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구속 포텐셜의 전자-압전 포논 상호 작용에 따른 GaAs의 자기장 의존 특성

The Magnetic Field Dependence of the Confinement Potential due to the Interaction of Electron and Piezoelectric Phonon in GaAs Semiconducting Materials

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Abstract - We consider the system is subject to the linearly polarized oscillatory external field. We study the optical quantum transition Line shapes(QTLS) which show the absorption power and the quantum transition line widths(QTLW) of electron-piezoelectric phonon interacting system. We analyze the magnetic field dependence of the QTLS and the QTLW in various cases. In order to analysis the quantum transition, we compare the magnetic field dependence of the QTLW and the QTLS of two transition process, the intra-Landau level transition process and the inter-Landau level transition process.

Key Words : Equilibrium average projection scheme (EAPS), Quantum transport theory(QTR), Quantum transition line widths(QTLW), Uantum transition line shapes(QTLS).

1. Introduction

For the numerical calculation the QTLS and the QTLW, we apply the quantum transport theory(QTR) to the system in the confinement of electrons by square well confinement potential. There are several methods to obtain the useful formulas of scattering factors of the electron-background particle correlation response function [1-5]. The study of the quantum transport theories based on the projected Liouville equation method is a useful tool to investigate the scattering mechanism of solids. Using the projected Liouville equation method [6-10] with the equilibrium average projection scheme (EAPS), we have suggested a new quantum transport theory of linear-nonlinear form [11, 12]. The merit of using EAPS is that the generalized susceptibility andscattering factor can be obtained in one step process of expanding the quantum transport theory.

In this work, we study the optical quantum transition line shapes(QTLS) which show the absorption power and the quantum transition line widths(QTLW) which show the scattering effect of electron-piezoelectric phonon interacting system [13-15]. Through the numerical calculation, we analyze the magnetic field dependence of the QTLS of polarized oscillatory external field in various cases. We also analyze the magnetic field dependence of the QTLW in various cases. The analysis of various cases would be difficult in other theories since they require the calculation of the absorption power to obtain QTLW. However, we can obtain the QTLW directly by the theory of EAPS. In order to analyze the quantum transition process, we compare magnetic field dependence of the QTLW and the QTLS of two transition process, the intra-Landau level transition process and the inter-Landau level transition process.

2. The System

When a static magnetic field is $\vec{B}=B_Z\hat{Z}$ applied to electron system, the single electron energy state is quantized to the Landau levels. We select a system of electrons confined in a infinite square well potential(SQWP) between z=0 and z=Lz in z-direction. Using Landau gauge $\vec{A}=(0,B_x,0)$, we obtain the eigenstate in the system, as below,

$$\psi_{N_\alpha,n_\alpha,k_y,k_z}(x,y,z)\equiv|\alpha>=\widetilde{C}_G\widetilde{\phi}_{kr}^{(plw)}(k)\widetilde{\varphi}_{N_\alpha}(x_1)\widetilde{\Phi}_{n_\alpha}^{(cfn)}(z) \quad (1)$$

where the plan wave is $\widetilde{\Phi}_{kr}^{(plw)}\equiv\exp(ik_ry)$, the explicit function is

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$$\widetilde{\varphi}_{N_\alpha}(x_1) = \widetilde{N}_r \exp(-\frac{x_1^2}{2l_0^2})H_{N_\alpha}(\frac{x_1}{l_0}). \quad (2)$$

Here $H_{N_a}(x)$ is the Hermite polynomials function, $l_0 = \sqrt{\eta/eB}$ is the radius of cyclotron motion, $\omega_c = eB/m_e^*$ is the cyclotron frequency, m_e^* is the effective mass of electron, $x_a = -\eta k_{za}/eB = -\eta k_{za}/m_e^* \omega_0$ is the center of cyclotron motion and $x_1 \equiv x - x_a$. The confined wave function is

$$\widetilde{\Phi}_{n_\alpha}^{(cfn)}(z) = \begin{cases} \frac{1}{\sqrt{\frac{z_0}{2}+\frac{1}{\kappa_{n_\alpha}}}}\sin(k_{n_\alpha} z) & (0 \le z \le z_0) \\ \frac{1}{\sqrt{\frac{z_0}{2}+\frac{1}{\kappa_{n_\alpha}}}}\exp(-\kappa_{n_\alpha}(z-z_0)) & (z_0 \le z) \end{cases} \quad (3)$$

where K_{n_a} and k_{n_a}(the quantization condition for the z-direction components of the electron wave vector of K and k) are obtained by solving the simultaneous equations $K = -k\cot kz_0$ and $K + k = 2m_e^* U_0/\eta$, with the conditions $0 < K$ and $0 < k$. Here the square well confinement potential $U(z) \equiv U_0$ is a constant potential in the region $0 < z < z_0$, and $U(z) \equiv \infty$in the region $z < 0,\ z_0 < z$. The values of normalization factors are $\widetilde{C_G} \equiv 1/\sqrt{L_y}$, $\widetilde{N}_r \equiv 1/\sqrt{(\sqrt{\pi}\,2^N N! l_0)}$. The values of normalization factors change in other systems. We obtain the corresponding eigenvalue, as

$$\varepsilon_{N_\alpha,n_\alpha,k_{y\alpha},k_{z\alpha}} = (N_\alpha + \frac{1}{2})\hbar\omega_c + n_\alpha^2 \frac{\hbar^2\pi^2}{2m_e^* L_{z(sys)}^2}$$
$$(N_a = 0,1,2,3,\ldots,\ n_a = 0,1,2,3,\ldots) \quad (4)$$

Here $L_{z(sys)} \equiv z_0$ is the size of materials in z-direction.

If we consider a system of many body which is subject to circularly polarized oscillatory external fields $E_+(t) = E_0 e^{(i\omega t)}$ where ω is the angular frequency, then, using Coulomb gauge $E(t) = \partial A(t)/\partial t$, the total Hamiltonian of the system is $H(t) = H_s + H'(t) = H_s + (-i/\omega)J_x E_x(t)$. For the other system, we consider a system of many body which is subject to linearly polarized oscillatory external fields, then the induced current operator caused by the linearly external field as

$$J_x = \sum_\beta j_{x\beta}^{(R)} a_\beta^+ a_{\beta+1} + \sum_\beta j_{x\beta}^{(L)} a_{\beta+1}^+ a_\beta \equiv J_x^{(R)} + J_x^{(L)} \quad (5)$$

where $J_x^{(R)}(J_x^{(L)})$ represent the right(left) linearly polarization-current, $j_x^{(R)}(j_x^{(L)})$ is the single electro current operator j in x direction and the matrix element is $j_{x\beta}^{(R)} \equiv \sum_\beta [\beta+1|\,j_x^{(R)}|\beta] = \tilde{g}_{(sys)} \sum_\beta \sqrt{N_\beta + 1}$, $j_{x\beta}^{(l)} \equiv \sum_\beta [\beta|\,j_x^{(l)}|\beta+1] = \tilde{g}_{(sys)} \sum_\beta \sqrt{N_\beta}$ and $|\beta > \alpha|$ is the eigenstate of single electron, where $\widetilde{g_{(sys)}} \equiv (-ie\overline{\eta}/m_e^*)\sqrt{1/l_0^2}$. The $\tilde{g}_{(sys)}$ can be change in other system and external field.

We have the Hamiltonian of the system of the electron-phonon interacting system as

$$H_s = H_e + H_P + V = \sum_\beta \langle\beta|h_0|\beta\rangle a_\beta^+ a_\beta + \sum_q \hbar\omega_q b_q^+ b_q + \sum_q \sum_{\alpha,\mu} C_{\alpha,\mu}(q) a_q^+ a_\mu (b_q + b_{-q}^+) \quad (6)$$

here He is electrons Hamiltonian, he is a single electron Hamiltonian, Hp is the phonon Hamiltonian and V is the electron-phonon(or impurity) interaction Hamiltonian, the $a_1(a_2^+)$ and $b_1(b_2^+)$ are the annihilation operator(creation operator) of fermion and boson particle, and $\tilde{q}$ is phonon(or impurity) wave vector. $C_{\alpha,\mu}(q)$ is the coupling matrix element of electron-phonon interaction $C_{\alpha,\mu}(q) \equiv V_q < \alpha|\exp(i\tilde{q} \bullet \tilde{r})|\mu >$, $\tilde{r}$ is the position vector of electron, Vq is coupling coefficient of materials. The electron-piezoelectric phonon interaction parameter Vq in the isotropic interaction formalism is given by $V(q)^2 = \frac{\overline{K}^2 \eta v_s e^2}{2\chi\epsilon_o qV}\frac{1}{q}$ where $\overline{K}$ is the electromechanical constant, and χ is the dielectric constant. Since that the long wavelength approximation, $\omega_p \approx \nu_z q$ is quite good for piezoelectric materials, we use Kubo's approximation for phonon energy, $\eta\omega_p \approx \eta\nu_z q$ where ν_z is sound velocity in solid.

3. The Absorption Power Formula and The Scattering Factor Function

We suppose that a oscillatory electric field $E(t) = E_0\exp(i\omega t)$ is applied along the z-axis, which gives the absorption power delivered to the system as $P(\omega) = (E_0^2/2)Re\,\sigma(\omega)$, here "Re" denotes "the real part of" and $\sigma(\omega)$ is the optical conductivity tensor which is the coeffitient part of the current formula. The absorption power can be represent the optical quantum transition line shapes(QTLS) and the scattering factor function can be represent the optical quantum transition line widths(QTLW).

We obtain the ohmic linearly current from the response formula with EAPS[11], as

$$J_k^{(L)}(\omega_l) = \left[\frac{-(i/\hbar)\Lambda_{kl}^{(L)}}{\omega_l - A_{kl}^{(L)} + \Xi_{kl}^{(L)}(\omega_l)}\right] E_l(\omega_l). \quad (7)$$

where $A_{kl}^{(L)} = -[(\frac{i}{\omega})\sum_\alpha J_{\alpha+1,\alpha}^+ J_{\alpha,\alpha+1}^+ (f_{\alpha 1} - f_{\alpha+})]$, $A_{kl}^{(L)} = i\omega_c$. The scattering factor functions of linearly polarized external field system. Using the properties of projection operator and the conventional series expansion of the propagator, we obtain the scattering factor as simple form with weak interacting system approximation in pair interacting system, as bellows,

$$\Xi_{kl}^{(L)}(\omega_l) \equiv \frac{i}{\hbar\ \Lambda_{kl}^{(L)}} \langle L'_{(L)} L_v G_d L_v J_x^{(R)} \rangle_B \tag{8}$$

where the diagonal propagator is $G_d = 1/(\eta\omega - L_d)$. In this work, we have a more rigorous interacting Hamiltonian commutative calculation with the moderately weak coupling(MWC) as

$$\begin{aligned} &[a_v^+ a_x (b_l + b_{-l}^+), a_\mu^+ a_{\alpha+1} (b_q + b_{-q}^+)] \\ &= a_v^+ a_x a_\mu^+ a_{\alpha+1} (\delta_{-l,q} + \delta_{l,-q}) + [a_v^+ a_x, a_\mu^+ a_{\alpha+1}](b_q b_{-l}^+ + b_{-q}^+ b_l)] \end{aligned} \tag{9}$$

Using the above relations, we obtain the matrix elements of electron-phonon interacting system. The scattering factor function $\Xi_{kl}(\omega_l)$ is complex as $\Xi_{kl}(\omega) \equiv i\Delta_{total} + \gamma_{total}(\omega)$. In the most cases, the real part of the scattering factor, $\gamma_{total}(\omega) \equiv Re\Xi_{kl}(\omega)$ gives the half width of response type formula. In most case, the imaginary part of the scattering factor Δ_{total} is neglected in real system as a small vale term. Then, through the continuous approximation of the appendix C, in the linearly polarized external field system, we obtain final result of the absorption power formula (or the QTLS formula),

$$P^{(JL)}(\omega) \propto \left(\frac{e^2\omega_c^2}{\pi^2\hbar\omega}\right)\left[\frac{\gamma_{total}^{(JL)}(\omega_c)\sum_{N_\alpha}\int_{-\infty}^{\infty} dk_{z\alpha}(N_\alpha+1)(f_\alpha - f_{\alpha+1})}{(\omega-\omega_c)^2 + (\gamma_{total}^{(JL)}(\omega_c))^2}\right] \tag{10}$$

here the scattering factor function(or QTLW) is given by

$$\begin{aligned} &\gamma_{total}^{(JL)}(\omega) \equiv \mathrm{Re}\,\Xi_{kl}^{(JL)}(\omega_l) \equiv \sum_{\mp}\sum_{N_\alpha=0}\sum_{N_\beta=0} \gamma_{\alpha,\beta}^{(JL)\mp} \\ &= \left(\frac{\Omega}{4\pi\hbar^2\upsilon_s}\right)\left(\frac{\pi}{L_z}(2+\delta(n_\alpha,n_\beta))\right)\sum_{\mp}\sum_{N_\alpha=0}\sum_{N_\beta=0}\int_{-\infty}^{\infty} dk_{z\alpha}\int_{-\infty}^{\infty} dq_z Y_{\alpha,\beta}^{(JL)\mp} \Big/ \sum_{N_\alpha=0}^{\infty}\int_{-\infty}^{\infty} dk_{z\alpha}(N_\alpha+1)(f_\alpha - f_{\alpha+1}) \end{aligned} \tag{11}$$

since the integrand-factors $Y_{\alpha,\beta}^{(JL)\mu}$ is complicate form.

4. The Analysis of the QTLS and QTLW Concluding Remark

It is well known that the piezoelectric-potential scattering is a dominant scattering process in the intrinsic semiconductors such as GaAs and CdS. In this study, from a numerical calculation of Eq. (10) and Eq. (11), the absorption power and line-widths in GaAs are investigated. We used $m^* = 0.066m_o$ and $\overline{m} = 0.40m_o$ which are the effective masses of GaAs. The other constants of GaAs used are the density $\rho = 536kg/m^3$, the longitudinal sound velocity $v_{sl} = 5614m/s$, the transverse sound velocity $v_{st} = 2987m/s$, the characteristic constants of the material $k = 2.52\times10^{-4}eV/K$, $\zeta = 204K$ and the electro-mechanical constant |K|2 = 2.98005×10-2 . The speed of sound ν_s is replaced by the average value $\overline{\nu_s}$ of ν_{sl} and ν_{st}, $\overline{\nu_s} = (\nu_{sl} + \nu_{st})/2$ and the energy gap $\epsilon_g(T)$ is replaced by $\tilde{\epsilon_g} = 1.519eV$, within an the approximation taking into consideration that the variation against the temperature is very small. We choose $\epsilon_0 = 8.85419\times10^{-12}c^2/Nm^2$. In order to compare the QTLW of GaAs. We obtain the line shapes, from which the width can be measured. We analyze the QTLS and QTLW of GaAs .

In Fig. 1., The relative frequency($\Delta\omega$) dependence of the absorption power(QTLS), $P^{(JL)}(\Delta\omega)$ of GaAs, with λ =84, 119, 220, 394, 513 μm at T=50K. From the graph of $P^{(JL)}(\Delta\omega)$, we can see the broadening effects near the resonance peaks for various external fields. The graph in the small box indicates the locations of resonance peaks for external fields.

We can read from graph of the small box, the magnetic-field dependence of the maximum absorption power. The analysis of the relative frequency dependence of the absorption power(QTLS) represent the magnetic field dependency property of absorption power, which is given the external field wavelength and the condition of the system.

In Fig. 2 we obtain the magnetic field dependence of the QTLW, $\gamma(B)$ of GaAs , at T=30, 40, 50, 55, 60, 70, 75, 80, 90, 120K . We see the $\gamma(B)^{(JL)}$ increases as the magnetic field increases in most temperature, while the $\gamma(B)^{(JL)}$ decreases as the magnetic field increases in some high field region(12Tesla ≤ B ≤ 16Tesla) at law temperature(T≤70K). We guess that this property caused from the geometrical characteristic of the sphalerite-type crystals. The analysis of the magnetic field dependence o fthe QTLW in the various magnetic fields is very important to understand the magnetic properties of materials. The analysis of the magnetic field dependence of the QTLW is very difficult in other theories or experiment, because it need to calculate or observe the absorption power in the various external field wavelengths. The QTR theory of EAPS has an advantageous aspect because we can directly obtain the QTLW, through EAPS, in the various external field wavelength. We do not have to calculate the absorption

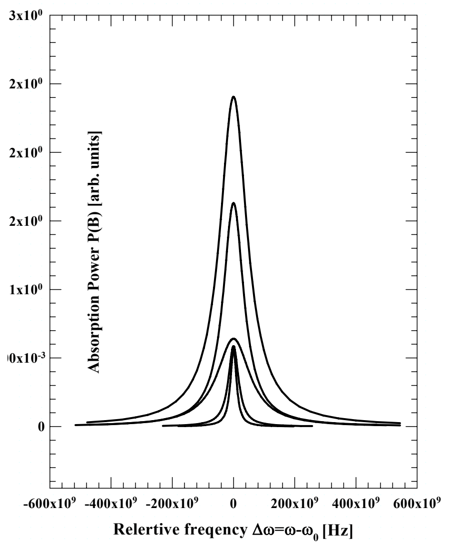

Fig. 1 The relativity frequency($\Delta\omega$) dependence of the absorption power(QTLS), P(B) of GaAs, with λ=84, 119, 220, 394, 513 μm(according to the order from the bottom line to the top line). at T=30K.

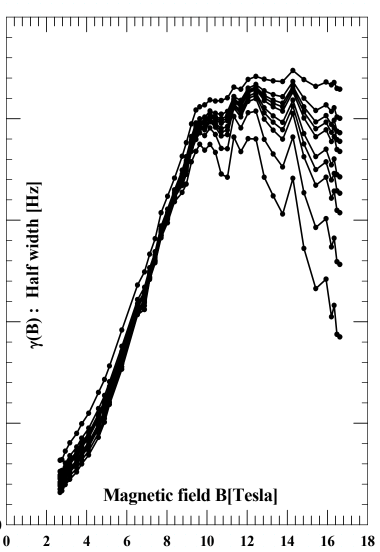

Fig. 2 The magnetic field dependence of of QTLW ,$\gamma(B)$ of GaAs at T=30, 40, 50, 55, 60, 70, 75, 80, 90, 120K (according to the order from the bottom line to the top line).

power to obtain QTLW.

In order to analyze the quantum transition process for the case of the RCF, we denote the total QTLW as $\gamma^{(JL)}_{total} \equiv \gamma(T)^{(JL)}_{intraL} + \gamma(T)^{(JL)}_{interL}$, where $\gamma^{(JL)}_{intraL} \equiv \gamma^{(JL)em}_{intraL} + \gamma^{(JL)ab}_{intraL}$ and $\gamma^{(JL)}_{interL} \equiv \gamma^{(JL)em}_{interL} + \gamma^{(JL)ab}_{interL}$ are the QTLW of the total phonon emission and absorption transition process, respectively. Here, $\gamma^{(JL)em}_{intraL} \equiv \gamma^{(JL)+}_{0,0}$, $\gamma^{(JL)em}_{interL} \equiv \gamma^{(JL)+}_{0,1}$, $\gamma^{(JL)ab}_{intraL} \equiv \gamma^{(JL)-}_{0,0}$ and $\gamma^{(JL)ab}_{interL} \equiv \gamma^{(JL)-}_{0,1}$ are the QTLW of the intra level emission transition, inter level emission transition process, the intra level absorption transition and inter level emission absorption, respectively.

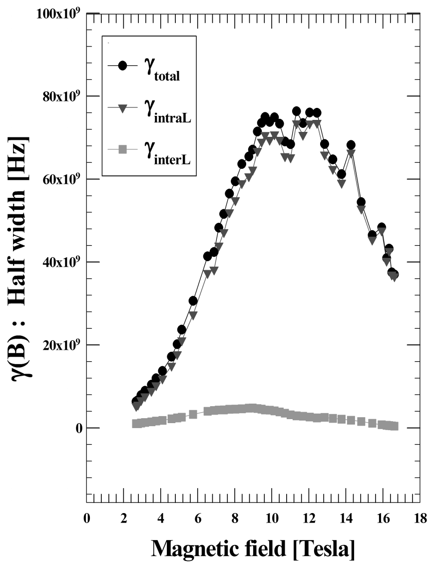

Fig. 3 Comparisons of the magnetic field dependence of QTLW, ɣ(T)total, ɣ(T)intraL, ɣ(T)interL, of GaAs, at T=30K.

In Fig. 3. Comparisons of the magnetic field dependence of QTLW, $\gamma(B)_{total}$, $\gamma(T)_{intraL}$ and $\gamma(T)_{interL}$ of GaAs, at T=50K. We see that $\gamma^{(JL)}_{intraL}$ and $\gamma(T)^{(JL)}_{intraL}$ increase as the magnetic field increases, while $\gamma^{(JC)}_{intraL}$ decreases as the magnetic field increase at high field region $(12\,Tesla \le B)$. The analysis of the contributions of two processes to the total scattering effect represent the characteristic of the magnetic field dependence of the scattering effect of the system. The contributions of two processes can be also appeared in various cases in various systems. In this work, our result show that values of QTLW are $\gamma(T)^{(JL)}_{interL} < \gamma(T)^{(JL)}_{intraL} < \gamma^{(JL)}_{total}$. We also guess these results are quiet reasonable to explain the directional characteristic of electron motion, which is given the magnetic field direction and the condition of the system.

In Fig. 4., we also compare the QTLS , P(B) of GaAs P(B) with the $\gamma^{(JL)}_{total}$, P(B) only with $\gamma(T)^{(JL)}_{interL}$ and P(B) only with $\gamma(T)^{(JL)}_{intraL}$. Since the value of scattering effect is relate to the opposite result of the broadening of the power absorptions, we see a good agreement between ɣ (T) at T=30K of Fig. 3 and the broadening of the power absorptions P(B) of Fig. 4. We also see in these analyses that the more dominant broadening effect of GaAs is the phonon intra-level process in the quantum limit low temperature region. Our result also indicate that the QTR theory of EAPS have some merits to explain the quantum transition in various cases.

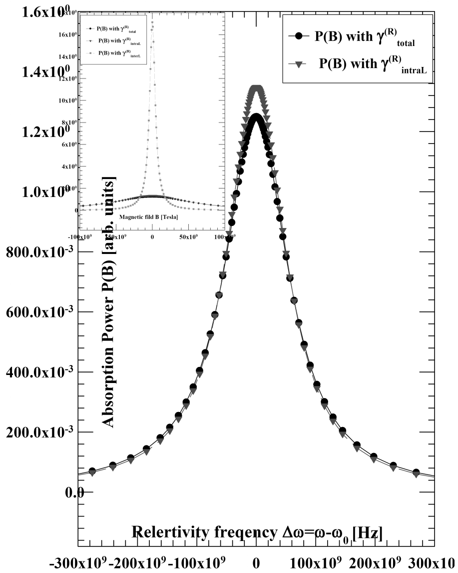

Fig. 4 The relativity frequency($\Delta\omega$) of absorption power, P(B) of GaAs, P(B) with ɣ(T)total, P(B) with ɣ(T)intraL, and P(B) with ɣ(T)interL, with λ=220μm, at T=30K.

For the concluding remarks, we want to emphasize that our EAPS theory makes these analyses of various cases much easier than other theories, since more steps are involved in the calculations in other theories. The EAPS theory enables us to separate the linewidths in terms of each quantum transition for various cases. The easy analysis of each quantum transition processes are the merits of our EAPS theory. Finally, we expect that the EAPS theory is also useful in other condensed material systems.

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