LONGITUDINAL CONDUCTANCE IN A QUANTUM DOT SUPERLATTICE STRUCTURE WITH RASHBA SPIN-ORBIT INTERACTION

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We have investigated longitudinal conductance in a quantum dot superlattice with Rashba spin-orbit interaction in the presence of a magnetic field parallel to the superlattice axis. In the case of a strong degenerate electron gas in the quantum limit, an analytical dependence of the longitudinal magnetoconductance on the magnetic field magnitude, Rashba spin-orbit coupling parameter, and Zeeman splitting has been investigated.

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Over the last few years, the transport properties of electrons in low-dimensional systems have been the focus of intensive experimental and theoretical investigations. This is because modern technologies make it possible to create nanostructures of various geometries.

In such systems, transport phenomena are sharply different from transport phenomena in macrosystems. Interesting transport effects occur when a magnetic field is applied to as simple. Longitudinal magnetoresistance refers to the change in resistance due to a magnetic field when the current and the magnetic field are parallel to each other.

In Ref. [1] [the exciton absorption coefficient was determined analytically for a semiconductor superlattice in crossed electric and magnetic fields, with the magnetic field being parallel and the electric field being perpendicular to the superlattice axis.

In paper [2] the magnetoresistance of layered crystals in a longitudinal quantizing magnetic field by taking into account the spin splitting was theoretically investigated. Ref. [3] considered the influence of interband and intraband transitions on vertical conductance oscillations in superlattices in a strong longitudinal magnetic field. Hashimzede et. all. [4] studied the electrical conductivity of an electron gas in parallel electric and magnetic fields directed along the plane of a parabolic quantum well and found the electrical conductivity applicable for any magnitudes of the magnetic field and the degree of degeneration of the electron gas.

The electrical conductivity of a nondegenerate electron gas with a complex-shaped quantum well was calculated in ref and the conductivity dependences on the temperature and the parameters of the quantum well were studied in the case of electron-phonon scattering [5].

Anisotropy of the thermoelectric power in superlattices on the scattering of charge carriers by impurity ions is studied. The anisotropy of thermopower in superlattices during the scattering of carriers by impurity ions has been studied in Ref. [5]. In Ref. [6] was calculated the specific heat of the quantum dot superlattice with Rashba spin–orbit coupling in quantizing the magnetic field.

Roles of the spin-orbit interaction on the transport properties have recently attracted much attention in the field of spintronics due to the electrical control of spins by spin-orbit interaction.

In this work, the longitudinal conductivity of a quantum dot superlattice is studied in the case when the magnetic and electric fields are parallel to the superlattice axis, taking into account the Rashba spin-orbit interaction. We consider the transport of an electron system in a quantum dot superlattice structure with a periodic potential V(z)= $\epsilon_0((1-cosdk_z))$ of a period along the z-direction by using a cosine shape under the tight-binding approximation. Here ϵ_0 is the miniband half-width of the superlattice. The electron gas in the quantum dot superlattice structure is assumed to be confined in parabolic lateral potential [7]:

$$V_c(\rho)=\frac{1}{2}m\omega_0^2\rho^2 \qquad (1)$$

Where $\hbar\omega_0$ is the characteristic confinement energy, ρ is the radius vector. A static magnetic field parallel to the superlattice z-axis.

In an axial magnetic field of the symmetric gauge for the vector potential $\vec{A}=\frac{B\rho}{2}\overrightarrow{e_\varphi}$,(where $\varphi$is the azimuthal angle) the Rashba spin-orbital term in the cylindrical coordinates is given by

$$V_{SO}^R(\rho,\varphi)=\sigma_z\alpha\frac{dV_c(\rho)}{d\rho}\left(-i\frac{1}{\rho}\frac{\partial}{\partial\varphi}+\frac{e}{2\hbar}B\rho\right) \qquad (2)$$

α is the Rashba spin-orbit coupling parameter, $\sigma_z$is the Pauli matrix. By including the Zeeman term Hamiltonian can be written as:

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$$H = -\frac{\hbar}{2m}\left(\frac{\partial}{\rho\partial\rho}\rho\frac{\partial}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2}{\partial\phi^2}\right) - i\frac{\hbar\omega_c}{2}\frac{\partial}{\partial\phi} + \frac{1}{8}m\omega_c^2\rho^2 +$$
$$+V_c(\rho) + V_{SO}^R(\rho,\varphi) + \frac{\sigma_z}{2}g\mu_b B + \epsilon_0(1 - cosak_z) \quad (3)$$

where $\omega_c = \frac{eB}{m}$ is the cyclotron frequency, $\mu_b$is the Bohr magneton, and g -is the Lande factor. The eigenfunctions and eigen energies of the Hamiltonian are given by

$$\psi(\rho, k_z, \phi) = \frac{1}{\sqrt{2\pi L}}e^{il\phi}R(\rho)\chi_\sigma \quad (4)$$

where

$$R(\rho) = \frac{\sqrt{2}}{\rho_\sigma}\sqrt{\left(\frac{n!}{(n+|l|)!}\right)exp\left(-\frac{\rho^2}{2\rho_\sigma^2}\right)}\left(\frac{\rho^2}{\rho_\sigma^2}\right)^{|l|/2}L_n^{|l|}\left(\frac{\rho^2}{\rho_\sigma^2}\right) \quad (5)$$

where $\rho_\sigma = \left(\frac{\hbar}{m\Omega_\sigma}\right)$, $L_n^{|l|}$ is the generalized Laguerre polynomial $\chi_\sigma$is the spin wave function, L is the z directional normalization lengths

$$\epsilon_{nl\sigma k_z} = \hbar\Omega_\sigma(2n + |l| + 1) + l\frac{\hbar\omega_c}{2} + \sigma\left(\frac{\mu_B}{2}gB + lm\alpha\omega_0^2\right) + \epsilon_0(1 - cosdk_z) \quad (6)$$

where $\sigma = \pm 1$ refers to the electron-spin polarization along the z-axis.

$$\Omega_\sigma = \sqrt{\omega_0^2 + \frac{\omega_c^2}{4} + \sigma\alpha\frac{m\omega_0^2}{\hbar}\omega_c} \quad (7)$$

The general expression for the density of states given by

$$g(\epsilon) = \sum_{nl\sigma k_z}\delta(\epsilon - \epsilon_{nl\sigma k_z}) \quad (8)$$

Replacing the summation over k_z by integration ϵ, using Eq. (6) we obtain, the density of states of electrons for unit volume in quantum dot superlattice

$$g(E) = \frac{L}{\pi a}\sum_{nl\sigma}\frac{\theta(E - E_{n\sigma l})\theta(2\varepsilon_0 - E + E_{n\sigma l})}{\sqrt{E - E_{n\sigma l}}\sqrt{2\varepsilon_0 - E + E_{n\sigma l}}} \quad (9)$$

where θ(E)- is the Heaviside step function, Lis the length along the z-direction. The number of electrons in the quantum dot superlattice system is calculated from Fermi-Dirac distribution functions $f(\epsilon_{nl\sigma k_z})$

$$N = \sum_{nl\sigma k_z} f(\epsilon_{nl\sigma k_z}) = \frac{L}{\pi}\sum_{nl\sigma k_z}\int_0^\infty f(\epsilon_{nl\sigma k_z})dk_z \quad (10)$$

Integrating the expression (10) by parts, we get

$$n = \frac{1}{\pi}\sum_{nl\sigma k_z}\int_0^\infty k_z\left(-\frac{\partial f(\epsilon_{nl\sigma k_z})}{\partial\epsilon}\right)d\epsilon \quad (11)$$

In the case of strongly degenerate electron gas with concentration n in the quantum limit (n=0, l=0, $\sigma = -1/2$), from formula (11) the equation for determination of the Fermi level, ζ, is

$$n = \frac{1}{a\pi}arccos\left(1 - \frac{\zeta - \left(\hbar\Omega_{-1} - \frac{\mu_B}{2}gB\right)}{\epsilon_0}\right) \quad (12)$$

here ζ is the chemical potential. From Eq. (12) for the Fermi level, we find:

$$\zeta = \varepsilon_0\left(1-\cos\left(\pi na\right)\right)+\hbar\Omega_{-1}-\frac{1}{2}g\mu_B B \tag{13}$$

Calculation of the electrical conductivity.

Consider an electron gas in a quantum dot superlattice system in an external electric and vertical magnetic field: $\vec{E} \upuparrows \vec{B} \upuparrows oz$. The magnetic field does not affect the movement of an electron along the z-axis, we can use a Boltzmann transport equation for the distribution function of the electrons. Then the current density in the direction of electric and magnetic fields reads as

$$j_z = -\frac{eL}{\pi}\sum_{nl\sigma}\int dk_z v_z f_1\left(E\right) \tag{14}$$

where -e is the charge, $v_z = \frac{\epsilon_0 a}{\hbar}\sin ak_z$ is the velocity of an electron, and $f_1(E)$ is the nonequilibrium addition to the Fermi-Dirac distribution function, $f_0(E)$. Using the relaxation time approximation can be written as:

$$f_1(E) = v_z\tau(E)\frac{\partial f_0}{\partial\epsilon}eE_z \tag{15}$$

Here $\tau(E)$ is the impulse relaxation time of the electron. By inserting (15) in (14), we get

$$j_z = \left(-e^2\frac{L}{\pi}\sum_{nl\sigma}\int v_z v_z\tau(E)\frac{\partial f_0}{\partial E}\frac{dk_z}{dE}dE\right)E_z \tag{16}$$

make $\frac{\hbar dk_z}{d\epsilon} = \frac{1}{v_z}$, we obtain the electrical conductivity.

$$\sigma_{zz} = \frac{j_z}{E_z} = \frac{e^2}{\hbar}\frac{L}{\pi}\sum_{nl\sigma}\int v_z\tau(E)\left(-\frac{\partial f_0}{\partial E}\right)dE \tag{17}$$

For the case of electronic scattering on acoustic phonons, the relaxation time $\tau(\epsilon)$ related to the scattering can be written as:

$$\tau(\epsilon)^{-1} = {\tau_0}^{-1}g(\epsilon) \tag{18}$$

where $g(\epsilon)$ is the density of states, and τ_0 is a constant independent of the energy of the electrons [9]. The density of states can be written as

$$g(E) = \frac{L}{a\pi\epsilon_0}\sum_{nl\sigma}(sin(ak_z)^{-1}) \tag{19}$$

Substitute (18) and (19) into (17) we get:

$$\frac{\sigma_{zz}}{\sigma_0} = \sum_{nl\sigma}\int\sin(ak_z(n,\sigma,E))\frac{1}{\sum_{nl\sigma}(sin(ak_z(n,\sigma,E))^{-1})}\left(-\frac{\partial f_0}{\partial\epsilon}\right)dE \tag{20}$$

Where

$$\sigma_0 = \frac{e^2(\epsilon_0 a)^2}{\hbar^2}\tau_0 \tag{21}$$

In the case of a strongly degenerate electron gas, the conductance has the form:

$$\frac{\sigma}{\sigma_0} = \left|\sin\left(\pi na\right)\right|\sqrt{1-\left(\frac{Bg\mu_B+\varepsilon_0\cos\left(\pi na\right)+\hbar\left(\Omega_1-\Omega_{-1}\right)}{\varepsilon_0}\right)^2} \tag{22}$$

This expression allows you to analyze the change in electrical conductivity depending on the magnetic field and Rashba coupling parameters.

CONCLUSIONS

The longitudinal conductance in a quantum dot superlattice system with lateral parabolic potential in the presence of a magnetic field parallel to the superlattice axis and Rashba spin-orbit interaction has been calculated. The calculation has been carried out for the case of electronic scattering on acoustic phonons for strong degenerate electron gas.

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