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Magnetic Quantum Effects in Electronic Semiconductors at Microwave-radiation Absorption

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Simulation of the temperature dependence on the microwave magnetoabsorption oscillations in electronic semiconductors is conducted using the Gaussian function and derivative of the Fermi-Dirac function by energy. Gaussian distribution function and derivative of the Fermi-Dirac function by energy are compared at different temperatures. It is shown that the distribution of the Gauss function is much more efficient and more rapidly tends to an ideal Dirac δ-function than the derivative of the Fermi-Dirac function by energy. The temperature dependence of the spectral density of states in semiconductors is calculated at quantizing magnetic fields. An analytical expression is obtained for the density of states in a quantizing magnetic field for narrow-gap semiconductors. Graphs of the temperature dependence of the density of states for InAs are constructed in a quantizing magnetic field. Oscillations of the absorption of microwave radiation in semiconductors are considered at different temperatures. A new mathematical model has been created for microwave absorption oscillations in narrow-band semiconductors. Using this model, the dependence of quantum oscillation phenomena on microwave absorption and temperature is calculated in electron gases. Graphs of oscillations of the derivative of the absorbed power by the magnetic field strength are obtained for InAs. A three-dimensional image of the absorption of microwave radiation for semiconductors has been constructed with the Kane dispersion law. The microwave magnetoabsorption oscillation was calculated in narrow-gap electronic semiconductors at different temperatures using the Gauss function. Formula for the dependence of the microwave magnetoabsorption oscillations on the electric field strength of an electromagnetic wave and temperature is obtained with the parabolic and Kane dispersion law. The calculation results are compared with experimental data. The proposed model explains the experimental results in HgSe at different temperatures.

Keywords: Microwave magnetoabsorption oscillations, Gaussian function and derivative of the Fermi-Dirac function by energy, Free electron gas.

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1. INTRODUCTION

Quantum oscillation phenomena in external fields in semiconductor structures are an interesting area of research and the basis for the establishment of optoelectronic and electronic devices. In particular, in works [1, 2] dependence of the derivative of power of microwave-radiation absorption with respect to magnetic field strength $H\left(\frac{dP}{dH}\right)$ was investigated in narrow-gap electronic semiconductors. In works [3, 4], for a quantizing magnetic field, the microwave magnetoabsorption oscillations were determined in narrow-gap semiconductors. In this case, the experimental investigation was carried at low temperatures and at constant electromagnetic fields.

In recent years, Shubnikov-de Haas and de Haas-van Alphen oscillations were considered in electronic and nanoscale semiconductors at different temperatures and at different pressures [5, 6]. For example, in [6, 7], the method of determining the thermodynamic density of states at different temperatures was developed in a quantizing magnetic field. Using these methods, quantum oscillation phenomena in semiconductors are investigated at different temperatures [7, 8]. However, in well-known works, the influence of a strong electromagnetic field on the temperature dependence of quantum oscillation phenomena in narrow-gap electronic semiconductors was not investigated using the Gauss function and the derivative of the Fermi-Dirac function with respect to energy.

The aim of this work is to simulate the influence of a strong electromagnetic field on the temperature dependence of Shubnikov-de Haas oscillations in narrow-gap electronic semiconductors and investigate with the help of this model the experimental data processing.

2. MODEL

2.1 Comparison of the Gaussian Distribution Function and the Derivative of the Fermi-Dirac Function with Respect to Energy at Different Temperatures

Let us consider the dependence of the distribution of the static function on energy at different temperatures. Gaussian distribution function and the derivative of the Fermi-Dirac function with respect to energy are defined for energy levels E_i by the following expression [9]:

$$Gauss(E,T)=\frac{1}{kT}\cdot\exp\left(-\frac{(E-E_i)^2}{(kT)^2}\right), \tag{1}$$

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$$\frac{\partial f_0(E,\mu,T)}{\partial E} = -\frac{1}{kT}\frac{\exp((E-\mu)/kT)}{\left[1+\exp((E-\mu)/kT)\right]^2}. \quad (2)$$

Here, $Gauss(E,T)$ is the Gaussian distribution function, $\partial f_0(E)/\partial E$ is the the derivative of the Fermi-Dirac function with respect to energy.

We now consider the temperature dependence of the Gaussian distribution function and the derivative of the Fermi-Dirac function with respect to energy. In Fig. 1, the dependences of the derivative of the Fermi-Dirac function with respect to energy and distribution Gauss functions on energy are compared at a temperature of $T = 300$ K. As can be seen from this figure, at high temperature, the height of the Gaussian distribution function is higher than the height of the derivative of the Fermi-Dirac function with respect to energy. At low temperatures, too, the peak height of the Gauss function is greater than the height of the derivative of the Fermi-Dirac function with respect to energy.

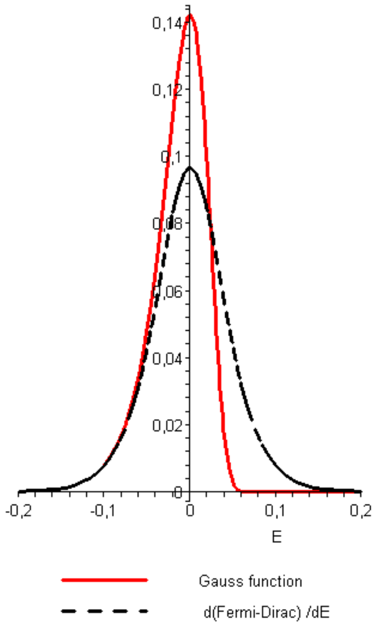

Fig. 1 – View of the Gaussian distribution function and the derivative of the Fermi-Dirac function with respect to energy at a temperature of $T = 300$ K

This is an important result, indicating that the Gaussian distribution function much more effectively and more rapidly tends to the ideal Dirac δ-function than the derivative of the Fermi-Dirac function with respect to energy.

2.2 Dependence of the Spectral Density of States on Tmperature in Electronic Semiconductor at a Quantizing Magnetic Field

We now consider the dependence of the spectral density of states on temperature in a quantizing magnetic field using the Gaussian distribution function and the derivative of the Fermi-Dirac function with respect to energy. In work [8], spectral densities of state of oscillations are studied and the analytical expression for the density of states in narrow-gap semiconductors is obtained:

$$N(E,H) = K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}, \quad (3)$$

$$K = \frac{(m)^{3/2}}{(2)^{1/2}\pi^2\hbar^3}.$$

Here, $N(E,H)$ is the spectral density of states for the zone with the Kane dispersion law, H is the magnetic field strength, E is the energy of a free electron and a hole in a quantizing magnetic field, N is the number of Landau levels, E_g is the band gap width of the semiconductor.

If the energy spectrum of electrons is discrete, then the density of energy states is equal to the sum of δ-functions [10]:

$$N_s(E) = \sum_i N_{si}\,\delta(E-E_i). \quad (4)$$

In the general case, the energy density of states is a set of δ-functional peaks located at $\hbar\omega_c$ from each other in a quantizing magnetic field [11].

If, $T\to 0$ and $\frac{1}{kT}\to\infty$, then that functions and $\partial f_0(E)/\partial$ are the Dirac delta-functions (Dirac δ-function).

Energy spectrum of charge carriers in the conduction band and in the valence band are quantized at low temperatures and at quantizing magnetic fields.

From here, using (3) and substituting (1) and (2) in (4), we obtain the analytical expression for the density of energy states in a quantizing magnetic field for narrow-gap semiconductors:

$$N_s[E,E_N,H,T] = K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}Gauss(E,E_N,T), \quad (5)$$

$$N_s[E,E_N,H,T] = K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\cdot\frac{\partial f_0(E_N,\mu,T)}{\partial E}. \quad (6)$$

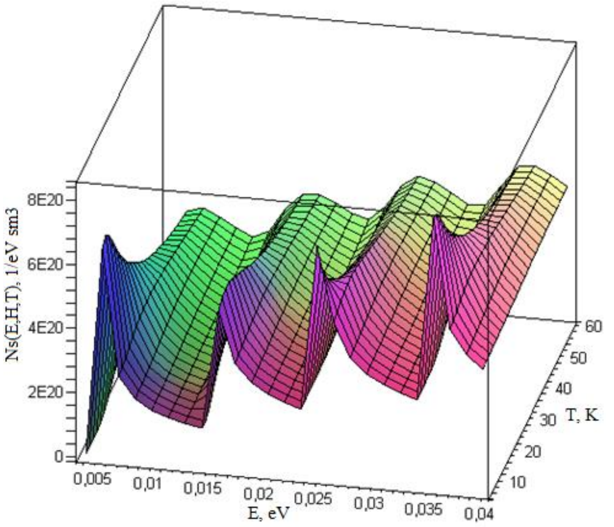

Fig. 2 – The dependence of the spectral density of states on the energy and temperature in InAs calculated using formula (5)

Using formulas (5) and (6), we consider the graphs of the spectral density of states. For example, Fig. 2 shows the spectral density of energy states of oscillations in a three-dimensional space for InAs ($E_g(0) = 0.414 eV$) [12] at the magnetic field of $H = 40$ kOe (or $B = 4$ T). This figure presents the dependences of the spectral density of states of oscillations on temperature and energy for InAs narrow-gap semiconductor. The graph in Fig. 2 was constructed using formula (5). As can be seen from this figure, at low temperatures ($T < 5$ K), the discrete Landau levels appear sharply. In addition, the height of discrete Landau levels is almost the same in the temperature range of 1 K < T < 4 K. When the energy spectrum is calculated by formula (4) (Fig. 2) in the temperature range of 50 K < T < 60 K, oscillations of the spectral density of states can be observed.

Thus, some experimental results for quantum oscillation phenomena can be explained using the Gaussian distribution function.

2.3 Simulation of Quantum Oscillation Phenomena in Narrow-gap Semiconductors in the Presence of a Strong Electromagnetic Field and Temperature

As known, spectral density of states of oscillations plays an important role in determining the Shubnikov-de Haas, de Haas-van Alphen and quantum Hall effect oscillations in massive and nanoscale semiconductors. Therefore, using formula (5), the quantum oscillation phenomena in narrow-gap semiconductors can be investigated. Now, we consider the quantum oscillation phenomena in narrow-gap semiconductors in the presence of a strong electromagnetic field and temperature. The power of microwave-radiation absorption is determined in a unit volume by the following expression [13]:

$$P = \sigma \cdot E_E^2. \tag{7}$$

Here, σ is the semiconductor conductivity, E_E is the electric field strength of the electromagnetic wave.

In a quantizing magnetic field, the longitudinal conductivity σ_{zz} depends on the spectral density of states of oscillations and the relaxation time $\tau(E)$. Then, according to [7], the expression of the longitudinal magnetic conductivity is as follows:

$$\sigma_{zz}(E, E_N, H, T) = -\frac{(2m)^{\frac{1}{2}} e^2}{\pi^2 \hbar^3} \hbar\omega_c \int_{\hbar\omega_c/2}^{\infty} \sum_N \tau(E) N_s(E, E_N, H, T) dE . \tag{8}$$

Here, $\tau(E)$ is the transport relaxation time. The transport relaxation time is taken as follows: $\tau = \tau_0 E^r$ [7]. The exponent r has different values for different scattering mechanisms. For example, in the case of scattering by acoustic vibrations and impurity ions, the exponent is – 1/2 and 3/2 [7]. τ_0 does not depend on the electron energy.

Substituting the expressions (5) and (8) into (7), we obtain the following expression:

$$P\left(E, E_N, H, T, E_E\right) = \sigma_{zz}(E, E_N, H, T) \cdot E_E^2 . \tag{9}$$

Differentiating (9) by H, that is $\frac{dP\left(H, T, E, E_N, E_E\right)}{dH}$, we obtained the expressions for the dependence of the Shubnikov-de Haas oscillations on the microwave-radiation absorption and temperature in narrow-band semiconductors:

$$\frac{dP^k\left(H, T, E, E_N, E_E\right)}{dH} = C \sum_{N=0}^{\max} \frac{\frac{2E}{E_g} + 1}{\sqrt{\frac{E^2}{E_g} + E - \left(N + \frac{1}{2}\right) AH}} \cdot \left(1 + \frac{AH\left(N + \frac{1}{2}\right)}{2\left(\frac{E^2}{E_g} + E - (N + \frac{1}{2}) AH\right)}\right) \cdot Gauss\left(E, E_N, T\right) \cdot \tau(E) \cdot E_E^2 ; \tag{10}$$

$$A = \frac{\hbar e}{mc}; \quad C = \frac{(m)^{3/2}}{(2)^{3/2} \pi^2 \hbar^3}.$$

Here, P is the microwave field power for the Kane model. Thus, we have the opportunity to calculate the oscillations $\frac{dP\left(H, T, E, E_N, E_E\right)}{dH}$ at a strong electromagnetic field and at different temperatures with the help of formula (10).

Thus, a new mathematical model has been created to determine the microwave-radiation absorption of oscillations in narrow-gap semiconductors. Based on the proposed model, it is possible to calculate the experimental oscillations at different temperatures.

Let us consider the analysis of quantum oscillation phenomena in semiconductors with the help of reduced model. In particular, we obtained the graph of expansion in a series of the Gaussian functions. Then, the temperature dependence of microwave-radiation absorption of oscillations in semiconductors can be explained at the constant electromagnetic field strength. As can be seen from this figure, at $T = 4$ K, oscillation amplitude of the microwave-radiation absorption increases with increasing magnetic field. Therefore, in this case, thermal broadening is very weak, that is $kT << \hbar\omega_c$ (ω_c is the cyclotron frequency). Every peak of oscillations corresponds to one discrete $\frac{dP(H,T,E,E_E)}{dH}$ of oscillations for InAs, using the formula (10). In Fig. 3 we show microwave-radiation absorption of oscillations in InAs $(Eg(0) = 0.414eV)$ [12] at $T = 4$ K and $E_E = 1.5\cdot 10^3 \frac{V}{sm}$. In this case, $E_E = const$. Thermal broadening of oscillations will be taken into account using the Gaussian distribution function. We investigated the spectral density of states with the help Landau level. With increasing temperature, the amplitude oscillation decreases, at sufficiently high temperatures the discrete energy spectrum of the zone turns to continuous (Fig. 4). This leads to the smoothing of oscillations $\frac{dP}{dH}$.

In Fig. 4 we present the dependence of microwave-radiation absorption oscillations on the temperature and magnetic field. This three-dimensional image is

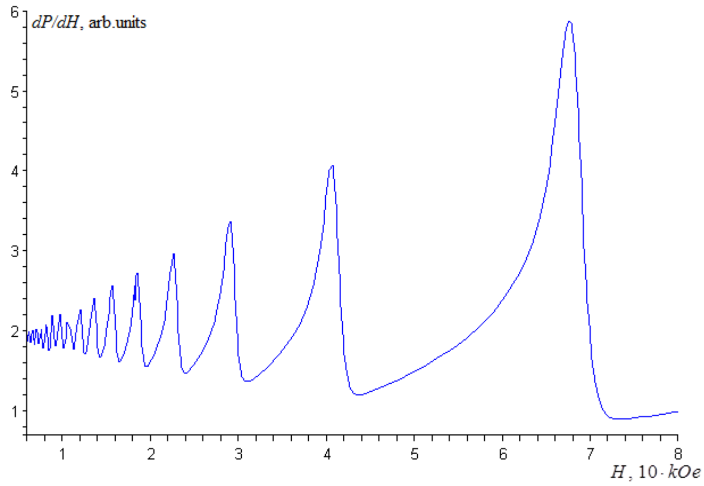

Fig.3 – Microwave-radiation absorption oscillations (*dP*/*dH*) in InAs at the temperature of $T = 4$ K and the electromagnetic field strength of $E_E = 1.5\cdot 10^3 \frac{V}{sm}$ calculated with the help of formula (10)

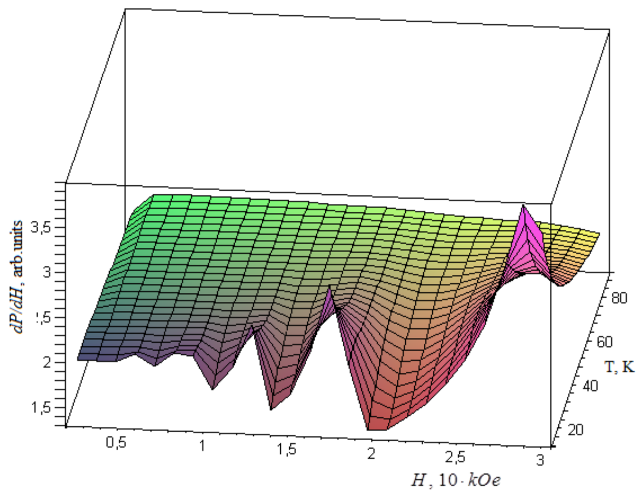

Fig.4 – Microwave-radiation absorption oscillations dependence on the magnetic field and temperature in InAs semiconductor with the Kane dispersion law. Electromagnetic field strength $E_E = 1.5\cdot 10^3 \frac{V}{sm}$, was calculated with the help of formula (10)

obtained in semiconductors with the Kane dispersion law. Using formula (10), we can obtain the same three-dimensional graphics for the narrow band gap semiconductors. As can be seen from these figures, with increasing temperature, the oscillation amplitude is gradually smoothed. At a temperature of $T = 77$ K, the microwave-radiation absorption oscillation amplitudes are virtually invisible and coincide with oscillations in the absence of a magnetic field in the interval of $H = 10$-25 kOe.

3. COMPARISON OF THEORY WITH EXPERIMENTAL RESULTS

Let us analyze the microwave-radiation absorption oscillations in semiconductors at the temperature and external fields. In work [1], microwave magnetoabsorption oscillations in semiconductors are observed. In Fig. 5, theory and experimental results were compared at a temperature of $T = 2.7$ K and constant power of electromagnetic wave over the entire measurement range for HgSe samples. Here, the dependences of $\frac{dP}{dH}$ oscillations on the inverse magnetic field at low temperatures are shown. In work [1], oscillations were obtained for a narrow-gap semiconductor. From here, using formula (10), we determined $\frac{dP}{dH}$ oscillations at a temperature of $T = 2.7$ K (Fig. 5). In this case, quantum oscillation amplitude begins abruptly. Using formula (10), experimental results can be explained at different temperatures.

In this case, Landau levels appear sharply. With increasing temperature, sudden bursts begin to smooth out. At high temperatures, the density of states turns into a continuous spectrum and the influence of a magnetic field will not be felt. This allows us to obtain the density of states, which depends on temperature. With increasing temperature, the oscillation $\frac{dP}{dH}$ amplitudes decrease and at values of H of a magnetic field are not felt. At room temperature, $\frac{dP}{dH}$ oscillations are smoothed out.

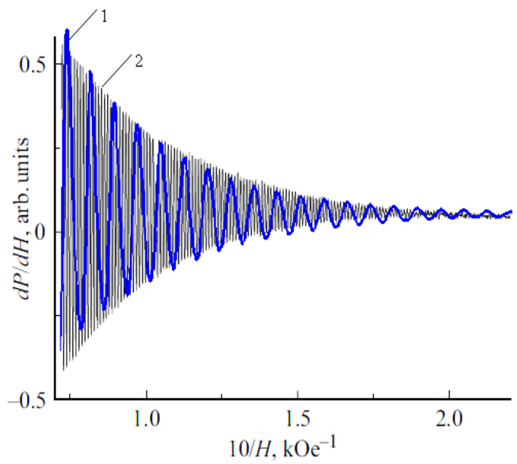

Fig.5 – Comparison of theory with experimental results: 1 – Shubnikov-de Haas oscillations in HgSe samples at $T = 2.7$ K calculated using formula (10); 2 – experimental data [1]

4. CONCLUSIONS

Based on the study, the following conclusion can be made: the model of determination of microwave magnetoabsorption oscillations in semiconductors is developed at different electromagnetic fields and temperatures. Formula for the dependence $\frac{dP}{dH}$ of oscillations on the electric field strength of an electromagnetic wave and temperatures is obtained with the Kane dispersion law. Using the proposed model, the experimental results for HgSe were investigated. Using formula (10), experimental oscillations $\frac{dP}{dH}$ in HgSe narrow-gap semiconductor are explained at different temperatures.

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Магнітні квантові ефекти в електронних напівпровідниках при поглинанні мікрохвильовим випромінюванням

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Моделювання температурної залежності НВЧ магнітопоглинання в електронних напівпровідниках проводиться за допомогою функції Гауса і похідної функції Фермі-Дірака. Функція розподілу Гауса і похідна функції Фермі-Дірака за енергією порівнюються при різних температурах. Показано, що розподіл функції Гауса набагато ефективніший і швидше прямує до ідеальної δ функції Дірака, ніж похідна функції Фермі-Дірака за енергією. Розраховано температурну залежність спектральної щільності станів у напівпровідниках при квантуванні магнітних полів. Отримано аналітичний вираз для густини станів у квантованому магнітному полі для вузькозонних напівпровідників. Побудовано графіки температурної залежності щільності станів для InAs від магнітного поля. Розглядаються коливання поглинання НВЧ-випромінювання в напівпровідниках при різних температурах. Створено нову математичну модель для поглинання НВЧ коливань у вузькосмугових напівпровідниках. Використовуючи цю модель, розрахована залежність квантових коливань від поглинання мікрохвиль і температури електронного газу. Для InAs отримані графіки коливань похідної поглиненої потужності від напруженості магнітного поля. Тривимірне зображення поглинання мікрохвильового випромінювання для напівпровідників було побудовано за допомогою закону дисперсії Кена. У вузькозонних електронних напівпровідниках при різних температурах з використанням функції Гауса розраховували НВЧ магнітопоглинання. Формулу для залежності НВЧ-магнітоадсорбційних коливань від напруженості електричного поля електромагнітної хвилі та температури отримано за допомогою параболічного та дисперсійного законів Кена. Результати розрахунків порівняно з експериментальними даними. Запропонована модель пояснює результати експерименту в HgSe при різних температурах.

Ключові слова: НВЧ магнітопоглинаючі коливання, Гаусова функція та похідна функції Фермі-Дірака за енергією, Газ вільних електронів.