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Current scientific research on Electrostatic accelerator EG-5 in JINR

Alexander S. Doroshkevich[1,2], *Efrain Rafael* Chavez Lomeli[3], *Edwin* Pedrero González[4], *Zhanna* V. Mezentseva[1], *Boris* L. Oksengendler[5], *Tatyana* Yu. Zelenyak[1], *Alisa* A. Tatarinova[1], *Phan Luong* Tuan[1,6], *Vesna* Teofilović[7], *Zoran* Ivanovich[8], *Carmen* Mita[9], *Diana* M. Mardare[10], *Nikoleta* Cornei[10], *Matlab* N. Mirzaev[11,12,13], *Nurbol* O. Appazov[14], *Andriy* K. Kirillov[1], *Ilya* A. Chepurchenko[1], *Anastasiya* I. Kruglyak[1], *Yulia* V. Aleksiayenak[1], *Vitaly* K. Ksenevich[15], *Aleksandr* V. Maletskii[1,16], *Altyn* Zh. Altynbasova[1, 17], *Anthony Carlos* Perez Moreno[1,18], *Rafael* Sh. Isayev[1,19,20], *Mahmoud* Ibrahim[1,21], *Silvia María* Fortuné Fábregas[1,22], *Luis Miguel* Ledo Pereda [1,23], *Ilya* O. Simonenko[1,2], *Vladislav* A. Kinev[24], *Alexey* R. Tameev[25]

[1]Joint Institute for Nuclear Research, Dubna, 141980, Russia
[2]Dubna State University, Dubna, 141980, Russia
[3]Física Nuclear y Aplicaciones de la Radiación Instituto de Física, UNAM, Mexico
[4]Institute of Materials Science and Technology (IMRE) of the University of Havana, Havana, Cuba
[5]Institute of Materials Science of the Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan
[6]Irradiation Center, Vietnam Atomic Energy Institute, Hanoi, Vietnam
[7]Faculty of Technology, University of Novi Sad, Novi Sad 21000, Serbia
[8]Laboratory of Physics, INN Vinča, University of Belgrade, Belgrade 11351, Serbia
[9]Faculty of Chemistry, "Alexandru Ioan Cuza" University of Iasi, Iasi 700506, Romania
[10]Faculty of Physics, "Alexandru Ioan Cuza" University of Iasi, Iasi 700506, Romania
[11]Institute of Radiation Problems, Ministry of Science and Education Republic of Azerbaijan, Baku, AZ1143, Azerbaijan
[12]Khazar University, Baku, AZ1096, Azerbaijan
[13]Azerbaijan State Oil and Industry University, Scientific-Research Institute Geotecnological Problems of Oil, Gas and Chemistry, AZ1010 Baku, Azerbaijan
[14]Laboratory of Engineering, Korkyt Ata Kyzylorda University, Kyzylorda 120014, Kazakhstan
[15]State Scientific and Production Association "Scientific-Practical Center of the National Academy of Sciences of Belarus", Minsk, Republic of Belarus
[16]Galkin Donetsk Institute for Physics and Engineering, 83114 Donetsk, Russia
[17]Karaganda Industrial University, Temirtau, 101400, Kazakhstan
[18]Voronezh State University, Voronezh, 394018, Russia
[19]National Research Nuclear University "MEPhI", Moscow, 115409, Russia
[20]IDDA, Department of Nuclear Research, Baku, AZ1069, Azerbaijan
[21]Tomsk Polytechnic University, Tomsk, 634050, Russia
[22]Photovoltaic Research Laboratory, Institute of Science and Technology of Materials (IMRE), University of Havana, Cuba
[23]Center for Technological Applications and Nuclear Development (CEADEN), Havana, Cuba
[24]JSC "Research and Production Enterprise "Integral", Dubna, Russia
[25]Frumkin Institute of Physical Chemistry and Electrochemistry Russian Academy of Sciences, Moscow, 119071, Russia

Abstract. The electrostatic accelerator (ESA) EG-5 has been operating stationary in the Nuclear Physics Department of the Nuclear Physics Department of JINR (Dubna) since 1965. Along with an experimental nuclear reactor and a pulsed accelerator IREN, ESA EG-5 occupies its own unique niche as part of a complex of nuclear physics installations. The beams of high-energy particles obtained using EG-5 have the highest energy stability (± 15 keV per 2 MeV), due to which it is possible to conduct unique studies of the elemental composition of solids, including depth profiling, conducting studies of fast neutron nuclear reactions, etc. ESA EG-5 is a universal research device that allows conducting both studies of the elemental composition and physical, chemical and biological modification of objects of inanimate and living nature, respectively. EG-5 electrostatic accelerator at FLNP JINR, used to produce intense fluxes of fast particles (H^+, He^+, D^+) and neutrons; for elemental analysis of surface layers of various objects using beams of α-particles, using non-destructive techniques RBS, ERD and PIXE; for implantation of ions into the surface layers of various materials; to study the radiation resistance of materials. Unique opportunities will appear after the implementation of a microbeam spectrometer at the EG-5 accelerator in period since 2025.

1 Electrostatic accelerator EG-5

Electrostatic accelerator (ESA) EG-5 - a long-liver laboratory of neutron physics, working properly since 1965. It is a reliable tool for solving a wide range of problems in the field of nuclear physics, solid state physics, radiation technologies. The ion beam of ESA at a relatively high current (up to 100 μA) has a very high energy stability, due to which the EG-5 plant can operate both in the mode of a neutron generator and an ion source for ion beam analysis. Today, with the help of EG-5, studies of nuclear reactions of neutrons with a solid body, accompanied by the departure of charged particles, studies of elementary depth profiles of multilayer semiconductor architectures, as well as irradiation (radiation modification) of materials are carried out.

Since 2023, the electrostatic accelerator has been the primary installation of the FNLP. It is a hardware complex that includes a high-voltage (up to 5MeV), a high-pressure gas cylinder system, a vacuum, electromagnetic ion beam control system, an electronic control system and automation of technological processes. The equipment of the complex is located in the building of the accelerator "tower" to 42 and the premises of two adjacent experimental halls (Fig. 1).

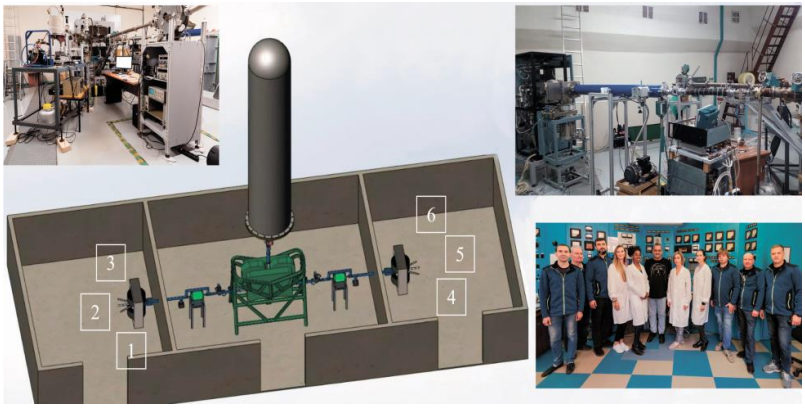

Fig. 1. EG-5 accelerator complex. 1 – Chamber for irradiation of silicon wafers (JSC Mikron); 2 – Chamber for irradiation with singly charged ions; 3 – Installation for studying reactions with the release of charged particles; 4 - Chamber of ion beam spectrometers; 5 – Microbeam spectrometer (within a few years); 6 – Installation for research using the channeling method [1].

The accelerated ion beam is distributed through ion pipelines to one of 6 channels (three for each experimental hall) equipped with terminal devices. Terminal devices are separate nuclear-physical installations, each of which is quite unique both within JINR and JINR Member States and Associate Members.

Naturally, among the accelerator units of the Joint Institute, EG-5 occupies its own unique niche.

Significant advantages of Electrostatic accelerator EG-5:
- high energy stability of ion beam;
- high intensity of ion beam;
- accelerated particles (H^+, He^+, D^+);
- accelerated voltage (from 1,1 MV to 3,5MV).

Areas of use of Electrostatic accelerator EG-5:
- Nuclear reactions with fast quasimonoenergetic neutrons;
- Ion Beam Spectrometry (Multilayer structures, isotope determination, elemental depth profiling);
- Radiation technologies (Science, technology, medicine, etc.).

Ion beam parameters of EG-5:
- Range of ion beam currents 0,01 - 30 μA (100 – 150 μA*);
- Ion beam energy range 1,1 – 3,5 MeV (4,1 MeV*);
- Energy resolution (H^+, He^+) - 15 keV;
- Charged particles flow (H^+, He^+) – 10^{12}–10^{13} part /s cm^{-2};
- Neutrons flow $5 \cdot 10^7$ pat/s cm^2;
- Neutrons energy 20 – 800 keV; 3,5 - 5,1MeV ± 0,1 MeV.

*- will be after modernization

The accelerator complex is not limited to ion beam spectrometers and irradiation chambers (Fig. 1). There is also a chemical laboratory synthesizing organic-inorganic perovskite structures (for solar energy harvesting and X-ray detection) and semiconductor CuO layers (tailored for nanostructured material-based solar cells), alongside an engineering center dedicated to developing functional architectures for nanoelectronics, nanosensors and renewable energy applications.

Appointment of the EG-5

Currently, particle energies up to 4-5 MeV are no longer of great importance for fundamental nuclear physics, but a range of various applications where EG-5 beams are needed, such as, in particular, bionanotechnology and interdisciplinary scientific fields. These studies are in demand, as evidenced by requests for results from international rating journals.

The "center of mass" of the spectrum of actual scientific problems for EG-5 has shifted in the field of applied research since its inception (1965). At the moment, several scientific areas have emerged in the sector, covering a wide range of the most pressing tasks of our time: from the development of promising electronics devices (homogeneous nanoelectronics) and the production of drought-resistant rice varieties to the study of astrophysical processes of stellar nucleosynthesis [2, 3, 4].

EG-5 unique opportunities

The accelerator system based on ESA EG-5 is multifunctional. In appropriate modes, it can be used as a source of ionizing radiation, as a tool for carrying out physical and chemical modification of materials, and, of course, as a spectrometric research instrument. For example, using fast neutrons with a narrow energy dispersion obtained by the (d-d) reaction on the accelerator EG-5 relatively high doses of radiation can be given to the test materials without inducing radioactivity in them. By implanting ions of inert helium gas, it is possible to significantly change in localized volumes of materials (near-surface layers) the field of mechanical stresses, than to induce structural-phase transformations or create the so-called "helium porosity." In the latter case, there is also a change in microstructure and atomic density. Helium porosity, like other radiation-induced defects, is a serious problem of radiation technologies and has always been a relevant subject of research [5, 6]. It should be noted that EG-5 is currently the only accelerator in JINR that allows such studies on helium in the energy range of 1-3.5 MeV. Implantation of hydrogen ions allows in strictly localized regions of the material to carry out partial chemical reduction of metal oxides, than to change the stoichiometric ratio of elements, i.e. to carry out chemical modification of materials. Implantation of ions into the crystal lattice of materials also allows changing their electronic structure and electrical properties, which is actively used in the electronic industry [7]. A significant advantage of accelerated implantation technologies is the accurate spatial localization of the implanted ions, and the presence of intermediate layers of material in the path of the ion beam is not a significant obstacle for this [8, 9].

Irradiation of biological objects with fast neutrons allows causing useful mutations for new varieties of agricultural products [4, 66, 67, 68]. Studies of neutron-induced reactions with the escape of charged particles provide valuable information about the mechanism of nuclear reactions and the structure of the atomic nucleus, the processes of stellar nucleosynthesis, etc. Recent significant results, indicating the need to clarify the existing ideas about the main neutron source in astrophysical processes - the $^{22}Ne(\alpha,n)^{25}Mg$ reaction, were obtained at EG-5 under the guidance of Professor Yu.M. Gledenov [1].

Within the last three years with use of EG-5 on fast neutrons sections (n, α) - reactions for ^{144}Sm, ^{66}Zn, ^{10}B, ^{25}Mg, $^{54,56}Fe$, $^{58,60,61}Ni$ elements were measured and at the moment together with Obninsk IPPE are conducted works on The Neutron Data Library BROND on a number of nucleus (^{6}Li, ^{14}N, ^{35}Cl, ^{91}Zr, ^{56}Fe) [10, 11].

Research of nuclear reactions

At the Van de Graaff accelerator of the FLNP JINR, the cross section for the reaction $^{35}Cl(n,\alpha)^{32}P$ was measured at a neutron energy in the range of 3.3-5.3 MeV [12].

Chlorine, widely distributed in nature, is one of the chemical elements necessary for man, and the content of the ^{35}Cl isotope is 75.77%. An experimental study of this reaction could complement the existing library of nuclear data and can be used to test the corresponding models of nuclear reactions, as well as to refine the parameters of the optical potential used in calculations of various astrophysical scenarios. The cross sections for the $^{35}Cl(n,\alpha)^{32}P$ reaction are useful for applications in nuclear technology. For example, they were used, to estimate the fast neutron flux during the JCO accident at the Tokaimura nuclear facility in 1999. The beta-radioactive product ^{32}P can be used to study the absorption of phosphate fertilizers by plants by radionuclide tracking. In addition, chloride is a component of the coolant of a molten-salt reactor, which is one of the six most promising GEN-IV reactors.

The physics of scattering of monoenergetic alpha particles by atoms of near-surface layers of matter is the basis of ion beam spectrometry methods. The uniqueness of these methods is due to the ability to study multilayer planar structures without destroying them by layer thinning, as, for example, when using the XPS method. Moreover, the sensitivity limit of ion-beam analysis is at least two orders of magnitude higher than XPS (is of the order of 10^{-3} – 10^{-4} atom %) [13]. It should be noted that ion-beam analysis methods allow for quantitative elemental analysis of light atoms, as well as isotopes. Using the EG-5 installation on helium ion beams, unique non-destructive experimental studies of elemental depth profiles with a depth resolution of about 10 nanometers are carried out. (RBS method) [14]. The high sensitivity of the method (up to 10^{15} atoms/cm^2 [15]) allows, for example, to determine the content of an impurity of heavy elements in an amount of 0.001 at.% [16] or to recognize a substance in the form of a layer up to 1 nm thick. In complex use, non-destructive testing methods (Elastic Recoil Detection (ERD), Nuclear Reaction Analysis (NRA), Particle Induced X-Ray Emission (PIXE)) based on proton and helium ion beams with energies from 1 to 3.1 MeV make it possible to determine with high accuracy the elemental composition and depth distribution in the near-surface layer of all elements of the Mendeleev's Periodic table and their isotopes (including hydrogen).

Characterization of elemental composition of materials

The elemental composition of glass/ITO/TiO_2/$CH_3NH_3PbI_3$-type functional structures for solid-state X-ray detectors in the form of thin films was investigated by XRD, RBS methods. The high spatial homogeneity of the obtained structures and the possibility of their further use for the manufacture of

radiation-resistant sensitive elements of a position-sensitive X-ray detector are shown [17].

Subnanoporosity of CaF_2-doped ErF_3 crystal by Rutherford Backscattering data

With use of a method of Rutherford Backscattering Spectrometry (RBS) the porosity of optical crystals of CaF_2 alloyed by ErF_3 (2.0 and 5.5%, respectively), received by the Bridgman method was investigated at the atomic level. The volume fraction and diameter of the pores present were found to range from 18 to 22% and from $2.4 \cdot 10^{18}$ to $3.0 \cdot 10^{18}$ atoms/cm^2, respectively [3].

He^+ ion implantation was applied to modify the structural properties of tin oxide films. On the basis of the X-ray diffraction analysis, it was found that both the initial and ion-implanted films are characterized by a multiphase structure consisting of SnO, SnO_2, and Sn_2O_3 phases. By means of the RBS method it was established that the implantation of He^+ ions with energy E = 2.4 MeV at an irradiation dose of $1.1 \cdot 10^{16}$ cm^{-2} into disordered films of tin oxides does not induce a significant redistribution between the content of Sn and O atoms through the whole films thickness [18].

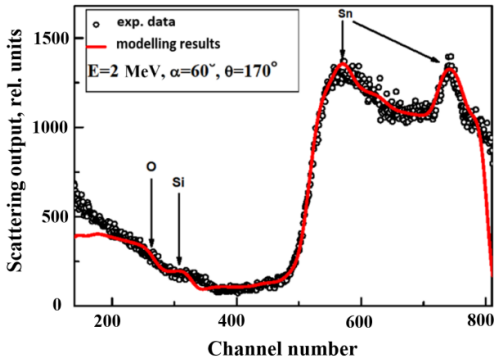

Fig. 2. Energy spectrum of tin oxides film in which He^+ ions with energy E = 2.4 MeV are implanted.

Surface and subsurface defects of dental alloys exposed to sandblasting have been investigated by using RBS and variable energy positron beam studies indicate shallow alumina deposition in material and show that small air pressure of 0.1 MPa is not enough to remove the most metal surface oxides completely in 60 s in all studied dental alloys [19]. It was observed that higher pressure causes the increase in roughness and damaged zone range. The type of defects was determined as vacancies and dislocations. The defect concentration decreases with the depth and depends on alloy's type and applied air pressure.

The irradiation-induced defects and their spatial distribution in pure (99.99% purity) polycrystalline iron samples after exposing of proton implantation with energies of 73 keV and 173 keV and doses of 3×10^{15}, 10^{16} and 3×10^{16} cm^{-2} were investigated by using Elastic Recoil Detection (ERD) and Variable Energy Positron beam (VEP) methods [9]. Analysis of VEP results was performed with VEPFIT code. The strong reduction of positron diffusion lengths in the implanted layers point out the presence of defects with high concentration. The thicknesses of these layers are in good agreement with hydrogen range evaluated by ERD. However, the presence of defects with lower concentration behind implanted zone was also detected when the free fitting was performed. The long-range effect cannot be excluded.

Using the technical capabilities of the EG-5 the fabrication by Swift Heavy-Ion (SHI) bombardment of nanometer-sized reduced graphene oxide (rGO) spots which can be considered graphene quantum dots (QDs) embedded in a non-conducting matrix was found. It were shown that both the number density and the diameter of the rGO spots can be tailored by a suitable choice of irradiation parameters (i.e., ion type, fluence, and energy). It was found that the degree of graphene oxide defunctionalisation by SHIs with different energies scaled well with the deposited electronic energy density. It was shown that the resistance of the samples decreased nonlinearly with increasing ion dose and, at fluences above 10^{13} ions/cm^2, was orders of magnitude lower than the initial value. It was found that an increase in the electronic stopping power of the ion resulted in suppression of the structural ordering at low fluences and in increased amorphization efficiency and formation of *sp*-hybridized carbon chains of both polyynes and polycumulenes at high influences. A hypothesis suggesting that the *sp*-C chains are bridges joining opposite sides of nanoholes created inside the track core and thus assuming the formation of a coupled QD-antidot system is presented. These phenomena were found to be absent in comparative experiments with 200 keV Xe ion irradiation, i.e., in the nuclear stopping regime [20].

Investigation the changes of mixing degree for implanted TiO_2/SiO_2 with changing of energy and mass of incident ion

The investigation of depth distribution of elements in the multilayer structures of $TiO_2/SiO_2/Si$ before and after ion irradiation was provided by using of EG-5 facilities. On the samples which were implanted with Ne^+, Ar^+, Kr^+ or Xe^+ ions with the energy 100, 150, 200 and 250 keV the transition layers existing between the TiO_2 and SiO_2 layers was found by using the Rutherford Backscattering Spectrometry method. Formation of these layers derived from the ion beam mixing that was occurred at TiO_2/SiO_2 interface after irradiation process. The depth profiles show that thickness of the transition layers increased with the growing energy and atomic mass of the implanted ions [5, 21]. The variation of the transition layer thicknesses of TiO_2/SiO_2 before and after the ion irradiation were investigated using the relative thickness. The values increase with increasing of ion's energy and mass, this behaviour corresponds with increasing of the energy transfer to the recoil atoms in the transition layers (calculated by SRIM software). Based on a comparison, contribution of decreasing FWHM to mixing is not significant, in contrast the displacement of the Ti atoms across the interface is predominant contributing to the broadening of the mixed layers towards the substrate more than that in the opposite direction.

Investigation of changing in chemical composition and optical properties of TiO_2/SiO_2 before and after irradiation

In addition to ion beam spectrometry, the group actively uses complementary methods for studying the physical properties of the surface, in particular, spectroscopic ellipsometry, impedance metering and volt-amperometry. These methods make it possible to characterize the electrical, electronic and optical properties of the studied objects.

The XPS spectra obtained from the original and implanted samples have different shapes and the intensity of the bands changes. It was found that under the influence of impinging ions, the intensity of the Ti and TiO_2 bands decreases, however, that of TiO and Ti_2O_3 increases with the increasing of energy from 100 to 250 keV. Decreasing concentration of TiO_2 after irradiation lead to increasing of deposited energy which is reflected in increasing amount of mixing or broadening of transition layers, this shows a good agreement with RBS method. Ellipsometric measurements of the material before and after ion implantation show a correlation between in the yields of the bands and the angle of incident ion beam. This is associated with the interference processes of light reflected from the examined structure. The refractive index *n* and the extinction coefficient *k* have been found to increase after implantation up to 200 keV then to decrease at 250 keV Xe ion. Furthermore, the increasing of the thickness of transition layers between the TiO_2 and SiO_2 materials that has been observed in the ellipsometric measurements are in good agreement with the RBS results [22].

The study of the effect of 250 keV Xe^+ implanted to GaAs samples with the ion fluence from 1×10^{12} to 3×10^{16} ions/cm^2 was made [8]. The spectroscopic ellipsometry approach reveals that the pseudo-dielectric function of implanted GaAs samples and the RBS exposes the depth-profile of As, Ga, and Xe in the implanted samples. The Nuclear reaction (NR) points out the existence of an oxygen-enriched layer on the surface of implanted GaAs samples.

An RBS/NR study was verified the presence of an relatively dense oxygen layers on the surface of the Xe^+ ion implanted GaAs samples with the fluence 3×10^{16} cm^{-2} in comparison with original sample. The changing in chemical composition of Ga and As atoms in the near surface layer and the presence of Xe in the samples reflects in the form of the changing of the channel number on the spectrums from 700 to 850 (Fig. 3, a).

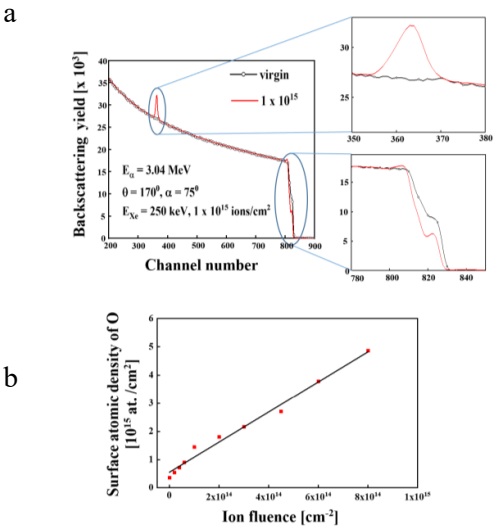

Fig. 3. RBS/NR spectra of samples before and after implanted.

This indicates a difference in diffusion process of Ga and As atoms during the ion irradiation with different fluence. The embedding of the implanted element (Xe element) into GaAs samples causes the change of atomic density. These changes are related to the increasing of the vacancies formed in the near surface layers of implanted GaAs. The number of vacancies produced during irradiation depend on the ion fluence. The thicknesses of the native oxide layers were determined based on RBS/NR spectra due to performing measurements at different energies of incident α particles. Was found that the thickness of the native oxide layer is a function is a linear function of the fluence in the range from 2×10^{13} up to 8×10^{14} ions/cm^2.

Engineering Oxide and Semiconductor Structures with Ion Beams

On semiconductor materials, together with the Department of Semiconductor Electronics and Semiconductor Physics, NUST MISIS, Moscow, a number of successful experiments were carried out with the irradiation of semiconductor crystals [6, 23, 24].

Reverse current recovery time is an important characteristic of diodes and transistors, determining their operating frequency and application. Defects in the semiconductor structure can significantly delay the recovery of the reverse current, reducing the speed of the device and leading to additional heating. Papers [6, 23, 24] present the results of determining the recovery time of a small reverse current in Schottky diodes based on α-Ga_2O_3 (Sn), β-Ga_2O_3, γ/β-Ga_2O_3 and NiO/Ga_2O_3 films. Measurements were made by applying current pulses of different polarity to the diode and taking a reverse current relaxation curve. It has been shown that in diodes based on the above films on their own substrate, the characteristic time of reverse restoration of small currents can reach 20 μs and is limited mainly by the characteristic decay time for the RC chain formed by the structure.

Irradiation of structures such as α-Ga_2O_3 (Sn), β-Ga_2O_3, γ/β-Ga_2O_3 and NiO/Ga_2O_3 with protons with an energy of 1.1 MeV leads to the appearance of a large number of defects inside the structure that can "work" as deep centers of carrier capture. In this case, thermal ejection of carriers from such centers can delay the relaxation of the reverse current recovery, slowing down the switching process. In the α-Ga_2O_3 sample after irradiation, the characteristic switching time was 6 μs, which is twice the time that would be expected based on the parameters of the equivalent RC chain.

The delay in the relaxation of the reverse current is determined not only by the discharge time of the RC chain, but also by the large number of deep centers that can be introduced by irradiation or occur during the growth or operation of the device. Using admittance spectroscopy and deep-level relaxation spectroscopy, data were obtained on the nature of the capture centers that slow down the process of switching the diode at room temperature: these are probably interstitial oxygen atoms. The obtained results can be used to improve crystal growth technology for producing Schottky diodes with high boundary frequency.

1.1 Powder Nanotechnologies

Functional transition for homogeneous electronics technologies

For the first time, a rectifying contact in the form of chemically homogeneous hydrated nanoparticles of the ZrO_2 –Y_2O_3 system, which is based on the dimensional effects of distortion of the zone structure by the surface of low-dimensional objects has been practically implemented and investigated. The use of new physical principles to obtain a rectifying contact on the specified model object opens up prospects for solving the problem of diffusion instability of chemically inhomogeneous heterostructures, which significantly limits the applicability of classical semiconductor devices under conditions of elevated temperatures and ionizing radiation. The prospects of creating homogeneous electronics devices that allow operation in harsh physical conditions, with optical transparency, mechanical strength, biocompatibility (in the case of using YSZ systems) and the ability to scale into a submicroscopic size range are shown [2]. Prospects for creation of homogeneous electronics devices of considerable interest for critical technologies.

In the framework of the Tamm theory of surface states and the generalized Seitz–Madelung model, the electronic structure of the near-surface states of nanoscale ion crystals was modeled with regard to ionic crystals, taking into account the Coulomb range and dispersion of electronic properties depending on the curvature of their surface (Fig. 4,b) [25]. The possibility of realizing the varizonicity (graded band-gap) of the electronic structure in chemically homogeneous ionic crystals, predicted earlier in [26, 27] was shown. The possibility of using the obtained structure to convert the energy of moisture adsorption into an electrical form was shown.

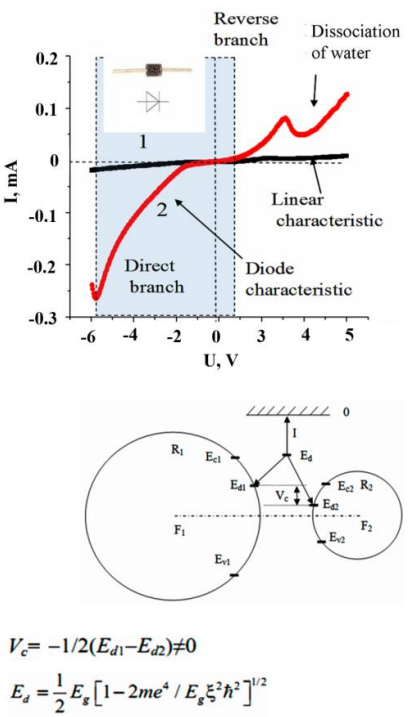

Fig. 4. The VAC of the nanoparticle contacts with the same (7.5 nm, curve 1) and different (7.5 and 9 nm, curve 2) nanoparticle diameters **(a)** and the schematic interpretation of the rectifying contact effect **(b)**.

1.2 Nanopowder metal-oxide ionistor

As part of studies of the processes of charge and material exchange of nanoscale systems with the external environment, a new dimensional effect of accumulation by the system of compacted zirconia nanoparticles (ZrO_2-3% mol Y_2O_3) of an electric charge with a density of up to 270 μF/g during exposure in an electric field (5000 V/m) under normal physical conditions was established [28]. Based on a qualitative complex analysis, it was shown that the object of localization of different charge carriers is the surface of nanoparticles. In the framework of the theory of dispersed systems, zone theory and the theory of contact phenomena in semiconductors, the proposed mechanism of effect is considered [29, 30]. It was concluded that it is caused by the phenomenon of localization of electron-type charge nanoparticles L^1 in the near-surface zone of the material (Fig. 5) in contact with the adsorption ion atmosphere. The effect is relevant for modern subvolt nanoelectronics, microsystem technology.

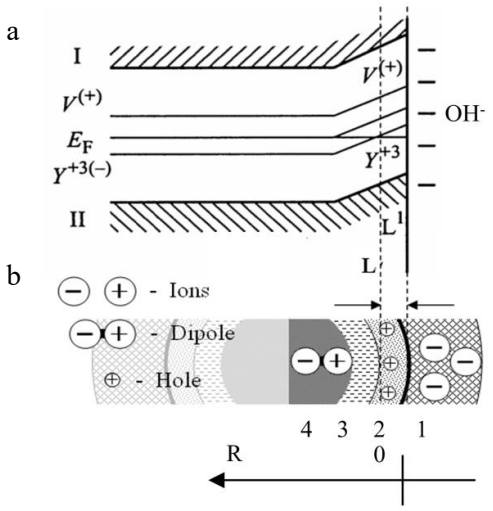

Fig. 5. (a) Qualitative band model of the surface of the ZrO_2-Y_2O_3 system with chemically adsorbed quasi-water molecule (OH^-). The surface is negatively charged.
I – conduction band;
II — valence band.
(b) Spatial distribution of charge in the nanoparticle volume and beyond.
1. Hydration shell.
2. Hole conductivity layer (L^1).
3. Field penetration area (L).
4. Neutral dielectric core of the nanoparticle.
R is the spatial coordinate [29].

In the framework of joint studies of dimensional phenomena, theoretical work to study the effect of radiation on the conformation of DNA molecules [31, 32]; processes of self-organization of nanopowder systems based on ZrO_2 in conditions of high hydrostatic pressure [33]; influence of group IV elements on sintering kinetics of ZrO_2 nanopowders [34], on the development of semiconductor heterostructures based on linearly ordered nanoparticle ensembles [35], heterodyne frequency spectrum converters for bionanoelectronics devices [36], nanosensorics devices [37], organo-inorganic perovskite photovoltaics [38-42] were conducted. Important scientific tasks of clarifying of nuclear data on the reactions of stellar nucleosynthesis and the study of the mechanisms of the influence of cosmic radiation on the evolution of animate organisms of the Earth on the example of rice seeds [43].

2 Radiation materials science

The admixture of helium atoms in materials is a typical product of (n, α) transmutation reactions initiated by neutron irradiation. Controlled introduction of impurity He into the test material using an ion beam is extremely promising as an alternative to long, complex and expensive experiments in a research nuclear reactor. The main problem with ion beam experiments is the significant heterogeneity of the ion doping profile, and therefore there is a certain difficulty in determining a relationship between the observed structural changes and the amount of impurity incorporated. With the use of a special target unit, which makes it possible to solve this problem by obtaining an ion doping profile in the sample that is uniform in the depth of stopping the embedded ions at the LNP accelerator EG-5 uniform doping with He ions (2,5 MeV) was carried out for the first time model samples made of 08Kh13 steel, the principle [44] and the design of a special target unit and software for determining the accumulated ion doping profile in real time of the experiment were tested. The helium-embedded steel samples obtained in the experiment were then used for electron microscopic observation of the development of gas porosity (during annealing) in helium-doped ferritic steel to a given concentration.

Light ion irradiation opens up new possibilities in controlling the properties of semiconductor materials. As part of work with the Arifov Institute of Ion-Plasma and Laser Technologies, studies were carried out on the radiation resistance of a metastable α-Ga_2O_3 that is promising for applications in radiation-resistant devices for opto-, micro- and nanoelectronics. Using the Rutherford Backscattering (RBS) method, voltammetry and impedance spectroscopy, the mechanism of radiation-induced processes in semi-insulating films of α-Ga_2O_3 and β-Ga_2O_3 was investigated. It has been shown that the radiation resistance of these materials relative to electrical properties exceeds the radiation resistance of the advanced material GaN. The determining role in the formation of radiation properties of the specified materials of Ga-vacancies, divacancy defects of Ga-O type and processes of their segregation near the surface is shown [45].

In single-crystal silicon samples and *n*-type films doped with P and Pt and Sn obtained by vapor deposition (by HVPE method), the effect of proton irradiation on electrical properties depending on the donor concentration was studied [46]. The effect of proton irradiation on the concentration of optically active oxygen in silicon samples was studied, and the types of radiation-induced defects were determined.

Due to the severe consequences of accidents with loss of coolant (abbreviated as LOCA - Loss of Coolant Accident), research is underway in the world to create emergency-resistant fuels (ATF). One of the directions is the preservation of zirconium-based alloys as fuel cladding materials by creating corrosion-resistant coatings on their surface in contact with the coolant. One of the materials studied as a coating is chromium, the oxide of which is Cr_2O_3 an effective oxygen barrier.

As part of joint work in the field of radiation materials science with specialized organizations, we have developed a unique technology for obtaining radiation-resistant chemical-inert coatings [47], radiation resistance studies of the corresponding ceramic materials [48, 49], non-stoichiometric TiZrCN coatings were carried out, TiZrNbCN and TiZrSiCN, it has been established that there are no changes in the morphology of coatings after irradiation with protons with an energy of 2.0 MeV at flows up to 10^{17} ion/cm^2, a promising method for protecting the inner surface of fuel element claddings made of EP823-Sh steel has been developed. The mechanism of liquid metal corrosion of

chromium steels of EP823-Sh type of ferrite-martensitic class used in reactor technologies has been investigated. Selective dissolution of steel components from the surface when interacting with molten lead under radiation conditions was recorded.

A significant dependence of the process on the oxygen content on the contact surface of the liquid and solid phases has been determined. It is shown that if oxygen concentration is less than stoichiometric value, corrosion products are formation of external oxide layer of magnetite, chromium spinel of non-stoichiometric composition of $Fe(Fe_{1-x},Cr_x)_2O_4$ type. The development of the internal oxidation zone along the grain boundaries has been established [50]. A unique method has been developed to prevent radiation-induced corrosion of the inner surfaces of steel fuel shells made of EP823-Sh steel with mixed nitride fuel, planned for use in the reactor BREST-300-OD by forming a special coating based on chromium [51].

The results of corrosion tests of chromium coating applied to the inner surface of the EP823-Sh steel shell by electrolytic deposition are presented. Electron microscopic studies of chromium coating on steel EP823-Sh did not reveal significant signs of corrosion damage during tests in the environment of fission product simulators (CsI + Te) and in liquid lead at a temperature of 650°C. Analysis of the interaction in the "coating-steel" system showed the prospect of using chromium as a protective coating on the inner surface of the fuel element cladding made of EP823-Sh steel [52].

Alloying with Si or Nb has not been found to affect the grain size of ceramic coatings, but leads to "swelling" of the grains after proton irradiation due to the accumulation of defects in the form of vacancies. All tested TiZrCN, TiZrSiCN and TiZrNbCN coatings showed good radiation resistance.

The effect of proton irradiation with a power of $1 \cdot 10^{17}$ units/cm^2 and an energy of 2 MeV on the structure and properties of composite ceramics of the composition ZrO_2–SiO_2–Al_2O_3 is shown [53]. It has been determined that at this irradiation dose, the phase composition of the ceramic does not change. Calculations using X-ray diffraction methods have shown that proton irradiation creates compressive stresses (stresses of the 1st kind) ranging from ~ –1 to –2 GPa on the surface of field ceramics, while microstresses (stresses of the 2nd kind) are practically absent. Analysis of SEM images of the ceramic surface after irradiation showed a chaotic arrangement of macropores in the t–ZrO_2 matrix, while pores in zircon particles are located exclusively along the boundaries of inclusions. A decrease in the level of hardness and density in ceramics after proton treatment was noted due to the formation of a large number of pores [54].

The work at the ESA EG-5 is underway to obtain radiation-resistant ceramics. The effect of processing powders with high hydrostatic pressure (HHP) (300, 500, 700 MPa) and stabilized zirconium dioxide (ZrO_2 + 3 mol.% Y_2O_3, (YSZ)) doping on the compaction of metastable nanopowders mixture with γ/θ-Al_2O_3 + n% YSZ (n = 0, 1, 5, 10, 15wt.%) composition during sintering was analyzed. It has been determined that sintering of compacts occurs in two stages: compaction of γ + θ-Al_2O_3 (I-st stage metastable phases), compaction of the stable α-Al_2O_3 (II-nd stage), accompanied by inhibition between them. A connection between the above mentioned inhibition and an increase in the YSZ additive was found. That, also, correlates to the effect of "mutual protection against crystallization" of Al_2O_3 – YSZ powder mixtures. A study of the mechanisms and activation energies of γ/θ-Al_2O_3 + *n*% YSZ systems' (*n* = 0, 1, 5, 10, 15 wt.%) sintering depending on the YSZ additive amount and the HHP value showed that a dopant and pressure increase leads to activation energy decrease of the initial sintering stage, and the prevailing sintering mechanism is volumetric diffusion in corundum grains. Also, the work shows that for γ/θ-Al_2O_3 + ≥5wt.% YSZ systems, the optimal compaction pressure is HHP ≥ 500 MPa, which corresponds to the transition of the sintering mechanism from grain-boundary diffusion to volumetric diffusion.

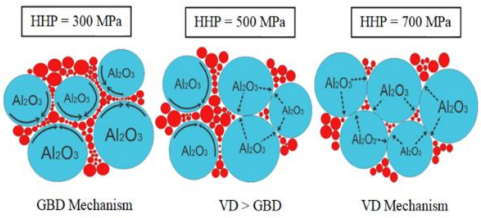

Fig. 6. Schematic representation of the effect of HHP on the sintering mechanism and the distribution of YSZ (at a concentration of ≥5wt.%) in the aluminum oxide matrix at the initial stage of sintering (● - YSZ; ● - Al_2O_3).

The paper [55] presents the results of the study of the structure and physico-mechanical properties of ceramics composites α-Al_2O_3 + *n* Y_2O_3 (*n* = 0; 0.5; 1; 1.5; 2; 3; 4; 5 wt.%) based on the polymorphic modifications γ/θ-Al_2O_3 depending on the concentration of the Y_2O_3 doping impurity and annealing temperature of the powder mixtures (800 and 900°C). The effect of mutual protection against crystallization was discovered, which results in mutual inhibition of crystallization processes in Al_2O_3–Y_2O_3 powder systems. The formation of a phase of yttrium-aluminum garnet $Y_3Al_5O_{12}$ (YAG) in ceramics has been established by X-ray diffraction analysis (Fig. 7). The dependence of the mechanical characteristics of the materials under study on the amount and size of the formed phase YAG has been revealed.

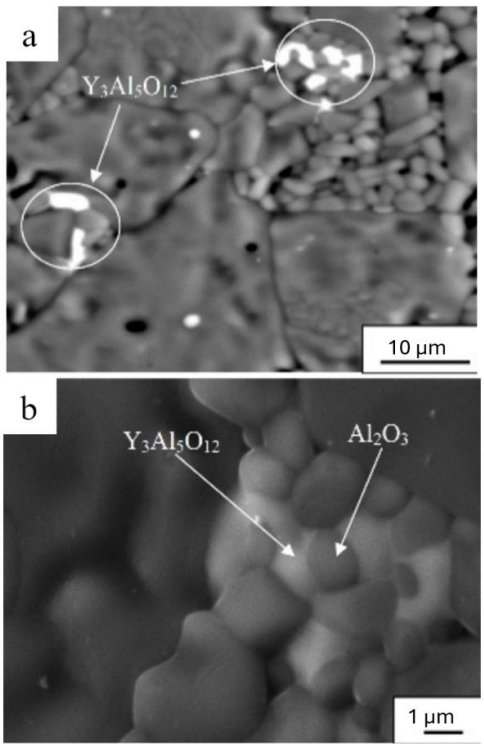

Fig. 7. Surface structure of ceramic samples of the composition Al_2O_3 + 0.5% Y_2O_3, sintered at a temperature of 1550°C from powders annealed at 800°C.

Neutron irradiation of plant seeds is a technique used to induce genetic mutations, often for the purpose of developing new plant varieties with desirable traits such as disease resistance or stress resistance, increased yield, and nutritional content [56-59]. However, successful application in breeding programs requires careful optimization of irradiation doses and a deep understanding of the balance between mutation induction and genomic stability. We conduct neutron irradiation studies on two cultures - rice *(Oryza Sativa)* and triticale *(× triticosecale*) at the EG-5 accelerator. Rice irradiation allowed obtaining mutant forms resistant to salinity and drought factors. Mutants forms of M3 generation with desired properties will be used in further in synthetic rice breeding [60, 61]. Triticale irradiation helped to induct plant variability [62]. These findings collectively highlight the potential of neutron irradiation to contribute significantly to advances in plant genetics and breeding.

As part of the work on the development of new-generation X-ray detectors for medical applications, the radiation resistance of new architectures based on organo-inorganic perovskites such as: PEDOT:PSS | P-TPD (30nm)| PVK (5nm) | G-22 QD (1) и PEDOT:PSS | ---| --- | G-22 QD | C60 | BCP (2), provided by the Frumkin Institute of Physical Chemistry and Electrochemistry of the Russian Academy of Sciences.

The radiation resistance of structures under conditions of continuous irradiation for 60 min was determined by Voltammetry (Potentiostat P-45X, Ellins. Chernogolovka, Russian Federation). The family of obtained V-I curves are shown on Figure 8. It can be seen that during the irradiation time with relatively intense X-ray fluxes of 1.7 x 10^{14} photons / s cm^2, the sample was resistant to radiation exposure.

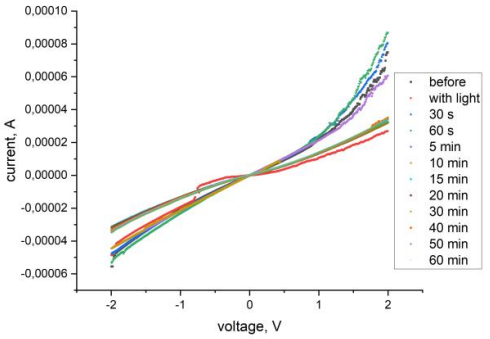

Fig. 8. The V-I family under irradiation flows of light and X-ray quanta.

An increase in current above the initial value (by about 12%) was observed, presumably due to photogeneration. It should be noted that the flux of light quanta on these samples did not lead to significant photogeneration. After exposure for 5 minutes, a sharp decrease in current (3 times) was observed, presumably due to radiation damage to the crystal structure/microstructure of the sample. During the 60 minutes during which the test was carried out, the functional heterojunction showed weakly pronounced semiconductor properties. It is concluded that the provided structures are sufficiently resistant to the effects of powerful X-ray fluxes and, probably, in the pulsed mode (micro- and millisecond pulses) they will be able to work for a long time (decades) in the form of matrix sensors of medical radiographic devices with a reduced dose load.

Since September 2021 there is an Ion Beam Analysis (IBA) active cooperation between Cuban and EG-5 researchers looking for the characterization of several functional materials developed by Cubans researchers in cooperation with colleagues of other countries, mainly from Mexico. Promoted by the EG-5 Group, in 2023 and 2024 cooperation agreements JINR-UH were signed to support this cooperation. Till December 2024 thirteen Research Problem Statements were proposed by Cubans researchers to study a variety of materials (PZT:Gd and lead free KNN ceramics, CuO/ZnO heterostructures, ZnO nanorods, Cu plasmonic nanoparticles into Cu_2O thin films, CZTS thin films growth by Isothermal Close Space Sublimation, CuO and CuO/CuO structures, Mo ground by DC and GaN, CdS, NRZnO/ZnO/ITO, CdS/ITO ground by RF Sputtering nanostructured films, TiO_2/CuO/FTO, PbS, PbS/CdS/ITO, powder from a fallen meteorite in the Viñales National Park Cuban area and zeolite material for agriculture, health and

environment protection applications). Two young's Cuban researchers from the UH were trained at EG-5 in 2023. In the period 2022-2024, RBS & PIXE measurements and irradiation experiments were carried out at the ESA EG-5 to study around one hundred samples of seven Cuban groups. Since August 2024, a UH young doctorate student started to work at EG-5 for three years, and a JINR (EG-5) - UNAM (LEMA) - UH (IMRE & InSTEC) Project to *Study of zeolites for agriculture, health and environment protection applications* with several methods like IBA, AMS, NAA and D&AC, it´s carrier out. The main scientific results of this cooperation were presented in international [63-66] and national [7] conferences. Quantitative compositional characterization of $(K_{0.44}Na_{0.52}Li_{0.04})_{0.97}La_{0.01}Nb_{0.9}Ta_{0.1}O_3$ and $Pb(Zr_{0.53}Ti_{0.47})O_3$:Gd ceramics first time was reported and samples stoichiometric composition determined in two directions on each studied sample by RBS shows that powder encapsulation grown method is adequate to avoid the evaporation of K, Pb, Na elements [63-65, 67]. The structural changes and defect formation in the nanostructured CuO layer resulting from the sequential thermal treatment were studied [66].

3 ESA EG-5 Modernization

A significant part of the accelerator's capabilities cannot be realized at the moment and an urgent problem is the physical wear of the main units and installation systems and the moral aging of the scientific and experimental base. It should be noted that the problem of obsolescence and stopping of accelerators over the past 30 years in the Russian Federation was of a systemic nature. To solve this technical problem, in the framework of the JINR Seven-Year Development Plan for 2023-2030, which provides for the concentration of resources for updating the accelerator and reactor base of the Institute [68], V.N. Shvetsov, Director of the Frank Laboratory of Neutron Physics, initiated a project in 2023 to modernize the EG-5 accelerator and its experimental infrastructure.

Currently, the EG-5 accelerator is in the process of planned modernization. As part of the 03-4-1146-2-2022/2026 JINR Problem-Thematic Plan [69], the project 03-4-1146-2-2022/2026 "Modernization of the EG-5 accelerator and its experimental infrastructure" is being implemented. As a result of the implementation of the project in 2024, in cooperation with the G.I. Budker Institute of Nuclear Physics SB RAS, the parameters of the high-voltage system of the EG-5 accelerator will be significantly improved: the ion source will be replaced with a modern UHF analogue with fiber-optic control; the accelerating tube will be changed to an analogue with condenser-type ion optics; the setup for ion-beam elemental analysis of planar objects will be modernized (replacement of the high-vacuum steam-oil pump with a modern a turbomolecular analogue, installation of the setup chamber on a vibration-proof foundation, replacement of the signal processing module with a modern analogue developed at JINR, improvement of overall performance of the setup by optimizing the arrangement of the vacuum system elements).

The modernization of the high-voltage accelerator system will bring us closer to solving the main technical tasks of the project – restoring the energy range of accelerated particles: 900 keV - 4.1 MeV and increasing the ion beam current to 100-250 μA while maintaining energy stability at a level of no worse than 15 eV and its spatial stability sufficient to implement the microbeam spectrometer/nuclear microprobe option. Activities in the framework of the project in 2024 will enable us to get closer to solving the problem of creating a neutron source (energy ranges of 20 keV - 1 MeV and 3 - 5.1 MeV, fluxes of up to 10^7 particles/s cm^2), which makes it possible to study neutron-nuclear reactions (measurement of energy spectra and angular distributions of charged particles from reactions (n, α) and (n, p) / (α, n) and (p, n), integral and differential cross sections of the latter), radiation resistance of solids and conduct studies of various objects using nuclear physics methods [70, 71]. Also, in 2024, it is planned to develop complementary experimental techniques for studying the structure, microstructure, optical, electrical and electronic properties of near-surface layers of solids.

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