CALCULATIONS OF THE ABSORPTION COEFFICIENT OF A WEAK ELECTROMAGNETIC WAVE BY FREE CARRIERS IN DOPING SUPERLATTICES BY THE KUBO-MORI METHOD

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Abstract: *Analytic expressions for the high-frequency conductivity tensor and the absorption coefficient of a weak electromagnetic wave (EMW) by free carriers for the case of electron-optical phonon scattering in doping superlattices are calculated by the Kubo-Mori Method in two cases: - The absence of a magnetic field. - The presence of a magnetic field applied perpendicular to its barriers. A different dependence of the high-frequency conductivity tensor and the absorption coefficients on the electromagnetic wave frequency ω, the temperature T of the system, the cyclotron frequency Ω (when a magnetic field is present) and characteristic parameters of a doping superlattice in comparison with normal semiconductors is obtained. The analytic expressions are numerically evaluated, plotted and discussed for a specific doping superlattice n-GaAs/ p-GaAs.*

1. Introduction

Recently, there have been considerable interest in the behaviour of low dimensional system, in particular, of two dimensional system, such as semiconductor superlattices, quantum wells and doping superlattices. The confinement of electrons in low dimensional systems considerably enhances the electron mobility and leads to their unusual behaviours under external stimuli. Many papers have appeared dealing with these behaviours, for examples: electron-phonon interaction and scattering rates,[1 - 3] *dc* electrical conductivity [4-5]. The problems of absorption coefficient of a weak electromagnetic wave (EMW) in semiconductor superlattices [6-7] and in quantum wells [8] have been investigated.

In this paper we study the high-frequency conductivity tensor and the absorption coefficient of a weak EMW by free carriers confined in a doping superlattice in the cases of the absence of a magnetic field and the presence of a magnetic field applied perpendicular to its barriers. The electron-optical phonon scattering mechanism is assumed to be dominant. We shall assume that the weak EMW is plane-polarized and has high frequency in the ranger $\omega\tau \gg 1$ (τ is characteristic momentum relaxation time and ω is the frequency of the weak EMW $\vec{E}(t) = \vec{E}_0 \cos(\omega t)$).

It starts from Kubo's formula for the conductivity tensor [9]:

$$\sigma_{\mu\nu}(\omega) = \lim_{\delta \to +0} \int_0^{\infty} e^{i\omega t - \delta t}(J_\mu, J_\nu(t))dt, \tag{1}$$

where J_μ is the μ - component of the current density operator ($\mu = x, y, z$) and $J_\mu(t)$ is the operator J_μ in Heisenberg picture $J_\mu(t) = \exp(-iHt/\hbar)J_\mu \exp(iHt/\hbar$. The quantity

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δ is infinitesimal and appears by the assumption of adiabatic interaction of an external electromagnetic wave. The time correlation function used in (1) is defined by the formula:

$$(A, B) = \int_0^\beta \langle e^{\lambda H} A e^{-\lambda H} B\rangle d\lambda, \tag{2}$$

where $\beta = 1/k_B T$ (k_B is the Boltzmann constant, T is the temperature of system), the symbol $< \cdot >$ means the averaging of operators with Hamiltonian H of the system.

In ref. 10, Mori pointed out that the Laplace's transformation of the time correlation function (2) could be represented in the form of an infinite continued fraction. One of advantages of this representation is that the function will converge faster than representation in a power series.

Using Mori's method in the second order approximation of interaction, we obtain the following formula for the components of the conductivity tensor [7, 11, 12]:

$$\sigma_{\mu\nu}(\omega) = \lim_{\delta\to+0} (J_\mu, J_\nu)\times \\ \times \left[\delta - i(\omega+\eta) + \left(\frac{i}{\hbar}\right)^2 (J_\mu, J_\nu)^{-1} \int_0^\infty e^{i\omega t-\delta t}([U, J_\mu], [U, J_\nu]_{int})\right]^{-1} dt \tag{3}$$

with

$$\hbar\eta = \langle [J_\mu, J_\nu]\rangle (J_\mu, J_\nu)^{-1}, \tag{4}$$

here G_{int} is the operator G in the interaction picture $G_{int} = \exp(-iHt/\hbar)G\exp(iHt/\hbar)$; $[A, B] = AB - BA$; U is the energy of electron-phonon interaction. The averaging of operators in eqs. (3) and (4) is implemented with non-interaction Hamiltonian H_0 of the electron-phonon system.

The structure of doping superlattices also modifies the dispersion relation of optical phonons, which leads to interface modes and confined modes [1]. However, the calculation on electron scattering rates [2] which showed that for large thickness of the layer of doping superlattices, the contribution from these two modes can be well approximated by calculations with bulk phonons. So in this paper, we will deal with bulk (3 dimensional) phonons and consider a compensated doping superlattice with equal thickness $d_n = d_p = d_i$ of the n-doping and p-doping layer, equal an constant doping consentration $n_D = n_A$ in the respective layers and zero thickness $d_i = 0$ of the undoped layers.

2. The Absorption Coefficient in the Case of the Absence of a Magnetic Field

It is well known that the motion of an electron is confined in each layer of doping superlattices and its energy spectrum is quantized into discrete levels. We assume that the quantization direction is the z direction. The Hamiltonian of the electron-optical phonon system in doping superlattices in the second quantization representation can be written as:

$$H = H_0 + U, \tag{5}$$

$$H_0 = \sum_{\vec{k}_\perp, n} \epsilon_{\vec{k}_\perp, n} a^+_{\vec{k}_\perp, n} a_{\vec{k}_\perp, n} + \sum_{\vec{q}} \hbar\omega_0 b^+_{\vec{q}} b_{\vec{q}}, \tag{6}$$

$$U = \sum_{\vec{k}_\perp, \vec{q}, n, n'} C_{\vec{q}} C_{n', n} a^+_{\vec{k}_\perp + \vec{q}_\perp, n} a_{\vec{k}_\perp, n'} (b_{\vec{q}} + b^+_{-vecq}), \tag{7}$$

where n denotes quantization of the energy spectrum in the z direction ($n = 1, 2, ...$), ($\vec{k}_{\perp, n}$) and ($\vec{k}_\perp + \vec{q}_\perp, n'$) are electron states before and after scattering, $\vec{k}_\perp(\vec{q}_\perp)$ is the in-plane (x, y) wave vector of electron (phonon); a^+_α and a_α ($b^+_{\vec{q}}$ and $b_{\vec{q}}$) are the creation and annihilation operators of electron (phonon), respectively, $\vec{q} = (\vec{q}_\perp, q_z)$; $\hbar\omega_0$ is the energy of optical phonon. The electron energy takes the simple form [13]:

$$\epsilon_{\vec{k}_\perp, n} = \frac{\hbar^2}{2m} k_\perp^2 + \hbar \left(\frac{4\pi e^2 n_D}{\chi_0 m^*} \right)^{1/2} \left(n + \frac{1}{2} \right) = \frac{\hbar^2}{2m} k_\perp^2 + a \left(n + \frac{1}{2} \right) \tag{8}$$

here m^* and e are the effective mass and charge of electron, respectively; n_D is a doping concentration; $C_{\vec{q}}$ is a constant, in the case of electron-optical phonon interaction it is [3,5]:

$$|C_{\vec{q}}|^2 = V^{-1} 2\pi e^2 \hbar\omega_0 (q_\perp^2 + q_z^2)^{-1} (\chi_\infty^{-1} - \chi_0^{-1}) \tag{9}$$

with V is the normalization volume; χ_0 and χ_∞ are the static and high-frequency dielectric constant, respectively;

$$C_{n', n} = \sum_{\ell} \int_0^{N_1 d} \phi_{n'}(z - \ell d) e^{iq_z z} \phi_n(z - \ell d) dz, \tag{10}$$

here $\phi_n(z)$ is the eigenfunction for a single potential well [16]; $d = 2d_i$ and N_1 is the number of period of doping superlattice.

The interaction of the system (5)-(7) with a weak EMW $\vec{E}(t) = \vec{E} \cos\omega t$ is etermined by Hamiltonian:

$$H_t^1 = -e \sum_a (\vec{r}_a, \vec{E}) \cos\omega t . e^{\delta t}, \qquad \delta \to +0 \tag{11}$$

where $\vec{r}_a$ is the radius - vector of $a - th$ electron;

Using the Kubo-Mori method, we obtain the following formula for the transverse component of the high-frequency conductivity tensor $\sigma_{xx}(\omega)$:

$$\sigma_{xx}(\omega) = \Gamma_\perp [-i\omega + F(\omega)]^{-1} \tag{12}$$

with $\Gamma_\perp = (J_x, J_x)$ and

$$F(\omega) = \lim_{\delta \to +0} \left(\frac{i}{\hbar} \right)^2 \Gamma_\perp^{-1} \int_0^\infty e^{i\omega t - \delta t} ([U, J_x], [U, J_x]_{int}) \, dt. \tag{13}$$

Knowing the high-frequency conductivity tensor, the absorption coefficient can be found by the common relation:

$$\alpha_{xx}(\omega) = (4\pi/cN^*)\mathrm{Re}\sigma_{xx}(\omega) \tag{14}$$

here N^* is the refraction index; c is the light velocity.

Since the weak EMW has a high-frequency, using formulae (3)-(14), in the special case $(N_1 d/\alpha_1) \ll 1$ and $q_z d \gg 1; \alpha_1 = \hbar(ma)^{-1/2}$, we obtain:

$$\alpha_{xx}(\omega) = \frac{4\pi}{cN^*}\frac{\Gamma_\perp G(\omega)}{G^2(\omega)+\omega^2}, \tag{15}$$

where

$$\Gamma_\perp = \frac{e^2}{4\pi\beta\hbar^2}e^{\beta(\mu-\frac{a}{2})}[csh(\beta a) + cth(\beta a) + 1], \tag{16}$$

$$G(\omega) = ReF(\omega) = G^+(\omega) + G^-(\omega), \tag{17}$$

$$G^\pm(\omega) = \Gamma_\perp^{-1}\frac{\pi^2 e^4}{\hbar m^*}e^{\beta\mu}(\chi_\infty^{-1} - \chi_0^{-1})\hbar\omega_0\frac{e^{\beta\hbar\omega}-1}{\hbar\omega}\left(N_{\vec{q}} + \frac{1}{2} \pm \frac{1}{2}\right)$$
$$\sum_{i=0}^{\infty}\sum_{n,n'}\left(\frac{N_1 d}{\alpha_1} + 2^{2i+1}\frac{\Gamma(i)}{\Gamma(2i+1)}\right)\left(\frac{N_1 d}{\alpha_1}\right)^{2i+1}\times$$
$$\times e^{-2\left(\frac{N_1 d}{\alpha_1}\right)^2} e^{-\beta a(n+\frac{1}{2})+\beta\lambda_\pm}|\lambda_\pm|K_1(2\beta|\lambda_\pm|) \tag{18}$$

and

$$\lambda_\pm = a(n'-n) - (\hbar\omega \pm \hbar\omega_0), \tag{19}$$

with $N_{\vec{q}}$ is the equilibrium distribution of optical phonon; μ is the chemical potential; $\Gamma(x)$ is the Gamma function; $K_1(x)$ is the modified Bessel functions of the second kind. The signs ($\pm$) in the superscript of the mass operator $G^\pm(\omega)$ and in the lower-script of the function $\lambda_\pm$ correspond to the sign ($\pm$) in the Eqs. (18) and (19). The upper sign (+) corresponds to a phonon absorption and the lower sign (-) to a phonon emission in the absorption process.

From eqs.(12) and (15) we can easily see that $G(\omega)$ plays the role of the well known mass operator of electron in the Born approximation in the case of the absence of a magnetic field.

3. The Absorption Coefficient in the Case of the Presence of a Magnetic Field

We consider doping superlattices with a magnetic field B applied perpendicular to its barriers (z direction). The Hamiltonian of the electron-optical phonon system in the second quantization representation can be written as [1, 5, 13, 14]:

$$H = H_0 + U \tag{20}$$

$$H_0 = \sum_\alpha \epsilon_\alpha^H a_\alpha^+ a_\alpha + \sum_{\vec{q}} \hbar\omega_0 b_{\vec{q}}^+ b_{\vec{q}} \tag{21}$$

$$U = \sum_{\alpha,\alpha',\vec{q},\vec{q}} C_{\vec{q}} C_{n',n}(q_z) C_{N',N}(u) a_\alpha^+ a_{\alpha'}(b_{-\vec{q}}^+ + b_{\vec{q}}), \tag{22}$$

where N is the Landau level index ($N = 0, 1, 2, ...$); $\alpha \equiv (N, n, k_x)$ and $\alpha' \equiv (N', n', k'_x)$, $k'_x = k_x + q_x$ are the set of quantum numbers characterizing electron's states before and after scattering; a^+_α and a_α are the creation and annihilation operators of electron, respectively, and ϵ^H_α is the energy of electron in doping superlattices in the presence of magnetic field applied in z direction:

$$\epsilon^H_\alpha = \left(N + \frac{1}{2}\right)\hbar\Omega + \hbar\left(\frac{4\pi e^2 n_D}{m^* \chi_0}\right)^{1/2}\left(n + \frac{1}{2}\right) \equiv \left(N + \frac{1}{2}\right)\hbar\Omega + a\left(n + \frac{1}{2}\right) \quad (23)$$

C_q and $C_{n',n}(q_z)$ are defined by eqs. (9) and (10), respectively, and $C_{N',N}(u)$ takes the form

$$C_{N',N}(u) = \int_{-\infty}^{+\infty} \Psi_{N'}(r_\perp - a_c^2 k_\perp - a_c^2 q_\perp) e^{iq_\perp r_\perp} \Psi_N(r_\perp - a_c^2 k_\perp) dx, \quad (24)$$

where $r_\perp$ is the position of electron and a_c is the radius of the orbit in the (x, y) plane: $a_c^2 = c\hbar/eB$; $u = a_c^2 q_\perp^2/2$; $\Psi_N(x)$ represents harmonic oscillator wave fuctions; Ω is the cyclotron frequency ($\Omega = eB/cm$).

The interaction of the system (20)-(22) with a weak EMW $\vec{E}(t) = \vec{E}\cos\omega t$ is determined by Hamiltonian (11)

When a magnetic field is present, for using Kubo-Mori method [7, 8, 12] instead of J_x and J_y we use operators J_+ and J_- with $J_\pm = J_x \pm iJ_y$. The transverse components of conductivity tensor are defined by the formula:

$$\sigma_{xx}(\omega, \Omega) = \sigma_{yy}(\omega, \Omega) =$$
$$= \lim_{\delta \to +0} \frac{1}{4}\left\{\int_{0}^{\infty} e^{i\omega t - \delta t}(J_-, J_+(t))dt + \int_{0}^{\infty} e^{i\omega t - \delta t}(J_+, J_-(t))dt\right\}, \quad (25)$$

Instead of Eqs. (3)-(4), in the second order approximation of interaction we obtain:

$$\int_0^\infty e^{i\omega t - \delta t}(J_-, J_+(t))dt =$$
$$= (J_-, J_+)\left[\delta - i(\omega - \Omega) + \left(\frac{i}{\hbar}\right)^2 (J_-, J_+)^{-1}\int_0^\infty e^{i\omega t - \delta t}\left([U, J_-], [U, J_+]_{int}\right) dt\right]^{-1}, \quad (26)$$

$$\int_0^\infty e^{i\omega t - \delta t}(J_+, J_-(t))dt =$$
$$= (J_+, J_-)\left[\delta - i(\omega + \Omega) + \left(\frac{i}{\hbar}\right)^2 (J_+, J_-)^{-1}\int_0^\infty e^{i\omega t - \delta t}\left([U, J_+], [U, J_-]_{int}\right) dt\right]^{-1}. \quad (27)$$

From Eqs. (20)-(27) we obtain the following expression for transverse components of the high-frequency conductivity tensor:

$$\sigma_{xx}(\omega, \Omega) = \sigma_{yy}(\omega, \Omega) = \frac{1}{4}\left\{\frac{(J_-, J_+)}{-i(\omega - \Omega) + F_{-,+}(\Omega)} + \frac{(J_+, J_-)}{-i(\omega + \Omega) + F_{+,-}(\Omega)}\right\}, \quad (28)$$

with

$$F_{-+}(\Omega) = \lim_{\delta\to+0}\left(\frac{i}{\hbar}\right)^2 (J_-, J_+)^{-1}\int_0^\infty e^{i\omega t-\delta t}\left([U, J_-], [U, J_+]_{int}\right)dt. \qquad (29)$$

$$F_{+-}(\Omega) = \lim_{\delta\to+0}\left(\frac{i}{\hbar}\right)^2 (J_+, J_-)^{-1}\int_0^\infty e^{i\omega t-\delta t}\left([U, J_+], [U, J_-]_{int}\right)dt. \qquad (30)$$

Knowing the high- frequency conductivity tensor, the absorption coefficient can be found by eq. (14). The transverse components of the absorption coefficient of a weak EMW in doping superlattices in the presence of a magnetic field take form:

$$\sigma_{xx}(\omega,\Omega) = \frac{\pi}{cN^*}\left[\frac{(J_-, J_+)G_1(\omega,\Omega)}{G_1^2(\omega,\Omega)+(\omega-\Omega)^2} + \frac{(J_+, J_-)G_2(\omega,\Omega)}{G_2^2(\omega,\Omega)+(\omega+\Omega)^2}\right], \qquad (31)$$

where

$$G_1(\omega,\Omega) = ReF_{-+}(\Omega) = G_1^+(\omega,\Omega) + G_1^-(\omega,\Omega), \qquad (32)$$

$$\begin{aligned} G_1^\pm(\omega,\Omega) = {}& \frac{e^4 m^{*2} e^{\beta\mu}\Omega^4\hbar\omega_0}{2\pi^2\hbar^3}(\chi_\infty^{-1}-\chi_0^{-1})\frac{(e^{\beta\hbar\omega}-1)}{\hbar\omega}e^{-\frac{1}{2}\beta(\hbar\Omega+a)}\times \\ & \times (J_-, J_+)^{-1}\sum_{i=0}^{\infty}\sum_{N,N'}\sum_{n,n'} e^{-\beta(\hbar\Omega N+an)}\times \\ & \times\left(\frac{N_1 d}{\alpha_1}+2^{2i+1}\frac{\Gamma(i)}{\Gamma(2i+1)}\right)\left(\frac{N_1 d}{\alpha_1}\right)^{2i+1} e^{-2\left(\frac{N_1 d}{\alpha_1}\right)^2}\times \\ & \times [N+N'+1]\left(N_{\vec q}+\frac{1}{2}\mp\frac{1}{2}\right)\delta(\Delta\epsilon-\hbar\omega\pm\hbar\omega_0), \end{aligned} \qquad (33)$$

$$G_2(\omega,\Omega) = \mathrm{Re}F_{+-}(\omega)G_2^+(\omega,\Omega) + G_2^-(\omega,\Omega), \qquad (34)$$

$$\begin{aligned} G_2^\pm(\omega,\Omega) = {}& \frac{e^4 m^2 e^{\beta\mu}\Omega^4\hbar\omega_0}{2\pi^2\hbar^3}(\chi_\infty^{-1}-\chi_0^{-1})\frac{(e^{\beta\hbar\omega}-1)}{\hbar\omega}e^{-\frac{1}{2}\beta(\hbar\Omega+a)}\times \\ & \times (J_+, J_-)^{-1}\sum_{i=0}^{\infty}\sum_{N,N'}\sum_{n,n'} e^{-\beta(\hbar\Omega N+an)}\times \\ & \times\left(\frac{N_1 d}{\alpha_1}+2^{2i+1}\frac{\Gamma(i)}{\Gamma(2i+1)}\right)\left(\frac{N_1 d}{\alpha_1}\right)^{2i+1} e^{-2\left(\frac{N_1 d}{\alpha_1}\right)^2}\times \\ & \times [N^2+(N'+1)^2]\left(N_{\vec q}+\frac{1}{2}\mp\frac{1}{2}\right)\delta(\Delta\epsilon-\hbar\omega\pm\hbar\omega_0). \end{aligned} \qquad (35)$$

$$(J_-, J_+) = \frac{(\sqrt{2}e\Omega a_c)^2 m^* e^{\beta\mu}}{2\pi\hbar^2}(1-2^{-\beta\hbar\Omega})e^{-\frac{1}{2}\beta(\hbar\Omega+a)}\sum_{n,N}(N+1)e^{-\beta(\hbar\Omega N+an)}, \qquad (36)$$

$$(J_+, J_-) = \frac{(\sqrt{2}e\Omega a_c)^2 m^* e^{\beta\mu}}{2\pi\hbar^2}(e^{\beta\hbar\Omega}-1)e^{-\frac{1}{2}\beta(3\hbar\Omega+a)}\sum_{n,N}(N+1)e^{-\beta(\hbar\Omega N+an)}, \qquad (37)$$

and

$$\Delta\epsilon = (N-N')\hbar\Omega + a(n-n'), \qquad 38)$$

with μ is the chemical potential; $\delta(x)$ is the Dirac-Delta function; The sign ($\pm$) in the superscript of the mass operators $G_1^{\mp}(\omega, \Omega)$ and $G_2^{\pm}(\omega, \Omega)$ corresponds to the sign ($\pm$) in the Eqs. (33) and (34). The upper sign (+) corresponds to a phonon absorption and the lower sign (-) to a phonon emission in the absorption process.

From eqs.(25) and (28) we can easily see that $F_{-+}(\Omega)$ and $F_{+-}(\Omega)$ play the role of the well known mass operators of electron in the Born approximation in the case of the presence of a magnetic field.

4. Numerical Calculation and Discussions

In order to clarify the different behaviour of quasi-two-dimensional electron gas confined in a doping superlattice with respect to bulk electron gas, in this section, we numerically evaluate the analytic formulae (14)-(19) and (31)-(39) for a specific doping superlattice n-GaAs/p-GaAs. Characteristic parameters of GaAs layer of this doping superlattice are $\chi_\infty = 10.9$, $\chi_0 = 12.9$, $n_D = 10^{17}\text{cm}^{-3}$; $d = 2d_n = 2d_p = 80nm$, $\mu = 0.01\text{meV}$, $m^* = 0.067m_0$, $\hbar\omega_0 = 36.1meV$ (m_0 is the mass of free electron). The system is assumed at room temperature (T=293^{0}K).

4.1. In the case of absence of a magnetic field

Plotted in Fig. 1 is the operator $G(\omega)$ as a function of ω-the frequency of the electromagnetic wave and the number of period of doping superlattice N_1 for the case of $n = 11; n' = 11$. From this graph, we can see that the absorption spectrum of the operator $G(\omega)$ to depend strongly on the number of period N_1 in the region of values $N_1 < 30$ and resonant regions of the absorption spectrum are from $N_1 = 5$ to $N_1 = 20$ on the number of period-axis. Another remark is that for all values ω and $1 \leq N_1 < 30$, $G(\omega)$ is different and great in comparison with the bulk GaAs and the quantum well GaAs [8]. That is because, the confinement of electrons in discrete levels and the influence of the doping concentration leads to more collisions in the system. Consequently, the life-time of an electron is shorter, or in other words, $G(\omega)$ is greater.

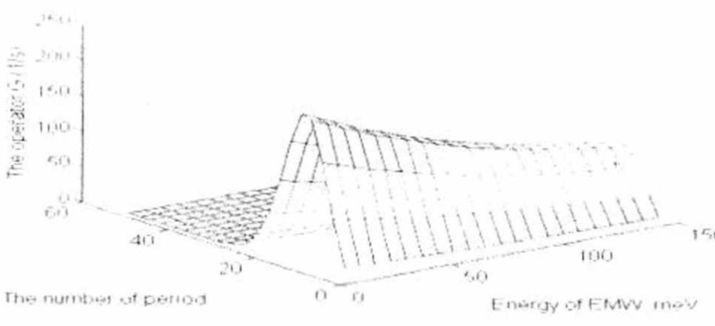

Fig.1: The dependence of the operator $\Gamma(\omega)(s^{-1})$ on the ω- frequency of EMW and the number of period N_1 in the case of $n = 11; n' = 11$.

Plotted in Fig.2 is the absorption coefficient $\alpha(\omega)$ as a function of ω-the frequency of the electromagnetic wave and the number of period N_1 for the cases: $n = 11; n' = 11$. From this graph, we can see resonant regions in absorption spectra of the absorption coefficient $\alpha(\omega)$. That is different in comparison with that of normal semiconductors and quantum wells.

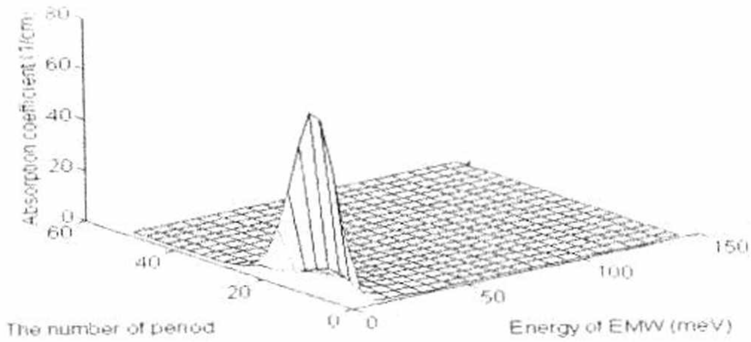

Fig.2: The dependence of the absorption coefficient of EMW (cm^{-1}) on the ω- frequency of EMW and the number of period N_1 in the case of $n = 11; n' = 11$.

4.2 In the case of presence of a magnetic field

Plotted in Fig.3 is the absorption coefficient of a weak EMW $\alpha(\omega, \Omega)$ as a function of ω - the frequency of a weak EMW with the condition (39). Based on the above-obtained results we give the following remarks:

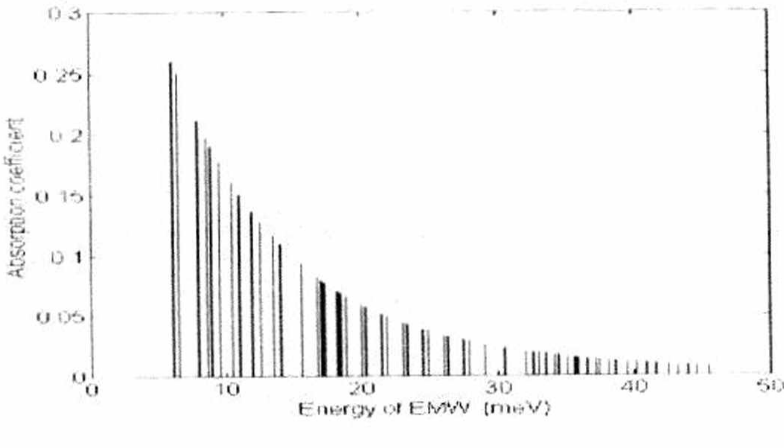

Fig.3: The influence of the magnetic field on the absorption coefficient of a weak EMW (cm^{-1}) in the doping superlattice n-GaAs/p- GaAs. The graph is plotted for the case $N = 7; N' = 7, n = 5, n' = 5$

The Dirac denta function in the expressions (33), (35) makes define the index of Landau-sub-bands N' which electrons can move to after absorption and the values of Ω- the cyclotron frequency which can influent to the absorption process. They satisfy condition

$$(N - N')\hbar\Omega + a(n - n') - \hbar\omega \pm \hbar\omega_0 = 0 \quad (39)$$

We can see that the index N' and the cyclotron frequency Ω depend on the frequency of the EMW ω, the limit frequency of optical phonon ω_0 and characteristic parameters of doping superlattices. And the dependence of the absorption coefficient $\alpha(\omega, \Omega)$ on the frequency ω with the condition (39) is not continuous. It is of line-form.

5. Conclusion

In this paper, we have given out the analytic formulae for the transverse components of absorption coefficient of a weak electromagnetic wave by free carriers in doping superlattices for the case of electron-optical phonon scattering mechanism in two cases: the absence of a magnetic field (15)-(19) and the presence of a magnetic field applied perpendicular to its barriers (31)-(38). The numerical evaluation of these formulae for a specific doping superlattice (n-GaAs/p- GaAs) show that the confinement of electrons in the doping superlattices not only leads to different dependence on the electromagnetic wave frequency ω and the temperature of system T in comparison with normal semiconductors and quantum wells but also creates many significant differences in the absorption coefficient.

In the case of the absence of a magnetic field, the resonant region on two side of main resonant peak in the absorption spectra of the operator $G(\omega)$ at $N_1 = 15$ (on the number of a doping layer-axis) is obtained. The results show that the lifetime of an electron to be smaller in comparison with semiconductor superllattices [7] and quantum wells [8].

In the case of the presence of a magnetic field applied perpendicular to the barriers, the analytic expressions indicate a complicated, different dependence of the high-frequency conductivity tensor and the absorption coefficient on the characteristic parameters of doping superlattices, the frequency of a weak EMW ω, the temperature of system T and the cyclotron frequency Ω in comparison with normal semiconductors[15.16] and quantum wells [8] in the presence of a magnetic field. The absorption spectra of a weak EMW in doping superllatices depends strongly on the condition (39) and the index of Landau sub-band which electrons can move to after absorption is defined by this condition.

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TẠP CHÍ KHOA HỌC ĐHQGHN, Toán - Lý, t.XVIII, n^{0}1 - 2002

TÍNH TOÁN HỆ SỐ HẤP THỤ SÓNG ĐIỆN TỪ YẾU BỞI ĐIỆN TỬ TỰ DO TRONG SIÊU MẠNG PHA TẠP BẰNG PHƯƠNG PHÁP KUBO-MORI

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Tính toán biểu thức giải tích cho tensor độ dẫn cao tần và hệ số hấp thụ sóng điện từ (SDT) yếu bởi điện tử tự do trong siêu mạng pha tạp với cơ chế tán xạ điện tử - phonon quang trong hai trường hợp:

- Không có mặt từ trường;
- Có mặt từ trường hướng vuông góc với trục siêu mạng.

Thu nhận sự phụ thuộc khác biệt so với bán dẫn thông thường của tensor độ dẫn cao tần và hệ số hấp thụ sóng điện từ (SDT) yếu vào tần số sóng điện từ yếu (ω, nhiệt độ của hệ T, tần số cyclotron (khi có mặt từ trường) và các tham số đặc trưng cho siêu mạng pha tạp. Thực hiện tính số các biểu thức giải tích thu được, vẽ đồ thị và bàn bạc các kết quả cho trường hợp cụ thể - bán dẫn phap tạp n-GaAs/p-GaAs.