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ELECTRO- AND MAGNETO-OPTICAL ABSORPTION IN QUANTUM WIRE

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Interband absorption coefficient is calculated in a parabolic semiconductor quantum wire in crossed electric and magnetic fields. The interband transition selection rules have been obtained. In presence of crossed electric and magnetic fields, the optical absorption threshold is shifted to lower energies. It turns out that the magnetic and electric fields produce notable changes in the optical properties of quantum wire. Numerical results are presented using parameters characteristic of GaAs/AlGaAs.

INTRODUCTION

Low-dimensional semiconductor systems, particularly quantum wires are attracting considerable attention recently, in part, because they exhibit novel physical properties and also because of potential applications involving them. In resent years, a number of innovative techniques have been developed to grow or to fabricate and to study experimentally a variety of quantum wire structures having different geometries and potentials. The optical properties of these systems are especially useful in giving detailed information about their microscopic physics.

The application of a magnetic field to a crystal changes the dimensionality of electronic levels and leads to a redistribution of the density of sates. Quantum wires in a magnetic field have been the subject of a few investigations [1-3]. Many recent experimental studies have been performed on quantum wires subjected to a transverse magnetic field [4-10]. This is partly because the measurements of magneto-optical and magnetotransport properties are the most powerful tools for determining the electronic structure and effective quantum confinement of the wires [4,5], and partly because many intrinsically interesting physical phenomena, such as the negative and positive magnetoresistance [6], the Aharonov-Bohm effect [9,10] and the quantum Hall effect [11], are related to the Landau level states in wires.

On the theoretical side the electronic properties of quantum wires in a transverse magnetic field have also been extensively investigated in the last years. The magnetoelectric subbands have been studied with various laterial confinement models, such as the parabolic potential model, the square well model .

Interband optical absorption [12] in rectangular quantum wires in a transverse magnetic field has been studied.

Electric field applied perpendicularly to the layer of quantum wells can change significantly the optical properties (absorption, reflection, and photoluminescence PL) of semiconductor quantum-well structures. This effect is reffered to as the quantum-confined Stark effect. Theoretically, the quantum wires can offer the advantage of lover switching energy and enhanced oscillator strength over the quantum well. Therefore, the quantum wires are promised for low-energy optoelectronics devices. Recently, the electro-optical properties have been investigated in V-shaped GaAs/AlGaAs quantum wires by PL experiments; blueshifts of PL peak under electric field was observed [13].

In this paper we mainly investigate the interband optical response of a parabolic quantum wire in the presence of transverse magnetic and electric fields. In this case, there are some significant modifications of the electronic structures due to the competing effects of the parabolic quantum confinement and the forces due to the magnetic and electric fields. Consequently, the optical response of the parabolic quantum wire is changed. In Section 2, the conduction- and valence-band electronic states in transverse electric and magnetic fields are shown. The expressions of the interband optical-absorption coefficient are presented in Section 3. In Section 4 detailed numerical calculations for different magnetic and electric fields are performed.

2. PARABOLIC QUANTUM WIRE STATES IN THE PRESENCE OF TRANSVERSE ELECTRIC AND MAGNETIC FIELD

We consider a quantum wire aligned along the y direction with a transverse magnetic field $\vec{H}=(0,0,H)$ applied along the z direction, and a homogeneous static electric field $\vec{F}=(F,0,0)$ applied in (x,z)-plane. We choose the vector potential $\vec{A}=(0,Hx,0)$ in the Landau gauge and confinement potential in parabolic form

$$V(x,z)=\frac{m^{*}\omega_0^2}{2}\left(x^2+z^2\right) \tag{1}$$

in the plane (x,z).

The envelope state of parabolic quantum wire with an applied transverse electric and magnetic fields obeys the Schrödinger equation

$$\left(\frac{1}{2m^{*}}\left(\vec{p}+\frac{e}{c}\vec{A}\right)^2+\frac{1}{2}m^{*}\omega_0^2\left(x^2+z^2\right)+eFx\right)\psi(x,y,z)=E\psi(x,y,z) \tag{2}$$

Here e is the absolute value of the electron electric charge. The electron effective mass $m^{*}=m_e$ when the conduction band is considered; and $m^{*}=m_v=-m_h$ when the valence band is considered, where m_h is the effective mass of the hole. The oscillator frequency $\omega_0=\omega_{0e}$ for the conduction band and $\omega_0=\omega_{0h}$ for the valence band. We look for the solution in the form

$$\psi(x,y,z)=\varphi(x)\eta(z)e^{\frac{i}{\hbar}p_y y}, \tag{3}$$

where p_y is the quasi-momentum of an electron.

After trivial shifting of the origin of coordinates and separating the variables in the usual way we obtain the eigenfunctions and eigenvalues of the Schrödinger equation (2) for conduction band:

$$\psi_{N_{1e},N_{2e},k_{y,e}}=\varphi_{N_{1e}}\left(\frac{x-x_{0e}}{\tilde{L}_e}\right)\eta_{N_{2e}}\left(\frac{z}{L_e}\right)e^{ik_{y,e}y}, \tag{4}$$

$$E_{N_{1e},N_{2e},k_{ye}}=\left(N_{1e}+\frac{1}{2}\right)\hbar\tilde{\omega}_e+\left(N_{2e}+\frac{1}{2}\right)\hbar\omega_{0e}+\frac{\hbar^2\omega_{0e}^2}{2m_e\tilde{\omega}_e^2}\left(k_{ye}-\frac{eF\omega_e}{\hbar\omega_{0e}^2}\right)^2-\frac{e^2F^2}{2m_e\omega_{0e}^2}, \tag{5}$$

where

$$\varphi_{N_{1e}}\left(\frac{x-x_{oe}}{\tilde{L}_e}\right)=\left(\frac{1}{\pi\tilde{L}_e^2}\right)^{1/4}\frac{1}{\sqrt{2^{N_{1e}}N_{1e}!}}\exp\left(-\frac{1}{2}\frac{(x-x_{oe})^2}{\tilde{L}_e^2}\right)H_{N_{1e}}\left(\frac{x-x_{oe}}{\tilde{L}_e}\right), \tag{6}$$

$$\eta_{N_{2e}}\left(\frac{z}{L_e}\right)=\left(\frac{1}{\pi L_e^2}\right)^{1/4}\frac{1}{\sqrt{2^{N_{2e}}N_{2e}!}}\exp\left(-\frac{1}{2}\frac{z^2}{L_e^2}\right)H_{N_{2e}}\left(\frac{z}{L_e}\right), \tag{7}$$

$$\tilde{\omega}_e=\sqrt{\omega_{0e}^2+\omega_e^2},\qquad \omega_e=\frac{eH}{m_e c}, \tag{8}$$

$$\tilde{L}_e=\sqrt{\frac{\hbar}{m_e\tilde{\omega}_e}},\qquad L_e=\sqrt{\frac{\hbar}{m_e\omega_{0e}}}, \tag{9}$$

$$x_{0e} = -\frac{\hbar\omega_e k_{ye} + eF}{m_e\tilde{\omega}_e^2}\,, \tag{10}$$

where ω_e is the cyclotron frequency for electron in conduction band. $H_n(\xi)$ is the Hermitian polynomial

$$H_n(\xi) = n!\sum_{k=0}^{[\frac{n}{2}]}\frac{(-1)^k}{k!(n-2k)!}(2\xi)^{n-2k}\,. \tag{11}$$

An envelope wave function for the valence -band electrons can be expressed as

$$\psi_{N_{1h},N_{2h},k_{yh}} = \varphi_{N_{1h}}\left(\frac{x-x_{0h}}{\tilde{L}_h}\right)\eta_{N_{2h}}\left(\frac{z}{L_h}\right)e^{ik_{yh}y}\,. \tag{12}$$

$\varphi_{N_{1h}}\left(\frac{x-x_{0h}}{\tilde{L}_h}\right)$, $\eta_{N_{2h}}\left(\frac{z}{L_h}\right)$ and etc. are similar to $\varphi_{N_{1e}}\left(\frac{x-x_{oe}}{\tilde{L}_e}\right)$ and $\eta_{N_{2e}}\left(\frac{z}{L_e}\right)$, etc., with the subscript e being replaced by h and the electron electric charge $(-e)$ by the hole electric charge, e, e.g.

$$\tilde{\omega}_h = \sqrt{\omega_{0h}^2 + \omega_h^2}\,, \qquad \omega_h = \frac{eH}{m_h c}\,, \tag{13}$$

$$\tilde{L}_h = \sqrt{\frac{\hbar}{m_h\tilde{\omega}_h}}\,, \qquad L_h = \sqrt{\frac{\hbar}{m_h\omega_{0h}}}\,, \tag{14}$$

$$x_{0h} = -\frac{\hbar\omega_h k_{yh} - eF}{m_h\tilde{\omega}_h^2}\,. \tag{15}$$

The energy eigenvalues for the valence-band electrons is given by

$$E_{N_{1h},N_{2h},k_{yh}} = -E_g - \left(N_{1h}+\frac{1}{2}\right)\hbar\tilde{\omega}_h - \left(N_{2h}+\frac{1}{2}\right)\hbar\omega_{0h} - \frac{\hbar^2\omega_{0h}^2}{2m_h\tilde{\omega}_h^2}\left(k_{yh}+\frac{eF\omega_h}{\hbar\omega_{0h}^2}\right)^2 + \frac{e^2F^2}{2m_h\omega_{0h}^2} \tag{16}$$

where E_g is the band gap and the energy origin has been chosen at the conduction-band minima. It appears from Eqs. (5) and (16) that in the absence of a transverse electric field the effective mass $m_j(H) = m_j(0)\frac{\tilde{\omega}_j^2}{\omega_{0j}^2} = m_j(0)\left(1+\frac{\omega_j^2}{\omega_{0j}^2}\right)$ (where $j = e,h$ is the band index) depends on the strength of the applied magnetic field quadratically. It is also clear from the equations above that the applied magnetic and electric fields have coupling effects on the wave functions and eigenenergies.

3. INTERBAND OPTICAL TRANSITIONS AND OPTICAL ABSORPTION COEFFICIENT

The interaction Hamiltonian betveen the electrons and the radiation field associated with the electromagnetic radiation is

$$H_{rad} = \left(\frac{e}{mc}\right)\vec{A}\cdot\vec{p}\,, \tag{17}$$

where m is the free-electron mass, $\vec{A} = A_0\vec{\varepsilon}$ is the vector potential of the light wave with amplitude A_0 and the polarization vector $\vec{\varepsilon}$, and $\vec{p}$ is the usual momentum operator.

Using first order perturbation theory, we can calculate the probability for transitions between electronic subbands in the valensce and conduction bands of the QWR

$$W = \frac{2\pi}{\hbar}\sum_{i,f}\left|H_{i,f}\right|^2 \delta\left(E_f - E_i - \hbar\nu\right), \tag{18}$$

where i and f represent the set of quantum numbers spesifying the initial and final states of the electron, and ν is the frequency of the incident photon.

The matrix element $H_{i,f}$ can be written as

$$H_{i,f} = \left(\frac{em}{c}\right) A_0(\vec{\varepsilon}\cdot\vec{p}_{cv})\int \psi^*_{N_{1h},N_{2h},k_{yh}}(x,y,z)\psi_{N_{1e},N_{2e},k_{y,e}}(x,y.z)dxdydz\,. \tag{19}$$

Here $\vec{p}_{cv}$ is the matrix element of the momentum operator between the band edge wave functions associated with the valence and conduction bands. When the properties of the wave functions $\psi_{N_{1h},N_{2h},k_{yh}}(x,y,z)$ and $\psi_{N_{1e},N_{2e},k_{y,e}}(x,y,z)$ are used in evaluating the integral occurring in (19), we find that the integral vanishes unless the following selection rule is obeyed

$$k_{ye} = k_{yh}\,, \tag{20}$$

(here the photon momentum is neglected).

The matrix element $H_{i,f}$ can now be written as

$$H_{i,f} = \left(\frac{em}{c}\right) A_0(\vec{\varepsilon}\cdot\vec{p}_{cv})\cdot I_{N_{1h},N_{1e}}\left(k_y\right)\cdot J_{N_{2h},N_{2e}}\cdot\delta_{k_{yh},k_{ye}}\,, \tag{21}$$

where

$$I_{N_{1h},N_{1e}}\left(k_y\right) = \int_{-\infty}^{+\infty}\varphi_{N_{1h}}\left(\frac{x-x_{0h}}{\tilde{L}_h}\right)\varphi_{N_{1e}}\left(\frac{x-x_{0e}}{\tilde{L}_e}\right)dx \tag{22}$$

and

$$J_{N_{2h},N_{2e}} = \int_{-\infty}^{+\infty}\eta_{N_{2h}}\left(\frac{z}{L_h}\right)\eta_{2e}\left(\frac{z}{L_e}\right)dz \tag{23}$$

are overlap integrals between the valence and conduction bands. There are no longer the selection rules for $N_{1e,h}$ and $N_{2e,h}$ because of the properties of the harmonic oscillator functions with different arguments.

Using (11) it can be obtained following expressions for $I_{N_{1h},N_{1e}}\left(k_y\right)$ and $J_{N_{2h},N_{2e}}$

$$\begin{aligned} I_{N_{1h},N_{1e}}(k_y) = {} & \left(\frac{1}{\pi}\right)^{1/2}\left(\frac{1}{\tilde{L}_h\tilde{L}_e}\right)^{1/2}\frac{N_{1e}!\,N_{1h}!}{\sqrt{2^{N_{1e}+N_{1h}}N_{1e}!\,N_{1h}!}}\sum_{k=0}^{[N_{1h}/2]}\sum_{j=0}^{[N_{1e}/2]}\frac{(-1)^{k+j}\,2^{N_{1h}+N_{1e}-2k-2j}}{k!\,j!\left(N_{1h}-2k\right)!\left(N_{1e}-2j\right)!}\cdot \\ & \cdot\left(\frac{1}{\tilde{L}_e}\right)^{N_{1e}-2j}\left(\frac{1}{\tilde{L}_h}\right)^{N_{1h}-2k}\sum_{\mu=0}^{N_{1h}-2k}\frac{\left(N_{1h}-2k\right)!}{\mu!\left(N_{1h}-2k-\mu\right)!}\left(x_{0e}-x_{0h}\right)^{N_{1h}-2k-\mu}\sum_{\nu=0}^{N_{1e}-2j+\mu}\frac{\left(N_{1e}-2j+\mu\right)!}{\nu!\left(N_{1e}-2j+\mu-\nu\right)!}\cdot \\ & \cdot\left[(-1)^{\nu}+1\right]\exp\left(-\frac{\left(x_{0e}-x_{0h}\right)^2}{2\left(\tilde{L}_e^2+\tilde{L}_h^2\right)}\right)\frac{1}{2}\left(\frac{\tilde{L}_e^2+\tilde{L}_h^2}{2\tilde{L}_e^2\tilde{L}_h^2}\right)^{-\frac{\nu+1}{2}}\Gamma\left(\frac{\nu+1}{2}\right)\left(-\frac{\tilde{L}_e^2\left(x_{0e}-x_{0h}\right)}{\tilde{L}_e^2+\tilde{L}_h^2}\right)^{N_{1e}-2j+\mu-\nu} \end{aligned} \tag{24}$$

and

$$J_{N_{2h},N_{2e}}=\left(\frac{1}{\pi}\right)^{1/2}\frac{1}{\sqrt{L_eL_h}}\sqrt{\frac{N_{2h}!N_{2e}!}{2^{N_{3e}+N_{3h}}}}\sum_{\alpha=0}^{[N_{2e}/2]}\sum_{\beta=0}^{[N_{3h}/2]}\frac{(-1)^{\alpha+\beta}2^{N_{2e}-2\alpha+N_{3h}-2\beta}}{\alpha!\beta!(N_{2e}-2\alpha)!(N_{3h}-2\beta)!}\cdot$$
$$\cdot\left(\frac{1}{L_e}\right)^{N_{2e}-2\alpha}\left(\frac{1}{L_h}\right)^{N_{3h}-2\beta}\left[(-1)^{N_{2e}+N_{3h}-2\alpha-2\beta}+1\right]\frac{\Gamma\left(\frac{N_{2e}+N_{3h}-2\alpha-2\beta+1}{2}\right)}{2\left(\frac{\sqrt{L_h^2+L_e^2}}{\sqrt{2}L_hL_e}\right)^{N_{2e}+N_{3h}-2\alpha-2\beta+1}} \quad (25)$$

Then the interband transition probability (18) can be written in the form

$$W=\frac{2\pi}{\hbar}\frac{e^2}{m^2c^2}A_0^2\left|\vec{\varepsilon}\cdot\vec{p}_{cv}\right|^2\sum_{N_{1e},N_{1h}}\sum_{N_{2e},N_{2h}}\sum_{k_y}\left|I_{N_{1h},N_{1e}}(k_y)\cdot J_{N_{2h},N_{2e}}\right|^2\cdot$$
$$\cdot\delta\left(C(\nu,H,F)+B(H,F)k_y+A(H)k_y^2\right), \quad (26)$$

where

$$C(\nu,H,F)=\hbar\nu-E_g-\left(N_{1e}+\frac{1}{2}\right)\hbar\tilde{\omega}_e-\left(N_{1h}+\frac{1}{2}\right)\hbar\tilde{\omega}_h-\left(N_{2e}+\frac{1}{2}\right)\hbar\omega_{0e}-$$
$$-\left(N_{2h}+\frac{1}{2}\right)\hbar\omega_{0h}+\frac{e^2F^2}{2}\left(\frac{1}{m_h\tilde{\omega}_h^2}+\frac{1}{m_e\tilde{\omega}_e^2}\right), \quad (27)$$

$$B(H,F)=\hbar eF\left(\frac{\omega_e}{m_e\tilde{\omega}_e^2}-\frac{\omega_h}{m_h\tilde{\omega}_h^2}\right) \quad (28)$$

and

$$A(H)=\left(\frac{\omega_{0e}^2}{m_e\tilde{\omega}_e^2}-\frac{\omega_{0e}^2}{m_h\tilde{\omega}_h^2}\right)\cdot\frac{\hbar}{2}. \quad (29)$$

The absorption coefficient α in the quantum wire is defined as $\hbar\nu$ times the number of transitions per unit volume per unit time divided by the incident power per unit area

$$\alpha=\frac{\hbar\nu\cdot W}{I_0\cdot V}, \quad (31)$$

where $I_0=\frac{n\nu^2A_0^2}{2\pi c}$ is the incident power of radiation in the electromagnetic field, n is the index of refraction and $V=\pi R^2L_y$ is the volume of the quantum wire.

Performing the summations over k_y in (26) and taking into account (31) we find

$$\alpha=\alpha_0\sum_{N_{1e},N_{1h}}\sum_{N_{2e},N_{2h}}\frac{\left[\left(I_{N_{1h},N_{1e}}(k_{y1})\right)^2+\left(I_{N_{1h},N_{1e}}(k_{y2})\right)^2\right]}{\sqrt{\frac{(B(H,F))^2}{4A(H)}+C(\nu,H,F)}}\left|J_{N_{2h},N_{2e}}\right|^2 \quad (32)$$

where

$$\alpha_0=\frac{e^2\left|\vec{\varepsilon}\cdot\vec{p}_{cv}\right|^2}{n\nu R^2m^2c\sqrt{A(H)}} \quad (33)$$

and

$$k_{y1,2}=\frac{B(H,F)\pm\sqrt{(B(H,F))^2+4A(H)\cdot C(\nu,H,F)}}{2A(H)} \quad (34)$$

are the roots of the delta function argument.

Let us make some remarks concerning the above equations. From Eq.(25) it follows that $I_{N_{2h},N_{2e}}$ vanishes unless $N_{2e}+N_{2h}=2n$, where n is an integer. So, transition can only take place between N_{2h} and N_{2e} subbands with the same parity ($2m\rightarrow 2n$; and $2m+1\rightarrow 2n+1$; m and n are integers). But for Eq. (24) quantum numbers N_{1h} and N_{1e} can change arbitrarily.

Hence, the following selection rules are obtained for interband transitions:

$$\left|N_{1h}-N_{1e}\right|=0,1,2,....; \qquad \left|N_{2h}-N_{1e}\right|=0,2,4... \tag{35}$$

In this case when $\left|N_{1h}-N_{1e}\right|=2n+1$ the spectrum shows maximums and when $\left|N_{1h}-N_{1e}\right|=2n$ the absorption spectrum shows singular peaks. The position of these structures are given as follows:

$$\left(B(H,F)\right)^2+4A(H)\cdot C(\nu,H,F)=0\,. \tag{36}$$

4. DISCUSSION OF THE RESULTS

In the following we present detailed numerical calculations of the optical absorption coefficient of GaAs/AlGaAs parabolic quantum wire in the presence of crossed electric and magnetic fields as a function $\hbar\nu/E_g$. The physical parameters used in our expressions are: $E_g=1.5177$ eV, $m_e=0.0665m_0$, $m_h=0.45m_0$ (the heave-hole band). Taking the ratio 60:40 for the band-edge discontinuity [14, 15], the conduction and valence barrier heights are taken to be $\Delta_e=255$ meV and $\Delta_h=170$ meV. The oscillation frequencies ω_{0e} and ω_{0h} of the parabolic quantum wire are determined via

$$\omega_{0e(h)}=\frac{2}{d}\sqrt{\frac{2\Delta_{e(h)}}{m_{e(h)}}},$$

where d -is the quantum wire diameter.

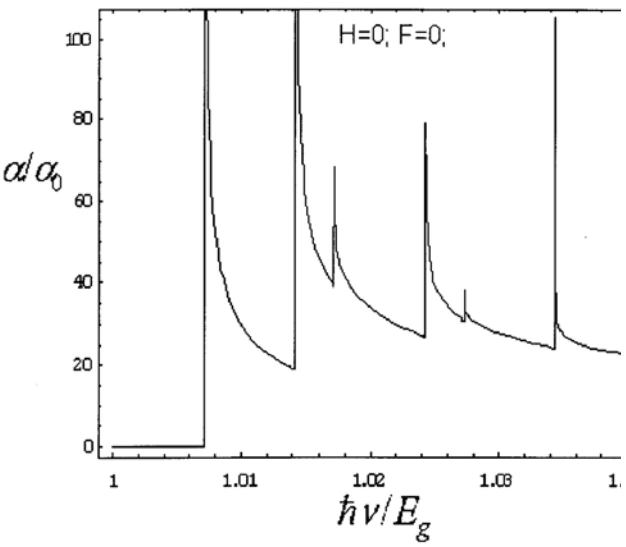


Fig.1.

Absorption as a function of $\hbar\nu/E_g$ for H=0, F=0.

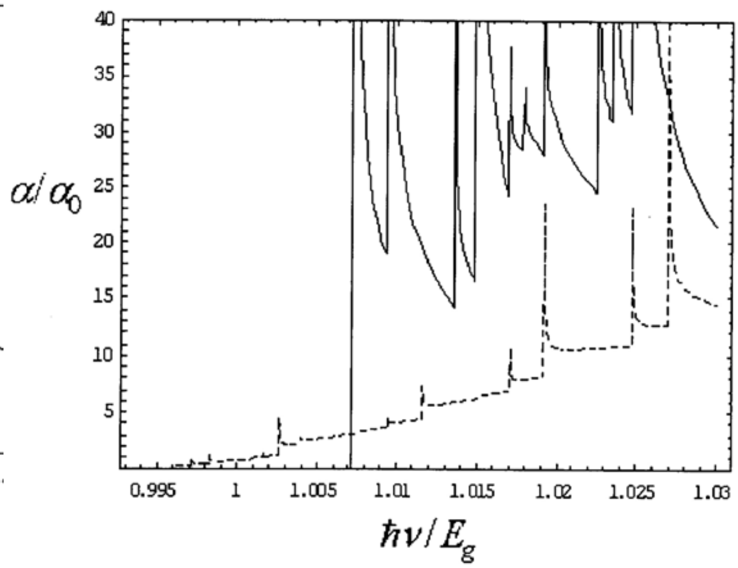


Fig.2.

Absorption as a function of $\hbar\nu/E_g$ for H=0, and for different electric fields.
F=3600V/cm (solid line) and
F=15000V/cm (dashed line).

Fig.1 shows the optical absorption spectra as a function of the photon energy for $H = 0$ and $F = 0$. The diameter d of the QWR is 2000Å. In this case the selection rules are $|N_{1h} - N_{1e}| = 2n$, $|N_{2h} - N_{2e}| = 2m$. The transition can only take place between (N_{1h}, N_{2h}) and (N_{1h}, N_{2h}) subbands with the same parity.

In Fig.2 we show results for the absorption coefficient as a function of the photon energy for different values of the electric-field strength at $H = 0$. We have chosen the same set of parameters as the Fig.1. It can be seen that the absorption has the threshold which is shifted to lower energy by amount

$$\Delta = \frac{e^2F^2}{2}\left(\frac{1}{m_h\omega_{0h}^2} + \frac{1}{m_e\omega_{0e}^2}\right)$$

in the presence of electric field. The value of α decreases with increasing electric field F .

Such behaviour is related with exponential factor in Eq.(24).

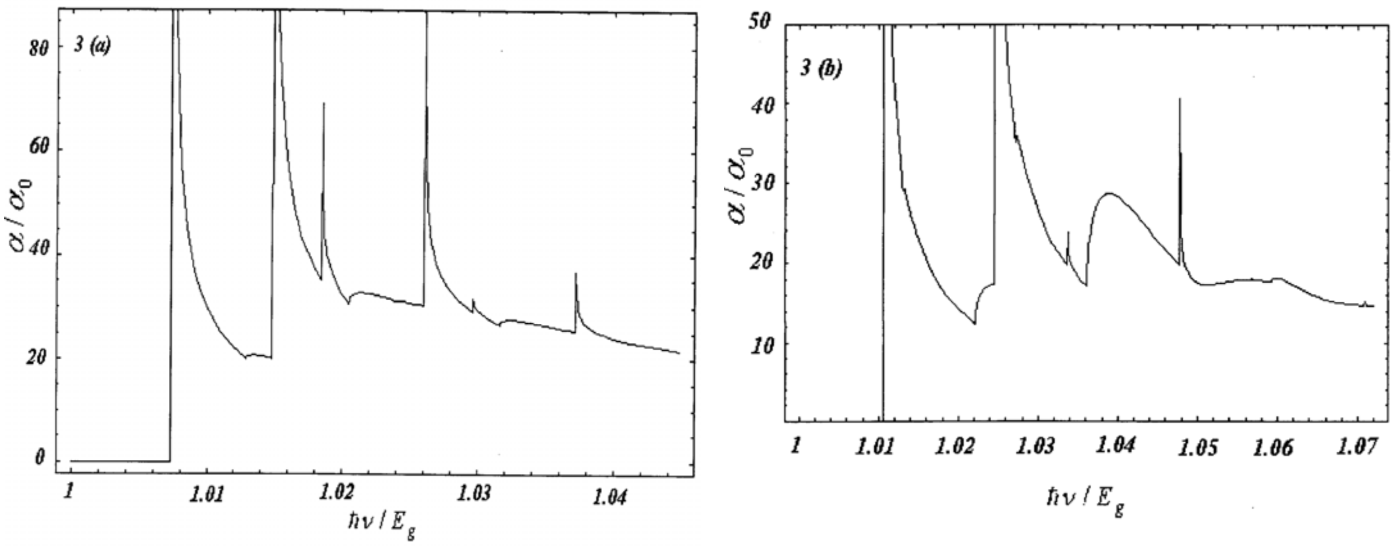
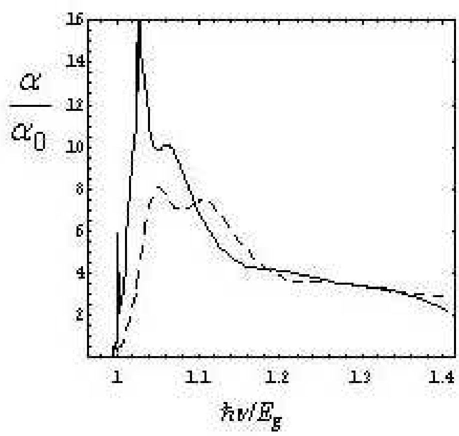


Fig.3

Absorption as a function of $\hbar\nu/E_g$ for F=0, and for different magnetic fields: (a)- H=2 Tl, (b)- H=10 Tl.

Fig.3(a,b) shows absorbtion spectra as a function $\hbar\nu / E_g$ for different magnetic fields $H =$. Here we keep the electric field at $F = 0$. From these pictures we can see that the threshold for the optical absorption is shifted to higher energies due to the magnetic quantization.



In Fig.4 we plot absorption coefficient for different magnetic and electric fields. In this case influence of the electric field on the magneto-optical oscillations leads following result: Singularities in the spectrum disappears and absorption becomes finitely for all frequency region.

Fig.4.

Absorption as a function of $\hbar\nu/E_g$ for different magnetic and electric fields. F=15000 V/cm, H=5 Tl (solid line) and F=20000 V/cm, H=7 Tl (dashed line).

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KVANT MƏFTİLİNDƏ ELEKTRO- VƏ MAQNİT UDULMA

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Çarpaz elektrik və maqnit sahələrində parabolik kvant məftilində zonalararası udulma əmsalı hesablanmışdır. Zonalararası keçidlərin seçmə qaydası tapılmışdır. Elektrik və magnit sahələrində optik udulmanın astanası spektrin kiçik enerjilər tərəfinə sürüşür. Göstərilmişdir ki, maqnit və elektrik sahələri kvant məftilinin optik xassələrinə güclü təsir edir. Ədədi hesablamalar GaAs/AlGaAs üçün aparılmışdır.

ЭЛЕКТРО- И МАГНИТОПОГЛОЩЕНИЕ В КВАНТОВОЙ ПРОВОЛОКЕ

Т. Г. ИСМАИЛОВ, Б.Г. МЕХТИЕВ

Вычислен коэффициент межзонного поглощения в параболической квантовой проволоке в скрещенных электрических и магнитных полях. Найдено правило отбора межзонных переходов. В электрических и магнитных полях порог поглощения смещается в низкоэнергетическую сторону спектра. Показано, что магнитные и электрические поля сильно влияют на оптические свойства квантовой проволоки. Численные расчеты были проведены для GaAs/AlGaAs.

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