Intraband optical absorption induced by Rashba spin-orbit coupling in two-dimensional electron gas

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Abstract: Semiconductor heterostructures in which the spin-orbit interaction is associated with the absence of a center of symmetry that limits the potential of the structure are the basis for future spintronics devices. One of the main methods for investigating into spin properties is the study of optical phenomena in magnetic fields. The article theoretically consider the effect of spin-orbit interaction on absorption in quantum wells, in particular, the intraband magnetic absorption of electromagnetic radiation of linear polarization by a two-dimensional electron gas with Rashba spin-orbit interaction. The coefficient of light absorption by free carriers in the quasi-two-dimensional system was calculated in the second order of perturbation theory. It is assumed that infrared electromagnetic radiation is absorbed in a quasi-two-dimensional system by free carriers, that are scattered by optical, piezoelectric, and acoustic lattice vibrations. The quantum-mechanical motion of an electron in a two-dimensional system in a constant uniform perpendicular magnetic field is described by the Hamiltonian taking into account the Rashba spin-orbit interaction and Zeeman splitting. We calculated the light absorption spectra of 2D electron gas for GaAs / In0.23Ga0.77As lattice structures.
Keywords: Rashba spin-orbit coupling, intraband magnetoabsorption, quasi-two-dimensional electron system, magnetic field, Landau levels, Zeeman splitting, wave functions

In recent years, considerable interest has been observed in the study of quantum states and transport Taking into account the spin – orbit interaction due to their applications in nanostructure physics. Interest in spin-dependent phenomena has recently increased significantly in connection with the rapidly developing direction of spintronics [1]. Particular attention is paid to semiconductor heterostructures[2], since the level of technology for their growth makes them the basis of future spintronics devices. A powerful method for studying spin properties is optical phenomena studies in a magnetic field. The quantum states of electrons and holes in semiconductor structures, where the spin – orbit interaction is associated with the absence of symmetry center that limits the structure potential, were studied in a number of theoretical and experimental works [3–5]. Taking into account the spin – orbit interaction in the system leads to a mixing of the electron states related to different magnetic subbands and, as a consequence, to a nontrivial structure of the energy spectrum and spin polarization [6]. Spin – orbit interaction also leads to the possibility of resonance transitions of conduction electrons in a magnetic field between Landau levels at frequencies representing linear combinations of cyclotron and Zeeman frequencies [7]. In recent years, much attention has been paid to the study of the optical properties of low-dimensional nanostructures[8,9]. In particular, intraband transitions in quantum wells were considered in [10,11], in quantum wires [12, 13]. Intraband magnetic absorption of electromagnetic radiation by quantum nanostructures was studied in [14,15].

In this connection, it is of interest to study the effect of spin – orbit interaction on the intraband magnetoabsorption of electromagnetic radiation in quantum wells. In the present work, the intraband magnetic absorption of electromagnetic radiation of linear polarization by a 2D electron gas with Rashba spin-orbit interaction is theoretically investigated.

The Hamiltonian describing the quantum-mechanical motion of an electron in a two-dimensional system in a constant uniform perpendicular magnetic field (H || oz) taking into account the Rashba spin-orbit interaction and the Zeeman splitting has the form [4]:

$$H = \frac{P^2}{2m^*} + \frac{a}{\hbar}\left(\sigma_x P_y - \sigma_y P_x\right) + \frac{1}{2} g\mu_B B\sigma_z \quad (1)$$

P is the momentum operator, σ is the Pauli matrix, μ *is the* Bohr magneton, α is the Rashba spin-orbit interaction constant, g is the Lande factor, and ħ is the Planck constant. For the vector potential of the magnetic field, the Landau gauge A = (0, H • x, 0) was chosen.

In paper [4], it was analitically solved the problem of the quantum states of an electron described by the Hamiltonian (1). So, the electronic spectrum is a discrete levels mixed in pairs

$$E_n^{\pm} = \hbar\omega_c n \pm \frac{1}{2}\sqrt{\left(\hbar\omega_c + 2g\mu_B H\right)^2 + \frac{8\alpha^2}{l_H^2} n} \quad (2)$$

$$n = 1,2,3,\ldots.\quad E_0^{+} = \left(\hbar\omega_c / 2 + g\mu_B B\right)$$

where $\omega_c = \dfrac{eH}{m^{*}c}$ is the cyclotron frequency.

The wave functions in this case had the form

$$\Psi_n^{+}(x,y) = \frac{e^{ik_y y}}{\sqrt{2\pi A_n}}\begin{pmatrix} D_n\Phi_n\left(\dfrac{x+x_0}{l_H}\right) \\ \Phi_n\left(\dfrac{x+x_0}{l_H}\right)\end{pmatrix} \quad (3)$$

for the branch E_n^{+},

$$\Psi_n^{-}(x,y) = \frac{e^{ik_y y}}{\sqrt{2\pi A_n}}\begin{pmatrix} \Phi_{n-1}\left(\dfrac{x+x_0}{l_H}\right) \\ -D_n\Phi_n\left(\dfrac{x+x_0}{l_H}\right)\end{pmatrix} \quad (4)$$

for the branch E_n^{-}.

The full wave function

$$\Psi(x,y,z) = \Psi(x,y)\xi_0(z),$$

where

$$\xi_0(z) = \sqrt{\frac{2}{d}}\sin\left(\frac{l\pi z}{d}\right)$$

In expressions (3), (4) Φ(z) is the oscillation function, $l_H = \sqrt{\hbar c / eH}$ is the magnetic length, $x_0 = k_y l_0^2$, $D_n = \dfrac{\sqrt{2n}\alpha / l_H}{E_0 + \sqrt{E_0^2 + 2n\alpha^2 / l_H^2}}$, $A_n = 1 + D_n^2$

Calculation of coefficient of light absorption by free carriers in quasi-two dimensional systems was carried out in the second order of perturbation theory. The rate of transition from the state kn to the state k′n ′ is determined in this case by the following formula:

$$W_i = \frac{2\pi}{\hbar}\sum_{fq}\left[\left|\langle f|M_{+}|i\rangle\right|^2\delta\left(E_f - E_i - \hbar\Omega - \hbar\omega_q\right) + \left|\langle f|M_{-}|i\rangle\right|^2\delta\left(E_f - E_i - \hbar\Omega + \hbar\omega_q\right)\right] \quad (5)$$

where

$$\langle f|M_{\pm}|i\rangle = \sum_{\alpha} \left(\frac{\langle f|H_R|\alpha\rangle\langle\alpha|V_s|i\rangle}{E_i - E_\alpha \mp \hbar\omega_q} + \frac{\langle f|V_s|\alpha\rangle\langle\alpha|H_R|i\rangle}{E_i - E_\alpha - \hbar\Omega} \right)$$

here $\hbar\Omega, \hbar\omega_q$ are photon and phonon energy respectively.

We choose the direction of polarization of the photons along the x axis. Then the electron-photon interaction operator is written in the form:

$$H_{\text{int}} = -\frac{e}{m^* c}\left(P - \frac{eA}{c}\right)A_0 + \frac{ea}{c\hbar}\sigma_y A_0$$

or

$$H_{\text{int}} = -\frac{i|e|\hbar}{m^* c} A_0 \frac{\partial}{\partial x} - \frac{|e|}{c}\frac{\alpha}{\hbar} A_0 \sigma_y \quad (6)$$

where A_0 is the amplitude of the electromagnetic wave, with the volume concentration of photons. Using expression (6) for H_{int} and wave functions (3), (4), we find

$$\langle \Psi_n^+(x,y)|H_{\text{int}}|\Psi_{n+1}^-(x,y)\rangle = \frac{1}{\sqrt{A_n A_{n+1}}}\frac{e}{c}A_0\left[\langle\Phi_n|\frac{p_x}{m}|\Phi_{n+1}\rangle + D_n D_{n+1}\langle\Phi_{n-1}|\frac{p_x}{m}|\Phi_n\rangle - i\frac{\alpha}{\hbar}D_{n+1}\right] \quad (7)$$

Using the following relations

$$\langle\Phi_n|\frac{p_x}{m*}|\Phi_{n+1}\rangle = i\sqrt{(n+1)/2}\,l_H\omega_0 \text{ and } \langle\Phi_{n-1}|\frac{p_x}{m*}|\Phi_n\rangle = i\sqrt{n/2}\,l_H\omega_0$$

for expression (7) we get:

$$\langle \Psi_n^+(x,y)|H_{\text{int}}|\Psi_{n+1}^-(x,y)\rangle = \frac{-il_H\omega_0}{\sqrt{2A_n A_{n+1}}}\left[\sqrt{n+1} + D_{n+1}\left(D_n\sqrt{n} + \sqrt{2}\,\alpha m * l_H/\hbar^2\right)\right] \quad (8)$$

The matrix element of the electron – phonon interaction has the following form:

$$\left|\langle k_y' n' l'|V_s|k_y n l\rangle\right|^2 = C_j'^2 \delta_{k_y', k_y \pm q_y} F_{nn'}^{\pm}(q_x q_y)\Lambda_{ll'}(q_z)$$

V_s is the energy operator of interaction between electron and phonon, C_j is the function, characterizing the interaction between electrons and phonons:

$$F_{nn'}^{\pm}(q_n) = \left| < \Psi_{\nu}(x,y) \middle| e^{i(q_x x + q_y y)} \middle| \Psi_{\nu'}(x,y) \right|^2$$

$$F_{nn}^{+}(q_{II}) = B_n^{n'}(\xi)\left[\sqrt{\frac{n}{n'}} D_n D_{n'} L_{n'-1}^{n-n'}(\xi) + L_{n'}^{n-n'}(\xi)\right]$$

$$F_{nn}^{-}(q_{II}) = B_n^{n'}(\xi)\left[\sqrt{\frac{n}{n'}} L_{n'-1}^{n-n'}(\xi) + D_n D_{n'} L_{n'}^{n-n'}(\xi)\right]^2$$

where

$$B_n^{n'} = \left(n'!\big/ n!\right)\xi^{n-n'} e^{-\xi} \delta_{k'_y k_q + q_y} \quad \xi = q_{II}^2 l_H^2 / 2$$

$$\Lambda_{ll'}(q_z) = \left| \frac{2}{d}\int_0^d dz \exp(iq_z z)\sin\left(\frac{l'\pi z}{d}\right)\sin\left(\frac{l\pi z}{d}\right) \right|^2$$

$$\int_0^\infty \Lambda_{ll'}(q_z) dq_z = \frac{2\pi}{d}\left(1 + \frac{1}{2}\delta_{ll'}\right)$$

$$C_j'^2 = C_j^2 F_j(q)$$

For the interaction of an electron with polar optical phonons, we have:

$$C_{POL}^2 = 2\pi e^2 \hbar \omega_0 \left\{\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right\}, \quad F_{POL} = \frac{N_0^{\pm}}{q^2},$$

$$N_0 = \left[\exp\left(\frac{\hbar\omega_0}{K_B T}\right) - 1\right]^{-1}, \qquad N_0^- = N_0, \quad N_0^+ = N_0 + 1$$

For the interaction of an electron with nonpolar optical phonons

$$C_{np}^2 = \frac{\hbar D^2}{2\rho\omega_0\Omega_0}, \qquad F_{np}(q) = N_0^{\pm}$$

For the interaction of electrons with piezo-electric phonons:

$$C_{PE}^2 = \frac{e^2 K_B T \beta_p}{2\rho \upsilon_s^2 \Omega_0 \varepsilon^2}, \qquad F_{PE}(q) = \frac{1}{q^2}$$

here β_p is the piezoelectric constant, where ε_∞ and ε_0 are high-frequency and statistic dielectric permittivity of the material, $\omega_q = \omega_0$ is the frequency of a longitudinal optical phonon, dispersion of which is neglected.

In the case of interaction of electrons with acoustic phonons:

$$C_{DP}^2 = \frac{E_{ac}^2 K_B T}{2\rho \upsilon_s^2 \Omega_0}, \qquad F_{DP}(q) = 1$$

here E_{ac} is the deformation potential, υ_s is the semiconductor sound speed.

Calculations of spectra of light absorption by 2D electron gas carried out for GaAs/$In_{0.23}Ga_{0.77}As$ lattice structures. The effective electron mass in $In_{0.23}Ga_{0.77}As$ was chosen equal to $m* = 0.05m_0, g = -4.0,$ Rashba spin-orbit interaction constant $\alpha = 2.5 \cdot 10^{-11}$ $эВ \cdot м$

Conclusion. Thus, in this work the absorption of light from the so-called rashba plane, of two-dimensional electron gas taking into account spin-orbital interaction in the presence of strong magnetic field normal to the structure plane. It is believed that in the conduction band only the zeroth Landau level is filled., i.e. it is assumed that the factor $2\pi n l_H \leq 2$. Splitting is considered to be exactly weak, i.e. supposed that conditions $2m\alpha^2 / \omega << 1, |g| \mu_B H / \omega_C = |g| m / 2m_0 << 1$. As a result of rather cumbersome transformations of the general formula (5), we manage to highlight pour the contribution of the spin-orbit interaction effects in intraband light magnetoabsorption.

The resulting formula generalizes the expression burning for intraband magnet absorption of light obtained by us earlier for quasi-two-dimensional electron gas in the absence of Rashba plane and Zeeman splittiing [15].

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