CALCULATION OF THE TEMPERATURE DEPENDENCE OF MAGNETORESISTANCE OSCILLATIONS IN NANOSTRUCTURED SEMICONDUCTORS

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Abstract

In this work, the temperature dependence of transverse electrical conductivity and magnetoresistance oscillations under the influence of a quantizing magnetic field in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells is analyzed. At low temperatures (T = 4.2 K), sharp oscillations in magnetoresistance are observed due to the discrete structure of Landau levels. As the temperature increases, the oscillation amplitude decreases, and when approaching 40 K, quantum effects disappear due to thermal broadening. A decrease in the quantum well thickness leads to an increase in the oscillation amplitude.

Keywords: Quantum well, magnetoresistance, Landau levels, oscillations, temperature dependence, low-dimensional semiconductors, heterostructure.

Introduction

Quantum effects arising under the influence of an external magnetic field in low-dimensional semiconductor structures, especially in quantum wells and heterostructures, are of great interest for modern physics and electronics. In particular, the discrete structure of energy levels resulting from the Landau quantization effect leads to the appearance of oscillations in kinetic parameters such as electrical conductivity and magnetoresistance. These oscillations - the Shubnikov–de Haas effect — serve as a powerful spectroscopic tool for determining the fundamental parameters of materials (effective mass, relaxation time, Fermi energy, etc.).

In this work, the dependence of transverse magnetoresistance oscillations on magnetic field and temperature in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells is studied. Experimental and theoretical analyses show that at low temperatures (T = 4.2 K), magnetoresistance oscillations are clearly manifested; as the temperature increases, their amplitude decreases and they completely disappear above a certain temperature (T ≈ 40 K). This phenomenon is explained by the increase in thermal energy relative to the energy difference between Landau levels

The main goal of this work is to theoretically calculate the regularities of changes in magnetoresistance oscillations at different temperatures and different quantum well thicknesses, and to reveal their physical mechanisms. The study takes into account the parabolic dispersion law, Fermi–Dirac statistics, and thermal broadening effects. The obtained results are important for ensuring temperature stability in low-dimensional semiconductor devices (e.g., high-sensitivity magnetic field sensors, quantum transport devices).

Figure 1 shows the dependence of transverse magnetoresistance oscillations on magnetic field (Fig. 1a) and on inverse magnetic field induction (Fig. 1b) in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells at constant low temperature. Here, the parameters of the $In_{0.53}Ga_{0.47}As$ quantum well are as follows: quantum well thickness d = 16.8 nm, effective mass of electrons in the conduction band of the quantum well m_n = $0.059m_0$, broadening parameter G = 0.5 meV, and temperature T = 4.2 K [1].

In this case, when drawing the $\rho_{\perp}^{2d}(E,B,T,d)$ graph, the number of Landau levels is assumed to be $n_L = 8$, and the number of dimensional quanta (number of dimensional quantizations) is assumed to be $n_Z = 1$. The magnetic field induction value at values of 1.5 T and higher shows a sharp increase in the amplitude of transverse magnetoresistance oscillations in the conduction band of the $In_{0.53}Ga_{0.47}As$ quantum well.

Figure 2 shows the effect of temperature on the dependence of transverse magnetoresistance oscillations on magnetic field induction (Fig. 2a) and on inverse magnetic field induction (Fig.2b) in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells according to the parabolic dispersion law. It can be seen from these graphs that as the temperature increases, the amplitude of electrical conductivity oscillations in the conduction band of the $In_{0.53}Ga_{0.47}As$ quantum well decreases. At sufficiently high temperatures, for example, at T = 40 K, magnetoresistance oscillations do not sense the quantizing magnetic field, and oscillations of kinetic parameters are not observed. This is because, in order to observe the effect of quantum oscillations in nanoscale semiconductor materials, the thermal energy of free charge carriers must be much less than the difference between two adjacent discrete energy levels.

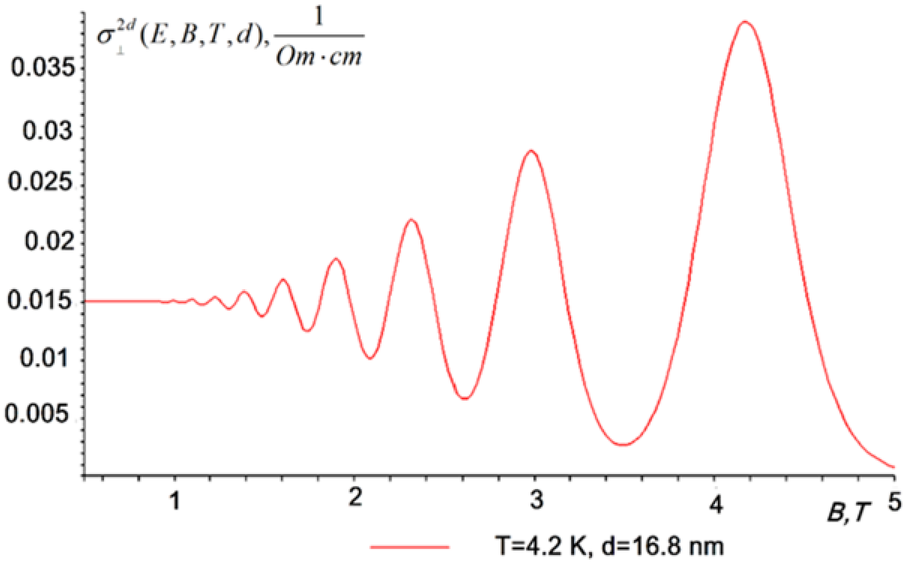

Fig.1a. Dependence of transverse electrical conductivity oscillations on magnetic field in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells at T = 4.2 K.

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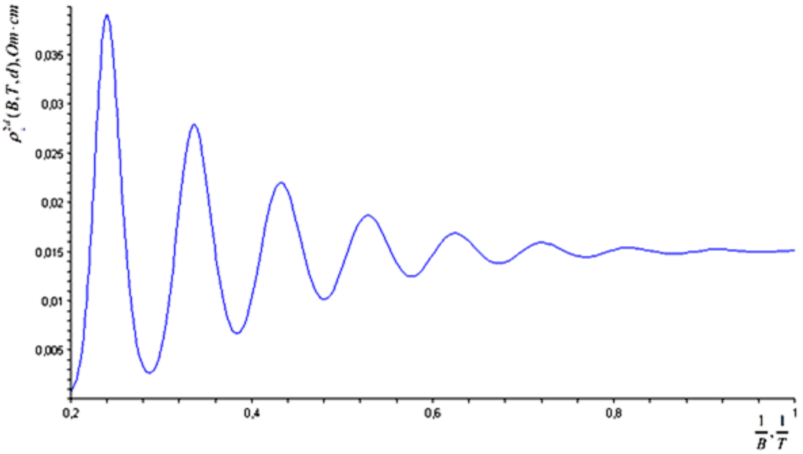

Fig.1b. Dependence of transverse electrical conductivity oscillations on inverse magnetic field induction in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells at T = 4.2 K.

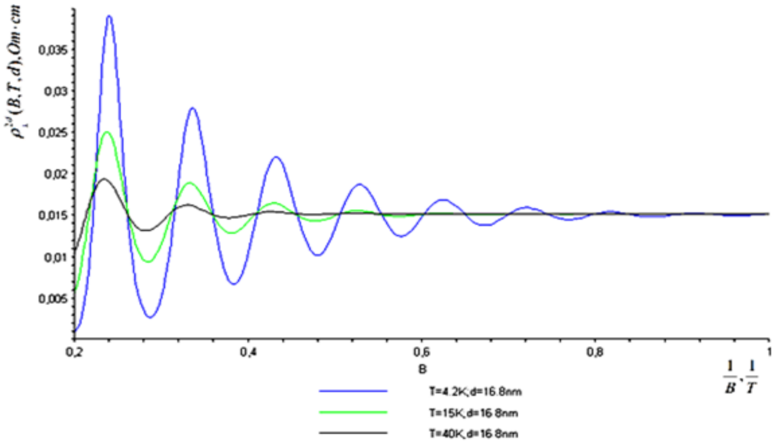

Fig.2a. Effect of temperature on the dependence of transverse magnetoresistance oscillations on inverse magnetic field induction in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells.

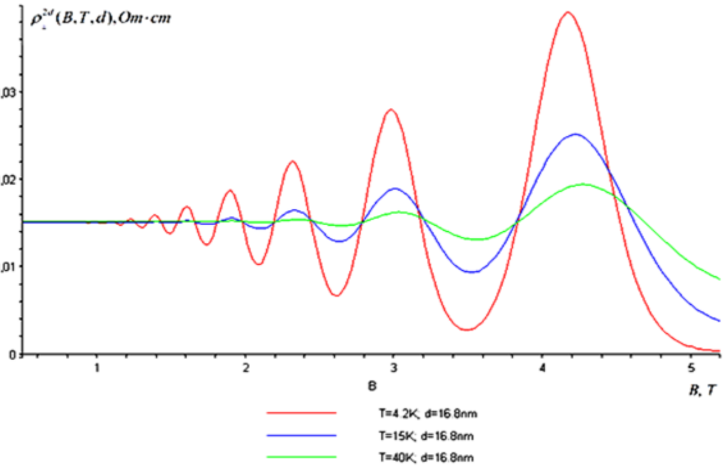

Fig.2b. Effect of temperature on the dependence of transverse magnetoresistance oscillations on magnetic field induction in heterostructures based on $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells.

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

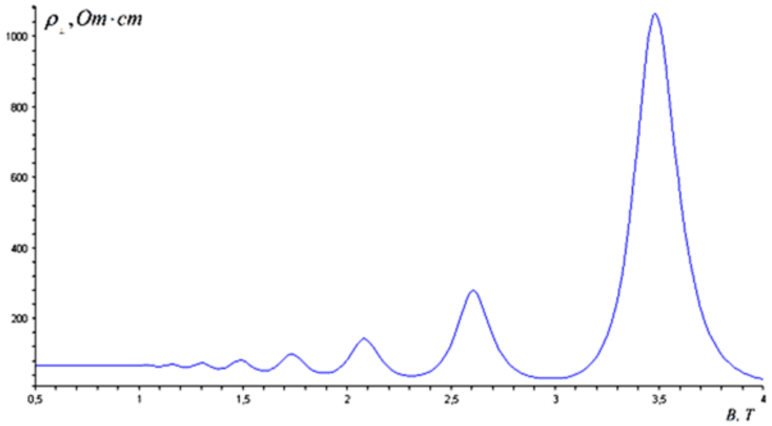

Fig.3a. Transverse magnetoresistance oscillations in the conduction band of the $In_{0.53}Ga_{0.47}As$ quantum well at T = 4.2 K.

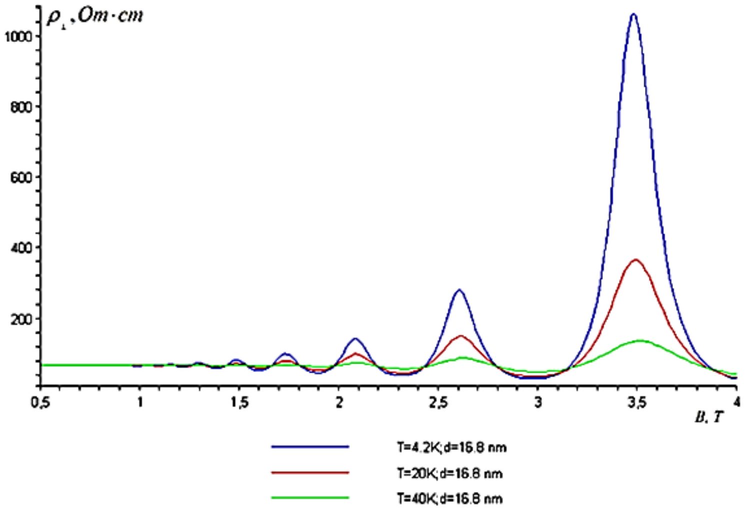

Fig.3b. Effect of temperature on transverse magnetoresistance $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations in the conduction band of an $In_{0.53}Ga_{0.47}As$ quantum well

It is known that the temperature dependence of the energy density of states oscillations in two- and three-dimensional semiconductor materials has been studied in detail from a theoretical point of view in [2-3]. At the same time, a new mathematical model has been developed. For constant low temperatures, the formula shows the energy and magnetic field dependence of the energy density of states oscillations in two-dimensional semiconductor materials $N_s^{2d}\left(E,B,n_L,d,n_Z\right)$.

The derivative of the Fermi-Dirac distribution function with respect to energy gives the $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$ delta function at very low temperatures, where the $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$ height decreases and the width increases with increasing temperature. Thus, the thermal broadening of the Landau levels is determined using the $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$ function. However, as can be seen from works [2-3], the oscillations of the quantum effect are realized by observing the $N_s^{2d}\left(E,B,n_L,d,n_Z\right)$. Therefore, by extending the $N_s^{2d}\left(E,B,n_L,d,n_Z\right)$ to the $\left(\frac{\partial f_0(E,T)}{\partial E}\right)$ series, the transverse magnetoresistance $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations of the quantum-enclosed heterostructure semiconductors are determined as a function of temperature.

In addition, using the analytical expression, it is possible to analyze the dependence of the transverse magnetoresistance $\rho_{\perp}^{2d}(E,B,T,d)$ oscillations of semiconductors with quantum well heterostructures on the thickness of the quantum well. Fig. 4 shows the dependence of the transverse magnetoresistance oscillations 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 for the parabolic dispersion law. Here, $\rho_{\perp}^{2d}(E,B,T,d)$ with a quantizing magnetic field of B=3.5 T

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

$$\rho_{\perp}^{2d}(T=3K,\ d=12{,}8\,nm)=1200\,Om$$

Thus, with a decrease in the thickness of the quantum well, the amplitude of the transverse magnetoresistance oscillations increases.

Therefore, we can conclude that the height of discrete Landau levels in two-dimensional semiconductor materials depends on both temperature and the thickness of the quantum well. It is proposed that the thickness of the quantum well should be as close as possible to the de Broglie length in order to observe the oscillations of the quantum effect even at high temperatures.

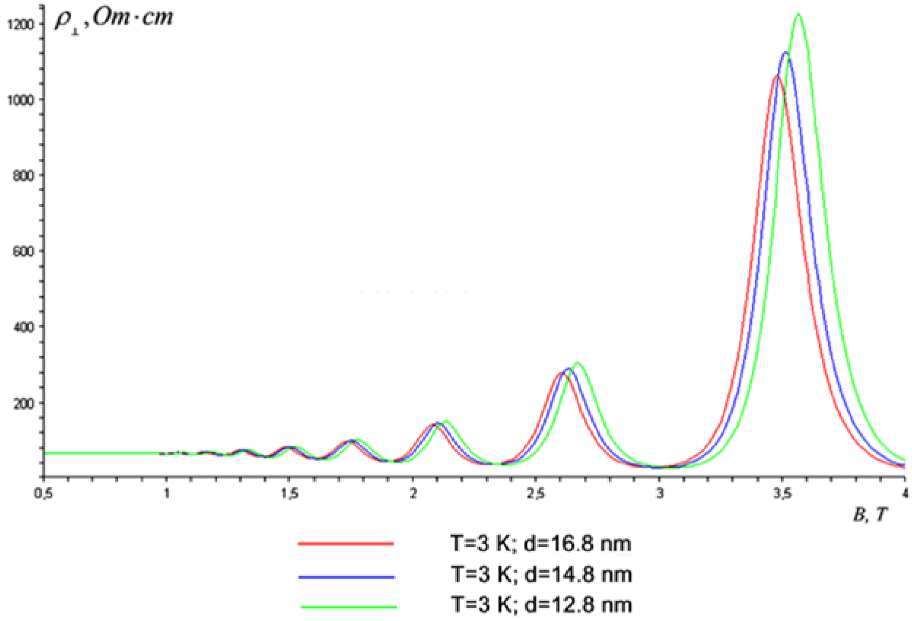

Fig. 4. Dependence of transverse magnetoresistance oscillations of the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/ In_{0.52}Al_{0.48}As$ heterostructure on the thickness of the $In_{0.53}Ga_{0.47}As$ quantum well for the parabolic dispersion law.

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