Proc. Natl. Conf. Theor. Phys. **37** (2012), pp. 168-173

PHOTOSTIMULATED QUANTUM EFFECTS IN QUANTUM WELLS WITH A PARABOLIC POTENTIAL

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Abstract. *The quantum theory of the photostimulated effects in quantum wells (QW) has been studied based on the quantum kinetic equation for electrons with a parabolic potential $V(z) = \frac{m\omega_0^2 z^2}{2}$ (where m is the effective mass of electron, ω_0 is the confinement frequency of QW). In this case, electrons system in QW is placed in a dc electric field $\overrightarrow{E}_0$, in a linearly polarized electromagnetic waves (EMW) $\overrightarrow{E}(t) = \overrightarrow{E}(e^{-i\omega t}+e^{i\omega t})$ and in a strong EMW field (laser radiation) $\overrightarrow{F}(t) = \overrightarrow{F}\sin\Omega t$. In the presence of laser radiation and polarized EMW an electric field with intensity vector $\overrightarrow{E}_0$ with open circuit conditions may appear. The analytic expressions of electric field intensity vector $\overrightarrow{E}_0$ along the coordinate axes has been calculated. The dependence of the components $\overrightarrow{E}_0$ on the frequency Ω of the laser radiation field, the frequencsω of the polarizerd EMW field, the frequency ω_0 of the parabolic potential is shown. From the analytic results, when $\omega_0 \to 0$, the result will give back the photostimulated kinetic effects in semiconductors.*

Keywords: photostimulated quantum effects, quantum wells, parabolic potential, dc electric field.

I. INTRODUCTION

In recent time, there have been many studies on the influence of laser radiation and polarized EMW in low dimensional systems. It is known that the presence of intense laser radiation can influence the electrical conductivity, optical conductivity and kinetic effects in materials [1 - 4]. Series of photostimulated kinetic effects such as Nernst Ettingshausen, Ettingshausen, and Peltier effects, ect... have been researched in semiconductors [5, 6, 12]. In isotropic semiconductors, the radioelectrical effect (RE) is longitudinal. And under anisotropic conditions, the transverse RE appears when the anisotropy of optical properties are induced [12]. However, in QW, the RE still opens for studying. In particular, the transverse RE can take place by the electron - phonon scattering of under influence of EMW. In this paper, we use the quantum kinetic equation for electrons system in quantum wells with a parabolic potential placed in a dc electric field $\overrightarrow{E}_0$, in a polarized EMW $\overrightarrow{E}(t) = \overrightarrow{E}(e^{-i\omega t} + e^{i\omega t})$ and in a laser radiation $\overrightarrow{F}(t) = \overrightarrow{F}\sin\Omega t$,. The problem is considered for electron-optical phonon scattering. The analytic expressions of electric field intensity vector $\overrightarrow{E}_0$ along the coordinate axes has been calculated under open circuit conditions. Numerical calculations are carried out with a specific GaAs/GaAsAl quantum wells and the comparison of the result of quantum wells to bulk semiconductors is given.

II. PHOTOSTIMULATED QUANTUM EFFECTS IN QUANTUM WELLS WITH A PARABOLIC POTENTIAL

II.1. Expressions for the photostimulated quantum effects in quantum wells with a parabolic potential

We examine the system which is placed in a linearly polarized EMW field ($\overrightarrow{E}(t) = \overrightarrow{E}(e^{-i\omega t} + e^{i\omega t}), \vec{H}(t) = \left[\vec{n}, \overrightarrow{E}(t)\right]$) (with $\omega \ll \bar{\varepsilon}; \bar{\varepsilon}$ is an average carrier energy, $\hbar = 1$), in a dc electric field $\overrightarrow{E}_0$ and in a laser radiation field $\overrightarrow{F}(t) = \overrightarrow{F}\sin\Omega t$ (which $\Omega\tau \gg 1$; τ is the characteristic relaxation time). The Hamiltonian of the electron-optical phonon system in the quantum wells (QW) in the second quantization representation can be written as [2, 7] follows:

$$H = H_0 + U = \sum_{n,\vec{p}_\perp} \varepsilon_n(\vec{p}_\perp - \frac{e}{\hbar c}\vec{A}(t)).a^+_{n,\vec{p}_\perp}.a_{n,\vec{p}_\perp} + \sum_{n,n'}\sum_{\vec{p}_\perp,\vec{q}} D_{n,n'}(\vec{q}).a^+_{n',\vec{p}_\perp+\vec{q}}.a_{n,\vec{p}_\perp}(b_{\vec{q}} + b^+_{-\vec{q}}) \quad (1)$$

with $H_0 = \sum_{n,\vec{p}_\perp} \varepsilon_n(\vec{p}_\perp - \frac{e}{\hbar c}\vec{A}(t)).a^+_{n,\vec{p}_\perp}.a_{n,\vec{p}_\perp} + \sum_{\vec{q}} \hbar\omega_{\vec{q}} b^+_{\vec{q}} b_{\vec{q}}$

and $U = \sum_{n,n'}\sum_{\vec{p}_\perp,\vec{q}} D_{n,n'}(\vec{q}).a^+_{n',\vec{p}_\perp+\vec{q}}.a_{n,\vec{p}_\perp}(b_{\vec{q}} + b^+_{-\vec{q}})$

where $|n, \vec{p}_\perp\rangle$ and $|n', \vec{p}_\perp + \vec{q}\rangle$ are electron states before and after scattering, $a^+_{n,\vec{p}_\perp}$ and $a_{n,\vec{p}_\perp}$ ($b^+_{\vec{q}}$ and $b_{\vec{q}}$) are the creation and annihilation operators of electron (phonon). $\hbar\omega_{\vec{q}}$ is the energy of an optical phonon with the wave vector $\vec{q}$; $\vec{A}(t)$ is the vector potential of laser field;$D_{n,n'}(\vec{q}) = C_{\vec{q}}.I_{n,n'}(\vec{q})$,where $C_{\vec{q}}$ is the electron - phonon interaction constants, $I_{n,n'}(\vec{q})$ is the electron form factor.

And $f_{n,\vec{p}_\perp}(t) = \left\langle a^+_{n,\vec{p}_\perp}.a_{n,\vec{p}_\perp}\right\rangle_t$ is an unknown distribution function perturbed due to the external fields. We consider the electron gas to be completely degenerate. Thus, the electron distribution function is given by Fermi - Dirac distribution function:

$$f_0(\varepsilon_{n,\vec{p}_\perp}) = \theta(\varepsilon_F - \varepsilon_{n,\vec{p}_\perp}) = \begin{cases} 1, \text{if} \varepsilon_F \geq \varepsilon_{n,\vec{p}_\perp} \\ 0, \text{if} \varepsilon_F < \varepsilon_{n,\vec{p}_\perp} \end{cases}$$

In order to establish the quantum kinetic equations for electrons in QW, we use general quantum equations for the particle number operator or electron distribution function

$$i\hbar\frac{\partial f_{n,\vec{p}_\perp}(t)}{\partial t} = \left\langle\left[a^+_{n,\vec{p}_\perp}.a_{n,\vec{p}_\perp}, H\right]\right\rangle_t \quad (2)$$

From Eqs. (1) and (2), we obtain the quantum kinetic equation for electrons in QW:

$$\begin{aligned} &\frac{\partial f_{n,\vec{p}_\perp}(t)}{\partial t} + \left(e.\vec{E}(t) + e.\vec{E}_0 + \omega_H\left[\vec{p}_\perp, \vec{h}(t)\right], \frac{\partial f_{n,\vec{p}_\perp}(t)}{\partial \vec{p}_\perp}\right) = \\ &= \frac{2\pi}{\hbar}\sum_{\vec{q}} M(q).\sum_{l=-\infty}^{\infty} J_l^2(\vec{a}\vec{q})\left[f_{n,\vec{p}_\perp+\vec{q}}(t) - f_{n,\vec{p}_\perp}(t)\right].\delta(\varepsilon_{n,\vec{p}_\perp+\vec{q}} - \varepsilon_{n,\vec{p}_\perp} - \hbar\omega_0 - l\Omega) \end{aligned} \quad (3)$$

where ω_H is the cyclotron frequency, $\vec{h} = \frac{\vec{H}}{H}$ is the unit vector in the magnetic field direction, $\vec{a} = \frac{e\tilde{F}}{m\Omega^2}$ is the amplitude of electron vibration in an EMW; $J_l(x)$ is the Bessel function of real argument; M(q) depends on the electron scattering mechanism. For simplicity, we limit the problem to the case of $l = 0, \pm 1$. We multiply both sides of Eq. (3) by $(-e/m)\vec{p}_\perp.\delta(\varepsilon - \varepsilon_{n,\vec{p}_\perp})$ and carry out the summation over n and $\vec{p}_\perp$. We obtain:

$$\frac{\vec{R}_0(\varepsilon)}{\tau(\varepsilon)} = \vec{Q}_0 + \vec{S}_0 + \omega_H \left[\vec{R}(\varepsilon) + \vec{R}^*(\varepsilon), \vec{h}\right] \tag{4}$$

where

$$\vec{Q}_0 = \frac{e}{m} \sum_{n,\vec{p}_\perp} \vec{p}_\perp \left(e.\vec{E}_0, \frac{\partial f_0(\varepsilon_{n,\vec{p}_\perp})}{\partial \vec{p}_\perp} \right) .\delta(\varepsilon - \varepsilon_{n,\vec{p}_\perp}) \tag{5}$$

and

$$\begin{array}{l} \vec{S}_0(\varepsilon) = -\frac{2\pi e}{m\hbar} \sum\limits_{\vec{q}} M(q).\frac{(\vec{a}\vec{q})^2}{4} \sum\limits_{n,\vec{p}_\perp} \left\{ f_0(\varepsilon_{n,\vec{p}_\perp}) + f_{10}(\vec{p}_\perp) \right\} \times \\ \times \left[\delta(\varepsilon_{n,\vec{p}_\perp+\vec{q}} - \varepsilon_{n,\vec{p}_\perp} - \hbar\omega_0 - \Omega) + \delta(\varepsilon_{n,\vec{p}_\perp+\vec{q}} - \varepsilon_{n,\vec{p}_\perp} - \hbar\omega_0 + \Omega) \right] \times \\ \times \left[(\vec{p}_\perp + \vec{q})\, \delta(\varepsilon - \varepsilon_{n,\vec{p}_\perp+\vec{q}}) - \vec{p}_\perp \delta(\varepsilon - \varepsilon_{n,\vec{p}_\perp}) \right] \end{array} \tag{6}$$

$\tau(\varepsilon)$ is the relaxation time of electrons with energy ε [13];

$$\vec{R}_0(\varepsilon) = -\frac{e}{m} \sum_{n,\vec{p}_\perp} \vec{p}_\perp.f_{10}(\vec{p}_\perp)\delta(\varepsilon - \varepsilon_{n,\vec{p}_\perp}) \tag{7}$$

has meaning of a partial current density transportable with energy ε. This quantity is related to the total current density $\vec{j}_{tot}$ by means of the relationship

$$\vec{j}_{tot} = \vec{j}_0 + \vec{j}(t) = \int_0^\infty \left\{ \vec{R}_0(\varepsilon) + \left[\vec{R}(\varepsilon).e^{-i\omega t} + \vec{R}^*(\varepsilon).e^{i\omega t} \right] \right\} .d\varepsilon \tag{8}$$

Taking the statistical average over the time of the total current density $\vec{j}_{tot}$ and paying attention to the open circuit conditions, we find the expressions for electric field intensity vector $\overrightarrow{E}_0$ along the coordinate axes:

$$E_{0x} = -\frac{E_{\mathrm{w}}}{\varepsilon_F - \omega_0(n+\frac{1}{2})} \left\{ \lambda \cdot \frac{\tau^2(\Omega)}{\tau(\varepsilon_F)} \cdot \frac{1-\omega^2\tau(\Omega)\tau(\varepsilon_F)}{1+\omega^2\tau^2(\Omega)} - A.\tau(\varepsilon_F) \cdot \frac{1-\omega^2.\tau^2(\varepsilon_F)}{1+\omega^2.\tau^2(\varepsilon_F)} \right\} \tag{9}$$

$$E_{0y} = -\frac{E_{\mathrm{w}}}{\varepsilon_F - \omega_0(n+\frac{1}{2})} \left\{ -\lambda_0.\tau(\Omega) + A_0.\tau(\varepsilon_F) \right\} \tag{10}$$

$$\begin{array}{l} E_{0z} = -\frac{E_{\mathrm{w}}}{\varepsilon_F - \omega_0(n+\frac{1}{2})} \left\{ \left[\left(\varepsilon_F - \omega_0(n+\frac{1}{2}) \right) - \tau(\Omega)\lambda_0 + \tau(\varepsilon_F)A_0 \right] + \right. \\ \left. + \frac{\tau^2(\Omega)}{\tau(\varepsilon_F)} \cdot \frac{1-\omega^2\tau(\Omega)\tau(\varepsilon_F)}{1+\omega^2\tau^2(\Omega)}\lambda - \tau(\varepsilon_F) \cdot \frac{1-\omega^2.\tau^2(\varepsilon_F)}{1+\omega^2.\tau^2(\varepsilon_F)} A \right\} \end{array} \tag{11}$$

where

$$\begin{array}{l} \lambda_0 = \frac{e^2F^2}{2m\Omega^3} M(\sqrt{2m\Omega}) \left[\sqrt{2m(\Omega - \omega_0(n+\frac{1}{2}))} + \right. \\ \left. + \sqrt{2m(\Omega - \omega_0(n+\frac{1}{2}))}.\sqrt{2m(\varepsilon_F - \omega_0(n+\frac{1}{2}))} - \sqrt{2m(\varepsilon_F - \omega_0(n+\frac{1}{2}))} \right] \end{array} \tag{12}$$

$$A_0 = \frac{e^2F^2}{2m\Omega^3} M(\sqrt{2m\Omega}) \left[1 + \sqrt{2m(\varepsilon_F - \omega_0(n+\frac{1}{2}))} - \sqrt{2m\Omega} \right] \tag{13}$$

$$\lambda = \frac{e^2F^2}{2m\Omega^3}M(\sqrt{2m\Omega})\sqrt{2m(\varepsilon_F - \omega_0(n+\frac{1}{2}))} \times \left[\sqrt{2m(\Omega - \omega_0(n+\frac{1}{2}))} - 1\right] \tag{14}$$

$$A = \frac{e^2F^2}{2m\Omega^3}M(\sqrt{2m\Omega})\sqrt{2m(\varepsilon_F - \omega_0(n+\frac{1}{2}))} \tag{15}$$

and $\vec{E}_{\mathrm{w}} = \left[\vec{E}, \vec{H}\right]$ is Umov-Poynting vector; $M(q) = \frac{2\hbar\omega_{LO}.e^2}{\epsilon_0} \times \left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right) \times \frac{1}{q^2}$. Here $E_{0\mathrm{x}}$, $E_{0\mathrm{y}}$ stand for the transverse RE and $E_{0\mathrm{z}}$ expresses the longitudinal RE. These expressions don't depends on the temperature T of the system. In the limit of $\omega_0 \to 0$, the results in Eqs. (9), (10), (11) give the same results as those obtained in bulk semiconductor [5, 12].

II.2. Numerical results and discussion

In this section, we will survey, plot and discuss the expressions for electric field intensity vector $\overrightarrow{E}_0$ along the coordinate axes for the case of a specific GaAs/GaAsAl quantum wells. The parameters used in the calculations are as follows [7, 8]: $\epsilon_0 = 12{,}5$; $\chi_\infty = 10{,}48$; $\chi_0 = 12{,}90$; $\hbar\omega_{LO} = 36{,}8$meV; m = 0,0665$m_0$ (m_0 is the mass of free electron); $e = 1,60219.10^{-19}C$; ε_F = 50meV; and we also choose $\tau(\varepsilon_F) \sim 10^{-11}s^{-1}; \tau(\Omega) \sim 10^{-10}s^{-1}$;

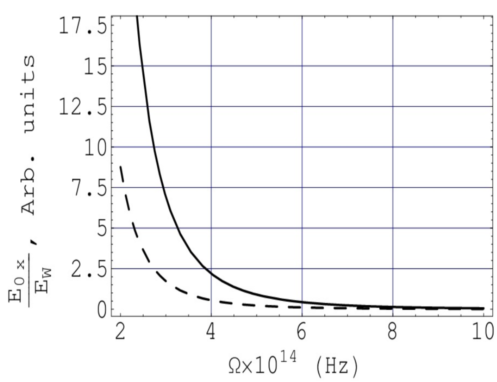

Fig. 1. The dependence of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ on the frequency Ω of the intense laser radiation (in case $\omega = 10^{10}Hz$; F = $10^5V/m$ (dashed line) and F = $2.10^5V/m$ (solid line)).

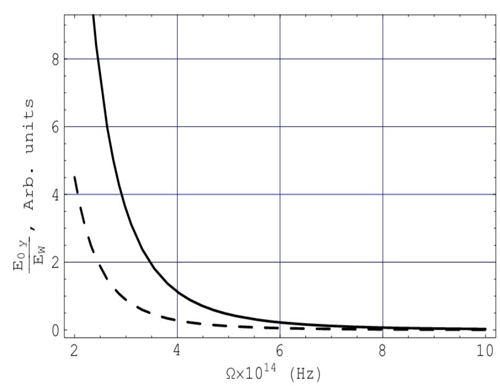

Fig. 2. The dependence of $E_{0\mathrm{y}}/E_{\mathrm{W}}$ on the frequency Ω of the intense laser radiation (in case $\omega = 10^{10}Hz$; F = $10^5V/m$ (dashed line) and F = $2.10^5V/m$ (solid line)).

In the Fig. 1 and Fig. 2, we show the dependence of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ and $E_{0\mathrm{y}}/E_{\mathrm{W}}$ (for the transverse RF) on the frequency Ω of the laser radiation. From these figures, we can see the nonlinear dependence of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ and $E_{0\mathrm{y}}/E_{\mathrm{W}}$ on the external parameters. When the frequency Ω of the laser radiation increases, the ratio $E_{0\mathrm{x}}/E_{\mathrm{W}}$ ($E_{0\mathrm{y}}/E_{\mathrm{W}}$) decreases. However, the value of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ is larger than $E_{0\mathrm{y}}/E_{\mathrm{W}}$.

Fig. 3 and Fig. 4 show the dependence of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ (the transverse RF) and $E_{0\mathrm{z}}/E_{\mathrm{W}}$ (the longitudinal RF) on the frequency ω of EMW. From these figures, we can see that in

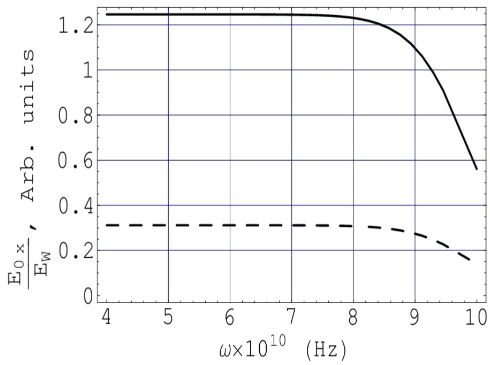

Fig. 3. The dependence of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ on the frequency ω of the EMW(in case $\Omega = 10^{14}Hz$; $\mathrm{F} = 10^5 V/m$(dashed line);$\mathrm{F} = 2.10^5 V/m$(solid line)).

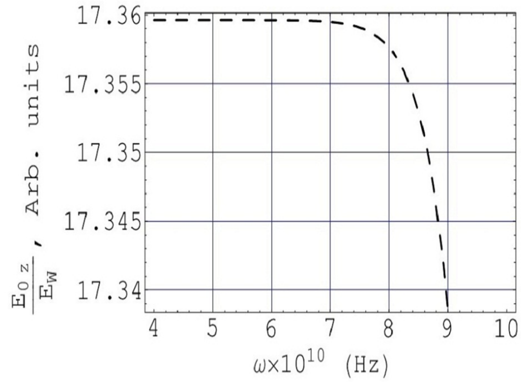

Fig. 4. The dependence of $E_{0\mathrm{z}}/E_{\mathrm{W}}$ on the frequency ω of the EMW (in case $\Omega = 10^{14}Hz$; $\mathrm{F} = 10^5 V/m$).

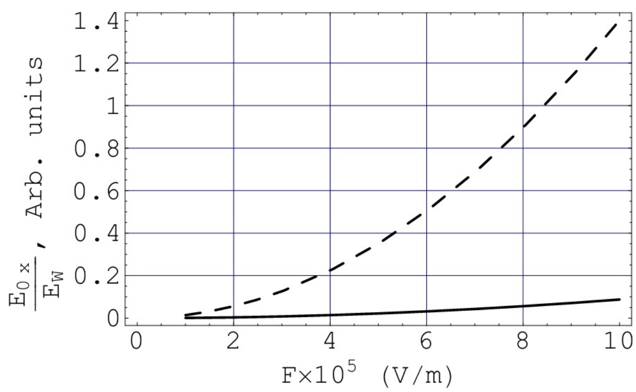

Fig. 5. The dependence of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ on the amplitude F of the intense laser radiation (in case $\omega = 10^{10}Hz$; $\Omega = 10^{14}Hz$ (dashed line) and $\Omega = 2.10^{14}Hz$ (solid line).

case the values of the laser radiation $\Omega = 10^{14}Hz$ and $\mathrm{F} = 10^5 V/m$ the value of $E_{0\mathrm{z}}/E_{\mathrm{W}}$ (longitudial RF) is larger than $E_{0\mathrm{x}}/E_{\mathrm{W}}$ (transverse RF).

The Fig. 5 shows the dependence of $E_{0\mathrm{x}}/E_{\mathrm{W}}$ on the amplitude F of the intense laser radiation in different cases of Ω. From this figure, we can see that the more amplitude F of the laser radiation increases, the more the quotient goes up.

III. CONCLUSION

In this paper, we have studied the photostimulated effects in quantum wells with a parabolic potential. When a two dimensional completly degenerate electron gas system is placed in an EMW and a laser radiation at high frequency. We obtain the expressions for electric field intensity vector $\overrightarrow{E}_0$, in which $E_{0\mathrm{x}}$, $E_{0\mathrm{y}}$ are for the transverse RE and $E_{0\mathrm{z}}$ expresses the longitudinal RE. The expressions of $\overrightarrow{E}_0$ show clearly the dependence of $\overrightarrow{E}_0$ on the amplitude E_{W}, on the frequency ω of the EMW, on the amplitude F and the frequency Ω of the laser radiation; and on the parameters QW with a parabolic potential. When $\omega_0 \to 0$, the Eqs. (9), (10), (11) give the same results as those obtained in bulk semiconductor [5, 12].

The analytical results are numerically evaluated and plotted for a specific GaAs/AlGaAs quantum wells. The comparison of the result of quantum wells to bulk semiconductors builk [5, 12, 14] and superlattice [10, 11] shows the difference between the cases.

ACKNOWLEDGMENT

This research is completed with financial support from the Program of Basic Research in National Foundation for Science and Technology Development (NAFOSTED, project No 103.01-2011.18).

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Received 30-09-2012.