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Original Article

The Magneto-electric Properties of Infinite Semi-parabolic Plus Semi-inverse Squared Quantum Wells in the Presence of a Strong Electromagnetic Wave

Nguyen Thu Huong[1], Nguyen Dinh Nam[2,*],
Bui Thi Dung[2], Nguyen Thi Nguyet Anh[2]

[1]*Academy of Air Defence and Air Force, Kim Son, Son Tay, Hanoi, Vietnam*

[2]*VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam*

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Abstract: The Magneto-electric properties of infinite Semi-parabolic Plus Semi-inverse Squared Quantum wells (ISPPSISQW) in the presence of a strong Electromagnetic Wave (EMW) are theoretically investigated by using Quantum Kinetic Equation. The system is subjected to an IEMW $E(t) = (E_0 \sin\Omega t)e_y$, a magnetic field $B = Be_z$, and a cross DC electric field $E= Ee_x$. The electron-optical phonon scattering is considered. The general expression of the Magnetoresistance (MR) is presented as a function of the temperature, the external magnetic field, the photon energy, and the intensity of the strong EMW as well as characteristic parameters of ISPPSISQW. The theoretical result for a specific GaAs/GaAsAl ISPPSISQW is achieved by using a numerical method. The computational result demonstrates that the maximum peaks appear satisfying the magneto-phonon-photon resonance condition. The resonance peak's position remains unaffected by temperature variations and changes by confinement frequency and by electric field; the MR decreases as temperature increases nonlinearly.

Keywords: Magnetoresistance, magneto-phonon-photon resonance, infinite semi-parabolic plus semi-inverse squared quantum wells, electromagnetic wave, quantum kinetic equation.

1. Introduction

The advent of low-dimensional materials has marked the beginning of a revolution in science and technology. Notably, physicists have discovered numerous methods to create various nano-

* Corresponding author.
E-mail address: nguyendinhnam@hus.edu.vn

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semiconductor structures, including low-dimensional semiconductor materials such as quantum wells and superlattices. Quantum wells are currently a vibrant research area in physics and materials science, with numerous applications in modern technology, particularly in semiconductors. Additionally, quantum wells are used in the fabrication of electronic and optical devices.

In quantum physics, the infinite semi-parabolic Plus Semi-inverse Squared Quantum Wells (ISPPSISQW) is a theoretical model describing a type of quantum well with an infinite semi-parabolic Plus Semi - inverse Squared shape. This model can be used to study phenomena related to regions of space-time with extremely high energy densities, a characteristic of ISPPSISQW. Potential applications of ISPPSISQW include researching space-time structures, providing crucial information about the properties of black holes, and using simulation and computation methods to predict and explain quantum physical phenomena.

In theoretical physics research, the problem of the Hall Magnetoresistance (MR) in low-dimensional semiconductor systems has been extensively studied [1-6]. However, for semiconductor materials in the form of ISPPSISQW, much remains unexplored. This is why we chose the topic the Hall MR in an infinite semi-parabolic Plus Semi inverse Squared Quantum Wells under the influence of a strong electromagnetic wave (EMW) for the case of Electron-optical Phonon Scattering Mechanism by using quantum kinetic equation.

The article is divided into four parts as follows: The first part is the introduction. In Section 2, we construct the analytical expression of Hall Magnetoresistance in ISPPSISQW for the case of optical electron-optical phonon scattering. Numerical calculation results and some brief evaluations are shown in Section 3. The final part is the conclusion on the above issues.

2. Theoretical Framework

2.1. The Wave Function and the Discrete Energy Spectrum of the Electron in ISPPSISQW

We consider a quantum well structure in which the electron moves freely in the XY plane and is confined along the z-axis by the confinement potential ISPPSISQW of the form:

$$U(z) = \begin{cases} \infty & z < 0 \\ \frac{1}{2} m_e \omega_z^2 z^2 + \frac{\hbar^2 \beta_z}{2 m_e z^2} & z > 0 \end{cases} \tag{1}$$

In which, m_e is the effective mass of the electron, $\hbar$ is reduced Planck's constant, β_z and ω_z are the characteristic parameters of the potential well and the confinement frequency, respectively.

We have wave functions and an energy spectrum of the electron in ISPPSISQW of the form:

$$\psi(\vec{r}) = \psi_0 \phi_N(x - x_0) e^{iK_y y} \phi_n(z) \tag{2}$$

$$\varepsilon_{nNk}^{HP} = \hbar\omega_z \left(2n + 1 + \frac{\sqrt{1+4\beta}}{2}\right) + \hbar\omega_c \left(N + \frac{1}{2}\right) + \hbar v_d k_y - \frac{1}{2} m v_d^2 \tag{3}$$

Here $\phi_n(x - x_0)$ is the harmonic wave function centered at x_0, $v_d = \frac{E_x}{B}$ is the drift velocity, B is the magnitude of external magnetic field, k_y is the electron's wave vector along the y-axis, n and N are the quantum numbers.

The electron form factor:

$$I_{n,n'} \equiv I = \frac{2^{\frac{-5}{2} - \sqrt{1-4\beta}} \pi \left[3 + 4\left(1 + \sqrt{1+4\beta}\right)\right] \Gamma\left(\frac{3}{2} + \sqrt{1+4\beta}\right)}{a_z \Gamma\left[\frac{1}{2} + \frac{1}{2}\left(1 + \sqrt{1+4\beta}\right)\right] \Gamma\left[\frac{3}{2} + \frac{1}{2}\left(1 + \sqrt{1+4\beta}\right)\right]} \tag{4}$$

$$a_z = \sqrt{\frac{\hbar}{m\omega_z}}\ ,\ s = \frac{1}{4}\left(1 + \sqrt{1 + 4\beta}\right)$$

Which $\Gamma(x)$ is the Gamma function.

2.2. Total Current Density Expression, Analytical Expression of Conductivity Tensor and Magnetoresistance in the Case of Electron–optical Phonon Scattering

When the SEMW is applied to the system, with the electric field vector $E = (0, E_0 \sin(\Omega t), 0)$ (where E_0 and Ω are the amplitude and frequency, respectively), the Hamiltonian of the electron-phonon system in ISPPSISQW can be expressed in the second quantization representation as follows:

$$H = H_1 + H_2 + H_3 + H_4 \tag{5}$$

$$H_1 = \sum_{n,N,\vec{k}} \varepsilon^H_{n,N,\vec{k}}\left(\vec{k} - \frac{e}{\hbar c}\vec{A}(t)\right) a^+_{n,N,\vec{k}} a_{n,N,\vec{k}}$$

$$H_2 = \sum_{\vec{q}} \hbar\,\omega_0 b^+_{\vec{q}} b_{\vec{q}}$$

$$H_3 = \sum_{n,N,\vec{k}} \sum_{n',N',\vec{q}} C_{\vec{q}} I_{n,n'}(q_z) J_{N,N'}(u) a^+_{n',N',\vec{k}+\vec{q}}\, a_{n,N,\vec{k}}\left(b_{\vec{q}} + b^+_{-\vec{q}}\right)$$

$$H_4 = \sum_{n,N,\vec{k}} \varphi(\vec{k})\, a^+_{n,N,\vec{k}+\vec{q}} a_{n,N,\vec{k}}$$

In eq. (5), $a^+_{n,N,\overrightarrow{k_\perp}}$ and $a_{n,N,\overrightarrow{k_\perp}}\left(b^+_{\vec{q}}\ and\ b_{\vec{q}}\right)$ are the creation and annihilation operators of the electron (phonon); $\hbar\omega_{\vec{q}}$ is the phonon energy. The vector potential of laser radiation as a SEMW $A(t) = \frac{c}{\Omega}E_0$ $cos\,(\Omega t)$, $n\ and\ n'$ are the band indices of states $|n, N, \overrightarrow{k_\perp}\rangle$ and $|n', N, \overrightarrow{k_\perp} + \overrightarrow{q_\perp}\rangle$, respectively. ε_n is electron energy, $\overrightarrow{k_\perp}, \vec{q}$ are the wave vectors of electrons and phonons, respectively. $C(q)$ is the electron–phonon scattering constant. We consider the case of electron-optical phonon scattering:

$$\left|C_{\vec{q}}\right|^2 = \frac{A}{V^2_{\vec{q}_\perp}} \tag{6}$$

$$A = \frac{2\pi e^2 \omega_0 \hbar}{\varepsilon_0}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right)$$

The quantum kinetic equation for the electron distribution function [5-7]:

$$i\hbar\frac{\partial f_{n,N,\vec{k}}(t)}{\partial t} = \langle\left[a^+_{n,N,\vec{k}} a_{n,N,\vec{k}}, H\right]\rangle_t \tag{7}$$

Where, $f_{n,N,\overrightarrow{k_\perp}}(t) = \langle a^+_{n,N,\overrightarrow{k_\perp}} a_{n,N,\overrightarrow{k_\perp}}\rangle$ is the electron distribution function, denotes the statistical average value at the moment t. To approximate the external magnetic field strength linearly, we only take l = 0, ±1 with $J^2_0(x) = 1 - \frac{(x^2)}{2}; J^2_{-1,1}(x) = \frac{x^2}{4}$, multiply both sides of the equation by $\frac{e}{m}\vec{k}\delta(\varepsilon - \varepsilon\vec{k})$ and then take the sum with respect to $\vec{k}$. The Eq. (7) has the form:

$$\frac{\partial f_{n,N,\vec{k}}(t)}{\partial t} = \frac{1}{\hbar}\left(e\vec{E} + \omega_H\left[\vec{k}, \vec{h}\right]\right)\frac{\partial f_{n,N,\vec{k}}(t)}{\partial \vec{k}} - \frac{i}{\hbar}\sum_{n',N',\vec{q}}\left|C_{\vec{q}}\right|^2\left|I_{n,n'}\right|^2 \times$$

$$\times \sum_{l,s=0}^{\infty} J_t(\wedge) J_s(\wedge) exp(-i(s-l)\Omega) \int_{-\infty}^{t} exp\frac{i}{\hbar}\left[\left(\varepsilon^H_{n',N',\vec{k}+\vec{q}} - \varepsilon^H_{n,N,\vec{k}} - \hbar\omega_0 - l\hbar\Omega + i\delta\right)(t - t_1)\right] \times$$

$$\times\left[f_{n,N,\vec{k}}(t_1)N_{\vec{q}}(t_1)-f_{n',N',\vec{k}+\vec{q}}(t_1)\left(N_{\vec{q}}+1\right)\right]+\left[f_{n,N,\vec{k}}(t_1)\left(N_{\vec{q}}+1\right)-f_{n',N',\vec{k}+\vec{q}}(t_1)\left(N_{\vec{q}}\right)(t_1)\right]\times$$
$$\times\, exp\left[\frac{i}{\hbar}\left[\left(\varepsilon^{H}_{n',N',\vec{k}+\vec{q}}-\varepsilon^{H}_{n,N,\vec{k}}+\hbar\omega_0-l\hbar\Omega+i\delta\right)(t-t_1)\right]\right]-$$
$$-exp\left[\frac{i}{\hbar}\left[\left(-\varepsilon^{H}_{n',N',\vec{k}-\vec{q}}+\varepsilon^{H}_{n,N,\vec{k}}-\hbar\omega_0-l\hbar\Omega+i\delta\right)(t-t_1)\right]\right]\times$$
$$\times\left[f_{n',N',\vec{k}-\vec{q}}(t_1)N_{\vec{q}}-f_{n,N,\vec{k}}(t_1)\left(N_{\vec{q}}+1\right)\right]-\left[f_{n',N',\vec{k}-\vec{q}}(t_1)\left(N_{\vec{q}}+1\right)-f_{n,N,\vec{k}}(t_1)\left(N_{\vec{q}}\right)\right]\times$$
$$\times\, exp\left[\frac{i}{\hbar}\left[\left(\varepsilon^{H}_{n,N,\vec{k}}-\varepsilon^{H}_{n',N',\vec{k}+\vec{q}}+\hbar\omega_0-l\hbar\Omega+i\delta\right)(t-t_1)\right]\right] \tag{8}$$

Where, Ω is the laser radiation's frequency, δ(x) is the Dirac delta functions, N_q is the equilibrium distribution function for phonons, which is given by the Bose–Einstein distribution function.

We set that:

$$\vec{R}(\varepsilon)=\frac{e\hbar}{m}\sum_{\vec{k}}\vec{k}n_{\vec{k}}\delta\left(\varepsilon-\varepsilon_{\vec{k}}\right) \tag{9}$$

$$\vec{Q}(\varepsilon)=\frac{e}{m}\sum_{\vec{k}}\left(\vec{F},\frac{\partial n_{nNk}}{\partial\vec{k}}\right)\delta\left(\varepsilon-\varepsilon_{\vec{k}}\right) \tag{10}$$

$$\vec{S}(\varepsilon)=-\frac{e}{m}\sum_{\vec{k},\vec{q}}\sum_{n,N}W(\vec{q})\vec{k}\ \delta\left(\varepsilon-\varepsilon_{\vec{k}}\right)\left\{\left(\bar{f}_{n,N,\vec{k}}-\bar{f}_{n',N',\vec{k}+\vec{q}}\right)\left(1-\frac{\Lambda^2}{2\Omega^2}\right)\times\right.$$
$$\times\left[\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}}-\varepsilon_{n,N,\vec{k}}-\hbar\omega_0+l\hbar\Omega\right)+\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}}-\varepsilon_{n,N,\vec{k}}+\hbar\omega_0-l\hbar\Omega\right)\right]-$$
$$-\left(\bar{f}_{n,N,\vec{k}}-\bar{f}_{n',N',\vec{k}+\vec{q}}\right)\frac{\Lambda^2}{4\Omega^2}\left[\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}}-\varepsilon_{n,N,\vec{k}}-\hbar\omega_0-l\hbar\Omega\right)+\right.$$
$$+\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}}-\varepsilon_{n,N,\vec{k}}+\hbar\omega_0-l\hbar\Omega\right)-$$
$$-\left(\bar{f}_{n,N,\vec{k}}-\bar{f}_{n',N',\vec{k}+\vec{q}}\right)\frac{\Lambda^2}{4\Omega^2}\left[\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}}-\varepsilon_{n,N,\vec{k}}-\hbar\omega_0+l\hbar\Omega\right)+\right.$$
$$\left.\left.+\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}}-\varepsilon_{n,N,\vec{k}}+\hbar\omega_0+l\hbar\Omega\right)\right]\right\} \tag{11}$$

By solving Eq. (8),(9),(10) and (11) we get the final expression of the specific current density $\vec{R}(\varepsilon)$:

$$\vec{R}(\varepsilon)=\frac{\tau(\varepsilon)}{1+\omega_H^2\tau(\varepsilon)^2}\times\left\{\vec{Q}(\varepsilon)+\vec{S}(\varepsilon)+\omega_H\tau(\varepsilon)\left[\vec{h}\vec{Q}(\varepsilon)+\vec{S}(\varepsilon)+\omega_H^2\tau(\varepsilon)^2\vec{h}\left(\vec{h},\vec{Q}(\varepsilon)+\vec{S}(\varepsilon)\right)\right]\right\} \tag{12}$$

Here, $\tau(\varepsilon)$ is the electron momentum recovery time, $\vec{h}=\frac{\vec{B}}{B}$ is the unit vector in the direction of magnetic field.

From Eq. (12) we have that the total current density function has the form:

$$j=L_0(Q_i)+L_0(S_i)=\sigma_{im}E_m+\beta_{im}\nabla T_m \tag{13}$$

With:

$$L_0(S_i)=\frac{be}{m}\frac{\tau(\varepsilon_F)}{1+\omega_H^2\tau^2(\varepsilon_F)}\left[\delta_{ij}+\omega_H\tau\varepsilon_{ijk}h_k+\omega_H^2\tau^2h_ih_j\right]\delta_{ij}\times$$
$$\times\frac{\tau}{1+\omega_H^2\tau^2}\left[\delta_{lm}+\omega_H\tau\varepsilon_{lmp}h_p+\omega_H^2\tau^2h_lh_m\right]E_m \tag{14}$$

$$L_0(Q)=\frac{a\tau}{1+\omega_H^2\tau^2}\left[\delta_{ij}+\omega_H\tau\varepsilon_{ijk}h_k+\omega_H^2\tau^2h_ih_j\right]E_j \tag{15}$$

After performing analytical calculations, from the expression of the current density J, the expression for the conductivity tensor is derived:

$$\sigma_{im} = \frac{a\tau}{1+\omega_H^2\tau^2}\left[\delta_{ij} + \omega_H\tau\varepsilon_{ijk}h_k + \omega_H^2\tau^2 h_i h_j\right]\delta_{jm} +$$
$$+\frac{be}{m}\left(\frac{\tau}{1+\omega_H^2\tau^2}\right)^2\left[\delta_{ij} + \omega_H\tau\varepsilon_{ijk}h_k + \omega_H^2\tau^2 h_i h_j\right]\delta_{ij} \times$$
$$\times\left[\delta_{lm} + \omega_H\tau\varepsilon_{lmp}h_p + \omega_H^2\tau^2 h_l h_m\right] \tag{16}$$

Set $\eta = \omega_H\tau$ and assume that $\vec{E} = (E_x, 0,0); \vec{h} = (0,1,0)$, We have explicit expressions of the tensors σ_{xx}, σ_{yx}:

$$\sigma_{xx} = \frac{a\tau}{1+\eta^2} + \frac{be}{m}\left(\frac{\tau}{1+\eta^2}\right)^2(1-\eta^2) \tag{17}$$

$$\sigma_{yx} = \frac{a\tau}{1+\eta^2}(-\eta) + \frac{be}{m}\left(\frac{\tau}{1+\eta^2}\right)^2(-\eta-\eta^2) \tag{18}$$

$$a = \frac{-e^2L_y}{4m\pi}\sum\nolimits_n exp\left[\alpha\left[\varepsilon_F - \left(\hbar\omega_z\left(2n+1+\frac{\sqrt{1+4\beta}}{2}\right) + \hbar\omega_c\left(N+\frac{1}{2}\right) + \hbar v_d k_y - \frac{1}{2}m_e v_d^2\right)\right]\right]$$

$$b = \frac{-L_y e\alpha\hbar v_d A}{m(2\pi)^3}N_0 \times I(N,N') \times \left|J_{N,N'}\right|^2 \times bb \times \sum\nolimits_{n,N}(I + II + III + IV + V + VI + VII + VIII)$$

$$bb = \left(\frac{eE}{m\Omega^2}\right)^2$$

$$I = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} - \hbar\omega_0\right)$$

$$II = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\left(-\frac{\Lambda^2}{2\Omega^2}\right)\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} - \hbar\omega_0\right)$$

$$III = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} + \hbar\omega_0\right)$$

$$IV = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\left(-\frac{\Lambda^2}{2\Omega^2}\right)\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} + \hbar\omega_0\right)$$

$$V = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\left(-\frac{\Lambda^2}{4\Omega^2}\right)\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} - \hbar\omega_0 - \hbar\Omega\right)$$

$$VI = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\left(-\frac{\Lambda^2}{4\Omega^2}\right)\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} + \hbar\omega_0 - \hbar\Omega\right)$$

$$VII = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\left(-\frac{\Lambda^2}{4\Omega^2}\right)\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} - \hbar\omega_0 + \hbar\Omega\right)$$

$$VIII = \frac{e}{m}\sum\nolimits_{\vec{k},\vec{q}}\sum\nolimits_{n,N} W(\vec{q})\vec{k}\overrightarrow{q_y} f_0'\left(-\frac{\Lambda^2}{4\Omega^2}\right)\delta\left(\varepsilon_{n,N,\vec{k}+\vec{q}} - \varepsilon_{n,N,\vec{k}} + \hbar\omega_0 + \hbar\Omega\right)$$

With $\vec{B}$ in the z direction and $\vec{E}$ in the x direction, the Magnetoresistance ρ_{xx} is calculated according to the formula:

$$\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{yx}^2} \quad (19)$$

3. Results and Discussion

To better understand the dependence of electrical conductivity and the Magnetoresistance on temperature of the system, external fields as well as material parameters in ISPPSISQW, we present numerical calculation results for a GaAs/GaAsAl quantum well using Matlab software in this section.

3.1. Dependence of the Conductivity Tensor on the Magnetic Field (Cyclotron Energy $\hbar\omega_c$) B for Different Values of Temperatures.

In Figure 1 we have T1 = 250K, T2 = 280K, T3 = 310K, $E_1 = 5 \times 10^2 (V.m^{-1})$ and $\omega_z = 0.5\omega_0$. Looking at the graph we see this curve has a maximum peak. The presence of this peak indicates that the peak satisfies the magneto-phonon-photon resonance condition. The resonance peak's position is determined by the resonance condition, which remains unaffected by temperature variations. Consequently, the peaks overlap at different temperatures but maintain the same position.

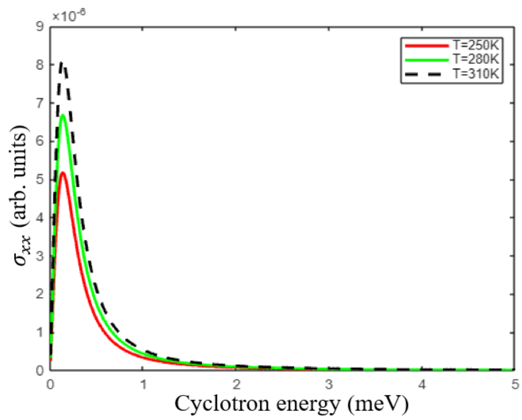

Figure 1. Dependence of the conductivity tensor σ_{xx} on the cyclotron energy $\hbar\omega_c$ for different values of temperatures (temperature T is 250K, 280K, 310K respectively as red, green, and black lines).

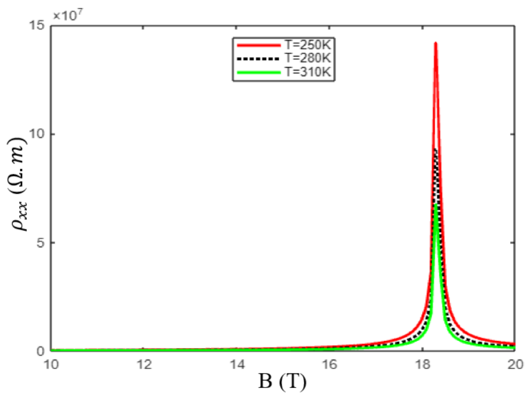

Figure 2. Dependence of Hall Magnetoresistance on the magnetic field B(T) for different values of temperatures. (temperature T is 250K, 280K, and 310K respectively as red, green, and black lines).

3.2. Dependence of Magnetoresistance on the Magnetic Field B for Different Values of Temperatures

In Figure 2, we have T1 = 250K, T2 = 280K, T3 = 310K, $E_1 = 5 \times 10^2 (V.m^{-1})$. It can be seen that the dependence of Hall Magnetoresistance on the magnetic field B changes when temperature changes. The resonance peak's position is determined by the resonance condition, which remains unaffected by temperature variations.

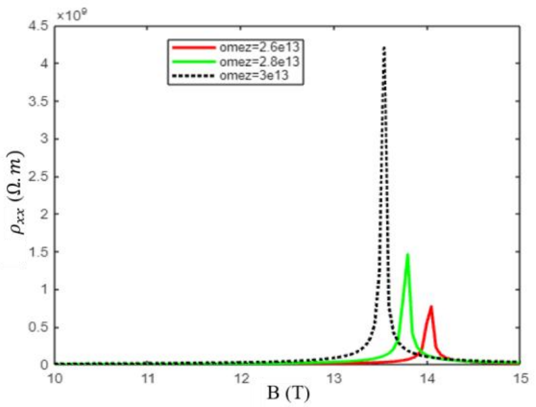

Figure 3. The dependence of Hall Magnetoresistance on the magnetic field B(T) for different values of confinement frequency (confinement frequency ω_z is 2.6×10^{13} (s^{-1}), 2.8×10^{13} (s^{-1}), 3×10^{13} (s^{-1}) respectively as red, green and black lines).

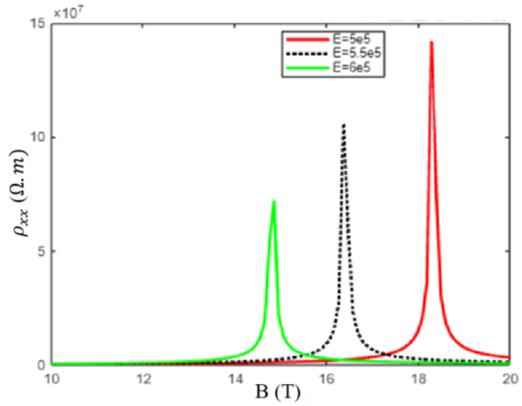

Figure 4. The dependence of Hall Magnetoresistance on magnetic field B(T) for different values of electric field (electric field $\vec{E}$ is $5 \times 10^{5} (V/m)$, $5.5 \times 10^{5} (V/m)$, $6 \times 10^{5} (V/m)$ respectively as red, black, and green lines).

3.3. Dependence of Magnetoresistance on the Magnetic Field B(T) for Different Values of Confinement Frequency

From Figure 3 we see that the peaks' positions shift in graphs dependent on the confinement frequency ω_z as the magnetic field B changes, the confinement factor ω_z impacts the resonance condition.

3.4. Dependence of Hall Magnetoresistance on Magnetic Field B(T) for Different Values of Electric Field

In Figure 4 it can be seen that the peaks' positions shift in graphs dependent on the electric field as the magnetic field B changes, as the electric field impact the resonance condition.

4. Conclusion

Using quantum kinetic equation method, we study the theoretical aspects of the Hall magnetoresistance in ISPPSISQW. By establishing the quantum kinetic equation for the distribution function, we derive the analytical expressions for the conductivity tensor and the Hall magnetoresistance as functions of external fields (magnetic field B, laser frequency Ω, and laser amplitude E), parameters of ISPPSISQW, and temperature for the electron-optical phonon scattering.

We apply numerical calculations to the theoretical results for the specific material GaAs/GaAsAl, obtaining graphs that show the dependence of the conductivity tensor on cyclotron energy and the dependence of the Hall magnetoresistance on different values of external magnetic fields and temperature. The results show a peak in the conductivity tensor's dependence on cyclotron energy when the peak satisfies the magneto-phonon-photon resonance condition. As the value of the external magnetic field increases, the Hall magnetoresistance also increases non-linearly. The Hall magnetoresistance strongly depends on the confinement frequency ω_z; as the confinement frequency of the quantum well increases, the Hall magnetoresistance increases. Additionally, the Hall magnetoresistance decreases non-linearly with increasing temperature.

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References

[1] B. D. Hoi, D. T. Long, P. T. Trang, L. T. Thiem, N. Q. Bau, The Hall Coefficient in Parabolic Quantum Wells with A Perpendicular Magnetic Field Under the Influence of Laser Radiation, Journal of Science of HNUE: Mathematical and Physical Sci., Vol. 58, No. 7, 2013, pp. 154-166.

[2] K. Klitzing, G. Dorda, Pepper, New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance, Phys. Rev. Lett., Vol. 45, 1980, pp. 494-497, https://doi.org/10.1103/PhysRevLett.45.494.

[3] R. B. Laughlin, Quantized Hall Conductivity in Two Dimensions, Phys. Rev. B, Vol. 23, 1981, pp. 5632-5633, https://doi.org/10.1103/PhysRevB.23.5632.

[4] D. C. Tsui, H. L. Stormer, A. C. Gossard, Two-dimensional Magnetotransport in the Extreme Quantum Limit, Phys. Rev. Lett., Vol. 48, 1982, pp. 1559-1562, https://doi.org/10.1103/PhysRevLett.48.1559.

[5] Bui Dinh Hoi, Nguyen Quang Bau, Nguyen Dinh Nam, Investigation of the Magnetoresistivity in Compositional Superllatices Under the Influence of an Intense Electromagnetic Wave, International Journal of modern physics B, Vol. 30, No. 4, 2016, pp. 1650004, https://doi.org/10.1142/S0217979216500041.

[6] N. Q. Bau, D. T. Long, Impact of Confined LO-phonons on the Hall Effect in Doped Semiconductor Superlattices, Journal of Science: Advanced Materials and Devices, Vol. 1, 2016, pp. 209-213, https://doi.org/10.1016/j.jsamd.2016.06.010.

[7] N. Q. Bau, N. V. Nhan, The Quantum Theory of Dynamic Effects in Semiconductors under the Influence of Strong Electromagnetic Waves, VNU Publishing House, 2016.