NANOSYSTEMS: PHYSICS, CHEMISTRY, MATHEMATICS, 2014, 5 (3), P. 378–383

THE ABSORPTION OF ELECTROMAGNETIC RADIATION IN A QUANTUM WIRE

V. V. Karpunin[1,2], V. A. Margulis[2]

[1] Mordovian State Pedagogical Institute, Saransk, Russia

[2] Mordovian State University, Saransk, Russia

karpuninvv@mail.ru, theorphysics@mrsu.ru

PACS 63.20.Kr,78.67.-n

The analytical expression for the absorption coefficient of the electromagnetic radiation by electrons a quantum wire is obtained. We used the first-order perturbation theory. The cases of linear and circular polarization of the electromagnetic wave are investigated. The resonance character of the absorption is shown and resonant frequencies are found.

Keywords: quantum wire, electron-photon interaction, absorption coefficient.

Received: 15 April 2014

1. Introduction

Optical and electronic properties of low-dimensional semiconductor structures are important part of the modern physics of semiconductors. In the last decade, scientists have investigated a number of similar systems. The splitting lines for the cyclotron resonance (CR) in the heterostructure of InAs/GaSb placed in a tilted magnetic field were theoretically and experimentally studied Ref. [1]. This splitting was shown to be stipulated by the mixing of electron and hole states, and the suppression of the splitting in a tilted magnetic field was also shown.

The splitting lines of the cyclotron resonance in weak magnetic fields in heterostructures of InSb/AlInSb with quantum wells is considered Ref. [2]. To explain this effect, the Rashba model the spin-orbital interaction was used. It was shown that this effect was not associated with nonparabolicity of conduction zone InSb.

In Ref. [3], the cyclotron resonance holes in InGaAs/GaAs heterostructures quantum wells in a quantizing magnetic fields were experimentally investigated.

The intraband absorption of light in parabolic quantum wells, located in the electric and the magnetic fields was theoretically studied [4]. The expression of the absorption coefficient (AC) for direct optical transitions, as well as for indirect transitions, when electron scattering occurs at an impurity center was obtained. The limiting cases were considered: the absence of a magnetic and an electric field. It was shown that in strong magnetic fields, the electron-impurity interaction increases.

Theoretical investigation of the absorption coefficient of light by an impurity with the use of the multiphonon model of optical processes was considered [5]. The expression of the AC was obtained with the used wave functions in the zero radius potential model. The dependence of the AC on frequency have the peaks of the Gaussian type.

The coefficient of the interband magneto-absorption in a constant electric field and a resonant laser radiation was calculated Ref. [6]. The paper considered the influence of the longitudinal electric field on the interband absorption coefficient (size-infrared resonance).

The oscillatory dependence of the AC on the frequency in the high-frequency region was marked.

Cyclotron resonance of electrons in narrow gap heterostructures HgTe/CdTe(013) in quantizing magnetic fields was theoretically and experimentally studied [7]. The experimental values of the cyclotron transitions energies were found to exceed the calculated values.

The absorption coefficient of electromagnetic radiation by a two dimentional electron gas is calculated [8]. The calculation was conducted taking into account the scattering of electrons by optical phonons. Consider the case of a tilted magnetic field. It was shown that the resonance curve had a doublet structure. The dependence of the absorption coefficient on the angle of tilted magnetic field to the plane of confinement was investigated.

Optical properties of three-dimensional quantum wires and the quantum cylinder were studied theoretically in Ref. [9]. Analytical expressions of the absorption coefficients were obtained and the form of the resonance curve was found. Cases of nondegenerate and degenerate electron gases were considered. It was shown that in the case of a degenerate electron gas, the curve of absorption had fractures.

The hybrid – phonon resonance in the three-dimensional anisotropic parabolic quantum well was investigated in [10]. Investigation of the resonance peak forms revealed their doublet structure.

The hybrid-photon resonances in a three-dimensional quantum wire was investigated [11]. Parabolic potential confinement and the model of a hard wall potential were used. The resulting formula for the absorption coefficient was obtain.

The absorption of electromagnetic radiation by electron gas, taking into account processes related to the combination scattering by ionized impurities was also studied in various nanostructures. This phenomenon in the three-dimensional anisotropic quantum wire was considered [12]. The expression of the absorption coefficient was obtained, the dependence of AC upon the radiation frequency and magnetic fields was studied.

Hybrid-impurity resonances in anisotropic quantum dots were studied [13]. The expression of the absorption coefficient was obtained, the dependence of the AC upon the magnetic field was also investigated. A decrease of absorption intensity at the increase of the electron quantum number was considered.

The theory of the one-phonon intraband resonance scattering of electromagnetic radiation in anisotropic quantum dots placed in a perpendicular magnetic field was developed [14]. The expression of the differential scattering cross sections was obtained. In the case of DO phonons, a doublet structure was found in the dependence of the differential cross section of scattering upon the magnetic field.

The purpose of this work is to obtain and study analytical expressions for the absorption coefficient of electromagnetic radiation of a quantum wire. We consider both cases the linear polarization of electromagnetic waves and the circular polarization. We analyze the dependence of AC upon the frequency of the electromagnetic radiation.

2. Absorption coefficient (case of linear polarization)

The Hamiltonian of an electron in the anisotropic parabolic wire has the form:

$$\hat{H} = \frac{p_z^2}{2m^*} + \frac{m^*}{2}(\omega_1^2 x^2 + \omega_2^2 y^2), \tag{1}$$

where m^* is the electron effective mass, ω_1 and ω_2 is frequencies of the parabolic confinement potential, p_z is momentum along the z-axis.

The corresponding wave function has the form:

$$\psi = \frac{1}{\sqrt{L_z}} \exp(ip_z z/\hbar) \varphi_{n_1}\left(\frac{x}{l_1}\right) \varphi_{n_2}\left(\frac{y}{l_2}\right), \tag{2}$$

where l_1, l_2 is characteristic length, φ_n is oscillator function.

It is the Hamiltonian of two disconnected oscillators. This spectrum has the form:

$$E_{n_1,n_2,p_z} = \hbar\omega_1\left(n_1 + \frac{1}{2}\right) + \hbar\omega_2\left(n_2 + \frac{1}{2}\right) + \frac{p_z^2}{2m^*}. \tag{3}$$

If we choose the polarization vector along the Oy axis, then the operator of the electron-photon interaction has the form:

$$H_R = -\frac{ie\hbar}{m^*}\sqrt{\frac{2\pi\hbar N_f}{\epsilon\omega}}\frac{\partial}{\partial y}, \tag{4}$$

where N_f is the number of photons.

Matrix elements H_R has the form:

$$\langle n_1, n_2, p_z | H_R | n_1', n_2', p_z' \rangle = -\frac{ie\hbar}{ml_2}\sqrt{\frac{2\pi\hbar N_f}{\epsilon\omega}}\delta_{p_z,p_z'}\delta_{n_1,n_1'} \times \tag{5}$$

$$\left(\sqrt{\frac{n_2+1}{2}}\delta_{n_2,n_2'-1} - \sqrt{\frac{n_2}{2}}\delta_{n_2,n_2'+1}\right).$$

where $\delta_{m,m'}$ is Kronecker delta symbol.

The absorption coefficient Γ, was calculated in first order of the perturbation theory by analogy with [9]. We consider only the case of the nondegenerate electron gas. Thus, the absorption coefficient can be expressed as:

$$\Gamma = \frac{2\pi\sqrt{\epsilon}}{c\hbar N_f}\sum_{n_1 n_2 p_z}\sum_{n_1' n_2' p_z'} f_0(E_{n_1,n_2,p_z}) \times \tag{6}$$

$$|\langle n_1, n_2, p_z | H_R | n_1', n_2', p_z' \rangle|^2 \delta(E_{n_1,n_2,p_z} - E_{n_1',n_2',p_z'} + \hbar\omega),$$

where $f_0(E_{n_1,n_2,p_z})$ is the electron distribution function, $\delta(E_{n_1,n_2,p_z} - E_{n_1',n_2',p_z'} + \hbar\omega)$ is Dirac delta function.

After calculating the sums entering (6), we obtain the expression:

$$\frac{\Gamma}{\Gamma_0} = \frac{\omega_2}{\omega}\left[\frac{1}{1+(\omega-\omega_2)^2}\left(\frac{\exp(\hbar\omega_2/2T)}{(\exp(\hbar\omega_2/T)-1)^2} + \frac{\exp(\hbar\omega_2/2T)}{\exp(\hbar\omega_2/T)-1}\right) - \tag{7}$$

$$\left.\frac{1}{1+(\omega+\omega_2)^2}\frac{\exp(\hbar\omega_2/2T)}{(\exp(\hbar\omega_2/T)-1)^2}\right],$$

where

$$\Gamma_0 = \frac{4e^2 n_e \tau\pi}{c\sqrt{\epsilon}m^*}\sinh(\hbar\omega_2/2T),$$

here n_e is the concentration of electrons, τ is relaxation time, T is temperature.

The expression (7) was obtained with taking into consideration Lorentz broadening delta peaks [9]:

$$\delta(x) = \frac{(\pi\tau)^{-1}}{\tau^{-2} + x^2}. \tag{8}$$

3. Absorption coefficient (case of circular polarization)

Next, we consider the case of circular polarization of an electromagnetic wave. Expression for electron–photon interaction of this case is taken to be:

$$H_R = -\frac{e\hbar}{m^*}\sqrt{\frac{2\pi\hbar N_f}{\epsilon\omega}}\left(i\frac{\partial}{\partial x}+\frac{\partial}{\partial y}\right). \tag{9}$$

The matrix element of the electron-photon interaction is found to be:

$$\langle n_1, n_2, p_z|H_R|n_1', n_2', p_z'\rangle = -\frac{ie\hbar}{m^* l_1}\sqrt{\frac{2\pi\hbar N_f}{\epsilon\omega}}\delta_{p_z,p_z'}\delta_{n_2,n_2'}\times \tag{10}$$

$$\left(\sqrt{\frac{n_1+1}{2}}\delta_{n_1,n_1'-1}-\sqrt{\frac{n_1}{2}}\delta_{n_1,n_1'+1}\right)-$$

$$\frac{e\hbar}{m^* l_2}\sqrt{\frac{2\pi\hbar N_f}{\epsilon\omega}}\delta_{p_z,p_z'}\delta_{n_1,n_1'}\left(\sqrt{\frac{n_2+1}{2}}\delta_{n_2,n_2'-1}-\sqrt{\frac{n_2}{2}}\delta_{n_2,n_2'+1}\right).$$

Expression of AC with matrix element (10) has the form:

$$\Gamma = \frac{2\pi\sqrt{\epsilon}}{c\hbar N_f}\frac{2\pi\hbar N_f}{\epsilon\omega}\sum_{n_1 n_2 p_z}\sum_{n_1' n_2' p_z'} f_0(E_{n_1,n_2,p_z})\times \tag{11}$$

$$\left[\left(\frac{e\hbar}{m^* l_1}\right)^2\delta_{p_z,p_z'}\delta_{n_2,n_2'}\left(\frac{n_1+1}{2}\delta_{n_1,n_1'-1}-\frac{n_1}{2}\delta_{n_1,n_1'+1}\right)+\right.$$

$$\left.\left(\frac{e\hbar}{m^* l_2}\right)^2\delta_{p_z,p_z'}\delta_{n_1,n_1'}\left(\frac{n_2+1}{2}\delta_{n_2,n_1'-1}-\frac{n_2}{2}\delta_{n_2,n_2'+1}\right)\right]\times$$

$$\delta(E_{n_1,n_2,p_z}-E_{n_1',n_2',p_z'}+\hbar\omega).$$

As in the previous case, in calculating the AC (6), we use (8). We consider only the case of a nondegenerate electron gas. After calculating all sums in (11), we get the final expression:

$$\frac{\Gamma}{\Gamma_0} = \sinh(\hbar\omega_1/2T)\frac{\omega_1}{\omega}\left[\frac{1}{1+(\omega-\omega_1)^2}\left(\frac{\exp(\hbar\omega_1/2T)}{(\exp(\hbar\omega_1/T)-1)^2}+\frac{\exp(\hbar\omega_1/2T)}{\exp(\hbar\omega_1/T)-1}\right)-\right. \tag{12}$$

$$\left.\frac{1}{1+(\omega+\omega_1)^2}\frac{\exp(\hbar\omega_1/2T)}{(\exp(\hbar\omega_1/T)-1)^2}\right]+$$

$$\sinh(\hbar\omega_2/2T)\frac{\omega_2}{\omega}\left[\frac{1}{1+(\omega-\omega_2)^2}\left(\frac{\exp(\hbar\omega_2/2T)}{(\exp(\hbar\omega_2/T)-1)^2}+\frac{\exp(\hbar\omega_2/2T)}{\exp(\hbar\omega_2/T)-1}\right)-\right.$$

$$\left.\frac{1}{1+(\omega+\omega_2)^2}\frac{\exp(\hbar\omega_2/2T)}{(\exp(\hbar\omega_2/T)-1)^2}\right],$$

where

$$\Gamma_0 = \frac{4e^2 n_e\tau\pi}{c\sqrt{\epsilon}m^*}.$$

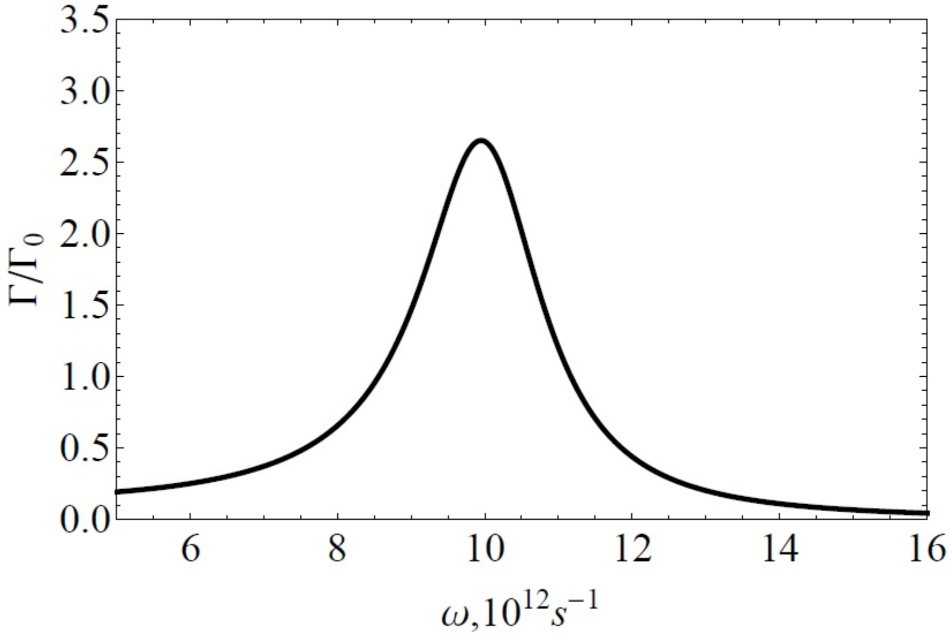

FIG. 1. The dependence of the absorption coefficient of electromagnetic radiation upon the radiation frequency. $\omega_1 = 10 \cdot 10^{12} c^{-1}, \tau = 10^{-12} c, T = 100K$ (linear polarization)

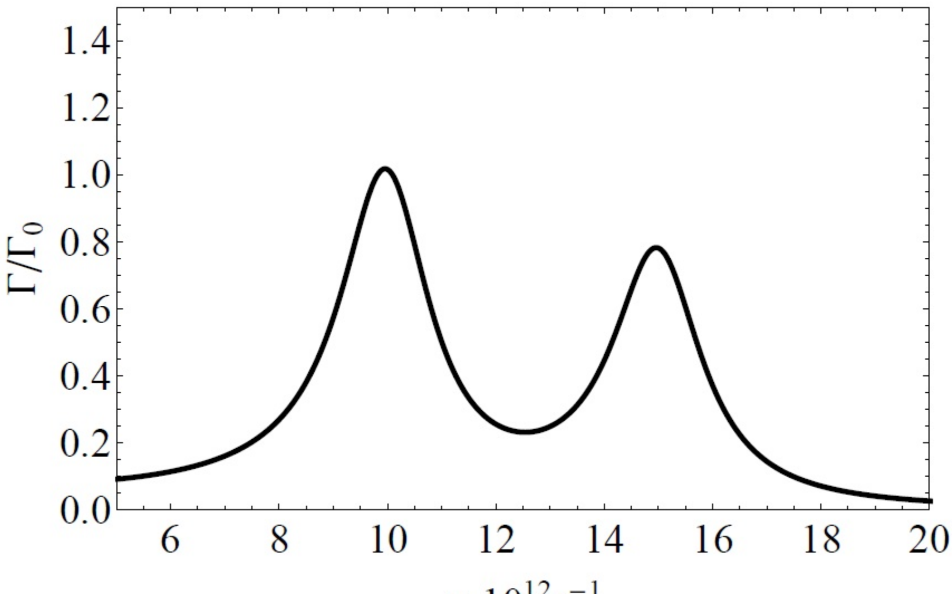

FIG. 2. The dependence of the absorption coefficient of electromagnetic radiation upon the radiation frequency. $\omega_1 = 10 \cdot 10^{12} c^{-1}, \omega_2 = 15 \cdot 10^{12} c^{-1}, \tau = 10^{-12} c, T = 100K$(circular polarization)

4. Conclusion

An analytic expression for the AC of electromagnetic radiation in a quantum wire was obtained. The cases of linear and circular polarization of an electromagnetic wave are investigated.

In the case of linear polarization, there can be only one resonance peak at the frequency $\omega = \omega_1$ (Fig.1). Another resonance frequency, $\omega = \omega_2$, appears in case when the polarization vector is directed along the ox axis.

Under conditions of circular polarization of the electromagnetic wave, a doublet structure is obtained for the resonance peaks (Fig.2). In the case of equal of frequencies, i.e. $\omega_1 = \omega_2$, there is only one resonance peak.

Acknowledgements

The work was financially supported by Russian Ministry of Education and Science by the project 2.2.1.2. Research and development of educational laboratory "Basics of nanotechnology and scanning probe microscopy".

References

[1] Greshnov A. A., Zegrya G. G., Vasil'ev Yu. B., Suchalkin S. D., Mel'tser B. Ya., Ivanov S. V., Kop'ev P.S. Cyclotron resonance in the InAs/GaSb heterostructure in an inclined magnetic field. *JETP Letters*, **76**, P. 222–226 (2002).

[2] Vasilyev Yu. B., Gouider F., Nachtwei G., Buckle P. D. The cyclotron resonance in heterostructures with the InSb/AlInSb quantum wells. *Semiconductors*, **44**, P. 1511–1514 (2010).

[3] Ikonnikov A. V., Spirin K. E., Gavrilenko V. I., Kozlov D. V., Drachenko O., Schneider H., Helm M. The cyclotron resonance of holes in InGaAs/GaAs heterostructures with quantum wells in quantizing magnetic fields. *Semiconductors*, **44**, P. 1492–1494 (2010).

[4] Sinyavskii E. P., Sokovnich S. M. Intraband light absorption in quasi-two-dimensional systems in external electric and magnetic fields. *Semiconductors*, **33**, P. 761–764 (1999).

[5] Sinyavskii E. P., Sokovnich S. M. Impurity absorption of light in confined systems subjected to a longitudinal magnetic field. *Semiconductors*, **34**, P. 815–816 (2000).

[6] Sinyavskii E. P., Karapetyan S. A. Influence of an electric field on the magnetoabsorption in a field of resonant laser radiation. *Physics of the Solid State*, **48**, P. 962–965 (2006).

[7] Ikonnikov A. V., Zholudev M. S., Marem'yanin K. V., Spirin K. E., Lastovkin A. A., Gavrilenko V. I., Dvoretskii S. A., Mikhailov N. N. Cyclotron resonance in HgTe/CdTe(013) narrowband heterostructures in quantized magnetic fields. *JETP Letters*, **95**, P. 406–410 (2012).

[8] Margulis V. A. A hybrid-phonon resonance in a quasi-two-dimensional nanostructure. *JETP*, **84**, P. 603–611 (1997).

[9] Galkin N. G., Margulis V. A., Shorokhov A. V. Intraband absorption of electromagnetic radiation by quantum nanostructures with parabolic confinement potential. *Physics of the Solid State*, **43**, P. 530–538 (2001).

[10] Margulis V. A., Shorokhov A.V. Hybrid-phonon resonances in a three dimentional anisotropic quantum well. *Phys.Rev. B*, **66**, P. 165324(1)-165324(6) (2002).

[11] Margulis V.A., Shorokhov A.V. Hybrid-phonon resonances in a three dimentional quantum wire. *Phys.stat.sol (c)*, **1**, P. 2642–2645 (2004).

[12] Margulis V. A., Pavlova N.F., Shorokhov A. V. Hybrid impurity resonance in a three-dimensional anisotropic quantum wire. *Physics of the Solid State*, **48**, P. 935–939 (2006).

[13] Margulis V.A., Shorokhov A.V. Hybrid-impurity resonances in anisotropic quantum dots. *Physica E*, **41**, P. 483–486 (2009).

[14] Shorokhov A.V., Margulis V.A. Intraband resonance scattering of electromagnetic radiation in anisotropic quantum dots. *Nanosystems: physics, chemistry, mathematics*, **1**, P. 178–187 (2010).