International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

http://ijpsat.ijsht-journals.org
Vol. 23 No. 2 November 2020, pp. 343-347

Carrier Energy Shift Influence on Quantum Oscillation Phenomena

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Abstract – The longitudinal electrical conductivity oscillations in narrow-gap semiconductors are investigated taking into account the Landau carrier energy shift levels. A method is developed for determining the longitudinal electrical conductivity oscillations in narrow-gap semiconductors taking into account the Landau spin-orbit splitting levels. A formula is obtained for the oscillations dependence of the longitudinal electrical conductivity on the energy, magnetic field, Fermi energy, and band gap of narrow-gap semiconductors with a non-square isotropic dispersion law.

Keywords – Narrow-Gap Semiconductor, Landau Level, Fermi Energy, Oscillation Phenomena, States Density.

I. Introduction

As is known, in a magnetic field at low temperatures, the degenerate electron gas conductivity oscillates with a change in the field (Shubnikov-de Haas effect). The reason for this effect is Fermi levels consecutive crossing by Landau levels in a quantizing magnetic field. In two-dimensional systems, conductivity small oscillations are observed in classical magnetic fields. The Shubnikov-de Haas effect in two-dimensional systems is theoretically studied in the works [1,2] .In bulk materials, $\Delta << \hbar\omega_c$ ratio is usually satisfied, so the Zeeman splitting does not affect the small Shubnikov-de Haas oscillations and only manifests itself in very strong magnetic fields.

When a magnetic field is applied at an angle to the electron gas plane, it becomes possible to narrow the ratio $r = \Delta / \hbar\omega_c$ over a wide range, since the Zeeman splitting is determined by the total magnetic field *B*, and the cyclotron splitting in strong dimensional quantization case of carriers, by the $B_\perp$ field component perpendicular to the electron gas plane.

In [4–8] works, the distances between neighboring Landau levels and the localized states density in the mobility gaps were determined when they are scanned by Fermi level.

In this work, the longitudinal resistance by the activation energy was determined from the temperature dependences. The magnetoresistance activation analysis curves was used as a tool to determine the mobility gaps between adjacent Landau levels, and were obtained large g factor values indications (about 30-80).

This work is devoted to the carrier energy shift influence study of Landau levels on the magnetic oscillation phenomenon in a quantizing magnetic field with a non-square dispersion law.

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II. STATES DENSITY IN A MAGNETIC FIELD FOR AN ELECTRON SYSTEM WITH A NON-SQUARE ISOTROPIC DISPERSION LAW.

In a quadratic ellipsoidal dispersion law in a magnetic field, the energy spectrum of electrons at $H = H_z$ is determined by the relation [11]:

$$E(N,s,k_z) = \frac{\hbar^2 k^2}{2m_e} + \hbar\omega_c\left(N + \frac{1}{2}\right) + \left|g^*\right| s\mu_B H \qquad (1)$$

where $N = 0,1,2,...$ and $s = \pm\frac{1}{2}$ -are orbital and spin quantum numbers, $\left|g^*\right|$ - is effective value of g -factor spin, μ_B - Bohr magneton.

The nonparabolicity of the conduction band in compounds 111-V and 11-V1 arises from the interaction between the conduction band and the three valence bands. In a magnetic field, the energy levels for three energy bands (except for the band of heavy holes, which does not interact with them) are given by the cubic equation [12]. see (15.8). Here, the bottom of the conduction band is chosen as the starting point for the energy. The terms depending on the spin are proportional to $1/L^2$ and give the spin splitting of the levels, which is proportional to the spectroscopic splitting g factor.

The eigenvalues E_N cubic equations can be represented as an expansion in the small parameter

$\beta = \frac{P^2}{L^2 E_g} << 1$ and we get [12]:

$$E_N = E_0 + \beta E_1 + \beta^2 E_2 + ... \qquad (2)$$

The β parameter for all commonly used magnetic fields is really small. Due to the β smallness in expression (2), it is sufficient to restrict ourselves to terms linear in β to find the energy shift of the magnetic field. This βE_1 shift consists of two parts, one of which depends on the orbital motion, the other on the spin, i.e. $E_1 = E_1(орб.) + E_1(сп.)$.

Calculating we obtain for the eigenvalues of the electron energy E_N in a quantizing magnetic field with a non-square dispersion law:

$$E_N = \frac{\hbar^2 k^2}{2m} + \left(N + \frac{1}{2}\right)\hbar\omega_c\left(1 + \frac{2E}{E_g}\right)^{-1} + \left| g_0 \right|\mu_B sH\left(1 - \frac{2E}{E_g}\right) \qquad (3)$$

At $E_g \to \infty$, expression (3) transforms into a parabolic dispersion law on (1).

Using the expression for the cyclotron mass, we find the states number with energies in the interval between two Landau levels.

Let us find the difference between the cross-sectional areas of two isoenergy surfaces, the energies of which differ by $\Delta E = \hbar\omega_c$:

$$\Delta S = \frac{2\pi m_c}{\hbar^2}\Delta E = \frac{2\pi m_c}{\hbar^2}\hbar\omega_c$$

The number of states per unit area in the $k_x\ k_y$ plane for quantization due to cyclic conditions is $\frac{L_x L_y}{(2\pi)^2}$. That number of states between two quantum orbits is:

$$\frac{L_x L_y}{(2\pi)^2}\Delta S = \frac{m\omega_c}{2\pi\hbar}L_x L_y \tag{4}$$

From equation (9), we define k_z:

$$k_z = \frac{(2m)^{1/2}}{\hbar}\left[\left(N+\frac{1}{2}\right)\hbar\omega_c\left(1+\frac{2E}{E_g}\right)^{-1} - |\ g_0\ |\mu_B sH\left(1-\frac{2E}{E_g}\right)\right]^{\frac{1}{2}} \tag{5}$$

Let us now return to calculating the states density with a nonparabolic dispersion law and the magnetic field presence. The electron motion is free along the z axis, that is, it is not quantized along k_z:

$$k_z = \frac{2\pi}{L_z}n_z. \tag{6}$$

According to expression (5) and (6), the state numbers in the energy range from $\left(N+\frac{1}{2}\right)\hbar\omega_c$ to E for n_z will be:

$$n_z = \frac{(2m)^{1/2}}{\pi\hbar}\left(E-\left(N+\frac{1}{2}\right)\hbar\omega_c\left(1+\frac{2E}{E_g}\right)^{-1} - |\ g_0\ |\mu_B sH\left(1-\frac{2E}{E_g}\right)\right)^{\frac{1}{2}} \tag{7}$$

The total number of quantum states with energies less than E is equal to:

$$N(E) = \frac{L_x L_y L_z m^{3/2}}{\pi^2\hbar^2}\hbar\omega_c\sum_{N=0}^{N_\infty}\left[E-\left(N+\frac{1}{2}\right)\hbar\omega_c\left(1+\frac{2E}{E_g}\right)^{-1} - |\ g_0\ |\mu_B sH\left(1-\frac{2E}{E_g}\right)\right]^{\frac{1}{2}} \tag{8}$$

As a result, we obtain the total states density in a magnetic field for an electron system with a non-square isotropic dispersion law in the form:

$$N_S(E) = \frac{dN(E)}{dE} = \frac{m^{3/2}}{\sqrt{2}\pi^2\hbar^2}\frac{\hbar\omega_c}{2}\sum_{N=0}^{N_\infty}\frac{1+\frac{2}{E_g}\left[\left(N+\frac{1}{2}\right)\hbar\omega_c\left(1+\frac{2E}{E_g}\right)^{-2} + |g_0|\mu_B sH\right]}{\left(E-\left(N+\frac{1}{2}\right)\hbar\omega_c\left(1+\frac{2E}{E_g}\right)^{-1} - |g_0|\mu_B sH\left(1-\frac{2E}{E_g}\right)\right)^{\frac{1}{2}}} \tag{9}$$

At $E_g \to \infty$ and without taking into account the spin, expression (9) transforms into a parabolic dispersion law in the following form:

$$N_S(E)=\frac{dN(E,H)}{dE}=\frac{m^{3/2}}{\sqrt{2}\pi^2\hbar^2}\frac{\hbar\omega_c}{2}\sum_{N=0}^{N_\infty}\frac{1}{\left(E-\left(N+\frac{1}{2}\right)\hbar\omega_c\right)^{\frac{1}{2}}} \tag{10}$$

III. OSCILLATIONS OF LONGITUDINAL ELECTRICAL CONDUCTIVITY IN WIDE-GAP SEMICONDUCTORS.

It is known that with the help of oscillatory phenomena it is possible to determine the main physical quantities (longitudinal electrical conductivity, magnetic susceptibility, thermoEMF and other transfer phenomena) in a quantizing magnetic field. In particular, longitudinal electrical conductivity oscillations and the magnetic susceptibility oscillations provide valuable information on the energy spectra of free electrons in semiconductor structures. In a strong magnetic field, the longitudinal electrical conductivity is determined using the kinetic equation [12]:

$$\sigma_{zz}=-\frac{e^2}{2\pi^2 m}\hbar\omega_c\sum_N\int_{\hbar\omega_c/2}^{\infty}k_z^2\tau_N(E)\frac{\partial f_0(E)}{\partial E}dk_z \tag{11}$$

We take the relaxation time in the following form:

$$\tau_N=\tau_0E^r\,. \tag{12}$$

The exponent r has different meanings for different scattering mechanisms. For example, in the scattering case by acoustic vibrations and impurity ions, the exponent is -1/2 and 3/2 [1].

The Fermi-Dirac function derivative with respect to energy is determined by the following expression:

$$\frac{\partial f_0(E,\mu,T)}{\partial E}=-\frac{1}{kT}\frac{\exp(\frac{E-\mu}{kT})}{\left(\exp(\frac{E-\mu}{kT})+1\right)^2} \tag{13}$$

Hence, substituting (5), (12) and (13) in (11), we obtain the temperature dependence of the longitudinal electrical conductivity oscillations in narrow-gap semiconductors, the strong magnetic field presence:

$$\sigma_{zz}=\tau_0E^r\frac{e^2}{2\pi^2 m}\hbar\omega_c\sum_N\int_{\hbar\omega_c/2}^{\infty}k_z^2dk_z\frac{1}{kT}\frac{\exp(\frac{E-\mu}{kT})}{\left(\exp(\frac{E-\mu}{kT})+1\right)^2} \tag{14}$$

where

$$k^2dk_z=\frac{(2m)^{3/2}}{2\hbar^3}\left[\frac{2}{E_g}\left(\left(N+\frac{1}{2}\right)\hbar\omega_c\left(1+\frac{2E}{E_g}\right)^{-2}+|g_0|\mu_BsH\right)\left(\left(N+\frac{1}{2}\right)\hbar\omega_c\left(1+\frac{2E}{E_g}\right)^{-1}-|g_0|\mu_BsH\left(1-\frac{2E}{E_g}\right)\right)^{1/2}\right]dE$$

For a semiconductors volume unit, the following condition is satisfied:

$$R_{zz}\left((E,H,T,E_g(T))\right)\approx\rho_{zz}\left((E,H,T,E_g(T))\right)=\frac{1}{\sigma_{zz}(E,H,T,E_g(T))} \tag{15}$$

Here, R_{zz} − is longitudinal magnetoresistance.

IV. CONCLUSION

Based on the study, the following conclusions can be drawn: The longitudinal electrical conductivity oscillations in narrow-gap semiconductors at different temperatures are studied taking into account the carrier Landau levels energy shift. A method is developed for determining the longitudinal electrical conductivity oscillations in narrow-gap semiconductors taking into account the spin-orbit splitting of Landau levels. A formula is obtained for the oscillations dependence of the longitudinal electrical conductivity on the energy, magnetic field, Fermi energy, and band gap of narrow-gap semiconductors with a non-square isotropic dispersion law.

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