OSCILLATIONS OF LONGITUDINAL MAGNETORESISTANCE OF LAYERED CRYSTALS IN A QUANTIZING MAGNETIC FIELD

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ABSTRACT

It is theoretically investigated the magnetoresistance of layered crystals in a longitudinal quantizing magnetic field taking into account the spin splitting. It has been obtained the general expression for the electrical conductivity of a quasi two-dimensional electron gas at the scattering on the deformation potential. It has been revealed peaks in the behavior of the specific resistance, at that a number of the peaks and their positions are dictated by the spin splitting magnitude.

Keywords: layered crystal, magnetic field, oscillations, magnetoresistance, energy spectrum.

I. INTRODUCTION

At present, electronic transport phenomena in low-dimensional systems such as layered crystals, superlattices, quantum wells, nanocomposites and heterostructures are intensively under investigation both experimentally and theoretically. An interest in the systems is connected with the possibility to control their band structure, giving them a number of special features. Among these is, in particular, the sharp spectrum anisotropy. The anisotropy leads to an unusual behavior of the electron gas specific resistance in a magnetic field what could be used on making high sensitive magnetic sensors. In works [1-5] the specific resistance of an electron gas of lowered dimensionality in strong magnetic fields was examined, but therewith the spin splitting was not taken into account. However, in the last years, there are experiments (e.g., [1,3]) for explaining results of which account must be taken of the spin splitting in the energy spectrum. fields.

II. RESULTS

In the present work it is theoretically studied the longitudinal magnetoresistance of an electron gas with the cosinodal dispersion law in the case when perpendicular to crystal layers electrical and magnetic fields are parallel each other taking into account the spin splitting in a quatizing magnetic field. It has been obtained the general expression for the longitudinal specific resistance of quasi two-dimensional systems. In the case of a degenerate electron gas in the quantum limit it has been investigated the analytical dependence of the longitudinal magnetoresistance on the magnetic field magnitude, effective mass and spin splitting. It has been shown that the specific resistance behavior substantially depends on the relation between the Fermi level, Landau level position and one-dimensional conduction band width. It has been revealed the peak-like behavior of the resistance in a magnetic field on which the spin splitting has significant influence.

In layered systems, electrons when passing across the layers along the z axis overcome a rather large potential barrier of width a and the energy spectrum of an electron in this direction can be described in the strong coupling approximation. In the plane of the layers electrons are practically free and it is held the dispersion law in the approximation of the effective mass [6]. In a strong magnetic field, parallel to the z axis, directed transverse to the layers, it is quantized the electron motion in the layer plane and removed the spin degeneracy, bringing about to the familiar electron energy spectrum in the form [7,8]

$$\varepsilon(N,k_z,\sigma)=(2N+1)\mu B+\varepsilon_0(1-\cos ak_z)+ \\ +g^*\sigma\mu_0 B \quad (1)$$

where N is the occupied Landau level number, k_z is the wave vector component along the z axis, B is the magnetic field induction, $\mu=(m_0/m_\perp)\mu_0$, $\mu_0=e\hbar/2m_0c$ is the Bohr magneton, m_0 is the free electron mass, $m_\perp$ is the electron mass in the plane of the layer, ε_0 is the one-dimensional conduction band half-width in the k_z direction, a is a lattice constant along the z axis, $\sigma=\pm 1/2$ is the electron spin quantum number, g^* is the spin splitting factor. The energy spectrum (1) describes an electron gas in layered crystals, transition metal dichalcogenides, in semiconductor compounds with a superlattice and in semiconductor heterostructures with deep wells between large barriers. In [4,5] it was examined the longitudinal magnetoresistance in semiconductors with a superlattice, the electron energy spectrum in which is similar to that being considered in this paper. As $k_0T<\varepsilon_0$ and $\mu B>k_0T$ conditions compiled, it can be restricted to consideration of the transport in the lowest subband, so the flat dispersion in the z direction takes place. The conditions are adequately realized for a strongly degenerate gas at low temperatures and strong magnetic fields when only the lowest subband is occupied.

For the energy spectrum of the form (1) we shall have the following expression for the density of states

$$g_B(\varepsilon) = \frac{1}{2(\pi R)^2 a} \sum_{N\sigma} \left(2\varepsilon_0 \varepsilon_z - \varepsilon_z^2\right)^{-1/2} \qquad (2)$$

Where $\varepsilon_0 \sin ak_z = (2\varepsilon_0\varepsilon_z - \varepsilon_z^2)^{1/2}$, $R^2 = \hbar/eB$. Here is introduced the notation $\varepsilon_z = \varepsilon(N, k_z, \sigma) - (2N+1)\mu B -$ $- g^*\sigma\mu_0 B$. It is seen that the density of states has a peculiarity each time as $\varepsilon_z = 2\varepsilon_0$.

It has been known that a longitudinal magnetic field has no effect on the electron motion along it and it can be applied the Boltzmann kinetic equation. Then the current density in the direction of electrical and magnetic field takes the form [8]

$$j_z = -\frac{e}{(2\pi R)^2} \sum_{N\sigma} \int v_z f_1(\varepsilon) dk_z \qquad (3)$$

where $f_1(\varepsilon)$ is the nonequilibrium addition to the Fermi-Dirac distribution function $f_0(\varepsilon)$, $v_z = \varepsilon_0 a \sin(ak_z)/\hbar$. If in the sample there is an electrical field E, directed in the z axis,

$$f_1(\varepsilon) = v_z \tau_B(\varepsilon) \left(\frac{\partial f_0}{\partial \varepsilon}\right) eE_z \qquad (4)$$

Here $\tau_B(\varepsilon)$ is the relaxation time of impulses in a quantizing magnetic field. As it is known when the condition $k_0 T \le \mu B$ is met, one can introduce the relaxation time, in doing so, it is inverse proportional to the density of states of electrons in a magnetic field $g_B(\varepsilon)$ and equals [4,8]

$$\frac{1}{\tau_B(\varepsilon)} = \frac{2\pi}{\hbar} D\, g_B(\varepsilon) \qquad (5)$$

where

$$D = R^2 \int_0^\infty dq_\perp q_\perp \exp\left(-\frac{1}{2} R^2 q_\perp^2\right) D(q_\perp)(2N_q + 1) \qquad (6)$$

here N_q is the Plank function. In the paper, there are considered the scattering on the deformation potential and $D(q_\perp) = D_0\, q_\perp$, where $D_0 = \hbar \Xi^2 / 2\rho u_0$, u_0 is the speed of sound, ρ is the crystal density, Ξ is the deformation potential.

Inserting nonequilibrium distribution function (4), obtained from the kinetic equation solution, into expression for the current density (3) and passing to the integration over energy for the electrical conductivity of strongly degenerate electron gas we shall receive

$$\sigma_{zz} = \frac{e^2 a^2 \tau_0}{2\hbar^2} \frac{\sum_{N\sigma} (\zeta_z)^{1/2} \left[2\varepsilon_0 - \zeta_z\right]^{1/2}}{\sum_{N'\sigma'} (\zeta_z)^{-1/2} \left[2\varepsilon_0 - \zeta_z\right]^{-1/2}} \qquad (7)$$

where $\tau_0^{-1} = (2\pi/\hbar) D_0$, $\zeta_z = \zeta - (2N+1)\mu B - g^*\sigma\mu_0 B$. From expression (9) it is evident that the resistance $\rho_{zz}(B) = \sigma_{zz}^{-1}(B)$ assumes an infinitely large value when it is fulfilled the condition $\zeta = 2\varepsilon_0 + (2N+1)\mu B + g^*\sigma\mu_0 B$.

In [9,10] there is an indication on the experimental observation of turning $\sigma_{zz}(B)$ into zero at certain values of the magnetic field. It should be noted that with increasing a magnetic field quantum levels lying below the Fermi level cross it, which results in the jump-wise decrease of the specific resistance magnitude. However, in the intervals between the jumps (offsets) the density of states rises and the resistance increases.

In [10] it was noticed that the spin splitting is experimentally observed when $N \le 3$, consequently based on formula (7) it has been investigated the dependence of $\rho_{zz}(B)$ on B where N varies from 0 to 3. Results of these calculations are displayed in Fig. 1 for the following parameters $\varepsilon_0 = 1meV$, $a = 1nm$, $n = 10^{23} m^{-3}$, $m_\perp = 0.2m_0$, $m_\perp = 0.3m_0$, $g^* = 2$. As seen from the Figure the resistance oscillates in a magnetic field when the Fermi level exceeds the one-dimensional conduction band width k_z. It might be noted that these oscillations weaken, as the effective mass along the layer decreases, and vanish at all when $\zeta < 2\varepsilon_0$. For comparison the dependence of $\rho_{zz}(B)$ on B without taking into account spin splitting are displayed in Fig. 2.

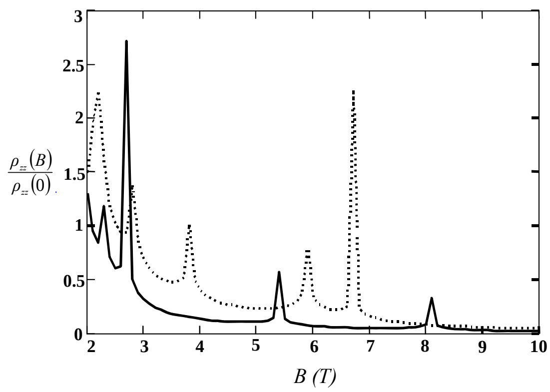

Fig.1 Dependence of the ratio $\rho_{zz}(B)/\rho_{zz}(0)$ on a magnetic field at $\zeta > 2\varepsilon_0$ and $m_\perp = 0.2m_0$ (solid curve), $m_\perp = 0.3m_0$ (dotted curve), with taking into account the spin splitting.

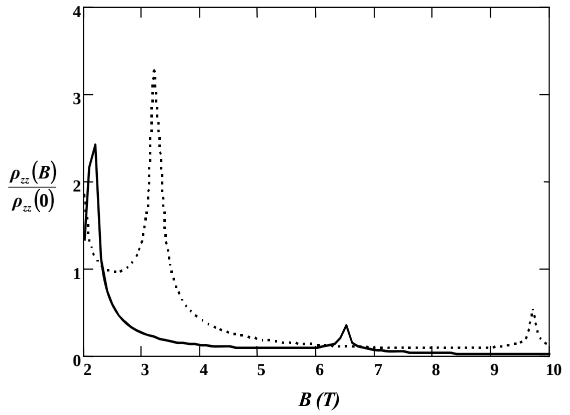

Fig.2. Dependence of the ratio $\rho_{zz}(B)/\rho_{zz}(0)$ on a magnetic field at $\zeta > 2\varepsilon_0$ and $m_\perp = 0.2m_0$ (solid curve), $m_\perp = 0.3m_0$ (dotted curve) without taking into account the spin splitting.

III. CONCLUSION

Point out that comparing the experimental data with theoretical calculations it can be determined physical characteristics such as the spin splitting factor g^*, band parameters of the layered crystal and magnetic field regions where the jumps of the specific resistance occur. These results in turn could be used on making high sensitive magnetic sensors.

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