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SIMULATION OF THE TEMPERATURE DEPENDENCE OF THE OSCILLATION OF MAGNETOSISTIVITY IN NANOSIZED SEMICONDUCTOR STRUCTURES UNDER THE EXPOSURE TO EXTERNAL FIELDS

R.G. Rakhimov
Namangan Institute of Engineering and Technology,
160115, Namangan, Uzbekistan
rgrakhimov@gmail.com

Abstract

Recently, a number of remarkable nonequilibrium phenomena have been discovered in semiconductor structures under strong alternating and constant excitation of the electron gas. Most attention has been drawn to microwave-induced resistivity oscillations, especially after the impressive observation of "zero-resistance states" at the oscillation minima. Two mechanisms of resistivity oscillations caused by microwave radiation have been proposed, one of which arises due to oscillations in the spectral density of states of Landau levels with extended disorder. Both mechanisms reproduce the observed phase of the ω/ωc oscillations. The displacement mechanism takes into account the disorder of scattering by microwave radiation in the presence of an electric field and creates temperature-independent oscillations of resistivity caused by microwave radiation, which is contrary to experiments. On the contrary, the inelastic mechanism associated with microwave-induced oscillatory changes in the electron energy distribution gives rise to resistivity oscillations with an amplitude proportional to the inelastic scattering time.

Keywords: Semiconductor, electron gas, oscillation, microwave, Landau levels, electric field, mathematical model, Shubnikov-de Haas oscillations

Introduction

In this article, a mathematical model for Shubnikov-de Haas oscillations in semiconductors upon absorption of microwave radiation is obtained and its temperature dependence is studied. A two-dimensional image of microwave magnetoabsorption oscillations in narrow-gap semiconductors is constructed. Using a mathematical model, oscillations of microwave magnetoabsorption are considered for various values of the electromagnetic field. The calculation results are compared with experimental data. The proposed model explains the experimental results in semiconductor structures at various temperatures.

Quantum oscillation phenomena in external fields in semiconductor structures are a promising area of scientific research and the basis for establishing optoelectronic and spintorch devices. In particular, the authors of [1-4] studied the dependence of the derivative of the microwave power

P with respect to the magnetic field strength $H\left(\frac{dP}{dH}\right)$ on the magnetic field strength H in narrow-gap semiconductors. The magnetoresistive effect in semiconductors and in quantizing magnetic fields is considered, and the oscillations of absorption of microwave radiation in narrow-gap semiconductors are determined [2,4]. In this case, experimental studies were carried out at low temperatures and at constant microwave fields.

1. Comparison of the distributions of the Lorentz, Gaussian functions and the derivative of the Fermi-Dirac function with respect to energy at different temperatures.

In works [5-18] consider the Shubnikov-de Haas and de Haas-van Alphen oscillations in bulk and nanosized semiconductors at different temperatures and at different pressures. For example, in [5–8], a method was developed for determining the temperature dependence of the thermodynamic density of states in a quantizing magnetic field. These methods are used to study quantum oscillation phenomena in semiconductors at various temperatures. However, these works did not investigate the influence of the microwave field (microwave radiation absorption) on the temperature dependence of quantum oscillation phenomena in semiconductors using the Gaussian, Lorentzian and energy derivative of the Fermi-Dirac function.

The purpose of this work is to compare the distributions of the Lorentz, Gaussian functions and the derivative of the Fermi-Dirac function with respect to energy at different temperatures.

Let us consider the dependence of the static distribution function on energy at various temperatures. The distribution functions of Gauss, Lorentz and the energy derivative of the Fermi-Dirac function for energy levels E_i is determined by the following expression [19]:

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

$$Lorentz\left(E,T\right)=\frac{1}{1+\frac{\left(E-E_i\right)^2}{\left(kT\right)^2}} \qquad (2)$$

$$\frac{\partial f_0\left(E,\mu,T\right)}{\partial E}=-\frac{1}{kT}\frac{\exp\left(\left(E-\mu\right)/kT\right)}{\left[1+\exp\left(\left(E-\mu\right)/kT\right)\right]^2} \qquad (3)$$

Here, $Gauss\left(E,T\right)$ is the Gaussian distribution function, is the Lorentz distribution function, $\partial f_0(E)/\partial E$ is the energy derivative of the Fermi-Dirac distribution function. Now consider the temperature dependence of the distribution of the Gaussian, Lorentzian and Fermi-Dirac functions. Figures 1, 2 and 3 show the dependences of the distributions of the Gaussian function, Lorentz function and the derivative of the Fermi-Dirac function on energy at various temperatures T_1=300 *K*, T_2=100 *K*, T_3=4 *K*.

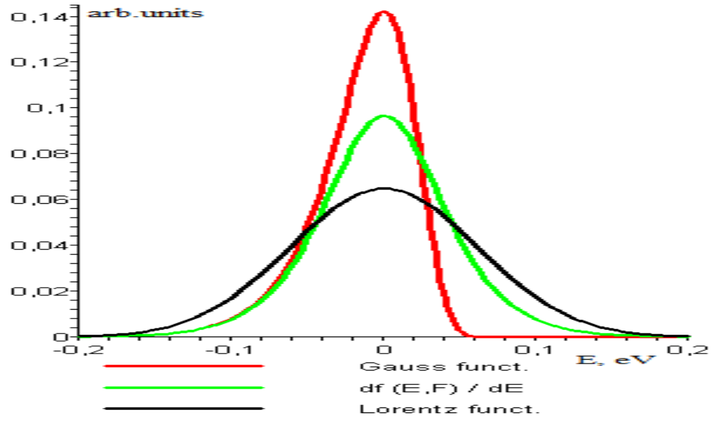

Fig.1. The form of the Gaussian function, the energy derivative of the Fermi-Dirac function and the Lorentz function at a temperature of *T=300 K*.

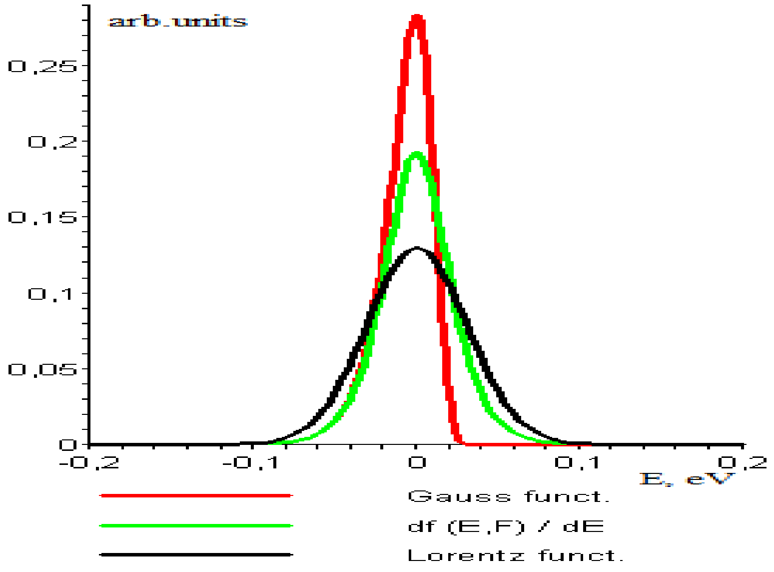

Fig.2. The form of the Gaussian function, the derivative of the Fermi-Dirac function with respect to energy and the Lorentz function at a temperature of *T=100 K*.

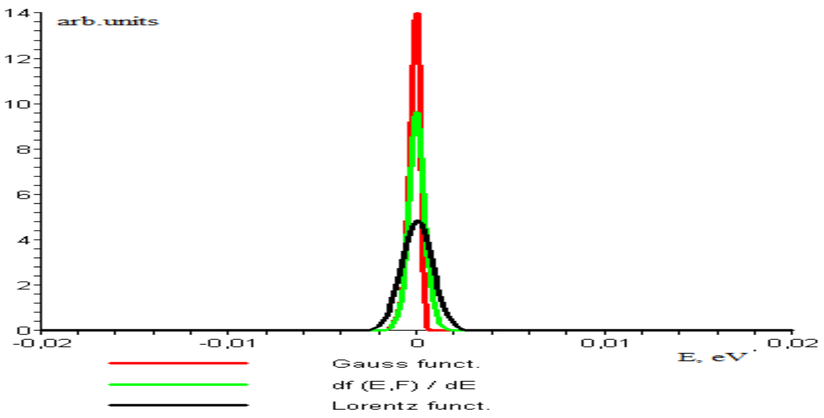

Fig.3. The form of the Gaussian function, the derivative of the Fermi-Dirac function with respect to energy and the Lorentz function at a temperature of *T=4 K*.

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As can be seen from these figures, at low temperatures, the height of the distribution of the Gaussian function is higher than the height of the Lorentz function and the height of the derivative of the Fermi-Dirac function. From Fig. 2 and 3, it can be seen that at high temperatures, the height of the peak of the Gaussian function is also greater than the height of the Lorentz function and the height of the derivative of the Fermi-Dirac function.

This is an important result, indicating that the distribution of the Gaussian function is much more efficient and tends to the ideal δ - Dirac function more quickly than the Lorentz functions and the derivative of the Fermi-Dirac function.

2. Temperature dependence of the spectral density of states in semiconductors in quantizing magnetic fields.

Let us now consider the temperature dependence of the spectral density of states in quantizing magnetic fields using the distribution of the Gaussian, Lorentzian and the energy derivative of the Fermi-Dirac function. In [8], oscillations of the spectral density of states in narrow-gap semiconductors were studied. The following expression was obtained for the density of energy states in quantizing magnetic fields for narrow-gap semiconductors:

$$N^k(E,H) = \frac{(m)^{3/2}}{(2)^{1/2}\pi^2\hbar^3}\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}} \tag{4}$$

Here, $N^k(E,H)$ 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 hole in a quantizing magnetic field, N is the number of Landau levels, and E_g is the band gap of the semiconductor.

This formula is applicable only for narrow-gap ($E_g < 0.6eV$) materials. As can be seen from this formula, if $E_g \to \infty$ (for wide-gap semiconductors) then $\frac{2E}{E_g} \to 0$ and $\frac{E^2}{E_g} \to 0$, then formula (4) turns into the density of states of the band with a parabolic dispersion law [20]:

$$N_s(E,H) = \frac{(m)^{3/2}}{(2)^{1/2}\pi^2\hbar^3}\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{1}{\sqrt{E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}} \tag{5}$$

If the energy spectrum of electrons is discrete, then the density of energy states is equal to the sum of δ-functions concentrated at points of the spectrum E_i, whose amplitude is $N_{si} = \psi_i^2(0) + \psi_i'^2(0)$, where $\psi_i(x)$ are the eigenfunctions normalized to unity [21]:

$$N_s(E) = \sum_i N_{si}\,\delta(E-E_i) \tag{6}$$

In the general case, the spectral density of energy states is a set of δ - functional peaks located from each other by $\hbar\omega_c$ in a quantizing magnetic field [22].

If $T \to 0$ and $\frac{1}{kT} \to \infty$, then the $Gauss(E,T)$, $Lorentz(E,T)$ and $\partial f_0(E)/\partial E$ functions turn into Dirac delta functions (δ is Dirac function).

The energy spectra of charge carriers in the conduction and valence bands are quantized in quantizing magnetic fields at low temperatures.

Let us consider the main relations that determine the distribution of oscillations of the spectral density of states in semiconductors under the action of a strong magnetic field. In a strong magnetic field, the energy spectrum of electrons and holes in the allowed band is quantized. At absolute zero temperature, we obtain an analytical expression for the spectral density of states:

$$N^k\left(E,H\right)=\frac{(m)^{3/2}}{(2)^{1/2}\pi^2\hbar^3}\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\sum_{i=1}^{m_k}\delta(E-E_{ki}) \qquad (7)$$

Where, $\delta(x-b)$, δ is Dirac function.

At low temperatures (0-5 K), the discrete Landau levels are clearly expressed, and at high temperatures, the Landau levels are smeared due to the thermal broadening of the discrete levels. At low temperatures ($T\rightarrow 0$) the Gaussian function turns into a Dirac delta function. Let us determine the oscillations of the spectral density of states by the Kane dispersion law using the functions $Gauss\left(E,T\right)$, $Lorentz\left(E,T\right)$ and $\partial f_0(E)/\partial E$.

From here, using (4) and substituting (1), (2), (3) into (7), we obtain an analytical expression for the density of states in a quantizing magnetic field for narrow-gap semiconductors:

$$N^k\left[Gauss\left(E,E_i,T\right),H\right]=K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\sum_{i=1}^{m_k}Gauss\left(E,E_i,T\right) \qquad (8)$$

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

$$N^k\left[\frac{\partial f_0(E_i,\mu,T)}{\partial E},H\right]=K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\sum_{i=1}^{m_k}\frac{\partial f_0(E_i,\mu,T)}{\partial E} \qquad (9)$$

$$N^k\left[Lorentz\left(E,E_i,T\right),H\right]=K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{\frac{2E}{E_g}+1}{\sqrt{\frac{E^2}{E_g}+E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\sum_{i=1}^{m_k}Lorentz\left(E,E_i,T\right) \qquad (10)$$

Using this formula, one can explain the temperature dependence of quantum oscillation processes in narrow-gap semiconductors.

Using this method and formula (5), one can calculate the temperature dependence of the spectral density of states in quantizing magnetic fields for wide-gap semiconductors:

$$N_s\left[Gauss\left(E,E_i,T\right),H\right]=K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{1}{\sqrt{E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\sum_{i=1}^{m_k}Gauss\left(E,E_i,T\right) \tag{11}$$

$$N_s\left[\frac{\partial f_0(E_i,\mu,T)}{\partial E},H\right]=K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{1}{\sqrt{E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\sum_{i=1}^{m_k}\frac{\partial f_0(E_i,\mu,T)}{\partial E} \tag{12}$$

$$N_s\left[Lorentz\left(E,E_i,T\right),H\right]=K\cdot\frac{\hbar eH}{2mc}\sum_{N=0}^{N_{\max}}\frac{1}{\sqrt{E-(N+\frac{1}{2})\frac{\hbar eH}{mc}}}\sum_{i=1}^{m_k}Lorentz\left(E,E_i,T\right) \tag{13}$$

Using formulas (8) and (10), we consider graphs of the spectral density of states. Figures 4 and 5 show oscillations of the density of states in two-dimensional space for *InAs* ($E_g(0)=0.414\,eV$) [23] at a magnetic field *H=40 kOe* (or *B=4 T*).

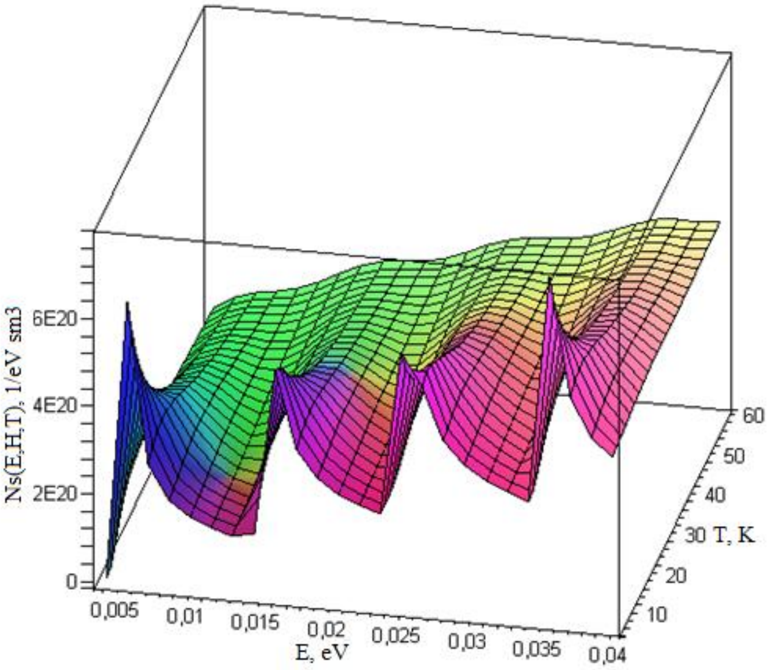

Fig.4. Energy and temperature dependence of the spectral density of states in *InAs* calculated using formula (10).

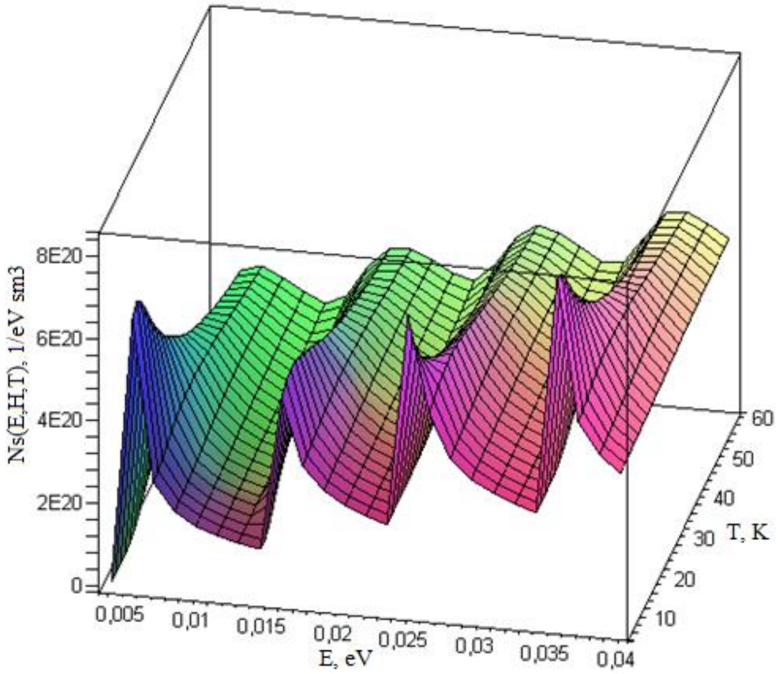

Fig.5. Energy and temperature dependence of the spectral density of states in *InAs* calculated using formula (8).

These figures show the temperature and energy dependences of the oscillations of the spectral density of states for the narrow-gap *InAs* semiconductor. The graph in Fig. 4 is built according to the formula (10), and the graph in Fig. 5 is built according to the formula (8). As can be seen from these figures, at low temperatures (T < 5 K), discrete Landau levels appear sharply. In addition, the height of discrete Landau levels looks almost the same in the temperature range 1K<T<4K. When the energy spectrum is calculated by formula (10) (Fig. 4) in the temperature range 50K<T<60K, the Landau levels are not discrete, and in Fig. 5 it is in this temperature range that oscillations of the spectral density of states can be observed.

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

Comparison of theory with experimental results

Let us analyze oscillations of microwave magnetoabsorption in semiconductors under the action of temperature and external fields. In work [1], oscillations in the absorption of microwave radiation in semiconductors are observed.

Figure 6 (curve 2) shows magnetoabsorption oscillations in *HgSe* samples at temperature T=2.7 K and constant wave power over the entire measurement range [1]. Shown here is the dependence of $\frac{dP}{dH}$ oscillations on the reverse magnetic field at low temperatures. In these papers, oscillations were obtained for a narrow-gap semiconductor. From here, using formula (22), we determine the $\frac{dP}{dH}$ oscillations at a temperature of T=2.7 K (Fig. 6, curve 1).

Figure 11 compares the theoretical and experimental data for microwave magnetoabsorption oscillations in *HgSe*. In this case, the amplitudes of quantum oscillations start abruptly. As can be seen from these figures, the theoretical and experimental plots are in good agreement. With the help of formulas (22), it is possible to explain the experimental results at different temperatures (Fig.7).

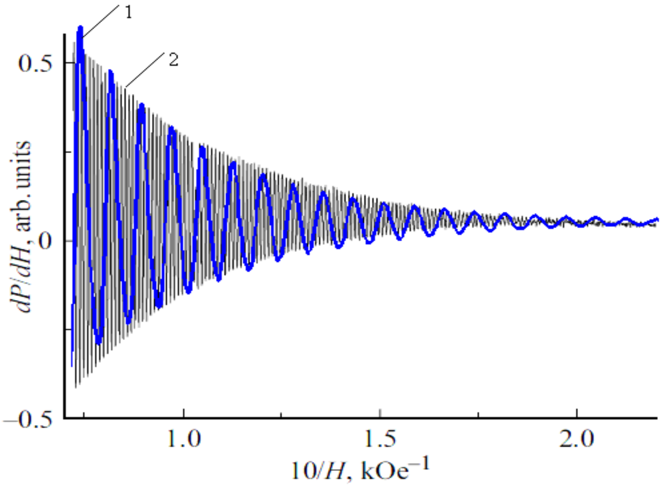

Fig.6. Shubnikov-de Haas oscillations in *HgSe* samples at constant electromagnetic wave strength and temperature T=2.7K.

1 – theory calculated using formula (22);

2–experiment [1].

Figure 7 shows the dependence of $\frac{dP}{dH}$ on $\frac{1}{H}$ for temperatures of 2.7 K, 50K, and 150K. As the temperature increases, the amplitudes of the $\frac{dP}{dH}$ oscillations decrease, and at values of H in the $\frac{10}{H}=1,5\div 2,5\ kOe^{-1}$ range, the influence of the magnetic field is not felt. As can be seen from the figure, at a temperature of T=100 K, the $\frac{dP}{dH}$ oscillations are smoothed out.

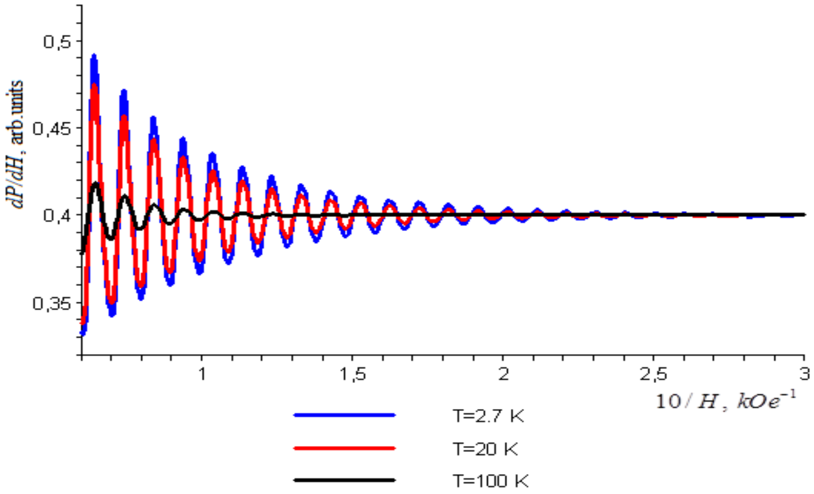

Fig.7. Effect of temperature on oscillations of microwave magnetoabsorption in *HgSe* samples, calculated using formula (22)

Conclusion

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

✓ A technique has been developed for determining the oscillations of microwave magnetoabsorption in semiconductors at various electromagnetic fields and temperatures.

✓ Mathematical modeling of the temperature dependence of the oscillations of microwave magnetoabsorption in semiconductors has been carried out using the Gaussian, Lorentzian functions and the derivative of the Fermi-Dirac function with respect to energy.

✓ Using this model, the dependences of quantum oscillation phenomena on microwave fields and temperature in semiconductors are calculated.

✓ Using the Gaussian function, the oscillation of the absorption of microwave radiation in narrow-gap semiconductors at various temperatures is calculated. The calculation results are compared with experimental data.

✓ A formula is obtained for the dependence of $\frac{dP}{dH}$ oscillations on the electric field strength of an electromagnetic wave and temperature for the energy spectrum with parabolic and Kane dispersion laws.

Using the proposed model, the experimental results of $HgSe$ are investigated. Using formula (22), the experimental $\frac{dP}{dH}$ oscillations in the narrow-gap semiconductor $HgSe$ at various temperatures are explained.

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