EAST EUROPEAN JOURNAL OF PHYSICS. 3. 133-145 (2023)
DOI:10.26565/2312-4334-2023-3-10 ISSN 2312-4334

DETERMINATION OF THE DEPENDENCE OF THE OSCILLATION OF TRANSVERSE ELECTRICAL CONDUCTIVITY AND MAGNETORESISTANCE ON TEMPERATURE IN HETEROSTRUCTURES BASED ON QUANTUM WELLS[†]

Ulugbek I. Erkaboev*, Rustamjon G. Rakhimov[§]
Namangan Institute of Engineering and Technology,160115 Namangan, Uzbekistan
**Corresponding Author e-mail: erkaboev1983@gmail.com, [§]Corresponding author: rgrakhimov@gmail.com*
Received June 10, 2023; revised June 22, 2023; accepted June 23, 2023

In this work, the influence of two-dimensional state density on oscillations of transverse electrical conductivity in heterostructures with rectangular quantum wells is investigated. A new analytical expression is derived for calculating the temperature dependence of the transverse electrical conductivity oscillation and the magnetoresistance of a quantum well. For the first time, a mechanism has been developed for oscillating the transverse electrical conductivity and magnetoresistance of a quantum well from the first-order derivative of the magnetic field (differential) $\partial\left(\rho_{\perp}^{2d}\left(E,B,T,d\right)\right)\big/\partial B$ at low temperatures and weak magnetic fields. The oscillations of electrical conductivity and magnetoresistance of a narrow-band quantum well with a non-parabolic dispersion law are investigated. The proposed theory explored the results of experiments with a narrow-band quantum well ($In_xGa_{1-x}Sb$).
Keywords: *semiconductor; conductivity; quantum well; magnetoresistance; magnetic field*
PACS: 73.63.Hs, 73.21.Fg, 73.21.−b

INTRODUCTION

In the presence of a quantizing magnetic field in nanoscale semiconductor structures, not only the optical or magnetic, but also the kinetic properties of free electrons or holes change significantly. The study of the oscillation of longitudinal and transverse magnetoresistance in heterostructures based on quantum wells, along with the Hall measurements, can provide important information about its characteristics, such as the effective masses of free electrons and holes [1,2], the number of occupied zones, spin degeneration, quantum relaxation time and other kinetic parameters [3]. In a series of experiments conducted in the last decade, it was discovered that the kinetic properties of a quantum well subjected to deformation, temperature, ultra-high frequency electromagnetic field, deformation and light in the applied magnetic field provide even richer information for the theory of quantum physics. In particular, in the works [4,5], in the quantum well GaAs, the semiclassical theory of magnetoresistance oscillation during irradiation with microwaves is analyzed. In a quantizing magnetic field, the specific magnetoresistance of the system demonstrates Shubnikov-de Haase oscillations at low temperatures. And also, experimental values were established for the quantum pit GaAs, under the illumination of microwave radiation. In the works [6-23] various experimental techniques have been developed for determining the temperature dependence of the Shubnikov-de Haase oscillation in heterostructures with quantum wells with parabolic and non-parabolic laws of dispersion. For example, in the work [6], quantum oscillation phenomena were observed in heterostructures with quantum wells $Ga_{1-x}In_xN_yAs_{1-y}$ using magnetotransport measurements. Shubnikov-de Haase oscillations are obtained at magnetic fields up to 3 T and temperatures up to 20 K, which are used to determine the effective mass, two-dimensional density of charge and Fermi energy carriers. In the work [7], measurements of magnetic conductivity during compression of quantum wells $In_XGa_{1-X}Sb$ and GaSb are presented. Hall and Van de Pau structures were manufactured and Shubnikov–de Haase oscillations in the temperature range T=2–300 K at magnetic fields B=0–9 T were measured. In these samples, the high mobility of the charge carriers makes it possible to observe the Shubnikov-de Haase oscillation.

And also, in work [8], in the heterostructures of GaInNAs/GaAs with quantum wells doped with modulation of n- and p- type, magnetoresistance measurements were made, both in weak (B < 0.08 T) and in a strong magnetic field (up to 18 T) at temperatures of 75 mK and 6 K. It is shown that quantum oscillations in ρ_{xx} and the quantum Hall effect in ρ_{xy} are affected by the presence of nitrogen in the lattice of $A_{III}B_V$. For such materials, in weak magnetic fields, Shubnikov-de-Haas oscillations develop with higher mobility at a temperature of 6 K, and with an increase in the composition of nitrogen, the amplitude of the Shubnikov-de Haas oscillation decreases.

From the above literature it can be seen that a full-fledged theory has not been built in the heterostructures of quantum wells.

As can be seen from the literature analyzed above, there is no clear and complete theory of the dependence of quantum oscillations on the temperature and magnetic field found in experiments in heterostructures with a quantum well. A new mathematical model has not been developed to determine the temperature dependence of Shubnikov-de Haase oscillations in heterostructural semiconductors with a quantum well through the density of energy states of two-dimensional materials.

[†] *Cite as:* U.I. Erkaboev, R.G. Rakhimov, East Eur. J. Phys. 3, 133 (2023), https://doi.org/10.26565/2312-4334-2023-3-10

The purpose of this work is to simulate the temperature dependence of magnetoresistance oscillation in heterostructures based on quantum wells, taking into account the thermal widening of the two-dimensional density of states.

MODEL

Kinetic equation of charge carriers in nanoscale semiconductor structures in the absence of a quantizing magnetic field

In nanoscale semiconductor structures, the analysis of the electrical conductivity of electrons or holes is carried out using the Boltzmann distribution function $f_n(k)$ and in a homogeneous electric field F, this distribution function satisfies the solutions of the following kinetic equation in the absence of a magnetic field [24,25]:

$$\frac{q}{\hbar}F\nabla_k f_n(k) = \sum_{n`k`} w_{nn`}(k,k`)(f_{n`}(k`) - f_n(k)) \tag{1}$$

Here, q is the charge of the charge carriers, $w_{nn`}(k,k`)$ is probability of scattering per unit time from the $|nk\rangle$ в $|n`k`\rangle$ state, n and n' are the subzone or minizone numbers.

In the case of classical electric fields, when the deviation of the distribution function $\varphi(k)$ from the equilibrium Fermi-Dirac function $f_0(E)$ can be considered small, in the one-minizone approximation the kinetic equation (1) is described as follows:

$$qFv(k)\frac{\partial f_0(E)}{\partial E} = \sum_{k`} w(k,k`)(\varphi(k`) - \varphi(k)) \tag{2}$$

Here, $\varphi(k) = f_1(k) - f_0(E)$; $E = E_1(k)$ is the energy of a free electron or hole in a main subzone or minizone; $v(k)$ is the velocity of a free electron or hole.

To solve equation (2), we can use the approximation of the relaxation time tensor taking into account the anisotropic nature of nanoscale semiconductors and obtain the following expression, in this approximation, to solve equation (2):

$$\varphi(k) = q\left(-\frac{\partial f_0(E)}{\partial E}\right)\sum_i \tau_i(E)F_i v_i(k) \tag{3}$$

In here

$$\frac{1}{\tau_i} = \sum_{k`} w(k,k`)\left(1 - \frac{v_i(k`)}{v_i(k)}\right) \tag{4}$$

The relaxation time tensor component in the principal axes of the tensor is inverse of the effective mass.

Influence of two-dimensional state density on temperature dependence of electrical conductivity oscillation in heterostructures with quantum wells at quantizing magnetic field

Now let's calculate the temperature dependence of the oscillation of longitudinal electrical conductivity in a quantum well when exposed to a quantizing magnetic field. In heterostructures with quantum wells for a two-dimensional free electron or hole, the addition to the distribution function (3), taking into account the symmetry, is written as:

$$\varphi(k) = q\left(-\frac{\partial f_0(E)}{\partial E}\right)\tau_\perp(E)Fv(k) \tag{5}$$

Here, $\tau_\perp = \tau_x = \tau_y$.

In this problem, the induction of the magnetic field is directed along the thickness of the quantum plate and is calculated perpendicular to the plane of the quantum plate (plane XY). Hence, when carrying out theoretical calculations, we introduce transverse electrical conductivity ($\sigma_\perp(E,B)$) perpendicular to the thickness of the quantum well (along the plane XY), one of the kinetic quantities calculated from the thickness of the quantum well is defined as longitudinal electrical conductivity ($\sigma_\parallel(E,B)$).

Using the expression (5) quantizing magnetic field, we can obtain the expression of the transverse electrical conductivity of $\sigma_\perp(E,B)$:

$$\sigma_\perp(E,B) = \sigma_{xx}(E,B) = \sigma_{yy}(E,B) = qn_s\mu_\perp(E,B) = \frac{e^2 n_s\langle\tau_\perp(E,B)\rangle}{m^*} \tag{6}$$

Here, the n_s is concentration of charge carriers for a two-dimensional electron gas; $\mu_\perp$ mobility; m^* is effective mass of the charge carriers in a quantum well. $\langle \tau_\perp(E,B) \rangle$ is the energy-averaged relaxation time of a free electron when exposed to a quantizing magnetic field, and is calculated by the following expression [24,25]:

$$\langle \tau_\perp(E,B) \rangle = \frac{\int_0^\infty N_s^{2d}(E,B)\left(\frac{\partial f_0}{\partial E}\right)\tau_\perp(E)EdE}{n_s} \tag{7}$$

Where, $N_s^{2d}(E,B)$ is the two-dimensional density of energy states in a quantizing magnetic field.

In a quantizing magnetic field, the two-dimensional density of energy states in the conduction zone of the quantum well is taken as the sum of Gaussian peaks [26]:

$$N_s^{2d}\left(E,B,d,n_Z\right) = \frac{eH}{2\pi c}\sum_{n_L}\sqrt{\frac{2}{\pi}}\frac{1}{G}\exp\left[-2\left(\frac{E-\left[\hbar\omega_c\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m^*d^2}n_Z^2\right]}{G}\right)^2\right] \tag{8}$$

Where, n_L is the number of Landau levels. $\omega_c = \frac{eH}{mc}$ is a cyclotron frequency. G is a widening parameter that is assumed to be constant.

In a strong magnetic field, two-dimensional electron systems of non-interacting electrons are considered according to the parabolic law of dispersion at low temperature T. In addition to the Gaussian peak of state density, at each Landau level there is a common multiplier of the magnetic field B before the total density of energy states. This means that as magnetic field B increases, each Landau level can contain more and more electrons. According to (8), there is no density of states between Landau levels if their distance $h\omega_c$ is noticeably greater than G.

Calculation of the temperature dependence of transverse electrical conductivity in quantum wells when exposed to a quantizing magnetic field

For the basic mechanisms, in massive semiconductors in the approximation of elastic scattering, the dependence of $\tau_3(E,T)$ relaxation time on energy and temperature is of a power nature [27]:

$$\tau_3(E,T) = \gamma_3(k_0T)^\beta E^\alpha \tag{9}$$

For free electrons in a quantum well, the change in the density of states and the energy spectrum, taking into account dimensional quantization, leads to the following equation [28]:

$$\tau_\perp / \tau_3 = \gamma dk_\perp = \gamma d\sqrt{\frac{2m^*E}{\hbar^2}} \sim E^{\frac{1}{2}} \tag{10}$$

From (10), we get:

$$\tau_\perp = \gamma_\perp(k_0T)^\beta E^{\alpha+\frac{1}{2}} \tag{11}$$

Here, d is the thickness of the quantum well. Taking into account (7), (8) and (11), the dependence of transverse electrical conductivity on the quantizing magnetic field and temperature in heterostructures with quantum wells takes the following form:

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

Thus, we can determine the temperature dependence of the oscillation of electrical conductivity in a quantum well when exposed to a quantizing magnetic field. And so, a new analytical expression was derived for calculating the oscillation of electrical conductivity in heterostructures with quantum wells in the presence of temperature and a magnetic field, based on the equation (12). Using equation (12), it is possible to analyze some experimental results at different temperatures and magnetic fields. In addition, using the equation (12), it is possible to calculate the temperature dependence of the oscillation of transverse magnetoresistance in the conduction zone of the quantum well in the presence of a quantizing magnetic field. Then, for a heterostructure based on a quantum well, the change in the oscillation of the transverse magnetoresistance $\rho_{\perp}^{2d}(E,B,T,d)$ with respect to temperature and quantizing magnetic field is determined in the following new analytical expression:

$$\rho_{\perp}^{2d}(E,B,T,d)=1/\sigma_{\perp}^{2d}(E,B,T,d)$$

$$\rho_{\perp}^{2d}(E,B,T,d)=\frac{1}{\left[\begin{array}{l}\dfrac{e^3B}{2\pi m^*c}\sqrt{\dfrac{2}{\pi}}\dfrac{1}{G}\cdot\\ \displaystyle\int_0^{\infty}\sum_{n_L}\exp\left[-2\left(\frac{E-\left[\hbar\omega_c\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m^*d^2}n_Z^2\right]}{G}\right)^2\right]\gamma_{\perp}(k_0T)^{\beta}E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE\end{array}\right]} \tag{13}$$

RESULTS AND DISCUSSION

Now, based on equations (12) and (13), let's consider the dependences $\sigma_{\perp}^{2d}(E,B,T,d)$ and $\rho_{\perp}^{2d}(E,B,T,d)$ on the graph. As can be seen from the new analytical expressions obtained, the term under the integral is a very complex function with respect to the energy E. That is, it is impossible to obtain an exact result by integrating it, and we will use a computer program to obtain $\sigma_{\perp}^{2d}(E,B,T,d)$ and $\rho_{\perp}^{2d}(E,B,T,d)$.

Figure 1 shows the dependence of the oscillation of the transverse electrical conductivity on the magnetic field (Figure 1a) and the reverse induction of the magnetic field (Figure 1b) in heterostructures based on the quantum well $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ at constant low temperatures. Here, the parameters of the quantum well $In_{0.53}Ga_{0.47}As$ are equal to the following value: the thickness of the quantum well $d = 16.8\ nm$, the effective mass of electrons in the conduction band of the quantum well $m_n = 0.059m_0$, the widening parameter $G = 0.5\ meV$ and the temperature $T = 4.2K$ [27].

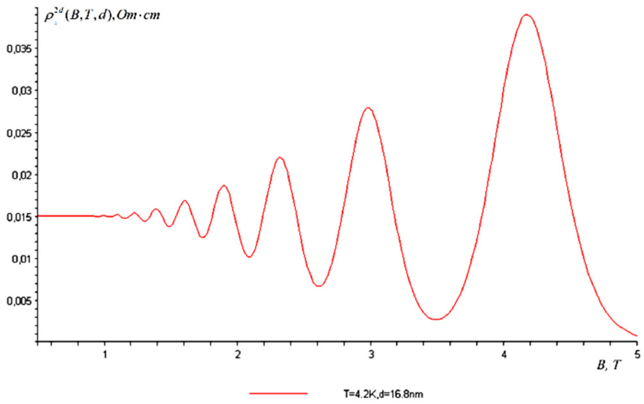

Figure 1a. Dependence of the oscillations of the transverse electrical conductivity on the magnetic field in heterostructures based on the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well at temperatures T=4.2 K.

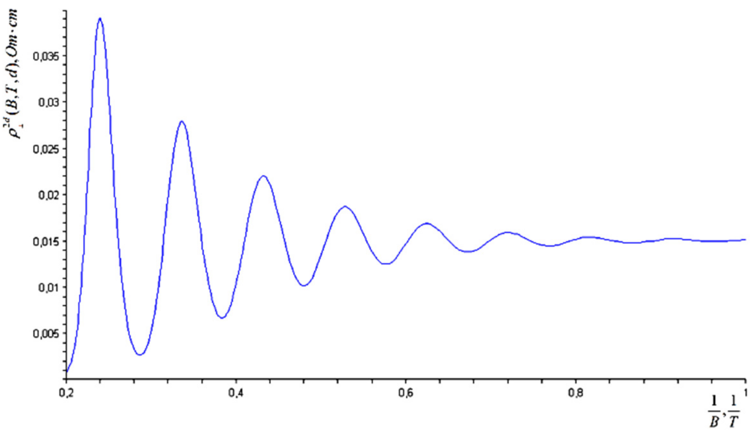

Figure 1b. Dependence of the oscillations of the transverse electrical conductivity on the reverse magnetic field induction in heterostructures based on the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well at temperatures T=4.2 K.

In this case, when constructing the $\sigma_{\perp}^{2d}(E,B,T,d)$ graph, the number of Landau levels was taken as $n_L = 8$, and the number of dimensional quanta (the number of dimensional quanta) as $n_Z = 1$. In the figures, there is a sharp increase in the amplitude of fluctuations in electrical conductivity in the conductivity zone of the quantum well $In_{0.53}Ga_{0.47}As$ at magnetic field induction values of 1.5 T and above. Figure 2 shows the effect of temperature on the dependence of the oscillation of transverse electrical conductivity on the induction of the magnetic field (Figure 2a) and the reverse induction of the magnetic field (Figure 2b) in heterostructures based on the quantum well $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ with a parabolic law of dispersion. As can be seen from these figures, with increasing temperature, the amplitude of the oscillation of electrical conductivity in the conduction band of the quantum well $In_{0.53}Ga_{0.47}As$ decreases. At sufficiently high temperatures, for example, at T = 40 K, magnetoresistance oscillations do not feel the quantizing magnetic field and do not observe oscillations of kinetic parameters. Because in nanoscale semiconductor materials to observe the effects of quantum oscillations, the thermal energy of the free charge carriers must be much smaller than the difference between two adjacent discrete energy levels.

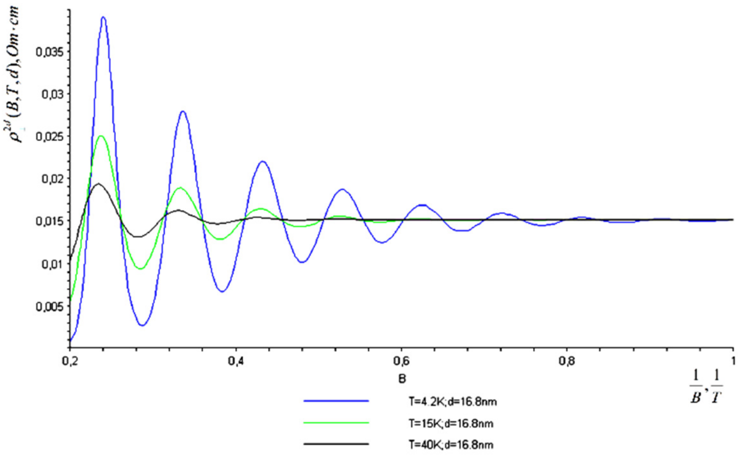

Figure 2a. Influence of temperature on the dependence of transverse electrical conductivity oscillations on magnetic field induction in heterostructures based on quantum well $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$

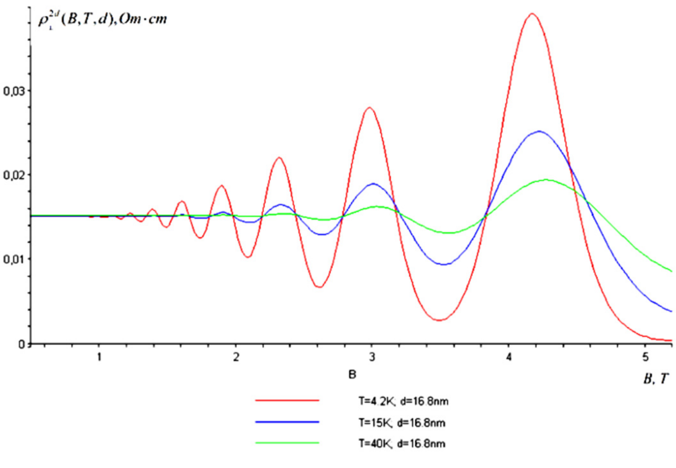

Figure 2b. Influence of temperature on the dependence of the oscillation of transverse electrical conductivity on the reverse induction of the magnetic field in heterostructures based on the quantum well $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$

Figure 3a shows the oscillations of the transverse magnetoresistance $\rho_{\perp}^{2d}(E,B,T,d)$ in the conduction band of the $In_{0.53}Ga_{0.47}As$ quantum well at low constant temperatures T=4.2K. This $\rho_{\perp}^{2d}(E,B,T,d)$ graph is obtained using equation(11). If we observe fluctuations in the induction of the quantizing magnetic field in the range from 0.5 T to 3.5 T, then the maximum value of the amplitude of the magnetic resistance of the quantum coil is about 1000 Om. With increasing temperature, a decrease in the amplitude of oscillations of the transverse conductivity is observed (Figure 3b). When the temperature reaches 40K, when the magnitude of the quantizing magnetic field reaches almost 3 T, the $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations begin to disappear, that is, the influence of the quantizing magnetic field becomes not noticeable. However, as the temperature decreases, the quantizing magnetic field begins to increase its effect. In a simplified way, this can be explained as follows: statistical physics is applied to these quantum effects, i.e. the temperature dependence of $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations is studied by thermal smearing (or thermal broadening).

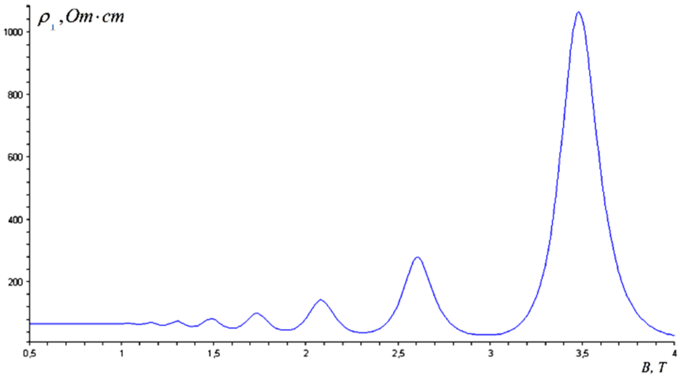

Figure 3a. Oscillations of transverse magnetoresistance $\rho_{\perp}^{2d}(E,B,T,d)$ in the conduction zone of the quantum well $In_{0.53}Ga_{0.47}As$ at temperatures T = 4.2 K.

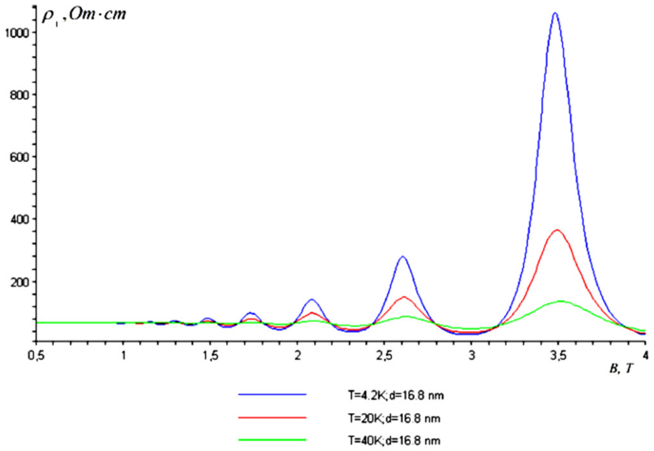

Figure 3b. Effect of temperature on oscillations of transverse magnetoresistance $\rho_{\perp}^{2d}(E,B,T,d)$ in the conduction zone of the quantum well $In_{0.53}Ga_{0.47}As$

It is known that the temperature dependence of oscillations of the density of energy states in two-dimensional and three-dimensional semiconductor materials has been studied in detail from a theoretical point of view in works [27, 28]. At the same time, a new mathematical model was developed. The equation (8) for constantly low temperatures shows the dependence of the energy density oscillations of the $N_s^{2d}\left(E,B,n_L,d,n_Z\right)$ states in two-dimensional semiconductor materials on the energy and magnetic field. The energy derivative of the Fermi-Dirac distribution function gives the delta function of $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$ at very low temperatures, with the height of $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$ decreasing and the width increasing with increasing temperature. Hence, the thermal widening of Landau levels is determined with the help of the $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$ function. However, as can be seen from the work [27,28], the oscillation of the quantum effect is carried out by observing $N_s^{2d}\left(E,B,n_L,d,n_Z\right)$. Therefore, by decomposing $N_s^{2d}\left(E,B,n_L,d,n_Z\right)$ into a series of $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$, oscillations of the transverse magnetoresistance of $\rho_{\perp}^{2d}(E,B,T,d)$ heterostructural semiconductors with a quantum well depending on temperature are determined.

In addition, using the analytical expression (13), one can analyze the dependence of the $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations of the transverse magnetoresistance of heterostructural semiconductors with quantum wells. Figure 4 shows the dependence of the oscillations of the transverse magnetoresistance of the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure on the thickness of the $In_{0.53}Ga_{0.47}As$ quantum well with a parabolic dispersion law. Here, $\rho_{\perp}^{2d}(E,B,T,d)$ at a quantizing magnetic field B = 3.5 T:

$$\rho_{\perp}^{2d}(T=3K,d=16,8nm)=1000\,Om;\quad \rho_{\perp}^{2d}(T=3K,d=14,8nm)=1100\,Om;$$
$$\rho_{\perp}^{2d}(T=3K,d=12,8nm)=1200\,Om$$

Thus, with a decrease in the thickness of the quantum well, the amplitude of the oscillations of the transverse magnetoresistance increases. Hence, we can conclude that the height of discrete Landau levels in two-dimensional semiconductor materials depends both on the temperature and on the thickness of the quantum well. In order to observe oscillations of the quantum effect even at higher temperatures, it is proposed that the thickness of the quantum well be as close as possible to the de Broglie length.

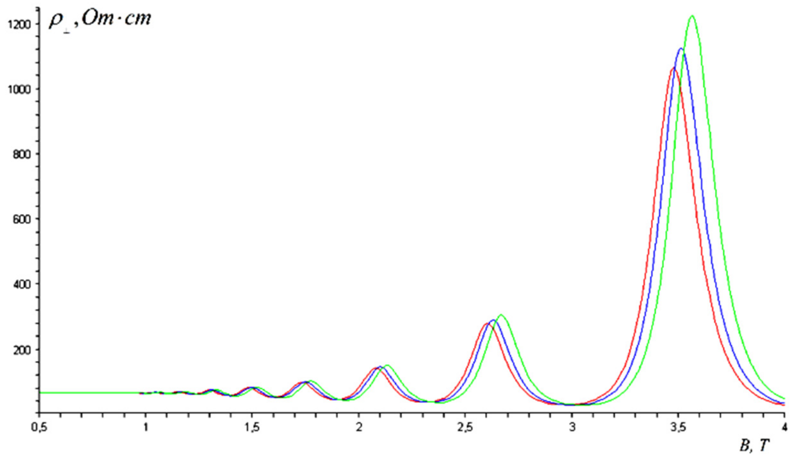

Figure 4. Dependence of the oscillation of transverse magnetoresistance of the heterostructure $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ on the thickness of the quantum well $In_{0.53}Ga_{0.47}As$ with a parabolic law of dispersion.

Calculation of the temperature dependence of differential oscillations of magnetoresistance $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ heterostructure with quantum well

As mentioned above, to observe the oscillation of the quantum effect in bulk and two-dimensional semiconductor materials, it is necessary to meet the conditions of a strong magnetic field and a very low temperature. Let's estimate the discrete quantum energy of a quantizing magnetic field and a quantum well at very low temperatures and the thermal energy of an electron corresponding to this energy level. In Figure 3a, the value of the induction of the magnetic field oscillations $\rho_{\perp}^{2d}(E,B,T,d)$ is calculated from 0.5 T to 4 T and at a temperature of 3 K. Temperature at T= 3 K $\frac{k}{e}T = 2{,}6\cdot 10^{-4}\,eV$. At a magnetic field B= 1, $\hbar\frac{eB}{m}\Big/e = 12.4\cdot 10^{-3}\,eV$.

Hence, $\frac{\hbar\frac{eB}{m}}{kT}\approx 48$, i.e. $\hbar\frac{eB}{m} >> kT$. Although this estimate is completely subject to the conditions for the formation of quantum oscillatory effects in heterostructures with quantum wells, however, as can be seen from Figure 3a, oscillatory processes are clearly observed starting from 1.5 T. Why is this happening? With a magnetic field of 0.6 T, 1 T or 1.2 T, oscillations of the transverse magnetoresistance are not formed in the conduction field of the quantum coil, or does it seem that the obtained analytical expression (13) is not fully satisfied? This process is explained as follows. The value of the transverse magnetoresistance of a quantum well semiconductor varies greatly due to the magnetic field induction. From here, according to the differential law of resistance, the first derivative of the magnetic field induction is obtained according to the equation (13).

That is:

$$\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}=\frac{e^3}{2\pi m^*c}\sqrt{\frac{2}{\pi}}\frac{1}{G}=\frac{\partial\left[B\int\limits_0^{\infty}\sum_{n_L}\exp\left[-2\left(\frac{E-\left[\hbar\frac{eB}{m_n^*}\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m^*d^2}n_Z^2\right]}{G}\right)^2\right]\gamma_{\perp}(k_0T)^{\beta}E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE\right]^{-1}}{\partial B} \tag{14}$$

From a theoretical point of view, taking the derivative of the magnetic field induction from equation (14) and obtaining its graph is a very difficult task. However, implementation using computer programs allows you to evaluate both accuracy and quality. To compare the graphical results obtained by equations (13) and (14), we consider them in the same coordinate system.

In Figure 5 shows the dependence of $\rho_{\perp}^{2d}(E,B,T,d)$ and $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ on the weak induction of the magnetic field at T=3 K in the heterostructure $In_{0.52}Al_{0.48}As$ / $In_{0.53}Ga_{0.47}As$ / $In_{0.52}Al_{0.48}As$ with a quantum well $In_{0.53}Ga_{0.47}As$. In this case, the number of Landau levels is n_L=7, and the dimensional quantum number is n_Z=1. Magnetic field induction was obtained in the range from 0.6 T to 1.22 T.

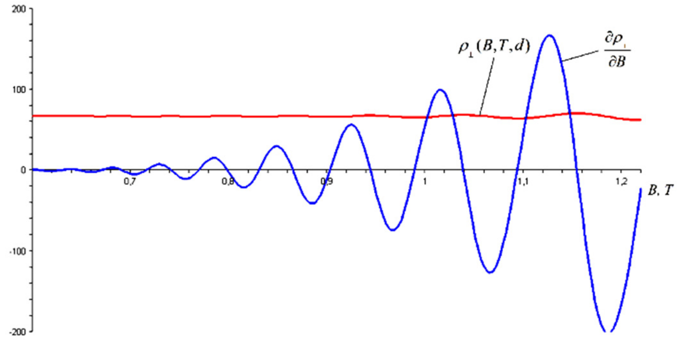

Figure 5. Dependence of $\rho_{\perp}^{2d}(E,B,T,d)$ and $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ on weak induction of the magnetic field at T = 3 K in heterostructures $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ with a quantum well $In_{0.53}Ga_{0.47}As$.

As in Figure 3a, $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations at 0.6÷1.22 T are practically not formed due to a too low magnetic field. However, the graph of its first order derivative with respect to the magnetic field $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ is completely different from $\rho_{\perp}^{2d}(E,B,T,d)$. That is, this indicates the presence of quantum effects, that is, Landau levels, even at low temperatures and weak magnetic fields. In fact, the purpose of taking the derivative of the magnetoresistance with respect to *B* was the same, that is, it was necessary to feel the magnetic field increased by one standard. At the same time, both positive and negative magnetoresistances can be observed on the $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ graph. In conclusion, we can say that the differential magnetoresistance of an $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ heterostructure with a quantum well makes it possible not only to study the sensitivity to the influence of a magnetic field in weak magnetic fields using equation (13), but also to visually observe the number of discrete Landau levels using equation (14).

Now consider how the oscillations of the differential magnetoresistance of $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ depend on temperature. As in Figure 3b, we will change the value of the induction of the magnetic field by 4 T and the temperature from 4.2 K to 40 K. As a result, a graph of the temperature dependence of fluctuations according to the equation (14) is obtained (Figure 6).

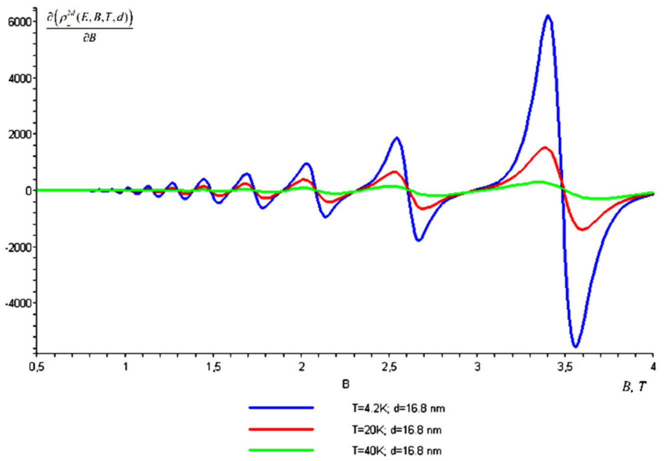

Figure 6. Influence of temperature on differential magnetoresistance $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ in quantum well $In_{0.53}Ga_{0.47}As$.

As can be seen from Figure 6, there is a decrease in the amplitude of oscillations of the differential magnetoresistance of $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ with increasing temperature. This leads to a decrease in the height of the discrete landau peaks and an increase in their width due to thermal expansion. In general, this leads to the fact that the effect of temperature on the differential oscillations of the magnetoresistance of $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ coincides with the above theoretical base.

Determination of transverse magnetoresistance oscillation in heterostructures based on narrow-band quantum wells with nonparabolic dispersion law

Let's analyze quantum oscillation phenomena for electrons and light holes in heterostructures based on narrow-band quantum wells when exposed to a strong magnetic field, with a non-parabolic law of dispersion. For the parabolic law of dispersion, the effective mass of charge carriers does not depend on its energy, but if the law of dispersion is non-quadratic, then the effective masses of charge carriers vary greatly in energy in the permitted zone of the quantum well.

The energy of charge carriers in the conduction band under the action of a quantizing magnetic field for a non-parabolic dispersion law in bulk semiconductor materials with a narrow band is calculated by the following expression [29]:

$$E_{N\pm}^{3d}(B)=-\frac{E_g^{3d}}{2}+\frac{1}{2}\sqrt{\left(E_g^{3d}\right)^2+4E_g^{3d}\left[\left(N+\frac{1}{2}\right)\hbar\omega_c+\frac{\hbar^2k_z^2}{2m_n}\pm\frac{g_0\mu_BH}{2}\right]}. \tag{15}$$

Here E_g^{3d} is the band gap of the bulk semiconductor material; $g_0\mu_BH$ - spin energy of charge carriers.

If the induction of the quantizing magnetic field is applied along the quantum well thickness (parallel to the Z axis) and perpendicular to the XY quantum well plane, assume that the band gap depends on the quantum well thickness, and take into account that the value of the spin energy is much less than the sum of the quantum and the magnetic field energy, then expression (13) takes the form:

$$E_N^{2d}(B,d)=-\frac{E_g^{2d}}{2}+\frac{1}{2}\sqrt{\left(E_g^{2d}\right)^2+4\left(E_g^{2d}\right)\left[\left(n_L+\frac{1}{2}\right)\hbar\omega_c+\frac{\pi^2\hbar^2}{2m_nd^2}n_z^2\right]}. \tag{16}$$

Here, $\frac{1}{\mu_n}=\frac{1}{m_n}+\frac{1}{m_p}$; $E_g^{2d}=E_g^{3d}+\frac{\pi^2\hbar^2}{2\mu_nd^2}n_z^2$

Equation (16) expresses the dependence of the narrow-field quantum well on the magnetic field, which quantizes the energy of free electrons in the conduction field for the nonparabolic dispersion law. It can be seen that the energy of free electrons in the conduction region of a narrow-gap quantum well under the action of a quantizing magnetic field strongly varies non-squarely with the band gap and quantum well thickness. This relation certainly strongly affects the two-dimensional energy density of states (8). Hence it follows that the oscillations of the magnetoresistance of a quantum well with a nonparabolic dispersion law differ significantly from the parabolic law. Consequently, the $\left[\hbar\omega_c\left(n_L+\frac{1}{2}\right)+\frac{\pi^2\hbar^2}{2m^*d^2}n_Z^2\right]$ term in expression (8) is the total energy of free electrons in the conduction field of a quantum well in a quantizing magnetic field for the parabolic dispersion law. In the non-parabolic dispersion law, the total energy is determined by expression (16). Then, substituting (16) into (8), we obtain an expression for the two-dimensional energy density of states in a quantizing magnetic field for the nonparabolic dispersion law:

$$N_{s,noparabolic}^{2d}\left(E,B,E_g^{2d},n_L,d,n_Z\right)=\frac{eH}{2\pi c}\sqrt{\frac{2}{\pi}}\frac{1}{G}\sum_{n_L}\exp\left[-2\left(\frac{E-\left[-\frac{E_g^{2d}}{2}+\frac{1}{2}\sqrt{\left(E_g^{2d}\right)^2+4\left(E_g^{2d}\right)\left[\left(n_L+\frac{1}{2}\right)\hbar\omega_c+\frac{\pi^2\hbar^2}{2m_nd^2}n_z^2\right]}\right]}{G}\right)^2\right] \tag{17}$$

It follows from this equation that, for a nonparabolic dispersion law, the quantum field depends on the magnetic field, which quantizes the density of energy states in the conduction region. It can be seen that equations (8) and (17) are fundamentally different from a mathematical point of view. In this case, if the band gap is narrow, then it is recommended to use equation (17), otherwise equation (8), i.e. if the semiconductor is wide-gap. We can also understand this by substituting (17) into (13) to get the following new analytic expression:

$$\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d})=\left[\frac{e^3B}{2\pi m^*c}\sqrt{\frac{2}{\pi}}\frac{1}{G}\gamma_\perp(k_0T)^\beta\cdot\int_0^\infty N^{2d}_{s,noparabolic}\left(E,B,E_g^{2d},n_L,d,n_Z\right)E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE\right]^{-1} \quad (18)$$

Analytical expression (18) is suitable mainly for heterostructural materials with narrow-field quantum wells, since the energy spectrum of narrow-gap semiconductors mainly obeys the non-parabolic dispersion law.

Now let's compare $\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d})$ and $\rho^{2d}_{\perp parabolic}(E,B,T,d,E_g^{2d})$ for two dispersion laws and look at their fluctuations at different magnetic fields and temperatures. The thickness of the InAs/GaInSb/InAs semiconductor heterostructure with a narrow-gap quantum well (InAs - quantum well) is 3.36 nm [30], the volume band gap is 0.426 eV at T=0 K [31], the effective mass of a free electron in the conduction field $m_n=0.026m_0$. Substituting these experimental values into the proposed analytical expressions (13) and (18), we calculate the oscillations of the transverse magnetoresistance of the InAs/GaInSb/InAs quantum well at T=4 K and obtain graphical results for $\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d})$ and $\rho^{2d}_{\perp parabolic}(E,B,T,d,E_g^{2d})$ (Figure 7). As can be seen from this figure, one can observe that the oscillations of the transverse magnetoresistance of the quantum well obtained for the parabolic and nonparabolic dispersion laws are fundamentally different. In conclusion, we can say that if the quantum well consists of a narrow-gap semiconductor, it is proposed to calculate the oscillations of the transverse magnetoresistance by expression (18), and if the material of the quantum well is classical and wide-gap, then it is proposed to calculate by equation (13).

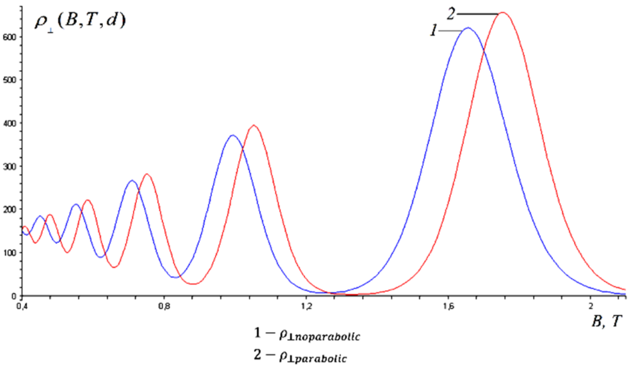

Figure 7. Comparison of transverse magnetoresistance oscillation for $\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d})$ and $\rho^{2d}_{\perp parabolic}(E,B,T,d,E_g^{2d})$ in the quantum well InAs/GaInSb/InAs at T=4 K

Comparison of experimental results with theory and their discussion

This work mainly presents the results of a comparison of experimental and theoretical studies of the oscillations of the transverse magnetoresistance on the example of a heterostructure with narrow quantum wells $In_xGa_{1-x}Sb$ [7]. The band gap and thickness of the quantum well of this material is $E_g^{3d}=0,49\,eV$ [32] and d=7.5 nm, and the effective mass of charge carriers is $m_n=0.06m_0$ [7]. In this work, oscillations of the transverse magnetoresistance of $In_xGa_{1-x}Sb$ are observed at a temperature of 2 K and at quantizing magnetic fields from 3 T to 9 T (Figure 8). Since this material is a narrow gap semiconductor with quantum wells, it obeys a non-parabolic dispersion law. From here, using the above experimental physical parameters, the oscillations of the transverse magnetoresistance of the $In_xGa_{1-x}Sb$ quantum well at a temperature of 2 K are theoretically calculated using equation (18). In Figure 9 shows the $\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d})$ graph of the theoretically calculated $In_xGa_{1-x}Sb$ quantum well. It can be seen that the experimental (Figure 8) and theoretical (Figure 9) results are very close to each other in terms of quality. If we look at the experimental results, then the oscillations of the $In_xGa_{1-x}Sb$ quantum well practically do not appear in the range of magnetic field induction values from 1 T to 2.9 T.

As if, at a temperature of 2 K and a magnetic field of 2.5 T, Landau levels are not visible, there is no quantization process. Although, on the graph obtained from a theoretical point of view, the amplitude of the magnetoresistance is formed precisely in this magnetic field, since the condition $kT \ll \hbar\omega c$ is satisfied. Even at such a very low temperature, the induction of the magnetic field must already be a quantization process at 1.5 T. This can also be observed on the $\frac{\partial\left(\rho^{2d}_{\perp nonparabolic}(E,B,T,d)\right)}{\partial B}$ plot using equations (14) for the non-parabolic dispersion law, i.e. differentiating equation (18) with respect to the magnetic field (Figure 10). Therefore, one should not rush to draw conclusions on the basis of oscillation amplitudes not seen in the experiment, i.e. it is necessary to rework it from a theoretical point of view, check it through quantization conditions, and in the process, it is necessary to study the state of charge carriers in perfection. This can be seen by comparing the experimental (Figure 8) and theoretical (Figure 10) results. Let us analyze the experimental oscillations of the transverse magnetoresistance according to the equation (18) using the dynamics of the temperature increase (Figure 11). On Figure 11 shows a three-dimensional graph of the oscillations of the transverse magnetoresistance of the $In_xGa_{1-x}Sb$ quantum well as a function of temperature and magnetic field. This three-dimensional graph is obtained from a theoretical point of view by substituting experimental values into equation (18). As can be seen from Figure 11, with increasing temperature, the amplitude of oscillations of the transverse magnetoresistance of the quantum coil decreases, and a broadening of the peak is observed. This is called thermal blur. This means that, due to thermal smearing, as the temperature rises from 40 K, the discrete Landau levels are transformed into continuous energy spectra. At the same time, it is possible to analyze the dependence of this experimental graph on the thickness of the quantum well using equations obtained from the theoretical side. In addition, with the help of the proposed new theory or the obtained new equation, it becomes possible to determine the dependence of external factors on experimental oscillations of the transverse magnetoresistance in bulk heterostructures with quantum wells.

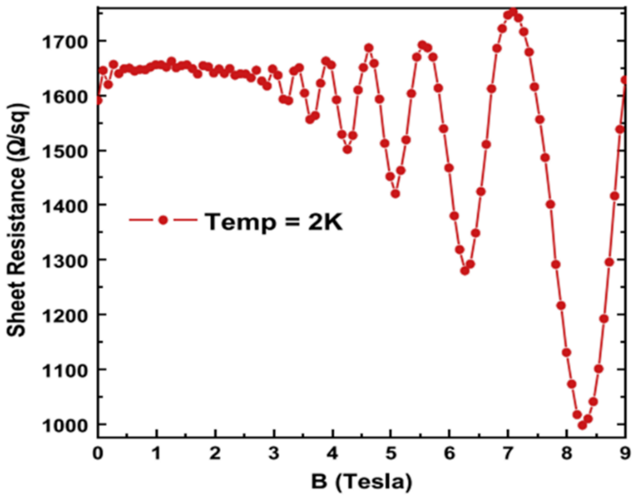

Figure 8. Oscillations of transverse magnetoresistance of the quantum well $In_xGa_{1-x}Sb$ at a temperature of 2 K [7].

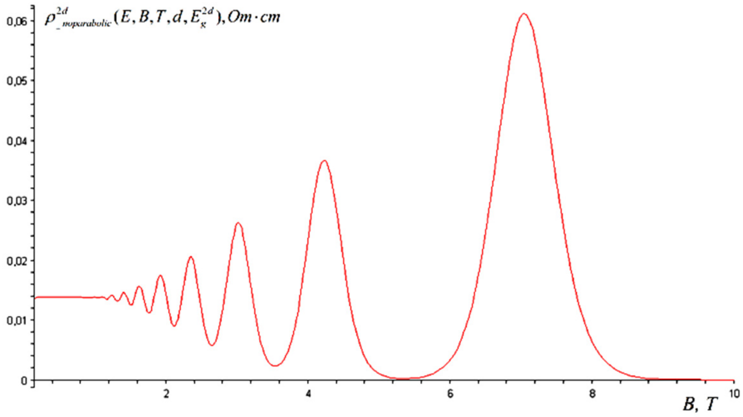

Figure 9. Oscillations of transverse magnetoresistance of the quantum well $In_xGa_{1-x}Sb$ at a temperature of 2 K, our results

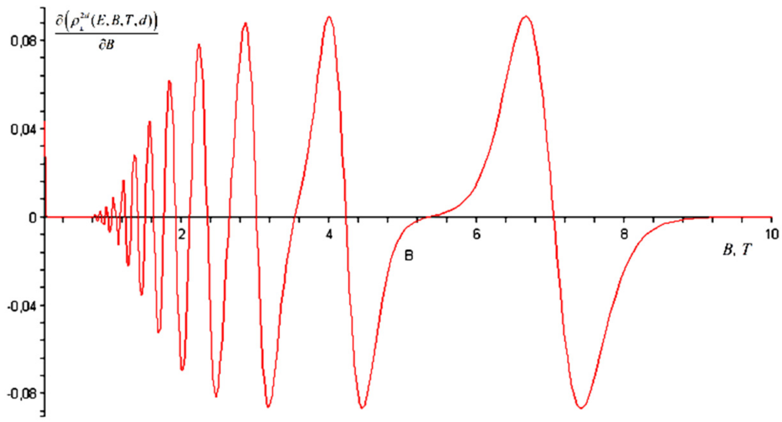

Figure 10. Dependence of $\frac{\partial\left(\rho^{2d}_{\perp nonparabolic}(E,B,T,d)\right)}{\partial B}$ on the magnetic field for narrow-band quantum wells $In_xGa_{1-x}Sb$ at a temperature of T = 2 K.

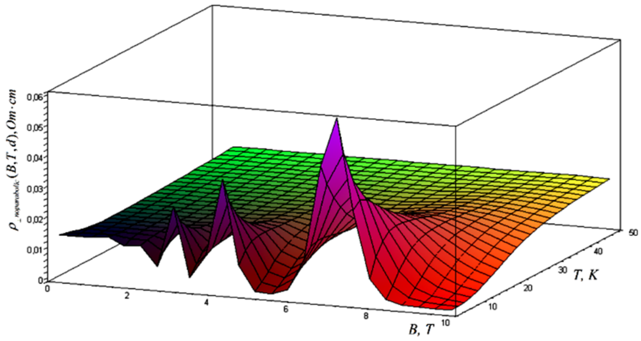

Figure 11. View of a three-dimensional graph of the oscillation of the transverse magnetoresistance of the quantum well $In_xGa_{1-x}Sb$

CONCLUSIONS.

Based on the study, the following conclusions can be drawn: A new analytical expression is derived for calculating the temperature dependence of the oscillations of the transverse electrical conductivity and magnetoresistance of a quantum well. A mechanism has been developed for the oscillation of the transverse electrical conductivity and magnetoresistance of a quantum well from the first-order derivative of the magnetic field (differential) $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ at low temperatures and weak magnetic fields. Oscillations of the electrical conductivity and magnetoresistance of a narrow-window quantum well with a nonparabolic dispersion law are studied. The proposed theory was used to study the results of experiments on a narrow-gap quantum well ($In_xGa_{1-x}Sb$). The Landau levels of the $In_xGa_{1-x}Sb$ quantum well in weak magnetic fields, which were not observed in the experiment, oscillate. This has been proven through the $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ theory of magnetoresistance. The experiment shows that the oscillations of the transverse magnetoresistance of the $In_xGa_{1-x}Sb$ quantum filament, measured at a temperature of 2 K, transform into a continuous energy spectrum due to thermal washing under the influence of the temperature growth dynamics.

ORCID

Ulugbek I. Erkaboev, https://orcid.org/0000-0002-6841-8214; **Rustamjon G. Rakhimov,** https://orcid.org/0000-0003-0850-1398

REFERENCES

[1] N.A. Yuzeeva, G.B. Galiev, E.A. Klimova, L.N. Oveshnikov, R.A. Lunin, and V.A. Kulbachinskii, Phys. Procedia, **72**, 425 (2015). https://doi.org/10.1016/j.phpro.2015.09.087
[2] V. Tarquini, T. Knighton, Zh. Wu, J. Huang, L. Pfeiffer, and K. West, Appl. Phys. Lett. **104**, 092102 (2014). https://doi.org/10.1063/1.4867086
[3] I.B. Berkutov, V.V. Andrievskii, Yu.F. Komnik, Yu.A. Kolesnichenko, R.J.H. Morris, and D.R. Leadley, Low Temp. Phys. **38**, 1145 (2012). https://doi.org/10.1063/1.4770520
[4] Y. Abdullah, and S. Kashif, J. Phys. Condens. Matter, **27**, 435007, (2015). https://doi.org/10.1088/0953-8984/27/43/435007
[5] A. Bogan, A.T. Hatke, S.A. Studenikin, A. Sachrajda, M.A. Zudov, L.N. Pfeiffer, and K.W. West, J. Phys. Conf. Ser. **456**, 012004 (2013). https://doi.org/10.1088/1742-6596/456/1/012004
[6] B.T. Abdulazizov, Eurasian J. Phys. Funct. Mater. **6**, 32 (2022). https://doi.org/10.32523/ejpfm.2022060103
[7] F. Sarcan, A. Erol, M. Gunes, M.Ç. Arikan, J. Puustinen, and M. Guina, Nanoscale Res. Lett. **9**, 141 (2014). https://doi.org/10.1186/1556-276X-9-141
[8] G. Gulyamov, U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, and N.A. Sayidov, Mod Phys Lett B. **37**, 2350015 (2023). https://doi.org/10.1142/S021798492350015X
[9] B.T. Abdulazizov, G. Gulyamov, P.J. Baymatov, Sh.T. Inoyatov, M.S. Tokhirjonov, and Kh.N. Juraev, SPIN. **12**, 2250002 (2022). https://doi.org/10.1142/S2010324722500023
[10] F. Nutku, O. Donmez, F. Kuruoglu, S. Mutlu, A. Erol, S. Yildirim, and M.C. Arikan, J. Phys. D: Appl. Phys. **48**, 305108 (2015). https://doi.org/10.1088/0022-3727/48/30/305108
[11] P.J. Baymatov, A.G. Gulyamov, B.T. Abdulazizov, Kh.Yu. Mavlyanov, and M.S. Tokhirjonov, Int. J. Mod. Phys. B, **35**, 2150070 (2021). https://doi.org/10.1142/S0217979221500703
[12] G. Gulyamov, U.I. Erkaboev, R.G. Rakhimov, and J.I. Mirzaev, J. Nano- Electron. Phys. **12**, 03012 (2020). https://doi.org/10.1142/S0217979220500526
[13] U.I. Erkaboev, G. Gulyamov, J.I. Mirzaev, and R.G. Rakhimov, Int. J. Mod. Phys. B, **34**, 2050052 (2020). https://doi.org/10.1142/S0217979220500526
[14] G. Gulyamov, B.T. Abdulazizov, and P.J. Baymatov, J. Nanomater. **2021,** 5542559 (2021). https://doi.org/10.1155/2021/5542559
[15] G. Gulyamov, U.I. Erkaboev, N.A. Sayidov, and R.G. Rakhimov, J. Appl. Sci. Eng. **23**, 453 (2020). https://doi.org/10.6180/jase.202009_23(3).0009
[16] Ch.T. Tai, P.Y. Chiu, Ch.Y. Liu, H.Sh. Kao, C.Th. Harris, T.M. Lu, Ch.T. Hsieh, Sh.W. Chang, and J.Y. Li, Adv. Mater. **33**, 2007862 (2021). https://doi.org/10.1002/adma.202007862

[17] F.S. Pena, S. Wiedmann, E. Abramof, D.A.W. Soares, P.H.O. Rappl, S. Castro, and M.L. Peres, Phys. Rev. B, **103**, 205305 (2021.) https://doi.org/10.1103/PhysRevB.103.205305
[18] U.I. Erkaboev, G. Gulyamov, J.I. Mirzaev, R.G. Rakhimov, and N.A. Sayidov, Nano, **16**, 2150102 (2021). https://doi.org/10.1142/S0217984921502936
[19] U.I. Erkaboev, R.G. Rakhimov, and N.A. Sayidov, Mod. Phys. Lett. B, **35**, 2150293 (2021). https://doi.org/10.1142/S0217984921502936
[20] P.J. Baymatov, A.G. Gulyamov, and B.T. Abdulazizov, Adv. Condens. Matter Phys. **2019**, 8317278 (2019). https://doi.org/10.1155/2019/8317278
[21] N.Q. Bau, and B.D. Hoi, Int. J. Mod. Phys. B, **28**, 1450001 (2014). https://doi.org/10.1142/S0217979214500015
[22] U.I. Erkaboev, R.G. Rakhimov, N.A. Sayidov, and J.I. Mirzaev, Indian J. Phys. **97**, 1601 (2023). https://doi.org/10.1007/s12648-022-02435-8
[23] U.I. Erkaboev, U.M. Negmatov, R.G. Rakhimov, J.I. Mirzaev, and N.A. Sayidov, Int. J. Appl. Sci. Eng. **19**, 2021123(2022). https://doi.org/10.6703/IJASE.202206_19(2).004
[24] I.B. Berkutov, V.V. Andrievskii, Yu.F. Komnik, and O.A. Mironov, Low Temp. Phys. **36**(12), 1076 (2010). https://doi.org/10.1063/1.3536348
[25] A.Ya. Shik, L.G. Bakueva, S.F. Musikhin, and S.A. Rykov, *Physics of low-dimensional system*, (Press “Science”, Saint Petersburg, 2001).
[26] U.I. Erkaboev, G. Gulyamov, and R.G. Rakhimov, Indian J. Phys. **96**, 2359 (2022). https://doi.org/10.1007/s12648-021-02180-4
[27] W. Zawadzki, A. Raymond, and M. Kubisa, Phys. Status Solidi B, **251**(2), 247 (2013). https://doi.org/10.1002/pssb.201349251
[28] A.I. Anselm, Phys.-Uspekhi. **85**(1), 183 (1965). https://doi.org/0.3367/UFNr.0085.196501f.0183
[29] G. Gulyamov, U.I. Erkaboev, and P.J. Baymatov, Adv. Condens. Matter Phys. **2016**, 5434717 (2016). https://doi.org/10.1155/2016/5434717
[30] P.J. Baymatov, and B.T. Abdulazizov, Ukr. J. Phys. **62**(1), 46 (2017). https://doi.org/10.15407/ujpe62.01.0046
[31] V.N. Brudnyi, N.G. Kolin, and A.I. Potapov, Semiconductors, **37**(4), 390 (2003). https://doi.org/10.1134/1.1568456
[32] R. Magno, E.R. Glaser, B.P. Tinkham, J.G. Champlain, J.B. Boos, M.G. Ancona, and P.M. Campbell, J. Vac. Sci. Technol. B: Nanotechnol. Microelectron. **24**(3), 1622 (2006). https://doi.org/10.1116/1.2201448

ВИЗНАЧЕННЯ ЗАЛЕЖНОСТІ ОСЦИЛЯЦІЇ ПОПЕРЕЧНОЇ ЕЛЕКТРОПРОВІДНОСТІ ТА МАГНІТООПОРУ ВІД ТЕМПЕРАТУРИ В ГЕТЕРОСТРУКТУРАХ НА ОСНОВІ КВАНТОВИХ ЯМ

Улугбек І. Еркабоєв, Рустамжон Г. Рахімов
Наманганський інженерно-технологічний інститут, 160115 Наманган, Узбекистан

У даній роботі досліджено вплив густини двовимірного стану на осциляції поперечної електропровідності в гетероструктурах з прямокутними квантовими ямами. Отримано новий аналітичний вираз для розрахунку температурної залежності осциляцій поперечної електропровідності та магнітоопору квантової ями. Вперше розроблено механізм осциляції поперечної електропровідності та магнітоопору квантової ями від похідної першого порядку магнітного поля (диференціала) $\partial\left(\rho_{\perp}^{2d}\left(E,B,T,d\right)\right)/\partial B$ при низьких температурах і слабких магнітних полях. Досліджено осциляції електропровідності та магнітоопору вузькосмугової квантової ями з непараболічним законом дисперсії. Із запропонованою теорією досліджено результати експериментів з вузькосмугою квантовою ямою ($In_xGa_{1-x}Sb$).

Ключові слова: *напівпровідник; провідність; квантова яма; магнітоопір; магнітне поле*