

Conference materials

UDC 537.622

DOI: <https://doi.org/10.18721/JPM.184.108>

Curvature-induced localization of magnetic domains in thin multilayer magnetic films on the surface of porous alumina

K.A. Rogachev¹ ✉, A.Yu. Samardak¹, M.A. Bazrov¹,

A.F. Shishelov¹, M.I. Sobirov¹, A.V. Ognev^{1,2}, A.S. Samardak^{1,2}

¹ Far Eastern Federal University, Vladivostok, Russia;

² Sakhalin State University, Yuzhno-Sakhalinsk, Russia

✉ kirpers26@gmail.com

Abstract. The curvature of the ferromagnetic nanostructure is among its most important properties because of the great influence on its magnetic behavior, induced by strong shape magnetic anisotropy. In this work, we discuss the preparation and investigation of the magnetic properties of Pt/[Co/Pt]_{x/y}/Pt thin films on the surface of convex (nanodomes) and concave (nanopits) nanorelief, in the form of anodized aluminum oxide and aluminum matrices with an etched anodized oxide layer, respectively. For all samples, the presence of perpendicular magnetic anisotropy was observed, which was also observed in the reference samples on the smooth surface of SiO₂. We show that an increase of the anodizing voltage leads to an increase in the interpore distance and curvature of the surface, which has a great influence on the coercive force and residual magnetization. In addition, we present the study of magnetic configuration of the obtained films, which showed the presence of the localization of magnetic domains on nanodomes and possible presence of skyrmions.

Keywords: porous oxide matrices, anodizing, thin films, skyrmions

Funding: This work was supported by the Russian Ministry of Science and Higher Education (State Task No. FZNS-2023-0012).

Citation: Rogachev K.A., Samardak A.Yu., Bazrov M.A., Shishelov A.F., Sobirov M.I., Ognev A.V., Samardak A.S., Curvature-induced localization of magnetic domains in thin multilayer magnetic films on the surface of porous alumina, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (4.1) (2025) 49–54. DOI: <https://doi.org/10.18721/JPM.184.108>

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

Материалы конференции

УДК 537.622

DOI: <https://doi.org/10.18721/JPM.184.108>

Наведенная пространственной кривизной локализация магнитных доменов в тонких многослойных магнитных пленках на поверхности пористого оксида алюминия

К.А. Рогачев¹ ✉, А.Ю. Самардак¹, М.А. Базров¹,

А.Ф. Шишелов¹, М.И. Собиров¹, А.В. Огнев^{1,2}, А.С. Самардак^{1,2}

¹ Дальневосточный федеральный университет, г. Владивосток, Россия;

² Сахалинский государственный университет, г. Южно-Сахалинск, Россия

✉ kirpers26@gmail.com

Аннотация. Кривизна ферромагнитной наноструктуры является одним из ее важнейших свойств из-за большого влияния на ее магнитное поведение, вызванного

сильной магнитной анизотропией формы. В этой работе мы обсуждаем получение и исследование магнитных свойств тонких пленок Pt/[Co/Pt]_{x9}/Pt на поверхности выпуклого (нанокупола) и вогнутого (наноямки) нанорельефа, в виде анодированного оксида алюминия и алюминиевых матриц с протравленным анодированным оксидным слоем, соответственно. Для всех образцов наблюдалось наличие перпендикулярной магнитной анизотропии, которая также наблюдалась в контрольных образцах на гладкой поверхности SiO₂. Мы показываем, что увеличение напряжения анодирования приводит к увеличению межпорового расстояния и кривизны поверхности, что оказывает большое влияние на коэрцитивную силу и остаточную намагниченность. Кроме того, мы представляем исследование магнитной конфигурации полученных пленок, которое показало наличие локализации магнитных доменов на нанокуполах и возможное присутствие скирмионов.

Ключевые слова: пористые оксидные матрицы, анодирование, тонкие пленки, скирмионы

Финансирование: Работа выполнена при поддержке Министерства науки и высшего образования Российской Федерации (Государственное Задание № FZNS-2023-0012).

Ссылка при цитировании: Рогачев К.А., Самардак А.Ю., Базров М.А., Шишелов А.Ф., Собиров М.И., Огнев А.В., Самардак А.С., Наведенная пространственной кривизной локализация магнитных доменов в тонких многослойных магнитных пленках на поверхности пористого оксида алюминия // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 4.1. С. 49–54. DOI: <https://doi.org/10.18721/JPM.184.108>

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

Introduction

In recent years, skyrmions have been center of interest in the fields of nanomagnetism and spintronics of science due to the unique properties of these topological quasiparticles, such as high stability, small sizes and the ability to move under the influence of low current densities [1]. Such properties open the prospect of their effective use as a unit of information transfer and storage in novel spintronics devices [2]. However, there are a number of difficulties that currently prevent their widespread use, with the stabilization of skyrmions at room temperature and in the absence of an external magnetic field [1] being among them. An approach to solving this problem is to use curved geometries nanostructures, which can create conditions for the formation and stabilization of skyrmions [3, 4].

Thin magnetic films with curved geometry, which are created by depositing magnetic materials on substrates with curved nanoscale relief, are an interesting object for research, as their geometry can cause magnetic phenomena that are not characteristic of flat films [3–5]. A recent experimental study has shown that a curved surface of asymmetric Pt/Co/Ta can significantly increase the stability and localization of skyrmions in nanodomains [6].

In this work, we investigate further the influence of curvature of the substrate and study the localization of magnetic domains in thin films with symmetric Pt/Co/Pt interfaces not only on a convex curved surface but also on a concave one to analyze the influence of mirrored substrate relief and different anodization voltages on magnetic properties of the magnetic films.

Materials and Methods

To modulate the surface, anodic alumina oxide (AAO) and aluminum with an AAO were used, which were obtained by electrochemical anodization of aluminum in a solution of 5% orthophosphoric acid H₃PO₄. To achieve a more even surface, the aluminum substrates were pre-annealed in a vacuum at a temperature of 500 °C for 30 minutes, then electrochemical polishing of aluminum was carried out in a solution of 1:4 HClO₄ + C₂H₅OH for 1.5 minutes at an initial temperature of 2 °C (cryostat KRYO-VIST-04) and a current density of 500 mA/cm² (laboratory power supply Agilent 6030A). After obtaining a smooth mirror-like surface, aluminum was anodized



in a 5% solution of H_3PO_4 at a temperature of $2^\circ C$ with a constant voltage of 90, 120 and 150 V for 6, 4 and 2 hours, respectively. For each used voltage, two types of substrates were achieved – first type was obtained by etching of AAO to obtain nanopits in the aluminum and second type synthesized by etching of aluminum to obtain nanodomains on AAO. Then, using magnetron sputtering (Omicron), $Pt(4\text{ nm})/[Co(0.7\text{ nm})/Pt(2\text{ nm})]_{x9}/Pt(2\text{ nm})$ films were deposited on the surface of nanodomains and nanopits. In addition, reference samples were synthesized by deposition of films on the flat surface of the silicon oxide substrate. The surface morphology was studied by scanning electron microscopy (SEM, ThermalScientific SCIOS 2) and atomic force microscopy (AFM, NT-MDT NTEGRA Aura). The magnetic properties of the samples were determined by vibrational magnetometry (VSM, LakeShore VSM 7410). Magnetic force microscopy (MFM, NT-MDT NTEGRA Aura) was used to visualize the magnetic configuration.

Results and Discussion

The morphology of domes on AAO templates and its imprint in aluminum as pits was investigated by SEM (Fig. 1, *a*) and AFM (Fig. 1, *b*) prior to deposition of magnetic films. For ease, the following sample notation was introduced: nanodomains – D, nanopits – P, the numbers indicate the anodizing voltage divided by 10. The letter L at the end of the sample name indicates that a magnetic film is deposited on the sample surface. As in the analysis of the dependence of the geometric dimensions of nanodomains and nanopits on the anodizing voltage shown (Fig. 1, *c*), with an increase in voltage, the diameter of the structures on the surface increases proportionally from $250 \pm 25\text{ nm}$ at 90 V to $400 \pm 19\text{ nm}$ at 150 V for nanodomains and from $270 \pm 12\text{ nm}$ at 90 V to $390 \pm 29\text{ nm}$ at 150 V for nanopits, which is typical for AAO. Moreover, with increasing voltage, the height of the obtained structures also increases from $53 \pm 6\text{ nm}$ at 90 V to $61 \pm 9\text{ nm}$ at 120 V and to $90 \pm 11\text{ nm}$ at 150 V for nanopits and $40 \pm 6\text{ nm}$ at 90 V to $52 \pm 9\text{ nm}$ at 120 V for nanodomains. The decrease in the height of the nanodomains with increasing voltage from 120 to 150 V and the overall lower height of the nanodomains compared to the nanopits may be associated with the impossibility of accurately studying the relief using AFM due to the large curvature of the surface at the boundary of two nanodomains.

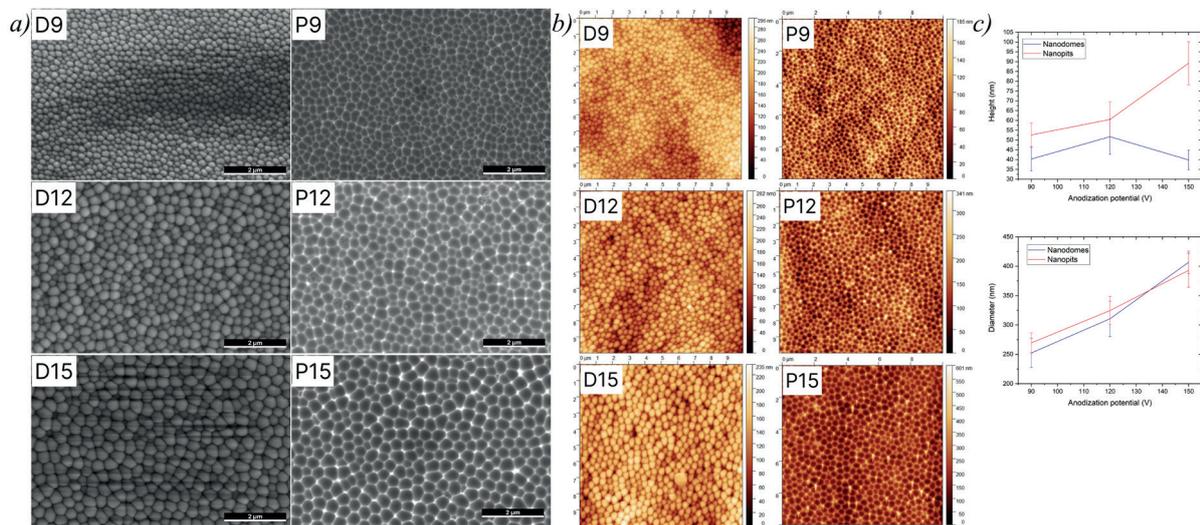


Fig. 1 SEM (*a*) and AFM (*b*) images of the surface of substrates with nanodomains (D) and nanopits (P) obtained at different anodizing voltages. Dependence of the geometric dimensions of the obtained nanoscale surface curvatures on the anodization voltage obtained from AFM (*c*)

After studying the geometric parameters of the nanorelief, thin $Pt(4\text{ nm})/[Co(0.7\text{ nm})/Pt(2\text{ nm})]_{x9}/Pt(2\text{ nm})$ films were sputtered on the prepared substrates. The study of the magnetic properties of the films by VSM is presented in Fig. 2. To achieve hysteresis loops, samples were magnetized in the out of plane direction of the external magnetic field H in a range of $\pm 1\text{ kOe}$.

All samples were able to maintain out of plane anisotropy despite the different curvatures of the underlayer (Fig. 2, *a, b*), yet all of the films obtained on the surface of the modulated nanorelief

were characterized by a lower residual magnetization M_R/M_S in comparison to the reference sample, which may be induced by additional points of nucleation induced by inhomogeneities of their substrate surfaces. The coercive force H_C of the films in nanopits decreases drastically from 244 Oe at an anodizing voltage of 90 V to 230 Oe at 120 V and 167 Oe at 150 V, while residual magnetization follows the same trend with a decrease from 0.893 at 90 V to 0.832 at 120 V and 0.745 at 150 V. The change in the magnetic behavior of the films on nanodomains with the change of anodization voltage is different in comparison to that of the films on nanopits, with oscillating M_R/M_S and H_C values. At 90 V, M_R/M_S and H_C are 0.69 and 160 Oe, respectively, at 120 V, M_R/M_S and H_C increase to 0.92 and 202 Oe, respectively. With an increase of anodization voltage up to 150 V, the decrease of these values is observed, marking values of M_R/M_S and H_C as 0.65 and 132 Oe. Since the dependences of M_R/M_S and H_C coincide more with the dependence of the height on the anodization potential (Fig. 1, c), we can conclude that the height of nanodomains and nanopits influences their magnetic behavior much more than the diameter of the pores.

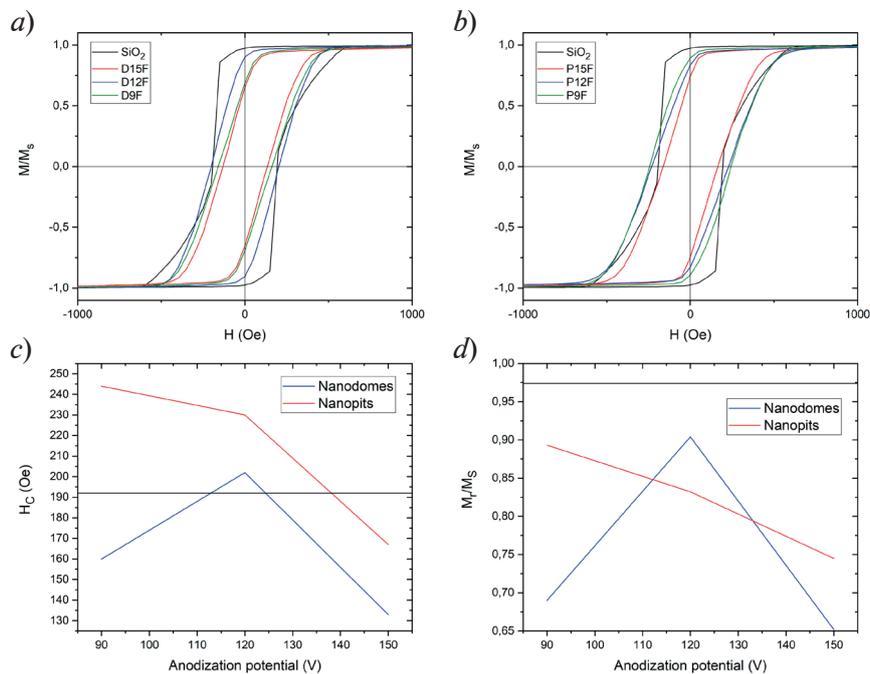


Fig. 2. Magnetic characteristics of the obtained multilayer films: (a) hysteresis of films on nanodomains and (b) nanopits in an out of plane configuration of \mathbf{H} , dependence of (c) residual magnetization and (d) coercive force on anodization voltage (straight gray lines in graphs (c) and (d) indicate residual magnetization and coercive force of the reference film on the surface of oxidized silicon)

The study of the domain structure of the samples by MFM (Fig. 3) showed that the magnetic configuration of the reference film on the surface of oxidized silicon has a labyrinth domain structure, which is typical for such films [7]. A similar structure is also observed in the film obtained on the surface with a modulated nanorelief. In all samples, round “bubble” domains were observed, which are signs of possible presence of skyrmions [6, 8, 9]. However, for films obtained on the surface of nanodomains, a higher localization of individual domains on the nanodomains is observed. The magnetic configuration of sample D12F exhibits a predominantly labyrinthine structure with a small number of localized bubble domains. The magnetic configuration of sample D15F demonstrates an increase in the number of bubble domains arising from the breakdown of the labyrinthine domain structure. Sample D9F exhibits the highest number of individual localized domains, weakly or not at all connected to their neighbors. The decrease in coercive force H_C and residual magnetization M_R/M_S for the D9F and D15F samples compared to the D12F sample could be connected to higher localization of the magnetic domains and the partitioning of the labyrinthine domain structure into bubble domains. In contrast, the magnetic configuration of films obtained on the surface of nanopits is mostly characterized not by localized bubble domains, but by a labyrinthine structure, as in the control sample.

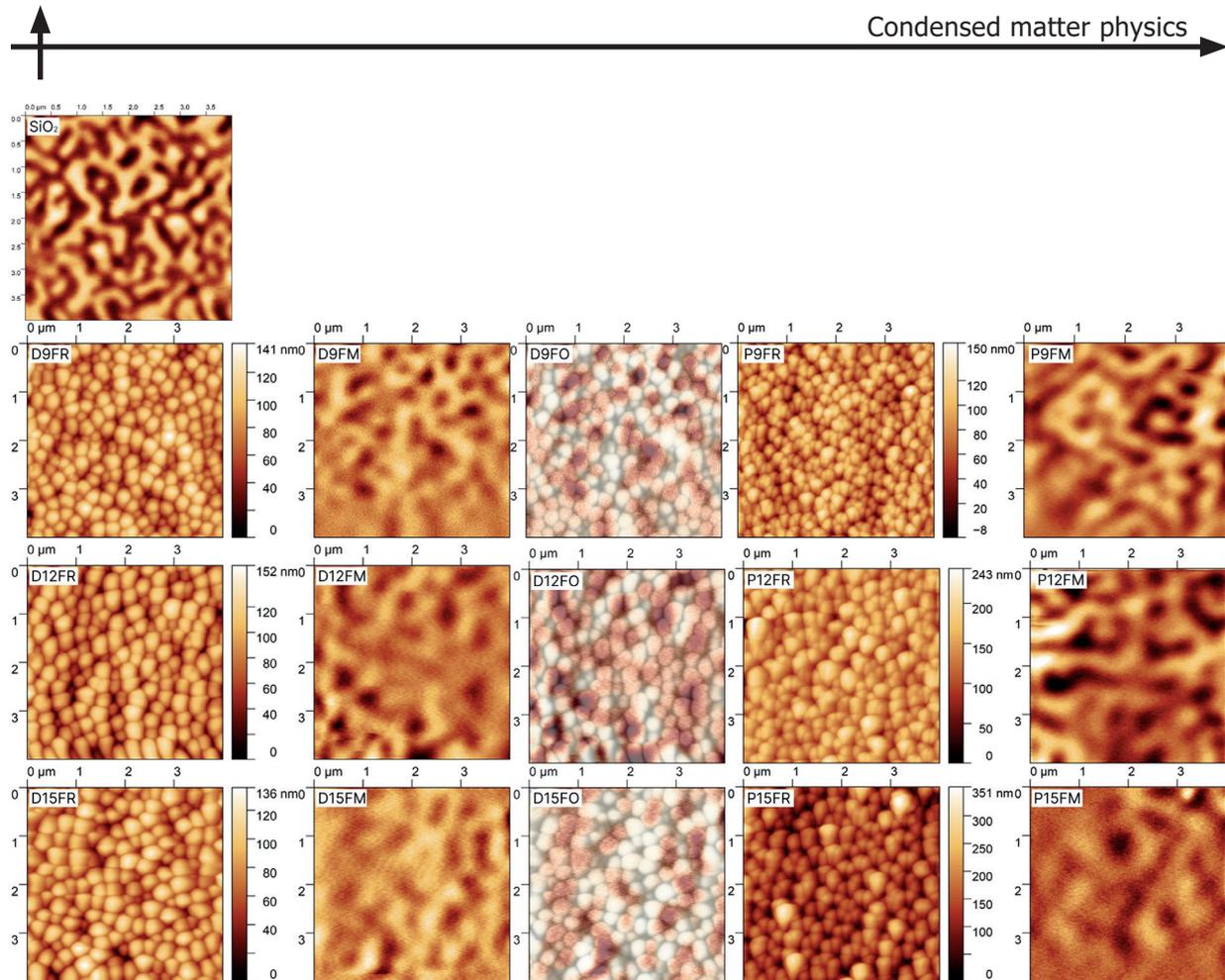


Fig.3 MFM image of the film scattering fields on the surface of SiO_2 , surface relief (postfix “R”) and MFM image of the scattering fields (postfix “M”) of the obtained films (postfix “O” means the imposition of the MSM image on the surface relief)

Conclusion

As a result of the carried out work, multilayer $\text{Pt}(4 \text{ nm})/[\text{Co}(0.7 \text{ nm})/\text{Pt}(2 \text{ nm})]_{x_0}/\text{Pt}(2 \text{ nm})$ films were obtained by magnetron sputtering on the surface of AAO substrate with non-trivial morphology. Despite the curvature of the underlayer, samples achieved on nanodomains and nanopits tend to maintain the perpendicular magnetic anisotropy, similar to a reference sample obtained on flat silicon oxide. It was shown that magnetic properties of the films depend heavily on the anodization voltage during the preparation of AAO templates, with an increase in the voltage leading to an increase in the curvature of the surface and a decrease of the coercive force H_C and residual magnetization M_R/M_S . In addition, the presence of bubble domains and observed localization of magnetic domains on nanodomains were shown as a result of studying the domain structure of the films. As was discovered, the localization of the magnetic domains heavily depends on the curvature of the underlayer as well, and nanodomains and nanopits are characterized by different domain structures, despite being mirror reflections of each other.

REFERENCES

1. Fert A., Reyren N. and Cros V., Magnetic skyrmions: advances in physics and potential applications, *Nature Reviews Materials* 2 (2017) 17031.
2. He M., Xu N., Gao Y., Hu C., Cai J., Zhang Y., Mixed-Type Skyrmions in Symmetric Pt/Co/Pt Multilayers at Room Temperature, *Materials*. 15 (2022) 8272.
3. Streubel R., Fischer P., Kronast F., Kravchuk V.P., Sheka D.D., Gaididei Y., Schmidt O.G., Makarov D., Magnetism in curved geometries, *Journal of Physics D: Applied Physics* 49. (2016) 363001.

4. **Carvalho-Santos V.L., Corona R.M., Altbir D., Castillo-Sepúlveda S.**, Shifts in the skyrmion stabilization due to curvature effects in dome- and antidome-shaped surfaces, *Physical Review B*. 102 (2020) 024444.

5. **Kravchuk V.P., Roßler U.K., Volkov O.M., Sheka D.D., Van den Brink J., Makarov D., Fuchs H., Fangohr H., Gaididei Y.**, Topologically stable magnetization states on a spherical shell: Curvature-stabilized skyrmions, *Physical Review B*. 94 (2016) 144402.

6. **Tejo F., Toneto D., Oyarzun S., Hermosilla J., Danna C.S., Palma J.L., da Silva R.B., Dorneles L.S., Denardin J.C.**, Stabilization of Magnetic Skyrmions on Arrays of Self-Assembled Hexagonal Nanodomains for Magnetic Recording Applications, *ACS Applied Materials & Interfaces*. 12 (2020) 53454–53461.

7. **Ermolaeva O.L., Gusev N.S., Skorohodov E.V., Petrov Yu.V., Sapozhnikov M.V., Mironov V.L.**, Magnetic Force Microscopy of Nanostructured Co/Pt Multilayer Films with Perpendicular Magnetization, *Materials*. 10 (2017) 1034.

8. **Jiang W., Upadhyaya P., Zhang W., Yu G., Jungfleisch M.B., Fradin F.Y., Pearson J.E., Tserkovnyak Ya., Wang R.L., Heinonen O., Te Velthuis S.G.E., Hoffmann A.**, Blowing magnetic skyrmion bubbles *Science*. 349 (2015) 283–286.

9. **Yang Q., Cheng Y., Li Y., Zhou Z., Liang J., Zhao X., Hu Z., Peng R., Yang H., Liu M.**, Voltage Control of Skyrmion Bubbles for Topological Flexible Spintronic Devices, *Advanced Electronic Materials*. 6 (2020) 2000246.

THE AUTHORS

ROGACHEV Kirill A.

rogachev.ka@dvfu.ru

ORCID: 0000-0002-8193-3851

SAMARDAK Aleksey Yu.

samardak.aiu@dvfu.ru

ORCID: 0000-0002-0795-374X

BAZROV Michail A.

bazrov.ma@dvfu.ru

ORCID: 0009-0002-4092-135X

SHISHELOV Aleksandr F.

shishelov.af@dvfu.ru

ORCID: 0000-0002-9703-4623

SOBIROV Mukhammad I.

sobirov.mi@dvfu.ru

ORCID: 0000-0002-8954-8413

OGNEV Aleksey V.

ognev.av@dvfu.ru

ORCID: 0000-0002-1619-3666

SAMARDAK Aleksandr S.

samardak.as@dvfu.ru

ORCID: 0000-0001-5917-4361

Received 20.09.2025. Approved after reviewing 10.10.2025. Accepted 13.10.2025.