East European Journal of Physics. 1. 322-326 (2024)
DOI:10.26565/2312-4334-2024-1-29 ISSN 2312-4334

PREPARATION OF N-Si-P-GaSe HETEROJUNCTIONS BASED ON AN AMORPHOUS GaSe LAYER WITHOUT IMPURITIES AND STUDY OF THEIR ELECTRICAL PROPERTIES

Rahim Salim Madatov[a], A.S. Alekperov[b], F.N. Nurmammadova[c], Narmin A. Ismayilova[d,e], Sakin H. Jabarov[a,*]

[a] *Institute of Radiation Problems, Ministry of Science and Education Republic of Azerbaijan, Baku, AZ-1143, Azerbaijan*
[b] *Azerbaijan State Pedagogical University, Baku, AZ-1000, Azerbaijan*
[c] *Baku Engineering University, Khirdalan, AZ-0101, Azerbaijan*
[d] *Institute of Physics, Ministry of Science and Education Republic of Azerbaijan, Baku, AZ-1143, Azerbaijan*
[e] *Western Caspian University, Baku AZ-1001, Azerbaijan*
**Corresponding Author e-mail: sakin@jinr.ru*
Received October 25, 2023; revised November 28, 2023; accepted December 11, 2023

The electrical and photoelectric properties of anisotype n-Si−p-GaSe heterojunctions obtained as a result of the deposition of a GaSe thin layer on a cold n-Si single crystal substrate by the thermal evaporation method were studied. It was determined that the height of the potential barrier in thermal annealing structures at T = 200°C during t = 3 hours occurs due to the decrease in the density of states of local levels located near the Fermi level in the amorphous layer. The mechanism of photosensitivity in an isotype heterostructures was analyzed and it was found that the photosensitivity of the heterojunction increases as a result of a decrease in the surface density of state at the contact boundary of the components, by thermal means. The spectral distribution of the quantum efficiency in the n-Si – p-GaSe heterojunction was studied and their perspective was determined.
Keywords: *GaSe; Thin film; Heterojunction; Electrophysical properties*
PACS: 73.40.Lq, 81.05.Gc, 61.82.fk

1. INTRODUCTION

Even though semiconductor materials have been studied for a long time, these studies are continued in this period with modern methods. The main reason for this is that they have different functional properties. Due to the change in functions under the influence of the size effect, extensive research is being carried out on these materials at the atomic level [1-7]. The study of heterojunctions in these materials is of particular importance [8-10]. Because the obtained results further increase their application areas. The study of physical processes in semiconductor structures is related to increasing the efficiency of photoconverters and reducing the cost of solar cells. The research conducted to increase the efficiency of solar cells is one of the important directions of solar energy. One of the promising solutions to this problem is the creation of thin-layer structures. GaSe crystal, which is of practical importance in small-sized electronic systems, occupies a special place among A_3B_6 type compounds. The high drift mobility (~7000 $cm^2/V \cdot s$) of electrons in ultra-thin GaSe nanosheets expands its application possibilities [11-14]. On the other hand, the width of the forbidden band gap of GaSe crystal nanolayers strongly depends on the thickness of the layer, and the variation of optical and photoelectric properties with control of thickness increases their application in optoelectronics [15-19]. To create effective photoconverter structures based on GaSe crystal, Si-based amorphous and single crystals as well as complex semiconductor compounds are used [16]. Spectral distribution of photosensitivity in a-Si:H − n-InSe and Si - GaN(O) structures obtained by a new technological method was investigated and the prospects of obtained heterojunctions were shown [17,18]. Since the creation of a potential barrier in disordered semiconductors in the aforementioned structures is based on the classical potential barrier model, the role of deep energy levels localized near the Fermi level in the formation of p-n junctions is not taken into account, so there is a need to conduct new research in this direction [19]. There exist several experimental and theoretical studies for the physical properties of GeS crystal but so far, its thin film properties are still not sufficiently studied.

The aim of the study is investigation of the important characteristics of the heterocontact (n-Si − p-GaSe) created based on Si single crystal and p-GaSe thin layer (amorphous and polycrystalline).

2. A METHOD FOR PRODUCING A HETEROCONTACT AND MEASUREMENT METHODOLOGY

During the creation of the photosensitive structure, a chemically cleaned (100) oriented n-Si (KEF-7,5) single crystal was taken as a substrate. As the second component, scraps of GaSe single crystal grown by the Bridgman method were used. GaSe scraps were deposited on a cold Si (thickness ~50 μm) substrate by thermal evaporation method in a vacuum (~10^{-6} mmHg). The thickness of the obtained thin layers was ~ 0.8-2 μm. To determine the crystallization temperature of the thin layer, it was thermally annealed in a vacuum at a temperature of t = 200 °C for a period of τ = 2-3 hours. The optical absorption coefficient, dark conductivity and stationary photoconductivity were measured in the thin film

Cite as: R.S. Madatov, A.S. Alekperov, F.N. Nurmammadova, N.A. Ismayilova, S.H. Jabarov, East Eur. J. Phys. 1, 322 (2024), https://doi.org/10.26565/2312-4334-2024-1-29

with amorphous and crystalline structure [20]. The volt-farad characteristic (VFC), electrical and photoelectric properties of the prepared n-Si - p-GaSe structure were studied [19].

3. RESULTS AND DİSCUSSİON

Figure 1 shows the volt-farad characteristics of n-Si - p-GaSe structures on a cold substrate (1) and thermally annealed (2).

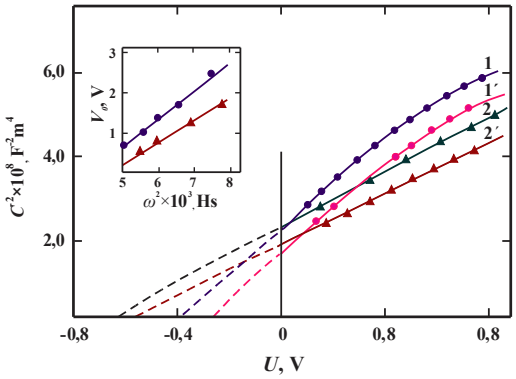

Figure 1. Voltage-Farad characteristics of the n-Si – p-GaSe structure

It can be seen from Figure 1 that the dependence of $C^2 \sim f(U)$ has a linear character in the thermally annealed sample (curve 2), while deviations from the linear dependence are observed in the sample with a cold base at high voltages. This shows that the distribution of impurity atoms in the region of bulk charges has a non-linear character (measurements were carried out at frequencies f = 50-100 kHz). The contact potential difference, p-n junction width, and electrostatic field intensity for both structures were calculated according to [19,21] and for the thermally annealed sample were ~ 0.5 V, $2\cdot10^{-4}$ cm, $3.2\cdot10^4$ V/cm, and for the sample with cold substrate were ~ 0.38 V, $3\cdot10^{-5}$ cm, $7.2\cdot10^2$ V/cm.

From the slope of the curves from VFC, the concentration of charge carriers was calculated according to [20] and was $2.3\cdot10^{15}$ cm^{-3} and $1.8\cdot10^{13}$ cm^{-3}, respectively. Based on the comparison of the parameters obtained during the calculation, it can be concluded that due to the weak interatomic bond in the GaSe layer obtained on a cold substrate, the nature of the distribution of ionized atoms in the range of bulk charges depends on the localized oxygen layer (dielectric layer) at the Si - αGaSe boundary during thermal evaporation. This fact is evident from the VFC extracted at different temperatures $C^2 \sim f(U)$. Figure 1 shows the VFC of the n-Si–p-GaSe structure at different temperatures. It can be seen from the figure that with increasing temperature, the dependence of $C^2 \sim f(U)$ in samples with a cold substrate (1) changes more sharply than in thermally annealed samples. The reason for this may be the high concentration of unstable defects.

Figure 2 shows the thermally annealed volt-ampere characteristics of the n-Si – p-GaSe structure at different temperatures.

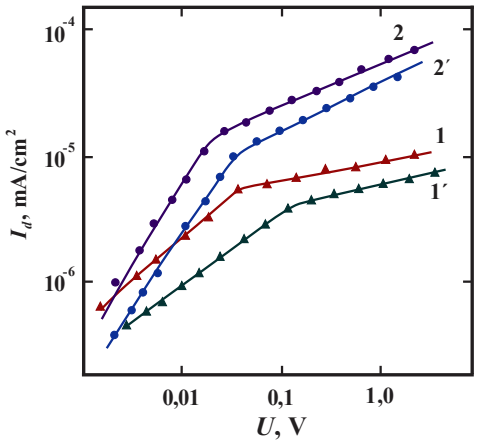

Figure 2. Current-voltage characteristics of the n-Si – p-GaSe structure (at different temperatures: T = 100 K (1' and 2'), T = 300 K (1 and 2), 1 and 1' GaSe obtained on a cold layer substrate, and 2 and 2' - a GaSe layer at a temperature of T = 473 K

It can be seen from Figure 2 that at temperature T = 300 K and at low voltages, the dependence of $I \sim f(U)$ obeys the law $I \sim \exp(eU/\beta kT)$ (β = 2-3), and at high voltages obey the law (0.3-0.4 V) $I \sim AU^m$ (m = 1.5-2). At low temperature (100 K), due to the increase of the voltage drop in the crystal, the Volt-Ampere characteristics (VAC) shift towards the high voltage region, but the exponential regularities are preserved. The analysis of the obtained experimental results shows that the rectifier capacitance of the p-n junction obtained on a cold substance is lower than that of the annealed

layer since the layer obtained on the cold substance is in an amorphous state. Crystallization centers formed in the amorphous layer during thermal annealing led to improvement of the current rectification property. Figure 3 shows the VAC opposite direction of the n-Si − p-GaSe structure at different temperatures. It can be seen from the figure (curves 1, 2) that the current in the thermally annealed sample (curve 1) obeys the law of $I \sim U^m$.

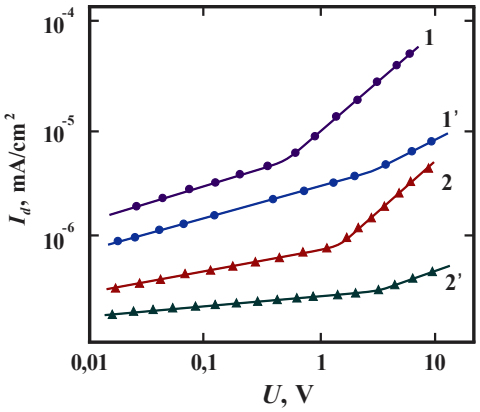

Figure 3. VAX of n-Si−p-GaSe structures in the opposite direction. T = 100 K (1', 2''), T = 300 K (1, 2), 1-1' GaSe layer obtained on a cold substrate, 2-2' – GaSe layer at T = 473 K

The slope of the dependence I ~ f(U) consists of two parts. In the region of U = 0-8 V, the diode coefficient is m ~ 1.1, and in the high voltage region it is m ~ 1.5. In the amorphous layered structure (2), small deviations are observed at values of reverse voltage U > 10 V, and the diode coefficient is close to m ~ 1. This may be due to the high layer and small barrier capacity of the layer, as shown in [19,22].

The VAC analysis of the n-Si-p-GaSe structure shows that the current flow mechanism in anisotropic n-Si-p-GaSe structures depends on the value of the contact potential difference that forms the area of bulk charges. As shown in [23], due to the high density of state in the vicinity of Fermi level (~10^{18} cm^{-3}), the height of the potential barrier decreases as a result of the change of the potential and electric field distribution in the area of bulk charges. This leads to a deterioration in the quality factor of the p-n junction relative to the structure undergoing crystallization.

Figure 4 shows the spectral characteristics of n-Si − p-GaSe structures (1,2- heated substrate; 3,4 cold substrate, GaSe surface illuminated) T = 300 K.

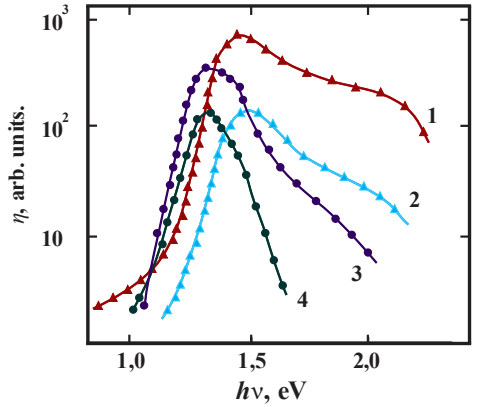

Figure 4. Spectral characteristics of n-Si/p-GaSe structures (1 – heated substrate; cold substrate, illuminated GaSe surface; 3 - heated cold substrate: cold substrate, surface illuminated from the Si side)

From curve 1 in Figure 4, it can be seen that the "window effect" observed in the spectral range of 1.0-3.0 eV during illumination from the wide-band surface of the heterojunction obtained on the heated substrate is related to the forbidden gap of the compounds. The width of the photosensitive region of the spectrum observed at the maximum photosensitivity $h\nu$ = ~1.5 eV was ΔS ~ 70-800 meV. the sharp decrease in photocurrent at values of hν > 2.6 eV is due to the decrease in interband electron transitions. As can be seen from curve 2 in Figure 4 the photosensitivity of the heterojunction formed on the cold substrate decreases compared to curve 1 and reaches its maximum value at hν = 1.5 eV. The half-width of the spectrum decreases and becomes ΔS ~ 45-500 meV. The shortening of photosensitivity and spectral range is due to high electroactive local defect density at the contact boundary [23].

The photosensitivity and spectral width decrease when the heterojunction formed on the heated substrate during illumination from the Si side (3rd curve in Figure 4). In this case, the energy corresponding to the maximum value of the photocurrent shifts to the lower energy region and becomes hν = 1.2 eV. When the heterojunction formed on the cold substrate and is illuminated from the Si side, the obtained spectrum shifts to the long-wave region (curve 4) and the the

short-wavelength border of photosensitivity corresponds to the band gap of the Si substrate. As can be seen from Figure 4, the red border of the spectral characteristics of n-Si − p-GaSe structures is determined by the forbidden gap of the substrate. Kinetic analysis of photocurrents in anisotropic n-Si − p-GaSe structures shows that the mechanism of photoconductivity depends on the distribution density of defects at the amorphous-crystalline boundary (HJ). Photosensitivity is reduced because photocarriers in the HJ, formed in a cold substrate illuminated from a wide bandgap, are trapped by local high-density levels formed at the interface. After thermal annealing (Fig. 4. curve 1) due to the orderly distribution of electroactive defects in the area of bulk charges, the height of the potential barrier for the main charge carriers increases (Fig. 1) and the photosensitivity of HJ increases several times. With the applying of an external voltage to HJ- (direct or opposite direction), the Fermi level position in the region of bulk charges changes, as well as the height of the potential barrier, as a result of which the diffusion and drift velocities of charge carriers are change. This causes a redistribution of charged defects in the area of bulk charges. From the comparison of the volt-farat characteristics of n-Si-p-GaSe structures, it can be seen that the processes occurring at the boundary during the amorphous GaSe - Si contact depend on the distribution of the electroactive density of states localized in the vicinity of the Fermi level. Considering that broken bonds in amorphous layers are sensitive to external influences (temperature, electric field, ionizing rays), their recovery process is accelerated during thermal annealing and due to the redistribution of electroactive local levels, occurs equilibrium in the area of bulk charges. This leads to an increase in the height of the potential barrier in the structure.

To clarify the current flow mechanism, the zone diagram of the studied heterojunction was built according to Anderson's model (Figure 5).

Since there is no information about the electron affinity parameter for the GaSe layer, the main parameters of the zone diagram –breakdown (ΔE_c and ΔE_V) were calculated according to the experimental values of the diffusion potential (V_{d1} and V_{d2}) taking into account the Fermi level of the components and the energy values of the forbidden gap. For the calculation, the electron affinity $\chi_n = \chi_p = 3.6$ eV for the GaSe crystal was used [22,23]. Based on the results of the mentioned literature, the breakdowns of the energy zones for the nSi-aGaSe heterojunction were calculated for conduction and valence bands $\Delta Ec \sim 1.55$ eV, $\Delta E_v \sim 0.15$ eV respectively. The high density of state at the contact boundary of the HJ, formed based on the used model, is due to the incompatibility of the structural parameters of the components. Since partial crystallization is observed in the a-GaSe layer during thermal annealing, the photosensitivity of the structure increases due to a decrease in the density of states of the surface. The obtained results correspond to the values given for InSe − GaSe and Si − GaSe in [15,17].

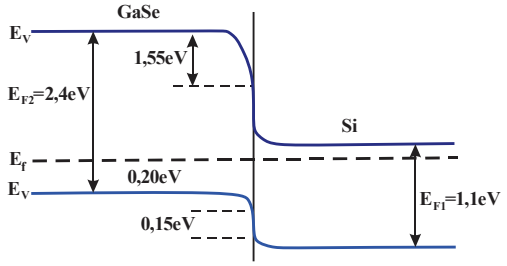

Figure 5. Band energy diagram of the n-Si-p-GaSe heterojunction

4. CONCLUSİONS

Thus, based on VFC, the influence of the charge density distribution on the electrostatic parameters in the region of bulk charges in a heterostructure formed based on amorphous GeSe and crystalline n-Si was determined. It was found that an increase in the contact potential difference in the dependence of $C^2 \sim f(V)$ for thermally annealed n-Si − p-GaSe sample is due to reduce the density of states near the Fermi level (from ~10^{19} $eV^{-1}cm^{-1}$ to 10^{16} $eV^{-1}cm^{-1}$) in the amorphous GaSe layer. In an amorphous GaSe layer, the distribution of potential and electric field intensity in the region of bulk charges changes due to the presence of the density of states of charged local levels located in the vicinity of the Fermi level. As a result of a decrease in the density of states at the contact boundary during thermal annealing, the intensity in the bulk charge region decreases, and the width of the region of bulk charges and the height of the potential barrier increase from 0.4 to 0.8. eV.

ORCID

Narmin A. Ismayilova, https://orcid.org/0000-0002-5388-4175; **Sakin H. Jabarov,** https://orcid.org/0000-0002-3153-5804

REFERENCES

[1] S.H. Jabarov, N.A. Ismayilova, D.P. Kozlenko, T.G. Mammadov, N.T. Mamedov, H.S. Orudzhev, S.E. Kichanov, et al., "Structural and elastic properties of $TlInSe_2$ at high pressure," Solid State Sciences, **111**, 106343 (2021). https://doi.org/10.1016/j.solidstatesciences.2020.106343

[2] Y.I. Aliyev, Y.G. Asadov, T.M. Ilyasli, F.M. Mammadov, T.G. Naghiyev, Z.A. Ismayilova, M.N. Mirzayev, and S.H. Jabarov, "Structural aspects of thermal properties of AgCuS compound," Modern Physics Letters B, **34**(05), 2050066 (2020). https://doi.org/10.1142/S0217984920500669

[3] A.S. Alekperov, S.H. Jabarov, M.N. Mirzayev, E.B. Asgerov, N.A. Ismayilova, Y.I. Aliyev, T.T. Thabethe, and N.T. Dang, "Effect of gamma irradiation on the microstructure of the layered $Ge_{0.995}Nd_{0.005}S$," Modern Physics Letters B, **33**(09), 1950104 (2019). https://doi.org/10.1142/S0217984919501045
[4] N.N. Mursakulov, N.N. Abdulzade, S.H. Jabarov, and Ch.E. Sabzalieva, "Investıgatıon of $CuIn_{1-x}Ga_xSe_2$ thin films for solar cells obtaıned by the magnetron sputterıng method from two magnetrons shıfted to each other," New Materials, Compounds and Applications, **6**(2), 140-147 (2022). http://jomardpublishing.com/UploadFiles/Files/journals/NMCA/v6n2/Mursakulov_et_al.pdf
[5] S.H. Jabarov, "First principles study of structural phase transition in Ag_2S under high pressure," Integrated Ferroelectrics, **230**, 23-28 (2022). https://doi.org/10.1080/10584587.2022.2102794
[6] Y.I. Alıyev, F.G. Asadov, T.M. Ilyaslı, A.O. Dashdemirov, R.E. Huseynov, and S.H. Jabarov, "Vibrational properties of $YbAs_2S_4$ and $YbAs_2Se_4$ compounds: by infrared spectroscopy," Ferroelectrics, **599**, 78-82 (2022). https://doi.org/10.1080/00150193.2022.2113641
[7] B.G. Tagiyev, O.B. Tagiyev, A.I. Mammadov, V.X. Quang, T.G. Naghiyev, S.H. Jabarov, M.S. Leonenya, et al., "Structural and luminescence properties of $Ca_xBa_{1-x}Ga_2S_4$: Eu^{2+} chalcogenide semiconductor solid solutions," Physica B: Condensed Matter, **478**, 58-62 (2015). https://doi.org/10.1016/j.physb.2015.08.061
[8] Sh.B. Utamuradova, Sh.Kh. Daliev, D.A. Rakhmanov, A.S. Doroshkevich, V.A. Kinev, O.Yu. Ponomareva, M.N. Mirzayev, et al., "IR – spectroscopy of n-Si<Pt> ırradıated wıth protons," Advanced Physical Research, **5**(2), 73-80 (2023). http://jomardpublishing.com/UploadFiles/Files/journals/APR/V5N2/Utamuradova_et_al.pdf
[9] A.S. Alekperov, A.O. Dashdemirov, N.A. Ismayilova, and S.H. Jabarov, "Fabrication of a Ge–GeS: Nd heterojunction and investigation of the spectral characteristics, Semiconductors," **54**, 1406-1409 (2020). https://doi.org/10.1134/S1063782620110044
[10] Sh.B. Utamuradova, D.A. Rakhmanov, A.S. Doroshkevich, I.G. Genov, Z. Slavkova, and M.N. Ilyina, "Impedance spectroscopy of p-Si<Pt>, p-Si<Cr> ırradıated wıth protons," Advanced Physical Research, **5**(1), 5-11 (2023). http://jomardpublishing.com/UploadFiles/Files/journals/APR/V5N1/Utamuradova_et_al.pdf
[11] G.A. Akhundov, N.A. Gasanova, and M.A. Nazametdinova, "Optical absorption, reflection and dispersion of GaS and GaSe layer crystals," Physica Status Solidi b, **15**, k109- k102 (1966). https://doi.org/10.1002/PSSB.19660150249
[12] A.G. Kazım-zade, A. Mokhtari, I. Hympanova, V.M. Salmanov, Yu. Asadov, and A.A. Agaeva, "Influence of stacking disorder on the optical properties of layered crystals GaSe," Acta Physica Universitatis Comenianae, **XLVI-XLVII**, 101-108 (2005-2006). https://dai.fmph.uniba.sk/~lucan/apuc/_vol46-47/Apuc12.pdf
[13] P.A. Hu, Z.Z. Wen, L.F. Wang, P.H. Tan, and K. Xiao, "Synthesis of few-layer GaSe nanosheets for high performance photodetectors," ACS Nano, **6**, 5988–5994 (2012). https://doi.org/10.1021/nn300889c
[14] T. Kushida, F. Minami, Y. Oka, Y. Nakazaki, and Y. Tanaka, "Edge emission in GaSe and GaS," Nuovo Cimento B, **39**, 650-654 (1977). https://doi.org/10.1007/BF02725806
[15] A.G. Kyazym-zade, M. Karabulur, A.Kh. Dincher, V.M. Salmanov, M.A. Dzhafarov, A.M. Guseinov, and R.M. Mamedov, "Structure, optical, and luminescent properties of GaSe nanoparticles," Nanotechnologies in Russia, **10**, 794-801 (2015).
[16] Yu.A. Nikolaev, V.Yu. Rud', Yu.V. Rud', and E.I. Terukov, "Photoelectric phenomena in a-Si:H/p-$CuInSe_2$ heterostructures," Semiconductors, **34**, 658-661 (2000). https://doi.org/10.1134/1.1188049
[17] V.N. Brudnyi, S.Yu. Sarkisov, and A.V. Kosobutsky, "On the charge neutrality level and the electronic properties of interphase boundaries in the layered ε-GaSe semiconductor," Semiconductors, **49**, 1307-1310 (2015). https://doi.org/10.1134/S1063782615100061
[18] S.E. Aleksandrov, T.A. Gavrikova, and V.A. Zykov, "Photoelectric properties of isotype and anisotype Si/GaN:O heterojunctions," Semiconductors, **34**, 1295-1300 (2000). https://doi.org/10.1134/1.1325426
[19] L.S. Berman, *Capacitive methods for the study of semiconductors*, (Nauka, Leninqrad, 1972). (in Russian)
[20] J Martínez-Pastor, A. Segura, J.L. Valdes, and A. Chevy, "Electrical and photovoltaic properties of indium - tin - oxide/p - InSe/Au solar cells," Journal of Applied Physics, **62**(4), 1477-1483 (1987). https://doi.org/10.1063/1.339627
[21] A. Milns, and D. Feucht, *Heterojunctions and metal-semiconductor transitions*, (Mir, Moscow, 1975). (in Russian)
[22] R.R. Daniels, G. Margaritondo, C. Quaresima, P. Perfetti, and F. Levy, "Summary Abstract: GaSe - Ge and GaSe - Si: two possible examples of schottky-like behavior of heterojunction interfaces," Journal of Vacuum Science Technology A, **3**(3), 979-980 (1985). https://doi.org/10.1116/1.573369
[23] N.V. Vishnyakov, S.P. Vikhrov, V.G. Mishustin, A.P. Avachev, I.G. Utochkin, and A.A. Popov, "Formation of potential barriers in undoped disordered semiconductors," Semiconductors, **39**, 1147-1152 (2005). https://doi.org/10.1134/1.2085261

ОТРИМАННЯ ГЕТЕРОПЕРЕХОДІВ N-Si-P-GaSe НА ОСНОВІ АМОРФНОГО GaSe ШАРУ БЕЗ ДОМІШОК ТА ДОСЛІДЖЕННЯ ЇХ ЕЛЕКТРИЧНИХ ВЛАСТИВОСТЕЙ

Рахім Салім Мадатов[a], А.С. Алекперов[b], Ф.Н. Нурмаммадова[c], Нармін А. Ісмаілова[d,e], Сакін Х. Джабаров[a]
[a]Інститут радіаційних проблем Міністерства науки і освіти Азербайджанської Республіки, Баку, AZ-1143, Азербайджан
[b] Азербайджанський державний педагогічний університет, Баку, AZ-1000, Азербайджан
[c] Бакинський інженерний університет, Хирдалан, AZ-0101, Азербайджан
[d] Інститут фізики Міністерства науки і освіти Азербайджанської Республіки, Баку, AZ-1143, Азербайджан
[e]Західно-Каспійський університет, Баку AZ-1001, Азербайджан

Досліджено електричні та фотоелектричні властивості анізотипних гетеропереходів n-Si−p-GaSe, отриманих в результаті осадження тонкого шару GaSe на холодну монокристальну підкладку n-Si методом термічного випаровування. Визначено, що підвищення висоти потенційного бар'єру в структурах термічного відпалу при T = 200 °C протягом t = 3 годин відбувається за рахунок зменшення густини станів локальних рівнів, розташованих поблизу рівня Фермі в аморфному шарі. Проаналізовано механізм фоточутливості в ізотипних гетероструктурах і встановлено, що фоточутливість гетероперехоу підвищується в результаті зменшення поверхневої щільності стану на межі контакту компонентів термічним шляхом. Досліджено спектральний розподіл квантової ефективності в гетеропереході n Si – p GaSe та визначено їх перспективу.

Ключові слова: *GaSe; тонка плівка; гетероперехід; електрофізичні властивості*