THE INFLUENCE OF A STRONG ELECTROMAGNETIC FIELD ON MAGNETORESISTANCE OSCILLATIONS IN QUANTUM-SCALE SEMICONDUCTOR STRUCTURES

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Abstract. In recent years, interest in studying quantum well semiconductor structures has been driven by their potential application as nanotechnological devices operating in the nanoscale range, as well as in various spintronic devices. The main reason why scientists are so interested in these quantum-scale structures is that the physical properties of such materials have a number of interesting scientific processes, which allow us to more fully understand the fundamental changes in these processes under the influence of various external factors. In particular, one of such external factors is a quantizing magnetic field and a strong electromagnetic wave, which change the trajectories of charged particles moving freely along the crystal lattice of bulk or small-sized materials. This leads to the emergence of quantum-physical phenomena such as the quantum Hall effect, the Shubnikov-de Haas and de Haas-van Alphen effects.

Key words: Semiconductor, quantum well, external factors, magnetic field, magnetoresistance, heterostructure, temperature.

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1. INTRODUCTION

As a result of applying the effects of a quantizing magnetic field and a strong electromagnetic field, it is possible to determine the main parameters of volumetric or nanoscale structures: magnetic field absorption, magnetoresistance, concentration, effective mass, mobility, *g*-factor, relaxation time, etc. [1–14]. For example, in works [4–7], experimental results of changes in magnetoresistance oscillations under the influence of a strong electromagnetic wave as a result of introducing small concentrations of impurities into bulk semiconductor materials are presented. In this case, a clear shift of the magnetoresistance oscillation graphs was observed as a result of changing the type and concentration of the impurity at low temperatures. However, the oscillation processes at high temperatures in these experimental studies have not been fully studied theoretically. In addition, in works [1, 15–18], the effects of strong electromagnetic fields, magnetic fields, and temperatures on magnetoresistance oscillations of quantum-walled heterostructure semiconductors were investigated.

For example, in these works, for the first time, the oscillations of the first (dP/dH) and second-order (d^2P/dH^2) differential signals in terms of the ultrahigh-frequency electromagnetic field strength (P) and the magnetic field strength (H) for an InAs/GaSb quantum-walled heterostructure were experimentally determined at different temperatures. In this case, a sharp decrease in the oscillation amplitudes with increasing temperature was observed, but the exact physical process was not explained in these experiments.

In works [19–26], the theory of the effects of ultra-high frequency field and temperature on the Shubnikov-de Gaas effect has been developed perfectly. In this work, a new mathematical model was proposed that explains a number of experimental results. However, the results obtained in these works are valid only for bulk semiconductor materials, the proposed model cannot be applied to small-sized semiconductors.

The main goal of the work is to determine the temperature dependence of the electrical conductivity oscillations of quantum-scale semiconductors in a strong electromagnetic field.

2. THEORETICAL PART

2.1. DEPENDENCE OF STRONG ELECTROMAGNETIC FIELD POWER ON ELECTRICAL CONDUCTIVITY

The electric current density in a single-component system in a strong electromagnetic field has the following expression [27]:

$$j = \sigma(T_e)E_E \qquad \text{or} \qquad j = j(E_E) \tag{1}$$

Here, T_e is the free electron temperature in a strong electromagnetic field; E_E is the electric field strength of a strong electromagnetic field.

For these $j(E_E)$ characteristics, it becomes convenient to discuss the relationship with the differential electrical conductivity σ_d namely:

$$\sigma_d(E_E) = \frac{dj}{dE_E} = \sigma + E\frac{d\sigma}{dE_E} \tag{2}$$

To calculate this expression (2) in a changing field, we investigate $j(\omega)$ and $E_E(\omega)$ using Fourier components. ω is the frequency of the changing electromagnetic field. Therefore, we assume that the strong electromagnetic field currently acting on the sample is acting in a time-invariant manner.

In that case, the equilibrium equation is [20]:

$$e(v_d, E_E) = \frac{\frac{2}{3}<E>-kT}{\tau_e} \tag{3}$$

Using (3), (2) can be reduced to the following form:

$$\sigma E_E^2 = nk\frac{T_e - T}{\tau_e} \quad (4)$$

The term on the right in expression (4) represents the power (P) of the strong electromagnetic field. Then, from (4):

$$P = \sigma E_E^2 \quad (5)$$

the expression comes from.

So, as can be seen from (5), the power of a strong electromagnetic field depends on the electrical conductivity of the material and the square of the electric intensity of the electromagnetic wave.

2.2. THE INFLUENCE OF A STRONG ELECTROMAGNETIC FIELD ON THE ELECTRICAL CONDUCTIVITY OSCILLATIONS OF QUANTUM-SCALE SEMICONDUCTORS

Now, using expression (5), we consider the electrical conductivity oscillations of semiconductor quantum well heterostructures in a strong electromagnetic field.

The electrical conductivity $\tau(E,B)$ of quantum well heterostructured semiconductors in a strong magnetic field is determined as follows [4, 28]:

$$\sigma(E,B) = \frac{e^2 n_s <\tau(E,B)>}{m^*} \quad (6)$$

where n_s is the concentration of free electrons for two-dimensional materials; $<\tau(E,B)>$ is the average relaxation time of charge carriers in a strong magnetic field.

The average relaxation time of free charge carriers in two-dimensional materials is:

$$<\tau(E,B)> = \frac{\int N_S^{2d}(E,B)\left(\frac{\partial f}{\partial E}\right)\tau(E)EdE}{n_S} \quad (7)$$

where $N_S^{2d}(E,B)$ is the energy density of states of a 2D dimensional semiconductor.

In works [2, 29], an analytical expression of the dependence of the density of energy states on the magnetic field and temperature for 2D materials was derived. In this, the authors used Gaussian distribution function. That is,

$$N_S^{2d}(E,B,N_L,d,n_z) = \sum_{N_L,N_z}^{\infty}\frac{eB}{\pi\hbar}\cdot\frac{1}{kT}\cdot\exp\left(-\frac{\left(E-\left(\hbar\omega_c\left(N_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m\cdot d^2}N_Z^2\right)\right)^2}{(kT)^2}\right) \quad (8)$$

Here, N_L is the number of discrete Landau levels; d is the quantum well width; n_z is the number of dimensional quanta; ω_c is the cyclotron frequency.

Using the relaxation time $\tau(E,T)$ in the elastic scattering approximation of scattering mechanisms for small-sized semiconductors and expressions (6), (7) and (8), the temperature dependence of the electrical conductivity oscillations in a quantizing magnetic field for quantum-sized semiconductors takes the following form:

$$\sigma_{\perp}^{2d}(E,B,T,d) = \frac{e^3 B}{2\pi m\cdot c}\sqrt{\frac{2}{\pi}}\frac{1}{G}\cdot \cdot\int_0^{\infty}\sum_{n_L}\exp\left[-2\left(\frac{E-\left[\hbar\omega_c\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m\cdot d^2}n_Z^2\right]}{G}\right)^2\right]\cdot \cdot\gamma_{\perp}(k_0T)^{\beta}E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE \quad (9)$$

As can be seen from (9), the oscillation process of quantum-scale semiconductors occurs mainly due to the density of 2D-dimensional energy states. However, in (9) the effect of a strong electromagnetic field is not taken into account. In (5), the dependence of the electromagnetic wave power on the electrical conductivity of the material is given. In this case, using expressions (5) and (9), the dependence of the strong electromagnetic field power P on the quantizing magnetic field B, quantum well width d, temperature T, and electric field strength E_E is obtained as $(P^{2d}(B,T,E_E,d))$. That is:

$$P^{2d}(B,T,E_E,d) = \sigma^{2d}(E,B,T,d)\cdot E_E^2 \quad (10)$$

or

$$P^{2d}(H,N_L,n_z,d,E_E,T) = = \frac{e^3 B}{2\pi m\cdot c}\sqrt{\frac{2}{\pi}}\frac{1}{G}\int_0^{\infty}\sum_{n_L}exp\left[-2\left(\frac{E-\left[\hbar\cdot\frac{eH}{m\cdot c}\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m\cdot d^2}n_Z^2\right]}{G}\right)^2\right]\cdot \cdot\gamma_{\perp}(k_0T)^{\beta}E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE\cdot E_E^2. \quad (11)$$

This derived formula serves to explain a number of experimental results and to interpret the essence of physical processes from them.

2.3. MODELING THE DEPENDENCE OF ELECTRICAL CONDUCTIVITY OSCILLATIONS OF QUANTUM WELL HETEROSTRUCTURED SEMICONDUCTORS ON STRONG ELECTROMAGNETIC FIELDS AND TEMPERATURE

In works [1, 4], experimental studies were carried out, that is, on the installation of electroparamagnetic resonance (EPR) in determining the influence of a strong electromagnetic field on the oscillations of electrical conductivity of quantum-sized materials. The reason is that the EPR method allows us to determine the dependence of the magnetoresistance or electrical conductivity oscillations of quantum-scale heterostructure materials on external fields. In this case, the maximum decrease in the strength of the strong electromagnetic field (*dP*) in the direct measurement of the EPR effect occurs due to transitions between energy levels (from one level to another) due to the energy of the electromagnetic wave. That is, the losses in *dP* serve to accelerate free charge carriers in the quantizing magnetic field (*H*). These energy levels are Landau levels, and the number of these levels depends on the magnetic field strength (*dH*). It follows that in order to observe more microwave field absorption in the electrical conductivity oscillations in the conduction band of the quantum well, it is necessary to increase the strength of the ultrahigh-frequency electromagnetic field. More precisely, the more *dH* increases, the more the number of Landau levels increases.

To observe the EPR phenomenon at each discrete Landau level, *dP* must be increased. In general, the ratio $\frac{dP^{2d}(H,T,d,E_E,N_L,n_z,)}{dH}$ is of great importance in conducting EPR experiments in quantum-sized semiconductors. Formula (11) can be used to develop the theory of these experiments and its new module.

In order to monitor the sensitivity of electrical conductivity oscillations of ultra-high-frequency electromagnetic field in heterostructures with quantum wells, the first-order derivative of the magnetic field strength is obtained from formula (11). As a result, formula (11) becomes:

$$\frac{dP^{2d}(H,T,d,E_E,N_L,n_z)}{dH} = E_E^2 \cdot$$

$$\frac{d\left[\frac{e^3B}{2\pi m\cdot c}\sqrt{\frac{2}{\pi}}\frac{1}{G}\int_0^{\infty}\sum_{n_L}\exp\left[-2\left(\frac{E-\left[\hbar\cdot\frac{eH}{m\cdot c}\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m\cdot d^2}n_Z^2\right]}{G}\right)^2\right]\gamma_{\perp}(k_0T)^{\beta}E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE\right]}{dH} \quad (12)$$

Using this formula (12), it is possible to calculate the electrical conductivity oscillations of quantum well heterostructures in an ultrahigh-frequency field. If, moreover, it becomes possible to observe the microwave field absorption at

each discrete Landau level of the quantum well with higher precision, then from (12) we obtain the derivative with respect to the magnetic field strength. That is:

$$\frac{d^2P^{2d}(H,T,d,E_E,N_L,n_z)}{dH^2} = E_E^2 \cdot$$

$$\frac{d^2\left[\frac{e^3B}{2\pi m\cdot c}\sqrt{\frac{2}{\pi}}\frac{1}{G}\int_0^\infty \sum_{n_L}\exp\left[-2\left(\frac{E-\left[\hbar\cdot\frac{eH}{m\cdot c}\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m\cdot d^2}n_Z^2\right]}{G}\right)^2\right]\gamma_\perp(k_0T)^\beta E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE\right]}{dH^2} \quad (13)$$

A new mathematical model has been developed based on formulas (12) and (13). This new mathematical model certainly serves to explain several experimental results.

3. RESULTS AND DISCUSSIONS

3.1. RESULTS AND DISCUSSION. COMPARISON OF THEORY AND EXPERIMENTAL RESULTS

Now, let us consider the proposed model for explaining the quantum oscillation effects observed in experiments under the influence of a strong electromagnetic field. In work [1], the dependence of the Shubnikov de Haas oscillations of heterostructured semiconductors based on the InAs/GaSb quantum well on a strong electromagnetic field and temperature was experimentally determined (Fig. 1).

In particular, Fig. 1 shows the temperature dependence of the microwave absorption coefficient (dP/dH) in a strong magnetic field with a quantum well thickness d = 8 nm (for GaSb). The results of this experiment were obtained in the EPR setup in the temperature range T = 2.7 K–250 K. The magnetic field strength vector is directed along the Z axis (H/Z), where Z corresponds to the direction of the quantum well thickness. In the experiment, the electric field magnitudes of a strong microwave were obtained as follows: microwave frequency $\nu = 9.35$ GHz, quantum energy $E = \hbar\omega = \hbar 2\pi\nu = 0.04$ meV, electromagnetic field power P = 1 mW [1]. Using these magnitudes, the electric field strength of the electromagnetic field can be calculated:

$$E_E = \frac{\hbar 2\pi\nu}{ed} = 0.5\cdot 10^3 \ \frac{\text{V}}{\text{M}} \quad (14)$$

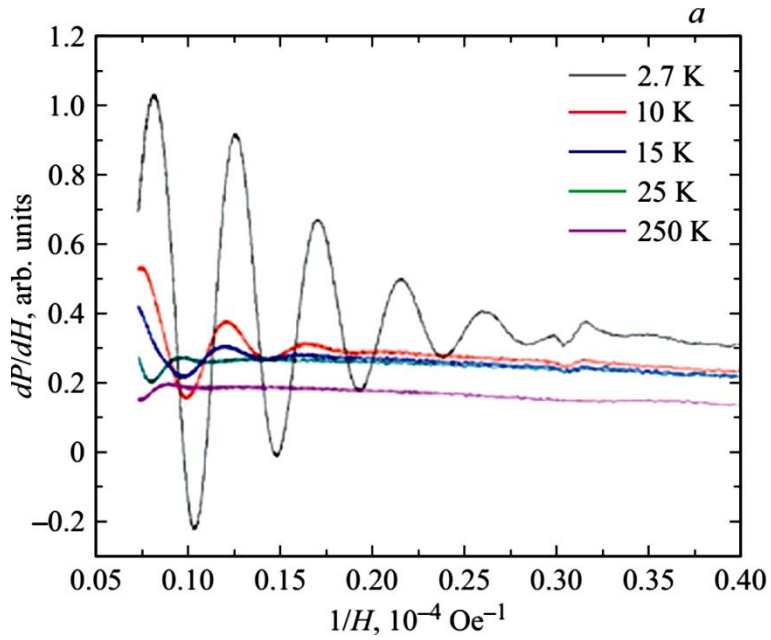

Fig. 1 – Temperature dependence of $\frac{dP}{dH}$ for InAs/GaSb quantum well semiconductors [1].

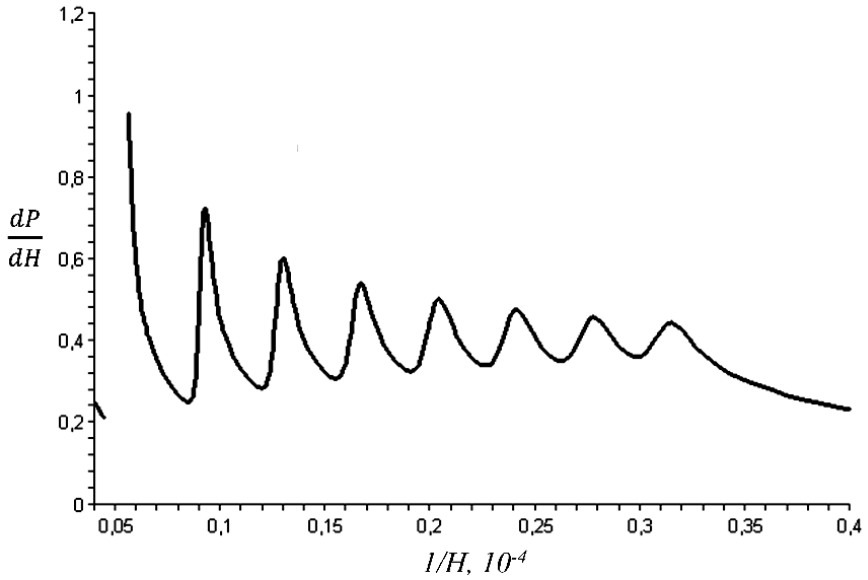

Fig. 2 – The dependence of $\frac{dP}{dH}$ on $\frac{1}{H}$ for InAs/GaSb quantum well semiconductors at a constant temperature T = 2.7 K. This graph is obtained based on formula (12).

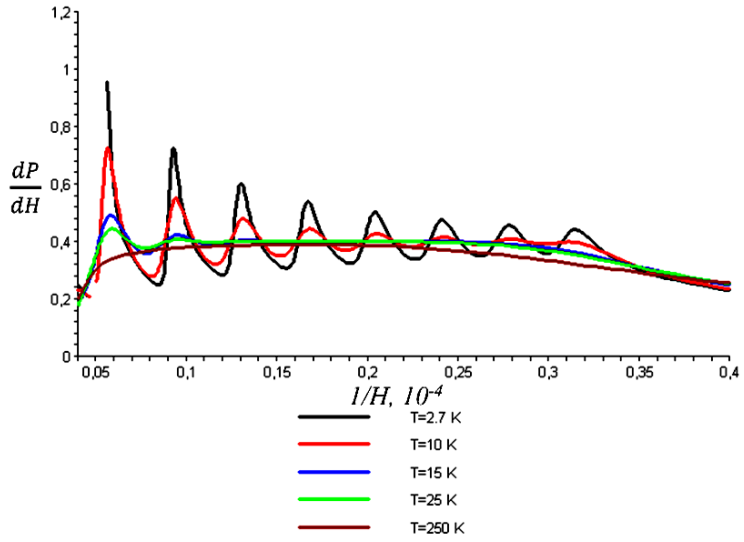

Fig. 3 – Temperature dependence of $\frac{dP}{dH}$ for InAs/GaSb quantum well semiconductors. These graphs are obtained according to the proposed model (12).

In addition, the magnetic field value in the experiment is given in the range $\frac{1}{H} = 0.05 \cdot 10^{-4} \div 0.4 \cdot 10^{-4}$ oersted.

Using the physical quantities presented in this experiment, we begin the theoretical analysis. Using the proposed model (based on the formula (12)), it is possible to determine the dependence of *dP/dH* on 1/*H*. However, as can be seen from the formula (12), this equation is transcendental and cannot be solved theoretically. This can be done using computer programs (Maple, Matchad, Matlab, Mathematica) and the necessary results can be achieved using the graphical method. Procedure functions are used to create the mathematical model software (Maple). For example, as can be seen from the formula (12), since the quantities that fundamentally change the quantum oscillation processes are *H*, *T*, *d*, E_E, N_L, n_Z the program uses the command proc (*H*, *T*, *d*, E_E, N_L, n_Z).

Figure 2 shows the graph of *dP/dH versus* 1/*H* for the new model (formula (12)) for $T = 2.7$ K, $E_E = 0.5 \cdot 10^3 \frac{V}{M}$, $N_L = 10$ and $n_Z = 1$ (the number of dimensional quantum levels $n_Z = 1$ is sufficient. This is because Landau quantum numbers (N_L) mainly begin to appear after n_Z). In this case, by substituting the experimental dimensional quantities given in [1] into (12), a graph of *dP/dH versus* 1/*H* is obtained. Since the condition $kT \ll \hbar\omega_C$ is fulfilled, the quantum oscillation amplitudes appear sharply.

The amplitude of the *dP/dH* amplitude is proportional to the magnetic field strength *H*, and as *H* decreases, the amplitude decreases. Of course, this law is

observed at constant low temperatures. However, with increasing temperature dynamics, the change in the $\frac{dP}{dH}$ amplitude becomes dependent not on $\frac{1}{H}$, but on T. Let us explain the results of another experiment in terms of the proposed model (12). In work [2], it was experimentally determined that $\frac{dP}{dH}$ depends on the magnetic field strength H and the temperature T for a Ge semiconductor material (Fig. 4).

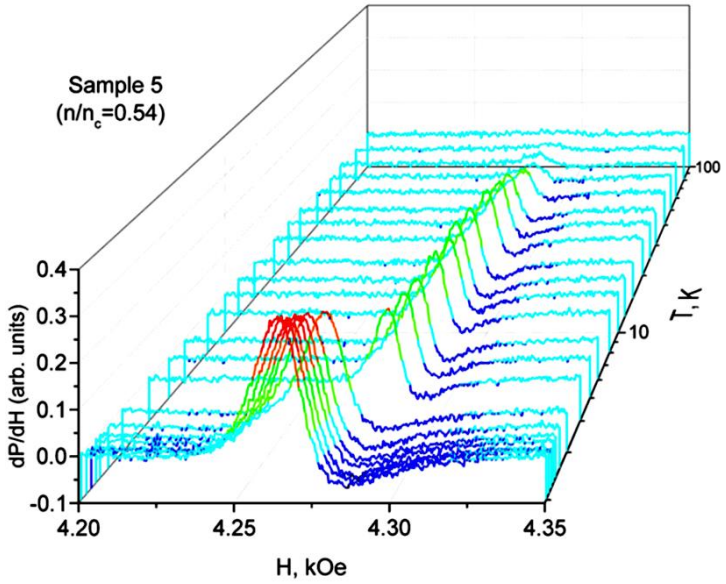

Fig. 4 – Experimental results of the temperature dependence of $\frac{dP}{dH}$ for the Ge bulk semiconductor [2].

In Fig. 4, the magnetic field H = 4.2 kE to 4.35 kE was taken. The oscillations of $\frac{dP}{dH}$ were measured in the temperature range from T = 3 K to 100 K. As can be seen from Fig. 4, as the temperature increases, the amplitudes of the $\frac{dP}{dH}$ oscillations decrease, and when T = 100 K is reached, the discrete energy levels turn into continuous energy levels. However, there are no sufficient experimental explanations for these physical processes. If we pay attention to the formula (12) in the model, we need to analyze the term $\frac{\pi^2\hbar^2}{2m\cdot d^2}n_z^2$. The reason is that the material considered in work [2] is 3D, and the thickness of the quantum well is not taken into account. In this case, the condition for $d \to \infty$ in $\frac{\pi^2\hbar^2}{2m\cdot d^2}n_z^2$ allows the model (12) to be applied to 3D semiconductor materials.

Figure 5 shows the graph obtained for the function $\frac{dP}{dH}$ (H,T), where (H,T) according to the model (12). The experimental results in Fig. 4 and the graph in

Fig. 5 are observed until they qualitatively match. At T = 3 K, the height of the discrete levels (oscillation amplitudes) begins to decrease at $kT << \hbar\omega e$. When the thermal expansion is very high ($kT >> \hbar\omega e$), continuous energy spectra begin to appear. As can be seen from experiment and theoretical calculations, this temperature corresponds to T = 100 K.

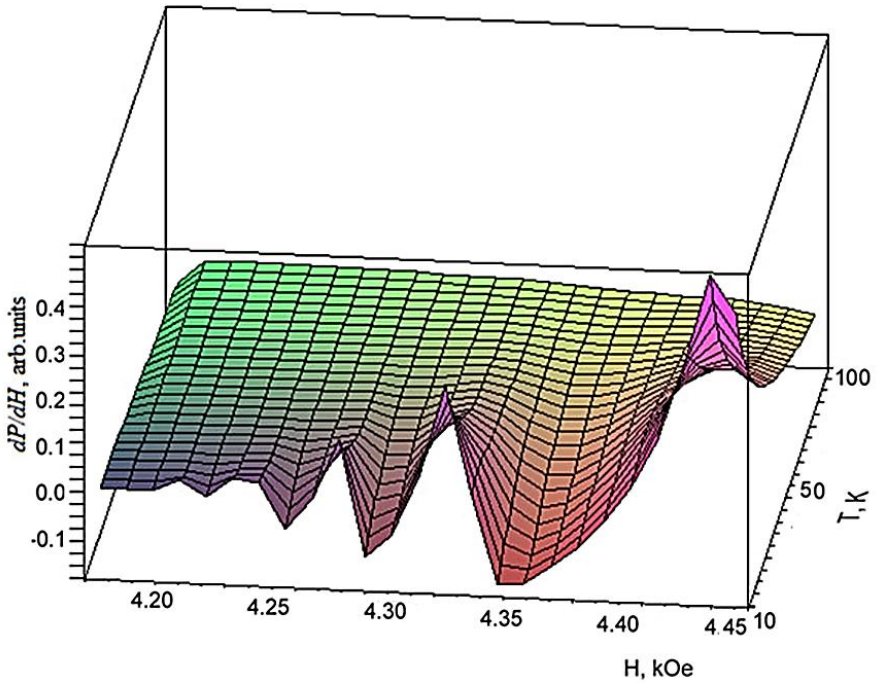

Fig. 5 – Theoretical results of the temperature dependence of $\frac{dP}{dH}$ for the Ge bulk semiconductor. This three-dimensional graph is obtained based on the proposed model (12).

In conclusion, we can say that the model we propose, $(\frac{dP}{dH}(H,T)$ function, allows us to apply it not only to 2D materials, but also to bulk semiconductors.

4. CONCLUSIONS

The following conclusions were reached from this research:

1. For quantum-sized semiconductors, the dependence of electric conductivity oscillations on a strong electromagnetic field is applied.

2. The analytical form of the first and second order differential expressions $(\frac{dP}{dH}, \frac{d^2P}{dH^2})$ obtained from the microwave field power (dP) magnetic field strength (dH) in quantum well heterostructure semiconductors was derived.

3. A mathematical model was developed to determine the dependence of quantum oscillation effects on microwave field power, quantizing magnetic field strength, and temperature for bulk and small-sized semiconductor materials.

4. It was possible to explain the experimental results obtained in quantum-sized and bulk semiconductor structures for high-temperature dynamics based on the proposed model.

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