

# Diffusion-Driven Formation Processes, Structural Characteristics, and Optical–Parametric Properties of $\text{Ge}_x\text{Si}_{1-x}$ Alloys

Giyosiddin Kushiev<sup>1, a)</sup>, Nurullo Zikrillaev<sup>1</sup>, Bobir Isakov<sup>1</sup>, Stansilav Tachilin<sup>1</sup>,  
Ernazar Kosbergenov<sup>2</sup>, Rakhmanov Ulugbek<sup>3</sup>, Islambek Kazakbaev<sup>1</sup>

<sup>1</sup> Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan

<sup>2</sup> National University of Uzbekistan named after Mirzo Ulugbek Tashkent, Uzbekistan

<sup>3</sup> University of Business and Science (UBS) Tashkent, Uzbekistan

<sup>a)</sup> Corresponding author: [giyosiddinabdivaxobogli@gmail.com](mailto:giyosiddinabdivaxobogli@gmail.com)

**Abstract.** In this study, a two-stage diffusion method was developed and applied to introduce germanium atoms into monocrystalline silicon and form nanoscale silicon–germanium ( $\text{Ge}_x\text{Si}_{1-x}$ ) compound layers. Due to the extremely low diffusion coefficient of Ge in silicon, direct incorporation of germanium atoms into the silicon lattice is technologically challenging. By gradually increasing the temperature during the diffusion process, controlled  $\text{Ge}_x\text{Si}_{1-x}$  layers with well-defined composition and thickness were successfully synthesized. Structural and compositional analyses conducted using FTIR and SEM confirmed the formation of Si–Ge clusters with a size of 1–2  $\mu\text{m}$  and high surface density. According to EDX microanalysis, the near-surface layer consisted of approximately 44% Si, 38% Ge, and 15% O, indicating that nearly half of the elemental composition was germanium. Optical measurements performed using a SHIMADZU UV-2700i spectrophotometer revealed that the bandgap energy of the synthesized  $\text{Ge}_x\text{Si}_{1-x}$  compounds ranged from 0.75 to 1.12 eV. As the silicon content in the compound increased to around 60–65%, the bandgap value approached that of monocrystalline silicon ( $E_g = 1.12$  eV) and remained stable. FTIR spectra also demonstrated the presence of  $\text{Ge}_x\text{Si}_{1-x}$  compounds through the characteristic absorption peak at 1066  $\text{cm}^{-1}$ . The obtained results show that the proposed diffusion technique enables the fabrication of stable  $\text{Ge}_x\text{Si}_{1-x}$  layers suitable for high-efficiency heterostructure solar cells, optoelectronic detectors, and simple electronic devices that do not require complex fabrication processes. The promising optoelectronic and structural properties of these materials make them strong candidates for next-generation nanoelectronic and photonic applications.

## INTRODUCTION

The development and large-scale implementation of modern electronic devices based on semiconductor materials is considered one of the most promising directions for attracting foreign investment and strengthening technological competitiveness. In Uzbekistan, sustainable progress in the field of electronics is directly linked to the renewal of existing industrial infrastructure, modernization of production facilities, and the integration of advanced technologies into manufacturing processes. Therefore, continuous upgrading of equipment, improving technological efficiency, and aligning production lines with global market requirements are essential tasks for enterprises operating in the electronic industry.

The fabrication of semiconductor-based electronic components involves multistage technological processes that require high precision, strict control, and the coordinated application of complex physical and chemical procedures. Among such materials, silicon–germanium ( $\text{Ge}_x\text{Si}_{1-x}$ ) alloys have become highly significant in monocrystalline silicon electronics and especially in nanoelectronics. Due to their advantageous electrophysical characteristics, these alloys are widely utilized in high-frequency devices, sensors, integrated circuits, and high-efficiency micro- and optoelectronic components [1–8]. Furthermore,  $\text{Ge}_x\text{Si}_{1-x}$  alloys demonstrate several advantages over traditional  $\text{A}_3\text{B}_5$  and  $\text{A}_2\text{B}_6$  semiconductor materials, including greater resistance to external influences, enhanced thermal stability, and favorable band-structure properties that make them suitable for next-generation electronic device fabrication.

Traditionally,  $\text{Ge}_x\text{Si}_{1-x}$  alloys are synthesized through liquid-phase epitaxy or vapor-phase deposition techniques, where Ge and Si atoms chemically bond to form epitaxial layers [8–12]. However, these approaches are limited in their ability to accurately control layer thickness, compositional gradients, and atomic-scale uniformity. They also present challenges in forming stable nanoscale Ge–Si structures within the silicon crystalline lattice.

Recent studies have shown that by gradually modifying the diffusion temperature, controlling the diffusion rate, and optimizing the sequence of technological stages, it is possible to obtain  $\text{Ge}_x\text{Si}_{1-x}$  binary layers with precisely controlled composition and thickness directly within a silicon monocrystal [13–15]. This approach enables fine-tuning of diffusion kinetics, compositional uniformity, and lattice incorporation, thereby facilitating the formation of highly effective nanoscale  $\text{Ge}_x\text{Si}_{1-x}$  structures suited for advanced electronic applications [16–18].

## EXPERIMENTAL RESEARCH

The diffusion of germanium impurity atoms into monocrystalline silicon is considered technologically and economically challenging due to the extremely low diffusion coefficient of Ge atoms in silicon. By employing a newly developed two-stage diffusion method,  $\text{Ge}_x\text{Si}_{1-x}$  alloy cells were successfully formed on the surface and near-surface region of silicon, enabling the creation of a heterostructure at the transition boundary between the alloyed layer and the monocrystalline silicon substrate [19–22].

Analysis of scientific literature shows that the temperature dependence of the diffusion coefficient of germanium impurity atoms in silicon is calculated using the following expression:

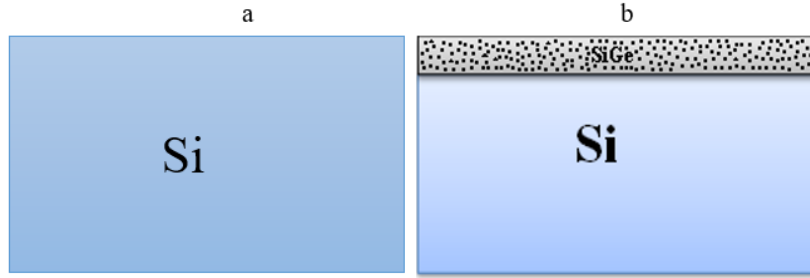
$$D = 6 \cdot 10^5 \exp\left(-\frac{5,28}{kT}\right) \quad (1)$$

Based on this equation, the diffusion coefficient of Ge atoms in silicon at  $T = 1250^\circ\text{C}$  is theoretically estimated to be extremely small, approximately

$$D \sim 4 \cdot 10^{-13} \text{ cm}^2/\text{V} \cdot \text{s}$$

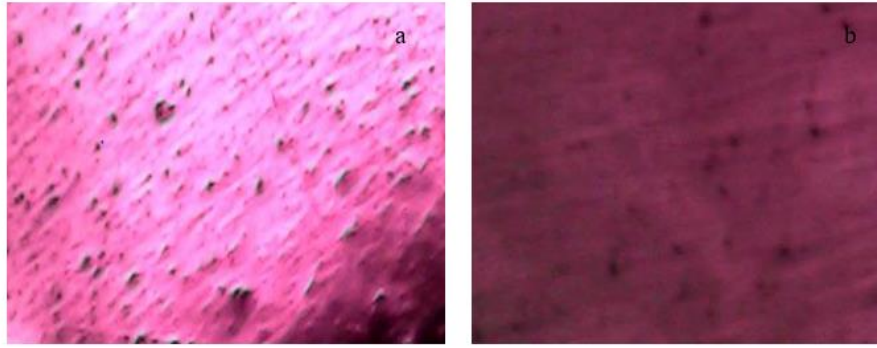
In the experiment, the diffusion of germanium impurity atoms into silicon was carried out by gradually increasing the temperature and smoothly reaching the required diffusion point. For this purpose, the MAGNETIC-type vacuum tube electric furnace was heated from room temperature to  $T = 950^\circ\text{C}$  over a period of  $t = 2$  hours, and the silicon samples were held at this temperature for  $t = 30\text{--}40$  minutes. After this pre-diffusion stage, the samples underwent the main diffusion process at  $T = 1250^\circ\text{C}$  for  $t = 10$  hours.

The experiment was repeated several times, and during each cycle three silicon samples were placed inside a quartz ampoule. As a result of the diffusion, the silicon structure shown in Figure 1 was obtained.



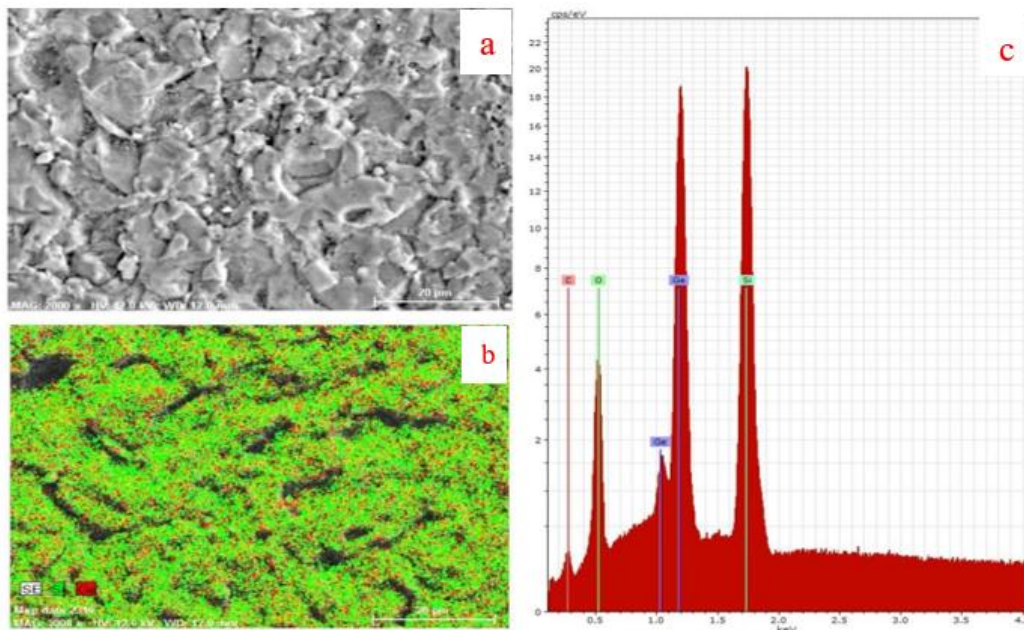
**Figure 1.** (a) Initial silicon sample of the KEF-100 grade; (b) distribution of germanium atoms introduced into silicon by the diffusion method.

To verify the formation of the structure depicted in Figure 1, the surfaces of silicon samples implanted with germanium atoms after the diffusion process were analyzed using a FTIR microscope (Figure 2) and a scanning electron microscope (SEM, Figure 3). The analysis indicated that the silicon-germanium compound clusters formed on the surface measured approximately  $1\text{--}2 \mu\text{m}$  in size, with a high density of such clusters observed across the sample surface (Figure 2a). Following the removal of the surface layer, about  $5\text{--}6 \mu\text{m}$  thick, through mechanical polishing (lapping), subsequent FTIR examination of the polished silicon surface revealed a substantially reduced presence of  $\text{Ge}_x\text{Si}_{1-x}$  type binary compounds (Figure 2b).



**Figure 2.** a) Appearance of  $\text{Ge}_x\text{Si}_{1-x}$  compounds formed in monocrystalline silicon after germanium atom diffusion.  
b) Surface of silicon after removal of a 5–6  $\mu\text{m}$  layer by polishing.

Figure 3 shows the surface topology of a silicon sample containing  $\text{Ge}_x\text{Si}_{1-x}$  compounds, obtained using a JSM-IT 200 scanning electron microscope (SEM). The compositional distribution of the layer containing germanium atoms on the silicon surface is presented in Figure 3b.



**Figure 3.** a and b – Topology of silicon doped with germanium atoms, c – Results of energy-dispersive X-ray microanalysis (EDX) (scale: 20  $\mu\text{m}$ ).

Table 1. Elemental composition of the sample based on SEM-EDS analysis (wt.%)

El	AN	Series	unn. C {wt. %}	norm.C {wt. %}	Error {wt. %}
Si	14	K	44.45	44.32	1.8
O	8	K	15.63	15.58	1.9
Ge	32	K	38.23	38.11	2.1
C	6	K	1.99	1.98	0.4
<b>Total:</b>			<b>100.29</b>	<b>100.00</b>	

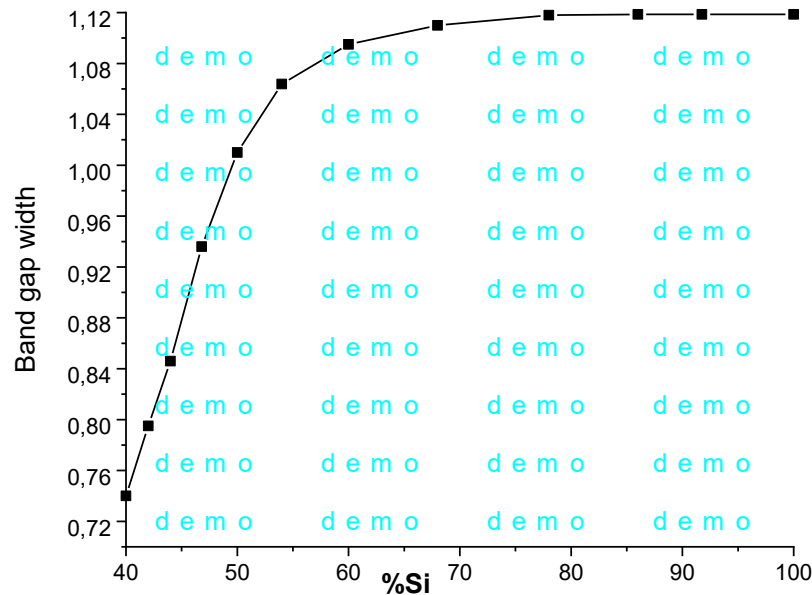
The results of the study indicate that after germanium atoms were diffused into the silicon surface, a thin compound layer was formed, with the elemental composition of this layer expressed in percentages (Figure 3c).

Based on energy-dispersive X-ray (EDX) microanalysis, the concentrations of atoms in the silicon surface and near-surface region were determined as follows: silicon ~44.32%, germanium ~38.11%, oxygen ~15.58%, and carbon ~1.98%. These findings demonstrate that in the near-surface layer of the silicon crystal, the amount of germanium atoms accounts for nearly half of the total elemental composition

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The bandgap energy of  $\text{Ge}_x\text{Si}_{1-x}$  compound cells formed on the surface of monocrystalline silicon was measured using an optical method with a SHIMADZU UV-2700i spectrophotometer, while preserving the  $\text{Ge}_x\text{Si}_{1-x}$  compound layer on the silicon surface. In the experiments, the measured bandgap of the  $\text{Ge}_x\text{Si}_{1-x}$  compounds ranged from  $E_g = 0.75$  to  $0.8$  eV, which is higher than the bandgap of pure semiconductor germanium. Figure 4 shows the relationship between the bandgap energy of the silicon-germanium compounds and the composition of the  $\text{Ge}_x\text{Si}_{1-x}$  binary compounds formed on the silicon surface.

Analysis of the physical mechanism of the formed compounds indicated that as the silicon content in the compound increased up to 65%, the bandgap energy of the resulting compound rose from  $0.75$  eV to  $1.12$  eV, reaching the bandgap energy of silicon. When the silicon content in the compound exceeded approximately 60%, the bandgap energy remained nearly unchanged, corresponding to the fundamental bandgap of monocrystalline silicon ( $E_g = 1.12$  eV). These findings were confirmed through experiments conducted on multiple silicon samples with germanium atom diffusion.

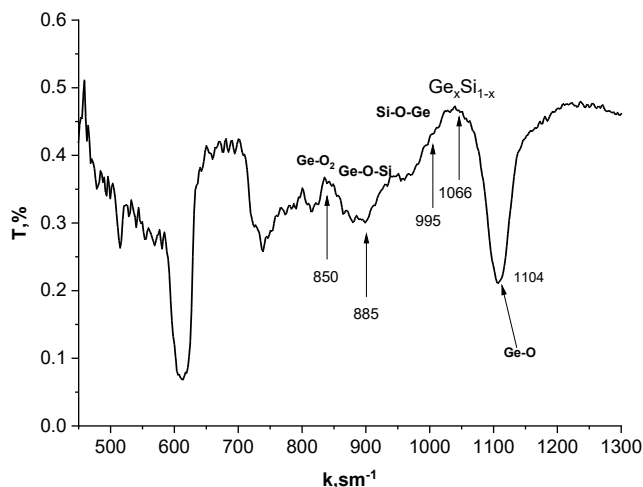


**Figure 4.** Dependence of the bandgap of silicon-germanium compounds on the elemental composition of the formed compound.

The composition and optical properties of the obtained  $\text{Ge}_x\text{Si}_{1-x}$  compounds were investigated using a Fourier-transform infrared (FTIR) spectrometer, FSM-1202. Before studying the optical properties of the silicon samples obtained after diffusion, both surfaces of the samples were polished using a polishing device with diamond paste, and the remaining four edges of the samples were removed to a depth of approximately  $100 \mu\text{m}$ . This preparation allowed for precise measurement of the composition of the resulting  $\text{Ge}_x\text{Si}_{1-x}$  compounds. The measurement results are presented in Figure 5, and their analysis led to the following conclusions.

The FTIR spectrum presented in Figure 5 clearly illustrates the optical response of the  $\text{Ge}_x\text{Si}_{1-x}$  compounds formed in monocrystalline silicon as a result of germanium diffusion. The absorption features observed near  $850\text{--}885 \text{ cm}^{-1}$  correspond to the vibrational modes of  $\text{Ge-O}_2$  and  $\text{Ge-O-Si}$  bonds, indicating partial oxidation of germanium during the diffusion process. Distinct peaks in the  $995\text{--}1008 \text{ cm}^{-1}$  region are attributed to stretching

vibrations of Si–O–Ge linkages, confirming the formation of mixed silicon–germanium oxide structures. The pronounced absorption band at  $1066\text{ cm}^{-1}$  represents a characteristic vibrational mode of the  $\text{Ge}_x\text{Si}_{1-x}$  alloy, demonstrating that germanium atoms were successfully incorporated into the silicon lattice. The feature detected around  $1104\text{ cm}^{-1}$  is associated with Ge–O vibrational modes, suggesting the presence of a thin germanium oxide layer at the sample surface. The consistent distribution of these peaks across the spectrum reflects the simultaneous formation of several types of chemical bonds within the surface and near-surface regions of silicon. The relatively high intensity of the  $\text{Ge}_x\text{Si}_{1-x}$  absorption mode indicates a significant concentration of germanium within the modified silicon layer.



**Figure 5.** IR absorption spectrum of silicon samples containing  $\text{Ge}_x\text{Si}_{1-x}$  compounds.

These FTIR observations are in agreement with SEM and EDX analyses, both of which confirm the formation of an ultrathin  $\text{Ge}_x\text{Si}_{1-x}$  compound layer on the silicon surface. Such spectral characteristics demonstrate that the diffusion process enabled stable formation of silicon–germanium structures with well-defined chemical composition. Overall, the FTIR analysis verifies that the resulting  $\text{Ge}_x\text{Si}_{1-x}$  layers exhibit physical–chemical properties suitable for various optoelectronic applications. These findings are also supported by conclusions reported by other authors [23–25].

## CONCLUSIONS

In this research, a two-stage diffusion technique was successfully developed to incorporate germanium atoms into monocrystalline silicon, enabling the formation of nanoscale  $\text{Ge}_x\text{Si}_{1-x}$  layers with precisely controlled composition and thickness. Structural and compositional analyses using SEM, FTIR, and EDX confirmed the presence of densely packed Si–Ge clusters, with germanium comprising nearly half of the near-surface elemental composition [26–36]. Optical measurements revealed that the bandgap of the synthesized compounds ranged from 0.75 to 1.12 eV, approaching the bandgap of pure silicon as the silicon content increased to approximately 60–65%. FTIR spectra further validated the formation of stable  $\text{Ge}_x\text{Si}_{1-x}$  compounds, indicated by characteristic absorption features. These results demonstrate that the proposed diffusion method enables the fabrication of robust  $\text{Ge}_x\text{Si}_{1-x}$  layers suitable for high-efficiency heterostructure solar cells, optoelectronic detectors, and simple electronic devices, highlighting their potential for next-generation nanoelectronic and photonic applications.

## REFERENCES

1. N.F. Zikrillaev, G.H. Mavlonov, L. Trabzon, S.B. Isamov, Y.A. Abduganiev, Sh.N. Ibodullaev, G.A. Kushiev. Magnetic Properties of Silicon Doped with Impurity Atoms of Europium. *Journal of Nano- and Electronic Physics*. (2023), 15, 6, 06001. DOI:10.21272/jnep.15(6).06001
2. U I Erkaboev, R G Rakhimov, J I Mirzaev, U M Negmatov and N A Sayidov. Influence of a magnetic field and temperature on the oscillations of the combined density of states in two-dimensional semiconductor materials. *Indian J Phys* (January 2024) 98(1):189–197 <https://doi.org/10.1007/s12648-023-02803-y>.

3. Kh.M. Iliev, S.V. Koveshnikov, B.O. Isakov, E.Zh. Kosbergenov, G.A. Kushiev, Z.B. Khudoynazarov. The Elemental Composition Investigation of Silicon Doped with Gallium and Antimony Atoms. *Surface Engineering and Applied Electrochemistry*, (2024), 60, 4, pp. 633 – 639. DOI: 10.3103/S106837552470025X
4. G.A. Kushiev, B.O. Isakov, U.X. Mukhammadjonov. The Prospects of Obtaining a New Material with a Hetero-Baric Structure  $\text{Ge}_x\text{Si}_{1-x}\text{-Si}$  Based on Silicon for Photo Energy Applications. *Journal of Nano- and Electronic Physics*. (2024), 16, 3, 03003. DOI: 10.21272/jnep.16(3).03003
5. U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov, U.M. Negmatov, *East Eur. J. Phys.* 1, 485 (2024), <https://doi.org/10.26565/2312-4334-2024-1-53>
6. N.F. Zikrillayev, F.E. Urakova, A.R. Toshev, G.A. Kushiev, T.B. Ismailov, Y.A. Abduganiev, N. Norkulov. Physical and magnetic properties of silicon doped with impurity germanium atoms. *East European Journal of Physics*. (2025), 1, pp. 184 – 189. DOI:10.26565/2312-4334-2025-1-18
7. N.F. Zikrillayev, Kh.M. Iliev, G.A. Kushiev, S.B. Isamov, S.V. Koveshnikov, B.A. Abdurakhmanov, B.O. Isakov. Study Of Photocells Based On  $\text{Ge}_x\text{Si}_{1-x}$  Structures. *Journal of Applied Science and Engineering*. (2026), 29, 3, pp. 685 – 691. DOI:10.6180/jase.202603\_29(3).0019
8. N.F. Zikrillayev, M.K. Khakkulov, B.O. Isakov. The mechanism of the formation of binary compounds between Zn and S impurity atoms in Si crystal lattice. *East European Journal of Physics*. (2023), 4, pp. 177 – 181. DOI: 10.26565/2312-4334-2023-4-20
9. N.F. Zikrillayev, S.B. Isamov, B.O. Isakov, T. Wumaier, Liang, Li wen, J.X. Zhan, T. Xiayimulati. New Technological Solution for the Tailoring of Multilayer Silicon-based Systems with Binary Nanoclusters Involving Elements of Groups III and V. *Journal of Nano- and Electronic Physics*. (2023), 16, 6, 06024. DOI:10.21272/jnep.15(6).06024
10. Kh.M. Iliev, N.F. Zikrillayev, K.S. Ayupov, B.O. Isakov, B.A. Abdurakhmanov, Z.N. Umarchodjaeva, L.I. Isamiddinova. Effect of GaSb Compound on Silicon Bandgap Energy. *Journal of Nano- and Electronic Physics*. (2024), 16, 2, 02004. DOI: 10.21272/jnep.16(2).02004
11. X.M. Iliyev, Z.B. Khudoynazarov, B.O. Isakov, M.X. Madjitov, A.A. Ganiyev. Electrodiffusion of manganese atoms in silicon. *East European Journal of Physics*. (2024), 2, pp. 384 – 387. DOI: 10.26565/2312-4334-2024-2-48
12. B.O. Isakov, X.M. Iliyev, Z.B. Khudoynazarov, G.A. Kushiev. Effective charge of Mn and Ni impurity atoms in silicon under the influence of an external electric field. *East European Journal of Physics*. (2025), 2, pp. 215 – 219. DOI: 10.26565/2312-4334-2025-2-23
13. G.H. Mavlonov, Kh.Kh. Uralbaev, B.O. Isakov, Z.N. Umarchodjaeva, Sh.I. Hamrokulov. Diffusion distribution of Cr and Mn impurity atoms in silicon. *East European Journal of Physics*. (2025), 2, pp. 237 – 241. DOI:10.26565/2312-4334-2025-2-27
14. X.M. Iliyev, S.B. Isamov, B.O. Isakov, U.X. Qurbonova, S.A. Abduraxmonov. A surface study of Si doped simultaneously with Ga and Sb. *East European Journal of Physics*, (2023), 3, pp. 303-307. DOI:10.26565/2312-4334-2023-3-29
15. X.M. Iliyev, V.B. Odzhaev, S.B. Isamov, B.O. Isakov, B.K. Ismaylov, K.S. Ayupov, Sh. I. Hamrokulov, S.O. Khasanbaeva. X-ray diffraction and Raman spectroscopy analyses of GaSb-enriched Si surface formed by applying diffusion doping technique. *East European Journal of Physics*, (2023), 3, pp. 363-369. DOI: 10.26565/2312-4334-2023-3-38
16. Zikrillayev, N.F., Koveshnikov, S.V., Trabzon, L., Mavlonov, G.Kh., Ismaylov, B.K., Ismailov, T.B., Urakova, F.E. Ferromagnetic Properties of Silicon Doped Manganese Atoms, *Surface Engineering and Applied Electrochemistry*, 2025, Vol. 61, No. 1. pp. 75–80. ISSN 1068-3755, <https://doi.org/10.3103/S1068375524700571>
17. Zikrillayev, N.F., Mavlonov, G.Kh., Trabzon, L., Koveshnikov, S.V., Kenzhaev, Z.T., Ismailov, T.B., Abduganiev, Y.A. MAGNETIC PROPERTIES OF SILICON WITH PARAMAGNETIC IMPURITY ATOMS, *East European Journal of Physics*, 2023, 2023(3), pp. 380–384, <https://doi.org/10.26565/2312-4334-2023-3-40>
18. B.A. Abdurakhmanov, A.Sh. Movlyanov, U.Kh. Sodikov, N. Norkulov. New materials for solar elements on the basis of silicon with CdS and ZnS quantum dots. *Elektronnaya Obrabotka Materialov*, (2005), 4, pp. 89-92.
19. B.A. Abdurakhmanov, M.K. Bakhadyrkhanov, Kh.M. Iliev, S.A. Tachilin, A.R. Toshev. Effect of stress on the Si solar cell parameters. *Applied Solar Energy (English translation of Geliotekhnika)*, (2005), 41, 2, pp. 65-67.
20. F. N. F. Zikrillayev, Kh. F. Zikrillayev, F. E. Urakova, G. A. Kushiev, D. M. Shukurova, and B. Kh. Ibrahimova. Photovoltaic Cells Based on Silicon with Binary Compounds  $\text{Ge}_x\text{Si}_{1-x}$ . *Surface Engineering and Applied Electrochemistry*, 2025, Vol. 61, No. 2, pp. 234–239. © Allerton Press, Inc., 2025
21. G.H. Mavlonov, N.F. Zikrillayev, A.A. Usmonov, G.A. Kushiev, Kh.S. Turekeev. X-Ray and Raman Spectroscopy of  $(\text{Si}_2)_{1-x}(\text{BP})_x$  Binary Compounds in Silicon.



22. B.A. Abdurakhmanov, Kh.M. Iliev, S.A. Tachilin, A.R. Toshev. Silicon solar cells with Si-Ge microheterojunctions. *Russian Microelectronics*. (2012), 41, 3, pp. 169-171. DOI: 10.1134/S1063739712020023
23. B.A. Abdurakhmanov, Kh.M. Iliev, S.A. Tachilin, A.R. Toshev, B.E. Egamberdiev. The effect of silicon-germanium microheterojunctions on the parameters of silicon solar cells. *Surface Engineering and Applied Electrochemistry*, (2010), 46, 5, pp. 505-507.
24. M.K. Bakhadyrkhanov, Kh.M. Iliev, S.A. Tachilin, S.S. Nasriddinov, B.A. Abdurakhmanov. Impurity photovoltaic effect in silicon with multicharge Mn clusters. *Applied Solar Energy (English translation of Geliotekhnika)*, (2008), 44, 2, pp. 132-134. DOI:10.3103/S0003701X08020151
25. N. F. Zikrillaevev, K. S. Ayupov, N. Narkulov, F. E. Urakova, G. A. Kushiev and O. S. Nematov. Silicon with Binary  $\text{Ge}_x\text{Si}_{1-x}$  Compounds. *Surface Engineering and Applied Electrochemistry*, 2024, Vol. 60, No. 6, pp. 806–813. © Allerton Press, Inc., 2024. DOI: 10.3103/S106837552470039X
26. N.F. Zikrillaevev, G.A. Kushiev, Sh.I. Hamrokulov, Y.A. Abduganiev. Optical Properties of  $\text{Ge}_x\text{Si}_{1-x}$  Binary Compounds in Silicon. *J. Nano- Electron. Phys.* 15 No 3, 03024 (2023) [https://doi.org/jnep.15\(3\).03024](https://doi.org/jnep.15(3).03024) M.K.
27. M.K. Bakhadyrkhanov, Kh.M. Iliev, K.S. Ayupov, B.A. Abdurakhmonov, P.Yu. Krivenko, R.L. Kholmukhamedov. Self-organization of nickel atoms in silicon. *Inorganic Materials*, (2011), 47, 9, pp. 962-964. DOI: 10.1134/S0020168511090020
28. Yusupjonova, M.B., Tashmukhamedova, D.A., Umirzakov, B.E., Saidakhmedova, Z.R., Salieva, S.K. Influence of implantation of active metal ions on the composition, emission and optical properties of mgo films. *East European Journal of Physics*, 2025, 2025(1), Pp. 260–264
29. Abraeva, S., Tashmukhamedova, D., Gulyamova, S., Yusupjanova, M., Xujaniyazova, A. Impact of bombardment by  $\text{Ar}^+$ ,  $\text{Na}^+$  and  $\text{O}^{2+}$  ions on spectra of elastically scattered electrons of single-crystal Ge. *E3s Web of Conferences* Open source preview, 2023, 401, 05006.
30. Ismailov K.A., Kenzhaev Z.T., Koveshnikov S.V., Kosbergenov E.Zh., Ismaylov B.K. Radiation stability of nickel-doped solar cells // *Physics of the Solid State*, 2022, Vol. 64, No. 4, pp. 154–156. DOI: 10.1134/S1063783422040011.
31. Kh.M. Iliev, K. A. Ismailov, E. Zh. Kosbergenov, V. B. Odzhaev, V. S. Prosolovich, Yu. N. Yankovsky, Z. T. Kenzhaev, B. O. Isakov, and G. A. Kushiev, The Influence of  $\gamma$ -Irradiation on the Electrophysical Parameters of Nickel-Doped Silicon Grown by the Czochralski Method // *Surface Engineering and Applied Electrochemistry*, 2025, Vol. 61, No. 6, pp. 851–856. <https://doi.org/10.3103/S1068375525700942>
32. Bakhadyrkhanov M.K., Ismailov K.A., Kosbergenov E.Zh. Thermal stability of electrical parameters of silicon crystal doped with nickel during growth // *Semiconductor Physics, Quantum Electronics & Optoelectronics*, 2022, Vol. 25, No. 1, pp. 6–9. DOI: 10.15407/spqeo25.01.006.
33. M. N. Mirzayev<sup>1,2,3</sup> · G. T. Imanova<sup>1,2,4</sup> · D. Neov<sup>5</sup> · M. Rasoul<sup>2</sup> · I. R. Bekpulatov<sup>6</sup> · F. K. Khallokov<sup>7</sup> · E. P. Popov<sup>5</sup> · K. Hasanov<sup>1</sup> · S. Isayeva<sup>8</sup> · B. Maueyev<sup>9</sup> · D. M. Mirzayeva<sup>10</sup> · F. Tatardar<sup>2</sup> · M. Dinu<sup>11</sup> · G. Kaminski<sup>12</sup> · A. Vladescu (Dragomir). Correction: Surface evaluation of carbonitride coating materials at high temperature: an investigation of oxygen adsorption on crystal surfaces by molecular dynamics simulation. *Journal of Porous Materials* (2024) 31:1541 <https://doi.org/10.1007/s10934-024-01637-1>
34. Umirzakov, B. E.; Bekpulatov, I. R.; Imanova, G. T.; Turapov, I. Kh.; and Jumaev, J. M. (2023) "Study of the dependence of the degree of disordering of the surface layers of Si(111) and Ge(111) single crystals upon bombardment with low-energy ions," *Eurasian Journal of Physics and Functional Materials*: Vol. 7: No. 4, Article 5. DOI: <https://doi.org/10.32523/ejpfm.2023070405>
35. N. F. Zikrillaevev, S. V. Koveshnikova, Kh. S. Turekeeva, and B. K. Ismaylova, Composition of Silicon Alloyed with Gallium and Phosphorus Atoms *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*, 2024, Vol. 18, No. 3, p. 764. © Pleiades Publishing, Ltd., 2024
36. N.F. Zikrillaevev et al., *J. Nano- Electron. Phys.* 17 No 2, 02014 (2025) [https://doi.org/10.21272/jnep.17\(2\).02014](https://doi.org/10.21272/jnep.17(2).02014)