

Received: 24 June 2026, Accepted: 06 September 2026

Edited by: Efraín Carreño-Morelli, University of Applied Sciences and Arts Western Switzerland, Switzerland

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DOI: <https://doi.org/10.4279/PIP.180005>

ISSN 1852-4249

Temperature dependences of the concentration and mobility of charge carriers of a film of a solid solution $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ grown from a bismuth melt solution

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The temperature dependences of the electron concentration and Hall mobility of $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial films grown on $n\text{-GaAs}(100)$ substrates from a bismuth solution-melt by liquid-phase epitaxy were investigated. The structural, morphological, and electrical transport properties of the epitaxial layers were studied using X-ray diffraction (XRD), scanning probe microscopy (SPM), and Hall-effect measurements. XRD analysis confirmed the formation of single-crystalline epitaxial layers with the zinc-blende structure and a very small lattice mismatch with the substrate, indicating high crystalline quality. SPM observations revealed a uniform nanoscale surface morphology consisting of conical protrusions with heights of approximately 6.5–7.5 nm and lateral dimensions of 110–120 nm. Hall-effect measurements performed in the temperature range of 303–603 K showed n -type conductivity with an electron concentration of approximately $3.36 \times 10^{16} \text{ cm}^{-3}$, a Hall mobility of about $664 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, and an electrical resistivity of approximately $0.3 \Omega \cdot \text{cm}$ at 303 K. The Hall mobility decreases with increasing temperature following a power-law dependence with an experimentally determined exponent of $m = 2.58 \pm 0.07$, obtained from linear regression of the data. Analysis based on Matthiessen's rule indicates that charge transport is governed by the combined effects of acoustic-phonon scattering, longitudinal optical phonon scattering, and scattering by structural defects. The obtained results demonstrate the high crystalline quality and favorable electrical transport properties of the grown epitaxial films and confirm the potential of the investigated epitaxial films for semiconductor electronic and optoelectronic applications.

1 Introduction

Semiconductor solid solutions composed of elemental semiconductors (Si, Ge) and III–V and II–VI compound semiconductors have attracted considerable attention because they enable continuous tuning of the band-gap energy, lattice parameters, carrier concentration, and optical absorption through compositional engineering [1, 3]. Owing to these advantages, such materials have found wide applications in optoelectronic devices, including photodetectors, light-emitting diodes, laser

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structures, and photovoltaic energy converters [1, 2]. Among these materials, the multicomponent solid solution $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ is of particular interest because it combines the high carrier mobility of GaAs, the wide band gap of ZnSe, and the favorable electronic properties of Ge, thereby enabling the fabrication of semiconductor heterostructures with enhanced structural, electrical, and optical performance [6–8]. The substantial difference in the band-gap energies of GaAs (1.43 eV), ZnSe (2.68 eV), and Ge (0.67 eV) provides favorable conditions for band-gap engineering over a broad spectral range [1, 2]. Such compositional flexibility enables simultaneous optimization of optical absorption and carrier transport, making these solid solutions promising candidates for broadband photodetectors and other photoelectric devices [1, 3, 4]. Furthermore, local compositional fluctuations in multicomponent solid solutions may give rise to nanoscale potential variations that influence carrier localization and recombination processes [7, 10]. Such compositional flexibility also makes these materials attractive for band-gap engineering in next-generation optoelectronic and photovoltaic devices [1, 5]. Liquid-phase epitaxy (LPE) remains one of the most effective methods for obtaining high-quality epitaxial semiconductor layers because crystal growth proceeds under conditions close to thermodynamic equilibrium, resulting in low defect density, smooth interfaces, and excellent crystalline quality [6, 7]. The LPE method enables the growth of epitaxial layers with continuously varying composition in multicomponent $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ solid solutions [7, 8]. This behavior can be attributed to the close matching of the covalent radii and lattice parameters of GaAs, ZnSe, and Ge, which reduces lattice mismatch, suppresses defect formation, and promotes the growth of high-quality epitaxial films [6, 8]. Compared with other epitaxial techniques, liquid-phase epitaxy provides relatively low-cost crystal growth while maintaining high crystalline quality and compositional homogeneity [6, 7].

The scientific literature contains a number of works devoted to the production of solid solutions similar in composition to those studied in the present work, as well as to the study of their optical and electrophysical properties [9]. Accordingly, the possibility of growing epitaxial layers of $(\text{GaAs})_{1-x}(\text{ZnSe})_x$ solid solutions on GaAs(100) substrates by LPE from a lead melt solution was demonstrated in [5]. The obtained epitaxial layers had *n*-type conductivity, a charge carrier concentration of $\sim 7.6 \times 10^{19} \text{ cm}^{-3}$, and a single-crystal

structure with a continuous composition change in the range $0 \leq x \leq 0.07$. In previous studies, layers of $(\text{Ge}_2)_{1-x-y}(\text{GaAs}_{1-\delta}\text{Bi}_\delta)_x(\text{ZnSe})_y$ were grown on GaAs substrates by liquid-phase epitaxy from a bismuth melt solution [8]. In these studies, special attention was paid to the quality of the epitaxial layers formed on the upper and lower substrates, as well as to the dependence of their electrophysical and optical characteristics on the position of the substrate relative to the melt solution. It was found that the quality of the formed films significantly depends both on the thickness of the melt solution layer and on the location of the substrate (upper or lower part of the melt). It is shown that at a solution-melt thickness $\geq 0.8 \text{ mm}$, the crystallization process is determined by the combined action of diffusion and gravitational mass transfer mechanisms, whereas at a thickness $\leq 0.8 \text{ mm}$, the growth of the solid solution layer occurs predominantly due to diffusion. The obtained epitaxial layers of the $(\text{Ge}_2)_{1-x-y}(\text{GaAs}_{1-\delta}\text{Bi}_\delta)_x(\text{ZnSe})_y$ solid solution had a thickness of about $10 \mu\text{m}$, *n*-type conductivity, a resistivity of about $10 \Omega \cdot \text{cm}$, and a charge carrier concentration of $\sim 1.5 \times 10^{16} \text{ cm}^{-3}$. In this case, the formation of a gradient composition in the range $0 \leq x \leq 0.53$, $0 \leq y \leq 0.74$ was noted [8]. Nevertheless, previous studies have not adequately investigated the distribution of the components across the thickness of the epitaxial layer, nor have they established quantitative relationships between the GaAs, ZnSe, and Ge constituents. Furthermore, the relationship between the surface nanostructure formed during liquid-phase epitaxy and the temperature dependence of carrier mobility has not yet been systematically clarified. To address these issues, epitaxial layers of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ solid solution were grown from a bismuth melt solution on GaAs substrates under conditions similar to those reported previously, with the aim of clarifying the relationship between surface nanostructure formation and temperature-dependent carrier transport mechanisms. This approach was selected because previous studies suggested that impurity-related states and nanostructures formed during epitaxial growth can significantly influence the spectral photosensitivity and photoresponse of multicomponent semiconductor solid solutions [10].

In addition to conventional Hall measurements, particular attention is devoted to correlating nanoscale surface morphology with carrier transport mechanisms in order to clarify the influence of nanos-

structural features on the electrical behavior of $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial films. The surface morphology of the obtained films, as well as the temperature dependences of the concentration and mobility of charge carriers, were studied. Particular attention was paid to the analysis of the distribution, dimensions, and ordering of cone-shaped surface nanostructures spontaneously formed on the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial films. The obtained results provide additional insight into the relationship between nanostructure formation and charge carrier transport in multicomponent semiconductor solid solutions, which is important for the design of advanced optoelectronic devices. Unlike previous studies, the present work focuses not only on the growth of multicomponent epitaxial layers but also on establishing a correlation between surface nanostructure formation and temperature-dependent carrier transport properties. Therefore, this study provides new insight into the relationship between epitaxial growth conditions, surface nanostructure formation, and temperature-dependent carrier transport in multicomponent semiconductor solid solutions.

2 Theory

To substantiate the possibility of forming substitutional solid solutions based on the semiconductor compounds GaAs, ZnSe, and the elemental semiconductor Ge_2 , this study utilizes the thermodynamic principle of crystal chemistry formulated by M. S. Saidov [6]. The proposed approach is also consistent with the general crystallochemical principles governing substitutional solid-solution formation, including atomic size compatibility, valence equivalence, and lattice similarity, which are widely accepted in semiconductor materials science. According to this principle, in any physicochemical system containing chemical components, regardless of their quantitative ratios, interactions occur between atoms (or ions), which creates the preconditions for the formation of new phase states.

In the present approach, molecular entities belonging to III–V, II–VI, and IV elemental semiconductor systems are treated as effective structural units participating in solid-solution formation. The possibility of forming substitutional solid solutions under certain thermodynamic conditions is determined primarily by the type of crystal lattice of the initial components, the geometric dimensions of the atoms and molecules, as well as

their charge states and the nature of the chemical bond.

Taking into account the above factors, as well as the possibility of replacing two, three, or four nearest neighboring atoms of the solvent matrix with di-, tri-, or tetra-atomic molecules of the soluble compound, respectively, M. S. Saidov formulated the conditions for the formation of substitutional solid solutions in his work [6]. According to these criteria, substitutional solid solutions are expected to form when the difference in the covalent radii does not exceed approximately 10% and the valence states of the substituting species remain equivalent.

Based on the theoretical principles outlined above, GaAs, ZnSe, and the elemental semiconductor Ge_2 were selected as the components for the formation of a solid solution in this study [1, 6]. A molecular substitutional solid solution of the type $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ was obtained from these compounds [6, 7]. Bismuth (Bi), which has a high dissolving capacity for the selected components and provides favorable thermodynamic and kinetic conditions for epitaxial growth, was used as the solvent [6, 7]. According to this crystallochemical model, the formation of substitutional solid solutions is governed by two independent criteria [6, 8]. The first criterion requires conservation of the total valence of the interacting molecular structural units [6]:

$$\Delta z = \sum_{i=1}^m z_i - \sum_{i=1}^n z_i = 0, \quad (1)$$

where z_i denotes the valence of the constituent atoms (or molecular structural units), while m and n correspond to the numbers of atoms participating in the solvent and substituting compounds, respectively. Satisfaction of Eq. (1) ensures charge neutrality during substitution and minimizes the formation of electrically active defects [6]. The second criterion describes the crystallochemical compatibility of the components [6, 8]:

$$\Delta r = \left| \sum_{i=1}^m r_i - \sum_{i=1}^n r_i \right| \leq 0.1 \cdot \sum_{i=1}^m r_i, \quad (2)$$

where r_i denotes the covalent radius of the corresponding atom (or molecular structural unit). Equation (2) states that the difference between the sums of the covalent radii of the substituted and substituting molecular structural units should not exceed approximately 10% of the corresponding reference value [6]. This criterion ensures crystallochemical compatibility and favors the

Table 1: Crystallochemical parameters of the semiconductor compounds used for the formation of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ solid solution.

Compound	Crystal structure	Total valence	Lattice constant (Å)	Band gap (eV)	Covalent radius (Å)
GaAs	Zinc blende	8	5.653	1.43	2.44
ZnSe	Zinc blende	8	5.668	2.68	2.45
Ge ₂	Diamond cubic	8	5.658	0.67	2.44

formation of a stable substitutional solid solution [6, 7]. The relatively small differences in the lattice parameters and covalent radii of GaAs, ZnSe, and Ge₂ indicate favorable crystallochemical compatibility, which reduces elastic strain during epitaxial growth [7, 8]. The fulfillment of both criteria provides the theoretical justification for selecting the GaAs–ZnSe–Ge system and is in good agreement with the experimental structural and electrical characteristics discussed in the following sections. For the GaAs–ZnSe–Ge system investigated in this work, both crystallochemical criteria are satisfied. The total valence of the interacting molecular structural units is identical (GaAs = 8, ZnSe = 8, and Ge₂ = 8), while the differences between the sums of their covalent radii remain within the 10% limit specified by Eq. (2). The corresponding crystallochemical parameters of the selected compounds are summarized in Table 1.

3 Experiment

Epitaxial films of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ solid solution were grown by liquid-phase epitaxy (LPE), see Fig. 1, from a Bi solution-melt containing GaAs, ZnSe, and Ge, confined between two horizontally arranged substrates [6, 7]. High-purity GaAs (6N–7N), ZnSe (5N–6N), Ge (8N–9N), and Bi (6N–7N) together with *n*-type GaAs(100) substrates were used as starting materials for liquid-phase epitaxy. The reactor was equipped with an automatic temperature control system. The growth process was carried out in a purified hydrogen atmosphere in order to eliminate oxygen- and moisture-related contamination [6]. The epitaxial growth process was performed in a forced-cooling mode at a cooling rate of $v = 1^\circ\text{C min}^{-1}$ over the temperature range of 750–650 °C under a hydrogen atmosphere purified by palladium [6, 7]. During cooling, GaAs crystallized first owing to its higher saturation temperature in the Bi solution-melt [6]. As the temperature decreased, ZnSe and Ge₂ were progressively incorporated into the growing epitaxial layer, resulting

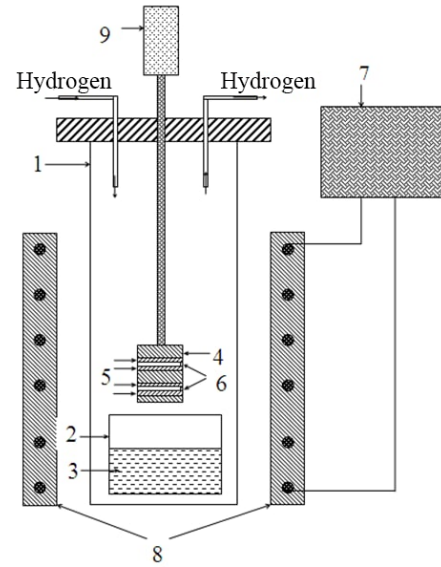


Figure 1: Schematic diagram of the vertical liquid-phase epitaxy (LPE) system used for the growth of $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial layers: (1) quartz reactor; (2) quartz crucible; (3) solution-melt; (4) graphite cassette; (5) GaAs substrates; (6) graphite supports; (7) control unit; (8) heating block; (9) electric motor.

in the formation of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ substitutional solid solution [6, 7]. The obtained epitaxial layers had an average thickness of approximately 10 μm. To determine the dislocation density, the surface of the epitaxial film samples was selectively etched using an HNO₃:H₂O solution (1:1) for 2–4 min, after which the etch pits were examined using an MII-4 optical microscope. The dislocation density at the interface was approximately $1 \times 10^7 \text{ cm}^{-2}$, whereas on the epitaxial layer surface it was about $4 \times 10^5 \text{ cm}^{-2}$.

Structural characterization was performed at room temperature (303 K) using a DRON-3M X-ray diffractometer (Russia) with CuK_α radiation

($\lambda = 0.15418$ nm) operating in the θ - 2θ scanning mode. The lattice parameters of the substrate and epitaxial layers were determined from the angular positions of the $\{200\}$, $\{400\}$, and $\{600\}$ reflections using the Nelson–Riley extrapolation function [11]. The average crystallite size was estimated from the full width at half maximum (FWHM) of the diffraction peaks using the Scherrer equation [12–14]. The electrical transport properties of the epitaxial layers were investigated by Hall-effect measurements using the Van der Pauw method [15]. The Hall coefficient, electrical conductivity, carrier concentration, and Hall mobility were measured using an HMS-7000 Hall Measurement System over the temperature range of 303–603 K. Ohmic contacts were formed at the four corners of the square-shaped samples using high-purity Ag. The Van der Pauw configuration was employed because it provides accurate determination of the electrical resistivity and Hall coefficient independently of the sample geometry [15]. The surface morphology of the epitaxial layers was investigated using an SPM-9700HT scanning probe microscope (Shimadzu, Japan) operating in dynamic atomic force microscopy (AFM) mode [18, 19]. The microscope provides a lateral resolution of 0.2 nm and a vertical resolution of 0.01 nm. The AFM images were analyzed to determine the surface morphology, nanostructure height, lateral dimensions, and surface density of the protrusions. The acquired AFM images were processed using the instrument software to evaluate the geometric parameters of the surface nanostructures.

4 Results and Discussion

i Structural characterization by X-ray diffraction

The crystal structure and phase composition of the grown $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial layers were investigated by X-ray diffraction (XRD). Figure 2 presents the XRD pattern of the epitaxial film grown on the GaAs(100) substrate. The high intensity of the main diffraction reflections $\{H00\}$, together with their narrow full width at half maximum (FWHM $\approx 10^{-3}$ rad), indicates the excellent crystallinity of the epitaxial layer [12, 13]. The excellent agreement between the experimental peak positions and the expected diffraction geometry confirms the high crystalline quality of the epitaxial layer [11, 12].

A magnified view of the (200) and (400) reflections is shown in Fig. 3.

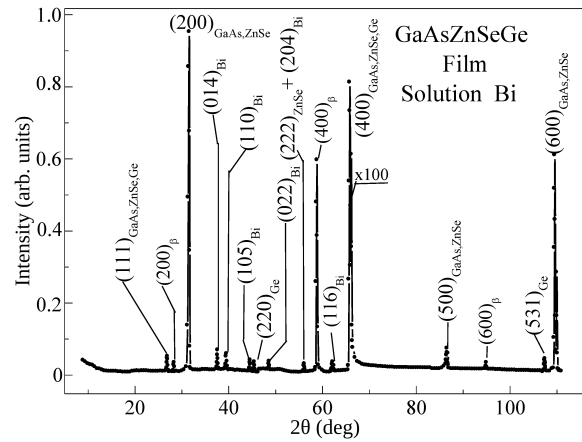


Figure 2: X-ray diffraction pattern of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial layer grown by liquid-phase epitaxy from a Bi solution-melt.

Further analysis of the XRD pattern showed that the angular positions of the main $\{H00\}$ reflections of the epitaxial layer and the substrate differ only slightly (by a few arc minutes) [11]. However, significant differences were observed in their diffraction intensities. Compared with the GaAs substrate, the intensities of the (200), (400), and (600) reflections increased by approximately 30%, 7%, and 3%, respectively. This increase suggests successful incorporation of ZnSe and Ge into the GaAs lattice while preserving the single-crystalline zinc-blende structure [7, 8]. This interpretation is supported by the lattice parameter of the epitaxial film, determined from the (200), (400), and (600) reflections using the Nelson–Riley extrapolation function [11]. The obtained lattice parameter was $a_f = 0.56623$ nm, which is slightly larger than that of the GaAs substrate ($a_s = 0.56612$ nm). The calculated lattice mismatch ($\xi = 1.9 \times 10^{-4}$) demonstrates excellent structural compatibility between the epitaxial layer and the GaAs substrate, indicating low residual strain [7, 8].

In addition, Ge and Bi incorporated into the epitaxial layer contribute to the appearance of several weak diffraction peaks in the XRD pattern [7, 8]. Among them, the reflection $[(111)_{\text{GaAsZnSeGe}} + (102)_{\text{Bi}}]$ at $2\theta = 27.0^\circ$ with $d = 0.3302$ nm is visible at small scattering angles, and the structural line $[(531)_{\text{ZnSeGe}}]$ at $2\theta = 107.3^\circ$ with $d = 0.0956$ nm is visible at correspondingly large scattering angles.

The average composition estimated from the diffraction analysis was approximately

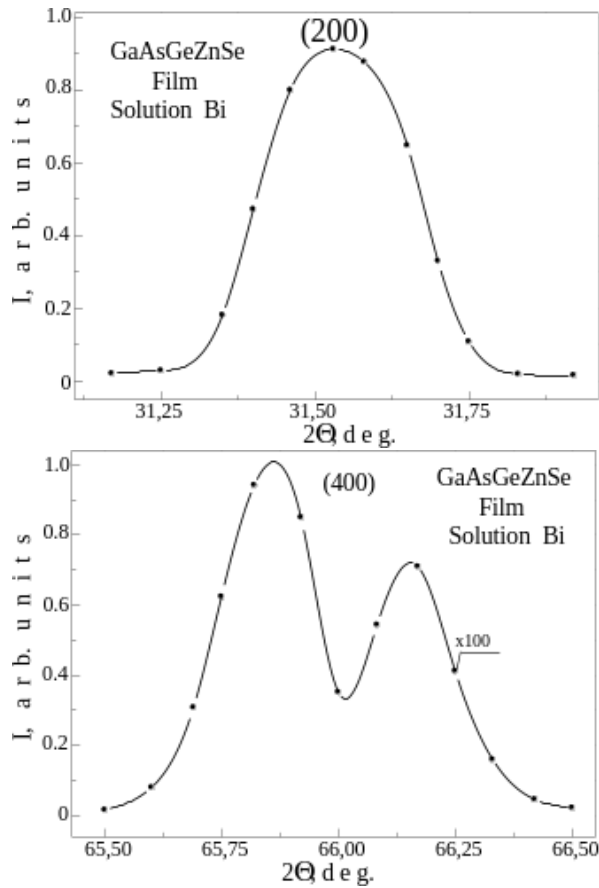


Figure 3: Magnified view of the (200) (**top**) and (400) (**bottom**) diffraction peaks of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial layer grown by liquid-phase epitaxy.

$(\text{GaAs})_{0.70}(\text{ZnSe})_{0.25}(\text{Ge}_2)_{0.05}$. The XRD pattern is dominated by reflections of the zinc-blende epitaxial layer, whereas the additional weak peaks are attributed to Ge- and Bi-containing phases [7,8]. These results indicate the high crystalline quality of the grown epitaxial layer.

ii Surface morphology

The surface morphology of the epitaxial films was investigated by scanning probe microscopy (SPM) using an SPM-9700HT (Shimadzu) instrument. The AFM images revealed that the film surface is characterized by uniformly distributed nanoscale crystalline protrusions over the entire investigated area (Fig. 4(**top**)). These protrusions are predominantly conical in shape, with

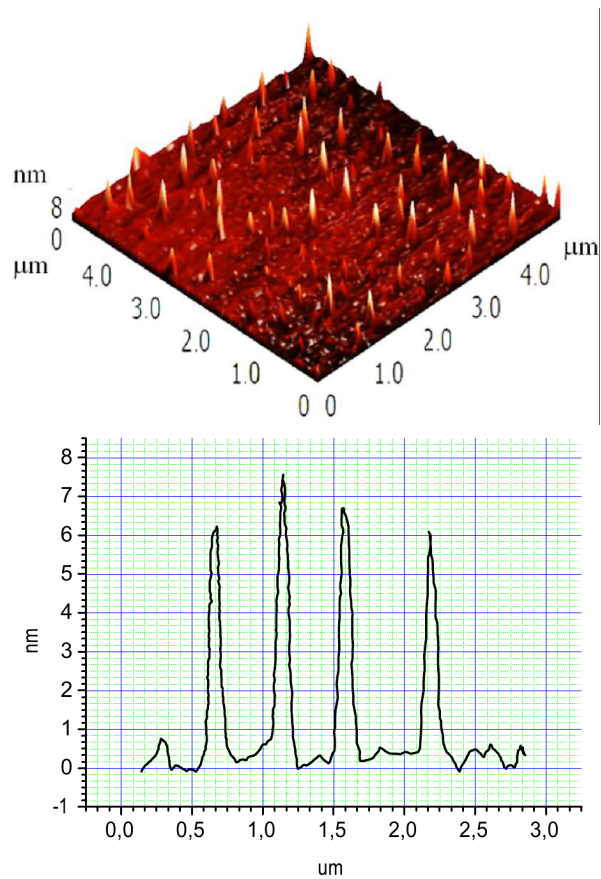


Figure 4: Three-dimensional AFM image (**top**) and AFM line profile of individual nanoprotusions (**bottom**) on the surface of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial film.

a characteristic height of approximately 6.5–7.5 nm, a base diameter of 110–120 nm, and a surface concentration of approximately $2.5 \times 10^8 \text{ cm}^{-2}$.

In addition, analysis of the AFM images revealed that the roughness of smooth surface areas does not exceed $\sim 1 \text{ nm}$, indicating high crystalline perfection of the epitaxial layer outside the regions of localized nanoprotusions [7,8]. Therefore, the surface of the grown $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ solid solution film is characterized by a weakly defined nanotextured morphology with small spatial scales, forming a combined “smooth matrix–nanoscale protrusions” structure.

The formation of nanoscale protrusions on the surface of the $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ epitaxial film is attributed to the competition between the bulk and

surface free energies of the system during crystallization from a multicomponent liquid melt solution [6, 7]. Under conditions of liquid-phase epitaxy occurring near thermodynamic equilibrium, even minor fluctuations in local supersaturation, chemical potential of the components, and surface energy can lead to instability of the flat crystallization front and initiate the process of spatial modulation of growth. A significant role in this process is played by the difference in the distribution coefficients of the constituent components GaAs, ZnSe, and Ge, as well as the mismatch of their crystallochemical parameters, which lead to local segregation and the formation of regions with lower Gibbs free energy [6, 8]. Such regions become energetically favorable centers of nucleation, resulting in the self-organized growth of nanoscale protrusions, which is consistent with the Stranski–Krastanov growth model reported for strained heteroepitaxial systems [20].

An additional factor contributing to the stabilization of nanoscale protrusions is the relaxation of elastic stresses arising from local compositional fluctuations and differences in crystal lattice parameters between the solid solution matrix and enriched regions [7, 8]. The formation of three-dimensional nanostructures leads to a decrease in the total elastic energy of the system, making this morphological texture thermodynamically preferable [7].

The observed nanostructured morphology reflects the self-organized growth process during liquid-phase epitaxy and confirms the formation of a uniform nanostructured surface.

iii Electrical transport properties (Hall effect)

The electrical transport properties of the epitaxial films were investigated by Hall-effect measurements using an HMS-7000 Hall Measurement System in the temperature range 303–603 K. The temperature dependences of the electron concentration and Hall mobility are presented in Fig. 5. At 303 K, the epitaxial $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ films exhibited *n*-type conductivity with an electron concentration of approximately $3.36 \times 10^{16} \text{ cm}^{-3}$, a Hall mobility of about $664 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, and an electrical resistivity of approximately $0.3 \Omega \cdot \text{cm}$.

As shown in Fig. 5(bottom), the Hall mobility decreases according to a power-law dependence, with an experimentally determined exponent $m = 2.58 \pm 0.07$, obtained from a linear regression of the logarithmically transformed mobility and temperature data shown in

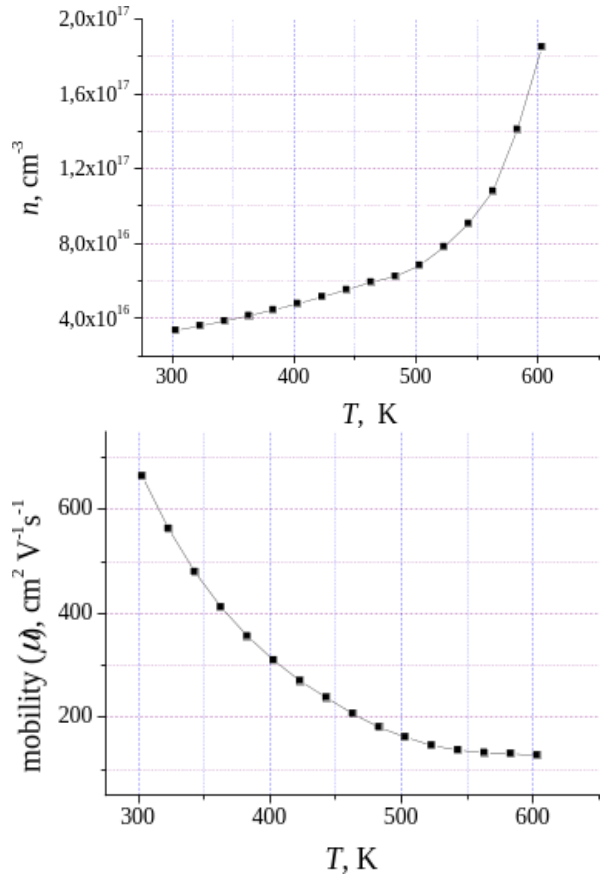


Figure 5: Temperature dependences of the concentration (**top**) and mobility (**bottom**) of charge carriers in an epitaxial film of the solid solution $n\text{-(GaAs)}_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$, grown on a *n*-GaAs(100) substrate from a Bi solution-melt.

Fig. 6. This exponent is significantly larger than the classical value ($m \approx 1.5$) expected for acoustic-phonon scattering via the deformation-potential mechanism and may be attributed to several factors [17]:

- The contribution of optical phonons or high-frequency acoustic modes with a strong temperature dependence [16, 17].
- Enhancement of the multicomponent scattering effect in a solid solution, when differences in the crystal parameters of the components (GaAs, ZnSe, Ge_2) lead to local segregation and the appearance of internal stresses [7, 8].
- Nanostructural effects and interactions with local-

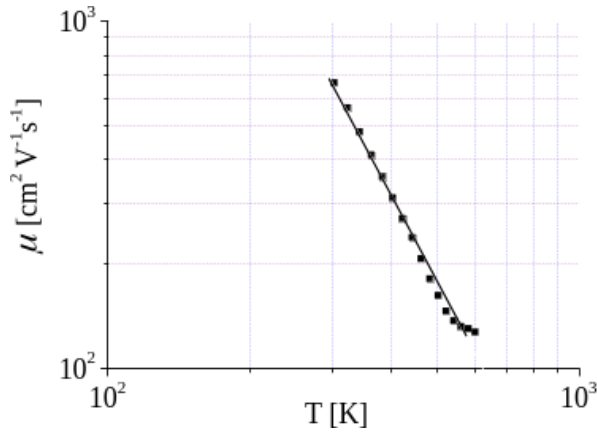


Figure 6: Log-log plot of Hall mobility versus temperature. The solid line represents the linear regression performed on the logarithmic data, yielding an effective temperature exponent $m = 2.58 \pm 0.07$.

ized defects or nanoprotusions, which enhance inelastic carrier scattering with increasing temperature [8,20].

The experimentally observed dependence of the charge carrier mobility in the epitaxial $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ films indicates that charge transport is governed by a combination of phonon scattering and structural inhomogeneities [16, 17]. According to Matthiessen's rule, the total Hall mobility can be expressed as the combined contribution of the dominant carrier-scattering mechanisms [17]:

$$\frac{1}{\mu(T)} = \frac{1}{\mu_{\text{AC}}(T)} + \frac{1}{\mu_{\text{LO}}(T)} + \frac{1}{\mu_{\text{def}}(T)}, \quad (3)$$

where μ_{AC} , μ_{LO} , and μ_{def} are the mobility components limited by acoustic-phonon scattering, longitudinal optical (LO) phonon scattering, and structural defects, respectively. Acoustic-phonon scattering is governed by the deformation-potential mechanism and, for high-quality semiconductor crystals, follows the classical temperature dependence $\mu_{\text{AC}}(T) \sim T^{-3/2}$. In polar semiconductors such as GaAs and ZnSe, an additional contribution arises from the interaction of charge carriers with LO phonons through the Fröhlich interaction. Since the occupation number of LO phonons obeys the Bose-Einstein distribution

$$N_{\text{LO}} = \left[\exp\left(\frac{h\nu_{\text{LO}}}{kT}\right) - 1 \right]^{-1},$$

as the population of LO phonons increases with temperature, the probability of electron-phonon scattering increases, leading to a reduction in the Hall mobility, which can be approximated by Eq. (4) [16]:

$$\mu_{\text{LO}}(T) \propto \left[\exp\left(\frac{h\nu_{\text{LO}}}{kT}\right) - 1 \right], \quad (4)$$

where $h\nu_{\text{LO}}$ is the energy of the LO phonon, k is the Boltzmann constant, and T is the absolute temperature. The third contribution is associated with scattering by structural defects, including dislocations, local elastic stresses, and nanoscale surface protrusions formed during liquid-phase epitaxy [8,20]. These structural imperfections introduce additional scattering centers, thereby reducing the carrier mobility. The experimentally measured Hall mobility exhibits a power-law dependence on temperature. The log-log plot shown in Fig. 6 is well described by a linear relationship between $\log_{10} \mu$ and $\log_{10} T$:

$$\log_{10} \mu = \log_{10} A - m \log_{10} T. \quad (5)$$

Here, A is a fitting constant and m is the effective temperature exponent determined from the experimental data. Linear fitting of the experimental data in Fig. 6 yielded $m = 2.58 \pm 0.07$ with a correlation coefficient $R = -0.994$ ($P < 0.0001$), indicating an excellent agreement with the power-law model. The obtained exponent is significantly larger than the classical value ($m \approx 1.5$) expected for scattering only by acoustic phonons [21]. These results suggest that charge transport in the investigated epitaxial films is governed by the combined effects of acoustic-phonon scattering, longitudinal optical phonon scattering, and scattering by structural defects rather than by a single scattering mechanism [16, 17].

5 Conclusion

Epitaxial films of the multicomponent solid solution $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$ were successfully grown on n -GaAs(100) substrates by liquid-phase epitaxy from a Bi solution melt. X-ray diffraction analysis confirmed the formation of single-crystalline zincblende epitaxial layers with a very small lattice mismatch ($\xi = 1.9 \times 10^{-4}$), indicating excellent structural compatibility between the epitaxial layer and the substrate. Atomic force microscopy revealed a uniform nanoscale surface morphology consisting of

conical protrusions with characteristic heights of 6.5–7.5 nm and lateral dimensions of 110–120 nm. Hall-effect measurements demonstrated *n*-type conductivity with an electron concentration of approximately $3.36 \times 10^{16} \text{ cm}^{-3}$, a Hall mobility of about $664 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, and an electrical resistivity of approximately $0.3 \Omega \cdot \text{cm}$ at 303 K. The Hall mobility decreases with increasing temperature according to a power-law dependence with an experimentally determined exponent $m = 2.58 \pm 0.07$. Analysis based on Matthiessen's rule indicates that carrier transport is governed by the combined contributions of acoustic-phonon scattering, longitudinal optical phonon scattering, and scattering by structural defects. The obtained results demonstrate the high crystalline quality and favorable electrical transport properties of the grown epitaxial films, confirming their potential for semiconductor electronic and optoelectronic applications.

Acknowledgements - This work was supported by the Programme of Research Activities of the Semiconductor Crystal Growth Laboratory, Physical-Technical Institute, Academy of Sciences of the Republic of Uzbekistan (2025–2029). We gratefully acknowledge Otabek Z Turgunov for performing the Hall-effect measurements and Alijon Sh Razzakov for providing valuable scientific advice and discussions.

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