Photostimulated Radio Electrical Longitudinal Effect in a Parabolic Quantum Well

Bui Duc Hung¹, Nguyen Thi Thanh Nhan¹, Nguyen Quang Bau¹ and Nguyen Vu Nhan²
¹Department of Physics, College of Natural Sciences, Hanoi National University, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam
²Department of Physics, Academy of Defence Force-Air Force, Hanoi, Vietnam
E-mail: hungphysics.qn@gmail.com

Abstract. The longitudinal radioelectrical effect in a parabolic quantum well (PQW) has been studied, based on the quantum kinetic equation for electrons under the action of a linearly polarized electromagnetic wave (EMW) and an intense laser field. Analytic expressions for the density of the current associated with the drag of charge carriers for the case of electron optical phonon scattering is calculated. The dependence of the current density on the intensity F and the frequency Ω of the laser radiation field, the frequency ω of the linearly polarized EMW field, the frequency ω₀ of the parabolic potential, the temperature T of the system are obtained. The analytic expressions are numerically evaluated and plotted for a specific quantum wells, GaAs/AlGaAs. All the results of PQW are compared with semiconductors bulk and superlattice shows that the difference.

1. Introduction
In recent years, there has been considerable interest in the behavior of low-dimensional systems, in particular two-dimensional systems, such as semiconductor superlattices, doped superlattices and quantum wells. The confinement of electrons in low-dimensional systems considerably enhances the electron mobility and leads to unusual behaviors under external stimuli. Thus, under the action of EMW, the electrical conductivity, optical properties and kinetic effects are very different from semiconductors bulk. Many papers have appeared dealing with problems related to the incidence of EMW [1] - [4]. The radioelectrical effect (the effect of drag of charge carriers by electromagnetic waves) is explained by the momentum transfer from photons to the electron, can be understood quasi-classically as being the result of the action of the Lorentz force on charge carriers moving in the ac electric and magnetic fields of the wave [5, 6]. The radioelectrical effect in isotropic semiconductors [7], in semiconductors [8, 9, 11, 13] have also been investigated and resulted by using the quantum kinetic equation for electrons system. In recent times, the radioelectrical effect in semiconductor superlattices has examined under the action of strong electric fields [16, 17] and of an elliptically polarized EMW [18]. However, the longitudinal radioelectrical effect in a PQW still opens for studying. In this paper, we examine the system current carriers + scatterers, which is place in a constant electric field $\vec{E}_0$, a linearly polarized EMW field $\vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t})$ and in the presence of an intense laser field $\vec{F}(t) = \vec{F}\sin \Omega t$, in quantum wells with a parabolic potential. We consider the case in which the electron-optical phonon interaction is assumed to be dominant and electron gas to be
nondegenerate. Numerical calculations are carried out with a specific GaAs/GaAsAl quantum wells. The comparison of the result of quantum wells to semiconductors bulk and semiconductor superlattices shows that the difference.

2. Photostimulated Radio Electrical Longitudinal Effect in a Parabolic Quantum Well

2.1. The electron distribution function in PQW

In this paper, we apply the quantum kinetic equation method to study the longitudinal radioelectrical effect in a PQW subjected to a dc electric field \( \vec{E}_0 = (0, 0, E_{0z}) \) and in a linearly polarized EMW field \( \vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t}), \vec{H}(t) = [\vec{n}, \vec{E}(t)] \), (\( \omega << \varepsilon \), \( \varepsilon \) is an average carrier energy, in this paper, we select \( \hbar \) polarized EMW field being assumed to be \( -\vec{f} \), electron distribution function; \( f_{\vec{h}} \) representation can be written as \([1-5]\) follows:

The Hamiltonian of the electron-optical phonon system in the PQW in the second quantization takes the form \([5, 16, 17, 18]\) approximation:

\[
H = \sum_{N, \vec{p}_\perp} \varepsilon_N(\vec{p}_\perp) - \frac{\varepsilon}{\varepsilon} \vec{A}(t) a_{N, \vec{p}_\perp}^\dagger a_{N, \vec{p}_\perp} + \sum_{\vec{q}} \omega_{\vec{q}} b_{\vec{q}}^\dagger b_{\vec{q}} \\
+ \sum_{N, \vec{p}_\perp, N', \vec{q}} C_{\vec{q}} I_{N, N'}(q_\perp) a_{N, \vec{p}_\perp + \vec{q}_\perp}^\dagger a_{N, \vec{p}_\perp} \left( b_{\vec{q}} + b_{-\vec{q}}^\dagger \right)
\]

(1)

where \( N \) denotes the quantization of the energy spectrum in the z direction \((N = 1, 2, ...), |N, \vec{p}_\perp\rangle \) and \(|N', \vec{p}_\perp + \vec{q}_\perp \rangle \) are electron states before and after scattering, \( a_{N, \vec{p}_\perp}^\dagger \) and \( a_{N, \vec{p}_\perp} \) (\( b_{\vec{q}}^\dagger \) and \( b_{\vec{q}} \)) are the creation and annihilation operators of electron (phonon): \( \omega_{\vec{q}} \) is the frequency of a phonon with the wave vector \( \vec{q} = (\vec{q}_\perp, q_z) \); \( \vec{A}(t) \) is the vector potential of laser field; \( C_{\vec{q}} \) is the electron-phonon interaction constant; \( I_{N, N'}(q_\perp) \) is the electron form factor in the PQW. The electron energy takes the simple:

\[
\varepsilon_N(\vec{p}_\perp) = \omega_p(N + \frac{1}{2}) + \vec{p}_\perp^2 2m(N = 0, 1, 2, ...)
\]

(2)

with \( \omega_p^2 = \omega_0^2 + \omega_H^2 \) and \( \omega_H = eH/mc \) are the confinement and the cyclotron frequencies.

2.2. Expressions for the drag of the charge carriers in the PQW

The quantum kinetic equation for electrons in the constant scattering time \((\tau)\) approximation takes the form \([5, 16, 17, 18]\]

\[
\frac{\partial f_{N, \vec{p}_\perp}(t)}{\partial t} - \left( e\vec{E}(t) + e\vec{E}_0 + \omega_H \left[ \vec{p}_\perp, \vec{n} \right] \right) \frac{\partial f_{N, \vec{p}_\perp}(t)}{\partial \vec{p}_\perp} = \left( f_{N, \vec{p}_\perp}(t) - f_0(\varepsilon_{N, \vec{p}_\perp}) \right) \frac{1}{\tau}
\]

(3)

where \( \vec{n} = \frac{\vec{H}(t)}{\|\vec{H}(t)\|} \) is the unit vector in the direction of magnetic field; \( f_0(\varepsilon_{N, \vec{p}_\perp}) \) is the equilibrium electron distribution function; \( f_{N, \vec{p}_\perp}(t) \) is the nonequilibrium distribution function. In order to find \( f_{N, \vec{p}_\perp}(t) = \left\langle a_{N, \vec{p}_\perp}^\dagger a_{N, \vec{p}_\perp} \right\rangle \), we use the general quantum equation for the particle number operator or the electron distribution function.
It is also assumed that the effect of the external field does not lead to a spatial inhomogeneity of the distribution function; i.e., \( \frac{\partial f_N,\vec{p}_\perp(t)}{\partial \vec{p}_\perp} = 0 \). From Eqs. (3) and (4), using the Hamiltonian in Eq. (1), we obtain the quantum kinetic equation for electrons in the PQW

\[
- \left( e \vec{E}(t) + e \vec{E}_0 + \omega_H \left[ \vec{p}_\perp, \vec{r}(t) \right] \right) \frac{\partial f_N,\vec{p}_\perp(t)}{\partial \vec{p}_\perp} = - \frac{f_N,\vec{p}_\perp(t) - f_0(\epsilon_N,\vec{p}_\perp)}{\tau} + \\
+ 2\pi \sum_{N,q} \left| C_q \right|^2 \sum_{l=-\infty}^{\infty} J_l^2(\bar{u}, \bar{q}_\perp) \times \{ [f_{N',\vec{p}_\perp+\bar{q}_\perp}(t),N_{\bar{q}}] \delta (\epsilon_{N',\vec{p}_\perp+\bar{q}_\perp} - \epsilon_{N,\vec{p}_\perp} - \omega_{\bar{q}} + \Omega) + \\
+ [f_{N',\vec{p}_\perp-\bar{q}_\perp}(t),N_{\bar{q}}] \delta (\epsilon_{N',\vec{p}_\perp-\bar{q}_\perp} - \epsilon_{N,\vec{p}_\perp} + \omega_{\bar{q}} - \Omega) \} (5)
\]

in which \( J_l(x) \) is the Bessel function of argument \( x; \bar{u} = \frac{e \vec{E}_0}{\hbar} \) is the amplitude of electron vibration in an EMW; \( N_{\bar{q}} \) is the time-independent component of distribution function of phonons. For simplicity, we limit the problem to the case of \( \tau = 0, \pm 1 \). We multiply both sides of Eq. (5) by \( -(e/m)\vec{p}_\perp \delta (\epsilon - \epsilon_{N,\vec{p}_\perp}) \) and carry out the summation over \( N \) and \( \vec{p}_\perp \). We obtain

\[
\frac{\vec{R}_0(\epsilon)}{\tau} = \vec{Q}_0(\epsilon) + \vec{S}_0(\epsilon) + \omega_H \left[ \vec{R}(\epsilon) + \vec{R}^*(\epsilon), \vec{r} \right] \tag{6}
\]

where

\[
\vec{Q}_0(\epsilon) = \frac{e}{m} \sum_{N,\vec{p}_\perp} \vec{p}_\perp \left( e \vec{E}_0, \frac{\partial f_0(\epsilon_{N,\vec{p}_\perp})}{\partial \vec{p}_\perp} \right) \delta (\epsilon - \epsilon_{N,\vec{p}_\perp}) \tag{7}
\]

and

\[
\vec{S}_0(\epsilon) = - \frac{2\pi e}{m} \sum_{N,N',\vec{p}_\perp,\bar{q}_\perp} \left| C_q \right|^2 \cdot N_{\bar{q}} \vec{p}_\perp \cdot f_{10}(\bar{p}_\perp) \cdot \{ 
\frac{1}{2} \left[ 1 - \frac{(\bar{q}_{\perp})^2}{2} \right] \times \\
\delta (\epsilon_{N',\vec{p}_\perp+\bar{q}_\perp} - \epsilon_{N,\vec{p}_\perp} - \omega_{\bar{q}}) + \\
\frac{(\bar{q}_{\perp})^2}{4} \delta (\epsilon_{N',\vec{p}_\perp+\bar{q}_\perp} - \epsilon_{N,\vec{p}_\perp} - \omega_{\bar{q}} + \Omega) + \\
\frac{(\bar{q}_{\perp})^2}{4} \delta (\epsilon_{N',\vec{p}_\perp-\bar{q}_\perp} - \epsilon_{N,\vec{p}_\perp} - \omega_{\bar{q}} + \Omega) + \\
\frac{(\bar{q}_{\perp})^2}{4} \delta (\epsilon_{N',\vec{p}_\perp-\bar{q}_\perp} - \epsilon_{N,\vec{p}_\perp} + \omega_{\bar{q}} + \Omega) + \\
\frac{(\bar{q}_{\perp})^2}{4} \delta (\epsilon_{N',\vec{p}_\perp-\bar{q}_\perp} - \epsilon_{N,\vec{p}_\perp} + \omega_{\bar{q}} - \Omega) \} \delta (\epsilon - \epsilon_{N,\vec{p}_\perp}) \tag{8}
\]

and \( \vec{R}_0(\epsilon), \vec{R}(\epsilon) \) have meaning of the partial current densities with energy \( \epsilon \). These quantities are related to the total current density in the form

\[
\vec{j}_{tot}(t) = J_0 + \vec{j}(t) = \int_0^\infty \left\{ \vec{R}_0(\epsilon) + \left[ \vec{R}(\epsilon)e^{-i\omega t} + \vec{R}^*(\epsilon)e^{i\omega t} \right] \right\} d\epsilon \tag{9}
\]
We also consider the electron-optical phonon interaction. We consider the electron gas to be nondegenerate, thus, the electron distribution function is given by the Boltzmann distribution. In this case, \( \omega_q \ll \omega_{LO} \) is the frequency of the optical phonon in the equilibrium state, and the electron-phonon interaction constant is

\[
|C_q|^2 = \frac{2\pi e^2 \omega_{LO}}{\epsilon_0 q^2} \left( \frac{1}{\chi_\infty} - \frac{1}{\chi_0} \right)
\]

(10)

with \( \epsilon_0 \) is the permittivity of free space; \( \chi_\infty \) and \( \chi_0 \) are the static and the high-frequency dielectric constants, respectively. After some calculation Eq. (9) and taking the statistical average over time, we find the expression for the current density \( j_z \) along the 0z axis which expresses for the longitudinal radioelectrical effect in a PQW

\[
\langle j_z \rangle = \left\{ a + \frac{1}{4} \sqrt{\frac{m}{2\pi\beta}} \frac{e^2F^2}{\hbar^2} \cdot b\tau \right\} \tau E_{0z} + \\
+ \left\{ a + \frac{1}{4} \sqrt{\frac{m}{2\pi\beta}} \frac{e^2F^2}{\hbar^2} \cdot b\tau \left[ \frac{1 - \omega^2}{1 + \omega^2} \right] \right\} \frac{\omega_y z^2}{1 + \omega x^2} E_x
\]

(11)

where \( \beta = \frac{1}{k_B T} \) and

\[
a = \frac{n_0^* e^2}{\pi \beta \omega_{L0}} \sum_N \exp \left\{ -\beta \omega_0 (N + \frac{1}{2}) \right\}
\]

(13)

\[
b = A \frac{n_0^* e^2}{\pi \beta \omega_{L0}} \sum_{N,N'} (b_1 + b_2 + b_3 + b_4 + b_5 + b_6)
\]

(14)

\[
b_1 = (2 + \delta_{N,N'}) B_1 \exp \left\{ -\beta \omega_0 (N + \frac{1}{2}) \right\} \cdot \exp \left\{ \beta B_1 \right\} K_1 \left\{ \beta B_1 \right\}
\]

(15)

\[
b_2 = (2 + \delta_{N,N'}) B_2 \exp \left\{ -\beta \omega_0 (N + \frac{1}{2}) \right\} \cdot \exp \left\{ \beta B_2 \right\} K_1 \left\{ \beta B_2 \right\}
\]

(16)

\[
b_3 = b_2(B_2 \rightarrow B_3); b_4 = -b_1(B_1 \rightarrow -B_4); \\
b_5 = -b_2(B_2 \rightarrow -B_5); b_6 = -b_2(B_2 \rightarrow -B_6);
\]

(17)

\[
b_3 = b_2(B_2 \rightarrow B_3); b_4 = -b_1(B_1 \rightarrow -B_4); \\
b_5 = -b_2(B_2 \rightarrow -B_5); b_6 = -b_2(B_2 \rightarrow -B_6);
\]

(18)

Equation (11) shows the dependence of the current density on the intensity \( F \) and the frequency \( \Omega \) of the laser radiation field, the frequency \( \omega \) of the linearly polarized EMW field, the frequency \( \omega_0 \) of the parabolic potential, the temperature \( T \) of the system. Now, we introduce the designations \( j_0 = n_0 e F L_x / \hbar \) and \( I = (c / 4\pi) E_x^2 \) is the EMW intensity. Then, we will give a deeper insight into this dependence by carrying out a numerical assessment.
Figure 1. The dependence of $\langle j_z \rangle / j_0$ on the frequency $\omega$ of the EMW at $\Omega = 5 \times 10^{14} \, (s^{-1})$, the frequency $\Omega$ of the laser radiation field at $F = 10^6 (V/m)$, $\omega_0 = 0.5\omega_{LO}$ and $E_{0z} = \omega = 10^{13} (s^{-1})$, $\omega_0 = 0.5\omega_{LO}$, $T = 270K$ and $E_{0z} = -10^3 (V/m)$.

Figure 2. The dependence of $\langle j_z \rangle / j_0$ on the frequency $\Omega$ of the laser radiation field at $\omega = 10^{13} (s^{-1})$, $\omega_0 = 0.5\omega_{LO}$, $T = 270K$ and $E_{0z} = -10^3 (V/m)$.

Figure 3. The dependence of $\langle j_z \rangle / j_0$ on $T$ at $\omega = 10^{13} (s^{-1})$, $\omega_0 = 0.5\omega_{LO}$, $F = 2\times10^6 (V/m)$, $\Omega = 5 \times 10^{14} (s^{-1})$, $F = 5 \times 10^5 (V/m)$, $T = 260K$ and $E_{0z} = -10^3 (V/m)$.

Figure 4. The dependence of $\langle j_z \rangle / j_0$ on $I$ at $\Omega = 5 \times 10^{14} (s^{-1})$, $\omega_0 = 0.5\omega_{LO}$, $F = 5 \times 10^5 (V/m)$, $T = 260K$ and $E_{0z} = -10^3 (V/m)$.

2.3. Numerical results and discussion

In this section, we will evaluate, plot and discuss the drag of the charge carriers for the case of a specific GaAs/GaAsAl quantum wells. The parameters used in the calculations are as follows: $\epsilon_0 = 8.86 \times 10^{-12}$; $\chi_\infty = 10.48$; $\chi_0 = 12.90$; $\hbar\omega_{LO} = 36.8$ meV; $m = 0.0665m_0$ ($m_0$ is the mass of free electron); $e = 1.60219 \times 10^{-19} C$; $\varepsilon_F = 50$ meV; and we also choose $\tau(\varepsilon_F) \sim 10^{-11} s^{-1}$; $\tau(\Omega) \sim 10^{-10} s^{-1}$;

In Fig. 1 shows the dependence of the current density on the frequency $\omega$ of the EMW at different values of the temperature $T$ of the system. From this figure, we can see that the current density increases strongly with increasing EMW frequency for the area of values $\omega < 5 \times 10^{13} (s^{-1})$ and reaches saturation as the frequency $\omega$ continues to increase. Besides, the value of the current density raises remarkably when the temperature $T$ increases.

The dependences of the current density on the intensity $F$ and the frequency $\Omega$ of the laser radiation field are shown in Fig. 2. We can see that the values of the current density reduce nonlinearly when the frequency $\Omega$ increases. And the more amplitude $F$ increases, the more the values of the current density raise up.
Fig. 3 shows that when the temperature $T$ of the system rises up, the current density along the Oz axis goes up too. This figure confirms once again that the current density strongly depends on the frequency $\Omega$ of laser radiation.

Specially, Fig.4 shows the dependence of the current density on the intensity $I$ of the EMW at different values of the confinement frequency $\omega_0$ of the parabolic potential. This figure shows that the current density increases strongly with increasing the intensity $I$ of the EMW. Moreover, the confinement of electrons in PQW also influences strongly on the current density along the Oz axis. The value of the current density reduces when the confinement frequency $\omega_0$ increases.

3. Conclusion

In this paper, we have investigated the longitudinal radioelectrical effect in a PQW subjected to a dc electric field, a linearly polarized EMW field and in the presence of an intense laser field. We obtain the expressions for the drag of the charge carriers in case the electron gas is nondegenerate. The dependencies of the current density on the intensity $F$ and the frequency $\Omega$ of the laser radiation field, the frequency $\omega$ of the linearly polarized EMW field, the frequency $\omega_0$ of the parabolic potential, the temperature $T$ of the system are obtained. The analytical results are numerically evaluated and plotted for a specific quantum wells, GaAs/AlGaAs, to confirm clearly once again that the current density strongly depends on the above elements. When $\omega_0 \to 0$, from (13, 14) we see $a, b$ and $\langle j_z \rangle$ don’t depend on $\omega_0$, so the result will give back this effect in semiconductor [13]. The expression (11) is quite similar to the expressions in a superlattice in case $l = 0, \pm 1$ [18, 19].

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).

References

[1] G. M. Shmelev, L. A. Chaikovskii and N. Q. Bau, Sov. Phys. Semicond. 12, (1978) 1932.
[2] N. Q. Bau, D. M. Hung and L. T. Hung, PIER Letters 15, (2010) 175.
[3] N. Q. Bau and D. M. Hung, PIER B 25, (2010) 39.
[4] N. Q. Bau, D. M. Hung and N. B. Ngoc, J. Korean Phys. Soc 54, (2009) 765.
[5] N. Q. Bau and B. D. Hoi, J. Korean Phys. Soc. 60, (2012) 765.
[6] F. G. Bass, A. A. Bulgakov, and A. P. Tetervov, High-Frequency Properties of Semiconductors with Superlattices (1989) Nauka, Moscow.
[7] K. Seeger, Semiconductor Physics (1973) Springer-Verlag, Wien/New York.
[8] G. M. Shmelev, N. Q. Bau and N. H. Shon, Izv. Vyssh. Uch. Zaved. Fiz. 7 (1981) 105.
[9] V. L. Malevich and E. M. Epshtein Izv. Vyssh. Uch. Zaved. Fiz. 2 (1976) 121.
[10] V. L. Malevich Izv. Vyssh. Uch. Zaved. RadioFizika. 20 (1977) 151.
[11] N. H. Shon, G. M. Shmelev and E. M. Epshtein Izv. Vyssh. Uch. Zaved. Fiz. 5 (1984) 19.
[12] D. E. Milovzorov, Technical Physics Letters, 22 (1996) 896.
[13] G. M. Shmelev, G. I. Tsurkan and E. M. Epshtein, Physica Status Solidi B, 109 (1982) 53
[14] Cheng Wenhui, Huang Yi, Zhou Junming, Feng Wei, Xu Geng; CPL, 7 (1990) 284.
[15] G. M. Shmelev, N. H. Shon, G. I. Tsurkan, Izv. Vyssh. Uch. Zaved. Fiz. 2 (1985) 84.
[16] D. V. Zavyalov, S. V. Kryuchkov, and E. S. Sivashova, Tech. Phys. Lett 32 (2006) 143.
[17] D. V. Zavyalov, S. V. Kryuchkov, and E. I. Kukhar, Semiconductors 41 (2007) 704.
[18] S. V. Kryuchkov, E. I. Kukhar and E. S. Sivashova, Physics of the Solid State, 50 (2008) 1150.
[19] Bui Duc Hung, Nguyen Vu Nhan, Luong Van Tung and Nguyen Quang Bau, Proc. Natl. Conf. Theor. Phys. 37 (2012) 168.