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The Magnetic Field Dependence Properties of Quasi Two Dimensional Electron-piezoelectric Potential Interacting System in GaN and ZnO

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We investigated theoretically the magnetic field dependence of the quantum optical transition of qusi 2-Dimensional Landau splitting system, in GaN and ZnO. We apply the Quantum Transport theory (QTR) to the system in the confinement of electrons by square well confinement potential. We use the projected Liouville equation method with Equilibrium Average Projection Scheme (EAPS). Through the analysis of this work , we found the increasing properties of the optical Quantum Transition Line Shapes(QTLSs) which show the absorption power and the Quantum Transition Line Widths(QTLWs) with the magnetic-field in GaN and ZnO. We also found that QTLW, $\gamma(B)_{total}$ of GaN $<\gamma(B)_{total}$ of ZnO in the magnetic field region B < 25 Tesla.

Keywords : GaN and ZnO, quantum transport theory, equilibrium average projection scheme (EAPS), electron phonon coupling system, quantum transition line shapes (QTLS), quantum transition line widths (QTLW), cyclotron resonance

1. Introduction

We investigated the quantum optical transition properties of GaN and ZnO, in qusi 2-Dinensinal Landau splitting system, based on quantum transport theory. The study of magneto-optical transitions has been known to be a good tool for investigating the transport behavior of electrons in low-dimensional electron systems. There are many theories regarding the quantum transport problems in various methodologies [1-16], among them we use the projected Liouville equation method with the Equilibrium Average Projection Scheme (EAPS) [11]. The merit of using EAPS is that the quantum response function and the scattering factor formula can be obtained in a one-step process by expanding the quantum transport theory. However, the previous work [12], we applied the EAPS theory in Ge and Si, since there are abundant experimental date [13] in non-confining potential systems. We compared our results of numerical calculations of the EAPS theory [12] with existing experimental data [13] and got a good agreement between them. This indicated that the EAPS theory is useful in analyzing many-body systems. But, the previous work [12] restricted for non-confining potential systems with the extremely weak coupling (EWC) approximation. The optical power absorption spectrum of the transitions measured in experiments is directly related to the electric conductivity tensor, and the spectrum's line-width to its line-shape function. Hence, it is important to obtain an explicit expression of the line-shape function for a given confining potential system on the basis of a theoretical formulation. Recently, we suggested a more precise procedure of expanding and application of EAPS in Low-dimensional electron systems with the moderately weak coupling (MWC) approximation in Ref. [14-16]. In the MWC scheme, the distribution components can provide an adequate explanation of the quantum transition processes [14-16]. In a previous work [12] of EWC scheme, the intermediate states of quantum transition processes do not appear.

Recently, we suggested the absorption power formula in Ref. [16] in confining potential systems. With the continuous approximation [15], in a right circularly polarized external field, the absorption power formula (or the QTLS formula) and the scattering factor function (or QTLW) were obtained. Through the numerical calculation of the

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theoretical result, we investigate the optical Quantum Transition Line Shapes (QTLSs) which show the absorption power and the Quantum Transition Line Widths (QTLWs), which show the scattering effect in the electron-piezoelectric potential phonon interacting system.

2. Formulae

When a static magnetic field $\vec{B}=B_z\hat{z}$ is applied to an electron system, the single electron energy state is quantized to the Landau levels. We select a system of electrons confined in an infinite square well potential (SQWP) between $z=0$ and $z=L_z$ in the z-direction. We use the eigenvalue and eigenstate of Ref. [10] of the square well potential system. We suppose that an 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 $P(\omega)=(E_0^2/2)\mathrm{Re}\{\sigma(\omega)\}$, where "R" denotes the real component and $\sigma(\omega)$ is the optical conductivity tensor that is the coefficient of the current formula. Here the absorption power represents the optical QTLS, and the scattering factor function represents the optical QTLW. We consider the electron-phonon interacting system and then we have the Hamiltonian of the system as follow.

$$H_s = H_e + H_P + V = \sum_{\beta}\langle\beta|h_0|\beta\rangle a_\beta^+ a_\beta + \sum_q \hbar\omega_q b_q^+ b_q + \sum_q\sum_{\alpha,\mu} C_{\alpha,\mu}(q) a_q^+ a_\mu \left(b_q + b_{-q}^+\right) \tag{1}$$

In (1), H_e is the electron Hamiltonian, h_0 is a single-electron Hamiltonian, H_P is the phonon Hamiltonian and V is the electron-phonon (or impurity) interaction Hamiltonian. The $b_1(b_2^+)$ is the annihilation operator (creation operator) of boson particle, and $\vec{q}$ is phonon (or impurity) wave vector. The interaction Hamiltonian of electronphonon (or impurity)-interacting system is $V \equiv \sum_q\sum_{\alpha,\mu} C_{\alpha,\mu}(q) a_\alpha^+ a_\mu \left(b_q + b_{-q}^+\right)$ where the coupling matrix element of electron-phonon interaction $C_{\alpha,\mu}(q)$ is $C_{\alpha,\mu}(q) \equiv V_q < \alpha | \exp(i\vec{q}\cdot\vec{r}) | \mu >$, $\vec{r}$ is the position vector of electron and V_q is the coupling coefficient of the materials. For the optical quantum transition system under a right circularly polarized external field current, we replace the current with $J_k \equiv J^-$ and $J_l \equiv J^+$ for the current system under an oscillating external field of frequency ω. The many-electron current operators J^- and J^+ are defined $J^- \equiv \tilde{g}_{(sys)} \sum_\beta \sqrt{N_\beta} a_\beta^+ a_{\beta+1}$ and $J^+ \equiv \tilde{g}_{(sys)} \sum_\beta \sqrt{(N_\beta+1)} a_{\beta+1}^+ a_\beta$ with $\tilde{g}_{(sys)} \equiv (-ie\hbar/m_e^*)\sqrt{1/l_0^2}$. where $l_c^2 \equiv \hbar/eB$ $\tilde{g}_{(sys)}$ can be changed for other systems and external fields.

Recently, we suggested a more precise procedure of expanding and application of EAPS with the moderately weak coupling (MWC) approximation in Ref. [14-16]. Using the properties of the projection operator and the conventional series expansion of the propagator, we obtained a right circularly polarized external field current $J^R(\omega)$ and the scattering factor $\Xi_{kl}^{(R)}(\omega)$ in a simple form by using a weak interacting system approximation in pair interacting system as

$$J^R(\omega) = \left[\frac{-(i/\hbar)\Lambda_{kl}^{(R)}}{\omega - A_{kl}^{(R)} + \Xi_{kl}^{(R)}(\omega)}\right] E(\omega), \tag{2}$$

where $\Lambda_{kl}^{(R)} = -\{(\frac{i}{\omega})\sum_\alpha j_{\alpha+1,\alpha}^+ j_{\alpha,\alpha+1}^+ (f_{\alpha+1} - f_\alpha)\}$, $A_{kl}^{(R)} = i\omega_c$.

$$\Xi_{kl}^{(R)}(\omega_l) \equiv \frac{i}{\hbar\,\Lambda_{kl}^{(R)}} \langle L_+' L_v G_d L_v J^- \rangle, \tag{3}$$

where the diagonal propagator is $G_d = 1/(\hbar\omega - L_d)$ and $\omega_c = eB/m_e^*$, m_e^* are the cyclotron frequency and the effective mass of electron.

Here, we used the Ref. [11], $Tr^{(e)}\{J_k L_1 L_2 \cdots\cdots L_n L' \rho_s\} = (-1)^{n+1}\langle L' L_n \cdots\cdots L_2 L_1 J_k\rangle$, and the $\langle\cdots\rangle$ means the ensemble average of the electron states and background particle state.

The scattering factor function, $\Xi_{kl}(\omega_l)$, is expressed in a complex form like $\Xi_{kl}(\omega_l) \equiv i\Delta_{total} + \gamma_{total}(\omega)$ with $\Delta_{total} \equiv \mathrm{Im}(\omega_l)$, giving a line shift of a response-type formula, and $\gamma_{total}(\omega) \equiv \mathrm{Re}\Xi_{kl}(\omega)$ giving the half-width of the response-type formula. In most cases, the imaginary part of the scattering factor, Δ_{total}, is negligible in a real system because of its small value. In the continuous approximation [15], in a right circularly polarized external field, the absorption power formula (or the QTLS formula) is obtained finally as bellow.

$$P(\omega) \propto \left(\frac{e^2\omega_c^2}{\pi^2\hbar\omega}\right)\left\{\frac{\gamma_{total}(\omega_c)\sum_{N_\alpha}\int_{-\infty}^{\infty} dk_{z\alpha}(N_\alpha+1)(f_\alpha - f_{\alpha+1})}{(\omega-\omega_c)^2 + (\gamma_{total}(\omega_c))^2}\right\} \tag{4}$$

Here, the scattering factor function (or QTLW) is given by the following formula:

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

In continuous approximation [12], the interaction matrix

part in the SQWP system are as below,

$$[C_{N_\alpha,N_\beta}(q)C_{N_\beta,N_\alpha}(q)]^{\mp} \equiv \left|V_q\right|^2 K^{\alpha,\beta}_{\beta,\alpha}(t)\,|\,F_{\alpha,\beta}(q)\,|^2\ \delta_{k_{\beta_z},k_{\alpha_z}\pm q_z},$$
$$[C_{N_\beta,N_\alpha}(q)C_{\ N_\alpha,N_\beta}(q)]^{\mp} \equiv \left|V_q\right|^2 K^{\beta,\alpha}_{\alpha,\beta}(t)\,|\,F_{\beta,\alpha}(q)\,|^2\ \delta_{k_{\beta_z},k_{\alpha_z}\mp q_z}, \quad (5)$$

and, if $N_\alpha < N_\beta$ and $N_\kappa < N_\lambda$, the K-matrix is

$$K^{\alpha,\beta}_{\chi,\lambda}(t) \equiv \sqrt{N_\alpha!/N_\beta!}\sqrt{N_\chi!/N_\lambda!}(\sqrt{t})^{(N_\beta-N_\alpha)}(\sqrt{t})^{(N_\lambda-N_\chi)} \exp(-t)L^{N_\beta-N_\alpha}_{N_\alpha}(t)L^{N_\lambda-N_\chi}_{N_\chi}(t), \quad (6)$$

where the Legendre function is $L^m_n(t)=(n!)^{-1}\exp(t)t^{-m}(d^n/dt^n)[t^{n+m}\exp(-t)]$ and $t \equiv (r_0^2(q^{\mp\kappa\lambda}_{\perp n})^2)/2$. The matrix element of the confinement potential is

$$|F_{\beta,\alpha}(q)|^2 \equiv \left|\int_{-\infty}^{\infty}\widetilde{\Phi}^{(cfn)}_{\beta}(z)\exp(iq_z z)\widetilde{\Phi}^{(cfn)}_{\alpha}(z)dq_z\right|^2 = \frac{\pi}{L_z}(2+\delta_{N_\alpha,N_\beta}). \quad (7)$$

Then, through continuous approximation, we obtain the final derivation of the integrand of the scattering factor is

$$\begin{aligned} Y^{\mp}_{\alpha,\beta} \equiv\ & J^{A\mp}_{\beta,\alpha+1}\binom{\alpha,\beta}{\beta,\alpha}(N_\alpha+1)(f_{\alpha+1}-f_\alpha) \\ & - J^{B\mp}_{\beta,\alpha+1}\binom{\alpha,\beta}{\beta+1,\alpha+1}\sqrt{(N_\alpha+1)(N_\beta+1)}\left(f^{\pm}_{\beta+1}-f^{\pm}_{\beta}\right) \\ & - J^{C\mp}_{\alpha,\beta+1}\binom{\beta,\alpha}{\alpha+1,\beta+1}\sqrt{(N_\alpha+1)(N_\beta+1)}\left(f^{\mp}_{\beta+1}-f^{\mp}_{\beta}\right) \\ & + J^{D\mp}_{\alpha,\beta}\binom{\beta,\alpha+1}{\alpha+1,\beta}(N_\alpha+1)(f_{\alpha+1}-f_\alpha) \end{aligned}$$

here, the terms of electron-phonon- interacting parts are

$$\begin{aligned} J^{A\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu}) \equiv\ & \left\{\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\beta\alpha}_{\perp 1})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\beta\alpha}_{\perp 1})\pm\left(1-f^{\pm}_{\beta}\right)\right]\right. \\ & \left.+\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\beta\alpha}_{\perp 2})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\beta\alpha}_{\perp 2})\pm\left(1-f^{\pm}_{\beta}\right)\right]\right\} \\ J^{B\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu}) \equiv\ & \left\{\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\beta\alpha}_{\perp 1})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\beta\alpha}_{\perp 1})\mp f_{\alpha+1}\right]\right. \\ & \left.+\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\beta\alpha}_{\perp 2})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\beta\alpha}_{\perp 2})\mp f_{\alpha+1}\right]\right\} \\ J^{C\mp}_{\alpha,\beta}(^{\kappa,\eta}_{\mu,\nu}) \equiv\ & \left\{\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\alpha\beta}_{\perp 3})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\alpha\beta}_{\perp 3})\pm\left(1-f^{\mp}_{\beta+1}\right)\right]\right. \\ & \left.+\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\alpha\beta}_{\perp 4})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\alpha\beta}_{\perp 4})\pm\left(1-f^{\mp}_{\beta+1}\right)\right]\right\} \\ J^{D\mp}_{\alpha,\beta}(^{\kappa,\eta}_{\mu,\nu}) \equiv\ & \left\{\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\alpha\beta}_{\perp 3})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\alpha\beta}_{\perp 3})\mp f^{\mp}_{\beta}\right]\right. \\ & \left.+\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu})(q_z,q^{\mp\alpha\beta}_{\perp 4})\left[\widetilde{N}^{\pm}_q(q_z,q^{\mp\alpha\beta}_{\perp 4})\mp f^{\mp}_{\beta}\right]\right\} \end{aligned} \quad (8)$$

with the interacting matrix, the $\tilde{S}$-matrix, being

$$\widetilde{S}^{\mp}_{\beta,\alpha}(^{\kappa,\eta}_{\mu,\nu};q_z,q^{\mp\beta\alpha}_{\perp n}) \equiv V(q_z,q^{\mp\beta\alpha}_{\perp n})^2\frac{\sqrt{(q^{\mp\beta\alpha}_{\perp n})^2+q_z^2}}{|\hbar v_s q_{\perp n}|}K^{\kappa,\eta}_{\mu,\nu}(\frac{r_0^2}{2}(q^{\mp\beta\alpha}_{\perp n})^2)\cdot \quad (9)$$

Here, the vertical components of phonon wave vectors $q^{\mp\kappa\lambda}_{\perp n}$ (n = 1, 2, 3, 4) are

$$q^{\mp\beta\alpha}_{\perp 1} \equiv +\sqrt{\left(\frac{\pm}{\hbar v_s}\right)^2\left\{\widetilde{E}^{(el)}_{\beta\alpha}-\widetilde{E}^{(cfp)}_{\beta\alpha}-\widetilde{E}^{(k\varepsilon)}_1\right\}^2-\widetilde{q}^2_{sys}} \equiv -q^{\mp\beta\alpha}_{\perp 2}, \quad (10)$$

$$q^{\mp\beta\alpha}_{\perp 3} \equiv +\sqrt{\left(\frac{\pm}{\hbar v_s}\right)^2\left\{\widetilde{E}^{(el)}_{\alpha\beta}-\widetilde{E}^{(cfp)}_{\alpha\beta}+\widetilde{E}^{(k\varepsilon)}_3\right\}^2-\widetilde{q}^2_{sys}} \equiv -q^{\mp\beta\alpha}_{\perp 4} \quad (11)$$

where

$$\widetilde{E}^{(el)}_{\beta\alpha} \equiv \hbar\omega-(N_\beta-N_\alpha)\hbar\omega_0,\ \widetilde{E}^{(cfp)}_{\beta\alpha} \equiv \left[(N_\beta+1)^2-(N_\alpha+1)^2\right]\hbar\widetilde{w}_0$$

$$\widetilde{E}^{(k\varepsilon)}_1 \equiv \frac{\hbar^2}{2m^*}(\pm 2k_{z_\alpha}q_z+q_z^2),\quad \widetilde{E}^{(k\varepsilon)}_3 \equiv \frac{\hbar^2}{2m^*}(\mp 2k_{z_\alpha}q_z+q_z^2),$$

$$\widetilde{q}_{sys} \equiv q_y^2+q_z^2$$

$\widetilde{w}_0 \equiv \widetilde{\varepsilon}^{(sys)}_0/\hbar \equiv \hbar\pi^2/2m^*L^2_{z(sys)}$, $L_{z(sys)} = 20$ nm. The electron-piezoelectric phonon interaction parameter with the vertical components of phonon wave vectors $q^{\mp\kappa\lambda}_{\perp n}$ (n = 1, 2, 3, 4) is

$$V(q_z,q^{\mp\kappa\lambda}_{\perp n})^2 = \frac{\overline{K}^2\hbar\upsilon_s e^2}{2\chi\varepsilon_0 V}\frac{1}{\sqrt{q_z^2+(q^{\mp\kappa\lambda}_{\perp n})^2}} \quad (12)$$

The Fermi-Dirac distribution functions are $f_\alpha = 1/[e^{\varepsilon_\alpha/k_\beta T}+1]$ and $f^{\pm}_{\beta} = 1/[e^{\tilde{\varepsilon}^{\pm}_\beta/k_\beta T}+1]$, where eigenvalues are $\varepsilon_\alpha \equiv \varepsilon_{N_\alpha n_\alpha k_{y\alpha}k_{z\alpha}}+(\varepsilon_c-\varepsilon_F)$, $\tilde{\varepsilon}^{\pm}_\beta \equiv \left[\varepsilon_{N_\alpha,n_\alpha,k_{y\alpha},k_{z\alpha}}+(\varepsilon_c-\varepsilon_F)\right]\tilde{\Delta}(k_{r\beta})$, here $\tilde{\Delta}(k_{r\beta}) \equiv \Delta(k_{x\beta}, k_{x\alpha}\pm q_x)\,\Delta(k_{y\beta}, k_{y\alpha}\pm q_y)$, and the chemical potential energy is $\varepsilon_c-\varepsilon_F(T) = 0.5[E_g(T)-(3/4)K_BT\ln(\overline{m}/m^*)]$, and ε_c is the conduction band minimum energy, $\varepsilon_F(T)$ is the Fermi energy, $E_g(T) = E_g(0)-\kappa T/(T+\xi)$ is the band gap energy at T, κ and ξ are characteristic constant of the material, m^* is the effective mass of electron, $\overline{m}$ is the effective mass of hole. The phonon distribution parts are $\tilde{N}^{-}_q \equiv \langle b^+_q b_l\rangle = n_q\delta_{ql}$ and $\tilde{N}^{+}_q \equiv \langle b_l b^+_q\rangle = (n_q+1)\delta_{ql}$, where the Bose-Einstien distribution function is $n_q = \{[e^{\varepsilon(q,T)}-1]^{-1}\}$. Here the phonon energy is

$$\varepsilon(q,T) = \left\{\frac{\hbar\omega_q}{K_BT}\right\} = \left\{\frac{\hbar v_s}{K_BT}\sqrt{(q^{\mp\kappa\lambda}_{\perp n})^2+q_z^2}\right\}. \quad (13)$$

The result can be apply directly to numerical analysis through wave vector integration.

3. Result and Discussion

In this work, in GaN and ZnO, we investigate the optical Quantum Transition Line Shapes(QTLSs) that show the absorption power and the Quantum Transition Line Widths (QTLWs), that show the scattering effect in the electron-piezoelectric potential phonon interacting system. The analysis of the magnetic field dependence of the QTLWs is very difficult in alternative theories or experiment,

Table 1. Material constant of GaN.

Symbol	Contents	Value
m^*	Effective mass of electron	0.22 m_0
$\overline{m}$	Effective mass of hole	0.58 m_0
ρ	Mass density	4820 kg/m^3
κ	Characteristic constant	8.58×10^{-4} eV/K
ξ	Characteristic constant	235 K
$\overline{K}$	Electromechanical constant	2.6×10^{-2} m/s
$\overline{v}_s$	Speed of sound	3045 m/s
$\tilde{\varepsilon}_s$	Energy gap	3.4 eV
L_z	Length of well of z direction	20×10^{-6} m

Table 2. Material constant of ZnO.

Symbol	Contents	Value
m^*	Effective mass of electron	0.27 m_0
$\overline{m}$	Effective mass of hole	1.8 m_0
ρ	Mass density	4090 kg/m^3
κ	Characteristic constant	17.88×10^{-4} eV/K
ξ	Characteristic constant	204
$\overline{K}$	Electromechanical constant	6×10^{-2} m/s
$\overline{v}_s$	Speed of sound	4300.5 m/s
$\tilde{\varepsilon}_s$	Energy gap	3.42 eV
L_z	Length of well of z direction	20×10^{-9} m

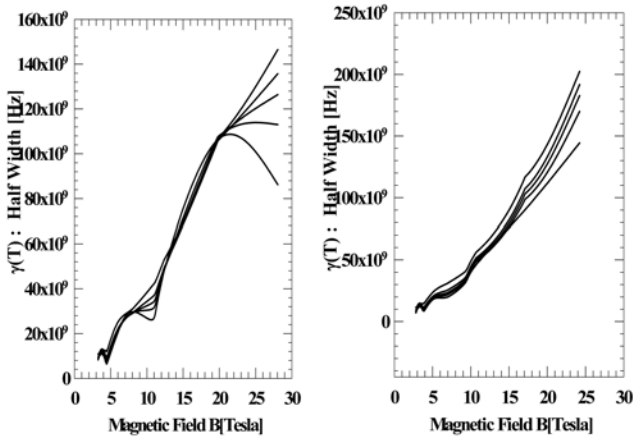

Fig. 1. Magnetic field dependence of QTLW, $\gamma(B)$ of GaN (left side) and ZnO (right side) at T = 50, 70, 90, 120 and 210 K (from the bottom line to the top line).

because the absorption power in the various external field wavelengths is required to be calculated or observed. The QTR theory of EAPS is advantageous in this respect as it allows the QTLWs to be directly obtained, through EAPS, in the various cases. In short the calculation of the absorption power is not required to obtain the QTLW. Through the numerical calculation of the theoretical result, of QTLS that of the QTLW, we analyze absorption

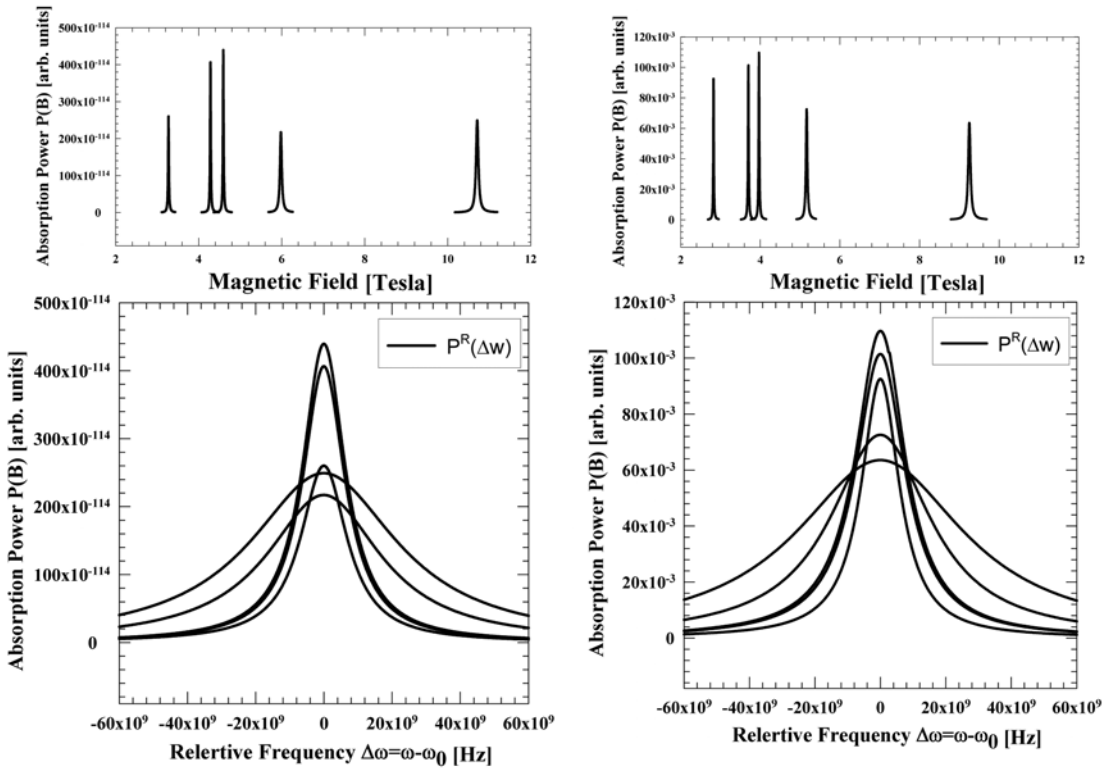

Fig. 2. The magnetic field dependence of the absorption power, $P(B)$ (QTLS) of GaN (upper of left side) and ZnO (upper of right side) and the relativity frequency dependence of $P(\Delta\omega)$ (QTLS) of GaN (lower of left side) and ZnO (lower of right side) with λ = 220, 394, 513, 550 and 720 μm at T = 50.

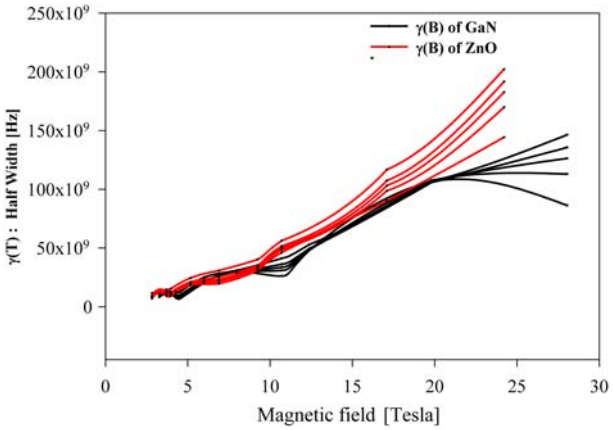

Fig. 3. (Color online) Comparisons Magnetic field dependence of QTLW, $\gamma(B)_{total}$ of GaN and $\gamma(B)_{total}$ of ZnO at T = 50, 70, 90, 120 and 210 K (from the bottom line to the top line).

power and line widths of GaN and ZnO. In order to analyze the QTLW and the QTLS, We use the material constant of reference [17-19]. We arrange the material constant at the Table 1 and 2.

In Fig. 1, it is shown that the magnetic field dependence of QTLW, $\gamma(B)_{total}$ of GaN (left side) and $\gamma(B)_{total}$ of ZnO (right side) at T = 50, 70, 90, 120 and 210 K. As shown in Fig. 1, $\gamma(B)_{total}$ of GaN and ZnO increase as the magnetic field increase at T = 50, 70, 90, 120 and 210 K. In the Fig. 2, we can read the magnetic-field dependence of the maximum absorption power of GaN (upper of left side) and ZnO (upper of right side). The Fig. 2 shows the relative frequency dependence of the absorption power (QTLS), $P(\Delta\omega)$ of GaN (lower of left side) and ZnO (lower of right side) with λ = 220, 394, 513, 550 and 720 μm at T = 50 K. The analysis of the relative frequency dependence of the absorption power (QTLS) represents the magnetic-field dependent property of the absorption power given for an external field wavelength and the conditions of the system. The broadening effects near the resonance peaks for various external fields appeared. In Fig. 3, Comparisons of the magnetic field dependence of QTLW, $\gamma(B)_{total}$ of GaN and $\gamma(B)_{total}$ of ZnO, at T = 50, 70, 90, 120 and 210 K, is shown. Our results reveal that $\gamma(B)_{total}$ of GaN < $\gamma(B)_{total}$ of ZnO in the magnetic field region B < 25 Tesla.

4. Summary

As a summary, the relatively easy approach to the analysis of the magnetic field dependence of QTLW and QTLS is one of merits of our EAPS theory. Through the analysis of the present study, we found the increasing properties of QTLW and QTLS of GaN and ZnO with the magnetic-field. we also found that $\gamma(B)_{total}$ of ZnO < $\gamma(B)_{total}$ of GaN in the magnetic field region B < 25 Tesla. We also showed the reasonable resonating pictures of QTLS. The results of this work will help to analyze experimental the scattering mechanisms in the electron-piezoelectric potential interacting materials. The results indicate that the QTR of EAPS is a useful method to explain the resonant phenomena based on the quantum transition and scattering effect in a microscopic view. It is to be regretted that this result cannot be checked experimentally because no experimental results are available as yet. However, we expect the results in Figs. 1 and 3 to be of help in any future experimental works.

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