East European Journal of Physics. 2. 220-225 (2025)
DOI:10.26565/2312-4334-2025-2-24 ISSN 2312-4334

MATHEMATICAL ANALYSIS OF THE FEATURES OF RADIAL p-n JUNCTION: INFLUENCE OF TEMPERATURE AND CONCENTRATION

J.Sh. Abdullayev[a]*, I.B. Sapaev[a,b], N.Sh. Esanmuradova[a,b,e], S.R. Kadirov[c], Sh.M. Kuliyev[d]
[a]*National Research University TIIAME, Department of Physics and Chemistry, Tashkent, Uzbekistan*
[b]*Western Caspian University, Baku, Azerbaijan*
[c]*Urgench State University, Urgench, Uzbekistan*
[d]*Physical-Technical Institute of Uzbekistan Academy of Sciences, 100084 Tashkent, Uzbekistan*
[e]*Kimyo International University in Tashkent, Uzbekistan*
**Corresponding Author e-mail: j.sh.abdullayev6@gmail.com*
Received November 11, 2025; revised January 7, 2025; in final form March 23, 2025; accepted April 1, 2025

In this article, the electrophysical characteristics of GaAs/Si radial heterojunctions are studied analytically over a temperature range of 50 K to 500 K in increments of 50 K, considering various doping concentrations. The analysis encompasses band gap narrowing (BGN), built-in potential, the difference in band gap between GaAs and Si, and capacitance-voltage (C-V) characteristics. In particular, we focus on shell radii of 0.5 μm and 1 μm within the structure. We found that the thickness of the depletion region of the GaAs/Si radial heterojunction increases with rising temperature. When the doping concentration changes from $2\cdot10^{15}$ to $2\cdot10^{18}$ BGN decreases by 2 meV. The charge capacity of the GaAs/Si radial heterojunction increases by 3 nF as the temperature rises from 50 K to 500 K. Additionally, the built-in potential of the GaAs/Si radial heterojunction decreases by 1.5 volts with increasing temperature.
Keywords: *Radial p-n and p-i-n junction; Light trap; External factors; Volt-farad; Volt-amper; Cryogenic temperatures*
PACS: 73.40. Lq, 73.61.Cw, 73.61.Ey, 72.20.Jv

INTRODUCTION

Over time, the ongoing surge in research on semiconductor electronic devices has led to significant advancements in their design, unique materials, optimization, and functionality. Key developments include two-dimensional transistors [1-4], nanowires [5], and notably, radial p-n and p-i-n junction structures [6,7]. Radial p-n junctions offer several advantages over traditional planar junctions, especially in submicron nanowire applications [8-11], including high internal and external quantum efficiency [12], low recombination due to short diffusion length [13], and a high surface-to-volume ratio [14]. Over the past two decades, these radial junctions have gained popularity for their enhanced optical and electronic properties, making them ideal for applications such as photodiodes, optical sensors [15], thermal and photovoltaic detectors [16], and solar cells [17]. Their design minimizes optical losses through efficient light absorption and charge carrier collection, thereby enhancing energy conversion efficiency. Additionally, the perpendicular alignment of light absorption and carrier transport in radial p-n junctions supports high-frequency performance, making them suitable for high-speed electronics and wireless communication systems.

Furthermore, radial junctions are integral to high-speed photodetectors [18], avalanche photodiodes [19], photovoltaic devices, gamma-ray detectors [20], and infrared sensors [21,22]. Their unique structural design provides superior efficiency, speed, and sensitivity [23], essential for various modern semiconductor applications [24]. Given their broad applications, it is crucial to investigate the electrophysical properties of these junctions, particularly ionization processes and their behavior across a wide temperature range. Both theoretical modeling and experimental validation are essential to ensure the reliability and accuracy of these semiconductor devices.

While radial p-n and p-i-n junctions have been extensively studied, research on heterojunction structures remains comparatively limited. In this work, we have focused on the GaAs/Si heterojunction structure, analyzing its electrophysical features theoretically and analytically. Using mathematical modeling, we have analyzed the electrophysical characteristics of the n-GaAs/p-Si heterojunction structure to gain insights into its performance under varying temperatures and applied voltages.

METHODS AND MATERIAL

2.1 Material and Geometric Parameters

Despite the development of new semiconductor materials, GaAs remains the primary material for optoelectronic devices, while Si continues to be the most widely used material due to its advanced development technology and abundance on the Earth's surface. Based on this perspective, Si and GaAs were selected for this study. Figure 1 shows the cross-sectional view of the selected radial p-n junction sample, cut along the Z-axis. We derived solutions for radial p-n junction structures with a p-type core radius of 0.5 μm and an n-type shell radius of 1 μm. Where r denotes the radial

Cite as: J.Sh. Abdullayev, I.B. Sapaev, N.Sh. Esanmuradova, S.R. Kadirov, Sh.M. Kuliyev, East Eur. J. Phys. 2, 220 (2025), https://doi.org/10.26565/2312-4334-2025-2-24

dimension, $\circ e^{+}$ and $\bullet e^{-}$ represents the densities of ionized N_D^+ donor and N_A^- acceptor atoms respectively, at the interface of the radial p-n heterojunction within the depletion region. If full ionization case $N_D^+ = N_D$, $N_A^- = N_A$. In Figure 1, the interval $0 < r < r_p$ represents the p-type quasi-neutral region (QNR), the interval $r_p < r < r_n$ represents the depletion region in the radial p-n heterojunction junction, the interval $r_n < r < 2R$ represents the n-type quasi-neutral region (QNR).

$$d_{p-n} = \sqrt{\frac{2(\varepsilon_{GaAs} N_A + \varepsilon_{Si} N_D)(\varphi_{bi}(T) - U)}{q \varepsilon_{Si} \varepsilon_{GaAs} \varepsilon_0 N_A \cdot N_D}} . \quad (1)$$

The interval $d_{p-n} = r_p < r < r_n$ represents the depletion region and this depends on temperature and external voltage and is represented by the expression (1): Where, $\varphi_{bi}(T)$ is the built-in potential of the radial p-n junction which is defined by the expression (3), $\varepsilon_{Si}, and\ \varepsilon_{GaAs}$ are dielectric constant of the Si and GaAs respectively, $\varepsilon_0 = 8.85 \cdot 10^{-12}\ F \cdot m^{-1}$ electrical constant. Heterojunction p-n structures are essential for advanced semiconductor devices, as they enhance performance through optimized band alignment and reduced recombination. The depletion region width plays a crucial role in determining device efficiency by influencing charge carrier distribution, breakdown voltage, and overall performance, particularly in high-frequency and high-power applications.

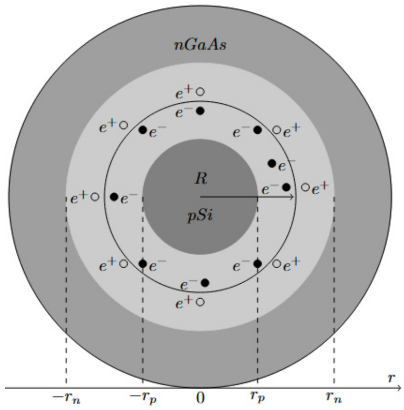


Figure 1. This figure illustrates a 2D cross-section of submicron radial p-n junction structures. The n-type GaAs region is represented by the light gray area, the p-type Si region by the dark gray area, and the depletion region is shown in very light gray

Precisely understanding and controlling this width is critical for improving the functionality and reliability of heterojunction-based devices. Figure 2 illustrates how the depletion region varies with external voltage at different temperatures, based on the results derived from Equation (1).

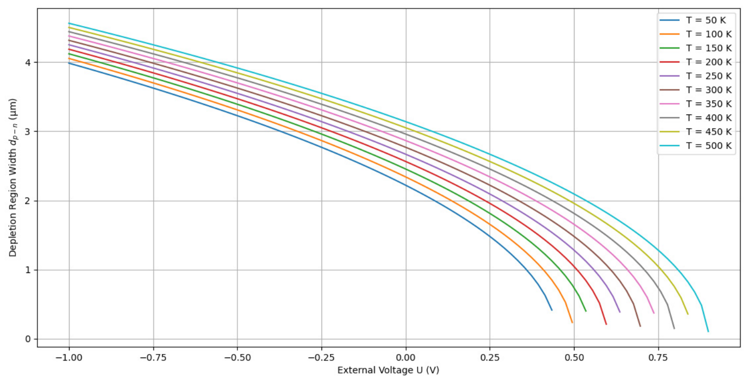


Figure 2. Temperature dependence of the depletion region thickness differences in the p-GaAs/n-Si heterojunction

The band gap is indeed one of the most critical parameters in semiconductor materials, especially for heterojunctions like p-GaAs/n-Si. In such heterojunctions, the difference in band gaps between GaAs (about 1.43 eV) and Si (about 1.12 eV) at 300K, plays a significant role in their behavior and performance, particularly affecting charge carrier dynamics, recombination, and junction properties. This balance of properties in GaAs/Si heterojunctions supports a wide range of applications in high-speed electronics and optoelectronic devices. The (2) expression represents the change in the width of the band gap with temperature variation.

$$\Delta E_g(T) = \Delta E_g(0) - T^2 \cdot \left(\frac{\alpha_{GaAs}}{T + \theta_{GaAs}} - \frac{\alpha_{Si}}{T + \theta_{Si}}\right) . \quad (2)$$

Where, $\Delta E_g(0)$ is differences of the band gap Si and GaAs at 0 K. θ_{GaAs} and θ_{Si} are Debye temperature GaAs and Si respectively. The Debye temperature can be calculated using the material's properties, but empirical values are often referenced.

$$\varphi_{bi}(T) = \Delta E_g(T) - \frac{kT}{q} \cdot \ln\left(\frac{N_A \cdot N_D}{n_{iGaAs} \cdot n_{iSi}}\right). \tag{3}$$

Here, k is the Boltzmann constant, T is the absolute temperature in Kelvin, q is the charge of an electron,N_A and N_D are acceptor and donor concentration respectively, n_{iSi} and n_{iGaAs} are intrinsic carrier concentrations of Si and GaAs respectively. The electrostatic potential difference in the radial p-GaAs/n-Si heterojunction varies with changes in the external source voltage, which can be expressed as follows:

$$\Delta\varphi_{p-n} = \varphi_{bi}(T) - U. \tag{4}$$

The charge capacity of the GaAs/Si radial heterojunction depends on the differences in electrostatic potential. The negative charge of the p-type acceptors is balanced by the positive charge of the n-type donors $Q = Q^+ = Q^-$. which is equal to the differential electric capacity derived from the change in charge with respect to voltage. The results of the analytical and mathematical expressions derived above are analyzed in the following section, along with proposed future expectations. Additionally, the obtained results have been calibrated. The charge capacity of the p-GaAs/n-Si heterojunction is expressed by equation (5)

$$C_{p-n} = S\sqrt{\frac{q\varepsilon_{Si}\varepsilon_{GaAs}\varepsilon_0 N_A \cdot N_D}{2(\varepsilon_{GaAs}N_A + \varepsilon_{Si}N_D)(\varphi_{bi}(T) - U)}}. \tag{5}$$

RESULTS AND DISCUSSION

In this section, the results are presented and analyzed. The analytical study of GaAs/Si radial heterojunctions over a temperature range of 50 K to 500 K provides significant insights into their electrophysical characteristics. One key finding is the observed increase in the depletion region thickness with rising temperature, while it decreases with increasing external voltage, as shown in Figure 2. This behavior is attributed to the intrinsic properties of the semiconductor materials involved. As temperature increases, thermal energy enhances charge carrier movement, effectively reducing the doping concentration within the depletion region. Consequently, a wider depletion width is required to maintain charge neutrality across the junction, which is critical for the heterojunction's operation.

The depletion region thickness in p-GaAs/n-Si heterojunctions is analyzed at various voltages, specifically -1 V and 1 V, across different temperatures ranging from 50 K to 500 K in 50 K increments, as depicted in Figure 2. The results indicate that the depletion region thickness decreases with increasing voltage and temperature. Additionally, the potential barrier of the p-n junction is directly influenced by the depletion region thickness, leading to observable variations in the potential barrier. This dependence plays a crucial role in the functionality of devices such as thermosensors, photosensors, and solar cells.

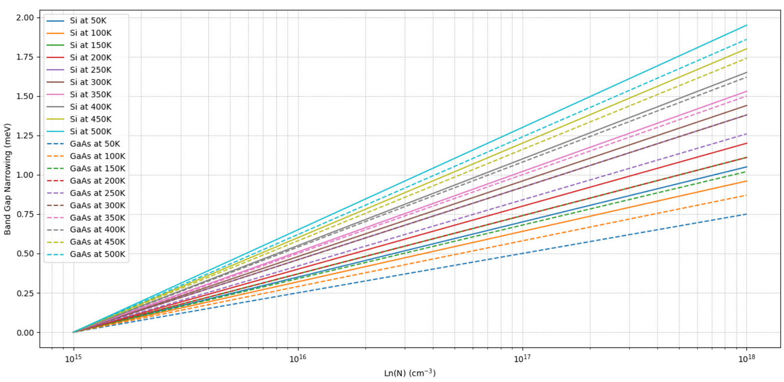
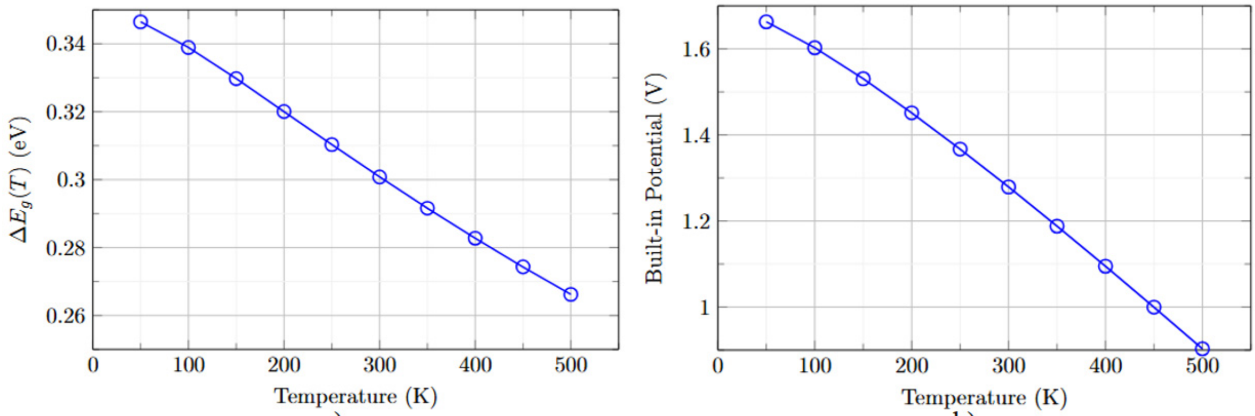


Figure 3. Bandgap narrowing as a function of logarithmic doping concentration in both n-Si and p-GaAs

Another noteworthy result is the decrease in band gap narrowing (BGN) by 2 meV as the doping concentration increases from changes from $2{\cdot}10^{15}$ to $2{\cdot}10^{18}$. This trend indicates that higher doping levels enhance the screening of ionized impurities, effectively reducing the interactions responsible for BGN. The implications of BGN on device performance are significant, as a narrower band gap can lead to increased leakage currents, potentially degrading the efficiency of heterojunction-based devices such as solar cells and light-emitting diodes, as shown in Figure 3. Understanding the interplay between temperature, doping concentration, and band gap narrowing is crucial for designing high-performance GaAs/Si radial heterojunctions. The results of this study highlight the potential of GaAs/Si heterojunctions in advancing semiconductor technology. By leveraging insights into BGN and temperature effects, manufacturers can design devices with improved performance, enhanced efficiency, and an extended operational range across various applications.



a) b)

Figure 4. a) Temperature dependence of the band gap differences in the p-GaAs/n-Si heterojunction,
b) The built-in potential of the p-GaAs/n-Si heterojunction varies with temperature from 50 K to 500 K

Moreover, the decrease in built-in potential by 1.5 volts with increasing temperature provides crucial insights into the stability of the junction. The built-in potential is vital for determining the electric field strength within the depletion region, which influences carrier recombination and overall junction performance.

The temperature dependence of the bandgap energy difference is also significant, as the bandgap decreases from 3.2 eV at 200K to 3.0 eV at 300K, suggesting a bandgap narrowing effect. This phenomenon, commonly observed in semiconductors, results from increased lattice vibrations, as shown in Figure 4.

As temperature rises, the reduced built-in potential may lead to increased thermal generation of electron-hole pairs, potentially elevating the reverse saturation current. This observation highlights the need for robust thermal management in device design, particularly for applications operating under varying thermal conditions.

The results of this study emphasize the intricate relationship between temperature, doping concentration, and the electrophysical characteristics of GaAs/Si radial heterojunctions. The increase in depletion width, the reduction in bandgap narrowing, the enhancement of charge capacity, and the decrease in built-in potential collectively provide valuable insights into optimizing device performance across different thermal environments.

Future work should focus on the experimental validation of these findings and exploring strategies to mitigate the adverse effects of temperature on the electrical characteristics of GaAs/Si radial heterojunctions, particularly for applications in high-performance semiconductor devices.

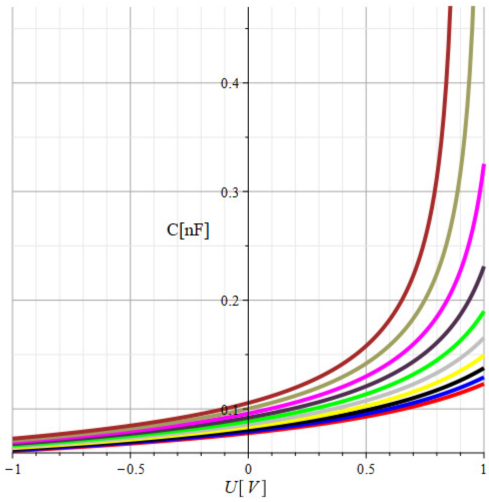


Figure 5. The charge capacity of the p-GaAs/n-Si heterojunction varies with external voltage over a temperature range from 50 K to 500 K, with the red line representing 50 K and the brown line representing 500 K

The observed increase in charge capacity by 3 nF with rising temperature from 50 K to 500 K reflects the temperature dependence of the capacitance-voltage (C-V) characteristics in Figure 5. As temperature increases, carriers are thermally excited, increasing their availability for conduction and, subsequently, enhancing the overall capacitance of the device. This behavior is particularly significant in high-frequency applications where capacitance stability is essential. It suggests that GaAs/Si radial heterojunctions could be designed to operate effectively across a broad temperature range, although careful consideration must be given to temperature effects on other parameters such as leakage current and noise.

CONCLUSIONS

In conclusion, this study provides a comprehensive analysis of the electrophysical characteristics of GaAs/Si radial heterojunctions across a temperature range of 50 K to 500 K, focusing on the effects of various doping concentrations and shell radii of 0.5 µm and 1 µm. Our findings reveal that the depletion region thickness increases with temperature, indicating enhanced charge distribution within the junction. Notably, the band gap narrowing (BGN) was found to decrease by 2 meV as the doping concentration varied from $2{\cdot}10^{15}$ to $2{\cdot}10^{18}$, highlighting the influence of doping on electronic properties. Furthermore, we observed an increase in charge capacity by 3 nF with temperature elevation, which signifies improved device performance at higher thermal conditions. Conversely, the built-in potential experienced a notable decrease of 1.5 volts as temperature increased, suggesting a reduction in the energy barrier for charge carriers. These insights into the temperature-dependent behavior of GaAs/Si radial heterojunctions contribute valuable knowledge for the design and optimization of semiconductor devices operating in varying thermal environments.

ORCID

Jo'shqin Sh. Abdullayev, https://orcid.org/0000-0001-6110-6616; **Ibrokhim B. Sapaev,** https://orcid.org/0000-0003-2365-1554

REFERENCES

[1] R. Elbersen, R.M. Tiggelaar, A. Milbrat, G. Mul, H. Gardeniers, and J. Huskens, "Controlled Doping Methods for Radial p/n Junctions in Silicon," Advanced Energy Materials, **5**(6), 1401745 (2014). https://doi.org/10.1002/aenm.201401745
[2] E. Gnani, A. Gnudi, S. Reggiani, and G. Baccarani, "Theory of the Junctionless Nanowire FET," IEEE Trans. Electron Devices, **58**(9), 2903 (2011). https://doi.org/10.1109/TED.2011.2159608
[3] J.Sh. Abdullayev, and I.B. Sapaev, "Optimization of The Influence of Temperature on The Electrical Distribution of Structures with Radial p-n Junction Structures," East Eur. J. Physics, (3), 344-349 (2024). https://doi.org/10.26565/2312-4334-2024-3-39
[4] J.Sh. Abdullayev, and I.B. Sapaev, "Optimizing the Influence of Doping and Temperature on The Electrophysical Features of p-n and p-i-n Junction Structures," Eurasian Physical Technical Journal, **21**(3(49), 21–28 (2024). https://doi.org/10.31489/2024No3/21-28
[5] J.Sh. Abdullayev, "Influence of Linear Doping Profiles on the Electrophysical Features of p-n Junctions," East Eur. J. Phys. (1), 245-249 (2025). https://doi.org/10.26565/2312-4334-2025-1-26
[6] O.V. Pylypova, A.A. Evtukh, P.V. Parfenyuk, I.I. Ivanov, I.M. Korobchuk, O.O. Havryliuk, and O.Yu. Semchuk, "Electrical and optical properties of nanowires based solar cell with radial p-n junction," Opto-Electronics Review, **27**(2), 143 (2019). https://doi.org/10.1016/j.opelre.2019.05.003
[7] R. Ragi, R.V.T. da Nobrega, U.R. Duarte, and M.A. Romero, "An Explicit Quantum-Mechanical Compact Model for the I-V Characteristics of Cylindrical Nanowire MOSFETs," IEEE Trans. Nanotechnol. **15**(4), 627 (2016). https://doi.org/10.1109/TNANO.2016.2567323
[8] R.D. Trevisoli, R.T. Doria, M. de Souza, S. Das, I. Ferain, and M.A. Pavanello, "Surface-Potential-Based Drain Current Analytical Model for Triple-Gate Junctionless Nanowire Transistors," IEEE Trans. Electron Devices, **59**(12), 3510 (2012). https://doi.org/10.1109/TED.2012.2219055
[9] N.D. Akhavan, I. Ferain, P. Razavi, R. Yu, and J.-P. Colinge, "Improvement of carrier ballisticity in junctionless nanowire transistors," Appl. Phys. Lett. **98**(10), 103510 (2011). https://doi.org/10.1063/1.3559625
[10] J.Sh. Abdullayev, and I.B. Sapaev, "Modeling and calibration of electrical features of p-n junctions based on Si and GaAs," Physical Sciences and Technology, **11**, 3-4 39–48 (2024). https://doi.org/10.26577/phst2024v11i2b05
[11] J.Sh. Abdullayev, and I.B. Sapaev, "Factors Influencing the Ideality Factor of Semiconductor p-n and p-i-n Junction Structures at Cryogenic Temperatures," East Eur. J. Phys. (4), 329-333 (2024). https://doi.org/10.26565/2312-4334-2024-4-37
[12] A.V. Babichev, H. Zhang, P. Lavenus, F.H. Julien, A.Y. Egorov, Y.T. Lin, and M. Tchernycheva, "GaN nanowire ultraviolet photodetector with a graphene transparent contact," Applied Physics Letters, **103**(20), 201103 (2013). https://doi.org/10.1063/1.4829756
[13] D.H.K. Murthy, T. Xu, W.H. Chen, A.J. Houtepen, T.J. Savenije, L.D.A. Siebbeles, *et al.*, "Efficient photogeneration of charge carriers in silicon nanowires with a radial doping gradient," Nanotechnology, **22**(31), 315710 (2011). https://doi.org/10.1088/0957-4484/22/31/315710
[14] B. Pal, K.J. Sarkar, and P. Banerji, "Fabrication and studies on Si/InP core-shell nanowire based solar cell using etched Si nanowire arrays," Solar Energy Materials and Solar Cells, **204**, 110217 (2020). https://doi.org/10.1016/j.solmat.2019.110217
[15] I. Aberg, G. Vescovi, D. Asoli, U. Naseem, J.P. Gilboy, C. Sundvall, and L. Samuelson, "A GaAs Nanowire Array Solar Cell With 15.3% Efficiency at 1 Sun," IEEE Journal of Photovoltaics, **6**(1), 185 (2016). https://doi.org/10.1109/JPHOTOV.2015.2484967
[16] J. Sh. Abdullayev, I. B. Sapaev, Kh. N. Juraev, "Theoretical analysis of incomplete ionization on the electrical behavior of radial p-n junction structures," Low Temp. Phys. **51**, 60–64 (2025), https://doi.org/10.1063/10.0034646
[17] J.Sh. Abdullayev, and I.B. Sapaev, "Analytic Analysis of the Features of GaAs/Si Radial Heterojunctions: Influence of Temperature and Concentration," East Eur. J. Phys. (1), 204-210 (2025). https://doi.org/10.26565/2312-4334-2025-1-21
[18] O. Toktarbaiuly, M. Baisariyev, A. Kaisha, T. Duisebayev, N. Ibrayev, T. Serikov, M. Ibraimov, *et al.*, "Enhancement of Power Conversion Efficiency of Dye-Sensitized Solar Cells Via Incorporation of Gan Semiconductor Material Synthesized in Hot-Wall Chemical Vapor Deposition Furnace," Eurasian Physical Technical Journal, **21**(4(50), 131–139 (2024). https://doi.org/10.31489/2024No4/131-139
[19] M.Sh. Isaev, A.I. Khudayberdieva, M.N. Mamatkulov, U.T. Asatov, and S.R. Kodirov, "The Surface Layer Morphology of Si<Cr> Samples," East Eur. J. Phys. (4), 297–300 (2024). https://doi.org/10.26565/2312-4334-2024-4-32
[20] L. Olimov, and I. Anarboyev, "Some Electrophysical Properties of Polycrystalline Silicon Obtained in a Solar Oven," Silicon, **14**, 3817–3822 (2022). https://doi.org/10.1007/s12633-021-01596-1

[21] L. Olimov, and I. Anarboyev, "Mechanism of thermoelectric material efficiency increase," AIP Conf. Proc. **3244**, 060015 (2024). https://doi.org/10.1063/5.0242092
[22] I. Sapaev, I.B. Sapaev, *et. al*., "Influence of the parameters to transition capacitance at NCDS-PSI heterostructure," E3S Web Conf., **383**, 04022 (2023). https://doi.org/10.1051/e3sconf/202338304022
[23] A.T. Mamadalimov, M.Sh. Isaev, M.N. Mamatkulov, S.R. Kodirov, and J.T. Abdurazzokov, "Study of Silicide Formation in Large Diameter Monocrystalline Silicon," East Eur. J. Phys. (2), 366-371 (2024). https://doi.org/10.26565/2312-4334-2024-2-45
[24] M.S. Isaev, U.T. Asatov, M.A. Tulametov, S.R. Kodirov, and A.E. Rajabov, "Study of the Inhomogeneities of Overcompensed Silicon Samples Doped with Manganese," East Eur. J. Phys. (2), 341-344 (2024). https://doi.org/10.26565/2312-4334-2024-2-40

МАТЕМАТИЧНИЙ АНАЛІЗ ОСОБЛИВОСТЕЙ РАДІАЛЬНОГО p-n ПЕРЕХОДУ: ВПЛИВ ТЕМПЕРАТУРИ ТА КОНЦЕНТРАЦІЇ

Й.Ш. Абдуллаєв[a], І.Б. Сапаєв[a,b], Н.Ш. Есанмурадова[a,b,e], С.Р. Кадиров[c], Ш.М. Кулієв[d]
[a]*Національний дослідницький університет ТІІАМЕ, фізико-хімічний факультет, Ташкент, Узбекистан*
[b]*Західно-Каспійський університет, Баку, Азербайджан*
[c]*Ургенчський державний університет, Ургенч, Узбекистан*
[d]*Фізико-технічний інститут Академії наук Узбекистану, Ташкент, Узбекистан*
[e]*Міжнародний університет Кіміо в Ташкенті, Узбекистан*

У цій статті аналітично досліджуються електрофізичні характеристики радіальних гетеропереходів GaAs/Si в діапазоні температур від 50 K до 500 K з кроком 50 K, з урахуванням різних концентрацій домішок. Аналіз охоплює звуження зони провідності (BGN), вбудований потенціал, різницю в ширині забороненої зони між GaAs та Si, а також характеристики ємності-напруги (C-V). Особливу увагу приділено оболонковим радіусам 0,5 мкм та 1 мкм у цій структурі. Було виявлено, що товщина збідненої області радіального гетеропереходу GaAs/Si збільшується з підвищенням температури. Коли концентрація домішок змінюється з $2\cdot10^{15}$ до $2\cdot10^{18}$, BGN зменшується на 2 meV. Ємність радіального гетеропереходу GaAs/Si збільшується на 3 nF при підвищенні температури з 50 K до 500 K. Крім того, вбудований потенціал радіального гетеропереходу GaAs/Si зменшується на 1,5 вольта з підвищенням температури. Отримані аналітичні результати були порівняні з експериментальними даними та відкалібровані.

Ключові слова: *радіальні p-n та p-i-n переходи; світлова пастка; зовнішні фактори; вольт-фарад; вольт-ампер; кріогенні температури*