East European Journal of Physics. **3.** 298-302 (2024)
DOI:10.26565/2312-4334-2024-3-31 ISSN 2312-4334

PHOTOELECTRIC CHARACTERISTICS OF THE HETEROJUNCTION *n*-GaAs-*p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$

Akramjon Y. Boboev[a,b]
[a]*Andijan state university named after Z.M. Babur, Andijan, Uzbekistan*
[b]*Institute of Semiconductor Physics and Microelectronics at the National University of Uzbekistan, 20 Yangi Almazar st., Tashkent, 100057, Uzbekistan*
Corresponding Author e-mail: e-mail: aboboevscp@gmail.com
Received April 18, 2024; revised June 29, 2024; accepted July 3, 2024

The photoelectric properties of *n*-GaAs – *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ heterostructures have been investigated both in photodiode and photovoltaic modes. It has been revealed that the spectral dependence of the photocurrent covers a wide range of energy intervals, ranging from 1.07 eV to 3 eV. It has been demonstrated that as the temperature of the crystallization onset (T_{oc}) increases, the peaks of the spectral dependencies of the photoelectromotive force (photo-EMF) shift towards shorter wavelengths. It has been observed that as the crystallization onset temperature (T_{oc}) of the solid solution layer $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ increases, the lifetime of photo carriers increases from 10^{-7} s at T_{oc}=650°C to $5\cdot10^{-5}$ s at T_{oc}=730°C. It is demonstrated that the peaks of the intrinsic photoluminescence band shift towards shorter wavelengths with an increase in the temperature of the crystallization onset. Additionally, the study of the intrinsic spectral region of photoluminescence in samples across the thickness of the epitaxial layer confirms the variability of the obtained structures.
Keywords: *Solid solution; Heterostructure; Temperature; Photoelectric property; Photo-EM; Photoluminescence; Photo carriers; Varizon structure*
PACS: 73.40. Lq, 78.20. –e, 81.05. Hd

INTRODUCTION

Semiconductors A^3B^5 and A^2B^6 are well known as promising materials for creating optoelectronic devices in the infrared and visible spectrums. Intensive research is being carried out to create various electronic devices based on GaP, GaAs, CdTe, ZnSe and their solid solutions [1-4]. Among these materials, GaAs-based compounds are of particular interest, as their electron and hole mobilities are much higher [5-9], thus enabling them to be used in high-speed optoelectronic devices. In addition, solid substitution solutions $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ make it possible to expand the spectral range of functioning of structures based on them to 400 nm [10, 11]. However, the mass use of device structures made on the basis of the A^3B^5 compound is limited, on the one hand, by the economic inexpediency of large-scale use of such device structures, and on the other hand, by insufficient knowledge of the photoelectric properties of such materials and heterojunctions based on them.

In this regard, this work reports the results of studies of some photoelectric properties of the *n*-GaAs - *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ heterojunction, which was synthesized by growing epitaxial layers from solid solutions $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ on an n-GaAs substrate oriented in the (100) direction.

MATERIALS AND METHODS

The growth processes of epitaxial layers were carried out from a limited volume of tin solution-melt on a GaAs substrate using forced cooling method. The thicknesses of the resulting films varied within 10-15 μm depending on the size of the gap between the substrates and the growth mode. X-ray diffraction patterns of layers $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$, taken on a third-generation diffractometer of the Empyrean Malvern PANalytical L.T.D type, confirmed that the grown layers have a sphalerite crystal lattice and are characterized by the lowest mechanical stresses, both in volume and near the interface of the layers.

The lux-volt characteristics were measured on a setup that can simulate sunlight. A 150 W tungsten incandescent lamp was used as the radiation source. The illuminance measurements were conducted using a digital illuminance meter, MASTKCH LUXMETER MS6610.

An investigation was conducted to analyze the spectral sensitivity of the samples by employing an optical spectrometer that featured a CARLZEISJENA mirror monochromator with quartz optics. This sophisticated setup allowed for the examination of the samples within the photon energy range of 1 to 3 eV.

The photoluminescence spectrum of the samples was studied at the KSVU-23 installation. Optical pumping of the surface of the epitaxial layer at a temperature of 300 K was carried out by a mercury lamp, the signal was recorded on the SDL-2 installation.

RESULTS AND DISCUSSION

The surfaces of the epitaxial layers of $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ solid solutions had p- type conductivity with Hall carrier concentrations $p=5\cdot10^{17}$ sm^{-3}. The literature highlights that the ZnSe epitaxial layer typically exhibits n-type

Cite as: A.Y. Boboev, East Eur. J. Phys. 3, 298 (2024), https://doi.org/10.26565/2312-4334-2024-3-31

conductivity as a result of the self-compensation effect under standard conditions [12]. We successfully produced epitaxial films containing the chemical composition $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ that exhibited p-type conductivity. Based on quantum chemical concepts, the possibility of increasing the binding energy of selenium in the composition of the Se-Ge dumbbell structure located at the nodes of the crystal lattice of the $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ solid solution compared with the nodal position in the crystalline ZnSe lattice. This can lead to a significant reduction in the number of V_{Se} vacancies, which usually lead to the appearance of electronic conductivity in ZnSe. In addition, part of the vacancies in the selenium V_{Se} sublattice in solid solutions can be occupied by Ge atoms, which also leads to a decrease in the number of V_{Se} vacancies. It is assumed that the appearance of epitaxy layers of a solid solution of the $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ type during the formation of the *n*-GaAs – *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ heterostructure is associated with partial dissolution GaAs substrates.

The photovoltaic properties of the obtained structures were studied by both photovoltaic and photodiode methods at a temperature of 300K. The surface was illuminated from the side of the solid solution. The lux-ampere characteristics of the structures, obtained under integral light illumination, have shown that the dependence of the short-circuit current (I_{sc}) on the illuminance exhibits a nonlinear relationship in the initial region. In other words, an increase in the incident light intensity leads to a wave-like increase in I_{sc}. This phenomenon may be attributed to changes in the parameters of the contacting semiconductors under the influence of the light flux, such as the lifetime of non-majority charge carriers and the diffusion length (Fig. 1). With increasing intensity of the incident light, the open-circuit EMF tended to saturate, reaching a value of 0.6 V, which may be due to the impossibility of reducing the thickness of the transition layer between the epitaxial film and the substrate under the influence of incident light.

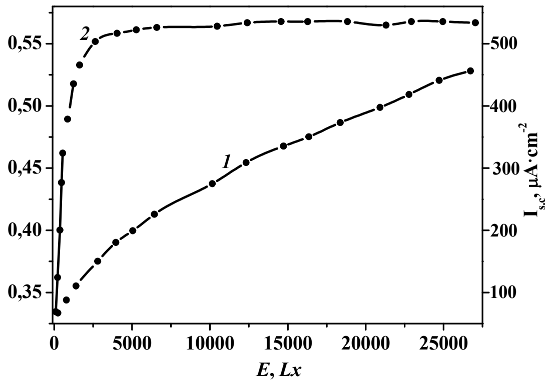

Figure 1. The dependence of the short-circuit current (1-curve) and the no-load EMF (2-curve) on the illumination by integral light

The lifetime of photocarriers in structures grown under various conditions is determined by the relaxation decay of the photo-EMF. The investigation revealed that as the temperature of the onset of crystallization (T_{oc}) of the $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ solid solution layer rose, the lifetime of photo carriers extended from 10^{-7} seconds at T_{oc} = 650°C to $5\cdot10^{-5}$ seconds at T_{oc}=730 °C. The spectral characteristics of $I_{s.c.}$(short-circuit current) and $U_{o.c.}$ (open-circuit voltage), as well as the photocurrent were measured in the photodiode mode. Monochromatic radiation was carried out from the solid solution $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$. Measurement of the spectral dependence of photocurrent in photodiode mode (Fig. 2, curves *a* and *b*) showed that it covered a wide range of incident photon energies from 1.07 to 3.0 V.

From Fig. 2, it can be seen that the spectrum of photodetectors in the energy range of 1-3 eV is characterized by six peaks with maximums at photon energies (eV): 1-at 1.37, 2-1.47, 3-1.65, 4-1.88, 5-2.3, 6-2.62 (Figure 2a).

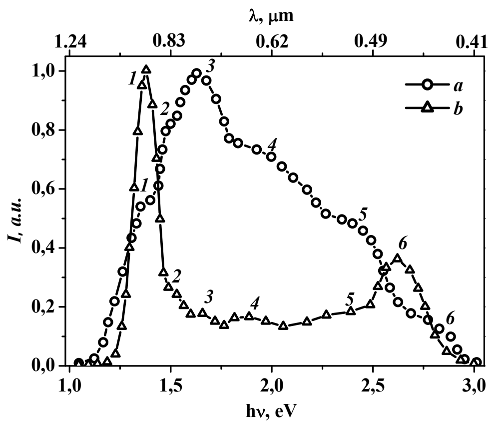

Figure 2. Spectral dependence of the photocurrent of the *n*-GaAs – *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ structure obtained in photodiode mode at various crystallization onset temperatures: *a* - T_{oc} = 730°C, *b* - T_{oc} = 650°C.

In curve b, Figure 2. the spectrum begins at a photon energy of 1.07 eV, which may be due to the bonding energy of paired Ge atoms, which partially substitute some of the gallium arsenide molecules and create the corresponding energy level [13]. Additionally, impurity germanium atoms self-organize into nanocrystals in defectable regions of the gallium arsenide lattice [10], forming their own energy level with an acceptor-like characteristics [10]. At a photon energy of 1.48 eV, a photopic corresponding to recombination from the conduction band to acceptor states in p-GaAs is observed [11]. The maximum of the spectral sensitivity dependence is observed at 1.64 eV, which may be due to the structural bandgap of the valence zone and isovalent impurities of Ge-Se compounds in the GaAs layer [14]. The following photopic peaks, curve *b*, Fig. 2, corresponding to photon energies of 1.89, 2.18, and 2.67 eV, may be attributed to compounds GaSe ($h\nu_{max}$ = 1.88 eV), ZnAs ($h\nu_{max}$ = 2.15 eV), and ZnSe ($h\nu_{max}$ = 2.69 eV) with deep levels in the valence zone of gallium arsenide [12].

The spectral dependencies of the photo-EMF of heterostructures *n*-GaAs – *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ are shown in Figure 3. It can be seen that the peaks of the spectral dependencies, characterized by the crystallization onset temperatures, shift towards the short-wavelength region with increasing displacement. Since carrier separation occurs in the solid solution $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ at the *p-n* junction, such mixing is likely associated with a decrease in the germanium content relative to ZnSe at the heterojunction boundary in the solid solution and an increase in the epitaxial onset temperature. Although the radiation falls on the side of the solid solution, some carriers generated from the surface of the solid solution at high energies of incident photons likely recombine without reaching the p-n junction boundary, where their separation occurs. Therefore, in almost all investigated cases of photo-EMF, a decrease in photosensitivity is observed in the short-wavelength region of the spectral dependence of photo-EMF. Some difference in the values of photosensitivity observed in the short-wavelength region for different samples can be explained by differences in film thickness.

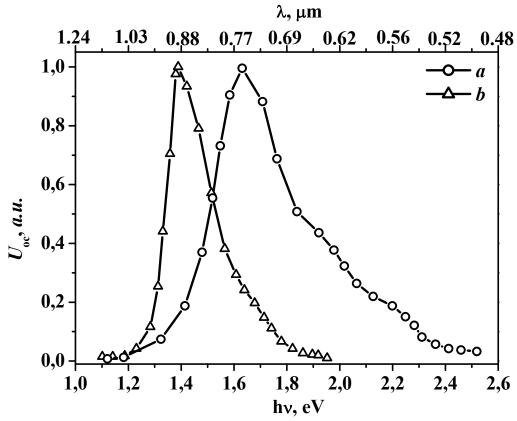

Figure 3. Spectral dependence of the open-circuit photo-EMF of the structures *n*-GaAs – *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ obtained at different crystallization onset temperatures: *a* - T_{oc} = 730°C, *b* - T_{oc} = 650°C.

Also, investigations of photoluminescence were conducted on the solid solutions $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ obtained by us in their intrinsic spectral range. Samples obtained at different crystallization onset temperatures were subjected to measurement. Scanning of the samples was performed on the surface of epitaxial layers. Optical pumping of the surface layers at a temperature of 300 K was performed using a mercury lamp.

Meanwhile, upon visual observation, luminescent glow ranging from green to blue was detected on the surface of epitaxial layers, depending on the sample conditions. By scanning the surface of the films in various directions, it was also possible to approximately visually assess the condition of the sample surfaces based on color and the uniformity of luminescence. In the photoluminescence spectra obtained by continuous recording (Figure 4 - *a* and *b*), it was found that the peaks of the intrinsic photoluminescence bands shift towards the short-wavelength region with increasing crystallization onset temperature.

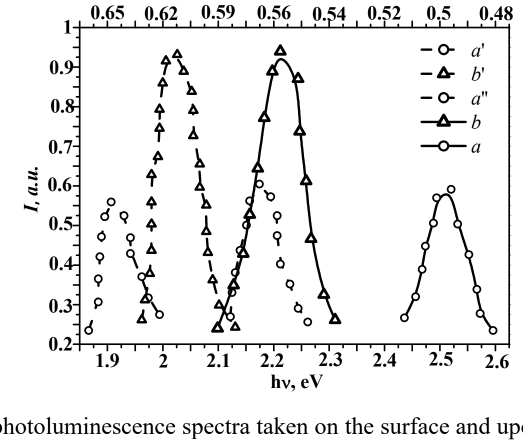

Figure 4. Intrinsic spectral range of photoluminescence spectra taken on the surface and upon sequential removal of the surface of epitaxial layers (*a*', *a*'', *b*'): a - T_{oc} = 730°C, b - T_{oc} = 650°C.

Investigating the photoluminescence spectrum of the solid solution $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ it was found that with the removal of surface layers, the peaks of the intrinsic band shift towards the long-wavelength region (Figure 4 - *a*', *a*", and *b*'). The research [15] demonstrated that in the solid solution, the zinc selenide content increases along the growth direction, consequently leading to an increase in the width of the bandgap.

Thus, the dependence of the bandgap width on the composition of germanium and zinc selenide in the volume of solid solution has a non-monotonic character, and the obtained solid solutions exhibit varizon structures. The bandgap widths, estimated from the photoluminescence spectra for the two specified samples, were 2.51 and 2.21 eV.

CONCLUSIONS

Thus, the photoelectric properties of *n*-GaAs – *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ heterostructures have been investigated both in photodiode and photovoltaic modes. It has been found that the spectral dependence of the photo-current covers a wide range of energy intervals from 1.07 eV to 3 eV. It has been demonstrated that with an increase in the temperature of the crystallization onset (Toc), the peaks of the spectral dependencies of the photo-electromotive force (photo-EMF) shift towards shorter wavelengths. It has been discovered that with an increase in the temperature of the crystallization onset (Tc) of the solid solution layer $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$, the lifetime of photo-carriers increases from 10^{-7} s at $T_{oc} = 650°C$ to $5\cdot10^{-5}$ s at $T_{oc} = 730°C$. Investigation of the photoluminescence on the surface of epitaxial layers $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$, it has been shown that the peaks of the intrinsic photoluminescence band shift towards shorter wavelengths with increasing crystallization onset temperature. Additionally, investigation of the intrinsic spectral range of photoluminescence in samples through the thickness of the epitaxial layer confirms the varizonality of the obtained structures.

Funding

The work was carried out using project funds allocated according to the order of the rector of Andijan State University dated February 7, 2024, No. 04-12.

ORCID

Akramjon Y. Boboev, https://orcid.org/0000-0002-3963-708X

REFERENCES

[1] W. Yang at. el, "Pseudobinary Solid-Solution: An Alternative Way for the Bandgap Engineering of Semiconductor Nanowires in the Case of GaP–ZnSe," Advanced Functional Materials, **25**(17), 2543 (2015). https://doi.org/10.1002/adfm.201404523

[2] A. Kosarev, V. Chaldysheva, V. Preobrazhenskii, M. Putyato, and B. Semyagin. "Effect of a Low-Temperature-Grown GaAs Layer on InAs Quantum-Dot Photoluminescence," Semiconductors, **50**(11)**,** 1519 (2016). https://doi.org/10.1134/S1063782616110154

[3] M. Szot, et al. "Experimental and Theoretical Analysis of PbTe-CdTe Solid Solution Grown by Physical Vapour Transport Method," Acta Physica Polonica A, **116**(5), 959 (2009).

[4] A. Reznitskya, A. Klochikhina, and M. Eremenko. "Thermally Activated Resonance Tunneling in Asymmetric Systems of CdSe/ZnSe Double Quantum Wells with Self Assembled Quantum Dots," Semiconductors, **48**(3)**,** 345 (2014). https://doi.org/10.1134/S1063782614030221

[5] A. Sharma, and T. Das. "Electronic band structure and optical properties of GaAsSb/GaAs for optoelectronic device applications: A 14 band k.p study," Optical Materials, **112,** 110734 (2021). https://doi.org/10.1016/j.optmat.2020.110734

[6] P. Sanmartin, F. Almonacid, M. Ceballos, A. Garcia-Loureiro, and E. Fernandez, "Wide-bandgap III-V materials for high efficiency air and underwater optical photovoltaic power transmission," Solar Energy Materials and Solar Cells, **266**, 112662 (2024). https://doi.org/10.1016/j.solmat.2023.112662

[7] A. Yachmenev, S. Pushkarev, R. Reznik, R. Khabibullin, and D. Ponomarev, "Arsenides-and related III-V materials-based multilayered structures for terahertz applications: Various designs and growth technology," Progress in Crystal Growth and Characterization of Materials, **66,** 100485 (2020). https://doi.org/10.1016/j.pcrysgrow.2020.100485Get rights and content

[8] N. Papez, R. Dallaev, ¸S. Talu, and J. Kastyl. "Overview of the Current State of Gallium Arsenide-Based Solar Cells (Review)," Materials, **14,** 3075 (2021). https://doi.org/10.3390/ma14113075

[9] J. Geisz, R. France, K. Schulte, M. Steiner, A. Norman, H. Guthrey, M. Young, et al., "Six-junction III–V solar cells with 47.1% under 143 Suns concentration," Nat. Energy, **5**(4), 326–335 (2020). https://doi.org/10.1038/s41560-020-0598-5

[10] S. Zaynabidinov, A. Saidov, A. Boboev, and D. Abdurahimov, "Structure, Morphology and Photoelectric Properties of n-GaAs-p-$(GaAs)_{1-x}(Ge_2)_x$ Heterostructure," Herald of the Bauman Moscow State Technical University, Series Natural Sciences, **100**(1), 72-87 (2022). https://doi.org/10.18698/1812-3368-2022-1-72-87

[11] S. Zainabidinov, A. Saidov, M. Kalanov, and A. Boboev, "Synthesis, Structure and Electro-Physical Properties n-GaAs–p-(GaAs)1–x–y(Ge2)x(ZnSe)y Heterostructures (Review)". Applied Solar Energy, **55**, 291–308 (2019). https://doi.org/10.1038/s41560-020-0598-510.3103/S0003701X1905013X

[12] S. Suprun, V. Sherstyakova, and E. Fedosenko. "Epitaxial Growth of ZnSe on GaAs with the Use of the ZnSe Compound as the Source". Semiconductors, **43**(11),1526–1531(2009) https://doi.org/10.1134/S1063782609110220

[13] S. Khludkov, O. Tolbanov, M. Vilisova, and I. Prudaev, *Semiconductor devices based on gallium arsenide with deep impurity centers*, (Publishing House of Tomsk State University, Tomsk, 2016).

[14] D. Bletskan, J. Madyar, and V. Kabaciy, "Effect of Nonstoichiometry and Doping on the Photoconductivity Spectra of GeSe Layered Crystals," Semiconductors, **40**(2), 137–142 (2006) https://doi.org/10.1134/S1063782606020047.

[15] S. Zainabidinov, Sh. Utamuradova, and A. Boboev, "Structural Peculiarities of the $(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ Solid Solution with Various Nanoinclusions," Journal of Surface Investigation X-ray Synchrotron and Neutron Techniques, **16**(6), 1130-1134 (2022). https://doi.org/10.1134/S1027451022060593

ФОТОЕЛЕКТРИЧНІ ХАРАКТЕРИСТИКИ ГЕТЕРОПЕРЕХОДУ n-GaAs-p-(GaAs)1-x-y(Ge2)x(ZnSe)y

Акрамжон Ю. Бобоєв[a,b]
[a]*Андижанський державний університет імені З.М. Бабур, Андижан, Узбекистан*
[b]*Інститут фізики напівпровідників та мікроелектроніки Національного університету Узбекистану,*
100057, вул. Янги Алмазар, 20, Ташкент, Узбекистан

Досліджено фотоелектричні властивості гетероструктур *n*-GaAs – *p*-$(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ як у фотодіодному, так і у фотоелектричному режимах. Виявлено, що спектральна залежність фотоструму охоплює широкий діапазон енергетичних інтервалів від 1,07 еВ до 3 еВ. Показано, що з підвищенням температури початку кристалізації (Toc) піки спектральних залежностей фотоелектрорушійної сили (фото-ЕРС) зміщуються в бік коротших довжин хвиль. Було помічено, що зі збільшенням температури початку кристалізації (T_{oc}) шару твердого розчину $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ час життя фотоносіїв збільшується з 10^{-7} с при T_{oc}= 650°C до $5\cdot10^{-5}$ с при T_{oc}=730°C. Показано, що піки власної смуги фотолюмінесценції зміщуються в бік коротших довжин хвиль зі збільшенням температури початку кристалізації. Крім того, дослідження власної спектральної області фотолюмінесценції зразків по товщині епітаксійного шару підтверджує варіабельність отриманих структур.

Ключові слова: *твердий розчин; гетероструктура; температура; фотоелектричні властивості; фото-ЕМ; фотолюмінесценція; фотоносії; варізонна структура*