Progress In Electromagnetics Research Letters, Vol. 15, 175–185, 2010

THE INFLUENCES OF CONFINED PHONONS ON THE NONLINEAR ABSORPTION COEFFICIENT OF A STRONG ELECTROMAGNETIC WAVE BY CONFINED ELECTRONS IN DOPING SUPERLATTICES

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Abstract—The influences of confined phonons on the nonlinear absorption coefficient (NAC) by a strong electromagnetic wave for the case of electron-optical phonon scattering in doped superlattices (DSLs) are theoretically studied by using the quantum transport equation for electrons. The dependence of NAC on the energy ($\hbar\Omega$), the amplitude E_0 of external strong electromagnetic wave, the temperature (T) of the system, is obtained. Two cases for the absorption: Close to the absorption threshold $|k\hbar\Omega - \hbar\omega_0| \ll \bar{\varepsilon}$ and far away from the absorption threshold $|k\hbar\Omega - \hbar\omega_0| \gg \bar{\varepsilon}$ ($k = 0, \pm1, \pm2, \ldots, \hbar\omega_0$ and $\bar{\varepsilon}$ are the frequency of optical phonon and the average energy of electrons, respectively) are considered. The formula of the NAC contains a quantum number m characterizing confined phonons. The analytic expressions are numerically evaluated, plotted and discussed for a specific of the n-GaAs/p-GaAs DSLs. The computations show that the spectrums of the NAC in case of confined phonon are much different from they are in case of unconfined phonon and strongly depend on a quantum number m characterizing confinement phonon.

1. INTRODUCTION

Recently, there are more and more interests in studying and discovering the behavior of low-dimensional system, in particular two-dimensional systems, such as semiconductor superlattices (SSLs), quantum wells and DSLs. The confinement of electrons in low-dimensional systems considerably enhances the electron mobility and leads to unusual

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behaviors under external stimuli. Many papers have appeared dealing with these behaviors, for examples, electron-phonon interaction and scattering rates [1–3] and electrical conductivity [4, 5]. The problems of the absorption coefficient for a weak electromagnetic wave (EMW) in semiconductor [6, 7], in quantum wells [8] and in DSLs [9] have also been investigated and resulted by using Kubo-Mori method. The nonlinear absorption problem of free electrons in normal bulk semiconductors [10] and confined electrons in quantum wells [11] with case of unconfined phonons have been studied by quantum kinetic equation method. However, the nonlinear absorption problem of an electromagnetic wave, which strong intensity and high frequency with case of confined phonons is stills open for study. So in this paper, we study the NAC of a strong electromagnetic wave by confined electrons in DSLs with the influence of confined phonons. Then, we estimate numerical values for a specific of the n-GaAs/p-GaAs DSLs to clarify our results and compare with case of unconfined phonons and the linear absorption [9].

2. NONLINEAR ABSORPTION COEFFICIENT IN CASE CONFINED PHONONS

In this paper, we assume that the quantization direction is the z direction. The Hamiltonian of the electron-optical phonon system in the second quantization representation can be written as:

$$H = \sum_{n,\vec{k}_\perp} \varepsilon_n \left(\vec{k}_\perp - \frac{e}{\hbar c}\vec{A}(t)\right) a^+_{n,\vec{k}_\perp} a_{n,\vec{k}_\perp} + \sum_{m,\vec{q}_\perp} \hbar\omega_{m,\vec{q}_\perp} b^+_{m,\vec{q}_\perp} b_{m,\vec{q}_\perp} + \sum_{m,\vec{q}_\perp} \sum_{n,n',\vec{k}_\perp} C_{m,\vec{q}_\perp} I^m_{n,n'} a^+_{n',\vec{k}_\perp+\vec{q}_\perp} a_{n,\vec{k}_\perp} \left(b_{m,\vec{q}_\perp} + b^+_{m,\vec{q}_\perp}\right) \tag{1}$$

here, n ($n = 1, 2, 3, \ldots$) denotes the quantization of the energy spectrum in the z direction, $(n, \vec{k}_\perp)$ and $(n, \vec{k}_\perp + \vec{q}_\perp)$ are electron states before and after scattering, $(\vec{k}_\perp, \vec{q}_\perp)$ is the in-plane (x, y) wave vector of the electron (phonon), $a^+_{n',\vec{k}_\perp}$, $a_{n,\vec{k}_\perp}$ ($b^+_{m,\vec{q}_\perp}$, $b_{m,\vec{q}_\perp}$) are the creation and the annihilation operators of the electron (phonon), respectively; $\vec{A}(t)$ is the vector potential open external electromagnetic wave. $\vec{A}(t) = \frac{c}{\Omega}\vec{E}_0 \cos(\Omega t)$ and $\hbar\omega_0$ is the energy of the optical phonon. $C_{m,\vec{q}_\perp}$ is a constant in the case of electron-optical phonon interaction:

$$\left|C^m_{\vec{q}_\perp}\right|^2 = \frac{2\pi e^2 \hbar\omega_0}{V}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right)\frac{1}{q^2_\perp - q^2_z} \tag{2}$$

here, V, e are the normalization volume (often $V = 1$), the effective charge, χ_0 and χ_∞ are the static and high-frequency dielectric constant, respectively. In case confined phonons: $q_z = \frac{m\pi}{d}$; d is in DSLs period; $m = 1, 2, \ldots$ is the quantum number characterizing confined phonons. The electron form factor, $I^m_{n,n'}$, is written as [3, 5]:

$$I^m_{n,n'} = \sum_{j=1}^{N} \int_0^d e^{iq_z z} \phi_n\left(z - jd\right) \phi_{n'}\left(z - jd\right) dz, \tag{3}$$

The electron energy takes the simple:

$$\varepsilon_n\left(\vec{k}_\perp\right) = \omega_p\left(n + \frac{1}{2}\right) + \frac{\hbar^2 k_\perp^2}{2m^*} \tag{4}$$

with $\omega_p = \hbar(\frac{4\pi e^2 n_D}{\varepsilon_0 m^*})^{1/2}$, ε_0 is the electronic constant, n_D is the doping concentration, m^* is the effective mass. In order to establish the quantum kinetic equations for electrons in DSLs, we use general quantum equations for the particle number operator (or electron distribution function) $n_{n,\vec{k}_\perp}(t) = \langle a^+_{n',\vec{k}_\perp} a_{n,\vec{k}_\perp}\rangle_t$ [6]

$$i\hbar \frac{\partial n_{n,\vec{k}_\perp}(t)}{\partial t} = \left\langle a^+_{n',\vec{k}_\perp} a_{n,\vec{k}_\perp}, H\right\rangle_t. \tag{5}$$

where $\langle\psi\rangle_t$ denotes a statistical average value at the moment t, and $\langle\psi\rangle_t = Tr(\hat{W}\hat{\psi})$ ($\hat{W}$ being the density matrix operator). Starting from Hamiltonian (1) and using the commutative relations of the creation and the annihilation operators, we obtain the quantum kinetic equation for electrons in DSLs:

$$\begin{aligned}
&\frac{\partial n_{n,\vec{k}_\perp}(t)}{\partial t} \\
&= -\frac{1}{\hbar^2} \sum_{s,l=-\infty}^{\infty} J_s\!\left(\frac{\lambda}{\Omega}\right) J_l\left(\frac{\lambda}{\Omega}\right) \exp[-i(s-l)\Omega t] \sum_{\vec{q}_\perp,n} |C^m_{\vec{q}}|^2 \left|I^m_{n,n'}(q_z)\right|^2 \int_{-\infty}^{t} dt_1 \\
&\quad \times \Big\{ \left[n_{n,\vec{k}_\perp}(t_1) N_{\vec{q}} - n_{n',\vec{k}_\perp+\vec{q}_\perp}(t_1)\left(N_{\vec{q}}+1\right)\right] \\
&\quad \exp\left[\frac{i}{\hbar}\left(\varepsilon_{n'}\left(\vec{k}_\perp+\vec{q}_\perp\right) - \varepsilon_n\left(\vec{k}_\perp\right) - \hbar\omega_0 - l\hbar\Omega + i\delta\right)(t-t_1)\right] \\
&\quad + \left[n_{n,\vec{k}_\perp}(t_1)\left(N_{\vec{q}}+1\right) - n_{n',\vec{k}_\perp+\vec{q}_\perp}(t_1) N_{\vec{q}}\right] \\
&\quad \exp\left[\frac{i}{\hbar}\left(\varepsilon_{n'}\left(\vec{k}_\perp+\vec{q}_\perp\right) - \varepsilon_n\left(\vec{k}_\perp\right) + \hbar\omega_0 - l\hbar\Omega + i\delta\right)(t-t_1)\right] \\
&\quad - \left[n_{n',\vec{k}_\perp-\vec{q}_\perp}(t_1)\left(N_{\vec{q}}+1\right) - n_{n,\vec{k}_\perp}(t_1) N_{\vec{q}}\right]
\end{aligned}$$

$$\exp\left[\frac{i}{\hbar}\left(\varepsilon_n\left(\vec{k}_\perp\right)-\varepsilon_{n'}\left(\vec{k}_\perp-\vec{q}_\perp\right)-\hbar\omega_0-l\hbar\Omega+i\delta\right)(t-t_1)\right]$$
$$-\left[n_{n',\vec{k}_\perp-\vec{q}_\perp}(t_1)\left(N_{\vec{q}}+1\right)-n_{n,\vec{k}_\perp}(t_1)N_{\vec{q}}\right]$$
$$\exp\left[\frac{i}{\hbar}\left(\varepsilon_n\left(\vec{k}_\perp\right)-\varepsilon_{n'}\left(\vec{k}_\perp-\vec{q}_\perp\right)+\hbar\omega_0-l\hbar\Omega+i\delta\right)(t-t_1)\right]\Bigg\} \quad (6)$$

It is well known that to obtain the explicit solutions from Eq. (6) is very difficult. In this paper, we use the first-order tautology approximation method to solve this equation. In detain, in Eq. (6), we use the approximation

$$n_{n,\vec{k}_\perp}(t)\approx\bar{n}_{n,\vec{k}_\perp};\quad n_{n,\vec{k}_\perp+\vec{q}_\perp}(t)\approx\bar{n}_{n,\vec{k}_\perp+\vec{q}_\perp};\quad n_{n,\vec{k}_\perp-\vec{q}_\perp}(t)\approx\bar{n}_{n,\vec{k}_\perp-\vec{q}_\perp}$$

where $\bar{n}_{n,\vec{k}_\perp}$ is the time-independent component of the electron distribution function. The approximation is also applied for a similar exercise in bulk semiconductors [3, 4]. We perform the integral with respect to t_1; next, we perform the integral with respect to t of Eq. (6). The expression for the electron distribution can be written as

$$\begin{aligned}n_{n,\vec{k}_\perp}(t) = &-\frac{1}{\hbar^2}\sum_{\vec{q},n'}\left|I^m_{n,n'}(q_z)\right|^2\left|C^m_{\vec{q}}\right|^2\\
&\sum_{k,l=-\infty}^{+\infty}J_k\left(\frac{e\vec{E}_0\vec{q}_\perp}{m\Omega^2}\right)J_{l+k}\left(\frac{e\vec{E}_0\vec{q}_\perp}{m\Omega^2}\right)\frac{\hbar}{l\Omega}\exp(-ik\Omega t)\\
&\times\left\{\frac{\bar{n}_{n',\vec{k}_\perp-\vec{q}_\perp}N_{m,\vec{q}}-\bar{n}_{n,\vec{k}_\perp}\left(N_{m,\vec{q}}+1\right)}{\varepsilon_n\left(\vec{k}_\perp\right)-\varepsilon_{n'}\left(\vec{k}_\perp-\vec{q}_\perp\right)-\hbar\omega_0-l\hbar\Omega+i\delta\hbar}\right.\\
&+\frac{\bar{n}_{n',\vec{k}_\perp-\vec{q}_\perp}\left(N_{m,\vec{q}}+1\right)-\bar{n}_{n,\vec{k}_\perp}N_{m,\vec{q}}}{\varepsilon_n\left(\vec{k}_\perp\right)-\varepsilon_{n'}\left(\vec{k}_\perp-\vec{q}_\perp\right)+\hbar\omega_0-l\hbar\Omega+i\delta\hbar}\\
&-\frac{\bar{n}_{n,\vec{k}_\perp}N_{m,\vec{q}}-\bar{n}_{n',\vec{k}_\perp+\vec{q}_\perp}\left(N_{m,\vec{q}}+1\right)}{\varepsilon_{n'}\left(\vec{k}_\perp+\vec{q}_\perp\right)-\varepsilon_n\left(\vec{k}_\perp\right)-\hbar\omega_0-l\hbar\Omega+i\delta\hbar}\\
&\left.-\frac{\bar{n}_{n,\vec{k}_\perp}\left(N_{m,\vec{q}}+1\right)-\bar{n}_{n',\vec{k}_\perp+\vec{q}_\perp}N_{m,\vec{q}}}{\varepsilon_{n'}\left(\vec{k}_\perp+\vec{q}_\perp\right)-\varepsilon_n\left(\vec{k}_\perp\right)+\hbar\omega_0-l\hbar\Omega+i\delta\hbar}\right\}\end{aligned}\quad (7)$$

where $N_{m,\vec{q}}\equiv N_{m,\vec{q}_\perp}$ is the time-independent component of the phonon distribution function, $\vec{E}_0$ and Ω are the intensity and the frequency of electromagnetic wave; $J_k(x)$ is the Bessel function. The carrier current density formula in DSLs takes the form

$$\vec{J}_{\perp}(t) = \frac{e\hbar}{m^*} \sum_{n,\vec{k}_{\perp}} \left(\vec{k}_{\perp} - \frac{e}{\hbar c}\vec{A}(t)\right) n_{n,\vec{k}_{\perp}}(t) \tag{8}$$

Because the motion of electrons is confined along the z direction in a DSLs, we only consider the in-plane (x, y) current density vector of electrons, $\vec{J}_{\perp}(t)$. Using Eq. (8), we find the expression for current density vector:

$$\vec{J}_{\perp}(t) = -\frac{e^2}{m^*c} \sum_{n,\vec{k}_{\perp}} \vec{A}(t)\, n_{n,\vec{k}_{\perp}}(t) + \sum_{l=1}^{\infty} \vec{J}_l \sin(l\Omega t). \tag{9}$$

The NAC of a strong electromagnetic wave by confined electrons the DSLs takes the simple form:

$$\alpha = \frac{8\pi}{c\sqrt{\chi_{\infty}}E_0^2} \left\langle \vec{J}_{\perp}(t)\, \vec{E}_0 \sin\Omega t \right\rangle_t. \tag{10}$$

By using Eq. (10), the electron-optical phonon interaction factor $C_{\vec{q}}$ in Eq. (2), and the Bessel function, from the expression of current density vector in Eq. (8) we established the NAC of a strong electromagnetic wave in DSLs:

$$\begin{aligned}\alpha =\ & \frac{32\pi^3 e^2 \Omega k_B T}{c\sqrt{\chi_{\infty}}E_0^2} \left(\frac{1}{\chi_{\infty}} - \frac{1}{\chi_0}\right) \sum_{n,n'} \sum_{\vec{k}_{\perp},\vec{q}_{\perp}} \sum_{l=1}^{\infty} \left|I_{n,n'}^{m}\right|^2 \frac{l^2}{q^2} J_l^2 \left(\frac{e\vec{E}_0\vec{q}_{\perp}}{m\Omega^2}\right) \\ & \times \bar{n}_{n,\vec{k}_{\perp}} \delta\left[\varepsilon_{n'}\left(\vec{k}_{\perp} + \vec{q}_{\perp}\right) - \varepsilon_{n'}\left(\vec{k}_{\perp}\right) + \hbar\omega_0 - \hbar\Omega\right]\end{aligned} \tag{11}$$

Equation (11) is the general expression for the nonlinear absorption of a strong electromagnetic wave in a DSLs. We will consider two limited cases for the absorption: close to the absorption threshold and far away form this, to find out the explicit formula for the absorption coefficient.

2.1. The Absorption Close to the Threshold

In the case, the condition: $|k\hbar\Omega - \hbar\omega_0| \ll \bar{\varepsilon}$ is needed. Therefore, we can't ignore the presence of the vector $\vec{k}_{\perp}$ in the formula of δ function. This also mean that the calculation depends on the electron distribution function $n_{n,\vec{k}_{\perp}}(t)$. Finally, the expression for the case of absorption close to its threshold in DSLs is obtained:

$$\alpha = \frac{\pi e^4 (k_B T)^2 n_0^*}{2\varepsilon_0 c\sqrt{\chi_\infty}\hbar^3\Omega^3}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\left\{\exp\left[\frac{\hbar}{k_B T}(\omega_0-\Omega)-1\right]\right\}\sum_{m,n,n'}\left|I_{n,n'}^m\right|^2$$
$$\times \exp\left[-\frac{\hbar^2}{2k_B T}(\xi+|\xi|)\right]\left[1+\frac{3}{16}\frac{e^2E_0^2k_BT}{\hbar^2 m^*\Omega^4}\left(2+\frac{|\xi|}{k_BT}\right)\right], \quad (12)$$

here, $\xi = \hbar\omega_p(n'-n)+\hbar\omega_0-\hbar\Omega$; $n_0^* = \frac{n_0 e^{3/2}\pi^{3/2}\hbar^3}{Vm^{*3/2}(k_BT)^{3/2}}$; ($n_0 = \sum_{n,\vec{k}_\perp} n_{n,\vec{k}_\perp}(t)$ is the electron density in DSLs).

When quantum number m characterizing confined phonons reach to zero, the expression for the case of absorption close to its threshold in DSLs with case of unconfined phonons can be written:

$$\alpha = \frac{\sqrt{2}\pi n_0^* (k_BT)^2 e^4}{8c\sqrt{m^*\chi_\infty}\hbar^3\Omega^3}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\sum_{n,n'}\left|I_{n,n'}\right|^2\exp\left[\frac{\hbar\omega_p\left(n+\frac{1}{2}\right)+\frac{\xi}{2}}{k_BT}\right]$$
$$\times e^{-2\sqrt{\rho\sigma}}\left(\frac{\rho}{|\xi|\sigma}\right)^{\frac{1}{2}}\left\{1+\frac{3}{16\sqrt{\rho\sigma}}+\frac{3e^2E_0^2}{32m^{*2}\Omega^4}\left(\frac{\rho}{\sigma}\right)^{\frac{1}{2}}\left[1+\frac{1}{\sqrt{\rho\sigma}}+\frac{1}{16\rho\sigma}\right]\right\}. (13)$$

with, $\rho = \frac{m^*\xi^2}{2\hbar^2k_BT}$; $\sigma = \frac{\hbar^2}{8m^*k_BT}$.

2.2. The Absorption Far Away from Threshold

In this case, the condition: $|k\hbar\Omega - \hbar\omega_0| \gg \bar{\varepsilon}$ must be satisfied. Here, $\bar{\varepsilon}$ is the average energy of an electron. Finally, we have the explicit formula for the NAC of a strong EMW in DSLs for the case of the absorption far away from its threshold, which is written:

$$\alpha = \frac{\pi^3 e^4 k_BT n_0^*}{\varepsilon_0 c\sqrt{\chi_\infty}\hbar^2 m^*\Omega^3}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\left\{1-\exp\left[\frac{\hbar}{k_BT}(\omega_0-\Omega)-1\right]\right\}\sum_{m,n,n'}\left|I_{n,n'}^m\right|^2$$
$$\times\left[1+\frac{3}{16}\frac{\varepsilon_0^2E_0^2}{\hbar^2m^*\Omega^4}\xi\right]2m^*\xi^{3/2}\left[2m^*\xi+\left(\frac{m^*\pi\hbar}{d}\right)^2\right]^{-1}, \quad (14)$$

when quantum number m characterizing confined phonons reach to zero, the expression for the case of absorption close to its threshold in DSLs with case of unconfined phonons can be written as:

$$\alpha = \frac{\pi^2 e^4 k_BT n_0^*}{c\sqrt{\chi_\infty}\hbar^2 m^*\Omega^3}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\sum_{n,n'}\left|I_{n,n'}\right|^2\left[\frac{2m^*}{\hbar}\omega_p(n-n')+\frac{2m^*}{\hbar}(\Omega-\omega_0)\right]^{\frac{1}{2}}$$
$$\times\left\{1+\frac{3}{32}\left(\frac{eE_0}{m^*\Omega}\right)^2\left[\frac{2m^*}{\hbar}\omega_p(n-n')+\frac{2m^*}{\hbar}(\Omega-\omega_0)\right]^{\frac{1}{2}}\right\} \quad (15)$$

The term in proportion to quadratic intensity of a strong electromagnetic wave tend toward zero, the nonlinear result in Eqs. (13), (15) will turn back to the linear case which was calculated by another method-the Kubo-Mori method [9].

3. NUMERICAL RESULTS AND DISCUSSIONS

In order to clarify the mechanism for the nonlinear absorption of a strong electromagnetic wave in DSLs, in this section we will evaluate, plot and discuss the expression of the NAC for the specific n-GaAs/p-GaAs DSLs. The parameters used in the calculation are as follow [9]: $\chi_\infty = 10.8$, $\chi_0 = 12.9$, $n_0 = 10^{20} m^{-3}$, $n_D = 10^{17} m^{-3} m^* = 0.067 m_0$, ($m_0$ being the mass of free electron), $d = 80\,\text{nm}$, $\hbar\omega_0 = 36.25\,\text{mev}$, $\Omega = 2 \times 10^{14}\text{s}^{-1}$.

3.1. The Absorption Close to the Threshold

Figures 1–4 show the nonlinear absorption coefficient of strong in a DSLs for the case of the absorption close to its threshold. Figures 1–2 show that the curve increases following amplitude E_0 of external strong electromagnetic wave rather fast than following the temperature T of the system. Both figures show that the spectrums of NAC are much different from these in case the linear absorption [9].

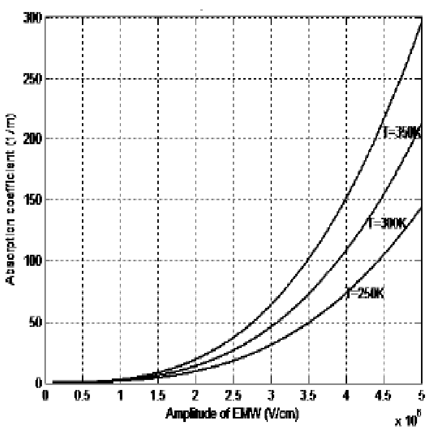

Figure 1. The dependence of α on the E_0, T (*in case of confined phonon*).

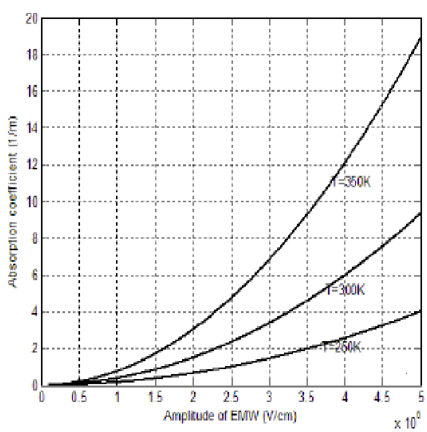

Figure 2. The dependence of α on the E_0, T (*in case of unconfined phonon*).

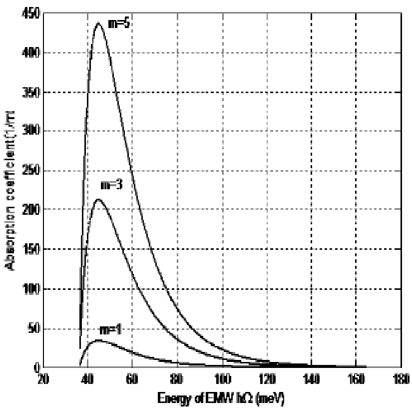

Figure 3. The dependence of α on the $\hbar\Omega$ (*in case of confined phonon*).

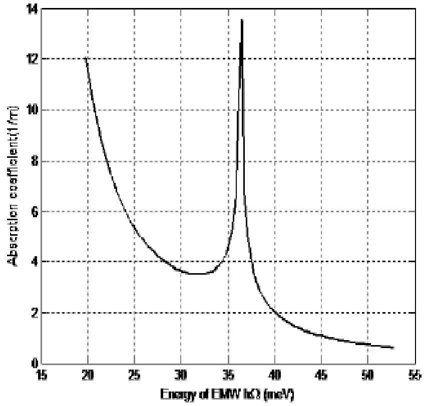

Figure 4. The dependence of α on the $\hbar\Omega$ (*in case of unconfined phonon*).

But there is no difference in appearance but only in the values of NAC between two case of energy $\hbar\Omega$. It is seen that NAC depends very strongly on the energy of the strong EMW, they are greeter when the energy of strong EMW increases. There is a resonant peak in both case of unconfined phonons (when $\Omega = \omega_0$) and confined phonons (when $\Omega > \omega_0$). So it is seen that the confined phonons causes the change of resonance peak position. The NAC also depends very strongly on quantum number m characterizing of confined phonons, they increases following quantum number m characterizing confined phonons.

3.2. The Absorption Far Away from Threshold

Figures 5–8 show the nonlinear absorption coefficient of a strong in a DSLs for the case of the absorption far away from threshold. In this case, the dependence of the nonlinear absorption coefficient on other parameters is quite similar with case of the absorption close its threshold.

However, the values of a are much smaller than above case. Also, it is seen that a depends strongly on the electromagnetic field amplitude and the temperature of the system, the energy of strong EMW $\hbar\Omega$ and quantum number m characterizing of confined phonons (Figures 5–8). But there is no difference in appearance but only in the values of NAC between two case of confined phonons and unconfined phonons.

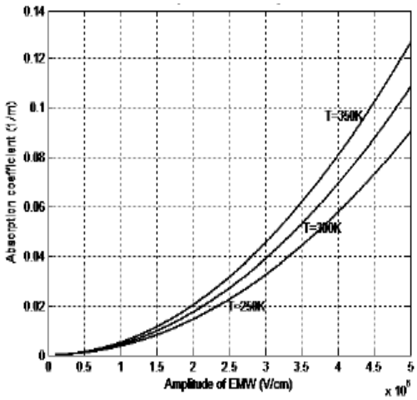

Figure 5. The dependence of α on the E_0, T (*in case of confined phonon*).

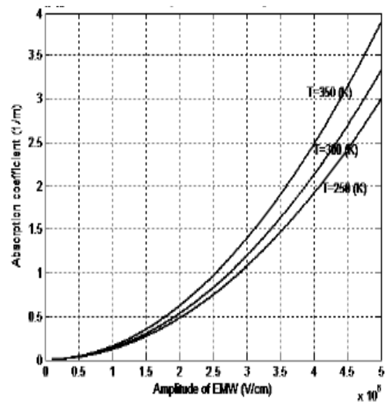

Figure 6. The dependence of α on the E_0, T (*in case of unconfined phonon*).

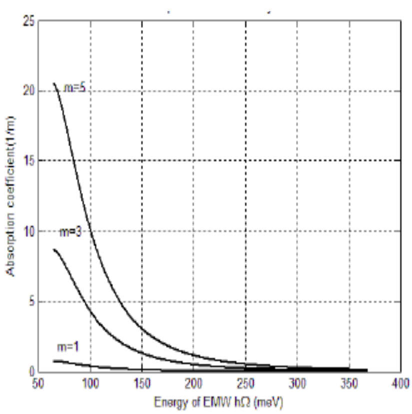

Figure 7. The dependence of α on the $\hbar\Omega$ (*in case of confined phonon*).

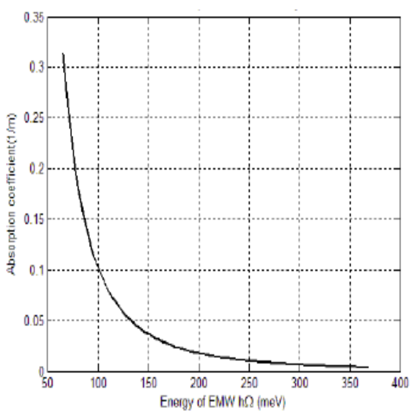

Figure 8. The dependence of α on the $\hbar\Omega$ (*in case of unconfined phonon*).

4. CONCLUSION

In this paper, we have theoretically studied the influences of confined phonons on the nonlinear absorption of a strong EMW by confined electrons in DSLs. We are close to the absorption threshold, Eq. (12) and far away from the absorption threshold, Eq. (14). The formula of the NAC contains a quantum number m characterizing confined phonons and easy to come back to the case of unconfined phonon when quantum number m characterizing confined phonons reach to zero and the linear absorption [9], when the amplitude E_0 of external strong electromagnetic wave reach to zero. We numerically calculated and graphed the nonlinear absorption coefficient for a specific of the n-GaAs/p-GaAs DSLs clarify the theoretical results. Numerical results present clearly the dependence of the NAC on the amplitude E_0, energy ($\hbar\Omega$) of the external strong electromagnetic wave, the temperature (T) of the system. There is a resonant peaks of the absorption coefficient appearing and the spectrums of the absorption coefficient are different from there in case of unconfined phonons. In short, the confinement of phonons effect strongly on the nonlinear optical properties in DSLs.

ACKNOWLEDGMENT

This research is completed with financial support from the Vietnam-NAFOSTED (No. 103.01.18.09).

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