Photostimulated Quantum Effects in Quantum Wire with a Parabolic Potential

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Abstract— The quantum theory of the photostimulated effects in quantum wire has been studied based on the quantum kinetic equation for electrons with a parabolic potential $V(z) = \frac{m\omega_0^2 z^2}{2}$. In this case, electrons system in quantum wire is placed in a constant electric field $\vec{E}_0$, an electromagnetic wave $\vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t})$ and in the presence of an intense laser field $\vec{F}(t) = \vec{F}\sin\Omega t$. In the presence of laser radiation and polarized electromagnetic wave can influence that current carrier, and do appear an electric field intensity vector $\vec{E}_0$ with open circuit conditions. Hence, the analytic expressions of electric field intensity vector $\vec{E}_0$ **along the coordinate axes has been calculated**. The dependence of the components $\vec{E}_0$ on the frequency Ω of the laser radiation field, the frequency ω of the electromagnetic wave field, the frequency ω_0 of the parabolic potential are shown. From the analytic results, when $\omega_0 \to 0$, the result will turn back to the photostimulated kinetic effects in semiconductors.

1. INTRODUCTION

In recent times, there have been many studies on the influence of intense laser radiation and polarized electromagnetic wave in low dimensional systems. It is known that the presence of intense laser radiation can influence the electrical conductivity and kinetic effects in material [1–4]. A serial of photostimulated kinetic effects such as Nernst-Ettingshausen, Ettingshausen, and Peltier effects, ect. ... have been researched in semiconductors [5, 6, 12]. However, in quantum wire, the photostimulated quantum effects still opens for studying. In this paper, we use the quantum kinetic equation for electrons system is placed in a constant electric field $\vec{E}_0$, an electromagnetic wave $\vec{E}(t) = \vec{E}(e^{-i\omega t}+e^{i\omega t})$ and in the presence of an intense laser field $\vec{F}(t) = \vec{F}\sin\Omega t$, in quantum wire with a parabolic potential. The problem is considered for electron-optical phonon scattering, the analytic expressions of electric field intensity vector $\vec{E}_0$. Numerical calculations are carried out with a specific GaAs/GaAsAl quantum wire. The comparison of the result of quantum wire to semiconductors builk shows that the difference.

2. PHOTOSTIMULATED QUANTUM EFFECTS IN QUANTUM WIRE WITH A PARABOLIC POTENTIAL

2.1. Expressions for the Photostimulated Quantum Effects in Quantum Wire with a Parabolic Potential

We examine the system which is placed in a linearly polarized EMW field ($\vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t})$, $\vec{H}(t) = [\vec{n}, \vec{E}(t)]$), in a dc electric field $\vec{E}_0$ and in a strong radiation field $\vec{F}(t) = \vec{F}\sin\Omega t$. The Hamiltonian of the electron-optical phonon system in the quantum wire (QW) in the second quatization representation can be written as [7, 8]

$$\begin{aligned}
H =& H_0 + U = \sum_{n,l,\vec{p}_z} \varepsilon_{n,l,\vec{p}_z}\left(\vec{p}_z - \frac{e}{hc}\vec{A}(t)\right)\cdot a^+_{n,l,\vec{p}_z}\cdot a_{n,l,\vec{p}_z} + \sum_{\vec{q}} h\omega_{\vec{q}} b^+_{\vec{q}} b_{\vec{q}} \\
&+ \sum_{n,l,n',l'}\sum_{\vec{p}_z,\vec{q}} C_{n,l,n',l'}(\vec{q})\cdot I_{n,l,n',l'} a^+_{n',l',\vec{p}_s+\vec{q}}\cdot a_{n,l,\vec{p}_z}(b_{\vec{q}} + b^+_{-\vec{q}}) \\
H_0 =& \sum_{n,l,\vec{p}_z} \varepsilon_{n,l,\vec{p}_z}\left(\vec{p}_z - \frac{e}{hc}\vec{A}(t)\right)\cdot a^+_{n,l,\vec{p}_z}\cdot a_{n,l,\vec{p}_z} + \sum_{\vec{q}} h\omega_{\vec{q}} b^+_{\vec{q}} b_{\vec{q}} \\
U =& \sum_{n,l,n',l'}\sum_{\vec{p}_z,\vec{q}} C_{n,l,n',l'}(\vec{q})\cdot I_{n,l,n',l'} a^+_{n',l',\vec{p}_s+\vec{q}}\cdot a_{n,l,\vec{p}_z}\left(b_{\vec{q}} + b^+_{-\vec{q}}\right)
\end{aligned} \quad (1)$$

with $f_{n,l,\vec{p}_z}(t) = \langle a^+_{n,l,\vec{p}_z}\cdot a_{n,l,\vec{p}_z}\rangle_t$ is an unknow distribution function perturbed due to the external fields.

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

$$ih\frac{\partial f_{n,l,\vec{p}_z}(t)}{\partial t} = \left\langle \left[a^{+}_{n,l,\vec{p}_z} \cdot a_{n,l,\vec{p}_z}, H\right] \right\rangle_t \tag{2}$$

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

$$\begin{aligned}&\frac{\vec{P}_z}{m}\frac{\partial f_{n,l\vec{p}_z}(t)}{\partial t} - \left(e\cdot\vec{E}(t) + e\cdot\vec{E}_0 + \omega_H\left[\vec{p}_z, \vec{h}(t)\right]\right)\frac{1}{h}\frac{\partial f_{n,l,\vec{p}_z}(t)}{\partial \vec{p}_z} + \frac{\partial f_{n,l,\vec{p}_z}(t) - f_0}{\tau}\\
=&\frac{2\pi}{h}\sum_{n',l',\vec{q}}|D_{n,l,n',l'}(q)|^2\cdot\sum_{L=-\infty}^{\infty}J_L^2\left(\frac{\Lambda}{\Omega}\right)\cdot N_q\{[f_{n',l',\vec{p}_z+\vec{q}}(t) - f_{n,l,\vec{p}_z}(t)]\cdot\delta(\varepsilon_{n',l',\vec{p}_z+\vec{q}_z} - \varepsilon_{n,l\vec{p}_z} - h\omega_{\vec{q}} - Lh\Omega)\\
&+\left[f_{n',l',\vec{p}_z-\vec{q}_z} - f_{n,l,\vec{p}_z}\right]\delta\left(\varepsilon_{n',l',\vec{p}_z-\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} + h\omega_{\vec{q}} - Lh\Omega\right)\}\end{aligned} \tag{3}$$

where ω_H is the cyclotron frequency, $\vec{h} = \frac{\vec{H}}{H}$ is the unit vector in the magnetic field direction, $J_L(x)$ is the Bessel function of real argument; $N(q)$ depends on the electron scattering mechanism.

For simplicity, we limit the problem to the case of $l = 0, \pm 1$. We multiply both sides Eq. (3) by $(-e/m)\vec{p}_\perp \cdot \delta(\varepsilon - \varepsilon_{n,\vec{p}_\perp})$ are carry out the summation over n and $\vec{p}_\perp$, we obtain

$$\vec{j}_{tot} = \vec{j}_0 + \vec{j}(t) = \int_0^\infty \left\{\vec{R}_0(\varepsilon) + \left[\vec{R}(\varepsilon)\cdot e^{-i\omega t} + \vec{R}^*(\varepsilon).e^{i\omega t}\right]\right\}\cdot d\varepsilon \tag{4}$$

$$\vec{R}_0(\varepsilon) = \tau(\varepsilon)\left(\vec{Q}_0 + \vec{S}_0\right) + \frac{\omega_H\tau^2(\varepsilon)}{1+\omega_H^2\tau^2(\varepsilon)}\left[\vec{Q}, \vec{h}\right] + \omega_H\tau^2(\varepsilon)\mathrm{Re}\left\{\frac{\left[\vec{S}, \vec{h}\right]}{1 - i\omega_H\tau(\varepsilon)}\right\} \tag{5}$$

$$\vec{R}(\varepsilon) = \frac{\tau(\varepsilon)}{1 - i\omega_H\tau(\varepsilon)}\left(\vec{Q} + \vec{S}\right) \tag{6}$$

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

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

$$\begin{aligned}E_{0x} =& -\left\{a + \frac{e^2F^2}{\beta h^4\Omega^4}\cdot b\tau(\varepsilon_F)\right\}^{-1} \times \frac{\omega_H\tau(\varepsilon_F)}{1+\omega_H^2\tau^2(\varepsilon_F)}\\
&\times\left\{a\left[E_yh_z - E_zh_y\right] + \frac{e^2F^2}{\beta h^4\Omega^4}\cdot b\frac{\tau(\varepsilon_F)\left[1-\omega_H^2\tau^2(\varepsilon_F)\right]}{1+\omega_H^2\tau^2(\varepsilon_F)}\times E_yh_z\right\}\end{aligned} \tag{7}$$

$$\begin{aligned}E_{0y} =& -\left\{a + \frac{e^2F^2}{\beta h^4\Omega^4}\cdot b\tau(\varepsilon_F)\right\}^{-1} \times \frac{\omega_H\tau(\varepsilon_F)}{1+\omega_H^2\tau^2(\varepsilon_F)}\\
&\times\left\{a\left[E_zh_x - E_xh_z\right] - \frac{e^2F^2}{\beta h^4\Omega^4}\cdot b\frac{\tau(\varepsilon_F)\left[1-\omega_H^2\tau^2(\varepsilon_F)\right]}{1+\omega_H^2\tau^2(\varepsilon_F)}\times E_xh_z\right\}\end{aligned} \tag{8}$$

$$E_{0z} = -\frac{\omega_H\tau(\varepsilon_F)}{1+\omega_H^2\tau^2(\varepsilon_F)}\left\{1 + \frac{e^2F^2}{\beta h^4\Omega^4}\frac{b}{a} - \frac{\tau(\varepsilon_F)\left[1-\omega_H^2\tau^2(\varepsilon_F)\right]}{1+\omega_H^2\tau^2(\varepsilon_F)}\right\}(E_xh_y - E_yh_x) \tag{9}$$

where

$$a=\frac{n_0^* e^2}{2\pi m h^2}\sqrt{\frac{2m\pi}{\beta}}\sum_{n,l}\exp\left\{-\beta h\omega_0(2n+l+1)\right\} \tag{10}$$

$$b=a(b_1+b_2+b_3+b_4+b_5+b_6);\quad b_1=A\sum_{n,l,n',l'}\left|I_{n,l,n',l'}(q_\perp)\right|^2 B_1\exp\left\{\frac{\beta B_1}{2}\right\}K_1\left\{\frac{\beta B_1}{2}\right\} \tag{11}$$

$$b_2=\frac{A}{2}\sum_{n,l,n',l'}\left|I_{n,l,n',l'}(q_\perp)\right|^2 B_2\exp\left\{\frac{\beta B_2}{2}\right\}K_1\left\{\frac{\beta B_2}{2}\right\};\quad b_3=\frac{A}{2}\sum_{n,l,n',l'}\left|I_{n,l,n',l'}(q_\perp)\right|^2 B_3\exp\left\{\frac{\beta B_3}{2}\right\}K_1\left\{\frac{\beta B_3}{2}\right\} \tag{12}$$

$$b_4=A\sum_{n,l,n',l'}\left|I_{n,l,n',l'}(q_\perp)\right|^2 B_4\exp\left\{\frac{\beta B_4}{2}\right\}K_1\left\{\frac{\beta B_4}{2}\right\};\quad b_5=A\sum_{n,l,n',l'}\left|I_{n,l,n',l'}(q_\perp)\right|^2 B_5\exp\left\{\frac{\beta B_5}{2}\right\}K_1\left\{\frac{\beta B_5}{2}\right\} \tag{13}$$

$$b_6=A\sum_{n,l,n',l'}\left|I_{n,l,n',l'}(q_\perp)\right|^2 B_6\exp\left\{\frac{\beta B_6}{2}\right\}K_1\left\{\frac{\beta B_6}{2}\right\};\quad A=\frac{e^2 h\sqrt{2m\pi\beta}}{m^2\in_0}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right) \tag{14}$$

$$B_1=h\omega_{L_0}-2h\omega_0(n'-n)-h\omega_0\left(l'-l\right);\quad B_2=B_1+h\Omega;\quad B_3=B_1-h\Omega \tag{15}$$

$$B_4=h\omega_{L_0}+2h\omega_0(n'-n)+h\omega_0\left(l'-l\right);\quad B_5=B_4-h\Omega;\quad B_6=B_4+h\Omega \tag{16}$$

3. NUMERICAL RESULTS AND DISCUSSION

In this section, we will survey, plot and discuss the expressions for E_{0z} for the case of a specific GaAs/GaAsAl quantum wire. The parameters used in the calculations are as follows [7, 8]: $\epsilon_0 = 12,5$; $\chi_\infty = 10.48$; $\chi_0 = 12.90$; $h\omega_{LO} = 36.8\,\text{meV}$; $m = 0.0665 m_0$ (m_0 is the mass of free electron); $e = 1.60219\cdot 10^{-19}\,\text{C}$; $\varepsilon_F = 50\,\text{meV}$; and we also choose $\tau(\varepsilon_F) \sim 10^{-11}\,\text{s}^{-1}$; $\tau(\Omega) \sim 10^{-10}\,\text{s}^{-1}$.

In the Fig. 1 and Fig. 2, we show the dependence of E_{0z} (express for the longitudinal radioelectric effect) on the frequency Ω of the intense laser radiation (Fig. 1) and on the frequency ω of the EMW (Fig. 2). From these figures, we can see that the appearance and the nonlinear dependence of E_{0z} on the exterior elements.

From this figure, we can see that the more amplitude F of the intense laser radiation increases, the more the quotient goes up.

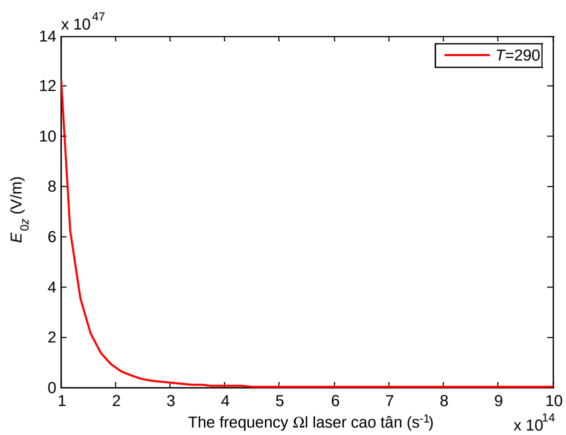

Figure 1: The dependence of E_{0z} on the frequency Ω of the intense laser radiation (in case $\omega = 10^{10}$ Hz; $F = 1.2\cdot 10^5$ V/m).

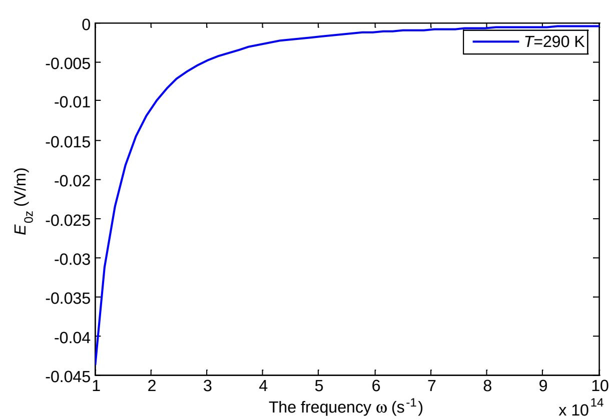

Figure 2: The dependence of E_{0z} on the frequency ω of the EMW (in case $\Omega = 10^{14}$ Hz; $F = 1.2\cdot 10^5$ V/m).

4. CONCLUSIONS

In this paper, we have studied photostumilated quantum effects in quantum wire with a parabolic potential. In this case, two dimensional electron gas systems is placed in an EMW and a laser radiation at high frequency, and the electron gas is completely degenerate. We obtain the expressions for electric field intensity vector $\vec{E}_0$, in which E_{0x}, E_{0y} express for the longitudinal radioelectric effect and E_{0z} expresses for the horizontal radioelectric effect. And, the expressions of $\vec{E}_0$ show clearly the dependence of $\vec{E}_0$ on the amplitude E_w, on the frequency ω of the EMW and on the amplitude F, the frequency Ω of the intense laser radiation; and on the basic elements of QW with a parabolic potential. The analytical results are numerically evaluated and plotted for a specific quantum wire, GaAs/AlGaAs. The comparison of the result of quantum wire to semiconductors builk [5, 7, 10] and superlattice [11, 12] shows that the difference.

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