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Influence of Confined Optical Phonons and Laser Radiation on the Radioelectric Effect in a Cylindrical Semiconductor Quantum Wire with Parabolic Potential

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Abstract: Based on the quantum kinetic equation method, the influence of confined optical phonons and laser radiation on the Radioelectric effect in a cylindrical semiconductor quantum wire with parabolic potential subjected to a dc electric field and a linearly polarized electromagnetic wave has been theoretically studied. The obtained analytical expression of the Radioelectric field (REF) depends on frequencies and amplitudes of the external electromagnetic waves, the quantum wire parameters, the temperature of the system, and especially the quantum numbers (*n* and *m*) which characterize the phonon confinement. Numerical calculations for the GaAs/GaAsAl quantum wire show the strongly impact of the confined optical phonons as well as the laser radiation on the REF magnitude and posture. The REF also has more resonance peaks in comparison with that in case of bulk phonon.

Keywords: Confined optical phonon, laser radiation, Radioelectric field, Cylindrical quantum wire, quantum kinetic equation.

1. Introduction

The Radioelectric effect in semiconductor systems has attracted many interests in recent years. It is known that with the propagation electromagnetic wave (EMW), free carriers absorb both energy and EMW momentum, thereby electrons are generated with directed motion, and in this direction a Radioelectric field (REF) arises under opened circuit conditions [1, 2]. The longitudinal and the transverse REF has been theoretically calculated in the bulk semiconductor [1] and in the superlattices [3], the Radioelectric current has been shown to be considered and be certainly observable by experiments [4, 5]. Since the confined modes of phonons were experimentally observed in low-dimensional semiconductors systems [6, 7], there have been many paper dealing with the impact of confined phonon on kinetic properites of them, such as the cyclotron-phonon resonance in semiconducting quantum well [8], the additional resonant peak of the absorption coefficient of strong EMW in doped superlattices due to confined phonon [9], the dispersion of confined LO phonons in

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quantum well [10], the frequency separation of confined AlAs LO modes has found in superlattices [11], the carrier capture processes in semiconductor superlattices due to emission of confined phonons [12]. Also, the additional strong EMW has been shown to enhance the nonlinear properties of these structures [9, 13]. Hence, the Radioelectric effect is much more interesting in low-dimensional semiconductor system under the influence of confined phonons and laser radiation. In [13], the REF in doped superlattices has multiple resonant peaks and its magnitude increases as the increasing of phonon confinement. In this paper, to show the differences of the Radioelectric effect when changing the material confinement potential, we consider a cylindrical semiconductor quantum wire (CQW) with parabolic potential subjected to a linearly polarized electromagnetic field and varying laser radiation. This leads to change the electron wave function and energy, the matrix element of confined electron – confined optical phonon interaction as well as the Hamiltonian of the system, thus, creating new properties of the REF in a CQW. We predict the extra resonant peaks and the raising in magnitude of the REF in a CQW under the influence of confined phonons and the laser radiation.

The article is organized as follows: in the section 2 we present the confinement of electrons and optical phonons in a CQW. We have derived the analytical expression for the REF by using the quantum kinetic equation method in the section 3. Numerical results and discussion for the GaAs/AlAs cylindrical quantum wire are given in the section 4. And the final section shows remarks and conclusions.

2. The confinement of electrons and phonons in a cylindrical semiconductor quantum wire

Consider a cylindrical quantum wire with parabolic potential $V = \frac{1}{2} m_e \omega_1^2 R^2$ subjected to a linearly polarized electromagnetic field: $\vec{E}(t) = \vec{E}\left(e^{-i\omega t} + e^{i\omega t}\right)$, $\vec{B}(t) = \frac{1}{c}\left[\vec{n}, \vec{E}(t)\right]$ and a laser radiation $\vec{F}(t) = \vec{F} \sin \Omega t$. Under the influence of the material confinement potential, the motion of carriers is restricted in x, y direction and free in the z one. So, the wave function of an electron and its discrete energy now becomes [14]:

$$\Psi_{l,j}(r,\phi,z) = \frac{1}{\sqrt{V_0}} e^{ij\phi} e^{ik_z z} \varphi_{l,j}(r), \text{ where } \varphi_{l,j}(r) = \sqrt{\frac{2l!}{(l+|j|)!}} \rho e^{-r^2\rho^2/2} (r\rho)^{|j|} L_l^{|j|}(r^2\rho^2), \quad (1)$$

$$\varepsilon_{l,j}(\vec{p}_z) = \frac{\hbar^2 p_z^2}{2m_e} + \hbar\omega_1 (2l + |j| + 1), \quad (2)$$

where $\vec{p}_z, m_e$ is the wave vector and the effective mass of an electron, R being the radius of the CQW, $l = 1,2,3,...$ and $j = 0, \pm 1, \pm 2, ...$ being the quantum numbers characterizing the electron confinement, $\rho = \sqrt{\frac{m_e \omega_1}{\hbar}}$ and $L_l^{|j|}$ is the generalized Laguerre polynomial.

When phonons are confined in a CQW, the wave vector and frequency of them are given by [14,15]:

$$\vec{q} = (q_{m,n}, \vec{q}_z),\ q_{m,n} = \frac{x_{m,n}}{R},\ \omega_{m,n,\vec{q}_z}^2 = \omega_0^2 - \gamma^2 \left(q_{m,n}^2 + q_z^2\right), \quad (3)$$

where γ is the velocity parameter, $x_{m,n}$ is the *n*th zero of the *m*th order Bessel function, and $m,n = 1,2,3,...$ being the quantum numbers characterizing the phonon confinement.

Also, the matrix element for confined electron – confined optical phonon interaction in the CQW now becomes [14] $D^{m,n}_{l,j,l',j',\vec{q}_z} = C_{m,n,\vec{q}_z} I^{m,n}_{l,j,l',j'}$ where:

$$\left|C_{m,n,\vec{q}_z}\right|^2 = \frac{2\pi e^2 \hbar\omega_0}{\varepsilon_0 V_0 J^2_{m+1}\left(x_{m,n}\right)}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right)\frac{1}{q^2_{m,n} + q^2_z}, \quad (4)$$

$$I^{m,n}_{l,j,l',j'} = \frac{2}{R^2}\int_0^R J_m\left(x_{m,n}\frac{r}{R}\right)\varphi^*_{l',j'}(r)\varphi_{l,j}(r)rdr. \quad (5)$$

Through equations (1-5), it has been seen that the CQW with new material confinement potential gives the different electron wave function and energy. In addition, the contribution of confined phonon could enhance the probability of electron scattering. As a result, the Radioelectric effect in a CWQ under the influence of confined optical phonon and laser radiation should be studied carefully to find out the new properties.

3. The radioelectric field in a cylindrical semiconductor quantum wire with parabolic potential under the influence of confined optical phonons and laser radiation

The effect of confined optical phonons and the laser radiation modify the Hamiltonian of the confined electrons – confined optical phonons system in the CQW. This leads the quantum kinetic equation for electron distribution now become:

$$\frac{\partial f_{l,j,\vec{p}_z}(t)}{\partial t} + \left(e\vec{E}(t) + e\vec{E}_0 + \hbar\omega_c\left[\vec{p}_z, \vec{h}(t)\right], \frac{\partial f_{l,j,\vec{p}_z}(t)}{\hbar\partial\vec{p}_z}\right) = \frac{2\pi}{\hbar}\sum_{\substack{l',j',\\ m,n,\vec{q}_z}}\left|C_{m,n,\vec{q}_z}\right|^2\left|I^{m,n}_{l,j,l',j'}\right|^2\sum_{s=-\infty}^{+\infty}J^2_s\left(\frac{e\vec{F}}{m_e\Omega^2}, \vec{q}_z\right)\times$$

$$\times\left\{\left[\left\{f_{l',j',\vec{p}_z+\vec{q}_z}(t)\left(N_{m,n,\vec{q}_z}+1\right) - f_{l,j,\vec{p}_z}(t)N_{m,n,\vec{q}_z}\right]\delta\left(\varepsilon_{l',j'}\left(\vec{p}_z+\vec{q}_z\right) - \varepsilon_{l,j}\left(\vec{p}_z\right) - \hbar\omega_{m,n,\vec{q}_z} - s\hbar\Omega\right)+\right.$$

$$+\left\{\left[\left\{f_{l',j',\vec{p}_z-\vec{q}_z}(t)N_{m,n,\vec{q}_z} - f_{l,j,\vec{p}_z}(t)\left(N_{m,n,\vec{q}_z}+1\right)\right]\delta\left(\varepsilon_{l',j'}\left(\vec{p}_z-\vec{q}_z\right) - \varepsilon_{l,j}\left(\vec{p}_z\right) + \hbar\omega_{m,n,\vec{q}_z} - s\hbar\Omega\right) \quad (6)\right.$$

where $\vec{h} = \vec{B}/B$ is the unit vector along the magnetic field, $\omega_c = eB/m_e$ and $\delta(x)$ being the Dirac delta function.

It has been seen that equation (6) contains new terms $\varepsilon_{l,j}$, $\varepsilon_{l',j'}$, $I^{m,n}_{l,j,l',j'}$, ω_{m,n,q_z} in comparison with that in [13]. These terms characterize the effect of CQW confinement potential and the phonon confinement. This leads to change the electron distribution function, the current density and the Radioelectric field in a CQW.

Let us consider that the electron gas is non-degenerate and limit the problem to the cases of *s=-1, 0,1*, meaning the processes with more than one photon are ignored. Suppose the linearly polarized electromagnetic wave propagates along the *x* axis, $\vec{E}\,||\,Oz$, $\vec{B}\,||\,Oy$, $\vec{F}\,||\,Oz$. After some manipulation, the expression for the longitudinal Radioelectric field E_{0x} is obtained:

$$E_{0x} = \frac{2\omega_c\tau}{1+\omega_c^2\tau^2}\left(1 + \frac{1-\omega^2\tau^2}{1+\omega^2\tau^2}\frac{b}{a}\right)E, \quad (7)$$

where $$a = \sum_{l,j} exp\left[\mu\left(\varepsilon_F - \varepsilon_{l,j}\right)\right],\ \mu = \left(k_B T\right)^{-1},\tag{8}$$

$$b = \frac{\sqrt{2\pi} e^2 \omega_0 \tau F^2}{2 m_e^{3/2} \hbar^2 \Omega^4}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right)\left[exp\left(\mu\hbar\omega_0\right) - 1\right]^{-1}\left\{2b_{1,0} + 2b_{-1,0} - b_{-1,-1} - b_{-1,1} - b_{1,-1} - b_{1,1}\right\},\tag{9}$$

$$b_{\alpha\beta} = -\sum_{\substack{m,n,\\ l,j,l',j'}}\left|I^{m,n}_{l,j,l',j'}\right|^2 exp\left[\mu\left(\varepsilon_F - \varepsilon_{l,j} - \xi_{\alpha\beta}/2\right)\right]\left\{\xi_{\alpha\beta} K_1\left(\mu\left|\xi_{\alpha\beta}\right|\right) + \left(\xi_{\alpha\beta} - \varepsilon_{m,n}\right) K_0\left(\mu\left|\xi_{\alpha\beta}\right|\right) -\right.$$
$$\left. - \varepsilon_{m,n}\, sgn\left(\xi_{\alpha\beta}\right) K_{-1}\left(\mu\left|\xi_{\alpha\beta}\right|\right)\right\},$$

here $\xi_{\alpha\beta} = \varepsilon_{l',j'} - \varepsilon_{l,j} + \alpha\hbar\omega_{m,n} + \beta\hbar\Omega$, $\varepsilon_{l',j'} = \hbar\omega_1\left(2l' + |j'| + 1\right)$, $\varepsilon_{l,j} = \hbar\omega_1\left(2l + |j| + 1\right)$, $\varepsilon_{m,n} = \dfrac{\hbar^2 x^2_{m,n}}{2 m_e R^2}$, $\omega^2_{m,n} = \omega_0^2 - \gamma^2 q^2_{m,n}$, $sgn(x)$ denotes the sign function and $K_n(x)$ being the Bessel function of second kind.

Formula (7) shows the dependence of the Radioelectric field on parameters of the system: the frequency Ω and amplitude *F* of the laser radiation, the frequency ω of the linearly polarized electromagnetic wave, the temperature *T*, the CQW radius *R* and especially the quantum numbers *m*, *n* characterizing the phonons confinement. It has seen that terms $\varepsilon_{l,j}$, $\varepsilon_{l',j'}$ show the effect of the CQW confinement potential, while components containing *m*, *n* associate with the effect of phonon confinement. When *m*, *n* go to zero, we obtain the results in the case of bulk phonons.

4. Numerical results and discussions

In this section, we present the numerical evaluation of the Radioelectric field for the GaAs/AlAs cylindrical quantum wire. Parameters used in this calculation are as follows: $m^* = 0.067 m_0$ (m_0 is the free mass of an electron); $\chi_\infty = 10.9$; $\chi_0 = 12.9$; $\tau = 2.10^{-12}\,s$; $\omega = 10^{11}\,s^{-1}$; $\omega_1 = 7.10^{12}\,s^{-1}$; $F = 10^5\,V/m$; $T = 290K$; $\varepsilon_F = 50meV$; $\hbar\omega_0 = 36.6meV$; $v = 8.73.10^4\,m.s^{-1}$; $R = 20nm$; $l = 1$, $j = 0$, $l' = 1$, $j' = 1$, (the transition between the lowest and the first excited level of an electron).

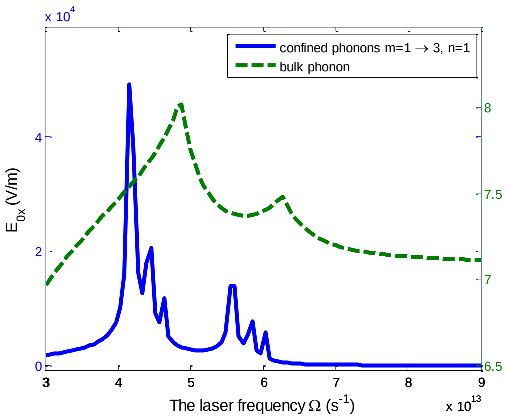

Figure 1. The dependence of the Radioelectric field E_{0x} on the Laser Frequency Ω for confined phonons (solid line) and bulk phonon (dashed line) in a CQW.

Figure 1 shows the dependence of the Radioelectric field on the frequency of the laser radiation for confined phonons $m=1\rightarrow 3, n=1$ in a CQW and bulk phonon in a CQW. It has been seen that the REF reaches a saturating value as the raising of the laser frequency. In addition, the REF has more resonance peaks for the confined optical phonon in comparison with that for the bulk phonon in the CQW. These peaks are corresponding to the condition:

$$\varepsilon_{l',j'} - \varepsilon_{l,j} \pm \hbar\omega_{m,n} \pm \hbar\Omega = 0 .$$

As we can see, when the electrons are confined in a CQW, there are peaks associated with the laser energy $\hbar\Omega = \hbar\omega_0 \pm \Delta_{1,0}^{1,1}$ where $\Delta_{l,j}^{l',j'} = \varepsilon_{l',j'} - \varepsilon_{l,j}$. Since the phonon confinement is considerable, the optical phonon frequency is now modified to $\omega_{m,n} = \sqrt{\omega_0^2 - \gamma^2 q_{m,n}^2}$, here $m=1\rightarrow 3, n=1$. Thus, from the left to the right, these peaks of the RFF now correspond with the conditions $\hbar\Omega = \hbar\omega_{3,1} - \Delta_{1,0}^{1,1}, \hbar\omega_{2,1} - \Delta_{1,0}^{1,1}, \hbar\omega_{1,1} - \Delta_{1,0}^{1,1}$, $\hbar\omega_{3,1} + \Delta_{1,0}^{1,1}, \hbar\omega_{2,1} + \Delta_{1,0}^{1,1}, \hbar\omega_{1,1} + \Delta_{1,0}^{1,1}$. Also, the contribution of confined optical phonon leads to an increase of the REF magnitude. The mechanism of this increase is the raising in the probability of electron scattering due to the CQW confinement potential and the effect of phonon confinement, thus, the REF increases as a result.

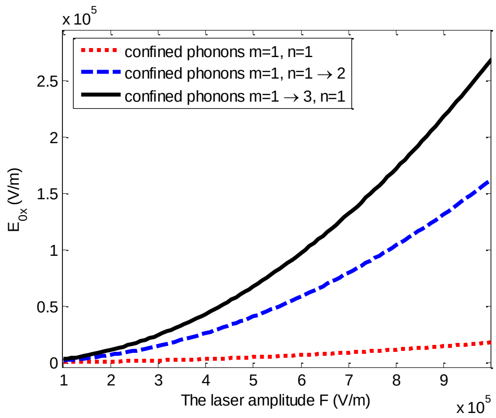

Figure 2. The dependence of the Radioelectric field E_{0x} on the Laser Amplitude for confined phonons in a CQW for $m=1, n=1$ (dotted line), $m=1, n=1\rightarrow 2$ (dashed line), $m=1\rightarrow 3, n=1$ (solid line).

Figure 2 shows the dependence of the Radioelectric field on the amplitude of the laser radiation at different value of quantum number m, n, here $\Omega = 5.10^{13} s^{-1}$. The Radioelectric field increases nonlinearly as the increasing of the laser amplitude and the effect of phonon confinement.

So, the confined optical phonon and the laser radiation lead the REF in a CQW increase in magnitude and have extra resonant peaks. This phenomenon is different from that in doped superlattices [13] due to the new material confinement potential, the different electron wave function and energy spectrum as well as the new form of the confined electron – confined optical phonon interaction in a CQW.

5. Conclusions

In this work, the influence of confined optical phonons on the Radioelectric effect in a cylindrical semiconductor quantum wire with parabolic potential under the presence of a linearly polarized electromagnetic wave and the laser radiation has been studied base on quantum kinetic equation method. The analytical expression for the Radioelectric field is obtained. The theoretical result are very different from previous ones [1-5] because of i) the different electron energy and wave function due to the new material confinement potential ii) the contribution of the optical phonon confinement iii) the effect of laser radiation. As a result, the REF expression contains new terms characterizing the confined optical phonons, the CQW confinement effect and the laser radiation. The REF dependence complex on the frequency Ω and amplitude *F* of the laser radiation, the frequency ω of the linearly polarized EMW, the temperature *T*, the CQW radius *R* and especially the quantum numbers *m, n* characterizing the phonons confinement. Numerical calculation is also applied for the GaAs/AlAs cylindrical quantum wire. Results show that the increasing of the laser amplitude and the effect of phonon confinement lead the REF magnitude increase nonlinearly. In addition, the REF decreases to a saturating value as the raising of the laser frequency. Furthermore, the effect of phonon confinement lead the REF have more resonance peaks in comparison with that in case of bulk phonon, these peaks correspond to the condition $\varepsilon_{l',j'} - \varepsilon_{l,j} \pm \hbar\omega_{m,n} \pm \hbar\Omega = 0$. In conclusion, confined optical phonons and laser radiation make remarkable contribution on the magnitude of the Radioelectric field as well as the selection rules for electron transition in the cylindrical quantum wire.

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