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Theoretical investigation of magnetoresistivity oscillations modulated by a terahertz field in quantum wells with parabolic potential

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ABSTRACT

The magnetoresistivity (MR) in a parabolic quantum well (PQW), subjected to a crossed dc electric field and magnetic field, modulated by a terahertz field (TF), is theoretically calculated. The electron - acoustic phonon interaction is taken into account at low temperatures. In the case of absence of the TF, the Shubnikov - de Haas oscillations are observed. The temperature dependence of the relative amplitude of these oscillations is in good agreement with previous theories and experiments in some two-dimensional electron systems. In the presence of the TF, there exist the oscillations in the MR which are similar to those observed experimentally in some two-dimensional electron systems. The amplitude of these oscillations increases with increasing the TF amplitude (intensity).

1. Introduction

The discoveries of the quantum Hall and Shubnikov - de Haas (SdH) effects open up a large number of applications in materials science. SdH oscillations in the magnetoresistance can be used in experiments to extract basic information of materials such as the carrier concentration, the effective mass, the momentum relaxation time, the carrier mobility, and so on [1]. For example, in the works [2,3] the authors investigated experimentally the dependence of the magnetoresistance on the temperature and used the temperature-dependent relative amplitude of SdH oscillations to determine the electron effective mass. Theoretically, the dependence of the relative amplitude of these oscillations on temperature had been studied before in a two-dimensional electron gas (2DEG) [1,2] utilising a connection between the conductivity and the density of states, which is a function of the single-relaxation time. The results showed that the relative amplitude at a fixed magnetic field decreases as the temperature increases.

When 2DEGs are subjected simultaneously to a magnetic field and a microwave, one can observe the so-called microwave-induced magnetoresistance oscillations [4–11]. It has been shown that the occurrence of maximum peaks of the magnetoresistance is governed by the ratio of the cyclotron and the electromagnetic wave (EMW) frequency [4–11]. However, little theoretical discussion has been made thus for. On the other hand, the Boltzmann equation was applied to study theoretically the Hall effect in three-dimensional (3D) materials under the influence of EMWs [12–17]. The odd and even properties of the magnetoresistance were also considered. The problem is that in a strong quantum limit (high magnetic field, low temperature), the Boltzmann equation is no longer valid. Then, a quantum theory is necessary to study these effects at quantum conditions [18]. In this work, based on the Hamiltonian of electrons in a parabolic quantum well (PQW), subjected to a crossed

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dc electric field and magnetic field in the presence of a terahertz EMW, we derive a quantum transport equation for electron. From this equation, the magnetoresistivity (MR) is calculated for the electron - acoustic phonon scattering at low temperatures and one-photon absorption/emission limit. The paper is organised as follow. In the next section, we describe our theoretical model and the brief derivation of the quantum transport equation for electrons. The calculation of the MR is presented briefly in Sec. 3. Numerical results and discussion are given in Sec. 4. Finally, remarks and conclusions are given briefly in Sec. 5.

2. Theoretical model and transport equation for electrons

We consider the transport of an electron gas in a quantum well structure, in which a one-dimensional electron gas is confined in a heterostructure by a parabolic potential $U(z)$ along the z-direction, and electron motions are free along two directions (assumed the $(x-y)$ plane). A static magnetic field $\vec{B}$ is applied in the z-direction and a dc electric field $\vec{E}_1$ is applied in the x-direction. Then, the one-electron Hamiltonian (h^0), its normalised eigenfunctions ($|\xi\rangle$), and the eigenvalues (ε_ξ) in the Landau gauge for the vector potential $\vec{A}=(0,Bx,0)$ are, respectively, given by Refs. [19–21]

$$h^0=\frac{\left(\vec{p}+e\vec{A}\right)^2}{2m_\mathrm{e}}+U(z)+eE_1x, \tag{1}$$

$$|N,n,k_y\rangle=\frac{1}{\sqrt{L_y}}\exp(\mathrm{i}k_yy)\phi_N(x-x_0)\psi_n(z), \tag{2}$$

$$\varepsilon_{N,n}\left(\vec{k}_y\right)=\left(N+\frac{1}{2}\right)\hbar\omega_\mathrm{c}+\varepsilon_n-\hbar v_\mathrm{d}k_y+\frac{1}{2}m_\mathrm{e}v_\mathrm{d}^2;\ N=0,1,2,\ldots, \tag{3}$$

where e and m_e are the charge and the effective mass of a conduction electron, respectively, $\vec{p}$ is its momentum operator, N is the Landau level index and n denotes level quantisation in z-direction, $v_\mathrm{d}=E_1/B$ is the drift velocity and $\omega_\mathrm{c}=eB/m_\mathrm{e}$ is the cyclotron frequency. Also, ϕ_N represents harmonic oscillator wave functions, centered at $x_0=-\ell_\mathrm{B}^2(k_y-m_\mathrm{e}v_d/\hbar)$ where $\ell_\mathrm{B}=\sqrt{\hbar/(m_\mathrm{e}\omega_\mathrm{c})}$ is the radius of the Landau orbit in the $(x-y)$ plane. Here, $\vec{k}_y$ and L_y are the wave vector and normalisation length in the y-direction, respectively. For a parabolic well given by $U(z)=m_\mathrm{e}\omega_z^2z^2/2$ with the characteristic frequency ω_z of the confinement potential, the one-electron normalised eigenfunctions and the corresponding eigenvalues in the conduction band are, respectively, given by Ref. [21]

$$\psi_n(z)\equiv|n\rangle=\left(\frac{1}{2^nn!\sqrt{\pi}\ell_z}\right)^{1/2}\exp\left(-\frac{z^2}{2\ell_z^2}\right)H_n\left(\frac{z}{\ell_z}\right), \tag{4}$$

$$\varepsilon_n=\left(n+\frac{1}{2}\right)\hbar\omega_z,\quad n=0,1,2,\ldots, \tag{5}$$

where $H_n(x)$ is the n^{th} Hermite polynomial and ℓ_z is $\sqrt{\hbar/(m\omega_z)}$.

When a terahertz field (TF) with the electric field vector $\vec{E}=(0,E_0\sin\omega t,0)$ (E_0 and ω are the amplitude and the frequency, respectively) propagates in the structure, the Hamiltonian of electron - phonon system, in the second quantisation representation, can be written similarly to the ones obtained in Refs. [22–24]. Then, one can obtain an equation for the time-dependent electron distribution function as

$$\begin{aligned}\frac{\partial f_{N,n,k_y}}{\partial t}=-\frac{2\pi}{\hbar}\sum_{N',n',\vec{q}}|D_{N,n,N',n'}(\vec{q})|^2\sum_{s=-\infty}^{+\infty}J_s^2\left(\frac{\lambda}{\omega}\right)\Big\{\Big[f_{N',n',k_y+q_y}\left(N_{\vec{q}}+1\right)-f_{N,n,k_y}N_{\vec{q}}\Big]\delta\Big(\varepsilon_{N',n'}\left(\vec{k}_y+\vec{q}_y\right)-\varepsilon_{N,n}\left(\vec{k}_y\right)\\-\hbar\omega_{\vec{q}}-s\hbar\omega\Big)+\Big[f_{N',n',k_y-q_y}N_{\vec{q}}-f_{N,n,k_y}\left(N_{\vec{q}}+1\right)\Big]\delta\Big(\varepsilon_{N',n'}\left(\vec{k}_y-\vec{q}_y\right)-\varepsilon_{N,n}\left(\vec{k}_y\right)+\hbar\omega_{\vec{q}}-s\hbar\omega\Big)\Big\},\end{aligned} \tag{6}$$

where $\lambda=eE_0q_y/(m_\mathrm{e}\omega)$, $N_{\vec{q}}$ is the equilibrium distribution function of phonons, $\hbar\omega_{\vec{q}}$ is the energy of a phonon with the frequency $\omega_{\vec{q}}$ and the wave vector $\vec{q}=(q_x,q_y,q_z)$, $J_s(x)$ is the s^{th}-order Bessel function of argument x, and [19,25]