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The Photon-Drag Effect in Cylindrical Quantum Wire with an Infinite Potential for the Case of Electrons – Acoustic Phonon Scattering

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Abstract: The photon - drag effect with electrons – acoustic phonon scattering in cylindrical quantum wire with an infinite potential is studied. With the appearance of the linearly polarized electromagnetic wave, the laser radiation field and the dc electric field, analytic expressions for the density of the direct current are calculated by the quantum kinetic equation. The dependence of the direct current density on the frequency of the laser radiation field, the frequency of the linearly polarized electromagnetic wave and the temperature of the system is obtained. The analytic expressions are numerically evaluated and plotted for a specific quantum wire, GaAs/AlGaAs. The difference of the density of the direct current in the quantum wires from quantum well and bulk semiconductor is due to potential barrier and characteristic parameters of system. These results are for every temperature and are new results.

Keywords: The photon, drag effect, the density of the direct current, cylindrical quantum wire, electrons, acoustic phonon, infinite potential.

1. Introduction

The photon-drag effect is explained by propagation electromagnetic wave carriers which absorb both energy and electromagnetic wave momentum, thereby electrons are generated with directed motion and a constant current is created in this direction. The presence of intense laser radiation can also influence electrical conductivity and kinetic effects in material [1]-[12]. The photon-drag effect has been researched in semiconductors [1], in superlattices [10-12]. In quantum wire, the photon drag effect with electrons – acoustic phonon scattering in cylindrical quantum wire with an infinite potential is still open for study. In this paper, using the quantum kinetic equation for an electron system interacting with acoustic phonon is placed in a direct electric field, an electromagnetic wave and the presence of an intense laser field in quantum wire with an infinite potential, the constant

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current density of the photon-drag effect is calculated and numerical calculations are carried out with a specific GaAs/GaAsAl quantum wire.

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

The particulate system is placed in a linearly polarized electromagnetic wave field, in a direct electric field and in a strong radiation field. Hamiltonian' system is:

$$H = H_0 + U = \sum_{n,l,\vec{p}_z} \varepsilon_{n,l,\vec{p}_z}\left(\vec{p}_z - \frac{e}{\hbar c}\vec{A}(t)\right).a^+_{n,l,\vec{p}_z}.a_{n,l,\vec{p}_z} + \sum_{\vec{q}} \hbar\omega_{\vec{q}} b^+_{\vec{q}} b_{\vec{q}} + \\ + \sum_{n,l,n',l'}\sum_{\vec{p}_z,\vec{q}} C_q . I_{n,l,n',l'}(\vec{q}) a^+_{n',l',\vec{p}_s+\vec{q}}.a_{n,l,\vec{p}_z}(b_{\vec{q}} + b^+_{-\vec{q}}) \quad (1)$$

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 acoustic phonon; C_q is the electron-acoustic phonon interaction constant: $C_q^2 = \frac{\xi^2 q}{2\rho v_s V}$, here V, ρ, v_s and ξ are volume, the density, the acoustic velocity and the deformation potential constant; $I_{n',l',n,l}(\vec{q})$ is form factor.

The electron energy takes the simple: $\varepsilon_{n,l,p_z} = \frac{p_z^2}{2m} + \frac{\hbar^2}{2mR^2}B_{n,l}^2$ ($n = 0,\pm 1,\pm 2,...$, $l = 1,2,3,...$ are quantum numbers; R is radius of wire; $B_{n,l}$ is solution of the Bessel function).

In order to establish the quantum kinetic equations for electrons in quantum wire, we use general quantum equations:

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

With $f_{n,l,p_z}(t) = \langle a^+_{n,l,p_z}a_{n,l,p_z}\rangle_t$ 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 $\vec{E}_0$):

$$\frac{\partial f_{n,l\,\vec{p}_z}(t)}{\partial t} + \left(e.\vec{E}(t) + e.\vec{E}_0 + \omega_c\left[\vec{p}_z,\vec{h}(t)\right]\right)\frac{\partial f_{n,l,\vec{p}_z}(t)}{\partial \vec{p}_z} = \\ = \frac{2\pi}{\hbar}\sum_{n',l',\vec{q}}\left|D_{n,l,n',l'}(\vec{q})\right|^2.\sum_{L=-\infty}^{\infty} J_L^2\left(\frac{e\vec{E}_0\vec{q}}{m\Omega^2}\right)N_q\left\{\left[f_{n',l',\vec{p}_z+\vec{q}}(t) - f_{n,l,\vec{p}_z}(t)\right].\delta(\varepsilon_{n',l',\vec{p}_z+\vec{q}_z} - \varepsilon_{n,l\,\vec{p}_z} - L\Omega) \\ + \left[f_{n',l',\vec{p}_z-\vec{q}_z}(t) - f_{n,l,\vec{p}_z}(t)\right]\delta\left(\varepsilon_{n',l',\vec{p}_z-\vec{q}_z} - \varepsilon_{n,l,\vec{p}_z} - L\Omega\right)\right\} \quad (3)$$

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: $N_q=\frac{k_BT}{v_sq_z}$; 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 $l=0,\pm1$. 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: $$\vec{R}(\varepsilon)=\frac{e}{m}\sum_{n,l,\vec{p}_z}\vec{p}_z f_1(\vec{p}_z)\delta\left(\varepsilon-\varepsilon_{n,l,p_z}\right) \quad (7)$$

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

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

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

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

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

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

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

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

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

The density of current:

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

where $A = \dfrac{n_0 e^3 F^2 \tau^2\left(\varepsilon_F\right)\xi^2}{32\pi m^4 \rho v_s^2 \Omega^2}\sum\limits_{n,l,n',l'} I^2_{n,l,n',l'}\,exp\left\{-\beta\dfrac{B^2_{n,l}}{2mR^2}\right\}$ (14)

$$C = -4N_1^{7/2}\left[12\psi_{(4,9/2;\beta\frac{N_1}{2m})} + 24\psi_{(3,7/2;\beta\frac{N_1}{2m})} + \psi_{(2,5/2;\beta\frac{N_1}{2m})}\right] - \\ -4N_2^{7/2}\left[12\psi_{(4,9/2;\beta\frac{N_2}{2m})} + 24\psi_{(3,7/2;\beta\frac{N_2}{2m})} + \psi_{(2,5/2;\beta\frac{N_2}{2m})}\right] \quad (15)$$

$$N_1 = -\frac{1}{R^2}(B^2_{n',l'} - B^2_{n,l}) - 2m\Omega \quad (16)$$

$$N_2 = -\frac{1}{R^2}(B^2_{n',l'} - B^2_{n,l}) + 2m\Omega \quad (17)$$

$$D = \frac{n_0^2 e^2\hbar}{4\pi m^2 k_B T}\left(\beta\frac{\hbar^2}{2m}\right)^{-2}\tau\left(\varepsilon_F\right)\sum_{n,l} exp\left\{-\beta\frac{B^2_{n,l}}{2mR^2}\right\} \quad (18)$$

$\Psi_{(a,b,z)} = \dfrac{1}{\Gamma_{(a)}}\int\limits_0^\infty e^{-zx}x^{a-1}(1+ax)^{b-a-1}dx$ is the Hypergeometrix function.

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

$$j_{0x} = \left[AC + D\right]E_{0x};\ j_{0y} = \left[AC + D\right]E_{0y} \quad (19)$$

$$j_{0z} = \left[AC + D\right]E_{0z} + \frac{2\omega_c\tau\left(\varepsilon_F\right)}{1+\omega^2\tau^2\left(\varepsilon_F\right)}\left[\frac{1-\omega^2\tau^2\left(\varepsilon_F\right)}{1+\omega^2\tau^2\left(\varepsilon_F\right)}AC + D\right]E \quad (20)$$

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; $\tau(\varepsilon_F)$ ~ $10^{-11}s^{-1}$; $n_0 = 10^{23} m^{-3}$; $\rho = 5.3\times 10^3 kg/m^3$; $\xi = 2.2\times 10^{-8} J$; E = 10^6 V/m; E_0 = 5.10^{6}V/m; F = 10^5N; v_s = 5220m/s; R = 5.10^{-9}m.

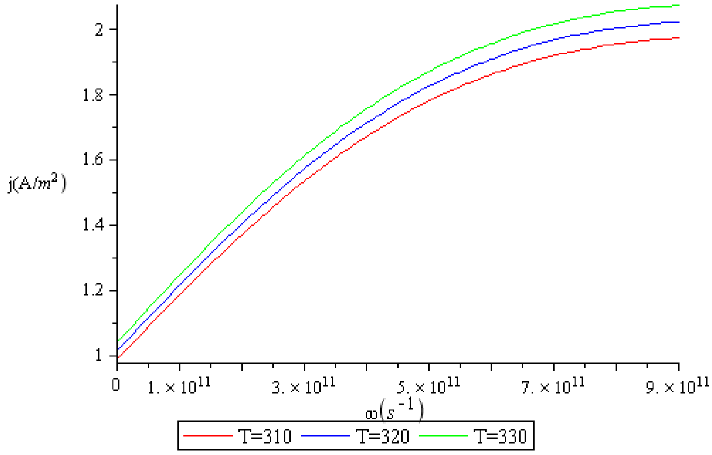

Fig. 1. The dependence of j_z on the frequency ω of the electromagnetic wave with different values of T.

Fig. 1 shows the dependence of j_{0z} on the frequency ω of the electromagnetic wave, when the frequency ω of the electromagnetic wave increases, j_{0z} also increases and toward a critical value.

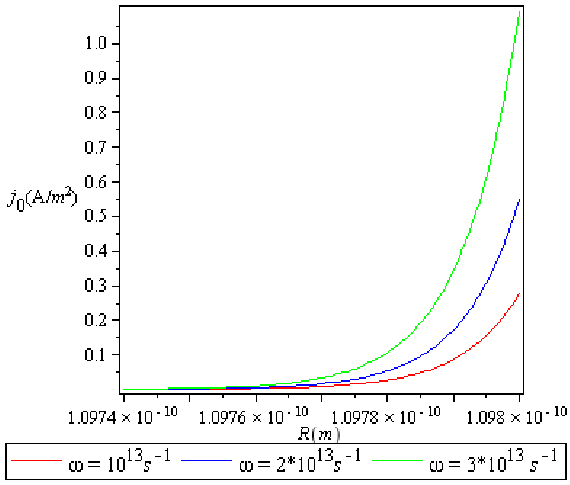

Fig. 2. The dependence of j_{0z} on the size of the wire.

Fig. 2 shows the dependence of j_{0z} on the size of the wire. From this figure, when radius increase j_{0z} also increases, when R continues to increase then j_{0z} foward the value of the bulk semiconductor.

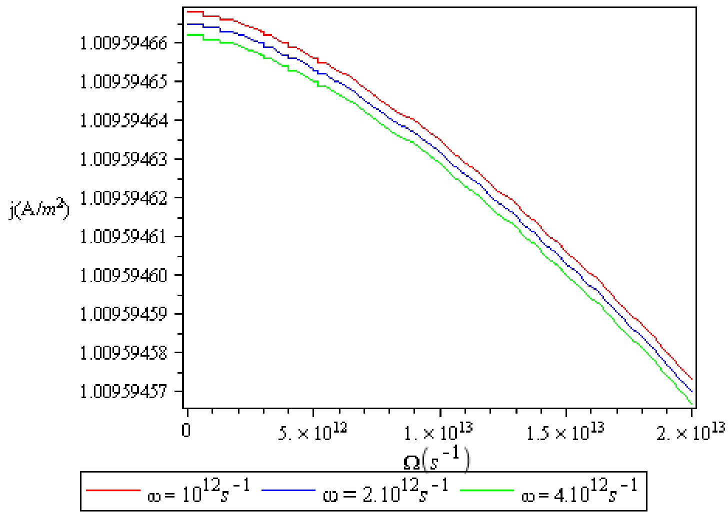

Fig. 3. The dependence of j_z on the frequency Ω of the laser radiation with different values of the frequency of electromagnetic wave.

Fig. 3 shows the dependence of on the frequency Ω of the intense laser radiation. From these figure, we can see the nonlinear dependence of j0Z on the frequency Ω of the intense laser radiation, when the frequency Ω of the intense laser radiation increases j0Z decreases.

4. Conclusions

In this paper, we have studied the drag - effect in cylindrical quantum wire with an infinite potential for the case electrons – acoustic phonon scattering. 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 , in which, plot and discuss the expressions for j_{0z} . The expressions 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 an infinite potential. These results are different from the results of bulk semiconductors, quantum well, superlattices because wave function and energy spectrum are different. 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.

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