

Voxob Rustamovich Rasulov
Farg‘ona davlat universiteti dotsenti.
E-mail. vr Rasulov83@gmail.com
Farrux Unvonovich Kasimov
Andijon davlat universiteti o‘qituvchisi.
E-mail. foruq7777@gmail.com
Nurillo Ubaydullo o'g'li Qodirov.
Farg‘ona davlat universiteti doktoranti.
UO‘K 541.123:54621

KOGERENT TO'YINGANLIK EFFEKTINI HISOBGA OLGAN HOLDA KRISTALLARDA QUTBLANGAN YORUG'LIKNING BIR FOTONLI YUTILISHI. 1 - QISM

Annotatsiya. Tetraedral simmetriyali kristallarda yengil va og'ir teshik tarmoqlaridan o'tkazuvchanlik zonasining tarmoqlariaro optik o'tishlar natijasida yuzaga keladigan bir fotonli yutilish koeffitsientining spektral hamda haroratga bog'liqligi hisoblangan. Bunda bir fotonli yorug'likning yutilish koeffitsientiga kogerentli to'yinish effektining hissasi hisobga olinadi.

Kalit so'zlar: qutblangan yorug'lik, yorug'lik bir fotonli yutilish koeffitsientining spektral va haroratga bog'liqligi, tetraedr simmetriyali kristall, kogerent to'yinish effekti.

Вохоб Рустамович Расулов
доцент Ферганского государственного университета.
Форрух Касимов
преподаватель Андижанского государственного университета.
Нурилло Убайдулло оглы Кодиров.
докторант Ферганского государственного университета.

МЕЖЗОННОЕ ОДНОФОТОННОЕ ПОГЛОЩЕНИЕ ПОЛЯРИЗОВАННОГО СВЕТА В КРИСТАЛЛАХ С УЧЕТОМ ЭФФЕКТА КОГЕРЕНТНОГО НАСЫЩЕНИЯ. 1 - ЧАСТЬ

Аннотация. Рассчитана спектрально-температурная зависимость коэффициента однофотонного поглощения света в кристаллах тетраэдрической симметрии, обусловленная оптическими переходами, происходящими из подзон легких и тяжелых дырок в зону проводимости. При этом учитывается вклад эффекта когерентного насыщения в коэффициент поглощения однофотонного света.

Ключевые слова: поляризованный свет, спектральная и температурная зависимость коэффициента однофотонного поглощения света, кристалл тетраэдрической симметрии, эффект когерентного насыщения.

Voxob Rustamovich Rasulov
associate professor of Fergana State University.

Forrukh Kasimov
teacher of the Andijan State University.

Nurillo Ubaydullo ogli Kodirov.
doctoral student of Fergana State University.

INTERBAND SINGLE-PHOTON ABSORPTION OF POLARIZED LIGHT IN CRYSTALS WITH ALLOWANCE FOR THE EFFECT OF COHERENT SATURATION. 1-PART

Abstract. The spectral-temperature dependence of the coefficient of single-photon absorption of light in crystals of tetrahedral symmetry, due to optical transitions occurring from the subbands of light and heavy holes to the conduction band, is calculated. In this case, the contribution of the coherent saturation effect to the single-photon light absorption coefficient is taken into account.

Keywords: polarized light, spectral and temperature dependence of the single-photon light absorption coefficient, crystal of tetrahedral symmetry, coherent saturation effect.

Introduction

As indicated in the first part of this work, the nonlinear absorption of light in a semiconductor with a degenerate valence band, which is due to direct optical transitions between the subbands of heavy and light holes 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 $E_{hh}(\mathbf{k}) - E_{hl}(\mathbf{k}) - \hbar\omega = 0$ to the resonance condition. Here, $E_{hh}(\mathbf{k})$ ($E_{hl}(\mathbf{k})$) is the energy spectrum of heavy (light) holes, and ω is the frequency of light.

In [1-10], the spectral-temperature dependence of the single-photon light absorption coefficient was not calculated. This work is devoted to the solution of this issue. For this, we consider various variants of single-photon interband absorption of polarized light, which differ from each other by intermediate states. In particular, in the case of single-photon interband absorption of light, these intermediate states can be located both in the subbands of the valence band, and in the conduction band, or in the spin-orbital splitting band. And also, depending on the energy of photons, optical transitions can occur, which differ from each other by initial states. In particular, in the frequency range $E_g \leq \hbar\omega \leq E_g + \Delta_{so}$, optical transitions are allowed between subbands of light

or heavy holes, but in the frequency range $\hbar\omega \geq E_g + \Delta_{so}$, optical transitions from the spin-orbit splitting zone to the conduction band are allowed. Therefore, we will consider them separately, where $\hbar\omega$ is the photon energy, E_g is the band gap, Δ_{so} is the spin-orbit splitting energy.

Calculation of the frequency-temperature dependence of the intraband light absorption coefficient

Let us first consider the one-photon absorption of light between the subbands of the valence band and the conduction band (at $E_g \leq \hbar\omega \leq E_g + \Delta_{so}$). Following [5–10], in further calculations of the spectral and temperature dependence of the single-photon light absorption coefficient, we neglect the light wave vector, i.e. we assume that the wave vector of current carriers in the final (initial and intermediate) state). Then

$$K_{C,\pm 1/2;V,\pm 3/2}^{(1)} = \frac{2\pi}{\hbar} \hbar\omega \frac{1}{I} \rho(\hbar\omega) F(\beta, 1, \omega) \times \left\langle \frac{|M_{C,\pm 1/2;V,\pm 3/2}^{(1)}(\vec{k})|^2}{\sqrt{1 + 4 \frac{\alpha_\omega}{\hbar^2 \omega^2} |M_{C,\pm 1/2;V,\pm 3/2}^{(1)}(\vec{k})|^2}} \right\rangle + \left\langle \frac{|M_{C,\pm 1/2;V,\pm 3/2}^{(1)}(\vec{k})|^2}{\sqrt{1 + 4 \frac{\alpha_\omega}{\hbar^2 \omega^2} |M_{C,\pm 1/2;V,\pm 3/2}^{(1)}(\vec{k})|^2}} \right\rangle, \quad (1)$$

where $I, (\omega)$ 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, $F(\beta, 1, \omega)$ is the distribution function of current carriers in the initial state, k_B is the Boltzmann constant, T is the sample

temperature, $E_{L=hh}(k_{c,L=hh}^{(\omega)}) = \frac{m_c}{m_c + m_{hh}} (\hbar\omega - E_g)$, $\rho(\hbar\omega) = \mu^* k_\omega / (\pi^2 \hbar^2)$, $F(\beta, 1, \omega) = [1 - \exp(-\beta \hbar\omega)] \exp[\beta (\mu - E_{L=hh}(k_{c,L=hh}^{(\omega)}))]$, μ^* is the reduced effective mass of current carriers, the form of which depends on the type of optical transitions.

Now we need to calculate

$$\left\langle \frac{|M_{C,\pm 1/2;V,\pm 3/2}^{(1)}(\vec{k})|^2}{\sqrt{1 + 4 \frac{\alpha_\omega}{\hbar^2 \omega^2} |M_{C,\pm 1/2;V,\pm 3/2}^{(1)}(\vec{k})|^2}} \right\rangle = \left(\frac{eA_0}{c\hbar} \right)^2 p^2 [\Re_1(I) + \Re_2(I)], \quad (2)$$

(it is these integrals that determine the averaged values of the matrix elements of the considered optical transitions) where

$$\Re_1(I) = \left\langle \frac{|e'_\pm|^2}{\sqrt{1 + \xi_\omega |e'_\pm|^2}} \right\rangle, \quad \Re_2(I) = \left\langle \frac{|e'_z|^2}{\sqrt{1 + \xi_\omega |e'_z|^2}} \right\rangle, \quad I = |\vec{S}| = \frac{n_\omega \omega^2 A_0^2}{2\pi c} \quad \text{is the light}$$

intensity, $\langle |M_{n'k',nk}^{(N)}|^2 \rangle$ is the square of the absolute value of the matrix element

$M_{n'k',nk}^{(N)}$ averaged over the solid angles of the vector $\vec{k}$, $\xi_\omega = 4 \frac{\alpha_\omega}{\hbar^2 \omega^2} \left(\frac{eA_0}{c\hbar} \right)^2 p^2$, the wave vector k_ω is determined from the energy conservation law. In particular,

for the optical transition considered above $k_\omega = k_{c,L} = \sqrt{\frac{2\mu_*^{(c,L)}}{\hbar^2} (\hbar\omega - E_g)}$,

$\mu_*^{(c,L)} = \frac{m_c m_L}{m_c + m_L}$, $E_c(\vec{k}) = \frac{\hbar^2 k^2}{2m_c} + E_g$, $E_L(\vec{k}) = -\frac{\hbar^2 k^2}{2m_L}$, $m_c(m_L)$ are the effective masses in the conduction band and in the valence band, $L = lh(hh)$ are for the subband of light (heavy) holes.

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 by the formula

$$K^{(i)} = \frac{4\pi e^2}{c\omega m_0^2 n_\omega} \sum_{nn'} \left| e p_{nn'}(\vec{k}) \right|^2 (f_{nk}^- - f_{n'k}^-) \delta(E_n(\vec{k}) - E_{n'}(\vec{k}) - \hbar\omega) \quad (3)$$

or

$$K_{c,SO}^{(i)} = \frac{4\pi e^2}{c\hbar n_\omega} \left\{ \iiint \frac{1}{2} p_{cV}^2 |e'_\pm|^2 (f_{hh,k}^- - f_{c,k}^-) \delta(E_c(\vec{k}) - E_{hh}(\vec{k}) - \hbar\omega) + \right. \\ \left. + \left\{ \iiint \left(\frac{2}{3} p_{cV}^2 |e'_z|^2 + \frac{1}{6} p_{cV}^2 |e'_\pm|^2 \right) (f_{lh,k}^- - f_{c,k}^-) \delta(E_c(\vec{k}) - E_{lh}(\vec{k}) - \hbar\omega) \right\} \right\} \quad (4)$$

where $E_{c,k}^- = \frac{\hbar^2 k^2}{2m_c} + E_g$ is the energy spectrum of electrons in the conduction

band, $E_{L,k}^- = \frac{\hbar^2 k^2}{2m_L}$ is the energy spectrum of holes in the subband of light

($L = lh$) and heavy ($L = hh$) holes, $E_{SO,k}^- = \frac{\hbar^2 k^2}{2m_c} + \Delta_{SO}$ is the energy spectrum of holes in the spin-orbital splitting zone.

Then, from the energy conservation law, we have expressions for the wave vectors of photoexcited current carriers involved in interband optical

transitions as $k_{c,lh}^{(1\omega)} = \sqrt{\frac{2\mu_*^{(c,lh)}}{\hbar^2} (\hbar\omega - E_g)}$, $k_{c,hh}^{(1\omega)} = \sqrt{\frac{2\mu_*^{(c,hh)}}{\hbar^2} (\hbar\omega - E_g)}$, where

$\mu_*^{(c,lh)} = \frac{m_c m_{lh}}{m_c + m_{lh}}$, $\mu_*^{(c,hh)} = \frac{m_c m_{hh}}{m_c + m_{hh}}$ is the reduced effective mass of electrons and holes.

The spectral-temperature dependence of the coefficient of interband single-photon absorption of light, taking into account the latter relations, has the form

$$K_{c,V}^{(1)} = \frac{1}{3} p_{cV}^2 \frac{e^2 p_{cV}^2}{c \hbar^3 n_{\omega}} \left[\left(f_{hh,k_{c,hh}^{(1\omega)}} - f_{c,k_{c,hh}^{(1\omega)}} \right) \mu_+^{(c,hh)} K_{c,hh}^{(1\omega)} + \left(f_{lh,k_{c,lh}^{(1\omega)}} - f_{c,k_{c,lh}^{(1\omega)}} \right) \mu_+^{(c,lh)} K_{c,lh}^{(1\omega)} \right] \quad (5)$$

or

$$K_{c,V}^{(1)} = \frac{1}{6} \frac{e^2 p_{cV}^2}{c \hbar^3 n_{\omega}} \left[f_{hh,k_{c,hh}^{(1\omega)}} K_{c,hh}^{(1\omega)} \mu_+^{(c,hh)} + f_{lh,k_{c,lh}^{(1\omega)}} \mu_+^{(c,lh)} K_{c,lh}^{(1\omega)} \right] \left\{ 1 - \exp \left[\frac{E_g}{k_B T} (x - 1) \right] \right\}, \quad (6)$$

where $x = \hbar\omega/E_g$, the distribution functions of photoexcited light and heavy holes are defined as

$$f_{lh,k_{c,lh}^{(1\omega)}} = \exp \left[\frac{E_F}{k_B T} \right] \cdot \exp \left[- \frac{1}{k_B T} \frac{\mu_+^{(c,lh)}}{m_{lh}} (\hbar\omega - E_g) \right], \quad (7)$$

$$f_{hh,k_{c,hh}^{(1\omega)}} = \exp \left[\frac{E_F}{k_B T} \right] \exp \left[- \frac{E_{hh}(k_{c,hh}^{(1\omega)})}{k_B T} \right] = \exp \left[\frac{E_F}{k_B T} \right] \cdot \exp \left[- \frac{1}{k_B T} \frac{\mu_+^{(c,hh)}}{m_{hh}} (\hbar\omega - E_g) \right], \quad (8)$$

and the Fermi energy is determined by the relation

$$e^{\frac{\mu}{k_B T}} = \frac{1}{2} p \left(\frac{k_B T}{2\pi\hbar^2} \right)^{-3/2} (m_{hh}^{3/2} + m_{lh}^{3/2})^{-1}. \quad (9)$$

Calculations show that 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 $(K_{c,lh}^{(1)})$ and heavy holes $(K_{c,hh}^{(1)})$ and the conduction band, as well as the resulting single-photon absorption of light, first increases with increasing temperature and photon energy and reaches a maximum, then falls. This behavior $K_{c,lh}^{(1)}$ and $K_{c,hh}^{(1)}$ is due to the peculiarity of the temperature Fermi energy, as well as the temperature and spectral dependences of the distribution function of current carriers in the initial state. Above, 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.

Conclusions

Thus, we have received:

1. 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, where the contribution of the coherent saturation effect to the coefficient of single-photon light absorption is not taken into account.

2. Results are obtained both with and without allowance for the temperature dependence of the band gap.

Literature

1. Ivchenko E.L. Two-photon absorption and optical orientation of free carriers in cubic crystals // Semiconductors. -1972.-Vol.14. No.12.-Pp. 3489-3485(in Russian).
2. Rasulov R.Ya. Polarization optical and photovoltaic effects in semiconductors with linear and nonlinear absorption of light. Dissertation for thesis. of doctor's degree phys.-math. sciences. St. Petersburg. -1993. – 206 p (in Russian).
3. Ganichev S.D., Ivchenko E.L., Rasulov R.Ya., Yaroshetskii I.D. and Averbukh B. Ya. Linear and circular dichroism of drag current due to nonlinear inter subband absorption of light in p-type Ge//Phys. Solid State. - 1983. -V.35. -No.1. -P.104-108.
4. Parshin D.A., Shabaev A.R. Theory of nonlinear absorption of infrared radiation in semiconductors with degenerate bands. // ZhETF. - 1987. - Vol.92. - Issue. 4. - S. 1471-1484.
5. Rasulov V.R. Rasulov R.Ya., Eshboltaev I. Linearly and circular dichroism in a semiconductor with a complex valence band with allowance for four-photon absorption of light // Physics of the Solid State. - 2017. - Vol. 59, No.3. - P. 463-468.
6. Rasulov R. Ya., Khoshimov G.Kh., Kholitdinov Kh. Linear-circular dichroism of the nonlinear absorption of light in n-GaP // Semiconductors. - 1996. T.30. No. 30. No. 2. -P.274-277 (in Russian).
7. Rasulov, R.Ya., Drag effect at three-photon absorption of light in semiconductors of the Ge type// Semiconductors. -1988. -Vol.22. -No. 11. -P. 2077-2080(in Russian).
8. Rasulov R. Ya. Linear circular dichroism in multiphoton interband absorption in semiconductors // Semiconductors. - 1993. - Vol.35. - No. 6.-Pp. 1674-1678 (in Russian).
9. Rasulov R. Ya., V.R. Rasulov, Eshboltaev I. The theory of the four photons of polarized radiation in a semiconductor with complex band structure // American Scientific journal. - 2016. - No.2, - P.93-96.
10. Rasulov V.R., Rasulov R.Ya., Eshboltaev I. Linear-circular dichroism of four-photon absorption of light in semiconductors with a complex valence band // Russian Physics Journal. -2015. -Vol. 58, No.12. - P.1681-1686.