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The Photon - Drag Effect in Rectangular Quantum Wire with An Infinite Potential

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Abstract: The photon - drag effect with optical phonon-electron scattering in rectangular quantum wire with an infinite potential is studied. Based on the quantum kinetic equation for electrons under the action of a linearly polarized electromagnetic wave, a dc electric field and an intense laser field, analytic expressions for the density of the direct current for the case of electron – optical phonon scattering are calculated. The dependence of the direct current density on the frequency Ω of the laser radiation field, the frequency ω of the linearly polarized electromagnetic wave, the size of the wire is obtained. The analytic expressions are numerically evaluated and plotted for a specific quantum wire, GaAs/AlGaAs. All these results of quantum wire are compared with bulk semiconductors and superlattices to show the differences.

Keywords: The photon – drag effect; rectangular quantum wire; optical phonon; infinite potential; the density of the direct current.

1. Introduction

The photon – drag effect by electromagnetic wave is explained by carriers absorb both energy and electromagnetic wave momentum, so electrons are generated with detected motion and a direct current arises in this direction, as well as for characterizing kinetic properties of semiconductors [1]. It is known that the presence of intense laser radiation can influence the electrical conductivity and kinetic effects in material [2-9]. In recent years [10 - 12], it has been revealed that the photon - drag effect in superlattices and in quantum wells should be characterized by new features under the action of strong fields. However, in quantum wire, the photon - drag effect still opens for studying.

In this work, we use the quantum kinetic to study the drag of charge carriers in rectangular quantum wire with an infinite potential by a linearly polarized electromagnetic, a dc electric field and a laser field. We obtained the density of the current for the case electrons interacting with optical phonon and results are compared with bulk semiconductors and superlattices. The paper has six sections: Introduction, calculating the density of the current by the quantum kinetic equation method, numerical results and discussion, conclusions.

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2. Calculating the density of the current by the quantum kinetic equation method

We examine the electron system, which is placed in a linearly polarized electromagnetic wave ($\vec{E}(t)=\vec{E}(e^{-i\omega t}+e^{i\omega t}),\vec{H}(t)=\left[\vec{n},\vec{E}(t)\right]$), 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 - phonon system in the quantum wire can be written as:

$$H = H_0 + U = \sum_{n,l,\vec{p}_z}\varepsilon_{n,l,\vec{p}_z}(\vec{p}_z-\frac{e}{\hbar c}\vec{A}(t)).a^+_{n,l,\vec{p}_z}.a_{n,l,\vec{p}_z}+\sum_{\vec{q}}\hbar\omega_{\vec{q}}b^+_{\vec{q}}b_{\vec{q}}+$$

$$+\sum_{n,l,n',l'}\sum_{\vec{p}_z,\vec{q}}C_q.I_{n,l,n',l'}(\vec{q})a^+_{n',l',\vec{p}_s+\vec{q}}.a_{n,l,\vec{p}_z}(b_{\vec{q}}+b^+_{-\vec{q}}) \quad (1)$$

Where $\vec{A}(t)$ is the vector potential of laser field (only the laser field affects the probability of scattering): $-\frac{1}{c}\vec{A}(t)=\vec{F}_0\sin\Omega t$; a^+_{n,l,p_z} and a^-_{n,l,p_z} (b^+_q and b^-_q) are the creation and annihilation operators of electron (phonon); ω_q is the frequency of optical phonon; C_q is the electron-optical phonon interaction constant: $C_q^2=\frac{2\pi e^2\hbar\omega_0}{\xi_0 q_z^2}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)$; $I_{n',l',n,l}(\vec{q})$ is form factor.

The electron energy takes the simple: $\varepsilon_{n,l,p_z}=\frac{p_z^2}{2m}+\frac{\pi^2\hbar^2}{2m}\left(\frac{n^2}{L_x^2}+\frac{l^2}{L_y^2}\right)$ ($n=0,\pm1,\pm2,...$, $l=1,2,3,...$).

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

$$i\hbar\frac{\partial f_{n,l,p_z}(t)}{\partial t}=<\left[a^+_{n,l,p_z}a_{n,l,p_z},H\right]>_t \quad (2)$$

With $f_{n,l,p_z}(t)=<a^+_{n,l,p_z}a_{n,l,p_z}>_t$ is distribution function. From Eqs. (1) and (2), we obtain the quantum kinetic equation for electrons in quantum wire (after supplement: a linearly polarized electromagnetic wave field and a direct electric field $\vec{E}_0$):

$$\frac{\partial f_{n,,l\vec{p}_z}(t)}{\partial t}-\left(e.\vec{E}(t)+e.\vec{E}_0+\omega_c\left[\vec{p}_z,\vec{h}(t)\right]\right)\frac{1}{\hbar}\frac{\partial f_{n,l,\vec{p}_z}(t)}{\partial\vec{p}_z}=$$

$$=\frac{2\pi}{\hbar}\sum_{n',l',\vec{q}}\left|D_{n,l,n',l'}(\vec{q})\right|^2.\sum_{L=-\infty}^{\infty}J_L^2(\frac{e\vec{E}_0\vec{q}}{m\Omega^2})N_q\left\{\left[f_{n',l',\vec{p}_z+\vec{q}}(t)-f_{n,l,\vec{p}_z}(t)\right].\delta(\varepsilon_{n',l',\vec{p}_z+\vec{q}_z}-\varepsilon_{n,,l\vec{p}_z}-\hbar\omega_{\vec{q}}-L\hbar\Omega)\right.$$

$$\left.+\left[f_{n',l',\vec{p}_z-\vec{q}_z}(t)-f_{n,l,\vec{p}_z}(t)\right]\delta\left(\varepsilon_{n',l',\vec{p}_z-\vec{q}_z}-\varepsilon_{n,l,\vec{p}_z}+\hbar\omega_{\vec{q}}-L\hbar\Omega\right)\right\} \quad (3)$$

Where $\vec{h}=\frac{\vec{H}}{H}$ is the unit vector in the magnetic field direction, $J_L(\frac{e\vec{E}_0\vec{q}}{m\Omega^2})$ is the Bessel function of real argument; N_q is the time-independent component of distribution function of phonon: $N_q=\frac{k_BT}{\hbar\omega_q}$; where ω_c is the cyclotron frequency, $\tau(\varepsilon)$ is the relaxation time of electrons with energy ε.

For simplicity, we limit the problem to the case of $l = 0, \pm 1$. We multiply both sides Eq. (2) by $(-e/m)\vec{p}_z \delta(\varepsilon - \varepsilon_{n,\vec{p}_\perp})$ are carry out the summation over n, l and $\vec{p}_z$, we obtained:

$$(-i\omega + \frac{1}{\tau(\varepsilon)})\vec{R}(\varepsilon) = \vec{Q}(\varepsilon) + \vec{S}(\varepsilon) + \omega_c\left[\vec{R}_0(\varepsilon), \vec{h}\right] \quad (4)$$

$$(-i\omega + \frac{1}{\tau(\varepsilon)})\vec{R}^*(\varepsilon) = \vec{Q}(\varepsilon) + \vec{S}^*(\varepsilon) + \omega_c\left[\vec{R}_0(\varepsilon), \vec{h}\right] \quad (5)$$

$$\frac{\vec{R}_0(\varepsilon)}{\tau(\varepsilon)} = \vec{Q}_0(\varepsilon) + \vec{S}_0(\varepsilon) + \omega_c\left[\vec{R}(\varepsilon) + \vec{R}^*(\varepsilon), \vec{h}\right] \quad (6)$$

With:

$$\vec{R}(\varepsilon) = -\frac{e}{m}\sum_{n,l,\vec{p}_z} \vec{p}_z f_1(\vec{p}_z)\delta\left(\varepsilon - \varepsilon_{n,l,p_z}\right) \quad (7)$$

$$\vec{Q}(\varepsilon) = -\frac{e^2\vec{E}}{m^2 k_B T}\sum_{n,l,p_z} p_z^2 f_0(\varepsilon_{n,l,p_z})\delta\left(\varepsilon - \varepsilon_{n,l,p_z}\right) \quad (8)$$

$$\vec{Q}_0(\varepsilon) = -\frac{e^2\vec{E}_0}{m^2 k_B T}\sum_{n,l,p_z} p_z^2 f_0(\varepsilon_{n,l,p_z})\delta\left(\varepsilon - \varepsilon_{n,l,p_z}\right) \quad (9)$$

$$\begin{aligned}\vec{S}_0(\varepsilon) = \frac{2\pi e}{m}&\sum_{n,l,n',l',p_z,q_z} C_q^2 \left|I_{n,l,n',l'}(q)\right|^2 N_q \vec{q}_z f_{10}(\vec{p}_z)\frac{e^2F^2q_z^2}{4m^2\Omega^4}\times\\ &\times\left\{\left[\delta(\varepsilon_{n',l',\vec{p}_z+\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} - \omega_q + \Omega) + \delta(\varepsilon_{n',l',\vec{p}_z+\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} - \omega_q - \Omega)\right] - \right.\\ &\left.-\left[\delta(\varepsilon_{n',l',\vec{p}_z-\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} + \omega_q + \Omega) + \delta(\varepsilon_{n',l',\vec{p}_z-\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} + \omega_q - \Omega)\right]\right\}\times\\ &\times\delta(\varepsilon - \varepsilon_{n,l,\vec{p}_z})\end{aligned} \quad (10)$$

where

$$f_{10}(\vec{p}_z) = -\vec{p}_z\vec{\chi}_0\frac{\partial f_0}{\partial\varepsilon_{n,l,p_z}};\ \vec{\chi}_0 = \frac{e}{m}\vec{E}_0\tau\left(\varepsilon_{n,l,p_z}\right);\ f_0 = n_0\exp(-\frac{\varepsilon_{n,l,p_z}}{k_B T})$$

n_0 is particle density; k_B is Boltzmann constant; T is temperature of system;.

$$\begin{aligned}\vec{S}(\varepsilon) = \frac{2\pi e}{m}&\sum_{n,l,n',l',p_z,q_z} C_q^2 \left|I_{n,l,n',l'}(q)\right|^2 N_q \vec{q}_z f_1(\vec{p}_z)\frac{e^2F^2q_z^2}{4m^2\Omega^4}\times\\ &\times\left\{\left[\delta(\varepsilon_{n',l',\vec{p}_z+\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} - \omega_q + \Omega) + \delta(\varepsilon_{n',l',\vec{p}_z+\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} - \omega_q - \Omega)\right] - \right.\\ &\left.-\left[\delta(\varepsilon_{n',l',\vec{p}_z-\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} + \omega_q + \Omega) + \delta(\varepsilon_{n',l',\vec{p}_z-\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} + \omega_q - \Omega)\right]\right\}\times\\ &\times\delta(\varepsilon - \varepsilon_{n,l,\vec{p}_z})\end{aligned} \quad (11)$$

with

$$f_1(\vec{p}_z) = -\vec{p}_z\vec{\chi}\frac{\partial f_0}{\partial \varepsilon_{n,l,p_z}}\ ;\ \vec{\chi} = \frac{e}{m}\vec{E}\frac{\tau\left(\varepsilon_{n,l,p_z}\right)}{1-i\omega\tau\left(\varepsilon_{n,l,p_z}\right)}$$

Solving the equation system (4), (5), (6), we obtain:

$$\vec{R}_0(\varepsilon) = \tau(\varepsilon)(\vec{Q}_0+\vec{S}_0) + \frac{2\omega_c\tau^2(\varepsilon)}{1+\omega^2\tau^2(\varepsilon)}\left[\vec{Q},\vec{h}\right] + 2\omega_c\tau^2(\varepsilon)\,\mathrm{Re}\left\{\frac{\left[\vec{S},\vec{h}\right]}{1-i\omega\,\tau(\varepsilon)}\right\} \tag{12}$$

The density of current:

$$\vec{j}_0 = \int_0^\infty \vec{R}_0(\varepsilon)d\varepsilon = \left[AC-D\right]\vec{E}_0 + \frac{2\omega_c\tau(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\left[\frac{1-\omega^2\tau^2(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}AC-D\right]\left[\vec{E},\vec{h}\right] \tag{13}$$

where

$$A = \frac{n_0e^6F^2\tau^2(\varepsilon_F)}{8\varepsilon_0m^4\Omega^4}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\sum_{n,l,n',l'} I^2_{n,l,n',l'}\exp\left\{-\beta\frac{\pi^2\hbar^2}{2m}\left(\frac{n^2}{L_x^2}+\frac{l^2}{L_y^2}\right)\right\} \tag{14}$$

$$\begin{aligned} C = &\left(\frac{1}{2}N_1+\frac{1}{2}N_2-\frac{1}{2}N_3-\frac{1}{2}N_4\right)\left(\beta\frac{\hbar^2}{2m}\right)^{-1/2} - N_1^{5/2}\left[\psi_{(2,5/2;\beta\frac{\hbar^2N_1}{2m})}-\psi_{(3,7/2;\beta\frac{\hbar^2N_1}{2m})}\right]- \\ &-N_2^{5/2}\left[\psi_{(2,5/2;\beta\frac{\hbar^2N_2}{2m})}-\psi_{(3,7/2;\beta\frac{\hbar^2N_2}{2m})}\right]-N_3^{5/2}\left[\psi_{(2,5/2;\beta\frac{\hbar^2N_3}{2m})}-\psi_{(3,7/2;\beta\frac{\hbar^2N_3}{2m})}\right]- \\ &-N_4^{5/2}\left[\psi_{(2,5/2;\beta\frac{\hbar^2N_4}{2m})}-\psi_{(3,7/2;\beta\frac{\hbar^2N_4}{2m})}\right]\end{aligned} \tag{15}$$

$\Psi_{(a,b,z)} = \frac{1}{\Gamma_{(a)}}\int_0^\infty e^{-zx}x^{a-1}(1+ax)^{b-a-1}dx$ is the Hypergeometrix function.

$$N_1 = -\frac{2m}{\hbar^2}\left[\frac{\pi^2\hbar^2}{2mL_x^2}(n'^2-n^2)+\frac{\pi^2\hbar^2}{2mL_y^2}(l'^2-l^2)-\hbar\omega_q+\hbar\Omega\right] \tag{16}$$

$$N_2 = -\frac{2m}{\hbar^2}\left[\frac{\pi^2\hbar^2}{2mL_x^2}(n'^2-n^2)+\frac{\pi^2\hbar^2}{2mL_y^2}(l'^2-l^2)-\hbar\omega_q-\hbar\Omega\right] \tag{17}$$

$$N_3 = -\frac{2m}{\hbar^2}\left[\frac{\pi^2\hbar^2}{2mL_x^2}(n'^2-n^2)+\frac{\pi^2\hbar^2}{2mL_y^2}(l'^2-l^2)+\hbar\omega_q+\hbar\Omega\right] \tag{18}$$

$$N_4 = -\frac{2m}{\hbar^2}\left[\frac{\pi^2\hbar^2}{2mL_x^2}(n'^2 - n^2) + \frac{\pi^2\hbar^2}{2mL_y^2}(l'^2 - l^2) + \hbar\omega_q - \hbar\Omega\right](\quad (19)$$

$$D = \frac{n_0^2 e^2\hbar}{4\pi m^2 k_B T}\left(\beta\frac{\hbar^2}{2m}\right)^{-2}\tau(\varepsilon_F)\sum_{n,l}\exp\left\{-\beta\frac{\pi^2\hbar^2}{2m}\left(\frac{n^2}{L_x^2} + \frac{l^2}{L_y^2}\right)\right\} \quad (20)$$

We obtain the expressions for the current density $\vec{j}_0$, and select: $\vec{E}\uparrow\uparrow 0x$; $\vec{h}\uparrow\uparrow 0y$:

$$j_{0x} = [AC - D]E_{0x};\ j_{0y} = [AC - D]E_{0y} \quad (21)$$

$$j_{0z} = [AC - D]E_{0z} + \frac{2\omega_c\tau(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\left[\frac{1-\omega^2\tau^2(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}AC - D\right]E \quad (22)$$

Equation (13) shows the dependent of the direct current density on the frequency Ω of the laser radiation field, the frequency ω of the linearly polarized electromagnetic wave, the size of the wire. We also see the dependence of the constant current density on characteristic parameters for quantum wire such as: wave function; energy spectrum; form factor $I_{n,l,n',l'}$ and potential barrier, that is the difference between the quantum wire, superlattices, quantum wells, and bulk semiconductors.

3. Numerical results and discussion

In this section, we will survey, plot and discuss the expressions for j_{0z} for the case of a specific GaAs/GaAsAl quantum wire. The parameters used in the calculations are as follows [2-12]: m = 0,0665m_0 (m_0 is the mass of free electron); ε_F = 50meV; $\tau(\varepsilon_F) \sim 10^{-11}s^{-1}$; $n_0 = 10^{23}m^{-3}$; $\rho = 5.3\times10^3 kg/m^3$; $\xi = 2.2\times10^{-8}J$; E = 10^6 V/m; E_0 = 5.10^6V/m; F = 10^5N.

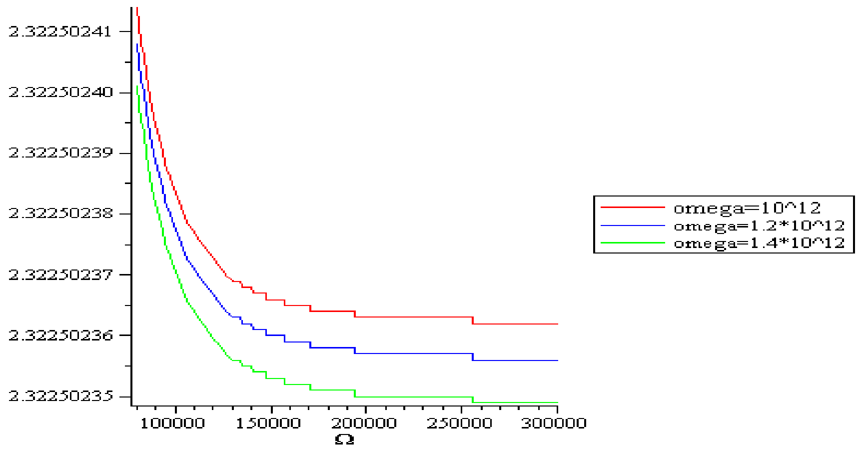

Fig. 1. The dependence of j_z on the frequency Ω of the laser radiation with different values of ω

Fig. 1 shows the dependence of j_{0z} on the frequency Ω of the intense laser radiation. From these figure, we can see the nonlinear dependence of j_{0z} on the frequency Ω of the intense laser radiation, when the frequency Ω of the intense laser radiation increase j_{oz} decreases.

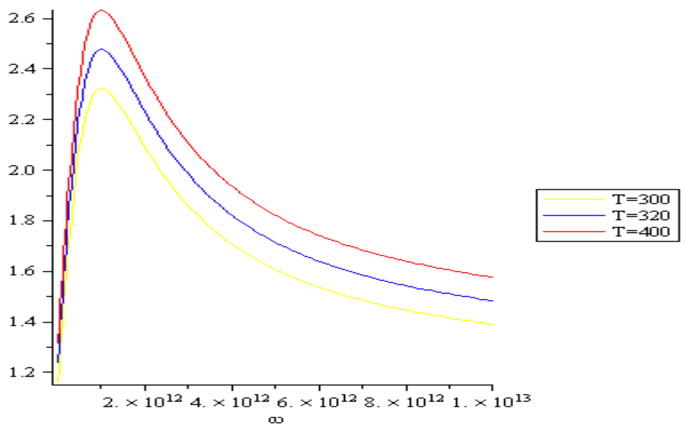

Fig. 2. The dependence of j_z on the frequency ω of the electromagnetic wave with different values of T.

Fig. 2 shows the dependence of j_{0z} on the frequency ω of the electromagnetic wave, we see there is a resonant peak when $\omega = 2.1*10^{12}$rad/s, it shows the resonance of optical phonon at a value of the frequency of electromagnetic wave.

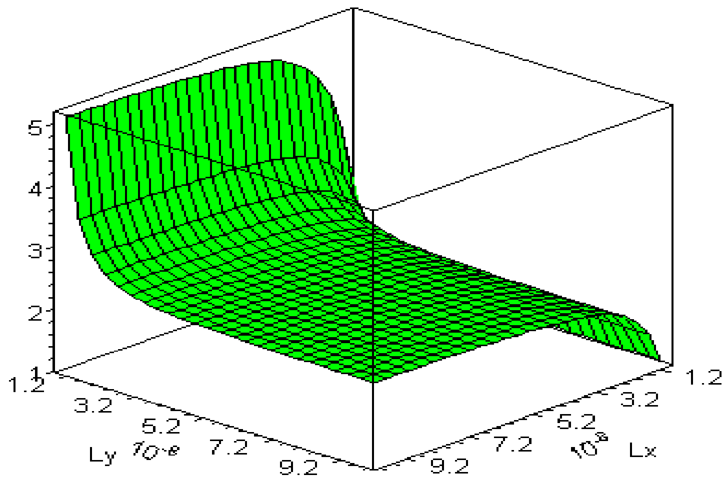

Fig. 3. The dependence of j_{0z} on the size of the wire.

Fig. 3 shows the dependence of j_{0z} on the size of the wire. From this figure, when radius increase j_{oz} decreases, when L_x, L_y continue to increase then j_{0z} will have a stable value, that is the value of the bulk semiconductor (L_x, $L_y \to \infty$).

4. Conclusions

In this paper, we have studied the drag - effect in rectangular quantum wire with a infinite potential. In this case, one dimensional electron systems is placed in a linearly polarized electromagnetic wave, a dc electric field and a laser radiation field at high frequency. We obtain the expressions for current density vector $\vec{j}_0$, in which, plot and discuss the expressions for j_{0z}. The expressions of j_{0z} show the dependence of j_{0z} on the frequency ω of the linearly polarized electromagnetic wave, on the size of the wire, the frequency Ω of the intense laser radiation; and on the basic elements of quantum wire with a infinite potential. The analytical results are numerically evaluated and plotted for a specific quantum wire GaAs/AlGaAs. These results are compared of the results of quantum wire with bulk semiconductors [1], quantum well [10] and superlattices [11, 12] to show the differences.

Acknowledgments

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