Original article
DOI: https://doi.org/10.18721/JPM.19209

RADIATION DEFECT FORMATION DURING SEQUENTIAL ION BOMBARDMENT OF ALPHA-GALLIUM OXIDE

A. I. Klevtsov[1,2]✉, *P. A. Karaseov*[1], *A. I. Titov*[1]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia;

[2] Joint-Stock Company "Research and Production Enterprise «ELAR»", St. Petersburg, Russia

✉ klevtsovanton@rambler.ru

Abstract. This paper presents the results of a study of radiation damage accumulation in α-Ga_2O_3 under sequential bombardment with fluorine and phosphorus ions with varying energies of the keV range. A significant effect of the ion irradiation sequence on both the number and depth distribution profile of stable defects was established. The physical nature of this noncommutativity is discussed.

Keywords: gallium oxide, ion implantation, sequential irradiation, radiation defects, Rutherford backscattering

Citation: Klevtsov A. I., Karaseov P. A., Titov A. I., Radiation defect formation during sequential ion bombardment of alpha-gallium oxide, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 19 (2) (2026) 98–106. DOI: https://doi.org/10.18721/JPM.19209

This is an open access article under the CC BY-NC 4.0 license (https://creativecommons.org/licenses/by-nc/4.0/)

Научная статья
УДК 539.1.043
DOI: https://doi.org/10.18721/JPM.19209

ОБРАЗОВАНИЕ УСТОЙЧИВЫХ РАДИАЦИОННЫХ ПОВРЕЖДЕНИЙ ПРИ ПОСЛЕДОВАТЕЛЬНОЙ ИОННОЙ БОМБАРДИРОВКЕ АЛЬФА-ОКСИДА ГАЛЛИЯ

А. И. Клевцов[1,2]✉, *П. А. Карасев*[1], *А. И. Титов*[1]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия;

[2] Акционерное общество «Научно-производственное предприятие «ЭЛАР»», Санкт-Петербург, Россия

✉ klevtsovanton@rambler.ru

Аннотация. В работе представлены результаты исследования накопления радиационных повреждений в α-Ga_2O_3 при последовательной бомбардировке ионами фтора и фосфора с различной энергией кэВ-диапазона. Установлено заметное влияние последовательности ионного облучения как на количество, так и профиль распределения устойчивых дефектов по глубине. Обсуждается физическая природа подобной некоммутативности.

Ключевые слова: оксид галлия, ионная имплантация, последовательное облучение, радиационный дефект, резерфордовское обратное рассеяние

© Klevtsov A. I., Karaseov P. A., Titov A. I., 2026. Published by Peter the Great St. Petersburg Polytechnic University.

Ссылка для цитирования: Клевцов А. И., Карасев П. А., Титов А. И. Образование устойчивых радиационных повреждений при последовательной ионной бомбардировке альфа-оксида галлия // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2026. Т. 2 № .19. С.98 –106. DOI: https://doi.org/10.18721/JPM.19209

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/)

Introduction

Ion implantation is a key process in modern semiconductor technology for selectively modifying material properties. It is well known that irradiation of semiconductors with accelerated ions always produces stable damage to the crystal lattice [1]. The extent of this radiation damage depends on several parameters, including ion mass and energy, flux density, temperature, and target composition [2, 3].

Sequential bombardment with ions of different energies and/or different chemical elements is widely used for fabricating semiconductor devices. A common example of this approach is forming a required depth distribution of dopant atoms [4]. Even though this approach is widespread, the mechanisms that determine the final degree of structural disorder in the target under sequential bombardment remain poorly understood for many semiconductors. In fact, they are virtually unexplored for such promising materials as gallium oxide.

Furthermore, it is known from the literature that defect accumulation under sequential bombardment with ions of different energies and/or types can be both non-additive and non-commutative [5–7]. Non-additivity means that the final damage profile is not simply the sum of the profiles produced by each individual irradiation with its energy and dose. Non-commutativity means that the final damage distribution can depend dramatically on the sequence in which irradiation is applied (see, e.g., data for silicon [5, 6] and gallium nitride [7]). Moreover, the second irradiation can even reduce the damage level introduced by the first implantation for certain ion combinations and bombardment sequences [8–14].

Wide-bandgap oxide semiconductors are attracting increasing attention for power electronics and optoelectronics, offering new opportunities but also calling for a deeper understanding of their radiation resistance and defect formation under accelerated ion implantation.

One of the most promising representatives of this family is gallium oxide [15–19], which exists in several polymorphic modifications [15]. The monoclinic β-phase of gallium oxide (β-Ga_2O_3), with a bandgap of about 4.8 eV, is already actively studied and introduced in the fabrication of Schottky diodes [20] and field-effect transistors [21]. The metastable rhombohedral α-phase of gallium oxide (α-Ga_2O_3) with a corundum structure has unique properties, such as

a large bandgap (up to ~5.3 eV),

and a high critical breakdown field (up to ~8 MV/cm);

moreover, it can be grown epitaxially on relatively inexpensive sapphire substrates [22, 23].

Practical devices based on α-Ga_2O_3 require reliable methods for local doping and isolation; ion implantation is the primary technique for this purpose. Thus, to lay the foundations for ion-beam modification of α-Ga_2O_3 , the mechanisms of radiation defect accumulation and annealing in this material must be understood, in particular under sequential irradiation. However, while the formation of structural disorder and radiation resistance of β-Ga_2O_3 have been studied actively in recent years [15–22, 24], data for α-Ga_2O_3 remain limited [25–27], and studies of sequential bombardment with different ion types and energies were virtually absent until recently [28].

In this work, we present the first study of radiation damage accumulation in α-Ga_2O_3 under sequential bombardment with light fluorine (F^+) and phosphorus (P^+) ions at keV energies typical of industrial applications.

© Клевцов А. И., Карасев П. А., Титов А. И., 2026. Издатель: Санкт-Петербургский политехнический университет Петра Великого.

Experimental procedure

We studied epitaxial α-Ga_2O_3 layers with a corundum structure, about 2 μm thick and with (0001) orientation, grown on the *c*-plane of a sapphire substrate by hydride vapour-phase epitaxy (HVPE) at Perfect Crystals LLC (St. Petersburg) [29]. The samples were irradiated with fluorine and phosphorus ions at room temperature using a 500 kV ion implanter (HVEE-500) at Research and Production Enterprise ELAR JSC (St. Petersburg). Irradiation was performed at an angle of 7° with respect to the [0001] crystallographic direction to minimize channeling effects in the crystal.

To ensure a valid comparison of the experimental data, radiation damage was evaluated at equal displacements per atom (DPA) generated in the target. The ion doses Φ_{DPA} were determined in the binary collision approximation as the ratio of the vacancy concentration at the maximum of the elastic energy loss profile (n_v) for a given ion fluence, calculated using the TRIM code [30], to the atomic concentration of α-Ga_2O_3 ($n_{at} = 1.03 \cdot 10^{23}$ atoms/cm^3), so that $\Phi_{DPA} = (n_v \cdot \Phi)/n_{at}$, where Φ is the fluence in cm^{-2}.

The ion flux density, defined as $F_{DPA} = d\Phi_{DPA}/dt$, was also kept constant in units of DPA/s. All irradiation parameters are given in the table.

Table

Parameters of ion irradiation used

Ion	Energy		R_p	R_{pd}	1 DPA	Ion current density		
	keV	keV/u	nm	nm	10^{14} cm^{-2}	μA/cm^2	10^{11} cm$^{-2}\cdot$s^{-1}	10^{-3} DPA/s
F^+	25	1.3	30	17	10.61	0.41	25.4	2.4
	50	2.6	55	36	12.15	0.47	29.2	
	60	3.0	74	48	12.72	0.49	30.6	
P^+	40	1.3	30	17	6.28	0.24	15.1	
	80	2.6	55	36	6.48	0.25	15.6	

Notations: R_p is the projected range of impurity ions (position of the maximum of the implanted impurity concentration); R_{pd} is the maximum of the primary defect generation function; DPA is the number of displacements per atom.

Note. Singly charged positive ions were used in all cases. The dose was 1.5 DPA in all cases.

The degree of disorder in the crystal structure of the samples after irradiation was measured by Rutherford backscattering spectrometry in channeling mode (RBS/C). The measurements used a probing beam of 0.7 MeV He^{++} ions along the [0001] crystallographic direction. The scattered particle detector was positioned at 170° relative to the incident beam direction.

Experimental results and discussion

Fig. 1 shows the generation functions of primary point defects and the corresponding elastic energy losses (solid lines), calculated with TRIM [30]. The values of the maxima of the implanted impurity concentration profile R_p and of the primary defect generation function R_{pd} are also summarized in the table. The ion energies were chosen so that the primary point defect distributions for F^+ (25 keV) and P^+ (40 keV) ions, as well as for F^+ (50 keV) and P^+ (80 keV) ions, were similar to each other (see Fig. 1). The ion energy for the second (high-energy) irradiation was chosen so that the maximum of the defect generation function was located at a depth corresponding to the position of defects formed in the bulk during the first (low-energy) irradiation.

Fig. 2 shows experimental RBS/C spectra for single irradiation with 25 and 50 keV fluorine ions at a dose of 1.5 DPA. The spectra represent the number of detected backscattered helium ions as a function of the channel number of the multichannel analyzer. In both cases, two maxima are observed in the spectra: one in the bulk of the sample, the bulk defect peak (BDP); the other in the surface region, the surface defect peak (SDP), associated with the formation of an amorphous surface layer due to diffusion of primary point defects from the bulk to the surface owing to their mobility [25]. For 25 keV fluorine ions, the BDP is located in the region of channel 246,

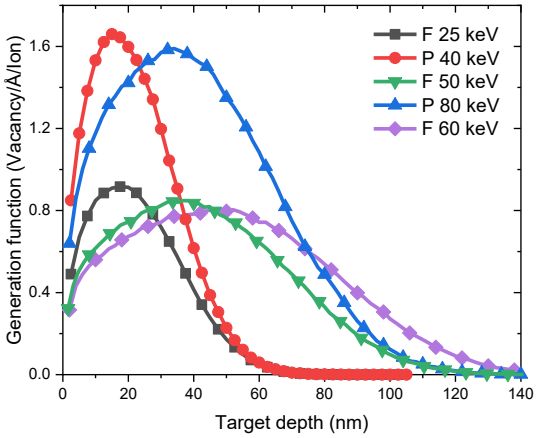


Fig. 1. Dependences of primary point defect generation function in α-Ga_2O_3 on the sample depth, calculated with TRIM for fluorine ions with energies of 25–60 keV and phosphorus ions with energies of 40 and 80 keV

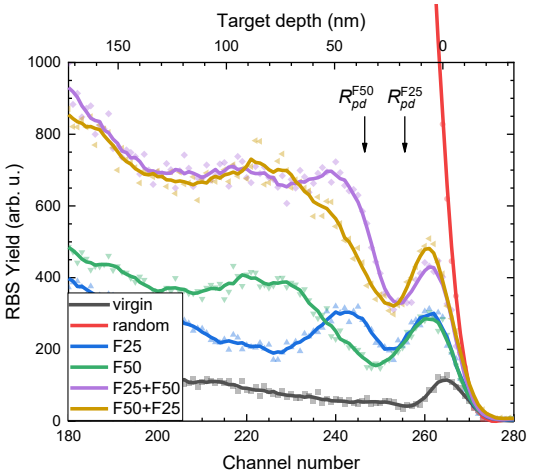


Fig. 2. Experimental RBS/C spectra for α-Ga_2O_3 samples irradiated with 25 and 50 keV fluorine ions under different conditions: single and double irradiations in different sequences (see legend). The spectra of unirradiated samples recorded in the aligned (virgin) and random directions of the probing beam

The dose was 1.5 DPA for each individual irradiation. The arrows mark the maxima of the primary point defect generation functions. Each maximum corresponds to irradiation with fluorine ions at one of the energies considered

which corresponds to a depth of about 35 nm and to the maximum of the generation function for 50 keV fluorine ions, for which, in turn, the BDP is located in the region of channel 229, equivalent to a depth of about 62 nm.

Fig. 2 also shows the results of sequential irradiation with fluorine ions for two sequences: low energy (25 keV) followed by high energy (50 keV), and the reverse, high energy (50 keV) followed by low energy (25 keV). Each irradiation step was performed with the same dose: 1.5 DPA. It follows from the data in Fig. 2 that the final shape of the spectrum and consequently the defect distribution strongly depend on the irradiation sequence, despite identical DPA and DPA/s values. Indeed, when the first irradiation is performed with low-energy fluorine ions, i.e., when the total energy is 25+50 keV, an increase in the BDP is observed after the second irradiation. Conversely, the BDP value is lower for the reverse irradiation order.

Therefore, irradiation with 25 and 50 keV fluorine ions is a non-commutative process [28].

Next, experiments were carried out to test the commutativity of ion irradiation of α-Ga_2O_3 samples with phosphorus ions. As noted above, the irradiation energies for phosphorus ions were chosen so that the primary point defect generation functions were similar to the corresponding functions for F^+ ions. The irradiation was performed with the same dose: 1.5 DPA. Fig. 3 shows the RBS/C spectra for single irradiations with 40 and 80 keV phosphorus ions; their BDP positions are also in the region of channels 246 (depth of ~35 nm) and 229 (~62 nm), respectively [25, 26]. The results of irradiation with phosphorus ions in different sequences, namely 40+80 keV and 80+40 keV, are also shown in Fig. 3. A significant increase in the signal is observed for the low-energy → high-energy sequence, with consequently a more intense accumulation of stable radiation damage. As in the case of fluorine ions, irradiation with 40 and 80 keV phosphorus ions is also a non-commutative process.

Finally, in the concluding experiment, the energy of the second fluorine irradiation was chosen to be 60 keV, so that the generation maximum lay somewhat deeper than the BDP position for 25 keV ions. The doses of each irradiation step were also 1.5 DPA. The resulting RBS/C spectra for the cases F^+ 25 + 60 keV and 60 + 25 keV are shown in Fig. 4. It can be seen that the generation maximum is shifted deeper into the sample by about 13 nm relative to the BDP position for F^+ 25 keV, and the BDP for F 60 keV is located in the region of channel 220 (~90 nm). As in the other cases, more intense defect formation was observed for the low-energy → high-energy irradiation sequence. Despite the increase in the energy of the second ion, irradiation with 25+60 keV fluorine ions also proved to be non-commutative.

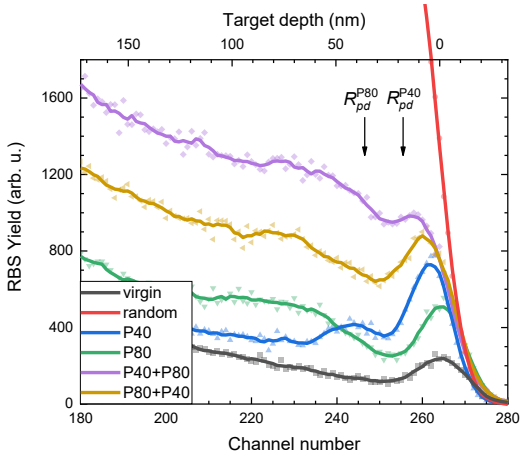


Fig. 3. RBS/C spectra similar to those in Fig. 2, but for irradiation with 40 and 80 keV phosphorus ions (see legend)

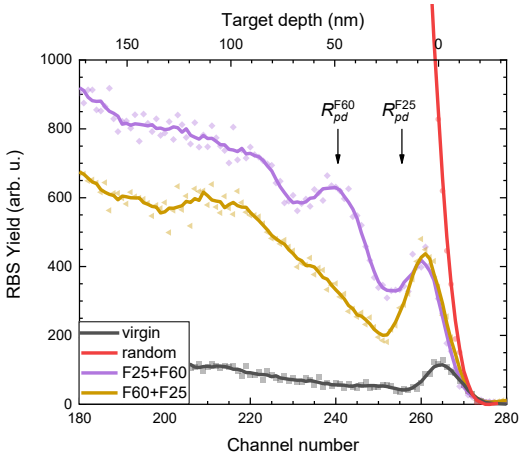


Fig. 4. Spectra similar to those in Fig. 2, but corresponding only to double irradiation with 25 and 60 keV fluorine ions in different sequences

To date, two mechanisms of ion implantation in semiconductors that lead to non-commutativity of structural damage accumulation have been proposed. Both have been confirmed to be valid.

The *first mechanism* [25] is the non-linearity of dose dependence of structural damage at different depths for each type of bombarding ion.

The *second mechanism* [7, 31] is the formation of a higher concentration of stable damage at depth upon irradiation with lower-energy ions, which leads to more efficient formation of stable defects involving mobile point defects during subsequent high-energy irradiation.

It is the second mechanism that we observed experimentally. In the case when high-energy irradiation was applied first, the concentration of stable damage in the bulk was lower (compared to low-energy irradiation) and mobile point defects were less efficiently trapped at depth and diffused to the interface between the amorphous surface layer and the crystalline layer. Further studies are clearly needed to elucidate the physical nature of non-commutativity under sequential ion implantation into α-Ga_2O_3 samples.

Conclusion

We studied radiation damage accumulation in gallium alpha oxide under sequential bombardment with fluorine ions and, separately, with phosphorus ions at different energies. It was found that the process is non-commutative: the final damage depends on the sequence of irradiation. We proposed possible mechanisms for this effect. Understanding the mechanisms and physical origin of the stable defect accumulation rate as a function of the ion implantation sequence can make it possible to predict and control the final defect profile in electronic devices based on α-Ga_2O_3. Further experimental and theoretical studies of this phenomenon are clearly necessary.

REFERENCES

1. **Feldman L. C., Mayer J. W.,** Fundamentals of surface and thin film analysis, North-Holland, Amsterdam, Netherlands, 1986.

2. **Davies J. A.,** High energy density collision cascades and spike effects (Ch. 4), In book: J. S. Williams, J. M. Poate (Eds.). Ion implantation and beam processing, Academic Press, Sydney, Australia (1984) 81–97.

3. **Thompson D. A.,** High density cascade effects, Radiat. Eff. 56 (3–4) (1981) 105–150.

4. **Taube A., Kaminska E., Kozubal M., et al.,** Ion implantation for isolation of AlGaN/GaN HEMTs using C or Al, Phys. Status Solidi A. 212 (5) (2015) 1162–1169.

5. **Abroyan I. A., Titov A. I., Khlebalkin A. V.,** Obrazovaniye defektov v kremnii pri kombinirovannom obluchenii ionami [The formation of defects in silicon under combined ion irradiation], Fiz. Tekh. Poluprovodn. (USSR). 13 (2) (1979) 227–233 (in Russian).

6. **Abroyan A. I., Konyshev V. V., Titov A. I., Khlebalkin A. V.,** Vliyaniye sostoyaniya kristallicheskoy struktury kremniya na nakopleniye defektov pri ionnom obluchenii [The influence of the state of the Si crystalline structure on the accumulation of defects during ion irradiation], Fiz. Tekh. Poluprovodn. (USSR). 15 (1) (1981)166–168 (in Russian).

7. **Titov A. I., Karaseov P. A., Karabeshkin K. V., Struchkov A. I.,** The formation of radiation damage in GaN during successive bombardment by light ions of various energies, Vacuum. 2020. 173 (March) (2020) 109149.

8. **Bai Q., Li L., Cheng F. F., et al.,** Study on microstructure and mechanical properties of He and H ion irradiated 6H-SiC, Nucl. Instrum. Meth. Phys. Res. B. 365 (Part A, 15 Dec) (2015) 347–351.

9. **Bogh E., Hogild P., Stensgaard I.,** Spatial distribution of defects in ion bombarded silicon and germanium, Rad. Eff. 7 (1–2) (1971) 115–121.

10. **Kool W.H., Roosendaal H. E., Wiggers L.W., Saris F. W.,** Production and beam annealing of damage in carbon implanted silicon. II, Rad. Eff. 36 (1–2) (1978) 41–48.

11. **Abroyan I. A., Nikulina L. M., Titov A. I.,** Ionically stimulated ordering of previously irradiated silicon, Fiz. Tekh. Poluprovodn. (USSR). 19 (6) (1985) 1030–1034 (in Russian).

12. **Abroyan I. A., Nikulina L. M.,** Molecular effect during light ion implantation in semiconductors, Fiz. Tekh. Poluprovodn. (USSR). 31 (10) (1997) 1164 –1167 (in Russian).

13. **Jiang W., Weber W. J., Zhang Y., et al.,** Ion beam analysis of irradiation effects in 6H–SiC, Nucl. Instrum. Meth. Phys. Res. B. 207 (1) (2003) 92–99.

14. **Pelaz L., Marqués L. A., Barbolla J.,** Ion-beam-induced amorphization and recrystallization in silicon, J. Appl. Phys. 96 (11) (2004) 5947–5976.

15. **Stepanov S. I., Nikolaev V. I., Bougrov V. E., Romanov A. E.,** Gallium oxide: properties and application – A review, Rev. Adv. Mater. Sci. 44 (1) (2016) 63–86.

16. **Pearton S. J., Ren F., Mastro M. (Eds.),** Gallium oxide. Technology, devices and applications, Elsevier Inc., Amsterdam (Netherlands), 2019.

17. **Pearton S. J., Ren F., Tadjer M., Kim J.,** Perspective: Ga_2O_3 for ultra-high power rectifiers and MOSFETS, J. Appl. Phys. 124 (22) (2018) 220901.

18. **Wellmann P. J.,** Power electronic semiconductor materials for automotive and energy saving applications – SiC, GaN, Ga_2O_3, and diamond, Z. Anorg. Allg. Chem. 643 (21) (2017) 1312–1322.

19. **Nikolskaya A., Okulich E., Korolev D., et al.,** Ion implantation in β-Ga_2O_3: Physics and technology, J. Vac. Sci. Technol. A. 39 (3) (2021) 030802.

20. **Cai Y., Feng Z., Wang Z., et al.,** Demonstration of the normally off β-Ga_2O_3 MOSFET with high threshold voltage and high current density, Appl. Phys. Lett. 123 (19) (2023) 193501.

21. **Farzana E., Roy S., Hendricks N. S., et al.,** Vertical PtO_x/Pt/β-Ga_2O_3 Schottky diodes with high permittivity dielectric field plate for low leakage and high breakdown voltage, Appl. Phys. Lett. 123 (19) (2023) 192102

22. **Ahmadi E., Oshima Y.,** Materials issues and devices of α-and β-Ga_2O_3, J. Appl. Phys. 126 (16) (2019) 160901.

23. **Polyakov S. J., Nikolaev S. J., Yakimov S. J., et al.,** Deep level defect states in β-, α-, and ε-Ga_2O_3 crystals and films: Impact on device performance, J. Vac. Sci. Technol. A. 40 (2) (2022) 020804.

24. **Azarov A., Galeckas A., Mikhaylov A. et al.,** Defect evolution and nitrogen incorporation in ion-implanted β-Ga_2O_3, Appl. Phys. Lett. 125 (19) (2024) 192107.

25. **Klevtsov A., Karaseov P., Azarov A., et al.,** Non-linear effects in α-Ga_2O_3 radiation phenomena, APL Mater. 12 (11) (2024) 111121.

26. **Klevtsov A. I., Karaseov P. A., Karabeshkin K. V., Titov A. I.,** Peculiarities of structure damage accumulation under the implantation of ions of different masses into alpha-gallium oxide at low damage levels, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (4) (2023) 42–49 (in Russian).

27. **Titov A., Klevtsov A., Fedorenko E., et al.,** Density and fractality of collision cascades in α-Ga_2O_3, Appl. Phys. Lett. 127 (15) (2025) 152107.

28. **Klevtsov A. I., Kleimanov R. V., Azarov A., et al.,** Damage accumulation in alpha gallium oxide during sequential keV light ion implantations, Proc. 2024 Int. Conf. on Electrical Engineering and Photonics (EExPolytech), Oct. 17–18, St. Petersburg, Russia, IEEE (2024) 339–342.

29. **Pechnikov A. I., Stepanov S. I., Chikiryaka A.V., et al.,** Thick α-Ga_2O_3 layers on sapphire substrates grown by halide epitaxy, Semicond. 53 (6) (2019) 780–783.

30. **Ziegler J. F., Biersack J. P., Littmark U.,** The stopping and range of ions in solids, Pergamon Press, New York, 1985.

31. **Titov A. I., Karaseov P. A., Kataev A. Yu., et al.,** Model for radiation damage buildup in GaN, Nucl. Instrum. Meth. Phys. Res. B. 277 (15 Apr) (2012) 80–83.

СПИСОК ЛИТЕРАТУРЫ

1**. Фелдман Л., Майер Д.** Основы анализа поверхности и тонких пленок. Пер. с англ. М.: Мир, 1989. 342 с.

2. **Davies J. A.** High energy density collision cascades and spike effects (Chapter 4) // J. S. Williams, J. M. Poate (Eds.). Ion implantation and beam processing. Sydney, Australia: Academic Press, 1984. Pp. 81–97.

3. **Thompson D. A.** High density cascade effects // Radiation Effects. 1981. Vol. 56. No. 3–4. Pp. 105–150.

4. **Taube A., Kaminska E., Kozubal M. et al.** Ion implantation for isolation of AlGaN/GaN HEMTs using C or Al // Physica Status Solidi A. 2015. Vol. 212. No. 5. Pp. 1162–1169.

5. **Аброян И. А., Титов А. И., Хлебалкин А. В.** Образование дефектов в кремнии при комбинированном облучении ионами // Физика и техника полупроводников. 1979. Т. 13. № 2. С. 227–233.

6. **Аброян А. И., Конышев В. В., Титов А. И., Хлебалкин А. В**. Влияние состояния кристаллической структуры кремния на накопление дефектов при ионном облучении // Физика и техника полупроводников. 1981. Т. 15. № 1. С. 166–168.

7. **Titov A. I., Karaseov P. A., Karabeshkin K. V., Struchkov A. I.** The formation of radiation damage in GaN during successive bombardment by light ions of various energies // Vacuum. 2020. Vol. 173. March. P. 109149.

8. **Bai Q., Li L., Cheng F. F., Bin R., Fa T., Fu E., Yao S. D.** Study on microstructure and mechanical properties of He and H ion irradiated 6H-SiC // Nuclear Instruments and Methods in Physics Research B. 2015. Vol. 365. Part A, 15 December. Pp. 347–351.

9. **Bogh E., Hogild P., Stensgaard I.** Spatial distribution of defects in ion bombarded silicon and germanium // Radiation Effects. 1971. Vol. 7. No. 1–2. Pp. 115–121.

10. **Kool W. H., Roosendaal H. E., Wiggers L. W., Saris F. W.** Production and beam annealing of damage in carbon implanted silicon. II // Radiation Effects. 1978. Vol. 36. No. 1–2. Pp. 41–48.

11. **Аброян И. А., Никулина Л. М., Титов А. И.** Ионно-стимулированное упорядочение структуры предварительно облученного кремния // Физика и техника полупроводников. 1985. Т. 19. № 6. С. 1030–1034.

12. **Аброян И. А., Никулина Л. М.** Молекулярный эффект при имплантации легких ионов в полупроводники // Физика и техника полупроводников. 1997. Т. 31. № 10. С. 1164–1167.

13. **Jiang W., Weber W. J., Zhang Y., Thevuthasan S., Shutthanandan V.** Ion beam analysis of irradiation effects in 6H–SiC // Nuclear Instruments and Methods in Physics Research B. 2003. Vol. 207. No. 1. Pp. 92–99.

14. **Pelaz L., Marqués L. A., Barbolla J.** Ion-beam-induced amorphization and recrystallization in silicon //Journal of Applied Physics. 2004. Vol. 96. No. 11. Pp. 5947–5976.

15. **Stepanov S. I., Nikolaev V. I., Bougrov V. E., Romanov A. E.** Gallium oxide: properties and application – A review // Reviews on Advanced Materials Science. 2016. Vol. 44. No. 1. Pp. 63–86.

16. **Pearton S. J., Ren F., Mastro M.** (Eds.). Gallium oxide. Technology, devices and applications. Amsterdam, Netherlands: Elsevier Inc., 2019. 479 p.

17. **Pearton S. J., Ren F., Tadjer M., Kim J.** Perspective: Ga_2O_3 for ultra-high power rectifiers and MOSFETS // Journal of Applied Physics. 2018. Vol. 124. No. 22. P. 220901.

18. **Wellmann P. J.** Power electronic semiconductor materials for automotive and energy saving applications – SiC, GaN, Ga2O3, and diamond // Zeitschrift für anorganische und allgemeine Chemie. 2017. Vol. 643. No. 21. Pp. 1312–1322.

19. **Nikolskaya A., Okulich E., Korolev D., et al.** Ion implantation in β-Ga_2O_3: Physics and technology // Journal of Vacuum Science & Technology A. 2021. Vol. 39. No. 3. P. 030802.

20. **Cai Y., Feng Z., Wang Z., et al.** Demonstration of the normally off β-Ga2O3 MOSFET with high threshold voltage and high current density // Applied Physics Letters. 2023. Vol. 123. No. 19. P. 193501.

21. **Farzana E., Roy S., Hendricks N. S., Krishnamoorthy S., Speck J. S.** Vertical PtO_x/Pt/β-Ga_2O_3 Schottky diodes with high permittivity dielectric field plate for low leakage and high breakdown voltage // Applied Physics Letters. 2023. Vol. 123. No. 19. P. 192102.

22. **Ahmadi E., Oshima Y.** Materials issues and devices of α-and β-Ga_2O_3 //Journal of Applied Physics. 2019. Vol. 126. No. 16. P. 160901.

23. **Polyakov A. Y., Nikolaev V. I., Yakimov E. B., Ren F., Pearton S. J., Kim J.** Deep level defect states in β-, α-, and ε-Ga_2O_3 crystals and films: Impact on device performance // Journal of Vacuum Science & Technology A. 2022. Vol. 40. No. 2. P. 020804.

24. **Azarov A., Galeckas A., Mikhaylov A., Nikolskaya A., Tetelbaum D., Korolev D., Monakhov E., Kuznetsov A.** Defect evolution and nitrogen incorporation in ion-implanted β-Ga_2O_3 // Applied Physics Letters. 2024. Vol. 125. No. 19. P. 192107.

25. **Klevtsov A., Karaseov P., Azarov A., Karabeshkin K., Fedorenko E., Titov A., Kuznetsov A.** Non-linear effects in α-Ga_2O_3 radiation phenomena // APL Materials. 2024. Vol. 12. No. 11. P. 111121.

26. **Клевцов А. И., Карасев П. А., Карабешкин К. В., Титов А. И.** Особенности накопления структурных нарушений при имплантации ионов разных масс в альфа-оксиде галлия при малых уровнях повреждения // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 4. С. 42–49.

27. **Titov A., Klevtsov A., Fedorenko E., Azarov A., Kuznetsov A., Karaseov P.** Density and fractality of collision cascades in α-Ga_2O_3 // Applied Physics Letters. 2025. Vol. 127. No. 15. P. 152107.

28. **Klevtsov A. I., Kleimanov R. V., Azarov A., Karaseov P. A., Karabeshkin K. V., Titov A. I.** Damage accumulation in alpha gallium oxide during sequential keV light ion implantations // Proceedings of the 2024 International Conference on Electrical Engineering and Photonics (EExPolytech). October 17–18, St. Petersburg, Russia. IEEE: 2024. Pp. 339–342.

29. **Печников А. И., Степанов С. И., Чикиряка А. В., Щеглов М. П., Одноблюдов М. А., Николаев В. И.** Толстые слои alpha-Ga_2O_3 на сапфировых подложках, полученные методом хлоридной эпитаксии // Физика и техника полупроводников. 2019. Т. 53. № 6. С. 789–792.

30. **Ziegler J. F., Biersack J. P., Littmark U.** The stopping and range of ions in solids. New York: Pergamon Press, 1985. 321 p.

31. **Titov A. I., Karaseov P. A., Kataev A. Yu, Azarov A. Yu, Kucheyev S. O.** Model for radiation damage buildup in GaN // Nuclear Instruments and Methods in Physics Research B. 2012. Vol. 277. 15 April. Pp. 80–83.

THE AUTHORS

KLEVTSOV Anton I.
Peter the Great St. Petersburg Polytechnic University,
Joint-Stock Company "Research and Production Enterprise «ELAR»»,
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
klevtsovanton@rambler.ru
ORCID: 9685-6988-0004-0009

KARASEOV Platon A.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
platon.karaseov@spbstu.ru
ORCID: 0000-0003-2511-0188

TITOV Andrei I.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
ATitov@spbstu.ru
ORCID: 0000-0003-4933-9534

СВЕДЕНИЯ ОБ АВТОРАХ

КЛЕВЦОВ Антон Игоревич – *ассистент кафедры физики Института физики и математики Санкт-Петербургского политехнического университета Петра Великого, инженер-технолог 1 категории Акционерного общества "Научно-производственное предприятие «ЭЛАР»".*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
klevtsovanton@rambler.ru
ORCID: 0009-0004-6988-9685

КАРАСЕВ Платон Александрович – *доктор физико-математических наук, профессор Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
platon.karaseov@spbstu.ru
ORCID: 0000-0003-2511-0188

ТИТОВ Андрей Иванович – *доктор физико-математических наук, профессор Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
ATitov@spbstu.ru
ORCID: 0000-0003-4933-9534

Received 20.05.2026. Approved after reviewing 03.06.2026. Accepted 03.06.2026.
Статья поступила в редакцию 20.05.2026. Одобрена после рецензирования 03.06.2026. Принята 03.06.2026.

© Peter the Great St. Petersburg Polytechnic University, 2026