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Influence of a quantizing magnetic field on the Fermi energy oscillations in two-dimensional semiconductors

Ulugbek I. Erkaboev*, Ulugbek M. Negmatov, Rustamjon G. Rakhimov, Jasurbek I. Mirzaev, Nozimjon A. Sayidov

Namangan Institute of Engineering and Technology, Kasansay street 7, 160115 Namangan, Uzbekistan

ABSTRACT

In this article we investigated the effects of quantizing magnetic field and temperature on Fermi energy oscillations in nanoscale semiconductor materials. It is shown that the Fermi energy of a nanoscale semiconductor material in a quantized magnetic field is quantized. The distribution of the Fermi-Dirac function is calculated in low-dimensional semiconductors at weak magnetic fields and high temperatures. The proposed theory explains the experimental results in two-dimensional semiconductor structures with a parabolic dispersion law.

Keywords: Semiconductor, Fermi energy, Quantizing magnetic field, Dispersion law, Two-dimensional semiconductor structure, 2D electron gas.

1. INTRODUCTION

At present, the interest in studying the properties of two-dimensional electronic systems is due to the prospects for their application in nanoscale semiconductor structures. In such systems, the quantum dimensional quantities of the dependence of the characteristics have, as a rule, an oscillating character (Korotun, 2015; Kurbatsky et al., 2004; Dmitriev et al., 2012; Dmitriev et al., 2007; Korotun, 2014; Korotun et al., 2015; Dymnikov, 2011; Gulyamov et al., 2019, Gulyamov et al., 2020). In two-dimensional semiconductors, macroscopic energy characteristics such as the density of states, effective masses of electrons, and the Fermi energy depend on the thickness of the quantum well. It is assumed that the size of the thickness of the material d will be commensurately equal to the de Broglie wavelength of the electron in low-dimensional semiconductors.

As is known, the energy spectrum of electrons has highly variable properties depending on the relative position of the Fermi level with respect to the Landau levels in two-dimensional semiconductors in the presence of a quantizing magnetic field. All electron gases have a single Fermi level μ, which at absolute zero temperature determines the level of filling the energy bands with electrons. As is known from the experimental and theoretical data (Kuz'min et al., 2009; Yaji et al., Babich et al., 2013; Gulyamov et al., 2020; Gulyamov et al., 2014; Erkaboev et al., 2020), in two-dimensional semiconductors, the Fermi surface at absolute temperature is characterized by rather high amplitudes of the Fermi energy (μ) oscillations. However, for a three-dimensional electron gas, μ oscillations will be very weak, even at low temperatures. In three-dimensional semiconductors, μ changes only linearly, as in classical magnetic fields.

When studying the electronic and magnetic properties of two-dimensional electronic systems, an important characteristic is the Fermi energy, which determines the main contribution to micro-and nanoscale semiconductors. Therefore, the aim of this work

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Corresponding Author:
Ulugbek I. Erkaboev
erkaboev1983@mail.ru

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is to research the effect of quantizing the magnetic field on the dimensional oscillations of the Fermi energy in two-dimensional semiconductor structures and to discuss the results of processing experimental data under the influence of an external action.

2. THEORETICAL PART

2.1 Effect of A Quantizing Magnetic Field on The Fermi Energy Oscillations in Two-Dimensional Semiconductors

In k-space isoenergic surfaces *E(k)=const* are closed and are represented in the form of a sphere. The allowed energy states have a constant density V/8π^3 and are distributed in *k*-space. Here, V is the volume of the crystal. Since two opposite orientations of the spin of the electron state are responsible for each value of *k*, then the wave numbers of all states that will be filled have values no more than k_F in the volume of the crystal V, according to the Pauli principle and k_F is determined (Gulyamov et al., 2021):

$$\frac{4}{3}\pi k_F^3 \frac{2V}{8\pi^3} = N^{3d} \quad (1)$$

From here

$$k_F = \left(\frac{3\pi^2 N^{3d}}{V}\right)^{\frac{1}{3}} \quad (2)$$

Here, N^{3d} is the electron concentration for a three-dimensional electron gas.

If the system of electrons is due to the Fermi-Dirac statistics, then the energy in the ground state, i.e., at absolute temperature, is called maximum:

$$E_F = \frac{\hbar^2 k_F^2}{2m} \quad (3)$$

E_F - called Fermi energy for 3D electron gas. The Fermi surface will have a spherical shape with a radius of k_F for the isotopic dispersion law. The expressions given above were obtained only for bulk materials and do not consider changes in the oscillations of the Fermi energy in two-dimensional electron gases.

Now, consider the dependence of the Fermi energy on the quantizing magnetic field in two-dimensional electron gases. In the absence of a magnetic field in two-dimensional electron gases, the electron energy is quantized along the Z-axis, so the electron moves freely only in the XY plane. These quantizations are called dimensional quantization. However, if the magnetic induction *H* is directed perpendicular to the XY plane, then the free energy of the electron is also quantized along the XY plane.

The question arises: how will the Fermi energy change in two-dimensional electron gases in the presence of a quantizing magnetic field.

For a 2D electron gas, the allowed energy states have a constant density S/4π^2 and are distributed in the XY plane. Here, S is the surface area of the crystal. Then, using Equations (1) and (2), we determine the electron concentration for a two-dimensional electron gas:

$$N^{2d} = 4\pi k_F^2 \frac{2L^2}{4\pi^2} \quad (4)$$

From here:

$$k_F^{2d} = \frac{1}{L}\left(\frac{\pi N^{2d}}{2}\right)^{\frac{1}{2}} \quad (5)$$

Now, we calculate the Fermi energy for a two-dimensional electron gas with parabolic law. Substituting (5) to (6), one can determine the Fermi energy in two-dimensional electron gases in the absence of a magnetic field (D. Shoenberg, 1984):

$$\mu^{2d} = \frac{p_\mu^2}{2m} = \frac{\pi\hbar^2 N^{2d}}{4mL^2} \quad (6)$$

Here, N^{2d} is the concentration of electrons in a two-dimensional electron gas, L^2 is the surface of the plane of motion, p_μ is the Fermi momentum.

In the motion of a plane perpendicular to the magnetic field, the classical trajectories of electrons are circles. In quantum physics, such trajectories of electrons (periodic rotation of an electron) are equidistant discrete Landau levels (D. Shoenberg, 1984):

$$E_n = \hbar\omega_c\left(n_L + \frac{1}{2}\right) \quad (7)$$

Where n_L is the number of Landau levels. $\omega_c = \frac{eH}{mc}$ - cyclotron frequency.

In three-dimensional semiconductors, a continuous quadratic energy spectrum of the $\frac{p_z^2}{2m}$ is added to the energy spectrum of Equation (7). However, in two-dimensional semiconductors, the movement of electrons along the Z-axis is quantized.

Indeed, the thickness of the quantum well *d* is covered by the dimensional quantization condition, in other words, the thickness is relatively close to the de Broglie wavelength of the electron in the crystal. The movement of an electron along the *Z* axis is calculated from the potential V_z:

$$V(z) = \begin{cases} 0, 0 < z < d, \\ \infty, z \leq 0, z \geq d \end{cases} \quad (8)$$

In the absence of a magnetic field in two-dimensional electron gases, the normalized wave functions of particles have the following form (Dymnikov et al., 2011):

$$\psi_{kfx,kfy,nfz}(x,y,z) = \frac{1}{\sqrt{L_{f1}}} exp(ik_{fx}x)\frac{1}{\sqrt{L_{f2}}} exp(ik_{fy}y)\phi_{nz}(z) \quad (9)$$

Where k_{fx}, k_{fy} are the wave numbers for the Fermi energy of electrons, n_{fz} is the number of dimensional quantizers along the *Z* axis.
In Equation (9), the normalized functions in accordance with (8) are written in the following form:

$$\phi_{nz}(z) = \sqrt{\frac{2}{d}} sin \frac{\pi nz}{d}, n = 1,2,3... \quad (10)$$

The Fermi energy of electrons corresponding to state (9) will be

$$E(k_{fx}, k_{fy}, n_{fz}) = \frac{\hbar^2}{2m}(k_{fx}^2 + k_{fy}^2) + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} \quad (11)$$

Substituting expressions (7), (11) into (6), we obtain the following Equation in the presence of a magnetic field:

$$\mu_F(H) = \frac{\pi\hbar^2 N^{2d}(H)}{4mL^2} + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} \quad (12)$$

For an area equal to one (L_xL_y=1) of Equation (12), the following is calculated:

$$\mu_F(H) = \frac{\pi\hbar^2 N^{2d}(H)}{4m} + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} = \frac{1}{8}\hbar\frac{eH}{mc}\cdot\frac{2\pi\hbar N^{2d}(H)c}{eH} + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} = \frac{1}{8}\hbar\omega_c\nu + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} \quad (13)$$

Here $\nu = \frac{2\pi\hbar c N^{2d}(H)}{eH}$ is the filling factor (Erkaboev et al., 2021). This is the number of Landau levels, taking into account their spin splitting, in a quantizing magnetic field, at absolute zero temperature, filled with electrons. This dimensionless parameter is used to facilitate the discussion of quantum oscillatory effects in 2D electron gases.

As can be seen from Equation (13), the Fermi energies are quantized if the filling factor is an integer, then the minimum energy quantum will be $\frac{1}{8}\hbar\omega_c$, that is, Equation (13) gives the exact value of the energy for the first level corresponding to the $\nu = 1$.

$$\mu_1(H) = \frac{1}{8}\hbar\omega_c + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} \quad (14)$$

For all other levels, the rigorous theory gives the expression

$$\mu(H) = \hbar\omega_c\left(\nu + \frac{1}{8}\right) + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} \quad (15)$$

Here, the filling factor is an integer $\nu = 0,1,2,3...$

In addition, in two-dimensional semiconductors, in the presence of a quantizing magnetic field, the energy spectrum of electrons is purely discrete. A purely discrete energy spectrum, in this case the Fermi energy, is usually characteristic of a quantum dot. In this case, the magnetic induction vector will be directed along the *Z* axis and perpendicularly along the plane of the transverse two-dimensional layer. In a transverse quantizing magnetic field, quantum wells become analogous to a quantum dot, in which the motion is limited in all three directions.

2.2 Dependence of Fermi Energy Oscillations on The Thickness of The Quantum Well and on Temperature in A Quantizing the Magnetic Field.

It can be seen from the obtained Equations (15) that the Fermi energies depend strongly on the magnetic field, on the concentration of electrons, and on the thickness of the quantum well. In quantizing the magnetic field, the electron concentration in the considered two-dimensional semiconductors is determined as follows (Zawadzki et al., 2014):

$$n^{2d} = \int_0^\infty \sum_{n_L} N_S^{2d}(E, H, n_L) f_0(E, E_F(H=0), T) dE \quad (16)$$

Here $N_S^{2d}(E, H, n_L)$ is the density of states of two-dimensional electronic systems under the influence of a quantizing magnetic field; $f_0(E, E_F(H=0), T)$ is the Fermi-Dirac distribution function in the absence of a magnetic field.

In two-dimensional electronic systems, the energy density of states is taken as the sum of Gaussian peaks in the presence of a magnetic field, disregarding spin splitting (Zawadzki et al., 2014):

$$N_S^{2d}(E, H, n_L) = \frac{eH}{2\pi c}\sum_{n_L}\sqrt{\frac{2}{\pi}}\frac{1}{G} exp\left[-2\left(\frac{E-\hbar\omega_c\left(n_L+\frac{1}{2}\right)}{G}\right)^2\right] \quad (17)$$

G is the parameter of broadening, taken constant. Here we consider two-dimensional electronic systems of noninteracting electrons according to the parabolic dispersion law at a finite temperature *T*, in the presence of a quantizing magnetic field *H* parallel to the growth direction.

And, two features should be highlighted here. First, in addition to the Gaussian peak in the density of states, at each Landau level, there is a common magnetic field factor *H* in front of the total energy density of states. This means that as the magnetic field *H* increases, each Landau level can contain increasing electrons. Secondly, according to the form taken in the Equation. According to (17), there is no density of states between the Landau levels if their distance $\hbar\omega_c$ is noticeably greater than *G*.

Using expressions (15), (16), and (17), one can determine the dependence of the Fermi energy oscillations on the magnetic field, temperature, and thickness of the quantum well in two-dimensional semiconductors with a parabolic dispersion law without taking into account the spin per unit surface of the plane of motion:

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$$\mu_F(H,T,d) = \frac{2\pi\hbar^2}{m}\int_0^{\infty}\sum_{n_L} N_s^{2d}(E,H,n_L) f_0(E,E_F(H=0),T)dE + \frac{\pi^2\hbar^2 n_{fz}^2}{2md^2} \quad (18)$$

Thus, using Equation (18), one can calculate the dependence of the oscillation of the Fermi energy on the magnetic field, temperature, and thickness of the quantum well with a quadratic dispersion law. As seen from Equation (18), the oscillations of the density of energy states strongly affect the Fermi energies for two-dimensional electronic systems.

Let us analyze the Fermi energy oscillations for two-dimensional semiconductors. In Fig.1 shows the dependence of the Fermi energy oscillations on the quantizing magnetic field for *InAs/GaSb/AlSb* quantum wells at a constant temperature and at a constant thickness of the quantum well. Here, the temperatures are T=4.2K, the thickness of the *InAs/GaSb/AlSb* quantum well is d=8 nm, the number of Landau levels is n_L=10, G=0.6 meV, E_F = 94 meV (Mikhailova et al., 2017). In this case, doped with Mn with a concentration of 5.1016 cm^{-3} on an n-InAs substrate and two quantum wells with dimensions of 12.5 nm (InAs) and 8 nm (GaSb) bounded by two AlSb barriers with a thickness of 30 nm (Mikhailova et al., 2017). As can be seen from Fig.1, as the magnetic field increases, the amplitude of the Fermi energy oscillations will increase.

The graph of $\mu_F(H,T,d)$ (Fig.1) is constructed using Equation (18).

In addition, using Equation (18), one can also obtain plots at different temperatures and at different thicknesses of quantum wells.

We now turn to the calculation of the dependence of the Fermi energy oscillations on the thickness of the *d* quantum well in quantizing the magnetic field with a parabolic dispersion law. We are interested in changes in the Fermi energy oscillations $\mu_F(H,T,d)$ at different *d* and at a constant temperature. It is seen that Equation (18), $\mu_F(H,T,d)$ is inversely proportional to d^2 with other constant values. Fig.2 shows the oscillations of the Fermi energy in a quantizing the magnetic field at different thicknesses of the *d* quantum well.

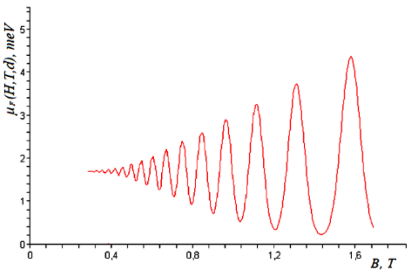

Fig.1. Dependence of the Fermi energy oscillations on the quantizing magnetic field for *InAs / GaSb / AlSb* quantum wells at T=4.2 K, d=8 nm. Calculated by Equation (18)

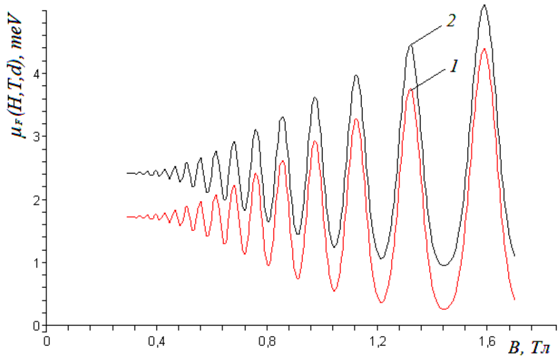

Fig.2. Influence of the thickness of the quantum well on the oscillations of the Fermi energy in a quantizing magnetic field. Here, T=4.2 K is calculated by Equation (18) for *InAs/GaSb/AlSb* quantum wells. 1) d = 8 nm, 2) d = 5 nm

As can be seen from Fig.2, a decrease in the thickness of the *d* quantum well leads to an upward movement of the Fermi oscillations. Modern scientific literature indicates that in the absence of a magnetic field, the amplitude of the Fermi energy oscillations strongly depends on the thickness of the *d* quantum well.

However, as can be seen from Fig.2, the increase in amplitude depends only on the value of the magnetic field, and the thickness of the *d* quantum well leads to its motion along the $\mu_F(H,T,d)$ axis.

2.3 Calculation of The Fermi-Dirac Function Distribution in Two-Dimensional Semiconductor Materials at High Temperatures and Weak Magnetic Fields.

Under the condition of the one-electron approximation, each electron moves independently of other particles, that is, the interaction between the electrons of a semiconductor is taken into account only by means of a self-consistent field. An ideal gas of electrons obeys the statistics of the Fermi-Dirac function in a state of statistical equilibrium. In a certain quantum state, the average number of free electrons is characterized by three quantum numbers at statistical equilibrium and has the following form:

$$f_0(E,T) = \frac{1}{1+exp\frac{E-\mu}{kT}} \quad (19)$$

In this case, at low temperatures, the $f_0(E,T)$ function takes on a stepped shape. In intrinsic semiconductors, at absolute temperature, the Fermi energy is equal to $-\frac{Eg}{2}$, that is, the Fermi level is located in the middle of the band gap.

The question arises: how is the Fermi level located in the forbidden gaps of intrinsic semiconductors when exposed to a quantizing magnetic field for two-dimensional electron gases? How will the distribution of the Fermi-Dirac function change in the presence of a magnetic field and temperature?

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Let us consider the change in the $f_0(E,T)$ function at low temperatures and in the presence of a magnetic field in two-dimensional materials. It can be seen from Equations (19) that the Fermi level is not dependent on the magnetic field. If substituting (16), (17), and (18) into Equation (19), then we can define the $f_0(E,T,H,d)$ functions:

$$f_0(E,T,H,d) = \frac{1}{1+exp\frac{E-\left(\frac{2\pi\hbar^2}{m}\int_0^\infty \frac{eH}{2\pi c}\sum n_L\sqrt{\frac{2}{\pi G}}\frac{1}{G}exp\left[-2\left(\frac{E-\hbar\omega_c\left(n_L+\frac{1}{2}\right)}{G}\right)^2\right]f_0(E,E_F(H=0),T)dE+\frac{\pi^2\hbar^2 n_{fz}^2}{2md^2}\right)}{kT}} \quad (20)$$

Thus, using Equation (20), one can estimate the dependence of the distribution of the Fermi-Dirac function on the magnetic field, on the thickness of the quantum well, and on the temperature in low-dimensional solid materials with a parabolic dispersion law. The obtained Equations (20) are a essential result for quantum oscillatory phenomena in heterostructures based on a quantum well. Therefore, when modulating the density of energy states at the Fermi level by a magnetic field, oscillations of the magnetoresistance, oscillations of the magnetic susceptibility and oscillations of quantum effects in two-dimensional electron gases under the action of a strong magnetic field and low temperatures are observed. In particular, in this work (Kochman et al., 2021) magnetophonon oscillations were observed in *InAs/GaSb* quantum well samples in a wide temperature range T=2.7÷270 K grown on a semi-insulating *InAs* substrate, without applying contacts. Here, a structure including *InAs* (12.5 nm) and *GaSb* (8 nm), i.e., a double quantum well, was grown on an *InAs* (100) substrate with an electron concentration n=5×10[16] cm[-3], with an *InAs* buffer nanolayer (30 nm) and limited by high barriers *AlSb* 30 nm thick. For *GaSb*, the band gap is 0.813 eV (Kunitsyna et al., 2018) at low temperatures. In this case, there are no impurity states, that is, the Fermi level passes through the center (0.4065 eV) of the *GaSb* band gap at H=0, and this is clearly seen from Fig.3a for *GaSb* (dashed line). In addition, Fig.3a shows the form of the Fermi-Dirac distribution function at d=8 nm, H=14 T, and T=2.7 K and at ν=1 (the number of electron filling factors) for an *InAs/GaSb* quantum well (solid line). These results were obtained using Equation (20). As can be seen from these figures, the hub-shaped distribution of the Fermi-Dirac function will not change in the absence and presence of a magnetic field and at low temperatures. The question arises: These functions, what will happen when the temperature rises and in the presence of a quantizing magnetic field? An increase in temperature leads to some "smearing" of the Fermi step boundary: instead of a jump-like change from 1 to 0, the distribution function makes a smooth transition (Fig.3b, Fig.3c, Fig.3d, dashed line). However, for an *InAs/GaSb* quantum well (d=8 nm) at strong magnetic fields (H=14 T) and at temperatures T=30 K, T=100 K, and T=300 K, the Fermi step almost does not change the shape, that is, everything level, up to the Fermi level, are occupied by electrons (Fig.3b, Fig.3c, Fig.3d, solid line). This means that for two-dimensional materials in a quantizing magnetic field and at high temperatures, all levels above the Fermi level are empty. In Fig.4a and Fig.4b show a three-dimensional image for an *InAs/GaSb* quantum well at H=0 and at H≠0. In these figures, the graphs of the dependence of the Fermi-Dirac distribution on temperature and energy are obtained for different magnetic fields.

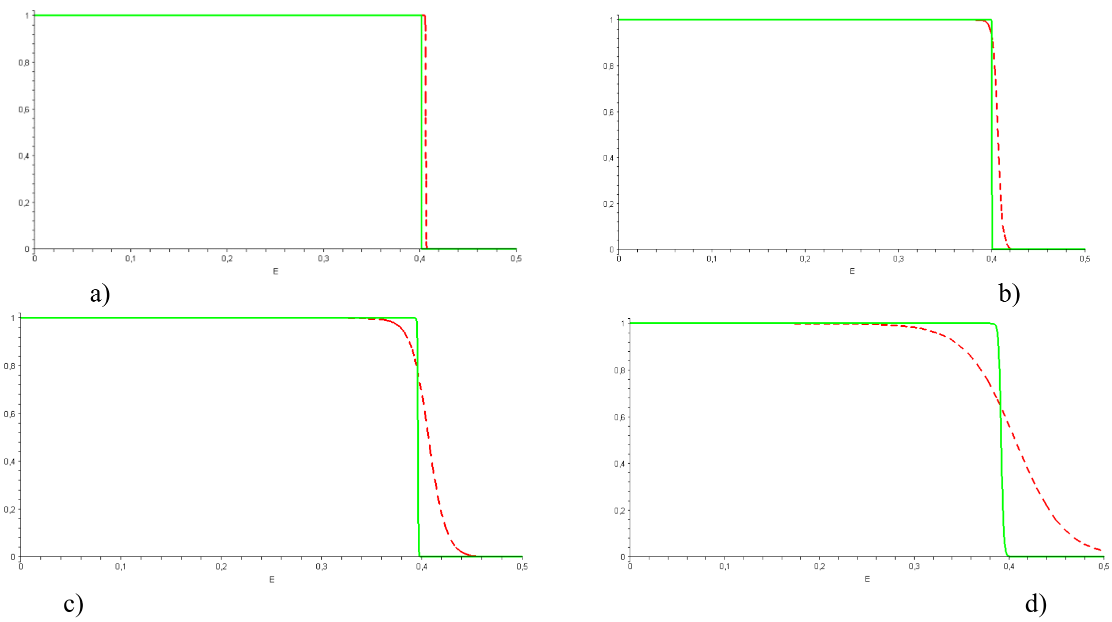

Fig.3. Distribution of the Fermi-Dirac function in nanoscale semiconductors at high temperatures and weak magnetic fields. Calculated by Equation (20). Solid green lines for $H \neq 0$, dashed red lines for $H = 0$. a) T=5 K. b) T=30 K. c) T=100 K. d) T=300 K

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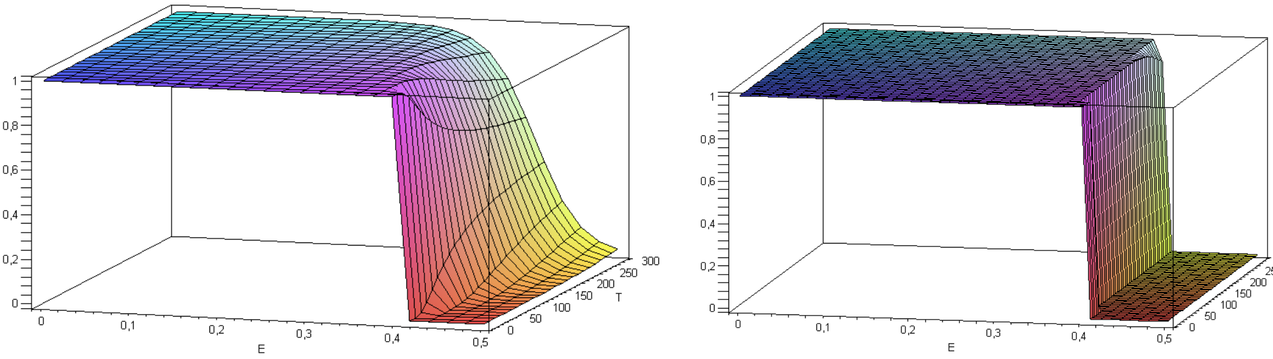


a) b)

Fig.4. Distribution of the Fermi-Dirac function for nanoscale semiconductors in three-dimensional space at a constant magnetic field (H=8 T). Calculated by Equation (20)

This process can be explained in two ways. Firstly, the exponent in the numerator is two exponential functions in Equation (20), that is, $exp\left[-2\left(\frac{E-\hbar\omega_c\left(n_L+\frac{1}{2}\right)}{\Gamma}\right)^2\right]$ and $f_0(E, E_F(H=0), T)dE$.

These functions lead to a hub-shaped Fermi-Dirac distribution at high temperatures. Another simple conclusion is that at high temperatures and with strong and weak magnetic fields, quantization (oscillations) of the Fermi energy can be observed in two-dimensional materials. These results give the possibility of some experimental data for oscillatory phenomena at high temperatures and weak magnetic fields.

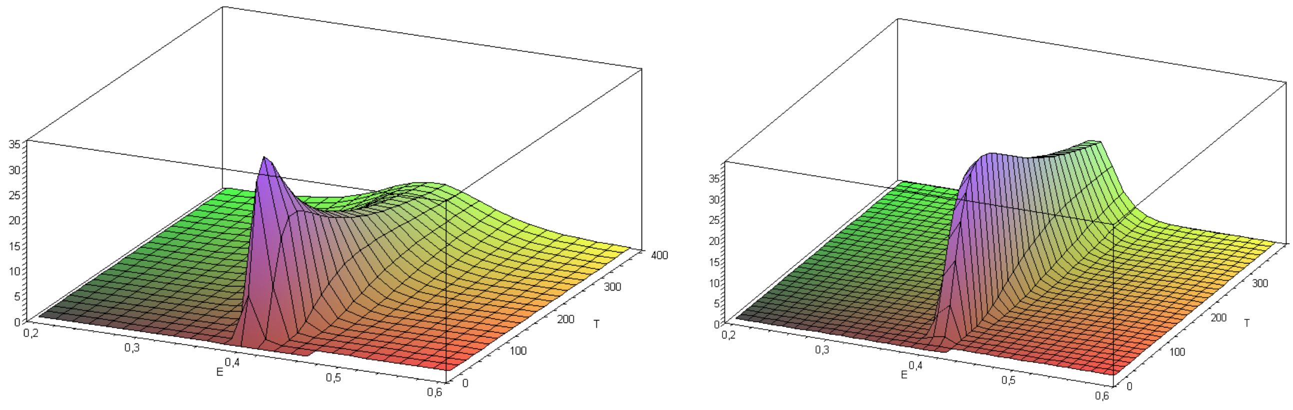
Now, to analyze Equations (19) and (20), consider its energy derivative:

$$\frac{\partial f_0(E,T)}{\partial E} = -\frac{1}{kT}\frac{exp\frac{E-\mu}{kT}}{\left[1+exp\frac{E-\mu}{kT}\right]^2} \quad (21)$$

$$\frac{\partial f_0(E,T,H,d)}{\partial E} = -\frac{1}{kT}\frac{exp\frac{E-\left(\frac{2\pi\hbar^2}{m}\int_0^\infty\frac{eH}{2\pi c}\Sigma_{n_L}\sqrt{\frac{2}{\pi G}}\frac{1}{}exp\left[-2\left(\frac{E-\hbar\omega_c\left(n_L+\frac{1}{2}\right)}{G}\right)^2\right]f_0(E,E_F(H=0),T)dE+\frac{\pi^2\hbar^2 n_{fz}^2}{2md^2}\right)}{kT}}{\left[1+exp\frac{E-\left(\frac{2\pi\hbar^2}{m}\int_0^\infty\frac{eH}{2\pi c}\Sigma_{n_L}\sqrt{\frac{2}{\pi G}}\frac{1}{}exp\left[-2\left(\frac{E-\hbar\omega_c\left(n_L+\frac{1}{2}\right)}{G}\right)^2\right]f_0(E,E_F(H=0),T)dE+\frac{\pi^2\hbar^2 n_{fz}^2}{2md^2}\right)}{kT}\right]^2} \quad (22)$$

As is known, for T→0 and 1/kT→∞, Equations (21) and (22) are delta-shaped functions.

In Fig.5a shows the 3D space in the absence of a magnetic field. These graphs are created using Equation (21). As can be seen from these figures, as the temperature rises, the height of the "bell" decreases, while its "width" increases. There is also shown for comparison the graph of the function, which is the derivative of the Fermi-Dirac function for the InAs/GaSb quantum well (d=8 nm) at strong magnetic fields (H=14 T) (Fig.5b).



a) b)

Fig.5. Derivative of the Fermi-Dirac function in nanoscale semiconductors at high temperatures and weak magnetic fields a) calculated by Equation (21); b) calculated by Equation (22)

It can be seen from the figure that the width of the $\frac{\partial f_0(E,T,H,d)}{\partial E}$ function is smaller and the height is higher than the height of the $\frac{\partial f_0(E,T)}{\partial E}$. This is an important result, indicating that the $\frac{\partial f_0(E,T,H,d)}{\partial E}$ function is much more efficient and tends more rapidly to the ideal δ-shaped function in two-dimensional materials at high temperatures and weak magnetic fields.

3. COMPARISON OF THEORY WITH EXPERIMENTAL RESULTS

In recent years, two-dimensional semiconductor materials have been the subject of intense theoretical and experimental studies and represent a dynamically developing field of semiconductor physics. The application of a strong magnetic field to two-dimensional semiconductor materials is a powerful tool for experimentally determining the basic parameters of the materials, that is, their effective mass, Fermi energy, and electron concentration. In quantizing magnetic fields, these parameters determine the relevance of experimental and theoretical studies of the magnetooptical and electronic properties of nanoscale semiconductor devices and heterostructures based on them.

Now, let us analyze the Fermi energy oscillations of specific low-dimensional materials in a quantizing magnetic field. In Fig.6 shows the Fermi energy oscillations when measuring m= $0.0665m_0$, N=8.10^{11} cm^2, G=0.5 meV, and T=6 K for two-dimensional electron gases in quantum wells (quantum wells, mainly *GaAs/GaAlAs* heterostructures) (Zawadzki et al., 2014).

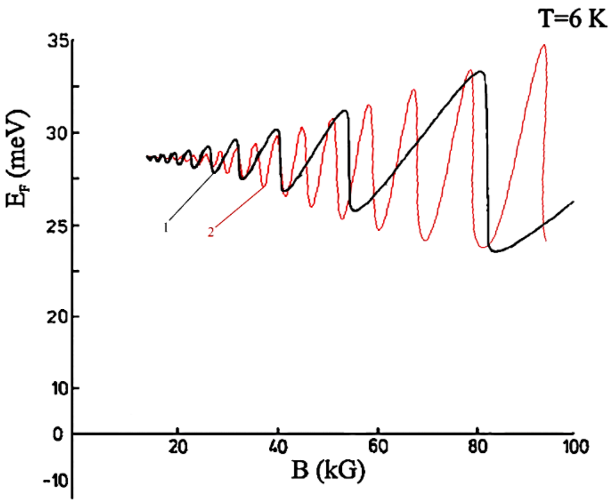


Fig.6. Oscillations of the Fermi energy when measuring m = $0.0665m_0$, N=8.10^{11} cm^2, G=0.5 meV, and T=6 K for two-dimensional electron gases in quantum wells (quantum wells, mainly *GaAs/GaAlAs* heterostructures) 1-experiment (Zawadzki et al., 2014); 2-theory calculated by Equation (18)

Let us calculate this graph of the quantized Fermi energy in terms of $\mu_F(H,T,d)$ -functions. When calculating the initial value, take the ideal $\mu_F(H,T,d)$ by Equation (18). A comparison of the theory with experiment is shown in Fig.6 at various magnetic fields and constant temperatures. Using Equation (18), it is possible to plot $\mu_F(H,T,d)$ graphs at high temperatures and at different quantum well thicknesses for quantum wells, mainly *GaAs/GaAlAs* heterostructures. It can be seen that the Fermi energy at a constant electron density is quantized rather strongly as a function of H in the theoretical and experimental plots in Fig.6.

4. CONCLUSIONS

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

1. It is shown that the Fermi levels of a nanoscale semiconductor in a quantized magnetic field are quantized.
2. A method is proposed for calculating the Fermi energy oscillations for a two-dimensional electron gas at different magnetic fields and temperatures.
3. An analytical expression for calculating the Fermi-Dirac distribution function at high temperatures and weak magnetic fields is obtained
4. Using the proposed Equation, the experimental results in nanosized semiconductor structures are investigated. Using Equation (18), the Fermi energy oscillations are explained for two-dimensional electron gases in quantum wells (quantum wells, mainly GaAs/GaAlAs heterostructures) with a parabolic dispersion law.

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