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LIGHT ABSORPTION BY FREE CHARGE CARRIERS IN THE PRESENCE OF PHONONS IN AN ANISOTROPIC QUANTUM WIRE

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Abstract. The absorption of light by free charge carriers has been theoretically studied considering the processes related to scattering from phonons in an anisotropic parabolic quantum wire. The case in which the electromagnetic wave is polarized along the axis of the wire and the case of non-degenerate electron gas statistics have been considered. In this work, it was determined that the dependence of the location of the peaks of the intraband optical absorption coefficient on the characteristic frequency of the confinement potential in quantum wires with asymmetric parabolic potential was $N\omega_x + P\omega_y \pm \omega_0 = \Omega$.

Keywords: *low-dimensional systems, free charge carriers, quantum wire, intraband absorption, asymmetric parabolic potential.*

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1. Introduction

Recently, researchers are interested in the unusual electronic, optical and magnetic properties of low-dimensional systems (Ibragimov & Ibayeva, 2020; Babanli & Ibragimov, 2020; Ibragimov, 2003b; 2004; Cunha *et al*., 2020; Thongnak *et al*., 2021; Tshipa & Masale, 2021; Ngoc *et al*., 2022) these properties are important for device applications.

Semiconductor quantum wires occupy a special place among quantum nanostructures. Quantum wires have been widely used in lasers, photodetectors and field-effect transistors (Jahromi & Zarifkar, 2021). Application of quantum wires in devices can have a positive effect on the characteristics of lasers and transistors. One of the main methods of studying the spectral properties of the electron gas and the parameters of lateral confinement in various low-dimensional structures is the study of intraband electronic transitions under the influence of electromagnetic radiation (Ibragimov, 2004,2002; Carpunin & Margulis, 2016; Bhargavi *et al*., 2015; Kubakaddi & Mulimani, 1985). The study of intraband absorption of high-frequency electromagnetic radiation is mainly related to the fact that in the case of a discrete energy spectrum, the absorption curve has a resonance peak at certain points, and the radiation frequency at these points

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is equal to the distance between the energy levels of electrons (Ibragimov, 2004, 2002; Kubakaddi & Mulimani, 1985). In this case, the experimentally determined resonance frequency allows obtaining information about lateral confinement in nanostructures and the parameters of the electronic energy spectrum. In the study of spectral properties of nanostructures, the study of resonance absorption is superior to kinetic measurements because it is not required to connect with contact systems that can affect the physical properties of the system.

Modern technologies allow creating structures of confinement, especially with parabolic potential. Therefore, the confinement potential of lateral quantum wires can be better described with the help of a parabolic potential. The given potential is widely used in studying the physical properties of quantum wires and is suitable for many experiments. In addition, the electron-electron interaction, which greatly affects the absorption, has practically no effect on it in the case of parabolic potential, according to Kohn's theorem.

Intraband processes such as light absorption by free charge carriers and direct absorption of electromagnetic radiation are possible in quantum wires. These processes make it possible to study scattering mechanisms in quantum wires and determine energy loss in optical devices. Light absorption by free charge carriers is possible only with the absolute presence of any third particle (quasiparticle), which can be phonons, additives, dislocations. The participation of a third particle in this process does not satisfy the law of conservation of momentum. Light absorption by free charge carriers has been studied theoretically in quantum wires. These quantum wires describe the rectangular potential of confinement in cases of boundary roughness (Ibragimov, 2003a) and alloy disorder (Ibragimov, 2002) when charge carriers are scattered from acoustic and optical phonons (Kubakaddi & Mulimani, 1985; Adamska & Spector, 1984).

In this work, quantum wires describing the parabolic confinement potential are considered. It is known that at the same time the probability of interaction of three particles is less than the probability of interaction of two particles. Therefore, the absorption coefficient in indirect transitions is lower than in direct transitions. Consider the absorption of electromagnetic radiation by the electrons of the quantum wire and the scattering by phonons simultaneously. Such processes can be considered in the second order perturbation theory according to electron-photon and electron-phonon perturbation . In this study, quantum wires describing the parabolic potential of confinement are considered, and in this case, the electron-electron interaction, according to the generalized Kohn theorem, does not affect the optical properties of the system, as a rule.

2. Theoretical analysis

In the parabolic potential model of electron confinement, the asymmetric quantum wire would be as follows.

$$V(x,z)=\frac{m}{2}\left(\omega_x^2x^2+\omega_z^2z^2\right) \tag{1}$$

Here ω_x and ω_z are parabolic potential frequencies.

The Hamiltonian for particles in asymmetric quantum wires will be:

$$H=\frac{P_y^2}{2m^*}+\frac{m}{2}\left(\omega_x^2x^2+\omega_z^2z^2\right) \tag{2}$$

The $\Psi_{n,m,P_y}(r)$ eigenfunction of the electron and the $E_{n,m}(p_y)$ eigenvalues of the Hamiltonian (2) in the conduction band are calculated by the following formulas:

$$\Psi_{n,m,p_y}(r) = \frac{1}{\sqrt{2\pi\hbar}} \Psi_n(x)\Psi_m(z)\exp(ip_y y) \tag{3}$$

$$E_{n,m}(p_y) = (n+\frac{1}{2})\hbar\omega_x + (m+\frac{1}{2})\hbar\omega_z + \frac{p_y^2}{2m} \tag{4}$$

Here, n = 0, 1, 2, ... and m = 0, 1, 2, ... are the indices of the levels of electron subband, p_y is the momentum component of the electron in the y direction (the direction of the y axis corresponds to the axis of the wire), $\Psi_n(x)$ and $\Psi_m(z)$- are the eigenfunctions of a simple harmonic oscillator.

If the electromagnetic wave is polarized along the axis of the wire, then intra-band absorption of light can occur when a "third body" that changes the quasi-momentum of the charge carrier is involved in the absorption process. In the presence of phonons, the process of light absorption by free charge carriers is calculated by the expression (Adamska & Spector, 1984):

$$\alpha = \frac{\in^{1/2}}{n_0 c}\sum_i W_i f_i \tag{5}$$

Here n_0 is the number of photons in the radiation field, f_i is the distribution function of free charge carriers.

Summation is done over all the initial ‘‘i’’ states of the system. W_i is the transition probability from state mnP_y to state $m'n'P_y'$ and is defined by expression:

$$W_i = \frac{2\pi}{\hbar}\sum_{fq}\left[\left|\langle f|M_+|i\rangle\right|^2 \delta\left(E_f - E_i - \hbar\omega - \hbar\omega_q\right) + \left|\langle f|M_-|i\rangle\right|^2 \delta\left(E_f - E_i - \hbar\omega + \hbar\omega_q\right)\right] \tag{6}$$

where E_i and E_f indicate the energy of electrons in the initial and final states, respectively, $\hbar\omega_q$ is the phonon energy, and $\langle f|M_+|i\rangle$ are matrix elements of the transition from the initial state to the final state for the interaction between electrons, phonons, and photons.

Matrix elements of transitions can be written as in formula:

$$\langle f|M_\pm|i\rangle = \sum_\alpha \left(\frac{\langle f|H_R|\alpha\rangle\langle\alpha|V_s|i\rangle}{E_i - E_\alpha \mp \hbar\omega_q} + \frac{\langle f|V_s|\alpha\rangle\langle\alpha|H_R|i\rangle}{E_i - E_\alpha - \hbar\omega} \right) \tag{7}$$

where the i,α,f indices indicate the initial, intermediate and final states of the electron. V_S is the electron-phonon interaction operator.

Summation is performed on all intermediate states of the α system. The summation over α in (7) represents the sum over the m,n quantum numbers and the integral over the P_y momentum . The first summation describes processes in which first scattering from phonons and then absorption of a photon occurs: and the second summation represents the processes of first absorption of a photon and then scattering from phonons.

The electron-photon interaction Hamiltonian is expressed as follows.

$$H_R = -\frac{ieh}{m^*}\sqrt{\frac{2\pi\hbar N_1}{\in(\omega)\omega}}\frac{\partial}{\partial y} \tag{8}$$

Using the wave function given by the expression (3), the matrix element of the electron-photon interaction can be written as follows:

$$\langle n'l'K'|H_R|nlK\rangle = -\frac{e}{m^*}\left(\frac{2\pi\hbar n_0}{V\Omega\in}\right)^{1/2}(\varepsilon P_y)\delta_{P_yP_y}\delta_{mm'}\delta_{nn'}\ , \tag{9}$$

Here V is the volume of the crystal. The radiation field is polarized along the y-direction, ε - is the polarization vector of the radiation field.

The $f_0\left(E_{nmP_y}\right)$ distribution function obeys the following normalization condition.

$$\frac{L_Y}{2\pi\hbar}\sum_{m=-\infty}^{\infty}\sum_{n=0}^{\infty}\int_{-\infty}^{\infty} f_0\left(E_{mnP_y}\right)dP_y = N \tag{10}$$

Here N is the number of electrons in a unit volume, L_y - is the length of the wire along the y axis.

Thus, taking into account the expression (10), the distribution function of electrons for the non-degenerate electron gas can be written as follows:

$$f_0\left(E_{nmP_y}\right) = \frac{8\pi\hbar N\sinh\left(\frac{h\omega_x}{2k_BT}\right)\sinh\left(\frac{\hbar\omega_z}{2k_BT}\right)}{\sqrt{2\pi m*kTL}}\exp\left(-\frac{E_{nmP_y}}{k_BT}\right) \tag{11}$$

3. Results and discussions

The matrix elements of the electron-phonon interaction can be expressed as follows:

$$\left\langle n''m''P_y''\left|V_s\right|nmP_y\right\rangle = D_q\sqrt{N_q+\frac{1}{2}\pm\frac{1}{2}}\left\langle n''m''P_y''\left|e^{\pm iqr}\right|nmP_y\right\rangle \tag{12}$$

The electron-phonon coupling constant for deformation (DO-phonons) and polarization scattering (PO-phonons) can be calculated as:

$$\left|D_q\right|^2 = \frac{2\pi\hbar^2\alpha_l\omega_0}{m*}\begin{cases}\sqrt{2m^*\hbar\omega_0}\,/\,q^2 - PO\\ 4\hbar^2/\sqrt{2m^*\hbar\omega_0} - DO\end{cases} \tag{13}$$

Here α_L is the dimensionless coupling constant.

Using the shift operator $\exp\left(\pm aP_x x/\hbar\right)\Phi(x) = \Phi(x\pm a)$ and

$$\int\exp\left(-c^2x^2\right)H_m(a+cx)H_n(b+cx)dx = \frac{2^n\sqrt{\pi m!b^{n-m}}}{c}L_m^{n-m}(-2ab), \qquad |\arg c| < \frac{\pi}{4}; m\le n \tag{14}$$

$$L_n^{m-n}(z) = \frac{m!}{n!}(-z)^{n-m}L_m^{n-m}(z) \tag{15}$$

expressions (Prudnikov *et al.*, 1981), the matrix elements of the electron-phonon interaction can be calculated.

(12) electron-phonon matrix elements, (9) electron-phonon matrix elements and (11) the distribution function of the non-degenerated electron gas should be taken into account in (5) – (7) expressions to calculate the α absorption coefficient.

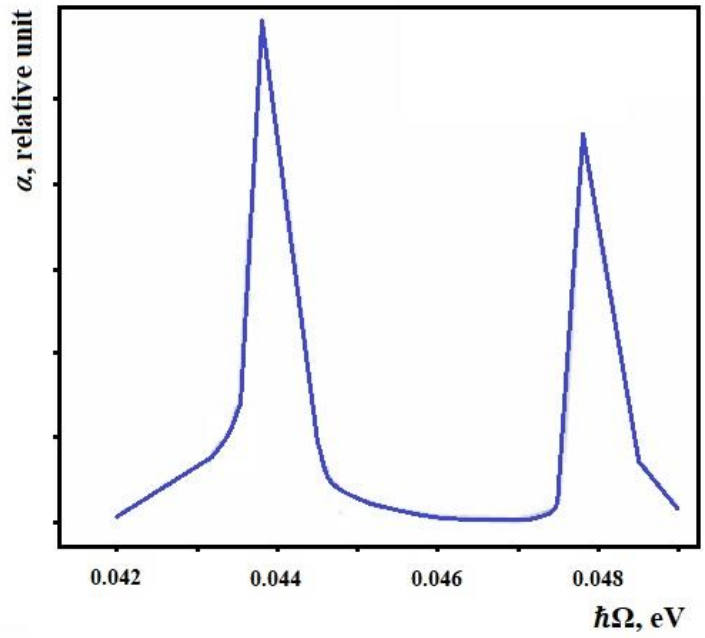

Fig. 1. Dependence of the absorption coefficient on the energy of the incidence photon for polar optical phonons in the cases of $h\omega_x = 0.004$ eV and $h\omega_z = 0.006$eV

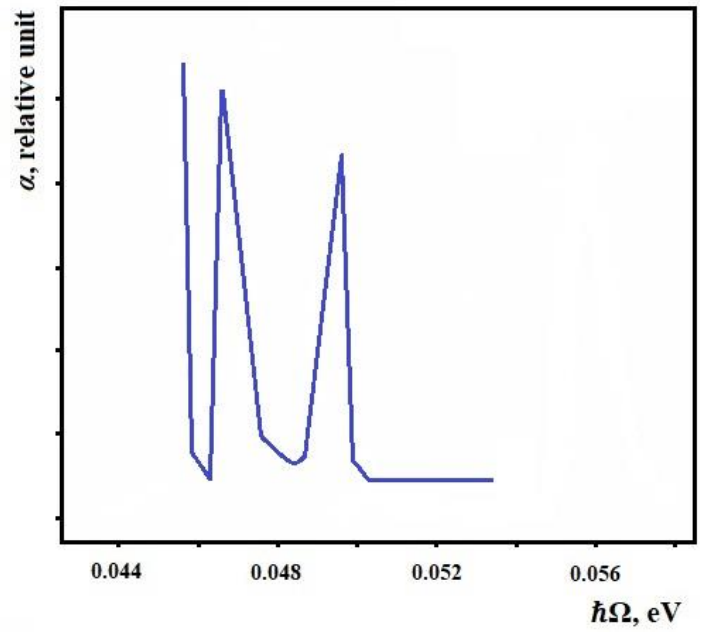

Fig. 2. Dependence of the absorption coefficient on the energy of the incidence photon for polar optical phonons in the cases of $h\omega_x = 0.004$ eV and $h\omega_z = 0.006$eV

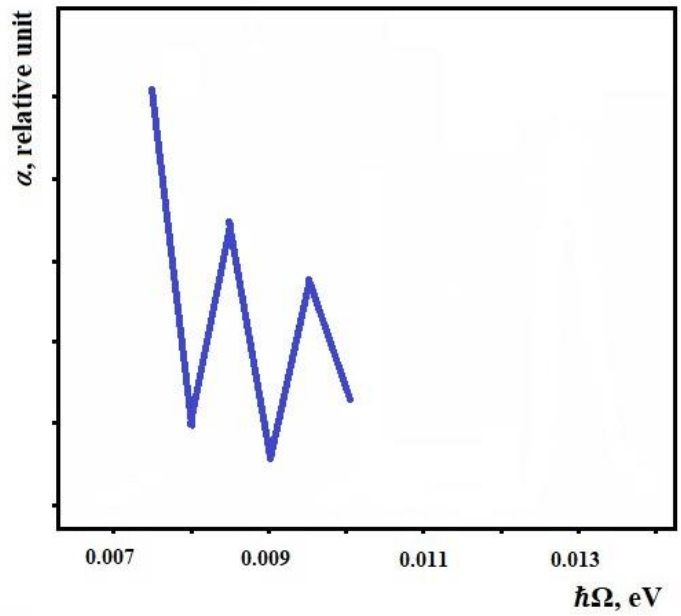

Fig. 3. Dependence of the absorption coefficient on the energy of the incidence photon for acoustic phonons in the cases of $h\omega_x = 0.004$ eV and $h\omega_z = 0.006$eV

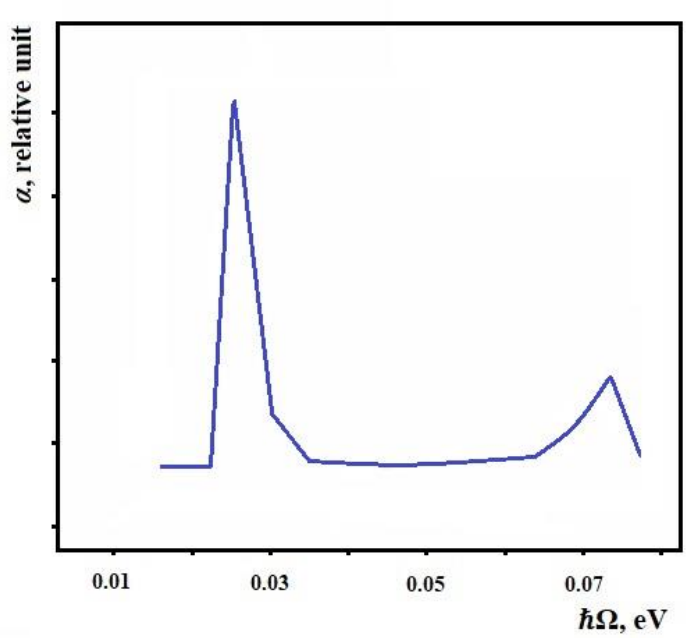

Fig. 4. Dependence of the absorption coefficient on the energy of the incidence photon for acoustic phonons in the cases of $h\omega_x = 0.004$ eV and $h\omega_z = 0.006$eV

5. Conclusion

The absorption of light in quantum wires, which are considered an anisotropic medium, has been studied. The research was carried out theoretically. Consequently, in this work, it was determined that the dependence of the location of the peaks of the intraband optical absorption coefficient on the characteristic frequency of the limiting

potential in quantum wires with asymmetric parabolic potential was $N\omega_x + P\omega_y \pm \omega_0 = \Omega$.

References

Adamska, H., Spector, H.N. (1984). Free carrier absorption in quantum well structures for polar optical phonon scattering. *Journal of Applied Physics*, 56, 1123-1127.

Babanli, A.M., Ibragimov, B.G. (2020). Aharonov-bohm paramagnetism" and compensation points in non-interacting diluted magnetic semiconductor quantum ring. *Journal of Magnetism and Magnetic Materials*, 495, 165882.

Bhargavi, K.S., Patil, S. & Kubakaddi, S.S. (2015). Acoustic phonon assisted free-carrier optical absorption in an n-type monolayer MoS_2 and other transition-metal dichalcogenides. *Journal of Applied Physics*, 118, 044308

Carpunin, V.V. & Marqulis, V.A. (2016). Absorption of electromagnetic radiation in a quantum wire with an anisotropic parabolic potential in a transverse magnetic fiel. *Physics and Technology of Semiconductors, 50*(6), 785-791.

Cunha, S.M., da Costa, D.R., Felix, L.C., Chaves, A. & Milton Pereira, J. (2020). Electronic and transport properties of anisotropic semiconductor quantum wires. *Physical Review B*, 102, 045427.

Ibragimov, G.B. (2002). Alloy scattering in quantum well wire structures of semiconductor ternaries. *Semiconductor Physics Quantum Electronics & Optoelectronics, 5*(4), 347-352.

Ibragimov, G.B. (2003a). Free-carrier absorption in quantum wires for boundary roughness scattering. *Journal of Physics: Condensed Matter*, 15, 1427-1435.

Ibragimov, G.B. (2003b). Alloy-disorder-scattering-limited mobility of electrons in cylindrical quantum well wires. *Physica Status Solidi (B)*, 236, 112-118.

Ibragimov, G.B. (2004). Optical intersubband transitions in quantum wires with an applied magnetic field. *Semiconductor Physics, Quantum Electronics & Optoelectronics*, 7, 283-286.

Ibragimov, G.B., Ibayeva, R.Z. (2020). Theory of intraband absorption of electromagnetic radiation in cylindrical quantum wires. *Journal of Non-Oxide Glasses, 12*(4), 31-34.

Jahromi, H.D., Zarifkar, A. (2021). A physical model for quantum wire infrared photodetectors under illumination condition. *Optics Communications*, 493, 127043.

Kubakaddi, S.S., Mulimani, B.G. (1985). Free-carrier absorption in semiconducting quantum well wires. *Journal of Physics C: Solid State Physics*, 18, 6647.

Ngoc, H.V., Bau, N.Q., Quang, D.M. & Hung, T.H. (2020). One-dimensional cylindrical quantum wire: The theoretical study of photo-stimulated Ettingshausen effect. *International Journal of Modern Physics B*, 36, 2250009.

Prudnikov, A., Brichkov, Y. & Marichev, O. (1981). *Integrals and series. Elementary functions*. Moscow: Science, 800.

Thongnak, V., Joonhuay, J. & Amthong, A. (2021). Polarization-selective absorption in an off-centered core-shell square quantum wire**.** *Optics Letters*, 46, 3259-3262.

Tshipa, M., Masale, M. (2021). Optical transition rates in a cylindrical quantum wire with a parabolic and inverse parabolic electric confining potential in a magnetic field. *Optical and Quantum Electronics*, 53, 622.