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Determination of oscillations of the density of energy states in nanoscale semiconductor materials at different temperatures and quantizing magnetic fields

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Abstract. At present, the interest in applied and fundamental research in the field of condensed matter physics has shifted from bulk materials to nanoscale semiconductor structures. Of particular interest are the properties of the energy spectrum of charge carriers in low-dimensional semiconductor structures exposed to a quantizing magnetic field. Quantization of the energy levels of free electrons and holes in a quantizing magnetic field leads to a significant change in the form of oscillations of the density of energy states in two-dimensional semiconductor structures. Thus, in this manuscript, we investigated the effect of the temperature and thickness of the quantum well on the oscillations of the density of energy states in the conduction band of nanoscale semiconductor structures. A new mathematical model has been developed for calculating the temperature dependence of the oscillations of the density of states in a rectangular quantum well under the influence of a transverse quantizing magnetic field..

Keywords: Nanoscale, semiconductor, low-dimensional semiconductor structures, quantizing magnetic field, density of energy states, quantum well, mathematical model, transverse quantization.

Introduction

In two-dimensional semiconductor materials, the study of the dependence of the density of energy states on the magnitude of the quantizing magnetic field and filling, allows one to obtain valuable information on the energy spectra of charge carriers in nanoscale semiconductor structures. Under longitudinal and transverse action of quantizing magnetic fields, in low-dimensional semiconductor materials, the density of states was measured by oscillating dependences of kinetic, dynamic and thermodynamic quantities - magnetoresistance, magnetic susceptibility, electronic heat capacity, thermopower, Fermi energies, and other physical parameters.

It follows from this that the study of oscillations of the density of energy states in the conduction band of a rectangular quantum well, in the presence of a transverse and longitudinal magnetic field, is one of the urgent problems of modern solid-state physics.

In particular, in [1-9], the calculations of the density of states of Landau levels in two-dimensional electron gases, with a uniform perpendicular magnetic field and with a random field of arbitrary correlation are considered. A semi classical nonperturbative approach of path integrals is developed for a random field of arbitrary correlation, and this provides an analytical solution for the density of states of Landau levels. The deviation of the density of states from the Gaussian shape increases with decreasing correlation length and weakening the magnetic field [1, 3].

Calculation of oscillations of the density of energy states in two-dimensional electron gases in the presence of a longitudinal and transverse strong magnetic field.

According to the band theory of a solid, the wave function of a free electron, in the presence of an external field, is a solution of the stationary Schrödinger equation with a parabolic dispersion law [9-15]:

$$\left\{-\frac{\hbar^2}{2m^*}\nabla^2+V(r)\right\}\psi(r)=E\psi(r) \tag{1}$$

Here, V(r) is the energy of free electrons in the presence of an external field, *E* is the energy of charge carriers in the absence of an external field, is the wave function. The dependence of the quantizing magnetic field on the wave function of electrons and the energy spectra of charge carriers in two-dimensional electron gases is determined using equation (1), in which the generalized momentum operator in a quantizing magnetic field should replace the momentum operator:

$$\left\{\frac{1}{2m^*}\left(-i\hbar\nabla-eA\right)^2+V(z)\right\}\psi(r)=E\psi(r) \tag{2}$$

Here, *A* is the vector potential of the induction of a strong magnetic field, $[B=rot(A)]$. To solve equation (2), the direction of the vector *B* is chosen in two different ways. In the first case, this vector will be directed along the plane of the two-dimensional layer (along the *X*-axis) and perpendicular to the *Z*-axis. For a longitudinal quantizing magnetic field, vector potential A can be chosen as *A=(0,-Bz,0)*. $\psi_{k\perp m}$ from the Schrödinger equation (3.2), for a deep rectangular quantum well, takes the following form:

$$\psi_{k\perp m}(r)=\frac{1}{\sqrt{S}}\exp\left(ik_\perp r_\perp\right)\varphi_n\left(z-z_0\right) \tag{3}$$

Then it can be solved by the method of separation of variables, using the function from [14]. This function describes localized motion in the *YZ* plane and the state of motion of a free electron along the *X* axis. In equation (3), the function $\varphi_n\left(z-z_0\right)$ is responsible for localized motion. Then the solution to equation (3) will be as follows:

$$\left\{-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2}+V(z)+\frac{1}{2}m^*\omega_c^2(z-z_0)^2\right\}\varphi_n(z-z_0)=E_n\varphi_n(z-z_0) \tag{4}$$

Here, $z_0=-\frac{\hbar k_y}{eB}$, $\omega_c=\frac{eB}{m^*}$. Equation (4) is called the equation of a quantum harmonic oscillator, the motion of which is additionally limited by a quantum well, and E_n is a discrete level.

In a quantizing magnetic field, if the width of the quantum well increases, the energy spectrum of free electrons will increase. That means, $a >> \lambda = \sqrt{\frac{\hbar}{eB}}$. Here, a is the width of the quantum well, λ is the magnetic length, which is equal in magnitude to the radius of the characteristic orbit of an electron in a quantizing magnetic field. Hence, the discrete energy levels E_n will be equal to the energies of the harmonic quantum oscillator:

$$E_N = \hbar\omega_c\left(N+\frac{1}{2}\right), \quad N = 0,1,2,3.... \tag{5}$$

According to equation (2), the velocity and momentum of charge carriers in the direction of the quantizing magnetic field can take any values. In other words, the motion of free electrons and holes in the direction of the XY plane (i.e., along the X axis) is not quantized. Hence, the total energy of free electrons in two-dimensional electron gases in the presence of a magnetic field directed along the X axis is determined by the following expression:

$$E_N = \hbar\omega_c\left(N+\frac{1}{2}\right)+\frac{\hbar^2 k_X^2}{2m} \tag{6}$$

Where, $\hbar\omega_c\left(N+\frac{1}{2}\right)$ is the energy of motion of a free electron in the YZ plane, these energies are called discrete Landau levels. $\frac{\hbar^2 k_X^2}{2m}$ is the energy of continuous motion along the X axis. Thus, in the presence of a longitudinal magnetic field, due to the quantization of the orbital motion of charge carriers in the YZ plane, the allowed energy zone is split into one-dimensional magnetic subbands, that is, into discrete Landau levels.

In three-dimensional and two-dimensional electron gases, a change in the energy spectrum of charge carriers leads to a change in the oscillations of the density of states in a quantizing magnetic field. In works [14,15], an analytical expression for the oscillations of the density of states in three-dimensional electron gases in the presence of a quantizing magnetic field with a nonparabolic dispersion law is derived. There, the temperature dependence of the oscillations of the density of energy states with a transverse strong magnetic field was discussed.

Now, at first let us calculate the oscillations of the density of energy states in two-dimensional electron gases in the presence of a longitudinal strong magnetic field. When the width of the quantum well becomes comparable to the de Broglie wavelength in two-dimensional semiconductor materials, then quantization occurs. That is, $L_Z \approx \lambda_D$ and $L_Y >> L_Z$. Hence, in the YZ plane, the cyclotron mass is calculated by the expression:

$$m_c = \frac{\hbar}{2\pi}\frac{\partial L_Y}{\partial E} \tag{7}$$

For a parabolic dispersion law, the effective cyclotron mass will be constant. The energy in the interval between the two Landau levels is $\Delta E = \hbar\omega_c$. Hence, for a two-dimensional semiconductor material, we find the difference in the section length of two isoenergy surfaces:

$$\Delta L_Y = \frac{2\pi m_c}{\hbar}\hbar\omega_c \tag{8}$$

The number of states for quantization, in the presence of a longitudinal quantizing magnetic field, in the *YZ* plane, due to the cyclic conditions, is equal to $\frac{L_Y}{2\pi}$. In expression (8), the number of states between two quantum orbits is

$$\frac{L_Y}{2\pi}\Delta L_Y = \frac{2\pi m_c}{\hbar}\hbar\omega_c \frac{L_Y}{2\pi} = m\omega_c L_Y \tag{9}$$

From formula (6) we find k_X:

$$k_X = \frac{(2m)^{1/2}}{\hbar}\left(E_N - \hbar\omega_c\left(N+\frac{1}{2}\right)\right)^{1/2} \tag{10}$$

In the presence of a longitudinal strong magnetic field, the movement of charge carriers along the *X* axis is not quantized in k_X and takes the following form:

$$k_X = \frac{2\pi}{L_X} n_X \tag{11}$$

With the help formulas (10) and (11), in the energy range from $\hbar\omega_c\left(N+\frac{1}{2}\right)$ to *E*, it is possible to determine the number of states along the *X* axis:

$$n_X = \frac{L_X (2m)^{1/2}}{2\pi\hbar}\left(E_N - \hbar\omega_c\left(N+\frac{1}{2}\right)\right)^{1/2} \tag{12}$$

Using formulas (9) and (12), in the presence of a longitudinal magnetic field and for a rectangular quantum well, we obtain the total number of quantum states by the following expression:

$$N_X^{2d}(E,H) = \frac{L_X L_Y (m)^{3/2}}{2^{1/2}\pi\hbar^2}\hbar\omega_c \sum_{N=0}^{N_{\max}}\left(E_N - \hbar\omega_c\left(N+\frac{1}{2}\right)\right)^{1/2} \tag{13}$$

Differentiate expression (13) with respect to energy *E* per unit area ($L_X L_Y$=1) and define $N_{S\,X}^{2d}(E,H)$:

$$N_{S\,X}^{2d}(E,H) = \frac{(m)^{3/2}}{2^{1/2}\pi\hbar^2}\hbar\omega_c \sum_{N=0}^{N_{\max}} \frac{1}{\left(E_N - \hbar\omega_c\left(N+\frac{1}{2}\right)\right)^{1/2}} \tag{14}$$

This formula is called the density of energy states, in two-dimensional electron gases (that is, in a rectangular quantum well), in the presence of a longitudinal quantizing magnetic field. This formula is analogous to the quantum thread equation (Fig.1). Obviously, with a longitudinal quantizing magnetic field, in a two-dimensional electron gas, the energies of free electrons in the *YZ* plane can take only some fixed values, but the electron energy along the *X* axis remains free (not quantized). Formula (14), for $H \to 0$, goes over into [13]:

$$N_S^{2d}(E) = \frac{m}{\pi\hbar^2} \tag{15}$$

This formula describes the density of energy states in two-dimensional electron gases in the absence of a magnetic field (Fig.1). In conclusion, we note that the main feature of the oscillation of the density of energy states for a two-dimensional electron gas, in the presence of a longitudinal strong magnetic field, is that it does not depend on the width of the quantum well or the size of the quantum well and is determined only by the magnitude of the magnetic field induction and energy. Also, the densities of states oscillate only in accordance with changes in the longitudinal magnetic field.

Now, consider the dependence of the oscillations of the density of states on the transverse quantizing magnetic field, in a rectangular quantum well or two-dimensional electron gases. In this case, the magnetic field is directed along the Z axis and will be perpendicular to the XY plane. Here, the energies of free electrons are quantized (discretely) along the Z axis, and charge carriers move freely.

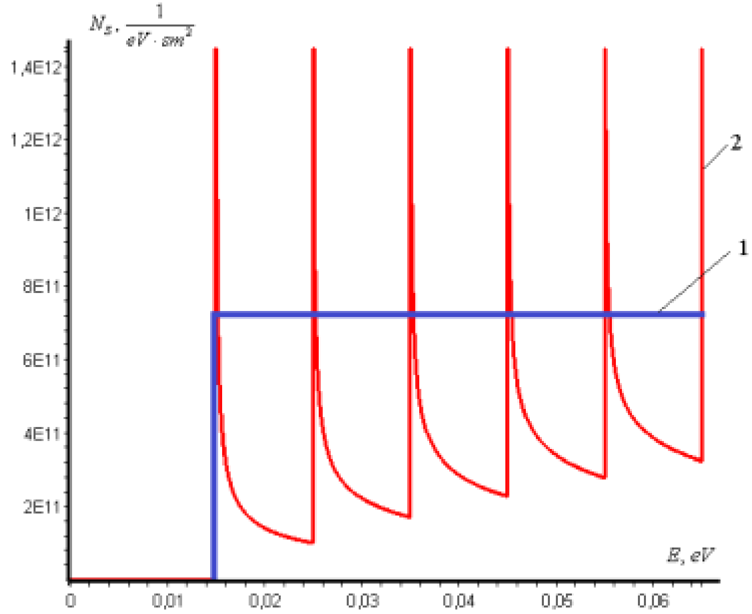

Fig.1. Dependence of the density of energy states on the energy of charge carriers in two-dimensional electron gases in the presence and in the absence of a longitudinal quantizing magnetic field.

1. B = 0, calculated by the formula (15) [13];
2. B = 10 T, calculated by the formula (14).

You can choose the vector potential of the magnetic induction in the form $A=(0,Bx,0)$. Hence, by solving equation (1), instead of formulas (3), we can obtain the following function:

$$\psi_{Ky\,Nm}(r)=f_N(x-x_0)\varphi_m(z) \tag{16}$$

Here, $\varphi_m(z)=\begin{cases}\sqrt{\frac{2}{a}}\cos\left(m\frac{\pi}{a}z\right), & m=2n+1\\ \sqrt{\frac{2}{a}}\sin\left(m\frac{\pi}{a}z\right), & m=2n\end{cases}$ is the envelope function of the dimensional quantization levels of the quantum well [7]. $f_N(x-x_0)$- solution of the

Schrödinger equation with zero boundary conditions for a quantum harmonic oscillator. In the same solution, the equation takes the following form:

$$\left\{-\frac{\hbar^2}{2m^*}\frac{d^2}{dx^2}+\frac{1}{2}m^*\omega_c^2(x-x_0)^2\right\}f_N(x-x_0)=E_N f_N(x-x_0) \quad (17)$$

Here, $x_0=-\frac{\hbar k_y}{eB}$. The eigenvalues of the energies E_N are called discrete Landau levels, corresponding to the functions from (16). In a rectangular deep quantum well, the discrete energy spectrum of dimensional quantization is:

$$E_m=\frac{\pi^2\hbar^2}{2md^2}m^2, \quad m=1,2,... \quad (18)$$

Hence, taking into account formulas (18) and (5), the energy eigenvalue E_{Nm} is determined by the following formula:

$$E_{Nm}=\hbar\omega_c\left(N+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m^*d^2}m^2 \quad (19)$$

As can be seen from the formula, the motion of free charge carriers in all three directions is limited, and in a transverse quantizing magnetic field the quantum well becomes an analogue of a quantum dot. In addition, the energy spectrum of free electrons will be completely discrete, each level in it is characterized by two quantum numbers: N_L ($N=N_L$ - is the number of Landau levels) и N_Z ($m=N_Z$ is the number of quanta in the Z axis). Then, with a transverse quantizing magnetic field in two-dimensional electron gases, the oscillation of the density of states, normalized to a unit area, has the form of a sum of delta functions:

$$N_{S,Z}^{2d}(E,B)=\frac{eB}{\pi\hbar}\sum_{N_L,N_Z}^{\infty}\delta\left(E-E\left(N_L,N_Z\right)\right) \quad (20)$$

Thus, in the presence of a longitudinal quantizing magnetic field corresponding to formula (14), it is possible to calculate the oscillations of the density of states for two-dimensional semiconductor materials. And in the presence of a transverse quantizing magnetic field, formula (20) can be used to determine the density of states. However, both formulas do not take into account thermal blurring in discrete Landau levels.

Influence of temperature on oscillations of the density of states in two-dimensional semiconductor materials in the presence of a transverse and longitudinal quantizing magnetic field.

Let us now consider the temperature dependence of the oscillations of the density of states in low-dimensional solids under the action of a transverse quantizing magnetic field. As is known, the effect of temperature on the Landau levels can be described by expanding the oscillations of the density of energy states in a series of delta-shaped functions [16-19]. By studying the oscillations of the density of energy states by means of a series expansion in delta-shaped functions, it was possible to explain the temperature dependence of discrete Landau levels in two-dimensional semiconductor materials. The temperature dependence of the oscillations of the density of states is determined by the thermal smearing of discrete Landau levels in a quantizing magnetic field. At absolute zero temperature, the Gaussian distribution function is delta-shaped and is determined by the following expression [20]:

$$Gauss(E,T)=\frac{1}{kT}\cdot\exp\left(-\frac{(E-E_i)^2}{(kT)^2}\right) \tag{21}$$

Then, thermal smearing can be described by the temperature dependence of the Gaussian distribution function. For an deep rectangular quantum well, the time of thermal ejection of charge carriers from deep levels E_i into the conduction band and into the valence band with energy E is determined by an exponential factor $\exp\left(-\frac{(E-E_i)^2}{(kT)^2}\right)$. Hence, deep filled discrete Landau levels exponentially depend on oscillations of the density of energy states and on the temperature of the sample. To determine the temperature dependence of the oscillations of the energy density of states, we will assume that the energy density of states at T=0 is equal to the known energy function $E_i(N_L,N_Z)$. For a two-dimensional semiconductor material, in a transverse quantizing magnetic field, the oscillations of the density of states are determined by formula (20). With increasing temperature, each state is blurred with energy $E(N_L,N_Z)$. Thermal smearing of discrete Landau levels with energy $E(N_L,N_Z)$ is determined by the Shockley-Reed-Hall statistics [21]. Thus, in the conduction and valence bands, the resulting density oscillations, taking into account the contribution of thermal smearing of all states, will be determined by the sum of all smears. Hence, at a finite temperature T, this reduces to a series expansion of the oscillations of the energy density of states in terms of Gaussian functions $N_{S,Z}^{2d}(E,B,T,d)$ for two-dimensional semiconductor materials.

In formula (20), thermal smears of discrete Landau levels are not taken into account. If we expand $N_{S,Z}^{2d}(E,B,T,d)$ in a series in terms of Gaussian functions, then we can take into account the temperature dependence of the oscillations of the density of energy states in two-dimensional electron gases. In this way, the temperature dependence of the oscillations of the density of states in a transverse quantizing magnetic field can be obtained. Thermal smearing of Landau levels in a transverse quantizing magnetic field leads to smoothing of discrete levels, and thermal smearing is determined using the Gaussian function. At low temperatures, the Gaussian distribution functions turn into a delta-shaped function of the form:

$$\underset{T\to 0}{Gauss(E,E_i,T)}\to\delta(E-E_i) \tag{22}$$

Thus, using formulas (19), (20), (21) and (22), we obtain the following analytical expressions:

$$N_{S,Z}^{2d}(E,B,T,d)=\sum_{N_L,N_Z}^{\infty}\frac{eB}{\pi\hbar}\cdot\frac{1}{kT}\cdot\exp\left(-\frac{\left(E-\left(\hbar\omega_c\left(N_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m^*d^2}N_Z^2\right)\right)^2}{(kT)^2}\right) \tag{23}$$

Here, $N_{S,Z}^{2d}(E,B,T,d)$ - oscillations of the density of energy states for an infinitely deep rectangular quantum well; d is the thickness of the quantum well; N_L is the number of Landau levels for a rectangular quantum well; N_Z is the number of quanta along the Z axis; B is the induction of the transverse quantizing magnetic field.

This formula is the temperature dependence of the oscillation of the density of energy states, in two-dimensional semiconductor materials, when exposed to a transverse quantizing magnetic field. The obtained expression is convenient for processing experimental data on oscillations of the density of energy states in two-dimensional electron gases at different temperatures and in transverse magnetic fields. Thus, a mathematical model has been obtained that describes the temperature dependence of the oscillation of the density of states in nanoscale semiconductor structures.

Now, for specific nanoscale semiconductor materials, we analyze the temperature dependence of the oscillations of the density of states in a transverse quantizing magnetic field. In work[22], the energy spectra of cyclotron resonance of free electrons in asymmetric heterostructures with quantum wells *HgCdTe/CdHgTe*, in the presence of a quantizing magnetic field, are determined. Here, the thickness of the quantum well is $Cd_xHg_{1-x}Te$ d=15 nm, the magnetic field is B=15 T and the temperature is T=4.2 K. In these works, the temperature dependences of the density of states for these materials were not discussed. Figure 2 shows the oscillations of the energy density of states for the quantum well $Cd_xHg_{1-x}Te$ d=15 nm [22] at T=4.2 K and with a transverse quantizing magnetic field B=15 T. $N_{S,Z}^{2d}(E,B,T,d)$ calculated there using formula (23). In Fig.2, the number of discrete energy levels is ten. These discrete energy peaks are called Landau levels (N_L=10) and these levels are observed in the conduction band. It shows oscillations of the density of energy states in a quantizing magnetic field $\hbar\omega_c = 0,02\ eV$ at T=4.2 K, kT=4.10^{-4} eV, $\frac{\hbar\omega_c}{kT} = 50$, $kT << \hbar\omega_c$. In this case, the thermal smearing of the Landau levels is very weak and the oscillations of the density of energy states do not feel deviation from the ideal shape. The first discrete Landau level (N_L=0) appeared at the bottom of the conduction band of the quantum well. The second (N_L=1), third (N_L=2), and other discrete Landau levels are located above the bottom of the conduction band of the quantum well. In this way, it is possible to calculate the peaks of the Landau levels in the valence band of the quantum well at low temperatures.

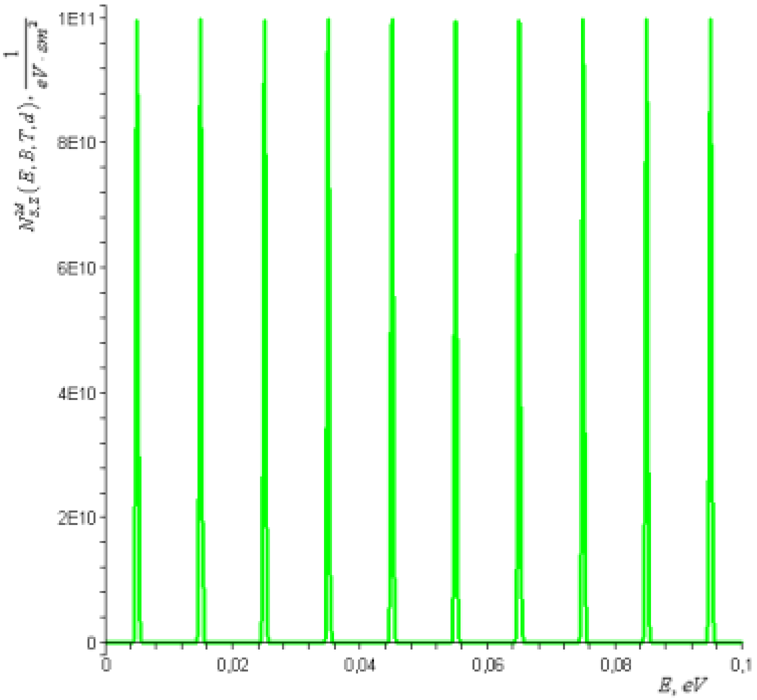

Fig.2. Oscillations of the density of energy states in the quantum well *HgCdTe/CdHgTe* [22] (quantum well $Cd_xHg_{1-x}Te$ d=15 nm) at B=15 T and T=4.2K, calculated by formula (23).

Fig.3 shows $N_{S,Z}^{2d}(E,B,T,d)$ for temperatures of 4.2 K, 20 K, 40 K, 60 K, 80 K, and 100 K. It can be seen from Fig.3 that, with increasing temperature, the sharp peaks of the Landau levels begin to smooth out, and at sufficiently high temperatures the discrete energy densities of states turn into continuous energy spectra. These results were obtained for a constant thickness of the quantum well and a magnetic field.

Let us consider the dependence of the thickness of the quantum well on the oscillations of the density of states in a transverse quantizing magnetic field. In work[21], the dependence of the thickness of the quantum well on $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ the energy spectrum of a two-dimensional electron gas in the absence of a magnetic field was determined. A decrease in the thickness of the quantum well leads to a spatial limitation of the movement of charge carriers in the transverse direction and to an increase in their energy. Fig.4 shows the dependence of the energy of charge carriers of interband recombination on the thickness of the quantum well $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$. The calculated significant shifts of the interband recombination energies from the QW thickness are explained by a change in the size quantization energy of charge carriers.

A change in the energy spectrum of electrons or holes in the allowed band of the quantum well lead to changes in the density of states. But, in the above-described work, the influence of the thickness of the quantum well on the oscillations of the density of energy states, with a transverse strong magnetic field, was not considered. Using formula (23), it is possible to calculate the dependence of the thickness of the quantum well on the oscillations of the density of energy states, with a parabolic dispersion law. In particular, Fig.5 shows the change in the oscillations of the density of states for the thickness of the quantum well d=5 nm, 10 nm, 15 nm, 20 nm, at T=2K and B=10 T. As can be seen from this figure, as the thickness of the quantum well increases, the discrete Landau levels move to the left (changes along the *X* axis), but the peaks of the Landau levels do not change.

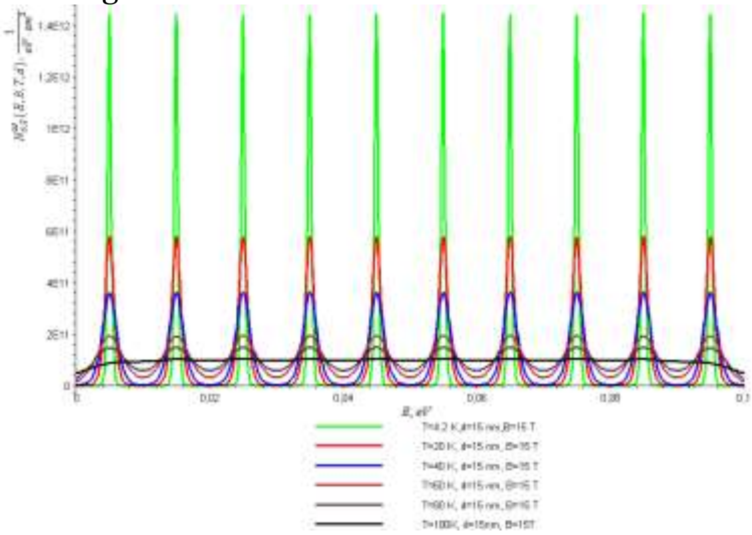

Fig.3. Influence of temperature on the oscillations of the energy density of states in the quantum well *HgCdTe/CdHgTe* [23] (quantum well $Cd_xHg_{1-x}Te$ d=15 nm) at B=15 T and d=15 nm, calculated by the formula (23).

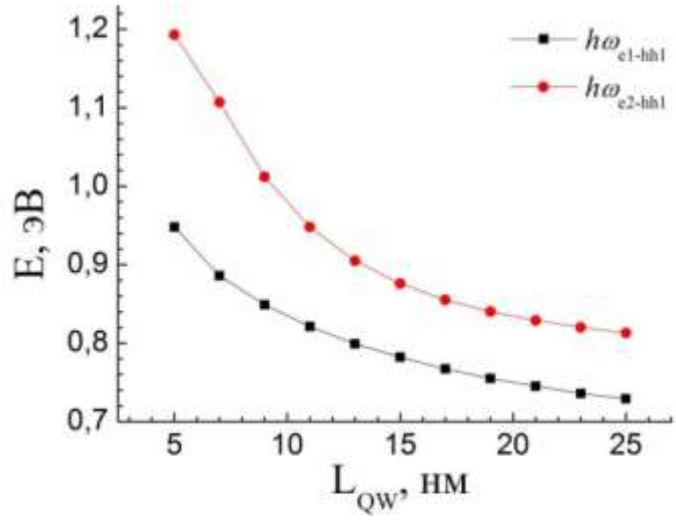

Fig.4. Dependence of the energy of charge carriers of interband recombination on the thickness of the quantum well $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ [23].

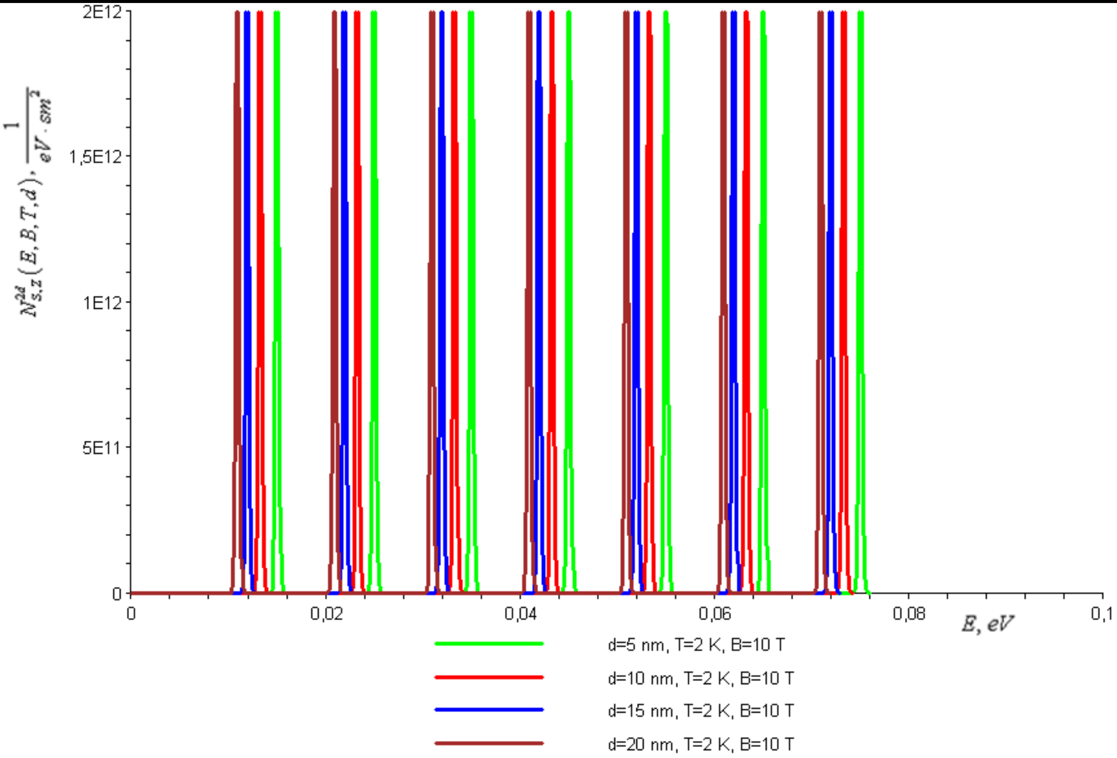

Fig.5. Influence of the thickness of the quantum well on $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ the oscillations of the density of states in a transverse quantizing magnetic field.

So, we conclude: the thickness of the quantum well strongly affects the energy spectrum of charge carriers, but the number of densities of states will be constant for different thicknesses of the quantum well in a quantizing magnetic field.

Processing of experimental results, two-dimensional semiconductor materials under the influence of a transverse quantizing magnetic field.

As is known, the properties of a nanoscale semiconductor structure under the action of a transverse quantizing magnetic field have been actively studied since the discovery of the quantum Hall effect. The nature of the oscillations of the density of energy states of a two-dimensional electron gas is a vital problem for understanding many quantum phenomena observed in the system, for example, the Shubnikov-de Haas and de Haas-van Alphen oscillations, cyclotron resonance, magnetic capacity, and heat capacity.

To date, the temperature dependence of the oscillations of the density of energy states in two-dimensional semiconductor materials has been little studied. This conclusion applies not only to the calculated density of states, but also to the measured oscillations of the density of states in the presence of a strong transverse magnetic field. Indeed, some experimenters reported the dependence of the oscillations of the density of states on the transverse quantizing magnetic field for a rectangular quantum well at constant low temperatures [1-29]. For example, in work[22], the dependence of the oscillation of the density of states on a strong quantizing magnetic field for a quantum well $GaAs/Al_xGa_{1-x}As/GaAs$ is determined. Oscillations of the density of states in a quantum well *GaAs/Al$_x$Ga$_{1-x}$As/GaAs* at constant low temperatures were obtained there.

Fig.6 compares theoretical calculations with experimental data at a temperature of T=1.5 K [22], the thickness of the quantum well d=5 nm, and the number of Landau levels N_L=10 (line 1 in Fig.6). Within the experimental accuracy, the density of states oscillates strongly with increasing magnetic field. In the experiment, thermal smearing is very weak, therefore T=1.5 K, kT=1,3.10^{-4} eV, $\frac{\hbar\omega_c}{kT}=165$, $kT << \hbar\omega_c$. In this case, oscillations of the density of states are observed in the conduction band of the quantum well *GaAs/Al$_x$Ga$_{1-x}$As/GaAs*. To process the experimental data on the oscillations of the density of states, we use formula (23). The theoretical results are shown in Fig.6 (line 2) for the given materials and at a temperature of T=1.5 K. It can be seen from Fig.6 that in the experiment the width of the oscillations of the density of states is greater, and the height is less than the height of the theoretical results. As can be seen from these figures, at a temperature of T=1.5 K, all discrete Landau levels are clearly distinguished on the graph. As can be seen from Fig.6, the theoretical results and experimental data are in good agreement in the magnetic field range from 1 T to 3 T. Let us consider the effect of temperature on oscillations of the density of states in the conduction band of quantum well *GaAs/Al$_x$Ga$_{1-x}$As/GaAs* at a magnetic field interval B=1÷3 T. Fig.7 shows the oscillations of the energy density of states for four different temperatures. With increasing temperature, it expands so that at T=45 K, the discrete Landau levels begin to smear. A further increase in temperature increases smearing, and at T=100 K gives a continuous spectrum in a quantum well *GaAs/Al$_x$Ga$_{1-x}$As/GaAs*. At this temperature, the densities of states do not sense a strong magnetic field and discrete Landau levels are washed out. Thus, the energy spectrum in the conduction band of a quantum well is strongly temperature dependent.

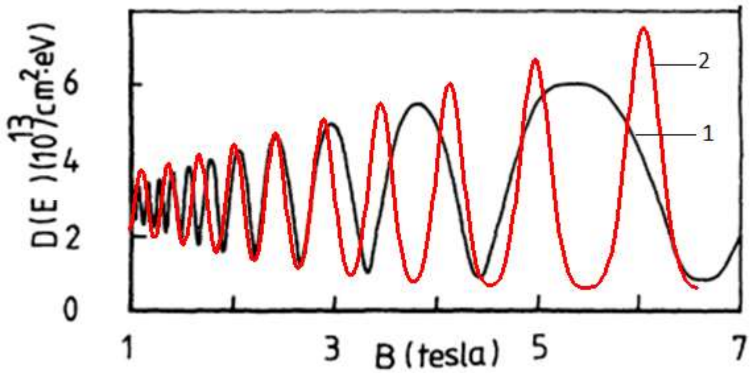

Fig.6. Dependence of oscillations of the density of energy states on the induction of the transverse quantizing magnetic field in a quantum well *GaAs/Al$_x$Ga$_{1-x}$As/GaAs* at a temperature of T=1.5 K.

1 - experiment [22]

2 - our results, calculated using the formula (23)

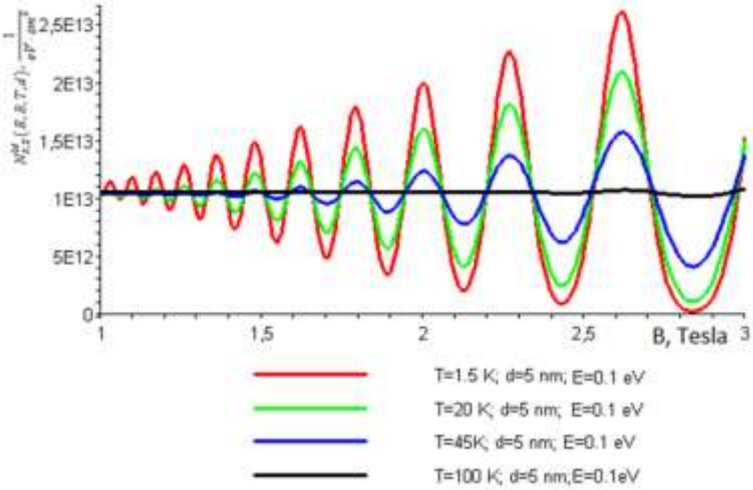

Fig.7. Influence of temperature on oscillations of the density of energy states in quantum well $GaAs/Al_xGa_{1-x}As/GaAs$.

Let us now consider the dependence of the oscillations of the density of states on the energy of the conduction band of the quantum well, at constant magnetic fields and at different temperatures[1-29]. In work[1] investigated the dependences of the oscillations of the density of states on the electron energy in two-dimensional semiconductor materials (*d*=7.5 nm) at *T*=1.5 K and at *B*=7 T. Fig.8 (line 1) shows the oscillation of the density of energy states from works [1,24], Fig.8 (line 2) shows the theoretical fitting oscillation of the density of energy states $N_{S,Z}^{2d}(E,B,T,d)$ obtained by expanding the experimental graph (line 1) in a series of $N_{S,Z}^{2d}(E,B,T,d)$ functions. These graphs were obtained at a constant low temperature. Oscillations of the density of states in two-dimensional semiconductor materials at different temperatures are calculated using numerical experiments. Fig.9 shows the temperature dependence of the oscillations of the density of states for a quantum well, at a magnetic field *B*=7 T. As can be seen from these figures, at sufficiently high temperatures, peaks of discrete Landau levels are not observed and oscillations of the density of energy states turn into a continuous energy spectrum of charge carriers with a parabolic dispersion law.

With increasing temperature, the sharp peaks of quantized discrete levels begin to smooth out, the height of each peak of the levels decreases, and at high temperatures, thermal smearing strongly affects the oscillations of the density of states. As can be seen from Figure 8, the experimental data and theoretical results are in good agreement in the energy range from 0 to 5 *meV* in the quantum well $GaAs/Al_xGa_{1-x}As/GaAs$ at *B*=7 T and *T*=1.5 K. Hence, using the proposed model, one can explain some experimental results for two-dimensional semiconductor materials, at different temperatures and different quantizing magnetic fields.

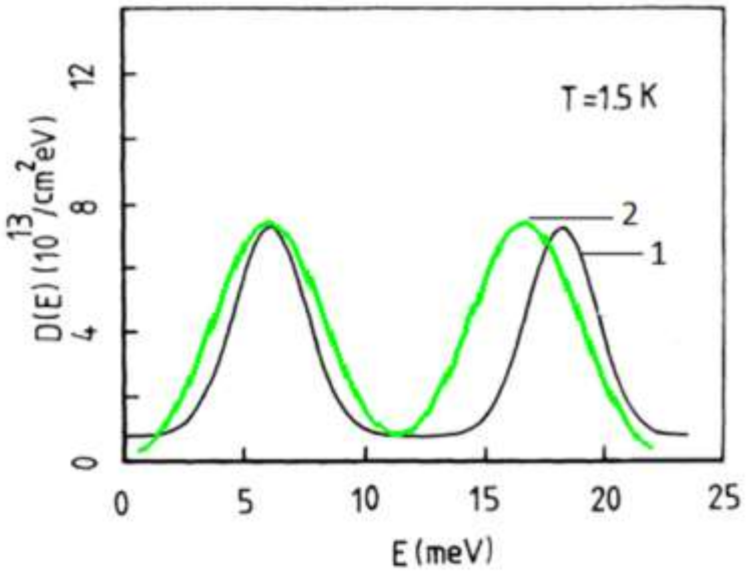

Fig.8. Dependence of oscillations of the energy density of states on the energy of band conduction in quantum well *GaAs/Al$_x$Ga$_{1-x}$As/GaAs* at *B*=7 T and *T*=1.5 K.

1 - experiments [1]

2 - theory, calculated using formula (23).

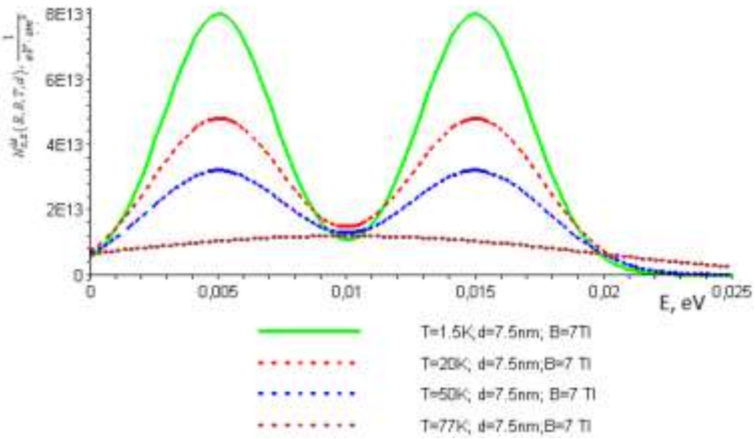

Fig.9. Oscillations of the density of energy states in quantum well *GaAs/Al$_x$Ga$_{1-x}$As/GaAs* at different temperatures.

Conclusion

Based on the study, the following conclusions can be drawn:

1. Analytical expressions are derived for oscillations of the density of states in two-dimensional electron gases in the presence of longitudinal and transverse quantizing magnetic fields with a parabolic dispersion law.
2. A new mathematical model has been developed to determine the temperature dependence of the oscillations of the density of energy states in two-dimensional semiconductor materials when exposed to a transverse quantizing magnetic field.
3. It is shown that with increasing temperature, discrete Landau levels are smoothed out due to thermal smearing and no oscillations of the density of energy states are observed in two-dimensional electron gases.

4. Using the proposed model, the graphs of the influence of the thickness of the quantum well on the oscillations of the density of states in the presence of a quantizing magnetic field were created.
5. Using a mathematical model, the experimental data in the quantum well $GaAs/Al_xGa_{1-x}As/GaAs$ are explained at different magnetic fields and temperatures.
6. The proposed mathematical model makes it possible to calculate the high-temperature density of states for a quantum well $GaAs/Al_xGa_{1-x}As/GaAs$.
7. It is shown that discrete Landau levels in the quantum well $GaAs/Al_xGa_{1-x}As/GaAs$, measured at a temperature of T=1.5 K, transform into a continuous spectrum of the density of energy states at high temperatures (T=100 K).

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