляризационная, спектральная и температурная зависимости коэффициента однофотонного поглощения света, линейно-циркулярный дихроизм, кристалл тетраэдрической симметрии, эффект когерентного насыщения.

I. 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 sub-bands 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 \( E_{hh}(k) - E_{lh}(k) - h\omega = 0 \) to the resonance condition. Here, \( E_{hh}(k) \) is the energy spectrum of heavy (light) holes, and is the frequency of light.

In [8], multiphoton linear-circular dichroism (LCD) in \( p\)-Ge was studied in the regime of developed nonlinearity, when \( n\)-photon processes make a comparable contribution to absorption with \( n = (1 \pm 5) \). In [5, 8], 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 be located not only in the light and heavy subbands, but also in both the conduction band and the spin-orbit splitting zone. When calculating intraband single-photon light absorption, we assume that the photon energy satisfies the condition \( h\omega \geq E_g \), \( E_g + \Delta_{SO} \), and for intraband two-photon light absorption \( 2h\omega < < E_g \cdot D_{SO} \), where \( E_g \) is the band gap, \( D_{SO} \) is the spin-orbit splitting of the valence band.

In case \( h\omega \geq E_g \), \( E_g + \Delta_{SO} \), there are two variants of interband optical transitions, the first of which satisfies the condition \( E_g \leq h\omega \langle E_g + \Delta_{SO} \rangle \), and in the second case the condition \( h\omega \geq E_g + \Delta_{SO} \) 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 will be analyzed separately.

II. Polarization dependences of single-photon interband linear-circular dichroisms

In the case \( h\omega \geq E_g \), \( E_g + \Delta_{SO} \), there are two variants of interband optical transitions, the first of which satisfies the condition \( E_g \leq h\omega \langle E_g + \Delta_{SO} \rangle \), and in the second case, the condition is satisfied \( h\omega \geq E_g + \Delta_{SO} \). Therefore, in the first case, optical transitions occur between the subbands of light and heavy holes of 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 [9], the matrix element of the single-photon optical transition from the heavy-hole subband \( |V, \pm 3/2 \rangle \) to the conduction band \( |c, \pm 1/2 \rangle \) is

\[
|V, \pm 3/2 \rangle \rightarrow |c, \pm 1/2 \rangle \text{, i.e., } M^{(1)}_{C,+1/2;V,3/2} = \left( \frac{eA_0}{ch} \right) p e',
\]

where \( e' \) is the projection of the light polarization vector, relative to the coordinates of the \( Oz \) axis of which is directed along the wave

\[
M^{(1)}_{C,+1/2;V,-3/2} = -i \left( \frac{eA_0}{ch} \right) p e',
\]

and the optical transition of the type \( |V, \pm 3/2 \rangle \rightarrow |c, \pm 1/2 \rangle \) is forbidden, where \( e'_x = e'_x \pm ie'_y \), \( e'_x (\alpha = x, y, z) \), are the projections of the light polarization vector, relative to the coordinates of the \( Oz \) axis of which is directed along the wave

\[
\langle c, \pm 1/2 | e'_x | V, \pm 3/2 \rangle = 0.
\]
photoexcited current carriers \((\vec{k})\). \(A_0\) is the amplitude of the potential vector of the electromagnetic wave, \(p_{eV}\) is the Kane parameter \([11, 12]\), the rest are well-known quantities.

The energy conservation law for this transition is described by the function

\[
\delta\left(E_c(\vec{k}) - E_{ih}(\vec{k}) - \hbar\omega_0\right) = \frac{\hbar^2 k^2}{2m_e} + E_g
\]

where \(E_c(\vec{k}) = \frac{\hbar^2 k^2}{2m_e} + E_g\) 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, \(m_L(m_e)\) are the effective masses of current carriers in the conduction band and in the valence band, \(L = lh (hh)\) is for the subband of light (heavy) holes.

**Figure 1.** Polarization dependence of the probability for \(|V, \pm 3/2 \rightarrow |C, \pm 1/2\rangle\) optical type transitions for both linear and circular polarizations

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 \(|V, \pm 3/2 \rightarrow |C, \pm 1/2\rangle\), the polarization dependence of the probability of a given transition, determined by the polarization dependence

\[
|M_{C,\pm 1/2, V, \pm 3/2}^{(1)}|^2 = \left( \frac{eA_0}{c\hbar} \right)^2 p_{eV}^2 |e'_V|^2
\]

is shown in fig. 1.

It can be seen from fig. 1 that 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. 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 \(|V, m\rangle (m \pm 1/2)\) to the conduction band, i.e.

\[
M_{C,m', V,m}^{(1)}\] which is schematically depicted as

\[
|M_{C,m', V,m}^{(1)}| = \left| \frac{eA_0}{c\hbar} \right|^2 \frac{1}{\sqrt{3}} p_{eV} |e'_V|^2 .
\]

Then the square of the modulus of the matrix elements of the considered optical transitions is expressed as:

\[
|M_{C,m', V,m}^{(1)}|^2 = \left( \frac{eA_0}{c\hbar} \right)^2 \frac{1}{3} p_{eV}^2 |e'_V|^2 .
\]
The energy conservation law of these transitions is described by a function. Then the wave vector of photoexcited current carriers is determined by

\[ k^{(\text{c, lh})}_{\text{e, c}, \text{h}} = \frac{2\mu^{(\text{c, lh})}}{\hbar^2} (\hbar \omega - E_k) \]

where \( \mu^{(\text{c, lh})} = \frac{m_e m_{\text{lh}}}{m_e + m_{\text{lh}}} \) is the reduced effective mass relative to the effective mass of electrons in the conduction band and light holes.

Figure 2. Polarization dependence of the probability for optical transitions of the type \( |V, \text{hh}\rangle \rightarrow |C\rangle \) for linear (a) and circularly polarized (b) light

Taking into account the polarization dependence of the matrix elements \( M^{(1)}_{\text{c, \pm 1/2, V, \pm 1/2}} \) and \( M^{(1)}_{\text{c, \pm 1/2, V, \pm 1/2}} \) for optical transitions of the type \( |V, \pm 1/2\rangle \rightarrow |C, \pm 1/2\rangle \) and \( |V, \pm 1/2\rangle \rightarrow |C, \mp 1/2\rangle \) type, it is possible to determine the polarization dependence of the probability of this transition, which is shown in fig. 2 a. It can be seen from fig. 2b that the 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 coherent saturation effect parameter, the oscillation amplitude decreases: by 20% for linear, 15% for circular polarization.

Figure 3. Polarization dependence of the single-photon linear-circular dichroism coefficient for optical transitions of the type \( |V, \text{hh}\rangle \rightarrow |C\rangle \)
On fig. 3 shows the polarization dependence of the single-photon linear-circular dichroism coefficient for optical transitions of the type \(|V, hh\rangle \rightarrow |C\rangle\). From fig. 3 shows that the polarization dependence of the coefficient of single-photon linear-circular dichroism for the considered optical transition also has an oscillatory character with respect to the angle between the polarization vectors and the wave vector of current carriers, the amplitude value of which is almost independent of the parameter of the coherent saturation effect. 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

\[ M_{c,m';SO,m}^{(l)}\]

which are schematically depicted as

\[ |SO,m\rangle \rightarrow |c,m'\rangle\], are defined as the relations:

\[ M_{C,+1/2,SO,+,1/2}^{(l)} = \left( \frac{eA_0}{ch} \right) \frac{1}{\sqrt{3}} p_v e' \xi , \]

\[ M_{C,+,1/2,SO,+,1/2}^{(l)} = \left( \frac{eA_0}{ch} \right) \frac{1}{\sqrt{3}} p_v e' \xi , \]

\[ M_{C,+,1/2,V,+,1/2}^{(l)} = \left( \frac{eA_0}{ch} \right) \frac{1}{\sqrt{3}} e' p_v \xi . \]

\[ M_{C,+,1/2,SO,+,1/2}^{(l)} = \left( \frac{eA_0}{ch} \right) \frac{i}{\sqrt{3}} p_v e' \xi . \] The law of conservation of energy for these transitions is described by the\[ \delta \left( E_v(\vec{k}) - E_{SO}(\vec{k}) - \hbar \omega \right) \]

function, where \[ E_{SO}(\vec{k}) = \frac{\hbar^2 k^2}{2m_c} + \Delta_{SO}\] is the energy of spin orbital splitting. Where do we get

\[ |M_{C,+1/2,SO,+,1/2}^{(l)}|^2 = \left( \frac{eA_0}{ch} \right)^2 \frac{1}{3} p_v e'^2 \xi , \]

\[ |M_{C,+,1/2,SO,+,1/2}^{(l)}|^2 = \left( \frac{eA_0}{ch} \right)^2 \frac{1}{3} p_v e'^2 \xi . \] In this case, the wave vector of photoexcited current carriers is defined as

\[ k_{c,SO}^{(l)} = \sqrt{\frac{2\mu_{c,SO}^2}{\hbar^2}} (\hbar \omega - E_v - \Delta_{SO}^c). \]

\[ \mu_{c,SO}^c = \frac{1}{\hbar^2} (\hbar \omega - E_v - \Delta_{SO}^c) \]

is the reduced effective mass relative 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

\[ |M_{C,+1/2,SO,+,1/2}^{(l)}|^2 \] and \[ |M_{C,+,1/2,SO,+,1/2}^{(l)}|^2 \] for optical transitions of the type \(|V, \pm 1/2\rangle \rightarrow |C, \pm 1/2\rangle\) and \(|V, \pm 1/2\rangle \rightarrow |C, \mp 1/2\rangle\) type, it is possible to determine the polarization dependence of the probability of this transition, taking into account the effect of coherent saturation (see fig. 4). 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 two times greater than for circular polarization. For both polarizations, the oscillation amplitude decreases with increasing coherent saturation effect parameter.

On fig. 5 shows the complex polarization dependence of the single-photon linear-circular dichroism coefficient for optical transitions of the type \(|SO\rangle \rightarrow |C\rangle\). Such a nonmonotonic 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, [3–5]).
III. INTERBAND SINGLE-PHOTON ABSORPTION OF POLARIZED LIGHT WITH ALLOWANCE FOR THE EFFECT OF COHERENT SATURATION

Next, we study various variants of single-photon interband absorption of polarized light, where we take into account the contribution of the coherent saturation effect [3–5] to the light absorption coefficient. Then the spectral-temperature dependence of the single-photon light absorption coefficient $K^{(1)}$ is determined by the formula [3-5]

$$K^{(1)}_{C,1/2;V,3/2} = \frac{2\pi}{h} \hbar \omega \frac{1}{l} \rho(\hbar \omega) F(\beta, 1, \omega) \times$$

$$\left( \frac{|M^{(1)}_{C,1/1;V,3/2}(\vec{k})|^2}{\sqrt{1 + 4 \frac{\alpha_{\omega}}{\hbar^2 \omega^2} |M^{(1)}_{C,1/1;V,3/2}(\vec{k})|^2}} \right) + \left( \frac{|M^{(1)}_{C,1/2;V,3/2}(\vec{k})|^2}{\sqrt{1 + 4 \frac{\alpha_{\omega}}{\hbar^2 \omega^2} |M^{(1)}_{C,1/2;V,3/2}(\vec{k})|^2}} \right).$$

(1)
where $I_0(\omega)$ is the intensity (frequency) of light, 
\[\rho(\hbar\omega)\] is the density of states of current carriers involved in optical transitions, where the law of conservation of energy is taken into account, is the distribution function of current carriers in the initial state, \[\beta^{-1} = k_BT,\quad k_B\text{ is the Boltzmann constant, } T\text{ is the sample temperature:}\]

\[
F(\beta, 1, \omega) = [1 - \exp(1\beta\hbar\omega)] \exp[\beta(\mu - E_{L=hh}(k_{c,L=hh}^{(a)})] \\
E_{L=hh}(k_{c,L=hh}^{(a)}) = \frac{m_c}{m_c + m_h^{(a)}} (\hbar\omega - E_g),
\]

\[\rho(\hbar\omega) = \mu^{(c,h)} \left( \frac{\pi^2 \hbar^2}{2} \right), \quad \mu^{(c,h)}\text{ is the reduced effective mass current carriers, the form of which depends on the type of optical transitions.}\]

It can be seen from (1) that it is necessary to perform angular averaging of the squares of the composite matrix elements over the solid angles of the wave vector of the current carriers, i.e. we need to perform an integration of the type

\[
\left\langle \frac{|M^{(1)}_{c,\pm 1/2,V,\pm 3/2}(\mathbf{k})|^2}{\sqrt{1 + 4 \frac{\alpha_{\omega}}{\hbar^2 \omega^2}} |M^{(1)}_{c,\pm 1/2,V,\pm 3/2}(\mathbf{k})|^2} \right\rangle^{3,2} = \frac{\exp((1 - \mathbf{1}) + \mathbf{1}_2)(1 - \mathbf{1}) + \mathbf{1}_2(1 - \mathbf{1})}{c\hbar^2},
\]

where \[\mathbf{R}_1(I)\] and \[\mathbf{R}_2(I)\] are the light intensity, \[\mathbf{I} = \left\langle S \right\rangle = \frac{n_{\omega} \omega^2 A_0^2}{2\pi c}\] is the light intensity,

\[
\left\langle |M^{(N)}_{n,k',nk}|^2 \right\rangle^{3,2} \text{ is the square of the absolute value of the matrix element } M^{(N)}_{n,k',nk}, \text{ averaged over the solid angles of the vector } \mathbf{k}, \quad \zeta_{\omega} = 4 \frac{\alpha_{\omega}}{\hbar^2 \omega^2} \left( \frac{eA_0}{c\hbar} \right)^2 p_{c\hbar}^2, \text{ the wave vector } \mathbf{k}_{\omega} \text{ is determined from the energy conservation law.}\]

In particular, for the optical transition considered above

\[
k_{\omega} = k_{c,k} = \sqrt{\frac{2\mu^{(c,L)}_{\omega}}{\hbar^2}} (\hbar\omega - E_g),
\]

\[
\mu^{(c,L)}_{\omega} = \frac{m_c m_L}{m_c + m_L}.\text{ Calculation of single-photon absorption of polarized light due to optical transitions from the subband of light and heavy holes to the conduction band is performed using the formula} [6–8].\]

\[
K^{(1)} = \frac{4\pi e^2}{\cos \theta} \int \sum_{m,n,k} \left| \mathbf{P}_{mn}(k) \right|^2 (f_{nk} - f_{nk}) \delta \left( E_n(k) - E_n(k) - \hbar\omega \right),
\]

whence, in the Luttinger-Kohn approximation and in the three-band Kane model [9], the spectral-temperature dependence of the coefficient of interband single-photon absorption of light takes the form

\[
K^{(1)}_{c,v} = \frac{1}{3} \frac{e^2}{c\hbar^2} \int \sum_{m,n,k} \left| \mathbf{P}_{mn}(k) \right|^2 \left( f_{n,k}^{(1)}(1) - f_{n,k}^{(1)}(1) \right) \mu^{(c,h)}_{\omega} k^{(1)}_{c,h} + \left( f_{n,k}^{(1)}(1) - f_{n,k}^{(1)}(1) \right) \mu^{(c,h)}_{\omega} k^{(1)}_{c,h}
\]
where the distribution functions of photoexcited light and heavy holes are defined as

$$f_{lh,K_{c, lh}}^{(10)} = \exp \left[ \frac{E_F}{k_B T} \right] \cdot \exp \left[ - \frac{1}{k_B T} \frac{\mu^{(c, lh)}_{lh}}{m_{lh}^{*}} \left( \hbar \omega - E_g \right) \right]. \quad (6)$$

$$f_{hh,K_{c, hh}}^{(10)} = \exp \left[ \frac{E_F}{k_B T} \right] \exp \left[ - \frac{E_{hh}}{k_B T} \left( K_{c, hh}^{(10)} \right) \right] \cdot \exp \left[ - \frac{1}{k_B T} \frac{\mu^{(c, hh)}_{hh}}{m_{hh}^{*}} \left( \hbar \omega - E_g \right) \right]. \quad (7)$$

and the Fermi energy is determined by the relation

$$e^{\frac{\mu_{c, lh}}{k_B T}} = \frac{1}{2} P \left( \frac{k_B T}{2 \pi \hbar} \right)^{3/2} \left( m_{lh}^{3/2} + m_{hh}^{3/2} \right)^{-1} \quad (8)$$

On fig. 6 shows the spectral and temperature dependences of the coefficient of single-photon absorption of polarized light in GaAs, due to optical transitions between the subbands of light \((K_{c, lh})\) and heavy \((K_{c, hh})\) holes (Fig. 6 a) and the conduction band, as well as the resulting single-photon absorption of light (Fig. 6 b), where the contribution of the coherent saturation effect to the single-photon light absorption coefficient is taken into account. In quantitative calculations, the maximum value is chosen as one.

From fig. 6 a and 6 b it can be seen that the spectral (temperature) dependence of the single-photon light absorption coefficient in GaAs, due to optical transitions between subbands of the valence band and the conduction band, first increases with increasing frequency (temperature) and, passing through a maximum, decreases. This is explained by the fact that the spectral dependence of the coefficient of single-photon absorption of light by the product of the density of states, with increasing frequency, which increases as a power function of frequency, and the distribution function of current carriers in the initial state, with increasing frequency, which decreases exponentially. The product of these quantities gives the graph shown in fig. 6. We note that here the temperature dependence of the band gap is not taken into account, the inclusion of which will lead to a noticeable change in the spectral and temperature dependence of the single-photon absorption coefficient of polarized light, and it is shown in Fig. 7 for GaAs. From fig. It can be seen from Fig. 7 that, when the temperature dependence of the band gap is taken into account, the amplitude value oscillates with increasing temperature in the region of low frequencies, while in the region of high frequencies, this value remains almost unchanged. In calculations, the temperature dependence of the band gap was chosen as:

$$E_g(T) = E_g(0) + \gamma_g T,$$

where

$$\gamma_g = 0,5405 \text{ meV} / K$$

for GaAs [10].

**Figure 6. Spectral - temperature dependence of the single-photon absorption coefficient of polarized light in GaAs, due to optical transitions between the subbands of light \((K_{c, lh})\) and heavy \((K_{c, hh})\) holes and the conduction band and their sum.**
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 number of oscillations for linear polarization is approximately twice that for circular polarization. For both polarizations, the oscillation amplitude decreases with increasing coherent saturation effect parameter.
3. Oscillation in the spectral-temperature dependence of the coefficient of single-photon absorption of polarized light in GaAs, due to optical transitions between the subbands of light holes and the conduction band \( K^{(1)}_{c,ln} \) without taking into account (a) and taking into account (b) the temperature dependence of the band gap on temperature.

References: