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On Temperature Dependence of Longitudinal Electrical Conductivity Oscillations in Narrow-gap Electronic Semiconductors

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Oscillations of longitudinal electrical conductivity, oscillations of magnetic susceptibility and oscillations of electronic heat capacity for narrow-gap electronic semiconductors are considered. A theory is constructed of the temperature dependence of quantum oscillation phenomena in narrow-gap electronic semiconductors, taking into account the thermal smearing of Landau levels. Oscillations of longitudinal electrical conductivity in narrow-gap electronic semiconductors at various temperatures are studied. An integral expression is obtained for the longitudinal conductivity in narrow-gap electronic semiconductors, taking into account the diffuse broadening of the Landau levels. A formula is obtained for the dependence of the oscillations of longitudinal electrical conductivity on the band gap of narrow-gap semiconductors. The theory is compared with the experimental results of Bi_2Se_3. A theory is constructed of the temperature dependence of the magnetic susceptibility oscillations for narrow-gap electronic semiconductors. Using these oscillations of magnetic susceptibility, the cyclotron effective masses of electrons are determined. The calculation results are compared with experimental data. The proposed model explains the experimental results in p-$Bi_{2-x}Fe_xTe_3$ at different temperatures.

Keywords: Oscillations of electronic heat capacity, Oscillations of magnetic susceptibility and oscillations of electrical conductivity, Electronic narrow-gap semiconductors, Cyclotron effective mass.

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1. INTRODUCTION

It is known that, using quantum oscillation phenomena it is possible to determine the basic physical quantities (longitudinal conductivity, magnetic susceptibility, thermoelectric power and other transport phenomena) in electronic and nanoscale semiconductors. In particular, oscillations of longitudinal electrical conductivity and oscillations of magnetic susceptibility provide valuable information on the energy spectra of free electrons in electronic semiconductor structures. In a strong magnetic field, the longitudinal conductivity is determined using the following expression [1]:

$$\sigma_{zz} = -\frac{e^2}{2\pi^2 m}\hbar\omega_c \sum_N \int_{\hbar\omega_c/2}^{\infty} k_Z^2 \tau_N(E) \frac{\partial f_0(E)}{\partial E} dk_Z = -\frac{(2m)^{\frac{1}{2}} e^2}{\pi^2 \hbar^3}\hbar\omega_c \int_{\hbar\omega_c/2}^{\infty} \sum_N \left[E - \left(N + \frac{1}{2}\right)\hbar\omega_c\right]^{1/2} \tau_N(E) \frac{\partial f_0(E)}{\partial E} dE \quad (1)$$

Here, N is the number of Landau levels, ω_c is the cyclotron frequency, $\tau_N(E)$ is the relaxation time, E is the energy of a free electron in a quantizing magnetic field, $\partial f_0(E)/\partial E$ is the energy derivative of the Fermi-Dirac function, which takes on the character of a delta function at low temperatures. From formula (1) it is seen that the effective mass is a constant, that is, this expression is applicable only for the parabolic dispersion law. But, if the dispersion law is nonparabolic (Kane's dispersion law), then the effective mass is strongly dependent on energy ($m^*(E)$). It is known that, just in narrow-gap electronic semiconductors, the effective mass depends on the energy ($m^*(E)$) [2-4]. Recently, many experiments have been performed on oscillations of longitudinal electrical conductivity and oscillations of magnetic susceptibility in narrow-gap electronic semiconductors [5-8]. In these works, quantum oscillation phenomena at a constant temperature were studied. However, until now, the theory of temperature dependence has not been developed for these processes in narrow-gap electronic semiconductors. The study of quantum oscillation phenomena associated with equilibrium and nonequilibrium quantities allows us to identify new properties of massive, low-dimensional, and electronic semiconductors. Such values include longitudinal magnetic susceptibility, electronic heat capacity, thermodynamic potential, electrical conductivity, and others. In a quantizing magnetic field and at low temperatures, such quantities oscillate. All quantum oscillation phenomena depend on the spectral density of energy states in semiconductors. The spectral density of states in semiconductors is determined by the energy spectrum of electrons and holes. As experiments show, the density of states depends on temperature. The temperature dependence is explained by thermal broadening of discrete levels in the sample. As shown in [9, 10], the density of states at low temperatures from a continuous spectrum turns into a discrete one. This is because, at low temperatures the thermal broadening of the discrete levels decreases, disappears, and the continuous spectrum turns into discrete levels. The temperature dependence of the spectral density of states in a quantizing magnetic field was considered in [9, 10]. It is shown that with increasing temperature, the density of

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states in a strong field turns into a continuous spectrum of the density of states of electrons in the absence of a magnetic field. In this case, with increasing temperature, in the collision of electrons, the thermal motion smears the discrete Landau levels and turns them into a continuous spectrum of density of states. The discontinuous nature of the function, the spectral density of states near the points $E = (N + 1/2)\hbar\omega_c$ leads to significant features of the phenomena of transport and magnetic susceptibility with the parabolic dispersion law. In works [11-13], oscillations of the longitudinal magnetic susceptibility were observed in wide-gap and narrow-gap semiconductors at constant temperatures. And also, in these works the temperature dependence of the oscillation amplitude of the longitudinal magnetic susceptibility was considered in a strong magnetic field. However, in the above works, a concrete theory of oscillations of the longitudinal magnetic susceptibility in narrow-gap semiconductors, taking into account the temperature dependence of the spectral density of states, was not constructed.

The aim of this work is to construct a theory of the temperature dependence of the oscillations of longitudinal electric conductivity and oscillations of the magnetic susceptibility in narrow-gap electronic semiconductors, taking into account the thermal broadening of the Landau levels.

2. THEORY

2.1 Dependence of Oscillations of Longitudinal Electrical Conductivity on the Band Gap in Narrow-gap Electronic Semiconductors

Let us consider oscillations of longitudinal electrical conductivity in narrow-gap electronic semiconductors. In a quantizing magnetic field, the electron energy of the conduction band is determined by the following expression [1]:

$$E_{N\pm} = -\frac{E_g}{2} + \frac{1}{2}\sqrt{E_g^2 + 4E_g\left[\left(N + \frac{1}{2}\right)\hbar\omega_c + \frac{\hbar^2 k_z^2}{2m_n} \pm \frac{g_0\mu_B H}{2}\right]} \quad (2)$$

where E_N is the electron energy of the conduction band in a quantizing magnetic field with a nonparabolic dispersion law, E_g is the band gap of narrow-gap semiconductors.

We define k_z from formula (2) excluding spin. From here, we find k_z^2 and determine the wave function along the Z-axis with the nonparabolic dispersion law:

$$k_z = \frac{\sqrt{2m}}{\hbar}\sqrt{\frac{E_N^2}{E_g} + E_N - \left(N + \frac{1}{2}\right)\hbar\omega_c} \quad (3)$$

Differentiating formula (3), we obtain the following expression and we determine the expression for the longitudinal conductivity in narrow-gap electronic semiconductors:

$$\sigma_{zz} = -\frac{(2m)^{\frac{1}{2}} e^2}{\pi^2\hbar^3}\cdot\hbar\omega_c \int_{\hbar\omega_c/2}^{\infty}\sum_N \left(\frac{2E_N}{E_g} + 1\right)\left[\frac{E_N^2}{E_g} + E_N - \left(N + \frac{1}{2}\right)\hbar\omega_c\right]^{1/2} \tau_N(E)\frac{\partial f_0(E)}{\partial E}dE \quad (4)$$

Now, let us analyze the longitudinal conductivity oscillations for various narrow-gap electronic semiconductors with a nonparabolic dispersion law. Formula (4) allows to graphically analyze the dependence of $\sigma_{zz}(E, H, T, E_g(T))$. Fig. 1 shows the dependence of the longitudinal conductivity oscillations on a strong magnetic field in InSb. Here, $T = 1$ K, $E_g = 0.234$ eV and the number of Landau levels in the conduction band is $N = 10$ [14, 15]. As can be seen from Fig. 1, with increasing magnetic field induction, the amplitudes of oscillations of the longitudinal conductivity increase. It can also be seen from the figure that the amplitude of the conductivity oscillation is 10. Each oscillation of the amplitude of the longitudinal conductivity corresponds to one discrete Landau level.

With the help of formula (4), we compare the oscillations of the longitudinal electrical conductivity for various values of the band gap. In Fig. 1, oscillation phenomena are presented for InSb and InAs at a constant temperature. Here, $T = 4$ K, $E_g = 0.234$ eV [15] for InSb, $E_g = 0.414$ eV [15] for InAs and the number of Landau levels in the conduction band is equal to $N = 12$. As can be seen from Fig. 1, with an increase in the band gap, one can observe a downward movement of the oscillation graph. For example, longitudinal electrical conductivity at $E_g = 0.234$ eV, $B = 0.5$ T, $T = 1$ K is equal to $\sigma_{zz} = 0.266$ (Ohm·cm)$^{-1}$. Longitudinal conductivity at $E_g = 0.414$ eV, $B = 0.5$ T, $T = 1$ K is equal to $\sigma_{zz} = 0.246$ (Ohm·cm)$^{-1}$. It follows that with the help of the band gap of narrow-gap semiconductors at constant temperatures, it is possible to control the oscillations of longitudinal electrical conductivity. Thus, from Fig. 1, a strong dependence of the longitudinal electrical conductivity on the band gap in narrow-gap semiconductors is seen. But, as can be seen from formula (1), for a spectrum with a parabolic dispersion law, the longitudinal electrical conductivity oscillations do not depend on the band gap.

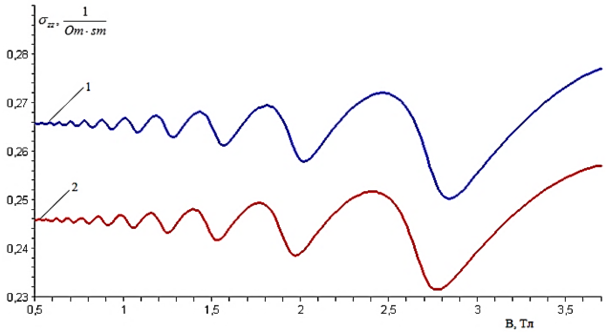

Fig. 1 – Longitudinal electrical conductivity oscillations in narrow-gap semiconductors at $T = 1$ K calculated by formula (4): 1 – for InSb; 2 – for InAs

2.2 Temperature Dependence of Longitudinal Conductivity Oscillations in Narrow-gap Electronic Semiconductors

Let us consider the temperature dependence of the longitudinal electric conductivity oscillations in narrow-gap electronic semiconductors. The graphs in Fig. 1 are obtained at low temperatures and strong magnetic fields. In this case, the Landau levels are manifested sharply and the thermal broadening is very weak. The broadening of the discrete levels is described by the derivative of the Fermi-Dirac energy distribution function $\partial f(E, \mu, T)/\partial E$. To take into account the temperature dependence of the longitudinal conductivity oscillations, we expand $\sigma_{zz}(E, H, T, E_g(T))$ in the derivative of the Fermi-Dirac distribution function $\partial f(E, \mu, T)/\partial E$. Then the longitudinal conductivity oscillations will depend on the temperature. As known, the band gap of semiconductors is highly dependent on temperature ($E_g(T)$) [15, 16]. The temperature dependence of the band gap of semiconductors can be determined using the empirical relation of Varshni [15, 16] or the analytical expression of Feng [16] and other relations. Hence, we obtain the temperature dependence of the longitudinal conductivity oscillations in narrow-gap semiconductors in the presence of a strong magnetic field:

$$\sigma_{zz}(E,H,T,E_g(T)) = -\frac{(2m)^{\frac{1}{2}}e^2}{\pi^2\hbar^3}\cdot\hbar\omega_c\cdot\int\limits_{\hbar\omega_c/2}^{\infty}\sum_N \tau_0 E^r\left(\frac{2E_N}{E_g(0)-\dfrac{\alpha_1T^2}{\alpha_2+T}}+1\right)\left[\frac{E_N^2}{E_g(0)-\dfrac{\alpha_1T^2}{\alpha_2+T}}+E_N-\left(N+\frac{1}{2}\right)\hbar\omega_c\right]^{1/2}\frac{\partial f_0(E,\mu,T)}{\partial E}dE \quad (5)$$

Thus, it becomes possible to calculate the longitudinal conductivity oscillations in narrow-gap semiconductors at various temperatures.

We plot the graph of the $\sigma_{zz}(E, H, T, E_g(T))$ dependences with the help of formula (5). Fig. 2 shows the oscillations of the longitudinal conductivity in InSb at temperatures $T = 1$ K, 25 K, and 77 K. It can be seen from Fig. 2 that at a temperature of 77 K, the amplitudes of the longitudinal electrical conductivity oscillations are practically unnoticeable and coincide with $\sigma_{zz}(E, H, T, E_g(T))$ in the absence of a magnetic field.

2.3 Investigation of Magnetic Susceptibility Oscillations in Narrow-gap Semiconductors at Various Temperatures

Let us consider the temperature dependence of the longitudinal magnetic susceptibility oscillations in narrow-gap semiconductors taking into account the temperature dependence of the density of states. For narrow-gap semiconductors, the spectral density of states is determined by the following expression [10]:

$$N_S(E,H) = \frac{(m)^{3/2}}{(2)^{1/2}\pi^2\hbar^3}\frac{\hbar\omega_c}{2}\sum_{N=0}^{N_{\max}}\frac{\dfrac{2E}{E_g}+1}{\sqrt{\dfrac{E^2}{E_g}+E-(N+\dfrac{1}{2})\hbar\omega_c}}, \quad (6)$$

where $N_S(E, H)$ is the spectral density of energy states with nonparabolic dispersion law. Integrating formula (6), we obtain the total number of quantum states per unit volume. In quantizing magnetic fields, the free energy of electrons without taking into account spin is expressed in terms of the total number of quantum states in the following form [1, 14]:

$$F(E,H,T) = n(\mu) - \frac{m^{\frac{1}{2}}}{(\pi\hbar)^2}\cdot\frac{eH}{c}\cdot\int\sum_{N=0}^{N_{\max}}\sqrt{\frac{E^2}{E_g}+E-\left(N+\frac{1}{2}\right)\frac{\hbar eH}{mc}}\cdot\left(1+\exp\left(\frac{E-\mu}{kT}\right)\right)^{-1}dE \quad (6)$$

where, n is the concentration of charge carriers, μ is the Fermi level. Differentiating (7) with respect to H we find $dF(E, H, T)/dH$, and differentiating again with respect to H we obtain $d^2F(E, H, T)/dH^2$:

$$\chi(E,H,T) = \frac{d^2F(E,H,T)}{dH^2} = -\frac{e^2m^{-\frac{1}{2}}}{4\hbar(c\pi)^2}\cdot\int\sum_{N=0}^{N_{\max}}\frac{\left(N+\dfrac{1}{2}\right)^2\dfrac{3\hbar eH}{mc}-4\left(N+\dfrac{1}{2}\right)\left(\dfrac{E^2}{E_g}+E\right)}{\sqrt{\left(\dfrac{E^2}{E_g}+E-\left(N+\dfrac{1}{2}\right)\dfrac{\hbar eH}{mc}\right)^3}}\cdot\frac{1}{\left(1+\exp\left(\dfrac{E-\mu}{kT}\right)\right)}dE \quad (7)$$

Here, $\chi(E, H, T)$ are magnetic susceptibility oscillations in narrow-gap electronic semiconductors. Thus, using formula (8), one can calculate the temperature dependences of the magnetic susceptibility oscillations in narrow-gap electronic semiconductors. Now consider the numerical calculations using the computer program Maple.

Using formula (8), we construct a graph of the dependence of the longitudinal magnetic susceptibility oscillations on the strong magnetic field strength in n-$Bi_2Te_{2.85}Se_{0.15}$ (Fig. 3). Here, $E_g(0) = 0.18$ eV [17], magnetic field strength $B = 0.1 \div 3$ T (or $H = 1 \div 30$ kOe) at $T = 2$ K. From Fig. 3 it follows that with an increase in the magnetic field induction, the oscillation amplitude of the longitudinal magnetic susceptibility increases

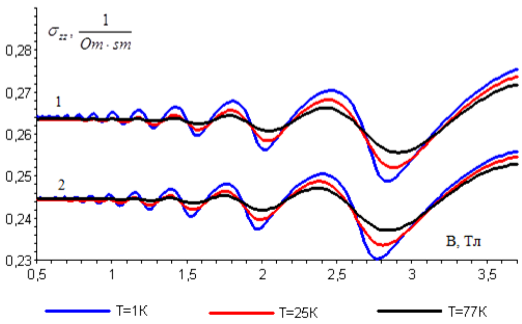

Fig. 2 – Temperature dependence of the longitudinal electrical conductivity oscillations in various narrow-gap electronic semiconductors calculated by the formula (5): 1 – for InSb and 2 – for InAs

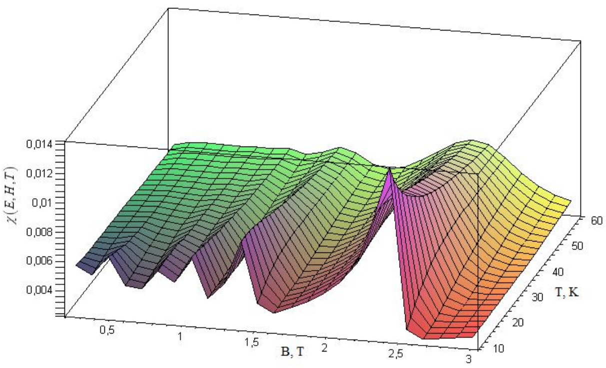

Fig. 3 – Dependence of the magnetic susceptibility oscillations on temperature and magnetic field in n-$Bi_2Te_{2.85}Se_{0.15}$ calculated by formula (8)

significantly. At low temperatures, the discrete Landau levels manifest themselves sharply and the thermal broadening of the discrete levels is not felt. Thermal broadening of the levels in a strong magnetic field leads to smoothing of discrete levels.

2.3.1 Influence of Temperature on Electronic Heat Capacity Oscillations

One of the methods for the determination of the spectral density of energy states oscillations of semiconductors in a strong magnetic field is based on measurements of oscillations of the electronic heat capacity. In the works [12, 13], oscillations of the electron specific heat in semiconductors at low temperatures were studied. However, in these works, the temperature dependence of the oscillations of the electronic heat capacity for narrow-gap semiconductors was not considered.

Now, we consider the oscillations of the electronic heat capacity in narrow-gap semiconductors at various temperatures. For a degenerate electron gas, the derivative of the Fermi-Dirac temperature distribution function has the following form:

$$\frac{\partial f_0(E,\mu,T)}{\partial T}=\frac{1}{kT^2}\cdot\frac{(E-\mu)\cdot\exp\left(\frac{E-\mu}{kT}\right)}{\left(1+\exp\left(\frac{E-\mu}{kT}\right)\right)^2} \qquad (9)$$

Using formulas (6) and (9), we obtain the following analytical expression for the temperature dependence of oscillations of the electronic heat capacity in a quantizing magnetic field:

$$C(E,H,T)=\frac{(m)^{3/2}}{(2)^{1/2}\pi^2\hbar^3}\frac{\hbar\omega_c}{2kT^2}\cdot\int E\cdot\sum_{N=0}^{N_{max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\hbar\omega_c}}\cdot\frac{(E-\mu)\cdot\exp\left(\frac{E-\mu}{kT}\right)}{\left(1+\exp\left(\frac{E-\mu}{kT}\right)\right)^2}dE \qquad (10)$$

Here, $C(E, H, T)$ are electronic specific heat oscillations for narrow-gap electronic semiconductors. Thus, with the help of the formula (10), it is possible to calculate the oscillations of the electronic heat capacity in narrow-gap semiconductors at various temperatures.

3. COMPARISON OF THEORY WITH EXPERIMENTAL RESULTS

In the work [18], the de Haas-van Alphen effect in magnetic semiconductors was observed. The magnetic susceptibility oscillations in p-$Bi_{2-x}Fe_xTe_3$ were obtained at $T = 2$ K, $x = 0$ [18] and $E_g(0) = 0.2$ eV [17]. Fig. 4 presents the theoretical and experimental graphs for p-$Bi_{2-x}Fe_xTe_3$ ($x = 0$) at $T = 2$ K. Using formula (8), a theoretical graph is obtained. As can be seen in this figure, the amplitude of the Landau levels on the theoretical curve is observed much higher than on the experimental graph. With the help of formulas (8), one can plot the graph of the magnetic susceptibility oscillations for p-$Bi_{2-x}Fe_xTe_3$ at various temperatures. It can be seen from Fig. 4 that at high temperatures, the oscillation amplitudes erode, and a strong magnetic field is not felt. This is due to the fact that the thermal broadening of the Landau levels is enhanced at high temperatures.

Let us analyze the longitudinal conductivity oscillations of specific narrow-gap electronic materials in a quantizing magnetic field. For a unit volume of semiconductors, the following condition is satisfied:

$$R_{zz}\left((E,H,T,E_g(T))\right)\approx\rho_{zz}\left((E,H,T,E_g(T))\right)= =\frac{1}{\sigma_{zz}(E,H,T,E_g(T))} \qquad (11)$$

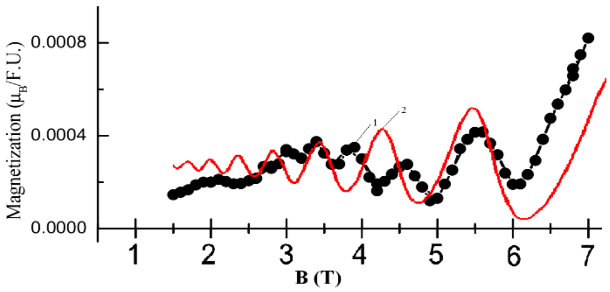

Fig. 4 – De Haas-van Alphen oscillations in p-$Bi_{2-x}Fe_xTe_3$ at $T = 2$ K and $x = 0$: 1 – experiment [18], 2 – theory calculated by formula (8)

Here, R_{zz} is the longitudinal magnetoresistance.

In Fig. 5, the results of theoretical calculations are compared with experimental data for Bi_2Se_3 [8] at a measurement temperature of $T = 4.2$ K, $E_g(T) = 0.15$ eV and in the magnetic field induction range $B = 0 \div 32$ T. The theoretical curve for $R_{zz}(E, H, T, E_g(T))$ is obtained with the help formula (11). As can be seen from this figure, discrete Landau levels are not observed in the range of the magnetic field induction $B = 5 \div 10$ T in the experimental graph. But, oscillations of the longitudinal magnetoresistance in the theoretical curve are manifested precisely in this interval of the magnetic field induction. Using formula (11), we can calculate the oscillations of the longitudinal magnetoresistance in Bi_2Se_3 at various temperatures. As can be seen from Fig. 5, the theoretical curve and experimental data are in good agreement.

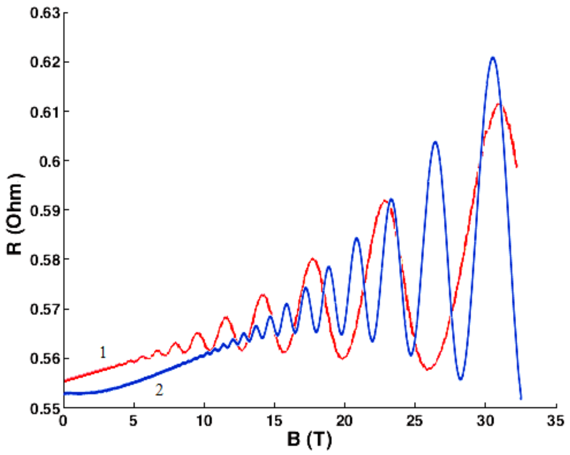

Fig. 5 – Magnetoresistance oscillations in Bi_2Se_3 at $T = 4.2$ K: 1 – theory calculated by formula (11); 2 – experiment [8]

4. CONCLUSIONS

Based on the study, the following conclusion can be made: for the first time, the theory of the temperature dependence on the longitudinal electrical conductivity and magnetic susceptibility oscillations in narrow-gap semiconductors was constructed taking into account the thermal smearing of Landau levels. Generalized mathematical expressions were obtained for the magnetic susceptibility, longitudinal electrical conductivity and electronic specific heat oscillations for narrow-gap electronic semiconductors in quantizing magnetic fields. The theory is compared with the experimental results of Bi_2Se_3 and p-$Bi_{2-x}Fe_xTe_3$. Using these oscillations of magnetic susceptibility, the cyclotron effective masses of electrons are determined.

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Про температурну залежність поздовжніх коливань електричної провідності в вузькозонних електронних напівпровідниках

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Розглянуто коливання поздовжньої електричної провідності, коливання магнітної сприйнятливості та коливання електронної теплоємності для вузькозонних електронних напівпровідників. Побудована теорія температурної залежності явищ квантових коливань у вузькозонних електронних напівпровідниках з урахуванням термічного розмивання рівнів Ландау. Досліджено коливання поздовжньої електричної провідності у вузькозонних електронних напівпровідниках при різних температурах. Отримано інтегральний вираз для поздовжньої електропровідності у вузькозонних електронних напівпровідниках з урахуванням дифузного розширення рівнів Ландау. Знайдена формула залежності коливань поздовжньої електричної провідності від ширини забороненої зони вузькозонних напівпровідників. Порівняно теорію з експериментальними результатами для Bi_2Se_3. Побудована теорія температурної залежності коливань магнітної сприйнятливості для вузькозонних електронних напівпровідників. За допомогою цих коливань магнітної сприйнятливості визначають ефективні циклотронні маси електронів. Результати розрахунків порівнюються з експериментальними даними. Запропонована модель пояснює результати експериментів у p-$Bi_{2-x}Fe_xTe_3$ при різних температурах.

Ключові слова: Коливання електронної теплоємності, Коливання магнітної сприйнятливості та коливання електропровідності, Електронні вузькозонні напівпровідники, Ефективна циклотронна маса.