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ABSTRACT

of the dissertation for the degree Doctor of Science

TRANSPORT PHENOMENA ANISOTROPY IN LOW-DIMENSIONAL ELECTRONIC SYSTEMS

Speciality:	2211.01 Solid State Physics
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GENERAL CHARACTERISTICS OF WORK

Relevance and currency of the research topic. The rapid development of modern nanoelectronics creates the need to study new physical phenomena in low-dimensional electronic systems, such as thin films, natural (for example $InSe_2$, GaSe, TaS_2, $NbTe_2$) and artificial superlattices (for example GaAs/ AlGaAs, Si-Ge), quantum wires and quantum wells. Due to the fact that using modern software, modern technology based on the methods of molecular beam epitaxy (MBE), gasphase epitaxy and nanolithograpphy, makes it possible to manufacture low – dimensional systems and profiles of quantum wells with different potentials, interest in the study of transfer phenomena in electronic systems of reduced dimension has increased enormously. The study of low-dimensional systems with anisotropy of physical properties, on the one hand, leads to the creation of new nanoelectronics devices, on the other hand, provides new methods for controlling the parameters of these structures.

There are several reasons why low-dimensional electronic systems are in the focus of attention of theoretical scientists and experimenters. The first reason is that interesting phenomena are observed in low-dimensional systems, such as weak and Anderson localization, negative magnetoresistance, negative differential conductivity, quantization of Hall conductivity, oscillations of kinetic coefficients, for example, magnetoresistance, which are not observed in massive samples. The second reason is the ability of the direct output of low-dimensional electronic systems to nanoelectronics. For example, heterostructures due to their high mobility in modulated doping heterojunctions are used to create ultrafast field-effect transistors; quantization of hall conductivity, to create a reproducible reference of the unit of resistance, as well as to more accurately determine the fine structure constant; superlattices with metal-dielectric phase transitions in quantizing magnetic fields are used to create highly sensitive sensors. Layered materials and superlattices are used as materials to reduce the size of devices, improve physical characteristics and create new technological structures. In addition, it should be noted that on the same sample, by changing the parameters of low-dimensional electronic systems, it is possible to obtain properties characteristic of structures with a different chemical composition. The third reason is related to the unusual reaction of these systems to external influences. For example, in these systems, the transfer phenomena depend on the magnitude and direction of the magnetic field, which creates an additional anisotropy. Another reason is related to new technologies that allow us to obtain pre-calculated parameters of a superlattice or the properties of quantum wells. In most works, when calculating kinetic coefficients, simplified model representations are used, which are often not performed for real objects. An important role in the complex nature of the current density distribution through the sample, which has anisotropy of electrical parameters, is played by the influence of boundaries, parameters of low-dimensional structures and scattering mechanisms. In this connection, the problem arises of constructing a theory taking into account the specific features of the anisotropy of systems: the parameters of low-dimensional systems and the profile of quantum wells, the relaxation time and the external influence of electric and magnetic fields, their magnitude and direction.Therefore, the transfer phenomena in low-dimensional electronic systems, despite a large number of works in this field, are of interest to researchers. Currently, galvanomagnetic phenomena are well studied, at the same time, compounds with anisotropy of thermomagnetic phenomena under the influence of external fields are increasingly used in modern nanoelectronics. In connection with the above, there is a need to study the anisotropy of thermomagnetic phenomena in low-dimensional systems.

The lack of a consistent theory of thermomagnetic phenomena is due to the fact that with a strong anisotropy of the energy spectrum, taking into account various scattering mechanisms and the orientation of the external magnetic field, which strongly affects the kinetic effects and leads to additional anisotropy, is quite diffi cult. Therefore, the study of anisotropic transport phenomena in quasi-two-dimensional layered systems with a cosine dispersion law in a magnetic field, as well as in asymmetric quantum wells, will provide an additional contribution to the theory of kinetic phenomena in low-dimensional electronic systems. The work was carried out within the framework of the research (Research work) “Kinetic, optical and magnetic properties of low-dimensional electronic systems” of the Department of Solid State Physics of Baku State University.

Research objects and subjects. The object of research is layered crystals, superlattices and quantum wells. As a subject of reseach, we studied transport phenomena anisotropy in the superlattices, layered systems and asymmetric quantum wells.

Aims and purpose of the research. To theoretically investigate the anisotropy of electrical conductivity, the electronic part of thermal conductivity, the galvanic and thermomagnetic coefficients of superlattices and layered compounds with a cosine law of dispersion, as well as the electrical conductivity and thermoelectric power of an asymmetric quantum well and to establish the features of kinetic phenomena associated with the anisotropy of the scattering mechanisms and the energy spectrum, as well as the influence of the parameters of a low-dimensional electron gas and external fields on these phenomena.

To achieve this goal, the following issues were raised and resolved in the dissertation:

1. Calculate the electrical conductivity (EC) and the electronic part of the thermal conductivity of an electron gas with a cosine dispersion law when scattering on impurity ions in the absence of a magnetic field. To determine the influence of the scattering anisotropy and the screening radius of the impurity ions on these kinetic coefficients.
2. To investigate the influence of the anisotropy of the energy spectrum and relaxation time on the galvanomagnetic effects during scattering by impurity ions: the Hall effect and magnetoresistance (MR) - at different orientations of the magnetic field and to analyze the dependence of these coefficients on the parameters of superlattices, the screening radius, as well as the magnitude and direction of the magnetic field.
3. Determine the Nernst-Ettingshausen (NE) coefficient and its anisotropy depending on the magnitude and direction of the mag-

netic field, the degree of mini-band filling of the superlattice when scattering by phonons and impurity ions. When scattering current carriers on impurity ions, to study the dependence of the NE on the screening radius and the concentration of impurities.

4. To investigate the influence of the magnitude and direction of the external magnetic field relative to the plane of the superlattice layer on the thermoelectric power (TEP) (longitudinal NE effect) during the scattering of current carriers on various types of phonons and impurity ions. To determine the dependence of the TEP and the Maggi-Rigi-Leduc (MRL) coefficient in the entire region of the magnetic field on the degree of mini-band filling, the period of the superlattice, the screening radius during scattering by impurity ions and the position of the Fermi level relative to the mini-band of the superlattice.

5. Consider the anisotropy of the transverse (TNE) and longitudinal (LNE) Nernst-Ettingshausen effects in the scattering of current carriers on impurity ions. To determine the influence of the shape of the Fermi surface of the superlattice, the magnitude and direction of the external magnetic field, on the anisotropy of these effects, depending on the direction of the temperature gradient.

6. Determine the conditions imposed on the confaiment–the potential of an asymmetric quantum well (QW). To study the dependence of the Fermi energy on the parameters of a semi-parabolic QW and the concentration of conduction electrons. To determine the influence of the surface potential, the width of the QW and the Fermi level on the EC and TEP of a semi-parabolic QW well during the scattering of conduction electrons on acoustic and polar optical phonons.

Research methods. The quasi-classical approximation of the Boltzmann equation, the Gibbs statistical method and the methods of quantum mechanics were used as a theoretical research method in the dissertation work.

Basic provisions for defence:

1. The anisotropy of the electrical conductivity (EC) of electronic systems with a cosine dispersion law when scattering by impurity ions increases with an increase in the screening radius

and when the Fermi surface is a corrugated cylinder becomes an order of magnitude larger. The anisotropy of the EC depends both on the concentration of impurities and on the period of the superlattice: for a given period of the superlattice, the degree of anisotropy of the EC decreases with an increase in the concentration of impurities.

2. With a change in the direction of the magnetic field relative to the plane of the layer, there is an inversion of the sign of the Hall coefficient. The sign change is due to the presence of regions with negative effective mass in the mini-band of the superlattice. The anisotropy of the Hall coefficient depends on the dimension of the electron gas: during the transition from quasi-three-dimensional to quasi-two-dimensional, the anisotropy decreases.

3. In the case of weak screening of impurity ions, the transverse magnetoresistance (MR) depends on the direction of the magnetic field: when the direction of the magnetic field changes from the transverse (perpendicular to the plane of the layer of the superlattice) to the longitudinal (in the plane of the layer), the sign of the transverse MR of superlattices changes to the opposite when the radius of the cyclotron orbit becomes of the order of the period of the superlattice. If the Fermi surface of an electron gas is a corrugated cylinder (a quasi-two-dimensional electron gas), then the transverse MR changes its sign from positive to negative with an increase in the transverse magnetic field and linearly depends on the magnetic field, i.e. the Kapitsa effect occurs. In a longitudinal magnetic field, the transverse MR is positive in a strong and negative in a weak field, and the magnitude of the negative transverse MR in the transverse field is less than in the longitudinal field. When the Fermi surface is an ellipsoid (quasi-three-dimensional electron gas) the transverse MR in the transverse field is always positive, and in the longitudinal field it changes its sign, taking small negative values.

4. The transverse MR in a longitudinal magnetic field is an alternating function of the screening radius: when the screening radius is less than the superlattice period, the resistivity decreases, and when it is greater, it increases, i.e. at large electron gas densities, the transverse MR is negative, and for small ones it is posi-

tive. The ratio of resistivity reaches its maximum value when the screening radius is several times greater than the period of the superlattice.

5. In intermediate magnetic fields, depending on the topology of the Fermi surface in transverse MR superlattices, its sign changes: when the Fermi surface is a corrugated cylinder, there is a region with a negative effective mass of conduction electrons in the minizone of the superlattice and the inversion of the transverse MR sign is associated with the mechanism of unequal scattering of two groups of electrons differing in the orientation of electron rotation along cyclotron orbits.

6.In a longitudinal magnetic field, when scattering by polar optical phonons in the same sample, the transverse Nernst - Ettingshausen (transverse NE) coefficient changes its sign twice depending on the degree of mini-band filling: with a small degree of filling of the mini-band, the transverse NE coefficient takes a large positive value, then with an increase in the degree of mini-band filling, it changes its sign and, passing through zero, becomes negative and then becomes positive again for a quasi-two-dimensional electron gas.

7.The coefficient of transverse NE in a longitudinal magnetic field when scattering on weakly screening impurity ions depends nonmonotonically on the magnitude of the magnetic field and the dimension of the electron gas: in a weak magnetic field for a quasi-two-dimensional electron gas at high concentrations of current carriers, the transverse NE coefficient is positive, slightly depend on the field and tends to zero, while in a strong magnetic field, the transverse NE is negative for a quasi-three-dimensional electron gas and changes its sign with an increase in the degree of mini-band filling.

8.When scattering by acoustic phonons, the TEP of a quasi-two-dimensional electron gas is zero in a strong longitudinal magnetic field, while in a transverse field it is nonzero. In the intermediate magnetic fields, there is a significant increase in the TEP at small degrees of mini-band filling. When scattering by polar optical phonons in a weak magnetic field, the anisotropy of the effect is insignificant, while in strong magnetic fields it is significantly and inversely proportional to the square of the mobility of two-dimensional electrons. During the transition from a quasi-three-dimensional electron gas to a quasi-two-dimensional TEP in strong magnetic fields begins to oscillate.

9.When scattering on weakly screening impurity ions, there is an inversion of the sign of the TEP in the longitudinal magnetic field, which is associated with the position of the Fermi level of the superlattice and the dependence of the screening radius on the concentration. When the Fermi surface in the form of a corrugated cylinder ($\varepsilon_F > 2\varepsilon_0$), TEP decreases with increase magnetic field and for the Fermi surface in the form of an ellipsoid $\varepsilon_F < 2\varepsilon_0$, at small values of the degree of mini-band filling it takes large values, remaining positive. Thermomagnetic coefficients can be controlled by adjusting the parameters of the superlattice.

10.The Maggi-Rigi-Ledyuk coefficient (MRL) of quasi-two-dimensional and quasi-three-dimensional electron gas is calculated when scattering by phonons and impurity ions. It is shown that the MRL coefficient in weak magnetic fields decreases with the field and tends to zero in strong magnetic fields, which makes it possible to experimentally determine the thermal conductivity of phonon gas in superlattices. The criterion of the magnetic field at which this is possible is given.

11.The electrical conductivity (EC) of a semi-parabolic quantum well is a step function of the Fermi energy, oscillates with the width of the quantum well (QW), and the oscillation period depends on the semi-parabolic potential of the QW and the concentration of charge carriers. The peaks of EC are caused by the position of the Fermi level relative to the energy levels of the QW. It is established that in the case of scattering by polar optical phonons, in contrast to scattering by acoustic phonons, the EC depends nonmonotonically on the potential and the width of the quantum well. It is revealed that the EC electrical conductivity increases abruptly with an increase in the potential of the QW and has a feature-loops that are formed when the energy levels of the QW cross the Fermi level.

12.The TEP of a two-dimensional electron gas in a semi-parabolic QW under electron-phonon scattering has features associated with the well profile: the formation of a loop, a sign change. The loops and the change in the sign of the TEP are explained by the value of the surface potential, the properties of electrons at the edges of the well, and the effects of localization /delocalization of electrons in the QW. Hysteresis loops are induced by Fermi energy fluctuat with the frequency of the quantum well potential $\omega_S = d^{-1}(2U_S/m)^{1/2}$ with an increase in the QW width and at low electron concentrations, the loops disappear.

Scientific innovations. For the first time:

– The dependences of the Hall coefficient on the Fermi energy, the parameters of the superlattice and the screening radius, as well as on the magnitude and direction of the magnetic field during the scattering of conduction electrons on impurity ions are determined. It is revealed that in a weak magnetic field, the Hall coefficient depends on the anisotropy of the effective mass in superlattices $m_{\|0}/m_{\perp}$, (here $m_{\|0}$ longitudinal component -is the effective mass of conduction electrons in the direction perpendicular to the layer plane and $m_{\perp}$ transverse component – is effective mass of conduction electrons in the layer plane) and is determined by the ratio between the Fermi energy and the conduction mini-band half-width. It is established that the Hall coefficient in a longitudinal magnetic field changes its sign and does not depend on the screening radius;

– The anisotropy of the transverse MR is determined when scattering on weakly screening impurity ions in low-dimensional electronic systems with a cosine law of dispersion depending on the direction of the magnetic field: for a quasi-two-dimensional electron gas in a transverse weak magnetic field, the transverse MR is positive, in intermediate fields it changes sign, becoming negative in strong ones, while in a longitudinal field, the opposite effect takes place: in a strong field, the transverse MR is positive, quadratically depends on the magnetic field, and in a weak magnetic field it takes small negative values. In a transverse strong magnetic field, the MR of a quasi-two-dimensional electron gas almost linearly depends on the magnetic field, i.e. the Kapitsa effect takes place. Alternating MR oscillations occur in the longitudinal magnetic field depending on the screening radius;

– A consistent theory of thermomagnetic effects in superlattices with a cosine law of dispersion is constructed, general expressions of galvano- and thermomagnetic tensors are found, the dependence of these effects on the parameters of the anisotropic energy spectrum, the dimension of the electron gas and scattering mechanisms, as well as the magnitude and direction of the external magnetic field is determined.

– The possibility of inversion of the sign of the thermomagnetic transverse Nernst-Ettingshausen effect during scattering by phonons has been discovered. It is shown that in a longitudinal magnetic field, when scattering by polar optical phonons in the same sample, the Nernst-Ettingshausen coefficient changes its sign twice. In a strong magnetic field, when the radius of the cyclotron orbit becomes of the order of the superlattice period, sign inversion takes place in the case of an open Fermi surface.

– The dependences of the TNE coefficient on the degree of mini-band filling of the superlattice, the magnitude and direction of the magnetic field during the scattering of current carriers on weakly screening impurity ions are investigated. It is found that the TNE coefficient depends nonmonotonically on the degree of mini-band filling: in a weak longitudinal magnetic field for a quasi-two-dimensional electron gas at high concentrations of current carriers, the TNE coefficient is positive, does not depend on the field and tends to zero, while in a strong magnetic field, the TNE is negative for small degrees of mini-band filling and changes its sign with increasing degree of mini-band filling;

– It is shown that with a change in the direction of the magnetic field, the longitudinal NE effect changes its sign from negative to positive. In a longitudinal strong magnetic field, when scattering by acoustic phonons and strongly screening ions, the TEP of a quasi-two-dimensional electron gas is zero, while that of a three-dimensional one is nonzero and positive. When scattering on polar optical phonons with a decrease in the degree of mini-band filling, the TEP first increases, and then, passing through the maximum, begins to decrease in magnitude, oscillating in a strong magnetic field.

When scattering on weakly screening impurity ions, the TEP of a quasi-two-dimensional electron gas decreases with an increase in the magnetic field, tending to zero, the change in the sign of the thermomagnetic coefficients of NE during scattering on impurity ions is due to the Fermi topology of the surface, as well as the which is due to the dependence of the screening radius on the concentration of impurities and the period of the superlattice.

– It is noted that the transverse and longitudinal Nernst-Ettingshausen effects, differing in the direction of the temperature gradient during the scattering of conduction electrons on impurity ions, depend nonmonotonically, in different ways, on the degree of filling of the mini-band, the magnetic field and the screening radius: in a strong magnetic field, the TEP is positive, while the NE coefficient takes negative values at small degrees of filling of the mini-band, then the NE coefficient becomes positive, passing through zero; the transverse NE coefficient of a quasi-two-dimensional electron gas increases significantly in a magnetic field, and the TEP decreases; for a quasi-three-dimensional electron gas, the NE coefficient tends to zero, and the TEP depends nonmonotonically on the field. The sign of both the longitudinal and transverse NE effects can change when moving the Fermi level through the mini-band. The change in the sign of the thermomagnetic coefficients of NE during scattering on impurity ions is due to the topology of the Fermi surface, as well as the dependence of the scattering radius on the concentration of impurities and the period of the superlattice.

– The EC of an asymmetric QW with a semi-parabolic potential and the influence of the parameters of the QW and the mechanisms of electron-phonon scattering on it are studied. When scattering on polar optical phonons, unlike scattering on acoustic phonons, the electrical conductivity depends nonmonotonically on the potential and width of the quantum well. It is shown that the electrical conductivity increases abruptly with an increase in the potential of the quantum well and forms loops that occur when the Fermi level crosses the energy level of the quantum well. Loops in the electrical conductivity are associated with a non-monotonic change in the position of the Fermi level relative to the energy levels of the *QW*, while the density of states experiences a jump, which leads to the presence of inflection points in the electrical conductivity.

– TEP in a semi-parabolic QW under electron-phonon scattering has been studied. It is established that the TEP has features related to the profile of the QW and the relationship between the Fermi level, the energy levels of the QW and the surface potential: hysteresis loops and the change of the sign of the TEP. These features are explained by localization/ delocalization effects and the position of the Fermi level relative to the energy levels of the QW. Also, the TEP oscillates with the Fermi level, and the oscillation period depends on the surface potential, the width of the QW and the concentration of charge carriers.

Theoretical and practical significance of the research of the work lies in the fact that the results obtained can be used to explain the effects of localization/delocalization in quantum wells and new physical phenomena observed in such low-dimensional electronic systems as natural and artificial superlattices, to estimate the parameters of quantum wells and superlattices and scattering mechanisms in them, as well as in the development of devices in the field of nano-optoelectronics. The resultsobtained in this work, such as the scattering mechanisms, the influence of external influence (magnetic field) and the parameters of a low-dimensional electron gas (for example, the mini-band width, the anisotropic effective mass and the Fermi surface in superlattices and the asymmetric surface potential in quantum wells) can be useful to supplement the existing theoretical concepts in the physics of low-dimensional systems. It should be noted that studying the dependence of the Fermi energy on the width of the QW and the concentration, it is possible to make a number of conclusions about the shape of the QW of a two-dimensional electron gas, and also using the dependence of the kinetic coefficients on the number of mini-band filling, it is possible to control the dimension of the electron gas. In addition, using the information obtained in the work on the EC and the electronic part of the thermal conductivity, it is possible to improve the thermoelectric figure merit of low-dimensional structures.

Approbation and application. The main results of the work were reported at symposiums and conferences: I Republican Scientific Conference "Actual problems of physics" (Baku, 1998), II Republican Scientific Conference "Actual problems of Physics" (Baku, 2001), III Republican Scientific Conference "Actual Problems of Physics" (Baku, 2004), IV Republican Scientific Conference "Actual Problems of Physics" (Baku, 2006), American Institute of Physics (AIP) Conference Proceeding. "Frontiers of Fundamental Physics: Eighth International Symposium FFP8" (USA, 2007), International Conference dedicated to the 90th anniversary of Baku State University (Baku, 2009), II International Scientific and Practical Conference "Modern Problems of Metal Physics" (Baku, 2009), International Conference Institute of Physics of ANAS (Baku, 2010), IV Republican Scientific Conference "Actual Problems of Physics" (Baku, 2010), 28th International Physics Congress, Turkish Physical Society (Bodrum, Turkey, 2011), International Conference on Nano science + Texnology (Paris, France, 2012), Turkish Physical Society, 30th International Physics Congress (Istanbul, Turkey, 2013), Anniversary, International Scientific Conference dedicated to the 80th anniversary of Academician of the Academy of Sciences of Azerbaijan B.M. Askerov "Actual problems of Physics" (Baku, 2013), Republican Scientific Conference "Actual Problems of Physics" (Baku, 2015), International Scientific and Practical Conference "Modern Problems of Metal Physics" (Baku, 2016), Turkish Physical Society, 32nd International Physical Congress (Bodrum, Turkey, 2016), Republican Scientific Conference "Actual Problems of Physics" (Baku, 2016), International Scientific Conference "Phase Transitions, critical and nonlinear phenomena in condensed media" (Makhachkala, Russia, 2017), International Scientific and Practical Conference "Actual Problems of Radiophysics" (Tomsk, Russia, 2017), I International Turkish World Engineeringand Science Congress Turkish Physical Society (Bodrum, Turkey, 2018), Uluslararası GAP Matematik-Mühendislik-Fen və Sağlık bilimləri Kongresi (Adıyaman, Turkey, 2019).

The study of thermoelectric phenomena (thermoelectric power (TEP), thermal conductivity) in superlattices makes it possible to develop thermoelectric converters with high thermoelectric figure merit used in nanoelectronics. The use of superlattices is particularly promising in solar cells. One of the applications is field-effect and single-electron transistors and semiconductor lasers created on the basis of quantum wells.

Thermoelectric power (TEP) amplification in the longitudinal magnetic field, at small degrees of mini-band filling in the superlattice can be used to convert energy and create a generator. The magnification of the thermomagnetic coefficients can be controlled by adjusting the structural parameters of the superlattice.

Based on the dissertation materials, 27 articles (8 of them in Clarivate Analitics journals with a high impact factor including in the Web of Science data base), 4 conference materials and 19 thesis were publiehed in local and foreign journals.

Name of the organization where the dissertation work is executed. The dissertation work was accomplished at the departments of Solid state physics of Baku State University.

Structure, volume and main content of dissertation work. Dissertation work is posted on 269 pages as a whole. It consists of an introduction, including 60 figures, 7 chapters, a conclusion, a list of 253 references titles, a list of abbreviations and symbols. The volume of the dissertation (with the exception of gaps, and pictures in the text, tables, graphs, appendices and list of reference) - 322307 characters (introduction - 39133, Chapter I - 46634, Chapter II - 30975, Chapter III - 37653, Chapter IV - 24607, Chapter V - 44593, Chapter VI - 45981, Chapter VII - 38661, result – 9666 characters).

CONTENT OF THE DISSERTATION WORK

The introduction provides a justification for the relevance of the chosen topic, defines the goal and the corresponding tasks to be solved. The scientific novelty, practical significance and the main provisions submitted for defense are formulated. The general characteristic of the dissertation work is given.

The first chapter is devoted to the study of transport phenomena in layered compounds and superlattices with a cosine dispersion law of conduction electrons in the absence of a magnetic field. The energy spectrum and the density of the state of the conduction electrons are given and the scattering of current carriers on impurity ions is studied. In strongly anisotropic layered crystals and superlattices, the motion of electrons in the plane of the layers is considered in the weak coupling approximation, and the motion in the direction perpendicular to the layers is considered in the strong coupling approximation, and the law of dispersion takes the form:

$$\varepsilon(k)=\frac{\hbar^2 k_\perp^2}{2m_\perp}+\varepsilon_0(1-\cos ak_z)\,. \tag{1}$$

Here $k_\perp^2=k_z^2+k_y^2$, $k_\perp$ and k_z – are the longitudinal and transverse components of the wave vector, ε_0 – is the conduction mini-band half-width, a – is the period of the superlattice in the direction perpendicular to the plane of the layers, $m_x=m_y=m_\perp$ – is the effective mass of conduction electrons in the plane of the layer.

Based on the anisotropic dispersion law in the Born approximation, the longitudinal and transverse components of the inverse relaxation time are found for the scattering of conduction electrons on impurity ions in the approximation $\gamma<1$ when $\gamma=m_\perp/m_\parallel$ ($m_\perp$ – is the effective mass of the conduction electrons in the layer plane $m_\parallel$ is the effective mass perpendicular to the layer plane), $1/m_{II}=(\varepsilon_0 a^2/\hbar^2)\cos ak_z$ which works well for layered connections and superlattices that have the form:

$$\frac{1}{\tau_\perp}=\frac{1}{\tau_0}\left\{\frac{2k_z r_0}{[1+(2k_\perp r_0)^2]\sqrt{1+(2kr_0)^2}\,\sqrt{1+(2k_z r_0)^2}}+\right.$$

$$\left.+\frac{F(\alpha,q)-E(\alpha,q)}{(2ak_\perp)^2\cdot[1+(2k_\perp r_0)^2]^{1/2}}\right\}, \tag{2}$$

$$\frac{1}{\tau_{II}}=\frac{1}{\tau_0}\cdot\frac{1}{2k_z r_0}\times$$

$$\times\left\{\frac{1}{[1+(2k_\perp r_0)^2]^{1/2}}-\frac{1}{[[1+(2k_z r_0)^2]^{1/2}[1+(2k_z r_0)^2]^{1/2}+(2k_\perp r_0)^2]^{1/2}}\right\}, \tag{3}$$

here

$$q=\frac{2(k_\perp r_0)}{\sqrt{1+4(k_\perp r_0)^2}},\ \alpha=arctg(r_0k_z),\ \tau_0=\frac{(m_\perp\chi)^{1/2}}{8\pi Nea^{3/2}},$$

$$F(\alpha,q)=\int_0^\alpha\frac{d\varphi}{\sqrt{1-q^2\sin^2\varphi}},\ \ E(\alpha,q)=\int_0^\alpha\sqrt{1-q^2\sin^2\varphi d\varphi}$$

$F(\alpha,q), E(\alpha,q)$ – elliptic integrals of the I and II kind, respectively. In the Born approximation $r_0<<r_B$ (where $r_B=\chi\hbar^2/me^2$ – is the effective Bohr radius). For a quasi-two-dimensional electron gas, the screening radius is determined by the formula:

$$r_0^{-2}=\frac{4\pi e^2}{\chi}\cdot\frac{m_\perp Z(\varepsilon_F)}{\pi^2\hbar^2a}=\frac{4\pi e^2\cdot n}{\chi},$$

here n – is the concentration of charge carriers of a quasi-two-dimensional electron gas, χ – the dielectric constant.

In the case of strong screening ($kr_0<<1$), the anisotropy of the relaxation time does not take place, the charged impurity ion behaves as a point defect with short – acting δ-shaped potentials.

In the case of weak screening, the relaxation time is significantly anisotropic and, if the condition is met $kr_0>>1$, the above formulas (2) and (3) can be reduced to an analytical form convenient for further calculation of the kinetic coefficients.

On the basis of the obtained relaxation time components, the electrical conductivity (EC) and the electronic part of the thermal conductivity are calculated in a semiclassical approximation. It is shown that the anisotropy of the EC depends differently on the period of the superlattice for different concentrations of impurities : at large concentrations of impurities, it increases, while for small concentrations it decreases (Figure 1) In the case of a degenerate electron gas, for the anisotropy coefficient of EC, we have:

$$\frac{\sigma_\perp}{\sigma_\parallel}=2\frac{r_0}{a}\cdot\frac{1}{\ln(2r_0Z_0/a)}\cdot\frac{I_{0,0,5/2}}{I_{1,2,1/2}},\tag{4}$$

Here Z_0 is degree of mini-band filling, $\varepsilon_F -$ energy Fermi,

$$Z(\varepsilon) = ak_z,\ I_{k,l,m} = \int_0^{Z_0} Z^k \cos^l (\cos Z - \cos Z_0)^m \, dZ \, .$$

It is shown that the anisotropy of EC depends on the dimension of the electron gas: during the transition from quasi-three-dimensional to quasi-two-dimensional, it increases significantly. It is also found that the anisotropy of EC increases with an increase in the screening radius, i.e. the degree of anisotropy of EC decreases with an increase in the concentration of impurities.

Figure 1. The dependence of the anisotropy of the EC $\sigma_{\perp}/\sigma_{II}$ on the period a of the superlattice at different values of the impurity concentration: 1 $- N_i = 10^{22} m^{-3}$, 2 $-$ $N_i = 10^{24} m^{-3}$.

It is established that the Wiedemann-Franz law holds for the electronic part of the thermal conductivity of superlattices. where the Lorentz number is anisotropic. With weak screening, the anisotropy of the electronic part of the thermal conductivity is determined by the degree of filling of the mini-zone and the ratio between the screening radius and the superlattice period, which follows from the formula:

$$\frac{k_{\perp}}{k_{\parallel}} = 4\frac{r_0}{a} \cdot \frac{k_0 T}{\varepsilon_0} \cdot \frac{1}{\ln(2r_0 Z_0/a)} \frac{2Z_0 - 3\sin 2Z_0 + 4Z_0 \cos^2 2Z_0}{Z_0^2 - Z_0 \sin 2Z_0 - 0{,}5\cos^2 2Z_0 + 0{,}5} \, . \quad (5)$$

When scattering on strongly shielded impurity ions, the anisotropy of the electronic part of the thermal conductivity, $k_{\perp}/k_{\|}$ which is a consequence only of the anisotropy of the energy spectrum, is determined by the anisotropy of the effective mass:

$$\frac{k_{\perp}}{k_{\|}}=\frac{m_{\|0}}{m_{\perp}}\cdot\frac{I_{-1,0,1}}{I_{-1,0,0}-I_{-1,2,0}}, \qquad (6)$$

$m_{\|0}/m_{\perp}$ – the ratio of the effective masses.

In the second chapter, we study the galvanomagnetic effects, namely, Hall and transverse magnetoresistance (MR), in quasi - two-dimensional and quasi-three-dimensional electronic systems in a transverse (perpendicular to the plane of the superlattice layer) magnetic field when scattering by impurity ions. If the condition is met $\varepsilon_0 >> \hbar/\tau$, the Boltzmann equation can be used to calculate the kinetic coefficients in the approximation of the relaxation time.

In a transverse weak magnetic field, the Hall coefficient is negative, depends on the anisotropy of the effective mass $m_{\|0}/m_{\perp}$ – and is determined by the ratio between the Fermi energy ε_F and the mini-band half-width ε_0 and does not depend on the ratio of the screening radius to the superlattice period (r_0/a).

For a quasi-two-dimensional electron gas ($\varepsilon_F > 2\varepsilon_0$), we have:

$$R_{\perp}=-\frac{\pi^2 a^3}{e}\cdot\frac{m_{\|0}}{m_{\perp}}\cdot\frac{\varepsilon_0}{\varepsilon-\varepsilon_0}\left[1+\frac{5}{2}\left(\frac{\varepsilon_0}{\varepsilon-\varepsilon_0}\right)^2\right]. \qquad (7)$$

In the quasi-three-dimensional case ($\varepsilon_F < 2\varepsilon_0$)

$$R=-\frac{\pi^2 a^3}{e}\cdot\frac{m_{\|0}}{m_{\perp}}\frac{Z_0\left(\frac{3}{4}+3\cos^2 Z_0+\cos^4 Z_0\right)-\frac{2}{3}\left(\frac{7}{8}+\cos^2 Z_0\right)\sin 2Z_0}{\sin^2\frac{Z_0}{2}\left[Z_0\left(\frac{1}{2}+\cos^2 Z_0\right)-\frac{3}{4}\sin 2Z_0\right]^2}. \qquad (8)$$

It can be seen from formulas (7) and (8) that the Hall coefficient is directly proportional to the anisotropy of the effective mass. Since the effective mass perpendicular to the layer plane is much greater than in the layer plane $m_{\|0} > m_{\perp}$, the Hall coefficient in two-dimensional systems is greater than in three-dimensional ones. The Hall coefficient in a weak magnetic field depends on the anisotropy of the effective mass and the degree of mini-band filling, and in a strong magnetic field - only on the concentration of current carriers. When scattering on strongly screening impurity ions, the Hall coefficient of a highly degenerate quasi-two-dimensional electron gas does not depend on the total concentration of current carriers and is determined only by the crystal parameters, while the Hall coefficient of a quasi-three-dimensional electron gas significantly depends on the degree of mini-band filling. For the transverse MR of a degenerate electron gas, a numerical calculation is performed and the dependence of the resistivity on the magnitude of the transverse magnetic field is constructed (Figure 2) and the degree of mini-band filling (Figure 3). Quasi-two-dimensional and quasi-three-dimensional electron gas are considered. The corners of the figures show the shapes of the Fermi surface for quasi-two-dimensional ($\varepsilon_F > 2\varepsilon_0$), quasi-three-dimensional electronic gas ($\varepsilon_F < 2\varepsilon_0$). The sign of transverse MR depends on the magnitude of the magnetic field (Figure 2), the degree of mini-band filling (Figure 3) and the relationship between the screening radius and the superlattice period.[1]

From the above dependences, it follows that when scattering by a long-range Coulomb potential in a transverse magnetic field, the transverse MR of a quasi-two-dimensional electron gas is positive in a weak magnetic field and negative in a strong magnetic field, where the transverse MR almost linearly depends on the magnetic field, i.e., the Kapitsa effect occurs. The transverse MR of a quasi-three-dimensional electron gas is positive in a strong field. (Figure 2). In a weak magnetic field, the MR of a quasi-three-dimensional electron gas at a certain ratio between the screening radius and the

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[1] Askerov B.M. Figarova S.R., Guseynov G.I., Figarov V.R. Magnetoresistance in quasi-two-dimensional electron qas at scattering on impurity ions // Physical Status Solidi B, – 2014. 251 (6), – p. 1197-1201.

period of the mesh oscillates with the degree of mini-band filling,

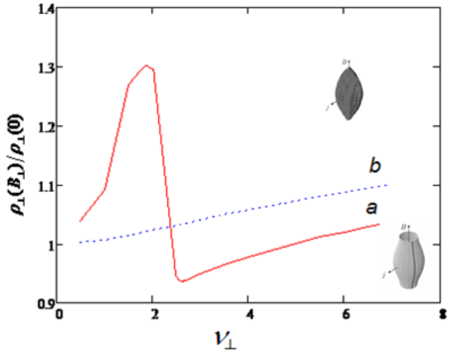

Figure 2. The dependence of the relative resistivity $\rho_\perp(B_\perp)/\rho_\perp(0)$ on the magnitude of the magnetic field perpendicular to the plane of the layer $\nu_\perp = \Omega_\perp\tau_\perp \;\; = eB\tau_\perp/m_\perp$ at $r_0/a = 3{,}5$ for a quasi-two-dimensional ($Z_0 = \pi$) (a) and quasi-three-dimensional electron gas ($Z_0 = \pi/3$) (b).

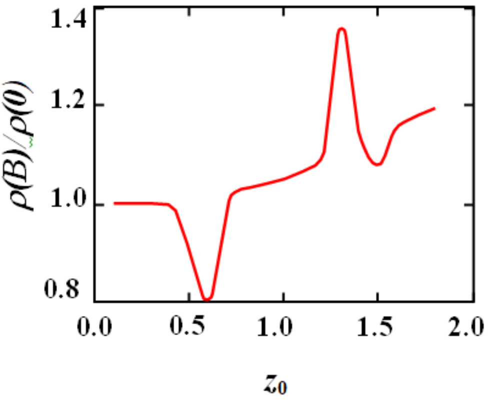

Figure 3. The dependence of the relative resistivity $\rho_\perp(B_\perp)/\rho_\perp(0)$ on the degree of mini-band filling Z_0 at $r_o/a = 5$.

changing its sign (Figure 3). Analytical expressions are obtained for limiting cases in terms of the dimension of the electron gas and the magnitude of the magnetic field.

In a weak magnetic field $(\Omega_\perp\tau_\perp) << 1$, the MR of a quasi-two-dimensional electron gas is equal to:

$$\frac{\Delta\rho(B)}{\rho(0)}=\frac{\nu_{\perp 0}^{2}}{\ln^{2}2\pi r_{0}}\left[5-\frac{9}{\varepsilon/\varepsilon_{0}-1}\right], \tag{9}$$

where $\nu_{\perp 0}=(eB/m_{\perp})\tau_{\perp 0}$. It can be seen from expression (9) that in this limit the MR is positive, quadratically dependent on the magnetic field and logarithmically weakly depends on the ratio between the screening radius and the superlattice period.

The MR of a quasi-two-dimensional electron gas in a strong magnetic field $(\Omega_{\perp}\tau_{\perp})>>1$, is expressed in terms of elliptic integrals and has the form:

$$\frac{\Delta\rho(B)}{\rho(0)}=\left[1-\frac{1}{2}\left(\frac{2\varepsilon_{0}}{\varepsilon}\right)\right]^{1/2}\cdot\frac{1}{\pi}K(k), \tag{10}$$

here $k=\frac{2\varepsilon_{0}}{\varepsilon_{F}}$, $K(k)=\int_{0}^{\pi/2}\frac{d\varphi}{\sqrt{1-k^{2}\sin^{2}\varphi}}$ – elliptic integral of the first kind, $\varphi=Z/2$.

Such a transverse MR behavior was experimentally detected in the GaAs/AlGaAs quasi-two-dimensional electron gas structure.

The transverse MR of a quasi-three-dimensional electron gas in a strong magnetic field is positive, is determined only by the degree of mini-band filling.

$$\frac{\rho(B)}{\rho(0)}=\frac{Z_{0}\sin Z_{0}-\frac{Z_{0}^{2}}{2}\cos Z_{0}-\sin^{2}\frac{Z_{0}}{2}}{(\sin Z_{0}-Z_{0}\cos Z_{0})^{2}}. \tag{11}$$

In the third chapter, we study the galvanomagnetic effects in a longitudinal (parallel to the plane of the superlattice layer) magnetic field in the case of a degenerate electron gas when current carriers are scattered on impurity ions. It is established that the Hall coefficient in a longitudinal magnetic field changes its sign and does not depend on the screening radius. In a weak magnetic field, the Hall coefficient is positive, depends on the anisotropy of the effective mass, the ratio between the Fermi energy and the mini-band width, and does not depend on the concentration of conduction electrons. For a quasi-two-dimensional electron gas, the Hall coefficient is determined by the expression:

$$R_{\|}=\frac{\pi^2 a^3}{e}\cdot\frac{m_{\|0}}{m_{\perp}}\left(\frac{\varepsilon_0}{\varepsilon_F-\varepsilon_0}\right)\left[1-\frac{8}{9}\left(\frac{\varepsilon_0}{\varepsilon_F-\varepsilon_0}\right)\cdot\frac{4}{\pi^2}-\frac{1}{4}\left(\frac{\varepsilon_0}{\varepsilon_F-\varepsilon_0}\right)^2\right]. \quad (12)$$

In a strong magnetic field, the Hall coefficient in both the transverse and longitudinal directions depends only on the concentration of conduction electrons. With a change in the direction of the magnetic field, the Hall coefficient changes its sign. The absolute value of the Hall coefficient anisotropy depends on the dimension of the electron gas: during the transition from quasi-three-dimensional to quasi-two-dimensional, the anisotropy $|R_{\perp}|/|R_{//}|$ decreases. Based on the general formula, a numerical calculation of the transverse MR of the magnetic field value is made (Figure 4) and the ratio of the screening radius to the superlattice period. The transverse MR of a quasi-two-dimensional electron gas is positive and monotonically depends on the magnetic field, while the transverse MR of a quasi-three-dimensional electron gas in the intermediate region of the

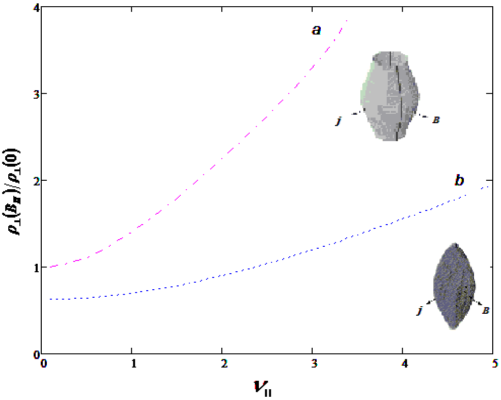

Figure 4. The dependence of the relative resistivity $\rho_{\perp}(B_{\|})/\rho_{\perp}(0)$ of the magnitude of the longitudinal magnetic field $\nu_{\|}=\Omega_{\|}\tau_{\|}$ of various values of the degree of mini-band filling: $a-Z_0=\pi$,

$b - Z_0 = \pi/2$.

magnetic field changes its sign, becoming positive in a strong magnetic field (Figure 4). In the longitudinal magnetic field, there are alternating transverse MR oscillations depending on the screening radius.

In the case of a quasi-two-dimensional electron gas, the transverse MR is positive in the entire region of the magnetic field and for a weak magnetic field it is determined by the formula:

$$\frac{\Delta\rho}{\rho(0)} = \frac{1}{3}\frac{v_{\perp 0} \cdot v_{\parallel 0}}{\ln(2\pi\, r_0/a)} > 0 . \tag{13}$$

The transverse MR for a quasi-three-dimensional electron gas can be either positive (Figure 6) in a strong magnetic field, or negative in a weak magnetic field, which follows from the formula

$$\frac{\Delta\rho}{\rho} = -1{,}31\frac{v_{\perp 0} \cdot v_{\parallel 0}}{\ln(2r_0 Z_0/a)} . \tag{14}$$

The inversion of the sign of the transverse MR is associated with the Fermi topology of the surface and with the presence of a region with a negative effective mass in the mini-band and occurs when the radius of the cyclotron orbit becomes of the order of the superlattice constant. The logarithmic singularity that appears when calculating the relaxation time during scattering by impurity ions leads to an oscillation of the electron density, which in turn leads to signalternating oscillations of the transverse MR depending on the ratio of the screening radius to the lattice period (Figure 5, 6). The presence of negative transverse MR in relatively strong magnetic fields is associated with the geometric effect of electron orbits and the mechanism of unequal scattering of two groups of electrons that differ in the orientation of the electron rotation along cyclotron orbits in a longitudinal magnetic field due to the presence of a region with a negative effective mass in the conduction band.

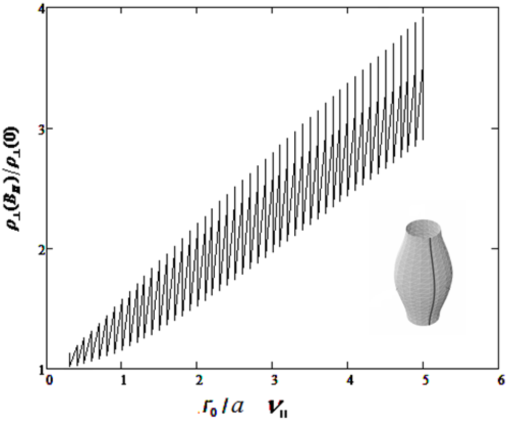

Figure 5. Dependence of the relative resistivity $\rho_\perp(B_\parallel)/\rho_\perp(0)$ the ratio of the radius of the screening to the period of the superlattice r_0/a, and longitudinal magnetic field $\nu_\parallel = eB\tau_\parallel/m_\parallel$, in the case of quasi-two-dimensional electron gas $\varepsilon_F > 2\varepsilon_0$.

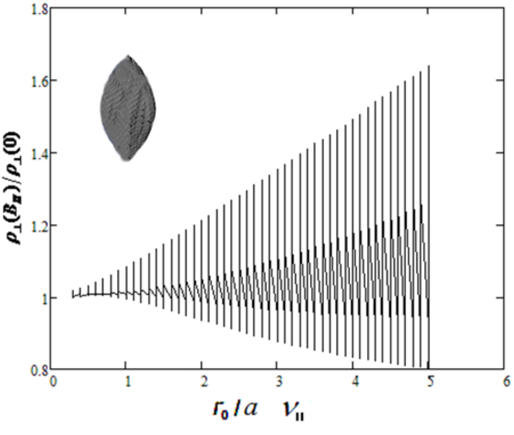

Figure 6. The dependence of the relative resistivity $\rho_\perp(B_\parallel)/\rho_\perp(0)$ the ratio of the radius of the screening to the period of the superlattice r_0/a, and longitudinal magnetic field $\nu_\parallel = eB\tau_\parallel/m_\parallel$, in the case of quasi-three-dimensional electron gas ($\varepsilon_F < 2\varepsilon_0$).

In the fourth chapter, the transverse Nernst-Ettingshausen effect (TNE) in superlattices in a transverse magnetic field is studied when scattering by phonons and impurity ions. The components of the thermomagnetic tensor in a transverse magnetic field are calculated for scattering on acoustic, nonpolar optical, polar optical and piezoacoustic phonons, as well as on impurity ions for a quasi-two-dimensional and quasi-three-dimensional degenerate electron gas, and on the basis of these components, general expressions of the TNE coefficient are obtained. It is shown that when scattering on acoustic, nonpolar optical phonons and strongly screening impurity ions for a quasi-two-dimensional degenerate electron gas, the NE coefficient is zero $Q=0$, and in the quasi-three-dimensional case, the coefficient is different from zero and has a negative sign $Q<0$.

When scattering on polar optical and piezoacoustic phonons, the NE coefficient has a positive sign $Q>0$ and decreases slightly with an increase in the degree of mini-band filling.

In a weak magnetic field $\Omega_\perp \tau_\perp << 1$, the transverse NE coefficient depends on the degree of mini-band filling and has a positive sign $Q>0$.

$$Q = Q_0 \frac{2}{Z_0} \cdot \left(\frac{3}{2} - \frac{\sin Z_0 - Z_0 \cos Z_0}{(0{,}5 Z_0 - 0{,}75 \sin 2Z_0 + Z_0 \cos Z_0)^2} I_{0,03} \right), \quad (15)$$

here $Q_0 = \frac{\pi^2}{3} \cdot \frac{k_0}{e} \cdot \frac{k_0 T}{\varepsilon_0} u_{\perp 0}, u_{\perp 0} = e\tau_{\perp 0} / m_\perp$ – the mobility of the conduction electrons in a perpendicular direction relative to the plane of the superlattice layer.

It follows from (15) that the NE coefficient of a quasi-two-dimensional electron gas (($\varepsilon_F > 2\varepsilon_0$), opened Fermi surface) $Q = 2Q_0$; quasi-three-dimensional electron gas (($\varepsilon_F < 2\varepsilon_0$), closed Fermi surface) $Q = \frac{4}{3} Q_0$.

In a strong magnetic field ($\Omega_\perp \tau_\perp >> 1$), NE coefficient

$$Q = \frac{1}{B^2} Q_0 \cdot \frac{1}{u_\perp^2} \cdot \frac{Z_0}{(\sin Z_0 - Z_0 \cos Z_0)^2} \quad (16)$$

It follows from formula (16) that the transverse NE coefficient is inversely proportional to the square of the electron mobility and in cases with a limit on the dimension of the electron gas has the form:

quasi-two-dimensional electron gas:

$$Q = Q_0 \cdot \frac{1}{3(u_\perp B)^2}; \tag{17}$$

quasi-three-dimensional:

$$Q = Q_0 \cdot \frac{1}{(u_\perp B)^2} \cdot \frac{1}{Z_0^2}; \tag{18}$$

When scattering on weakly screening impurity ions in a weak magnetic field, the transverse NE coefficient is expressed in terms of the functions I_{klm}.

$$Q = \frac{\pi^2}{3} \cdot \frac{k_0}{e} \cdot \frac{k_0 T}{\varepsilon_0} u_{\perp 0} \frac{1}{\ln(2 r_0 Z_0 / a)} \cdot \frac{1}{I_{0,0,5/2}} \left(4 I_{0,0,3} - \frac{5}{2} \cdot \frac{I_{0,0,3/2}}{I_{0,0,5/2}} I_{0,0,4} \right) \tag{19}$$

In the case of a quasi-two-dimensional electron gas ($\varepsilon_F > 2\varepsilon_0$, $Z_0 = \pi$).

$$Q = -4\pi^2 \left(\frac{k_0}{e} \right) \cdot \frac{k_0 T}{\varepsilon_0} \cdot u_{\perp 0}. \tag{20}$$

It can be seen that the NE coefficient of a quasi-two-dimensional electron gas does not depend on the screening radius, it is directly proportional to the electron mobility of the conductivity $u_{\perp 0}$ and the ratio $k_0 T / \varepsilon_0$. It can be seen from formula (20) that when scattering on weakly screening impurity ions in the quasi-two-dimensional case, the transverse NE effect becomes negative, and in the quasi-three-dimensional case, depending on the degree of mini-band filling, it can have both a positive and a negative sign.

In a strong magnetic field, for the NE coefficient, we have:

$$Q = \frac{1}{B^2} \cdot \frac{\pi^2}{3} \cdot \frac{k_0}{e} \cdot \frac{k_0 T}{\varepsilon_0} \cdot \frac{\ln(2 r_0 Z_0 / a)}{u_{\perp 0(ze)}} \cdot \left[\frac{1}{2} \cdot \frac{I_{0,0,-3/2}}{I_{0,0,1}} + \frac{I_{0,0,-1/2} I_{0,0,0}}{I_{0,0,1}^2} \right]. \tag{21}$$

Our calculation of the transverse NE coefficient for the scattering of current carriers on weakly screening impurity ions showed that even in a weak magnetic field perpendicular to the plane of the layer, the transverse NE coefficient changes sign. Note that the sign change in the concentration dependence of the transverse NE coefficient was observed in layered crystal Bi_2Te_3.

In the fifth chapter the NE coefficient is calculated for a quasi-two-dimensional and quasi-three-dimensional degenerate electron gas when scattering by phonons and impurity ions in a longitudinal magnetic field. Analytical expressions are obtained for the transverse NE coefficient in limiting cases in terms of the dimension of the electron gas, the magnitude of the magnetic field and the degree of screening of the Coulomb potential. The anisotropy of the transverse NE coefficient caused by a change in the direction of the magnetic field is considered.

Analytical expressions for degenerate electron gas when scattering on acoustic phonons for the TNE coefficient can be obtained within the limits of weak ($\Omega\tau_0 << 1$) and strong ($\Omega\tau_0 >> 1$) magnetic fields: In a weak magnetic field, the following is obtained:

$$Q = -\frac{k_0}{e}\cdot\frac{\pi^2}{3}\cdot\frac{k_0 T}{\varepsilon_0}u_{01}\cdot\frac{Z_0}{\sin Z_0 - Z_0\cos Z_0}\left(1-\Omega^2\tau_{01}^2\frac{\sin Z_0}{Z_0}\right). \quad (22)$$

It follows from formula (22) that in a weak magnetic field, the transverse NE coefficient weakly depends on the magnetic field and takes negative values for a quasi-two-dimensional electron gas.

In a strong magnetic field ($\Omega\tau_0 >> 1$) for the coefficient of NE we have:

$$Q = -\frac{k_0}{e}\cdot\frac{\pi^2}{3}\cdot\frac{e\tau_{01}}{m_{\|0}}\cdot\frac{k_0 T}{\varepsilon_0}u_{01}\cdot\frac{1}{(u_{\|}B)^2}\cdot\frac{\ln[tg(0{,}5Z_0+0{,}25\pi)]}{\sin Z_0 - Z_0\cos Z_0}. \quad (23)$$

When scattering by polar optical phonons, the relaxation time is anisotropic, which is reflected in the kinetic coefficients. The dependence of the transverse NE coefficient in this case on the magnetic field and the degree of filling of the mini-zone are shown in Figure 7, 8, respectively. It can be seen from Figure 7 that for a quasi-two-dimensional electron gas, there is a significant increase in the transverse NE coefficient.

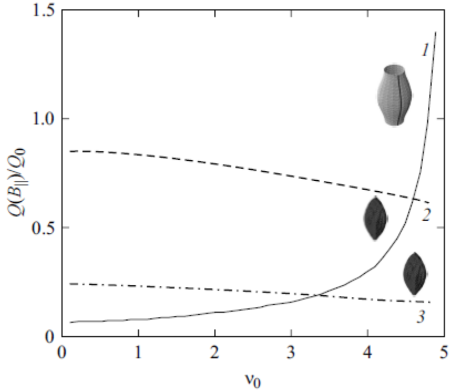

Figure 7. The dependence of dimensionless coefficient TNE $Q(B_{||})/Q_0$ on the magnetic field when scattering on polar optical phonons at different degrees of mini-band filling: 1 – $Z_0 = \pi$, 2 – $Z_0 = \pi/2$, 3 – $Z_0 = \pi/3$.

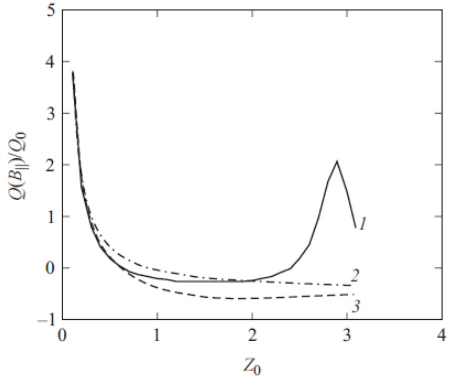

Figure 8. Dependence of the dimensionless TNE $Q(B_{||})/Q_0$ of the degree of mini-band filling Z_0 during scattering by polar optical phonons: 1–a strong magnetic field ($\nu = \Omega\sqrt{\tau_{\perp 0}\tau_{||0}} = 4{,}5$), 2 – a intermediate magnetic field ($\nu = 1$), 3–a weak magnetic field ($\nu = 0{,}5$). Here $\Omega = eB/\sqrt{m_{\perp} m_{||0}}$ is the cyclotron frequency of an electron in a longitudinal magnetic field.

It can be seen from Figure 8 that with a small degree of filling of the mini-band, the transverse NE coefficient Q takes large positive values, then in the neighborhood of $Z_0 \approx \pi/2$ changes its sign and for a quasi-two-dimensional electron gas ($Z_0 = \pi$) it becomes positive again, i.e. the transverse NE coefficient changes its sign twice. Depending on the degree of mini- band filling and the magnetic field, the sign of the effect may vary in the same sample. The sign of the transverse NE coefficient transverse effect in anisotropic systems is determined by the parameter $\gamma = \frac{m_{\parallel}}{m_{\perp}} \frac{\tau_{\perp}}{\tau_{\parallel}}$, i.e., the dependence of the relaxation time on energy and the anisotropy of the effective mass. In superlattices, when current carriers are scattered on polar optical phonons, the relaxation time depends differently on the components of the wave vector $k_{\perp}$ and $k_{\parallel}$. In addition, the effective masses of electrons along and perpendicular to the layer differ, $m_{\perp} < m_{\parallel}$, and $m_{\parallel}$ depends on the wave vector $k_{\parallel}$. Thus, there are two groups of electrons with different relaxation times and effective masses when moving along the plane of the layer and perpendicular to it, and the longitudinal magnetic field mixes up these movements. The electrons move in different cyclotron orbits and the relations between the radius of the cyclotron orbit and the free path length are different for them.

Asymptotics the transverse NE coefficient in a weak and strong magnetic field when scattering by polar optical phonons has the form, respectively:[2]

in a weak magnetic field ($\Omega\tau_0 << 1$):

$$Q = Q_0 \cdot \frac{1}{Z_0}\left[\frac{3}{2} + 2\frac{(\sin Z_0 - Z_0\cos Z_0)\cos Z_0}{0{,}5Z_0 - 0{,}75\sin 2Z_0 + Z_0\cos^2 Z_0}\left(1 + \frac{2}{3Z_0\sin Z_0}\right)\right], \quad (24)$$

in the quasi-two-dimensional case ($Z_0 = \pi$, $\varepsilon_F > 2\varepsilon_0$), at large con-

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[2] Figarova, S.R., Huseynov, H.I., Figarov, V.R. Transverse Nernst-Ettinqshausen effect in superlattices upon electron-phonon scattering // Semiconductors, – 2018. Jul; 52 (7), – p. 853-858.

centrations of current carriers, the TNE coefficient retains its sign.

strong magnetic field field ($\Omega\tau >> 1$):

$$Q = -Q_0 \frac{1}{2Z_0} \cdot \left(\frac{k_0 T}{\varepsilon_0}\right)^{3/2} \cdot \frac{1}{u_\perp u_{\|0} B^2} \cdot \frac{I_{-1,-1,-1/2}}{\sin Z_0 - Z_0 \cos Z_0} . \qquad (25)$$

Here

$$I_{-1,-1,-1/2} = \int_0^{Z_0} \frac{dZ}{Z \cos Z (\cos Z - \cos Z_0)^{1/2}} .$$

It follows from formulas (24) and (25) that a large value of the transverse NE coefficient is a consequence of the high mobility of current carriers in superlattices (for example, in the superlattice GaAs/AlGaAs $u_\perp = 9{,}5 \cdot 10^5\, sm^2/Bc$, $u_\| = 7{,}5 \cdot 10^3\, sm^2/Bc$) and depends on the position of the Fermi level. In a strong field, the transverse NE coefficient takes small negative values, and when the radius of the cyclotron orbit becomes of the order of the superlattice constant, there is a sign inversion. In a strong field, the transverse NE coefficient takes negative values.

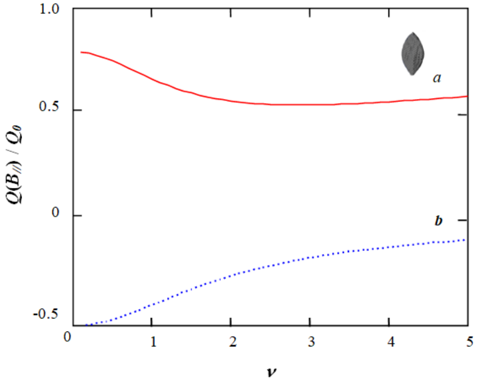

Figure 9. Dependence of the dimensionless transverse NE coefficient $Q(B_\|)/Q_0$ of the value of the longitudinal magnetic field $\nu = \Omega\tau_0$ for a quasi-three-dimensional electron gas when scattering by acoustic (*b*) and polar optical (*a*) phonons.

It is of interest to compare the dependence of the transverse NE coefficient on the direction of the magnetic field during the scattering of conduction electrons on acoustic and polar optical phonons for a quasi-two-dimensional electron gas.

It is shown that the transverse NE coefficient of a quasi-three-dimensional electron gas in the scattering of acoustic and polar optical phonons has different signs (Figure 9), while in the quasi-two-dimensional case (Figure 10) in a strong magnetic field the sign is the same.

In a weak magnetic field for scattering on acoustic phonons, this increase is almost three times greater than for scattering on polar optical phonons.

It is important to note that the criteria for a strong and weak magnetic field are influenced by the parameters of the superlattice a, ε_0 and the scattering mechanism.

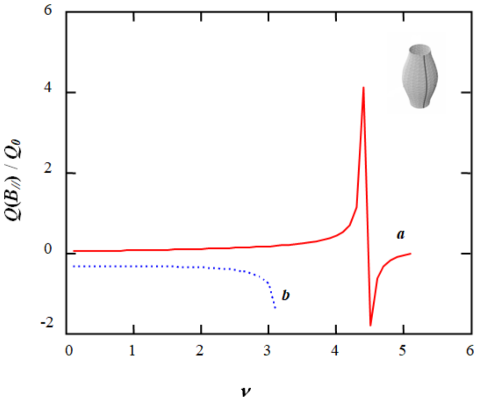

Figure 10. Dependence of the dimensionless transverse NE coefficient $Q(B_{\|})/Q_0$ of the value of the longitudinal magnetic field $\nu = \Omega\tau_0$ for a quasi-two-dimensional electron gas when scattering by acoustic (*b*) and polar optical (*a*) phonons.

When scattering on weakly screening impurity ions, the sign of the transverse NE coefficient in a longitudinal magnetic field also significantly depends on the topology of the Fermi surface and the ratios of the screening radius and the superlattice constant. The

TNE coefficient at small degrees of mini-band filling is negative, with an increase in the degree of mini-band filling, a sign change occurs when at $Z_0 \approx \pi/2$, passing through zero, the transverse NE coefficient becomes positive (Figure 11).

In a weak magnetic field $\Omega\tau << 1$, the transverse NE coefficient for the scattering of current carriers on weakly screening impurity ions has the form:

$$\frac{Q}{Q_0} = \left(\frac{\varepsilon_0}{k_0 T}\right)^{1/2} \frac{1}{\ln\left(\frac{2r_0 Z_0}{a}\right)} \left[-2\frac{I_{1,0,1} - I_{1,2,1}}{I_{1,0,1/2} - I_{1,2,1/2}} + \frac{5}{2} \cdot \frac{I_{0,0,3/2}}{I_{0,0,5/2}} \cdot \frac{I_{1,0,2} - I_{1,2,2}}{I_{1,0,1/2} - I_{1,2,1/2}} \right] \tag{26}$$

It can be seen from the formula that the transverse NE coefficient depends on the degree of mini-band filling, on the ratio of the width of the mini-band ε_0 to the thermal energy $k_0 T$, and logarithmically weakly depends on the ratio of the screening radius to the period of the superlattice.

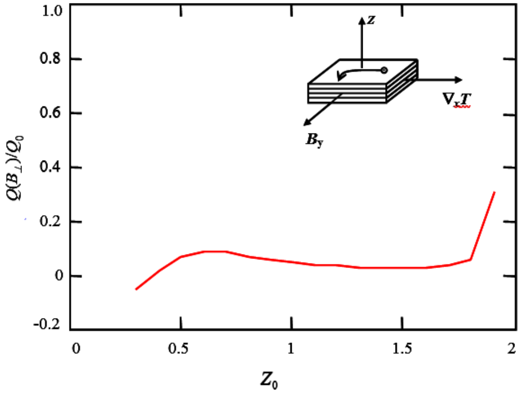

Figure 11. Dependence $Q(B_{||})/Q_0$ of the transverse NE coefficient depends on the degree of mini-band filling Z_0 in a strong longitudinal magnetic field ($\nu = 4$) when scattering on weakly screening impurity ions $r_0/a = 2$.

For a quasi-two-dimensional electrons gas, the transverse NE coefficient is positive and equal to:

$$\frac{Q}{Q_0} = \left(\frac{\varepsilon_0}{k_0 T}\right)^{1/2} \cdot \frac{1}{\ln(2r_0 Z_0/a)} = 0{,}15 > 0$$

and in the quasi-three-dimensional it has the form:

$$\frac{Q}{Q_0} = \left(\frac{\varepsilon_0}{k_0 T}\right)^{1/2} \cdot \frac{1}{Z_0^3 \cdot \ln(2r_0 Z_0/a)}$$

In this case, with small degrees of mini-band filling, the transverse NE coefficient begins to increase significantly.

In a strong magnetic field, the transverse NE coefficient in the scattering of conduction electrons on impurity ions takes the form:

$$\frac{Q}{Q_0} = -\frac{1}{B^2 u_{\perp 0(ze)} u_{II0(ze)}} \left(\frac{k_0 T}{\varepsilon_0}\right)^{3/2} \frac{1}{2Z_0} \frac{\int_0^{Z_0} Z^{-1} \cos^{-1} Z \cdot (\cos Z - \cos Z_0)^{-1/2}}{\sin Z_0 - Z_0 \cos Z_0}, \quad (27)$$

Here $u_{II0(ze)} = e\tau_{II0(ze)}/m_{II0}$ – is the mobility of the conduction electrons in the plane of the layer. An approximate calculation of the formula (27) gives (28)

$$\frac{Q(B)}{Q_0} = -\frac{1}{B^2 u_{\perp 0(ze)} u_{II0(ze)}} \cdot \left(\frac{k_0 T}{\varepsilon_0}\right)^{3/2} \cdot \frac{1}{2} \cdot \frac{\ln Z_0}{Z_0 \cos Z_0}. \quad (28)$$

It follows from (28) that in a strong magnetic field, when scattering on weakly screening impurity ions, the transverse NE coefficient is negative at small degrees of mini-band filling, and at large degrees of mini-band filling it becomes positive.

The anisotropy of the transverse NE effect is revealed due to a change in the direction of the magnetic field. In the transverse field, when scattering by acoustic phonons and strongly screening impurity ions, the transverse NE coefficient for a quasi-two-dimensional electron gas is zero, while in the longitudinal field it is different from zero.

When scattering on polar optical phonons, the transverse NE coefficient in a perpendicular magnetic field has a positive sign $Q > 0$ and decreases slightly with an increase in the degree of mini-band filling, while the transverse NE coefficient when scattering current carriers on weakly screening impurity ions in a weak magnetic field perpendicular to the plane of the layer changes its sign.

In a longitudinal magnetic field, when scattering on weakly screening impurity ions, the transverse NE coefficient changes its sign depending on the magnitude of the magnetic field and the degree of mini-band filling, and in strong magnetic fields it begins to oscillate, when scattering on polar optical phonons, the transverse NE coefficient changes its sign twice in a strong magnetic field depending on the degree of mini-band filling.

The sixth chapter is devoted to the study of the longitudinal Nernst-Ettingshausen (LNE) effect (thermoelectric power (TEP) in a magnetic field) in a transverse and longitudinal magnetic field, as well as the Maggi-Rigi-Leduc effect (MRL) in a transverse magnetic field of a degenerate low-dimensional electron gas in superlattices when scattering by phonons and impurity ions. It is shown that, depending on the position of the Fermi level relative to the top of the mini - band and the period of the superlattice, the TEP can change its sign and increase. The TEP increases significantly with a decrease in the Fermi energy. It is found that for the TEP in the longitudinal field, in contrast to the transverse one, the saturation effect and the inversion of the sign take place. In a strong magnetic field, with an increase in the degree of filling of the mini-band, the TEP begins to oscillate.

In superlattices, when scattering by acoustic and nonpolar optical phonons, the TEP $\alpha(B_\perp)$ is negative and in a transverse strong field does not depend on the magnetic field strength and is determined by the degree of mini-band filling.

$$\alpha(B_\perp) = -\frac{k_0}{e}\cdot\frac{\pi^2}{3}\frac{k_0 T}{\varepsilon_0}\cdot\frac{Z_0}{\sin Z_0 - Z_0\cos Z_0}\,. \qquad (29)$$

In this limit, the TEP depends linearly on the ratio of thermal energy to the energy of the mini-band of the superlattice k_0T/ε_0. In the quasi-two-dimensional case, it is determined only by the relation k_0T/ε_0.

$$\alpha(B)=-\frac{k_0}{e}\cdot\frac{\pi^2}{3}\frac{k_0T}{\varepsilon_0}. \tag{30}$$

In the longitudinal magnetic field, the TEP $\alpha(B_{\|})$ changes its sign and becomes positive. In weak magnetic fields ($\Omega_{\perp}\tau_{01}<<1$) depends nonmonotonically on the degree of mini-band filling.

$$\alpha(B_{\|})=\frac{k_0}{e}\cdot\frac{\pi^2}{3}\frac{k_0T}{\varepsilon_0}\cdot\frac{Z_0}{\sin Z_0-Z_0\cos Z_0}\left[1-(\Omega\tau_{01})^2\frac{\sin Z_0}{Z_0^3}\right].(31)$$

In strong magnetic fields ($\Omega\tau_{01}>>1$), the TEP is inversely proportional to the square of the magnetic induction and the electron mobility.

$$\alpha(B_{\|})=\frac{k_0}{e}\cdot\frac{\pi^2}{3}\frac{k_0T}{\varepsilon_0}\cdot\frac{Z_0^2}{B^2u_{\perp 0}u_{II0}}\cdot\frac{1}{\sin Z_0-Z_0\cos Z_0}\ln\left|tg\left(\frac{Z_0}{2}+\frac{\pi}{4}\right)\right| \tag{32}$$

In this limit, the TEP strongly depends on the degree of mini-band filling and for a quasi-two-dimensional electron gas tends to zero $\alpha(B_{\|})=0$.

When scattering by polar optical and piezoacoustic phonons, the coefficient of the longitudinal NE effect in a weak transverse magnetic field also depends on the ratio k_0T/ε_0 and on the degree of mini-band filling Z_0, for a quasi-two-dimensional electron gas it takes the following form:

$$\alpha(B_{\perp})=-\frac{k_0}{e}\cdot\frac{\pi^2}{3}\frac{k_0T}{\varepsilon_0}\cdot\frac{4}{3}\left[1-v_{\perp 0}^2\cdot\left(\frac{\varepsilon_0}{k_0T}\right)^2\cdot 0.1\right]. \tag{33}$$

It should be noted that the TEP in a strong magnetic field does not depend on the magnitude of the field and becomes twice as large as when scattering by acoustic phonons. With an increase in the degree of mini-band filling, the TEP decreases and begins to oscillate, and the oscillations weaken with the increase of the magnetic field and tend to zero. In the longitudinal magnetic field, the effect of saturation of the TEP takes place.

When scattering on weakly screening impurity ions, the TEP in a transverse weak magnetic field significantly depends on the energy parameter k_0T/ε_0, the magnetic field $B_\perp$, the number of degrees of mini-band filling Z_0 and logarithmically weakly depends on the ratio r_0/a, while in a strong field it does not depend on the field and is determined by the degree of mini-band filling:

$$\alpha(B_\perp) = -\frac{k_0}{e}\cdot\frac{\pi^2}{3}\frac{k_0T}{\varepsilon_0}\cdot\frac{\sin Z_0 - Z_0\cos Z_0}{0.5\cdot Z_0 - 0.75\sin 2Z_0 + Z_0^2\cos^2 Z_0}. \qquad (34)$$

It is established that in superlattices in a longitudinal magnetic field, when scattering on weakly screening ions, the TEP impurity depends nonmonotonically on the degree of mini-band filling (Figure 12).

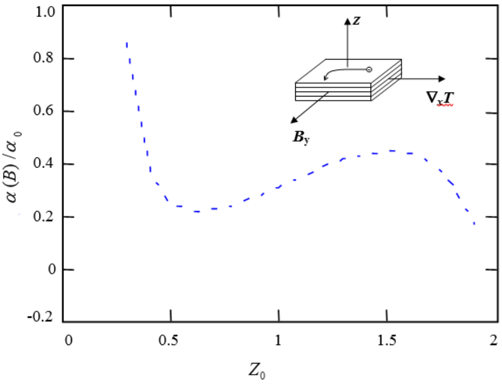

Figure 12. Dependence of the dimensionless TEP $\alpha(B_\parallel)/\alpha_0$ on the degree of mini-band filling Z_0 in strong magnetic fields ($\nu = 4$) in the case $r_0/a = 2$ of scattering by weakly screening impurity ions.

In a strong magnetic field, the TEP takes large positive values at a low degree of mini-band filling. The TEP of a quasi-three-dimensional electron gas depends nonmonotonically on the field, remaining positive, while the TEP of a quasi-two-dimensional electron gas decreases. This behavior of the TEP is associated with a change in the free path in a strong magnetic field, as well as with the fact that in the quasi-two-dimensional case, the screening radius does not depend on the concentration and the TEP is determined by the ratio of the superlattice period to the radius of the cyclotron orbit. TEP amplification can be used to convert energy and create a generator. [3]

The dependence of the TEP on the screening radius when scattering on weakly screening impurity ions is shown in Figure 13.

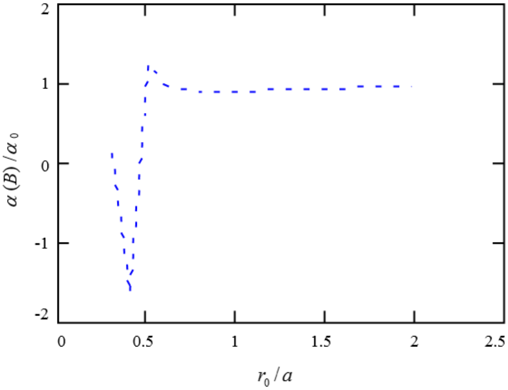

Figure 13. Dependence of the dimensionless TEP $\alpha(B_\parallel)/\alpha_0$ of a quasi-three-dimensional electron gas ($Z_0 = \pi/2$) on the ratios r_0/a in intermediate magnetic fields $\nu = 1$ during scattering by weakly screening impurity ions.

It follows from the figure that in the quasi-three-dimensional case, as the mini-band is filled, the screening radius decreases, while scattering at large angles increases, and the TEP depends nonmonotonically on the ratio between the screening radius and the superlattice period. At a certain ratio between the screening radius and the period of the superlattice in intermediate magnetic fields ($\nu \approx 1$), there is a change in the sign of the TEP, and when the degree of mini-band filling $Z_0 \approx \pi/2$ is equal to the singularity. This is due to the topology of the Fermi surface in the superlattice. For a positive curvature of the Fermi surface near the positive $k_z = 0$, the effective mass of the electron is small and in-

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[3] Figarova, S.R., Huseynov, H.I., Figarov, V.R. Magnetothermoelectric properties of layered structures for in impurity scattering // Superlattices and Microstructures, – 2018. Mar; 117, – p. 469-475.

creases positively and under the external influence of its energy, while for a negative curvature at the boundary $k_z = \pi/2$ of the mini-band, the effective mass is negative and the electron energy decreases, i.e. the sign of the TEP changes when the Fermi level moves in the mini-band in the superlattice. In the quasi-two-dimensional case, the screening radius does not depend on the concentration and its sign is determined by the ratio between the period of the superlattice and the radius of the cyclotron orbit, and when these values coincide, a non-monotonic behavior of the TEP is observed. In the quasi-three-dimensional case, the features in the behavior of the TEP are apparently related to the fact that the screening radius is a function of mini-band filling. At $r_0/a < 1$ ($r_0 \sim 1/n^{1/2}$), with a decrease in the density of the electron gas, the TEP changes its sign. A decrease in the superlattice period leads to a decrease in the TEP. As follows from Figure 13, when scattering on weakly screening impurity ions in a longitudinal field, depending on the ratio between the screening radius and the superlattice period, an inversion of the sign of the TEP occurs. The positive TEP is explained by the direction of the magnetic field relative to the plane of the layer and indicates that there is a region with a negative effective mass near the ceiling of the mini-band. The TEP increases significantly with a decrease in the Fermi energy, which corresponds to an experiment conducted on $r_0/a < 1$ ($r_0 \sim 1/n^{1/2}$) superlattices doped with *Nb*.

Thermomagnetic coefficients can be controlled by adjusting the parameters of the superlattice a, ε_0.

The Maggi-Rigi-Leduc coefficient in superlattices in a transverse magnetic field is calculated when scattering by acoustic, polar-optical phonons and impurity ions.It is shown that the MRL coefficient in superlattices during scattering by phonons and impurity ions in weak magnetic fields decreases in comparison with the electronic part of the thermal conductivity without a magnetic field. In strong magnetic fields, the electronic part of the thermal conductivity tends to zero.

In the seventh chapter, the theory of transport phenomena in an asymmetric quantum well (QW) with a semi-parabolic potential is developed in the absence of a magnetic field when current carriers are scattered on acoustic and polar optical phonons. Based on the solution of the Schrodinger equation, using the energy spectrum and wave functions of conduction electrons in a semi-parabolic QW, the dependence of the electrical EC and TEP of a degenerate two-dimensional electron gas on the profile of the QW, its width and the Fermi level is investigated in the approximation of the effective mass. The influence of the confaiment potential (restriction) on the EC and TEP of a semi-parabolic QW is discussed. It is shown that the EC and TEP are oscillates with the width of the QW and the oscillation period depends on the potential of the QW and the concentration of current carriers. The EC increases abruptly with an increase in the potential of the QW and forms loops that occur when the Fermi level crosses the energy level of the quantum wells, the number of branches corresponds to the number of energy levels. It is found that the TEP of a semi-parabolic QW has features: hysterical loops and sign change. These features depend on the surface potential and are explained by the effects of localization/delocalization in the QW. and the properties of the electron at the edges of the well, as well as the relationship between the Fermi level, the value of the surface potential and the energy levels of the QW.

The potential of an asymmetric QW has the form:

$$U(z) = \begin{cases} U_s (z/d)^2, & at \ \ 0 < z \le d \\ \infty, & at \ \ z \le 0 \end{cases} \tag{35}$$

Here $U_s -$ is the maximum value of the surface potential, $d -$ the width of the QW. From the boundary conditions imposed on the wave function of the conduction electrons, we obtained a condition for the surface potential $(d/2\hbar)(2mU_S)^{1/2} >> 1$, in which the solution of the Schrodinger equation for a semi-parabolic QW is finite on the right and infinite on the left and the law of dispersion of a two-dimensional electron gas in a semi-parabolic QW has the form:

$$\varepsilon = \frac{\hbar^2 k_\perp^2}{2m} + \hbar\omega_s\left(2n+\frac{3}{2}\right), \qquad (36)$$

where $k_\perp^2 = k_x^2 + k_y^2$, m – Is the effective mass, frequency $\omega_S = d^{-1}(2U_S/m)^{1/2}$ – of the semi-parabolic potential.

The energy spectrum (34) is realized in structures AlN/AlGaN/AlN and GaAs/AlGaAs. And for a given energy spectrum, the Fermi energy is determined by the formula:

$$\varepsilon_F = \frac{n_{el}\cdot\pi\hbar^2 d}{m(\bar{n}+1)} + \hbar\frac{1}{d}\cdot\sqrt{\frac{2U_S}{m}}\left(\bar{n}+\frac{3}{2}\right). \qquad (37)$$

The dependence of the Fermi energy on the parameters of the QW is non-monotonic (Figure 14) where is an $\bar{n}$ integer from $n = \frac{1}{2}\left(\frac{\varepsilon_F}{\hbar\omega} - \frac{3}{2}\right)$, which is found from the condition $\varepsilon_F = \varepsilon_n$.

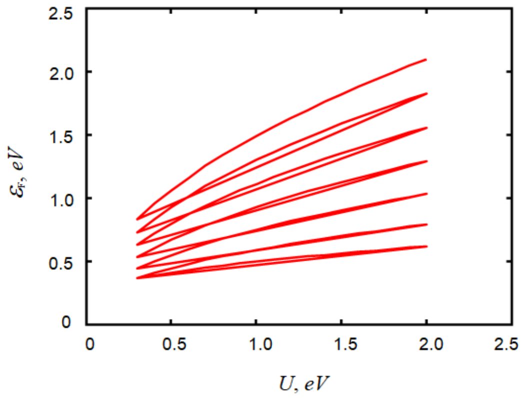

Figure 14. The dependence of the Fermi energy on the potential of the QW.

At width $d = d_{\min} = \frac{(\bar{n}+3/2)(\bar{n}+1)^{1/2}}{\pi n_{el}}\sqrt[4]{\frac{2mU_S}{\hbar^2}}$, the Fermi energy has an extremum that depends on the concentration of the electron gas and the QW potential (for $U_s = 0.3eV, n_{el} = 10^{25} m^{-3}$, $d_{\min} \approx 10\,nm$). At small QW widths, the Fermi energy drops sharply, and then begins to increase almost linearly.

The motion of electrons in the plane xy is described by the semiclassical Boltzmann equation, and the motion in the direction of the axis z is quantized in a semi-parabolic well with a potential $U(z)$; the temperature gradient is directed along the axis x: With such a geometry of the problem, when scattering current carriers on acoustic ($r = 0$) and polar optical ($r = 1$) phonons, the general expression for EC will be determined by the expression:

$$\sigma = \frac{e^2\tau_0}{m} \cdot n_0 \cdot \frac{\sum\limits_{n=0}^{\bar{n}} \int\limits_{\varepsilon_n}^{\infty} \Theta(\varepsilon^* - \varepsilon_n^*)(\varepsilon^* - \varepsilon_n^*)^{r+1} \left(-\frac{\partial f_0}{\partial \varepsilon^*} \right) \cdot d\varepsilon^*}{\sum\limits_{n=0}^{n-1} \Theta(\varepsilon^* - \varepsilon_n^*)}, \quad (38)$$

where

$$n_0 = \frac{mk_0T}{\pi d\hbar^2}, \; \tau_0 = \frac{\pi\hbar^2 dk_0T}{m} \left(\frac{2mk_0T}{\hbar^2} \right)^r \cdot \frac{1}{A_r}, \; \varepsilon_n^* = \frac{\varepsilon}{k_0T}, \; \varepsilon^* = \frac{\varepsilon_n}{k_0T}.$$

For a degenerate electron gas, summing up over all occupied energy levels of a QW and subtracting the value of the Fermi energy (35), when scattering on acoustic phonons for deep quantum wells ($\hbar\omega_s >> k_0T$), the EC has the form:

$$\frac{\sigma}{\sigma_0} = \frac{\pi\hbar^2 dn_{el}}{mk_0T} \cdot \frac{1}{(\bar{n}+1)(\bar{n}+2)} \quad (39)$$

where $\sigma_0 = \dfrac{e^2\tau_0 n_0}{m}$, $\bar{n}$ – is the number of sublevels below the Fermi level.

It can be seen from (39) that in this case the EC is directly proportional to the width of the well and the concentration of current carriers and does not depend on the surface potential of the QW. At the limit, for not deep quantum wells $\hbar\omega_s << k_0T$, the electrical conductivity is equal to:

$$\frac{\sigma}{\sigma_0}=\frac{\pi\hbar^2 d n_{el}}{m\cdot k_0 T}\cdot\left[\frac{1}{\bar{n}+1}-3\left(\frac{2\hbar\omega_s}{k_0 T}\right)^2\right].\qquad(40)$$

In this case, the EC depends both on the width of the pit and on the surface potential.

When scattering on polar optical phonons for EC, we have:

$$\sigma=\sigma_0\left[\left(\frac{\pi d\hbar^3 n_{el}}{m\cdot k_0 T(\bar{n}+1)}\right)^2+\left(\frac{\hbar\omega_s}{k_0 T}\right)^2\cdot\frac{\bar{n}(\bar{n}+2)}{3}\right].\qquad(41)$$

Based on the numerical calculation using the formula (36), the dependence of the EC on the Fermi energy (ε_F), the width (d) of the QW (Figure 15) and the QW potential (U_s) (Figure 16) for a semi-parabolic QW: GaAs/AlGaAs: $m=0{,}067m_0-, n=10^{25}m^{-3}-$, $T=60K$ – for acoustic phonons, 80 K for polar optical phonons.[4]

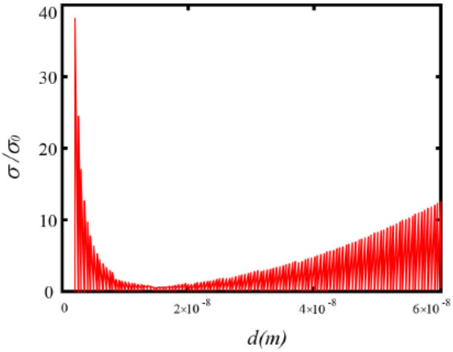

Figure 15. The dependence of the EC on the width of the QW when scattering on optical phonons at $U_s=0.9eV$.

The EC is a step function of the Fermi energy and oscillates with the well width with a period $\Delta d=(\sqrt{mU_S}/\pi\hbar n_{el})^{1/2}$ that depends on the QW potential and the concentration of current carriers.

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[4] Guliyev B.I., Figarova S.R., Huseynov H.I, Figarov V.R. Semi-parabolic quantum well electrical conductivity // European Physical Journal plus, – 2019. Jun; 134 (1), – p. 1-6.

Jumps in the EC occur when the Fermi level crosses the enegetic levels of the QW.

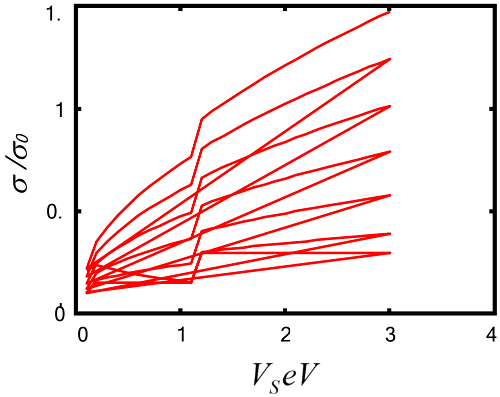

Figure 16. The dependence of the EC on the potential of the QW width $d = 10nm$.

It follows from Figure 16 that with an increase in the QW potential, loops appear in the EC, which are explained by a non-monotonic change in the position of the Fermi level relative to the energy levels of the QW, while the density of states experiences a jump, which leads to the presence of inflection points in the EC.

For TEP scattering by acoustic phonons, the general expression will be:

$$\alpha = -\frac{k_0}{e}\frac{\pi^2}{3}\frac{\sum\limits_n \Theta(\varepsilon_F^* - \varepsilon_n^*)}{\sum\limits_n (\varepsilon_F^* - \varepsilon_n^*)\Theta(\varepsilon_F^* - \varepsilon_n^*)} \tag{42}$$

When scattering by polar optical phonons, the TEP has the form:

$$\alpha = -\frac{k_0}{e}\cdot\frac{2\pi^2}{3}\cdot\frac{\sum\limits_n (\varepsilon_F^* - \varepsilon_n^*)\Theta(\varepsilon_F^* - \varepsilon_n^*)}{\sum\limits_n (\varepsilon_F^* - \varepsilon_n^*)^2\Theta(\varepsilon_F^* - \varepsilon_n^*)} \tag{43}$$

On the basis of the general formulas (42) and (43), the dependence of the TEP $\left|\frac{\alpha}{\alpha_0}\right|$ $\left(\alpha_0 = \frac{k_0}{e}\frac{\pi^2}{3}\right)$ on the Fermi energy and the potential QW (Figure 17-18) for QW was numerically calculated.[5]

The TEP oscillates with the Fermi energy and when the energy levels of the QW cross the Fermi level, the TEP experiences a jump at a certain width of the QW, depending on the ratio between the Fermi energy, the energy levels of the QW and the potential of the QW, the TEP has features: loops and a sign change (Figure 17, 18).

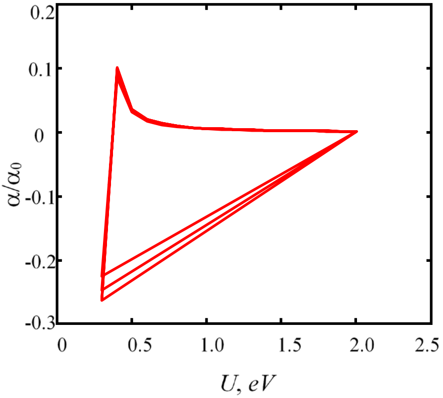

Figure 17. The dependence of the TEP on the QW potential in the scattering of current carriers on polar optical phonons at $a = 7\,nm$.

Hysteresis loops are induced by fluctuations in the Fermi energy with the frequency of the QW potential $\omega_S = d^{-1}(2U_S/m)^{1/2}$; with an increase in the QW width and at low electron concentrations, the loops disappear. From the expression for the two-dimensional electron gas concentration, it follows that at the same value of the electron gas concentration due to the localization and delocalization of electrons in the QW in the z direction (for example, during the

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[5] Figarova, S.R., Huseynov, H.I., Figarov, V.R. Thermoelectric power hysteresis in semiparabolic quantum well // Thin Solid Films, – 2021.721, – p.138554(1-4).

transition from the $n-$the quantum level to the $n+1$ level), the number of electrons in the xy plane changes, i.e. the same potential U_S can correspond to two values of the Fermi energy, which explains the hysteresis loops of the TEP in Figure 17, 18. When the Fermi level enters the region of the delocalized state, the charge density increases, and the TEP becomes negative, and vice versa, when the Fermi level falls into the region of the localized state, the charge density decreases and the TEP becomes positive. (Figure 17, 18). In a semi-parabolic QW, the distance between neighboring energy levels is twice as large as in a parabolic one, which affects the localization/delocalization processes.

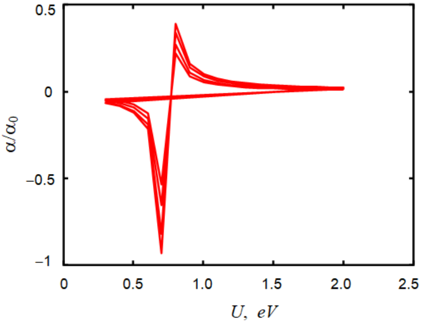

Figure 18. The dependence of the TEP on the potential of the QW in the scattering of current carriers on acoustic phonons at $a = 7\,nm$.

MAIN RESULTS

1. The electrical conductivity and the electronic part of the thermal conductivity of the superlattice are calculated on the basis of the relaxation time components obtained during the scattering of conduction electrons on impurity ions. It is shown that the anisotropy the electrical conductivity, in different ways, depends on the period of the superlattice: at large concentrations of impurities increases, while for small-decreases. A numerical calculation of the anisotropy of EC is performed depending on the ratio between the Fermi level and the mini-band width for different values of the ratio of the screening radius and the GaAs/AlGaAs

superlattice period. It is shown that with an increase in this ratio, the anisotropy of EC increases and when the Fermi surface is a corrugated cylinder becomes an order of magnitude larger.

2. It is revealed that the Hall coefficient in superlattices changes its sign depending on the direction of the magnetic field. The sign change is due to the presence of regions with a negative effective mass in the mini-band. The anisotropy of the Hall coefficient in a superlattice also depends on the dimension of the electron gas: during the transition from quasi-three-dimensional to quasi-two-dimensional, the anisotropy decreases.

3. It is established that the anisotropy of the transverse magnetoresistance (MR) in superlattices when scattering by impurity ions significantly depends on the degree of mini-band filling, the magnitude and direction of the magnetic field and the ratio between the screening radius and the superlattice period. In the case of weak screening, there is an inversion of the MR sign when the radius of the cyclotron orbit becomes of the order of the superlattice period. For a quasi-two-dimensional electron gas in a transverse weak magnetic field, the transverse MR is positive, and in strong ones it is negative. In a strong magnetic field, the transverse MR depends almost linearly on the magnetic field, i.e. the Kapitsa effect takes place. This behavior of the transverse MR was experimentally detected in GaAs/AlGaAs. In a longitudinal magnetic field, the transverse MR of a quasi-two-dimensional electron gas is positive in a strong and negative in a weak field. The transverse MR in the longitudinal magnetic field is an order of magnitude greater than in the transverse field. The transverse MR of a quasi-three dimensional electron gas in the transverse field is always positive, and in the longitudinal field it changes its sign.

4. The numerical calculation carried out for superlattices GaAs/AlGaAs shows that the transverse MR in a longitudinal magnetic field, in contrast to the transverse one, depends non-monotonically on the ratio between the screening radius and the superlattice period and, at a certain ratio, has a feature: alternating MR oscillations depending on the screening radius. It is found that

when scattering on strongly screening impurity ions, the MR positively and in a strong magnetic field does not depend on the screening radius, since the cyclotron orbit is outside the strongly screening impurity field.

5. In intermediate magnetic fields, the transverse MR changes its sign if the Fermi level is in the middle of the mini-band of the superlattice. When the Fermi surface is a corrugated cylinder, then there is a region with a negative effective mass in the mini-band. The change in the sign of the transverse MR is explained by the mechanism of unequal scattering of two groups of electrons that differ in the orientation of the electron rotation along cyclotron orbits in a magnetic field due to the presence of a region with a negative effective mass in the conduction band.

6. The transverse Nernst-Ettingshausen (TNE) effect in a longitudinal magnetic field during scattering by phonons is investigated. It is shown that when scattering by polar optical phonons in the same sample, the sign of the TNE coefficient changes its sign twice depending on the degree of mini-band filling. For scattering on acoustic phonons, the TNE coefficient is almost three times greater than for scattering on polar optical phonons. In a strong magnetic field, there is an inversion of the sign of the NE coefficient, which is explained by the presence of two groups of electrons with different dependence of the relaxation time on the wave vector and anisotropy of the effective mass.

7. The dependence of the TNE effect in a longitudinal magnetic field when scattering on weakly screening impurity ions on the magnitude of the magnetic field, the degree of mini-band filling of the superlattice and the ratio between the screening radius and the superlattice period is studied. It is shown that in strong magnetic fields, the TNE coefficient depends nonmonotonically on the degree of mini-band filling: at small degrees of mini-band filling, the transverse NE coefficient takes negative values, and then, passing through zero, becomes positive. The change in the sign of the TNE is due to the topology of the Fermi surface, the dependence of the screening radius on the concentration and the period of the

superlattice. The TNE coefficient of a quasi-two-dimensional electron gas increases significantly in a magnetic field, while for the quasi-three-dimensional case, the TNE coefficient tends to zero, this behavior is due to a change in the free path of electrons in a strong magnetic field, as well as the fact that in the quasi-two-dimensional case, the screening radius does not depend on the concentration.

8. The features of the anisotropy of the TNE effect depending on the scattering mechanism, the direction of the magnetic field and the size of the electron gas are revealed. It is found that in a transverse magnetic field, the TNE coefficient for a degenerate quasi-two-dimensional electron gas when scattered by acoustic phonons is zero, while in a longitudinal magnetic field it is different from zero. In the case of scattering by polar optical phonons and impurity ions in a perpendicular magnetic field, the TNE coefficient decreases with an increase in the degree of mini-band filling, while in the longitudinal field it depends nonmonotonically on the degree of mini-band filling, up to a sign change. Note that a change in the sign of the transverse NE coefficient was observed in layered crystals Bi_2Te_3.

9. The anisotropy of the thermoelectric power (TEP) in a magnetic field LNE (longitudinal Nernst-Ettingshausen effect) in a superlattice under the scattering of conduction electrons on phonons is studied. When scattering by acoustic phonons, the TEP of a quasi-two-dimensional electron gas is zero in a longitudinal strong magnetic field, while in a transverse field it is nonzero. When scattering by polar optical phonons in a weak magnetic field, the anisotropy of the effect is insignificant, while in strong magnetic fields it is significantly. Numerical calculation for TEP shows that in intermediate magnetic fields there is a significant increase in TEP at small degrees of mini-band filling, the TEP begins to oscillate in strong magnetic fields.

10. It is shown that when scattering on weakly screening impurity ions, there is an inversion of the sign of the TEP in the longitudinal magnetic field, which is due to the topology of the Fermi

surface and the dependence of the screening radius on the concentration. With a positive curvature of the Fermi surface, the effective mass of the electron positive, and with an external influence, its energy increases, while for a negative curvature at the boundary of the mini-band, the effective mass is negative and the energy of the electron decreases. Thus, the sign of the TEP can change when the Fermi level moves through the mini-band of the superlattice. A decrease in the superlattice period leads to a drop in the TEP. A significant increase in the TEP with a decrease in the Fermi energy was found experimentally in superlattices $SrTiO_3$ of the Nb alloy. The TEP also depends on the ratio between the superlattice period and the radius of the cyclotron orbit: at small screening radius the electron gas density decreases and the TEP changes sign.

11. The longitudinal and transverse NE coefficients of an electron gas are compared with the cosine dispersion law in magnetic field parallel to the plane of the layer when scattering by impurity ions. It is shown that the TNE and LNE effects depend nonmonotonically, in different ways, on the degree of mini-band filling, the magnetic field and the screening radius. In a strong magnetic field, the LNE coefficient is positive, and the TNE coefficient takes negative values at small degrees of the band, and then, as the mini-band is filled, passing through zero, it becomes positive. This behavior of the thermomagnetic coefficients is associated with a change in the free path of electrons in a strong magnetic field, as well as the fact that in the quasi-two-dimensional case, the screening radius does not depend on the concentration. In the quasi-three-dimensional case, with a decrease in the screening radius, the LNE coefficient in intermediate magnetic fields changes its sign, and the TNE coefficient decreases with an increase in the screening radius at a period of the superlattice and tends to zero. Thermomagnetic coefficients can be controlled by adjusting the parameters of the superlattice.

12. It is shown that the MRL coefficient in superlattices during scattering by phonons and impurity ions in weak magnetic fields

decreases in comparison with the electronic part of the thermal conductivity without a magnetic field. In strong magnetic fields, the electronic part of the thermal conductivity tends to zero, so the thermal conductivity of superlattices is equal to the thermal conductivity of the phonon gas and this makes it possible to experimentally measure the phonon part of the thermal conductivity.

13. The dependence of the electrical conductivity (EC) of a two-dimensional electron gas in an asymmetric QW with a semi-parabolic potential under electron-phonon scattering on the parameters of the QW and the Fermi energy is determined. The EC oscillates with the width of the QW, and the oscillation period depends on the potential of the QW and the concentration of conduction electrons. With an increase in the potential of the quantum well, the electrical conductivity increases abruptly and forms loops that occur when the Fermi level crosses the energy level of the QW, and the distance between the neighboring energy levels of a semi-parabolic quantum well is much larger compared to a parabolic one, which affects the effect of localization/delocalization of electrons in the QW. At a certain position of the Fermi levels relative to the energy levels, the localization of electrons decreases, and the number of electrons involved in EC increases. It is established that when scattering on acoustic phonons, the amplitude of the EC oscillation increases with the well width, while when scattering on optical phonons, this dependence is non-monotonic and is associated with delocalization of EC.

14. The effect of the surface potential on the TEP of a semi-parabolic QW during the scattering of charge carriers on phonons is investigated. The dependence of the TEP on the Fermi energy and the parameters of the QW is determined. It is shown that the TEP oscillates with the Fermi level, and the oscillation period depends on the surface potential, the width of the QW, and the concentration of charge carriers. Features in the behavior of TEP, such as loops and sign changes, occur with a certain correlation between the surface potential, the Fermi energy and the energy levels of the QW. It is shown that the presence of loops is associated with the properties of electrons at the edges of the QW and is

explained by the effects of localization / delocalization of electrons, and the sign change is associated with the position of the Fermi level relative to the energy levels of the QW. The change in the sign of the TEP occurs at high concentrations of electrons, when the Fermi level is located in a localized region.

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1. Гусейнов Г.И., Джабраилов Т.Г., Алиева Л.Р. Термомагнитные эффекты в пленках типа электронного кремния // Материалы I Республиканской научной конференции «Актуальные проблемы физики», – Баку: – 5 – 6 февраля, – 1998, –с. 54-55.
2. Гусейнов Г.И. Влияние анизотропии спектра на осцилляции кинетических коэффициентов в многодолинных полупроводниках // Материалы II Республиканской научной конференции «Актуальные проблемы физики», – Баку: – 30 – 31 октября, – 2001, – с.18-19.
3. Кулиев Б.И., Гусейнов, Г.И. Время релаксации носителей тока при рассеянии на фононах в многодолинных полупроводниках // Материалы II Республиканской научной конференции «Актуальные проблемы физики», – Баку: – 30 – 31 октября, – 2001, – с.16.
4. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. К теории рассеяния носителей тока на ионах примеси в полупроводниках с анизотропным законом дисперсии // – Баку: Вестник Бакинского Университета, Серия физико-математических наук, – 2003. №1, – с. 127-132.
5. Гусейнов Г.И. К теории рассеяния носителей тока на ионах примеси в полупроводниках типа электронного кремния // Материалы III Республиканской научной конференции «Актуальные проблемы физики», посвященной 80-летию член корр. NANA, профессора А.И. Мухтарова. – Баку: февраль, – 2004. – с.78.
6. Hüseynov H.İ. Kvaziikiölçülü elektron qazının aşqar ionlarından səpilməsi və elektrikkeçiriciliyi // «Fizikanın aktual prob-

lemləri» IV Respublika Elmi konfransının materialları, Bakı: – 2006. – c.47.

7. Askerov B.M., Figarova S.R., Guseinov G.I., Figarov V.R. Relaxation time and electricalconductivity anisotropy of layered crystals at the scattering of charge carriers by impurity ions // AIP Conference Proceedings «Frontiers of fundamental physics: Eighth international Symposium FFP8», – American Institute of Physics, USA: – 28 April, – 2007, Vol. 905, – p. 43-47.
8. Aѕкerov B.M., Figarova S.R., Huseynov H.İ., Figarov V.R. Anisotropy of impurity scattering and electrical conductivity in quasi-two-dimensional electronic systems//– Sankt-Petersburg:Physics of the Solid State,–2008.Vol.50, №4–p.746-750.
9. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. Гальваномагнитные эффекты в двумерных электронных системах при рассеянии на ионах примеси // – Баку: Вестник Бакинского Университета, Серия физико-математических наук, – 2009. №3, – с. 117-123.
10. Hüseynov H.İ. Kvaziikiölçülü sistemlərdə maqnit müqaviməti. «Metallar fizikasının müasir problemləri» // II Beynəlxalq elmi-praktik konfransın materialları, – Bakı: Az.MİU,–2009, c.41-42.
11. Hüseynov H.İ. Kvaziikiölçülü sistemlərdə Holl effekti // Bakı Dövlət Universitetinin 90 illik yubileyinə həsr olunmuş Beynəlxalq Elmi konfransın materialları, Təbiət elmləri, – Bakı: – 2009, – s.124-125.
12. Гусейнов Г.И. Магнитосопротивление в квазидвумерных электронных системах при рассеянии на ионах примеси со слабой экранировке кулоновского потенциала // Материалы VI Республиканской научной конференции «Актуальные проблемы физики», Баку: БГУ,–20 ноябрь, – 2010, – с.35-36.
13. Əsgərov B.M. Aşqar ionlarından səpilmə halında kvaziikiölçülü və kvaziüçölçülü elektron qazının maqnit müqaviməti / B.M. Əsgərov, S.R. Fiqarova, H.İ. Hüseynov [və s.] // Azərbaycan Fizika jurnalı, – Bakı: – 2010. 16 (2), – s. 11-14.
14. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. Поперечное магнетосопротивление низко размерной электронной системы при рассеянии на ионах примеси // – Баку: Известия НАН Азербайджана, Серия физико-математических и тех-

ических наук, физика и астрономия, – 2010. №5, – с. 3-8.

15. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. Гальваномагнитные эффекты в квазидвумерных электронных системах при рассеянии на сильно экранированных ионах примеси // – Баку: Вестник Бакинского Университета, Серия физико-математических наук, – 2011. №1, – с. 122-130.
16. Askerov B.M., Figarova S.R., Huseynov H.İ. Galvanomagnetic effects in superlattices at strong screening impurity ions scattering // Turkish Physical Society. 28th international Physics Congress. Abstract Book, – Turkey, Bodrum: – 6 – 9 September, – 2011, – p. 665-666.
17. Askerov B.M., Figarova S.R., Huseynov H.İ. Transverse magnetoresistance in layered crystals at impurity ion scattering // İnternational Conference on Nanosciencence+ Texnology. Abstract Book, – France, Paris: – 23 – 27 Jule, – 2012, – p.46.
18. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. Теории явлений переноса в квазидвумерных электронных системах при рассеянии на ионах примеси // – Баку: Journal of Qafqaz University, – 2012. №33, – с. 9-33.
19. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. Отрицательное магнитосопротивление в перпендикулярном оси сверхрешетки слабом магнитном поле при рассеянии на ионах примеси // – Баку: Известия НАН Азербайджана, Серия физико-математических и технических наук, физика и астрономия, – 2012. №5, – с. 3-9.
20. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. Поперечный эффект Нернста-Эттингсгаузена в сверхрешетках // – Баку: Вестник Бакинского Университета, Серия физико-математических наук, – 2013. №1, – с. 86-92.
21. Askerov B.M., Figarova S.R., Mahmudov M.M., Huseynov, H.İ. Magneto resistance in superlattices in parallel magnetic field // Turkish Physical Society, 30th international Physics congress. Abstract Book, – İstanbul-Turkey: – 2 – 5 September, – 2013, – p.467
22. Гусейнов Г.И. Эффект Нернста-Эттингсгаузена в квазидвумерных электронных системах // Международная научная конференция «Актуальные проблемы физики» посвящен-

ной 80-летию Академика Б.М. Аскерова. Материалы конференции,–БДУ,Баку:–6декабрь,–2013,–с.113-114.

23. Аскеров Б.М., Фигарова С.Р., Гусейнов Г.И. Поперечное магнетосопротивление в сверхрешетках при рассеянии на ионах примеси // Международная научная конференция «Актуальные проблемы физики» посвященной 80-летию академика Б.М. Аскерова. Материалы конференции, – БДУ, Баку, – 6 декабрь, – 2013, – с.107-108.
24. Askerov B.M. Figarova S.R., Huseynov H.I., Figarov V.R Magnetoresistance of layered semiconductors upon the scattering of charge carriers at impurity ions in a parallel magnetic field //– Sankt-Petersburg: Semiconductors, – 2014. 48 (6), – c. 768-773.
25. Askerov B.M. Figarova S.R., Guseynov G.I., Figarov V.R Magnetoresistance in quasi-two-dimensional electron qas at scattering on impurity ions // Physical Status Solidi B, – 2014. 251 (6), – p. 1197-1201.
26. Hüseynov H.İ. Kvaziikiölçülü elektron sistemlərində fononlardan səpilmə halında Nernst-Ettinqshauzen effekti // – Bakı, AzTU: Elmi əsərlər, Fundamental elmlər, –2015. 2(2),–s. 29-33.
27. Фигарова С.Р., Гусейнов Г.И. Электронная часть теплопроводности сверхрешеток // Республиканская научная конференция «Актуальные проблемы физики», – БГУ, Баку: – 17 Декабря, – 2015, – с.148-150.
28. Фигарова С.Р., Гусейнов Г.И. Электронная часть теплопроводности сверхрешетках при рассеянии на ионах примеси // – Баку: Вестник Бакинского Университета, Серия физико-математических наук, – 2016. №1, – с. 113-119.
29. Кулиев Б.И., Фигарова С.Р., Гусейнов Г.И. Энергия Ферми двумерного электронного газа в квантовой яме асимметричной форме // – Баку: Аз ТУ: Ученые записки. Фундаментальные науки. Физика, – 2016. Т. 2, №2, – с.80-86.
30. Гусейнов Г.И. Электропроводность двумерного электронного газа в квантовой яме асимметричной форме // Материалы IX Республиканской научной конференции «Актуальные проблемы физики», – БГУ, Баку: – 22 декабрь, – 2016, – с.151-154.

31. Кулиев Б.И., Фигарова С.Р., Гусейнов Г.И. Эффект Нернста-Эттингсгаузена в сверхрешетках в параллельном магнитном поле // Материалы международной научно-практической конференции «Современные проблемы физики металлов», – Az АСУ, Баку:–10–11 октябрь,–2016,–с.277-279.
32. Kuliev B.I., Figarova S.R., Huseynov H.İ. Nernst-Ettinshausen Effect in Superlattices with Cosine-Dispersion Law // Turkish Physical Society 32th Int. Phys. Congress. Abstract Book, –Turkey, Bodrum: – 6 – 9 September, – 2016, – c.357.
33. Фигарова С.Р., Гусейнов Г.И. Фигаров В.Р. Анизотропия эффекта Нернста-Эттингсгаузена в сверхрешетках при рассеянии на фононах // Материалы VII Международной научно-практической конференции «Актуальные проблемы радиофизики», – Россия, г.Томск, ТГУ: – 18 – 22 сентября, – 2017, – с.29.
34. Гусейнов Г.И., Панахов Т.М. Продольный эффект Нернста-Эттингсгаузена в сверхрешетках при рассеянии на сильно экранированных ионах примеси // Фазовые переходы, критические и нелинейные явления в конденсированных средах. Сборник трудов международной конференции, Институт физики ДНЦ РАН им Х.И. Амирханова, – Махачкала, – 6 – 9 сентябрь, – 2017, – с.373-376.
35. Figarova S.R., Huseynov H.I. Semiclassical Nernst-Ettinqshausen effect of quasi-two-dimensional electron gas // Proceeding Book: «1st International Turkish World Engineering and Science Congress in Antalya». Antalya, Turkey, – 7 – 10 December, – 2017, – p. 920-923.
36. Фигарова С.Р., Гусейнов Г.И., Асланлы А.Ф. Концентрационная зависимость коэффициента Нернста-Эттингсгаузена в слоистых полупроводниках в продольном магнитном поле // – Баку: Ученые записки. Фундаментальные науки, – 2017. №2, – с. 80-86.
37. Фигарова С.Р., Гусейнов Г.И., Мустафаева Р.К. Полевая зависимость эффекта Нернста-Эттингсгаузена при рассеянии носителей тока на сильно экранированных ионах примеси // – Баку: Вестник Бакинского Университета, Серия физико-математических наук, – 2017. №3, – с. 111-120.

38. Figarova S.R., Huseynov H.I., Figarov V.R. Anisotropy of Nernst-Ettinqshausen Effect in Siperlattices during scattering on Phonons // Russian Physics Journal, – 2018. Mar; 60 (11), – p. 1931-1937.
39. Figarova S.R., Huseynov H.I., Figarov V.R. Transverse Nernst-Ettinqshausen effect in superlattices upon electron-phonon scattering // Semiconductors, – 2018. Jul; 52 (7), – p. 853-858.
40. Figarova S.R., Huseynov H.I., Figarov V.R. Magnetothermo-electric properties of layered structures for in impurity scattering // Superlattices and Microstructures, – 2018. Mar; 117, – p. 469-475.
41. Kuliev B.I., Figarova S.R., Huseynov H.İ. Electrical conductivity of the asymmetric quantum well // Turkish Physical Society 34th international Physics congress. Book of abstracts, – Turkey, Bodrum: – 5 – 9 September, – 2018, – p.468.
42. Гусейнов Г.И. Продольной эффект Нернста-Эттингсгаузена в сверхрешетках при рассеянии на полярных оптических фононах // – Баку: Ученые записки. Фундаментальные науки, – 2019. №2, – с. 27-32.
43. Huseynov H.I. Anisotropy of the Nernst-Ettinqshausen effect in quasi – two dimensionalty and quasi-three-dimensionalty electronic systems // – Baku: Journal of Baku Engineering University – Physics, – 2019, 3 (1), – p. 63-81.
44. Guliyev B.I., Figarova, S.R., Huseynov, H.I., Figarov, V.R. Semi-parabolic quantum well electrical conductivity // European Physical Journal plus, – 2019. Jun; 134 (1), – p. 1-6.
45. Figarova S.R., Guliev, B.I., Huseynov, H.İ. Anisotropy of the longitudinal Nernst-Ettingshausen effect in the quasi-two dimensional electron gas for the optical phonons scattering // 2 International Scientific Conference on Mathematical, Engineering, Subject and Medical Sciences. Book of abstracts, – Turkey, Adıyaman: – 21-23 June, – 2019. – p.103.
46. Гусейнов Г.И. Эффект Маджи-Риги-Ледюка в сверхрешетках при рассеянии на акустических фононах // – Баку: Известия НАНА, Серия физико-математических и технических наук, физика и астрономия, – 2020. 40 (4), – с. 60-65.

47. Huseynov H.I. The electrical conductivity of nondegenerete electron gas in a quantum well asymmetric form // – Baku: Journal of Baku Engineering University, Physics, – 2020. Vol. 4, No. 1, – p. 3-7.
48. Фигарова С.Р., Гусейнов, Г.И., Махмудов, М.М. Эффект Маджи-Риги-Ледюка в квазидвумерном электронном газе при рассеянии на короткодействующем потенциале // – Баку: Вестник Бакинского Университета, серия физико-математических наук, – 2020. №2, – с. 89-95.
49. Фигарова С.Р., Гусейнов, Г.И., Махмудов, М.М. Гальваномагнитные эффекты в сверхрешетках в продольном магнитном поле при рассеянии на сильно экранированных ионах примеси // – Баку: Вестник Бакинского Университета, серия физико-математических наук, – 2020. №3, – с. 52-63.
50. Figarova S.R., Huseynov, H.I., Figarov, V.R. Thermoelectric power hysteresis in semi-parabolic quantum well // Thin Solid Films, – 2021.721, – p.138554(1-4).

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