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# DETERMINATION OF THE TEMPERATURE DEPENDENCE OF THE TRANSVERSE DIFFERENTIAL MAGNETORESISTANCE IN A QUANTUM WELL HETEROSTRUCTURE

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**Abstract**
In this paper, the temperature dependence of differential magnetoresistance oscillations in a heterostructure based on an $In_{0.53}Ga_{0.47}As$ quantum well is studied. The analysis was carried out in weak (0.6–1.22 T) and strong (up to 4 T) magnetic fields, over a temperature range of 3–40 K. While no oscillations are observed in ordinary magnetoresistance in weak fields, oscillations related to Landau levels appear when the differential magnetoresistance ($d\rho/dB$) is calculated. As the temperature increases, the amplitude of the oscillations decreases. The differential method enables visual observation of Landau quantization even in weak magnetic fields.

**Keywords**: Quantum well, differential magnetoresistance, Shubnikov–de Haas effect, Landau levels, temperature dependence, nonparabolic dispersion, narrow-gap semiconductors, heterostructure.

## Introduction

Quantum effects observed in low-dimensional semiconductor structures, particularly quantum wells and their heterostructures, under strong magnetic fields and low temperatures constitute one of the main research directions in modern nanoelectronics and materials science. Magnetoresistance oscillations, known as the Shubnikov–de Haas (SdH) effect, enable the determination of important parameters such as the effective mass of charge carriers, Dingle temperature, quantum scattering time, and Fermi surface geometry. The theoretical foundation of this effect is provided by the Lifshitz–Kosevich formula.

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Traditionally, observing quantum oscillations requires sufficiently large magnetic field induction values (typically above 1.5 T) and very low temperatures (4.2 K and below). This is because oscillations become clearly visible only when the energy difference between Landau levels exceeds the thermal energy. However, in some cases, it is difficult to detect quantum effects even in weak magnetic fields (e.g., up to 1 T), because the total magnetoresistance signal is "suppressed" by a strong monotonic background.

One effective method to solve this problem is to analyze the first derivative of magnetoresistance with respect to magnetic field induction (differential magnetoresistance). This method sharply increases sensitivity to the background and allows visual observation of the discrete structure of Landau levels even in weak fields.

This paper investigates the temperature dependence of differential magnetoresistance oscillations in an $In_{0.53}Ga_{0.47}As$ quantum well heterostructure. Additionally, analytical models for calculating magnetoresistance oscillations in narrow-gap (InAs/GaInSb/InAs) quantum well structures are compared for parabolic and nonparabolic dispersion laws. The results expand the possibilities for detecting quantum effects in weak magnetic fields and at relatively high temperatures.

As mentioned above, in order to observe the oscillations of the quantum effect in bulk and two-dimensional semiconductor materials, it is necessary to satisfy the conditions of a strong magnetic field and very low temperatures. Let us estimate the discrete quantum energy of the quantizing magnetic field and quantum hole at very low temperatures and the thermal energy of the electron corresponding to this energy level. In the graphs of previous works, the value of the induction of magnetic field oscillations is from 0.5 T to 4 T and $\frac{k}{e}T = 2,6 \cdot 10^{-4}\, eV$ at a temperature of 3 K. Magnetic field B = 1 Tl, $\hbar\frac{eB}{m}\Big/e = 12.4 \cdot 10^{-3}\, eV$. So $\frac{\hbar\frac{eB}{m}}{kT} \approx 48$, that is, $\hbar\frac{eB}{m} >> kT$. Although this estimate fully satisfies the conditions for the formation of quantum oscillation effects in quantum well heterostructures, as seen from Fig. 1a, oscillation processes are clearly observed starting from 1.5 T. Why does this happen? Do oscillations of transverse magnetoresistance not

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form in the conductivity region of the quantum well at magnetic fields of 0.6 T, 1 T, or 1.2 T, or does the resulting analytical expression not seem to be 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. Hence, according to the differential law of resistance, the first derivative with respect to magnetic field induction is taken based on the previous formula:

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

From a theoretical standpoint, taking the first derivative with respect to magnetic field induction from formula (1) and plotting its graph is a very difficult task. However, implementing it using computer programs allows both accuracy and quality assessment. To compare the graphical results obtained from the previous formula and formula (1), let us consider them in the same coordinate system.

Figure 1 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 magnetic field induction in the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure with an $In_{0.53}Ga_{0.47}As$ quantum well at T=3 K. Here, the number of Landau levels is $n_L$=7, and the measured quantum number is $n_Z$=1. The magnetic field induction was obtained in the range from 0.6 T to 1.22 T.

As in the previous graphs, at 0.6÷1.22 T, $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations are practically not formed due to the very low magnetic field. However, the graph of its first-order derivative of the magnetic $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ is completely different from $\rho_{\perp}^{2d}(E,B,T,d)$. That is, it indicates the presence of quantum effects, i.e. Landau levels, even at low temperatures and in weak magnetic fields. In fact, the goal of obtaining the derivative of the magnetic resistance with respect to $B$ was the same, namely, to feel the increase in the magnetic field by one standard. At

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the same time, both positive and negative magnetic resistances can be observed in 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 the $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ heterostructure with quantum well allows us to study not only the sensitivity to the influence of a magnetic field, but also in weak magnetic fields according to the previous formula, but using formula (1), it is possible to visually observe the number of discrete Landau levels.

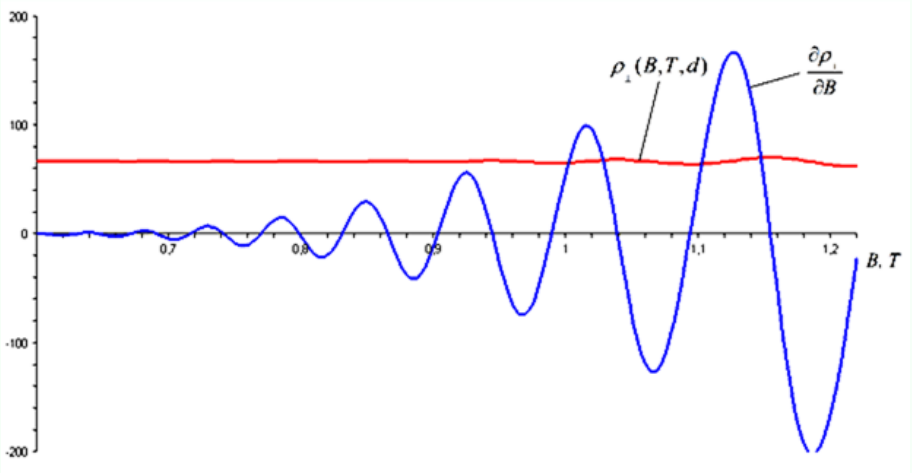


**Figure 1. Dependence of $\rho_{\perp}^{2d}(E,B,T,d)$ and $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ oscillations on weak magnetic field induction at T = 3 K in $In_{0.53}Ga_{0.47}As$ quantum well $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructures.**

Now let's see how the oscillations of the $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ differential magnetoresistance depend on temperature. As in previous works, we change the value of the magnetic field induction to 4 Tl and the temperature from 4.2 K to 40 K. As a result, we obtain a graph of the dependence of its oscillations on temperature according to formula (1) (Fig. 2). As can be seen from Fig. 2, with increasing temperature, a decrease in the amplitude of the oscillations of the $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ differential magnetoresistance is observed. 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

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temperature on the differential oscillations of the $\frac{\partial\left(\rho_{\perp}^{2d}(E,B,T,d)\right)}{\partial B}$ magnetoresistance corresponds to the theoretical basis given above.

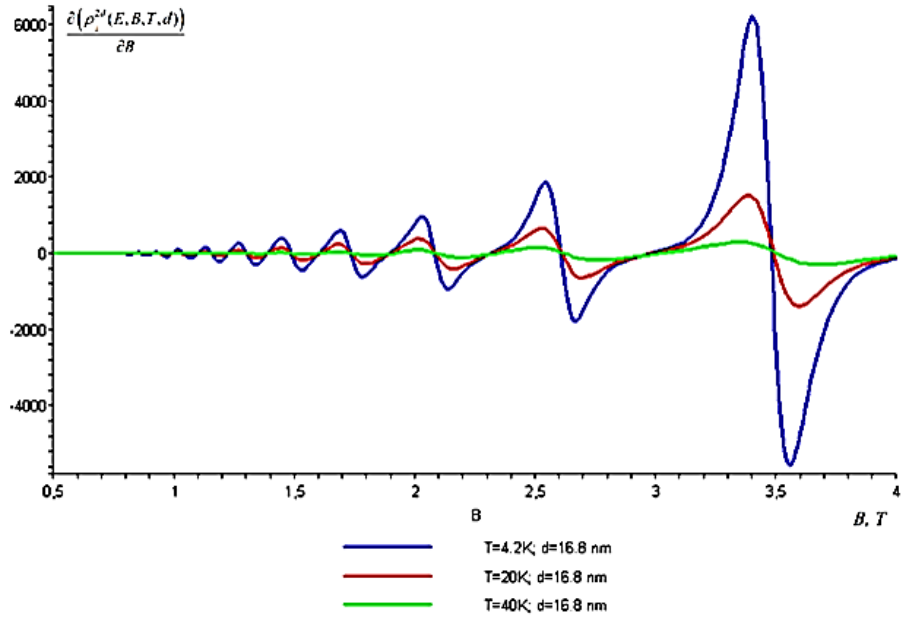


**Fig. 2. Effect of temperature on the differential magnetoresistance of an $In_{0.53}Ga_{0.47}As$ quantum well.**

**Determination of transverse magnetoresistance oscillations in narrow-area quantum-walled heterostructures for a non-parabolic dispersion law**

Let us analyze the quantum oscillation phenomena for electrons and light holes in narrow-area quantum well heterostructures under the influence of a strong magnetic field for a non-parabolic dispersion law. For a parabolic dispersion law, the effective mass of charge carriers does not depend on its energy, but if the dispersion law is non-quadratic, then the effective masses of charge carriers differ significantly from the energy in the allowed field of the quantum well. For a narrow-area non-parabolic dispersion law in bulk semiconductor materials, the energy of charge carriers in the conduction band under the influence of a quantizing magnetic field is calculated by the following expression [1]:

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

Here $E_g^{3d}$ is the bandgap width of the bulk semiconductor material; $g_0\mu_B H$ is the spin energy of the charge carriers. If the quantizing magnetic field induction is

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applied along the quantum well thickness (parallel to the $Z$ axis) and perpendicular to the $XY$ quantum well plane, the bandgap width is considered to depend on the quantum well thickness, and taking into account that the value of the spin energy is much smaller than the sum of the quantum and magnetic field energies, the expression takes the following form:

$$E_N^{2d}(B,d) = -\frac{E_g^{2d}}{2} + \frac{1}{2}\sqrt{\left(E_g^{2d}\right)^2 + 4\left(E_g^{2d}\right)\left[\left(n_L + \frac{1}{2}\right)\hbar\omega_c + \frac{\pi^2\hbar^2}{2m_n d^2}n_z^2\right]} \qquad (3)$$

Here, $\frac{1}{\mu_n} = \frac{1}{m_n} + \frac{1}{m_p}$; $E_g^{2d} = E_g^{3d} + \frac{\pi^2\hbar^2}{2\mu_n d^2}n_z^2$. Formula (3) expresses the dependence of a narrow-field quantum well on the magnetic field, which quantizes the energy of free electrons in the conduction band for the non-parabolic dispersion law. It is clear that under the influence of a quantizing magnetic field, the energy of free electrons in the conduction band of a narrow-field quantum well varies strongly non-quadratically with the width of the forbidden band and the thickness of the quantum well. This relationship, of course, strongly affects the two-dimensional energy density of states. Therefore, the oscillations of the magnetoresistance of a quantum well with a non-parabolic dispersion law differ significantly from the parabolic law. Consequently, the term $\left[\hbar\omega_c\left(n_L + \frac{1}{2}\right) + \frac{\pi^2\hbar^2}{2m^* d^2}n_Z^2\right]$ in the previous expression is the total energy of free electrons in the conduction band of the quantum well in the parabolic dispersion law for the parabolic dispersion law. The total energy in the non-parabolic dispersion law is determined by expression (3). Then, substituting (3) into the previous expression, we obtain the expression for the two-dimensional energy density of states in a quantizing magnetic field for the non-parabolic dispersion law:

$$N_{s,noparabolic}^{2d}\left(E,B,E_g^{2d},n_L,d,n_Z\right) = \frac{eH}{2\pi c}\sqrt{\frac{2}{\pi}}\frac{1}{G}$$

$$\sum_{n_L}\exp\left[-2\left(\frac{E - \left[-\frac{E_g^{2d}}{2} + \frac{1}{2}\sqrt{\left(E_g^{2d}\right)^2 + 4\left(E_g^{2d}\right)\left[\left(n_L + \frac{1}{2}\right)\hbar\omega_c + \frac{\pi^2\hbar^2}{2m_n d^2}n_z^2\right]}\right]}{G}\right)^2\right] \qquad (4)$$

It follows from this formula that for the non-parabolic dispersion law, the quantum field depends on the magnetic field, which quantizes the density of

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energy states in the conduction band. It is clear that formulas (2) and (3) are fundamentally different from a mathematical point of view. In this case, if the band gap is narrow, then formula (4) is recommended, otherwise, that is, if the semiconductor has a wide band gap, formula (2) can be used. This can also be understood by substituting (4) into (1) to obtain the following new analytical expression:

$$\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d}) = \\ =\left[\frac{e^3B}{2\pi m^* c}\sqrt{\frac{2}{\pi}}\frac{1}{G}\gamma_\perp(k_0T)^\beta\cdot\int_0^\infty N^{2d}_{s,noparabolic}\left(E,B,E_g^{2d},n_L,d,n_Z\right)E^{\alpha+\frac{3}{2}}\left(\frac{\partial f_0(E,T)}{\partial E}\right)dE\right]^{-1} \quad (5)$$

Analytical expression (5) is mainly suitable for heterostructure materials with narrow-gap quantum wells, because the energy spectrum of narrow-gap semiconductors predominantly obeys a nonparabolic dispersion law.

Let us 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 the two dispersion laws and consider their oscillations at different magnetic fields and temperatures. The thickness of the narrow-band quantum well (*InAs* - quantum well) *InAs/GaInSb/InAs* semiconductor heterostructure is 3.36 nm [2], the volume band gap at T = 0 K is 0.426 eV [3], and the effective mass of a free electron in the conduction band is $m_n=0.026m_0$. Substituting these experimental values (1) and (5) into the proposed analytical expressions, we calculate the transverse magnetoresistance oscillations of the *InAs/GaInSb/InAs* quantum well semiconductor at T = 4 K and obtain graphical results for $\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d})$ and $\rho^{2d}_{\perp noparabolic}(E,B,T,d,E_g^{2d})$ (Fig. 2). As can be seen from this figure, it can be observed that the transverse magnetoresistance oscillations obtained for parabolic and non-parabolic dispersion laws are fundamentally different.

In conclusion, it can be said that if the quantum well semiconductor has a narrow bandgap, it is proposed to calculate the temperature dependence of the transverse magnetoresistance oscillations using formula (5). If the forbidden bandgap of the quantum well corresponds to a wide bandgap semiconductor material, that is, it consists of a classical or wide bandgap semiconductor, its transverse magnetoresistance oscillations are calculated using formula (1).

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