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THE INFLUENCE OF ELECTROMAGNETIC WAVE ON THE RELATIVE MAGNETORESISTANCE IN QUANTUM WELLS WITH PARABOLIC POTENTIAL IN THE PRESENCE OF MAGNETIC FIELD

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Abstract. *The relative magnetoresistance (RMR) in quantum wells with parabolic potential (QWPP) in the presence of magnetic field under the influence of electromagnetic wave is theoretically studied based on a set of quantum kinetic equations for the electron phonon system. Analyzing the analytical expressions obtained, we see that the RMR depends on the intensity of electromagnetic waves , the magnetic field B, the frequency of the radiation and the relaxation time of carrier. Comparing with the results obtained in case of bulk semiconductors, we see the influence of finite-size effects on the relative magnetoresistance.*

I. INTRODUCTION

Nowadays, the study of the low-dimensional systems are increasingly interested [5-8], in particular, the electrical, magnetic and optical properties of the systems such as : the absorption of electromagnetic waves, the amplification of confined acoustic phonons and the Hall effect are of great interest. These results show us that there are some significant differences from the bulk semiconductor [1-4]. The RMR is also one of them. In this report, the calculation of the RMR in the QWPP in the presence of magnetic field under the influence of electromagnetic wave is carried out by using the quantum kinetic equation method that brings the high accuracy and the high efficiency. Comparing the results obtained in this case with in the case of the bulk semiconductors, we see some differences. We also estimate numerical values for a GaAs/GaAsAl quantum well.

II. THE RELATIVE MAGNETORESISTANCE IN QUANTUM WELLS WITH PARABOLIC POTENTIAL IN THE PRESENCE OF MAGNETIC FIELD UNDER THE INFLUENCE OF ELECTROMAGNETIC WAVE

Consider a quantum well with parabolic potential subjected to a crossed electric field $\overrightarrow{E_1} = (0, 0, E_1)$ and magnetic field $\overrightarrow{B} = (0, B, 0)$. If the confinement potential is assumed to take the form $\mathrm{V}(z) = m\omega_0^2(z - z_0)^2/2\pi$, then the single-particle wave function and its eigenenergy are given by :

$$\psi(\vec{r}) = \frac{1}{2\pi} e^{i\vec{k_\perp}\vec{r}} \psi(k_x, z), \tag{1}$$

$$\varepsilon_N(k_x) = \hbar\omega_p(N+\frac{1}{2}) + \frac{1}{2m^*}[\hbar^2 k_x^2 - (\frac{\hbar k_x \omega_c + eE_1}{\omega_p})^2], \quad (2)$$

where m and e are the effective mass and charge of conduction electron, respectively, $k_\perp = (k_x, k_y)$ is its wave vector in the (x,y) plan; $z_0 = (\hbar k_x \omega_c + eE_1)/m\omega_p^2)$; $\omega_p^2 = \omega_0^2 + \omega_c^2$, ω_0 and ω_c are the confinement and the cyclotron frequencies, respectively, and

$$\psi_m(z - z_o) = H_m(z - z_o)\exp(-(z - z_o)^2/2), \quad (3)$$

with $H_m(z)$ being the Hermite polynomial of m^{th} order. In the presence of an EMW with electric field vector $\overrightarrow{E} = \overrightarrow{E_0}\sin\Omega t$ (where E_0 and Ω are the amplitude and the frequency of the EMW, respectively), the Hamiltonian of the electron-acoustic phonon system in the above mentined QWPP in the second quantization presentation can be written as follows:

$$H = \sum_{N,\vec{k_x}} \varepsilon_N\big(\vec{k_x} - \frac{e}{\hbar c}\vec{A}(t)\big) a^+_{N,\vec{k_x}} a_{N,\vec{K_x}} + \sum_{\vec{q}} \hbar\omega_{\vec{q}} b^+_{\vec{q}} b_{\vec{q}} +$$
$$+ \sum_{N,N',\vec{k_x},\vec{q}} C_{N,N'}(\vec{q}) a^+_{N',\vec{k_x}+\vec{q_x}} a_{N,\vec{k_x}} (b_{\vec{q}} + b^+_{-\vec{q}}) + \sum_{\vec{q}} \phi(\vec{q}) a^+_{N,\vec{k_x}+\vec{q_x}} a_{N,\vec{k_x}}, \quad (4)$$

where $a^+_{N,\overrightarrow{k_x}}$ and $a_{N,\overrightarrow{k_x}}$ ($b^+_{\overrightarrow{q}}$ and $b_{\overrightarrow{q}}$) are the creation and the annihilation operators of electron (phonon), $|N, \overrightarrow{k_x}>$ and $|N, \overrightarrow{k_x} + \overrightarrow{q_x}>$ are electron states before and after scattering; $\hbar\omega_{\overrightarrow{q}}$ is the energy of an acoustic phonon; $\phi(q)$ is the scalar potential of a crossed electric field $\overrightarrow{E_1}$; $C_{N,N'}(\vec{q})$ is the electron-phonon interaction constant.
From the quantum kinetic equation for electron in single scattering time approximation and the electron distribution function, using the Hamiltonian in the Eq.(4), we find :

$$\frac{\partial f_{N,\vec{k_x}}}{\partial t} + \big(\frac{e\vec{E_1}}{\hbar} + \omega_c[\vec{k_x}, \vec{h}]\big)\frac{\partial f_{N,k_x}}{\partial \vec{k_x}} = \frac{2\pi}{\hbar}\sum_{N',\vec{q}} |C_{N,N'}(\vec{q})|^2 \sum_{l=-\infty}^{+\infty} J_l^2(\alpha q_x) \times$$
$$\times\Big\{[f_{N',\vec{k_x}+\vec{q_x}}(1-f_{N,\vec{k_x}})(1+N_{\vec{q}}) - f_{N,\vec{k_x}}(1-f_{N',\vec{k_x}+\vec{q_x}})N_{\vec{q}}]\delta\big(\varepsilon_{N'}(k_x+q_x) - \varepsilon_N(k_x) - \hbar\omega_{\vec{q}} - l\hbar\Omega\big) +$$
$$+[f_{N',\vec{k_x}-\vec{q_x}}(1-f_{N,\vec{k_x}})N_{\vec{q}} - f_{N,\vec{k_x}}(1-f_{N',\vec{k_x}-\vec{q_x}})(1+N_{\vec{q}})]\delta\big(\varepsilon_{N'}(k_x-q_x) - \varepsilon_N(k_x) + \hbar\omega_{\vec{q}} - l\hbar\Omega\big)\Big\}. \quad (5)$$

The frequency of the acoustic phonon is low so we can skip $\omega_{\overrightarrow{q}}$ in the delta function in the Eq.(5). Considering the distribution of phonons to be symmetric, in the presence of the magnetic field, the Eq.(5) has the following form :

$$\frac{\partial f_{N,\vec{k_x}}}{\partial t} + \big(\frac{e\vec{E_1}}{\hbar} + \omega_c[\vec{k_x}, \vec{h}]\big)\frac{\partial f_{N,k_x}}{\partial \vec{k_x}} = \frac{2\pi}{\hbar}\sum_{N',\vec{q}} |C_{N,N'}(\vec{q})|^2 (2N_{\vec{q}} + 1) \sum_{l=-\infty}^{+\infty} J_l^2(\alpha q_x) \times$$
$$\times (f_{N',\vec{k_x}+\vec{q_x}} - f_{N,\vec{k_x}})\delta\big(\varepsilon_{N'}(k_x + q_x) - \varepsilon_N(k_x) - l\hbar\Omega\big). \quad (6)$$

For simplicity, we limit the problem to case of $l = -1, 0, 1$. If we mutiply both sides of the Eq.6 by $(e/m)\overrightarrow{k_x}\delta(\varepsilon - \varepsilon_N(k_x))$, carry out the summation over N and k_x and use

$J_0^2(\alpha q_x) \approx 1-(\alpha q_x)^2/2$, we obtain :

$$\frac{\vec{R}(\varepsilon)}{\tau(\varepsilon)}+\omega_c[\vec{h},\vec{R}(\varepsilon)]=\vec{Q}(\varepsilon)+\vec{S}(\varepsilon), \tag{7}$$

where

$$\vec{R}(\varepsilon)=\sum_{N,\vec{k_x}}\frac{e}{m^*}\vec{k_x}f_{N,\vec{k_x}}\delta(\varepsilon-\varepsilon_N(k_x)), \tag{8}$$

$$\vec{S}(\varepsilon)=-\frac{2\pi e}{4\hbar m^*}\sum_{N',\vec{q}}|C_{N,N'}(q)|^2(2N_{\vec{q}}+1)(\alpha q_x)^2\sum_{N,\vec{k_x}}(f_{N',\vec{k_x}+\vec{q_x}}-f_{N,\vec{k_x}})\vec{k_x}\times$$
$$\times\Big[2\delta\big(\varepsilon_{N'}(k_x+q_x)-\varepsilon_N(k_x)\big)-\delta\big(\varepsilon_{N'}(k_x+q_x)-\varepsilon_N(k_x)-\hbar\Omega\big)-\delta\big(\varepsilon_{N'}(k_x+q_x)-\varepsilon_N(k_x)+\hbar\Omega\big)\Big], \tag{9}$$

$$\vec{Q}(\varepsilon)=-\frac{e}{\hbar m^*}\sum_{N,\vec{k_x}}\vec{k_x}(\vec{F},\frac{\partial f_{N,\vec{k_x}}}{\partial\vec{k_x}})\delta(\varepsilon-\varepsilon_N(k_x)), \tag{10}$$

with $\vec{F}=e\vec{E_1}-\nabla\varepsilon_F-\frac{\varepsilon-\varepsilon_N(k_x)}{T}\nabla T$.
Expressing $\vec{R}(\varepsilon)$ in term of $\vec{Q}(\varepsilon)$, $\vec{S}(\varepsilon)$ after some computation steps, we obtain the expression for conductivity tensor :

$$\sigma_{im}=\frac{e}{m^*}\frac{\tau(\varepsilon_F)}{1+\omega_c^2\tau^2(\varepsilon_F)}\Bigg\{a_o\delta_{ik}+b_ob_1\frac{\tau(\varepsilon_F)}{1+\omega_c^2\tau^2(\varepsilon_F)}\Big[\delta_{ik}-\omega_c\tau(\varepsilon_F)\varepsilon_{ikl}h_l+\omega_c^2\tau^2(\varepsilon_F)h_ih_k\Big]+$$
$$+b_ob_2\frac{\tau(\varepsilon_F-\hbar\Omega)}{1+\omega_c^2\tau^2(\varepsilon_F-\hbar\Omega)}\Big[\delta_{ik}-\omega_c\tau(\varepsilon_F-\hbar\Omega)\varepsilon_{ikl}h_l+\omega_c^2\tau^2(\varepsilon_F-\hbar\Omega)h_ih_k\Big]+$$
$$+b_ob_3\frac{\tau(\varepsilon_F+\hbar\Omega)}{1+\omega_c^2\tau^2(\varepsilon_F+\hbar\Omega)}\Big[\delta_{ik}-\omega_c\tau(\varepsilon_F+\hbar\Omega)\varepsilon_{ikl}h_l+\omega_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_ih_k\Big]\Bigg\}, \tag{11}$$

where

$$a_o=\sum_N\frac{eL_x}{\pi\hbar}\sqrt{\Delta_o}\theta(\Delta_o), \tag{12}$$

$$b_o=\sum_{N,N'}\frac{eL_x}{4\pi^2m^*}\frac{\xi^2k_BT}{\eta\nu^2}\frac{e^2E_o^2}{\hbar^4\Omega^4}\frac{eE_1\omega_c}{\hbar\omega_o^2}I(N,N'), \tag{13}$$

$$b_1=\sum_{N,N'}4\sqrt{\frac{\Delta_o}{\Delta_1}}(\Delta_o+3\Delta_1)\theta(\Delta_o)\theta(\Delta_1)-2\sqrt{\frac{\Delta_o}{\Delta_2}}(\Delta_o+3\Delta_2)\theta(\Delta_o)\theta(\Delta_2)-$$
$$-\sqrt{\frac{\Delta_o}{\Delta_3}}(\Delta_o+3\Delta_3)\theta(\Delta_o)\theta(\Delta_3)+2\frac{\Delta_o^2-\Delta_1^2}{\sqrt{\Delta_o\Delta_1}}\theta(\Delta_o)\theta(\Delta_1), \tag{14}$$

$$b_2=\sum_{N,N'}\frac{\Delta_1^2-\Delta_4^2}{\sqrt{\Delta_4\Delta_1}}\theta(\Delta_4)\theta(\Delta_1), \tag{15}$$

$$b_3 = \sum_{N,N'} \frac{\Delta_1^2 - \Delta_5^2}{\sqrt{\Delta_5 \Delta_1}} \theta(\Delta_5)\theta(\Delta_1), \tag{16}$$

$$\Delta_o = \big(\frac{eE_1\omega_c}{\hbar\omega_o^2}\big)^2 - \frac{2m^*\hbar\omega_p^3(N+\frac{1}{2}) - e^2E_1^2 - 2m^*\omega_p^2\varepsilon_F}{\hbar^2\omega_o^2} \approx \frac{2m^*\omega_p^2}{\hbar^2\omega_o^2}\big(\varepsilon_F - \hbar\omega_p(N+\frac{1}{2})\big), \tag{17}$$

$$\Delta_1 = \frac{2m^*\omega_p^2}{\hbar^2\omega_o^2}\big(\varepsilon_F - \hbar\omega_p(N'+\frac{1}{2})\big), \tag{18}$$

$$\Delta_2 = \frac{2m^*\omega_p^2}{\hbar^2\omega_o^2}\big(\varepsilon_F + \hbar\Omega - \hbar\omega_p(N'+\frac{1}{2})\big), \tag{19}$$

$$\Delta_3 = \frac{2m^*\omega_p^2}{\hbar^2\omega_o^2}\big(\varepsilon_F - \hbar\Omega - \hbar\omega_p(N'+\frac{1}{2})\big), \tag{20}$$

$$\Delta_4 = \frac{2m^*\omega_p^2}{\hbar^2\omega_o^2}\big(\varepsilon_F - \hbar\Omega - \hbar\omega_p(N+\frac{1}{2})\big), \tag{21}$$

$$\Delta_5 = \frac{2m^*\omega_p^2}{\hbar^2\omega_o^2}\big(\varepsilon_F + \hbar\Omega - \hbar\omega_p(N+\frac{1}{2})\big), \tag{22}$$

The RMR is given by the formula :

$$\frac{\Delta\rho}{\rho} = \frac{\sigma_{zz}(H)\sigma_{zz}(0)}{\sigma_{zz}^2(H) + \sigma_{xz}^2(H)} - 1, \tag{23}$$

where σ_{zz} and σ_{xz} are given by the Eq.(11).
We see that it is easy for the RMR in Eq.(23) to come back to the case of the RMR in the bulk semiconductor when the confinement frequency (ω_o) reaches to zero. The Eq.(23) shows the dependence of the RMR on the external fields, including the EMW. In the next section, we will give a deeper insight into this dependence by carrying out a numerical evaluation.

III. NUMERICAL RESULTS AND DISCUSSION

In order to clarify the mechanism for the RMR in QWPP in the presence of magnetic field under the influence of electromagnetic wave, in this section, we will evaluate, plot and discuss the RMR for a specific quantum well : AlAs/AlGaAs. The parameters used in the calculations are as follows : $\varepsilon_F = 50meV$, $\chi_0 = 12.9$, $\chi_\infty = 10.9$, $m = 0.067m_0$ with m_0 is the mass of a free electron. For the sake of simplicity, we also choose $N = 0$, $N' = 1$, $\tau = 10^{-12}s$.
Figure 1 shows the RMR as a function of the electromagnetic wave frequency (EMWF) in a quantum well. When the EMWF is low enough, the RMR has a sharp drop. It remains stable when the EMWF reaches a certain value. The RMR is also gets the different values when the magnetic field changes. These dependences are different from the case of the RMR in the bulk semiconductor published.

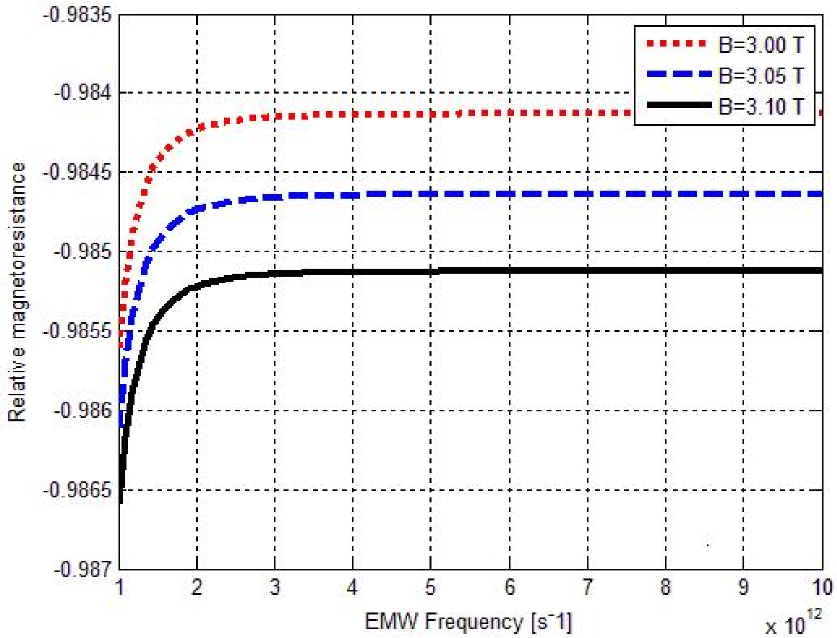

Fig. 1. The dependence of the RMR on the frequency of laser radiation

IV. CONCLUSIONS

In this paper, we studied the influence of electromagnetic wave on the RMR in the quantum well with parabolic potential in the presence of the magnetic field. The electron-phonon interaction is taken into account at low temperatures, and the electron gas is nondegenerate. We obtain the analytical expression of the RMR in the quantum well. We see that the RMR in this case depends on some parameters such as : the intensity of electromagnetic waves, the magnetic field B, the frequency of the radiation, the relaxation time of carrier, the temperature and the parameters of the quantum well. We estimate numerical values and graph for a GaAs/GaAsAl quantum well to see clearly the nonlinear dependence of the RMR on the electromagnetic wave frequency. Looking at the graph, we see that the RMR gets the negative values. The more the electromagnetic wave frequency and the magnetic field increase, the more the RMR decreases. When the electromagnetic wave frequency reaches a certain value, the RMR will reach the saturation value. There are some differences from the case of the RMR in the bulk semiconductor. Based on this idea, we can put forward a capability about changing the functions of low-semiconductor materials, that may be applied for electronics.

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