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Radiation-induced degradation effects of optical properties of MgO ceramics caused by heavy ion irradiation

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ABSTRACT

The paper presents the results of a study of the connection between structural changes caused by irradiation with heavy Xe^{22+} ions in MgO ceramics, which are characteristic of the damage accumulation caused by exposure to nuclear fuel fission fragments. Interest in this type of ceramics, as one of the promising classes of dielectrics, is due to the potential for using them as materials for creating a matrix that holds fissile nuclear fuel, and in the case of consideration of these ceramics as dopants used to enhance the resistance of inert matrices to destruction caused by irradiation. The obtained assessment results of the alterations in the transmittance coefficient for irradiated ceramics contingent upon the irradiation fluence indicate the transmittance degradation of irradiated ceramics in the UV range, caused by the accumulation of structural distortions caused by irradiation, alongside a growth in the concentration of absorbing centers and oxygen vacancies. It has been established that the dominant type of defects in the damaged layer are oxygen vacancies, the accumulation of which occurs due to deformation distortions and the rupture of chemical bonds. At the same time, the observed change in the crystal structure volume is due to the formation of complex defects of the Mg + V_O type, the formation of which results in deformation broadening of the crystal lattice parameters.

1. Introduction

The key objective of the presented study is to determine the destruction mechanisms of the near-surface layer of MgO ceramics caused by the accumulation of structural damage and vacancy defects in the case of high-dose irradiation with heavy Xe ions, characteristic of the effects of deep overlapping of structurally disordered regions formed along the trajectory of ion movement in the material. The initiation of structural change processes caused by heavy ion irradiation is comparable to radiation damage caused in the near-surface layer material by fission of nuclear fuel when placed in an inert matrix [1–3]. At the same time, the study of the near-surface layer destruction is determined not only by the expansion of the understanding of the radiation damage mechanisms, especially in the case of high-dose irradiation with heavy ions, but also by the determination of the destabilization mechanisms of strength and thermal physical parameters necessary for determination of the critical points of applicability of these materials as inert matrices [4–7]. At the same time, the unique combination of thermal-physical parameters (the thermal conductivity coefficient is more than 70 W/(m × K), and the high melting point (more than 2800 °C), in combination with strength parameters, alongside low density, makes this type of ceramics one of the promising materials for nuclear power engineering, including the possibility of creating inert matrices on their basis, as well as use in the creation of radiation-resistant transparent glasses used in conditions of heightened radiation background [8–10]. It is also important to understand the radiation damage mechanisms in the MgO structure when using them as optical elements used as output windows for laser and ultraviolet devices operating under conditions of heightened background radiation, not only exposure to heavy ions, but also neutron irradiation. The results of high dose heavy ion irradiation experiments under certain assumptions can be used to compare structural changes caused by neutron exposure to the material, taking into

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account the ion range and, as a consequence, the damaged layer thickness. In this case, the change in the optical characteristics of ceramics caused by irradiation and associated with the formation of vacancy defects in the damaged layer, as well as absorption centers, can have a significant impact on the potential applicability of these materials in laser devices, since a reduction in transmittance is a key factor determining the operating modes and service life [11–14].

It should be noted that much attention to the study of the radiation damage mechanisms in MgO ceramics was focused on experiments related to neutron irradiation, the result of which were the dependences of changes in the optical, strength and thermal parameters of ceramics [15–18]. Moreover, the first works on this topic date back to the 60–70s, in which the results of the study of the radiation damage kinetics in MgO ceramics as a result of neutron irradiation, as well as their role in changing the properties of materials, were obtained [19,20]. At the same time, interest in this topic does not subside, and in light of the latest trends in the development of the nuclear industry and the prospects for the transition to new generation reactors, interest in the study of candidate refractory materials, in particular, oxide ceramics such as MgO, Al_2O_3, BeO, ZrO_2, $MgAl_2O_4$, is increasing many times over due to the possibility of using them as inert matrix materials, radiation-resistant materials for creation of glass, etc. [21–24]. It should also be noted that the use of these ceramics as radiation-resistant materials requires research not only into their resistance to neutron irradiation, but also into the effects of heavy ions comparable to the effects of nuclear fuel fission fragments, which will make it possible to determine their damage resistance when inert matrices are used as materials.

2. Materials and methods

The studied samples were MgO ceramics obtained by solid-phase sintering under pressure, which made it possible to obtain highly ordered ceramics with a cubic type of crystal lattice, possessing fairly good transparency indicators in the UV range and visible light. The initial powders were magnesium oxide with grain sizes of about 1 μm, chemical purity of about 99.95 %, purchased from Sigma Aldrich. The samples were sintered in a muffle furnace at a temperature of 700 °C, which was chosen for the purpose of thermal relaxation of deformation distortions that arose during compression of the samples during pressing, the annealing time was about 10 h, after which the samples cooled together with the furnace for 20 h. The pressure at compression was about 250 MPa. The thickness of the samples was about 20–25 μm; this thickness was achieved by grinding the back side of the samples after pressing in order to thin the ceramics to the thickness required for conducting experimental work involving heavy ion irradiation.

Irradiation with heavy Xe^{22+} ions with an energy of 230 MeV in order to simulate radiation damage comparable to the impact of fission fragments was carried out at the heavy ion accelerator DC-60, located in the Astana branch of the Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan. The current density was about 10–15 $nA/cm^2 \times s$, the irradiation time varied from 10 min to two days depending on the irradiation fluence.

Irradiation fluences were selected in the range from 10^{11} to 10^{15} ion/cm^2, the choice of which was based on the possibility of simulation of the structural deformation processes arising as a result of interaction both in the case of isolated structurally altered regions, the sizes of which can be of the order of 1–10 nm in diameter, and their deep overlap, the result of which is the formation of highly disordered inclusions in the structure that do not have short-range structural order. The choice of the ion type was determined by the possibility of simulation of the impact of nuclear fuel fission fragments on materials, which is typical for fission reactions during the operation of these materials as structural materials. The choice of irradiation fluences was determined by the possibilities of simulation of the effects of the formation of single structural damage and the effects of deep overlapping of defective areas in the damaged layer. An increase in the irradiation fluence above 10^{12}–10^{13} ion/cm^2 leads to the formation of the effect of overlapping defective inclusions in the damaged layer, which creates additional structural damage and high concentrations of defective inclusions in the form of vacancy and point defects, the presence of which can lead to an acceleration of the degradation processes of the damaged layer.

The lower limit of the selected fluence range is due to the possibility of forming single isolated structurally altered areas in the damaged layer, the presence of which is associated with the formation of point defects. The upper limit of the irradiation fluence (10^{15} ion/cm^2) was chosen to simulate the processes of deep overlapping of defective areas, and to assess structural changes in the case of multiple overlapping, resulting in destabilization of the damaged layer, alongside possible amorphization.

Irradiation was carried out at room temperature; the effect of thermally stimulated relaxation of defects, which could arise as a result of heating the target, was excluded by irradiating the samples on a water-cooled target holder, which results in neutralization of the effect of thermal action on structural changes in the damaged layer. An analysis of the ionization loss values of the studied ceramics during their interaction with heavy Xe^{22+} ions with an energy of 230 MeV revealed that the main role in the structural changes is played by effects associated with changes caused by the interaction of ions with electron shells, as a result of which the ionization effect of the damaged layer is formed (see Fig. 1a). The calculations were performed in the SRIM Pro software code, using a model that takes into account the formation of cascade effects during irradiation [25].

It should also be noted that the resulting thermal effects caused by the transformation of the transferred kinetic energy into thermal energy as a result of the interaction of the incident ions with the crystal lattice should also be taken into account when describing the observed structural changes, especially in the case of high radiation doses. Fig. 1b shows the assessment results of alterations in the value of atomic displacements caused by irradiation in the near-surface layer along the ion trajectory in the material, as well as in the maximum of the ion path length, caused by the loss of ion energy as a result of elastic and inelastic interactions. According to the data presented, the most significant changes in the atomic displacement values are observed for samples irradiated with a fluence of 10^{15} ion/cm^2, for which the damage value is about 1.4 dpa, which is comparable with a neutron flux of about 10^{21} neutron/cm^2 (for the case of irradiation with neutrons with an energy of more than 0.1 MeV). In this case, the occurrence of such effects causes the formation of deep overlapping areas of structurally deformed inclusions in the structure, which in turn can result in destabilization of the damaged layer.

The study of the effect of structural changes caused by irradiation with heavy ions Xe^{22+} in the damaged layer of ceramics was carried out using the method of comparative analysis and processing of optical transmission and absorption spectra, alongside changes calculated on their basis, associated with variations in optical density and irradiation-induced absorption. These spectra used for further processing and interpretation of the obtained data on the dependence of changes on the radiation damage degree at irradiation fluence growth were obtained on a SPECORD 200/210/250 PLUS UV spectrophotometer (Analytik Jena, Jena, Germany).

The definition of the refractive index ($n^{optical}$) was calculated using formula (1) [26,27]:

$$\frac{\left[\left(n^{optical}\right)^2 - 1\right]}{\left[\left(n^{optical}\right)^2 + 2\right]} = 1 - \sqrt{\frac{E_g}{20}} \tag{1}$$

The determination of the optical transmission ($T^{optical}$) and refraction loss (R^{loss}) values was performed using calculation formulas (2) and (3), respectively, which were taken from the works [26,27]:

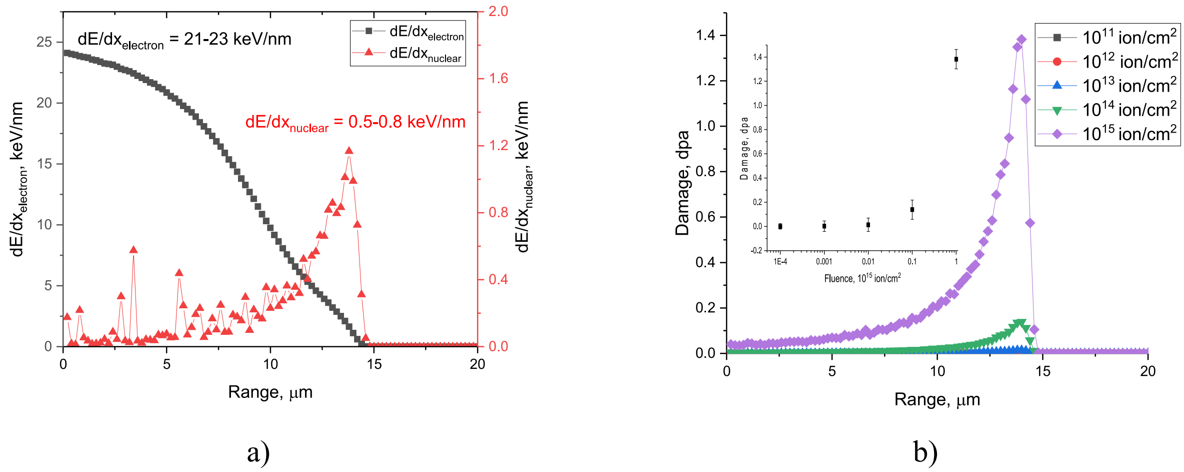

Fig. 1. a) Simulation results of ionization losses of incident Xe^{22+} ions along the trajectory of motion in the damaged layer of MgO ceramics; b) Simulation results of the dependence of the change in the atomic displacement value along the trajectory of ion movement in the damaged layer, calculated on the basis of changes in the concentration of accumulation of structural distortions and vacancies (the inset shows the results of the change in the concentration of atomic displacements depending on the irradiation fluence).

$$T^{optical} = \frac{2\left(n^{optical}\right)}{\left(n^{optical}\right)^2 + 1} \tag{2}$$

$$R^{loss} = \left(\frac{\left(n^{optical}\right) - 1}{\left(n^{optical}\right) + 1}\right)^2 \tag{3}$$

The calculation of the static and optical permittivity values was done using formulas (4) and (5), taken from the works [26,27]:

$$\varepsilon^{static} = \left(n^{optical}\right)^2 \tag{4}$$

$$\varepsilon^{optical} = \varepsilon^{static} - 1 \tag{5}$$

The concentration of the defective fraction was determined according to the results of the assessment of changes in the structural parameters, as well as changes in the intensity of diffraction reflections associated with deformation distortions of the crystal structure as a result of the accumulation of damage in the damaged layer. The assessment was carried out using the calculations given in Ref. [28].

3. Results and discussion

One of the most accurate methods for assessment of structural changes caused by irradiation, especially for optical materials such as MgO, Al_2O_3, $MgAl_2O_4$, is the study of alterations in optical spectra, the variation of which causes changes associated with the formation of point defects, and complex defects that arise during high-dose irradiation. At the same time, the analysis of the observed alterations is usually determined by the radiation dose, the variation of which results in more pronounced changes associated with the formation of absorbing centers in the structure, as well as structural distortions caused by ionization and athermal effects, the appearance of which is associated with the processes of interaction of incident ions with the crystalline structure of ceramics.

The study of the optical properties of MgO ceramics exposed to irradiation with heavy Xe^{22+} ions with an energy of 230 MeV and fluences from 10^{11} to 10^{15} ion/cm^2 was performed using optical UV–Vis spectroscopy methods, the use of which made it possible to evaluate the effect of structural changes on transmission and their absorption properties. The results of alterations in the optical transmission and

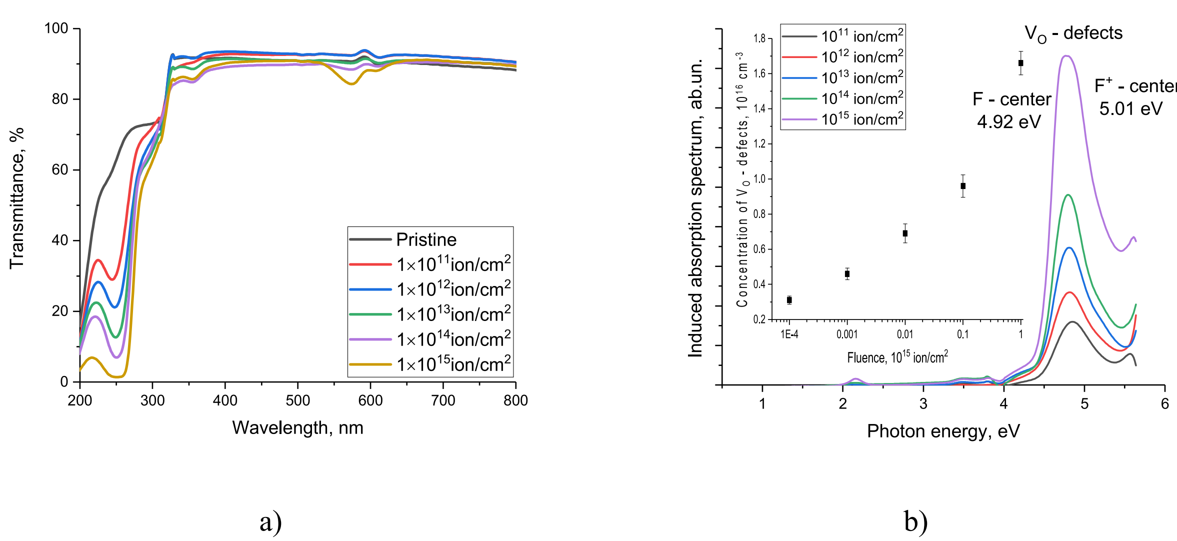

Fig. 2. a) Dependence of the change in the transmission spectra of MgO ceramics at irradiation fluence growth; b) Evaluation results of the induced absorption spectra for irradiated MgO ceramics depending on the irradiation fluence, reflecting changes associated with the accumulation of oxygen vacancies in the structure (data on the change in the concentration of V_O defects depending on the irradiation fluence are shown in the inset to the figure).

absorption spectra depending on the irradiation fluence are presented in Fig. 2a and b. It should be noted that the minor changes in the transmission value in the low energy region in this case can be explained by small differences in the thickness of the samples that were obtained during the experiments.

The general appearance of the observed changes in optical transmission spectra depending on the irradiation fluence is characterized by a decrease in transmission intensity and, as a consequence, an elevation in deformation distortions in the damaged layer structure associated with the accumulation of radiation defects. In the case of MgO ceramics in the initial state, the value of the transmittance coefficient is quite large, from which it follows that in the initial state the obtained ceramics have a sufficiently small number of defects, alongside absorption centers in the structure. In this case, the main changes observed in the optical spectra of irradiated samples are observed in the region of 200–400 nm, corresponding to the UV range, while in the region of visible light the ceramics remain transparent, from which it follows that the observed defects in the structure of the damaged layer have a characteristic nature of the formation of absorption centers associated with vacancy defects, as well as changes in the electron density arising as a result of the interaction of ions with the electron subsystem. It is important to highlight that, unlike ZrO_2 ceramics, considered as one of the candidate materials for similar practical applications, irradiation with heavy ions of which results in pronounced changes in optical transmission in the entire range of wavelengths, in the case of MgO ceramics, even in the case of high-dose irradiation, transparency in the visible and near IR range is maintained [29,30].

Analysis of the observed optical spectra of induced absorption depending on the irradiation fluence, presented in Fig. 2b, showed that for the irradiated samples, the formation of an asymmetrical absorption band is observed, characterized by the formation of F and F^+ centers associated with oxygen vacancies (V_O^0 and V_O^{1+}) in the ceramic structure during irradiation [31–33]. Moreover, irradiation fluence growth indicates an elevation in the intensity of these F and F^+ centers, which in turn indicates that their concentration is directly proportional to the irradiation fluence and, as a consequence, to the radiation damage concentration in the ceramic structure (see data in the inset to Fig. 2b). The concentration was determined using the calculation formula given in Ref. [31].

The assessment results of the change in the transmittance coefficient of MgO ceramics in the UV region are presented in Fig. 3a. The data were obtained by comparing the transmittance intensity at a wavelength of 270 nm for the initial sample (the value of which was chosen as 1) and the irradiated samples depending on the irradiation fluence. The general appearance of the presented alterations in the transmittance coefficient indicates the degradation of the transmittance of ceramics, as a result of the damage accumulation caused by irradiation, and associated structural changes, the concentration of which is due to the irradiation fluence variation.

In this case, by assessing the change in the transmittance coefficient (see data in Fig. 2a), two characteristic areas, corresponding to different trends in alterations, which may be associated with different natures of structural distortions caused by irradiation, can be identified. The transmittance was determined by comparing the transmittance values at wavelengths of 300 nm for the original sample and after irradiation, which made it possible to evaluate the effect of irradiation on the change in optical characteristics associated with the accumulation of structural defects.

Also, the change in transmission for irradiated samples can be caused by the effects of swelling and damaged layer porosity growth during its deformation distortion. The analysis of structural parameters (in particular, the value of the crystal lattice volumetric swelling during its irradiation) in comparison with these changes in the optical transmission value are presented in Fig. 3b. The concentration of the defect fraction was determined by calculating the change in the structural parameters and crystal lattice volume of the caused by deformation broadening, alongside the formation of defects of the $Mg + V_O$ type, the formation of which, as shown in Ref. [34], causes deformation broadening of the parameters and, as a consequence, the crystal lattice volume. The general appearance of the presented dependence indicates a correlation between structural defects and changes in optical transmission, the change of which is observed during the analysis of optical spectra. It should be noted that in the case of irradiation fluence growth above 10^{13} ion/cm^2, for which, according to a number of studies [35–37], in the case of heavy ions, the formation of the effect of overlapping of defective areas arising along the trajectory of ion movement in the material is characteristic, the change in the transmittance has a less pronounced downward trend depending on the concentration of the defect fraction, which can be explained by the effects of changes in the types of structural defects arising in the structure during high-dose irradiation. Structural changes, expressed in the formation of

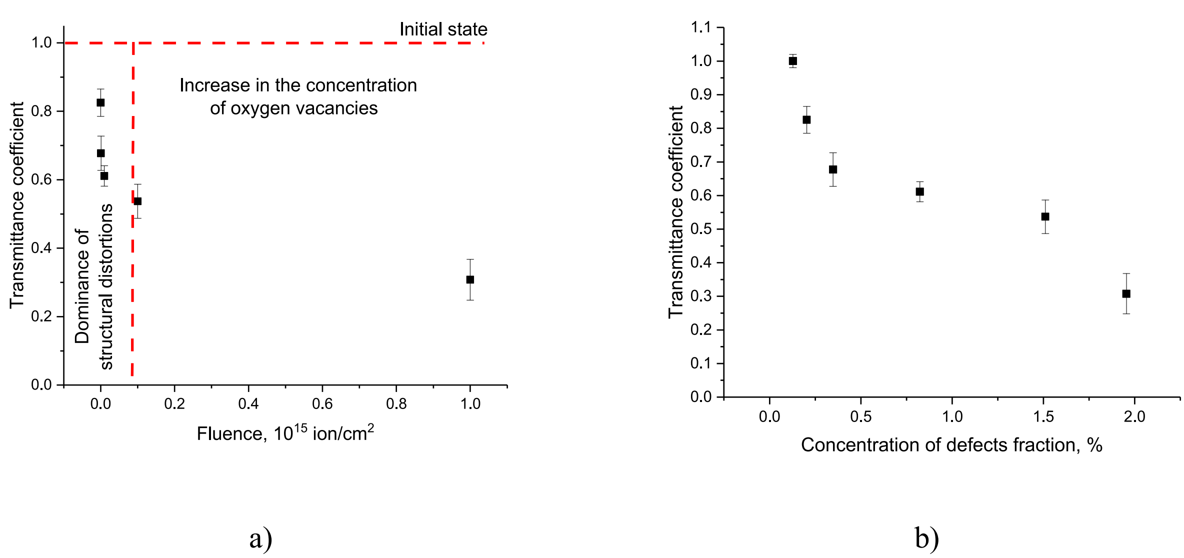

Fig. 3. Assessment results of changes observed in optical spectra caused by irradiation: a) assessment results of changes in the transmittance of MgO ceramics at a wavelength of 270 nm depending on the irradiation fluence (data calculated for irradiated samples are presented in the form of a comparison with the transmittance value of the initial sample taken as 1); b) Dependence of the change in the transmittance coefficient on the concentration of structural defects calculated on the basis of alterations in the crystal lattice volume, the deformation of which is caused by the interaction of ions with the crystal structure.

absorption bands associated with oxygen vacancies, in the case of high-dose irradiation can be explained by athermal effects, which occur as a result of the transformation of the kinetic energy of incident ions during collision into thermal energy, the distribution of which along the trajectory of ion movement in the material can result in rapid heating of the crystalline structure to fairly high temperatures. It is known that heating of MgO ceramics above 800–900 °C can lead to a disordered distribution of Mg and O atoms, resulting in the formation of additional structural distortions, as well as the rupture of crystalline and chemical bonds. In this case, the observed changes in the volume of the crystalline structure associated with the defect fraction growth in the damaged layer indicate radiation-induced degradation.

Fig. 4 illustrates the comparison results of the change in the absorbance values and the concentration of the defect fraction in the damaged ceramic layer depending on the irradiation fluence. In this case, the absorbance value characterizes the change in the optical density value associated with the change in the concentration of defects and absorbing centers in the structure of the damaged layer caused by irradiation. The observed direct correlation between changes in the absorbance values and the concentration of structural defects in the damaged layer indicates a connection between the accumulation of defects caused by irradiation and their negative impact on the reduction of the optical properties of ceramics. At the same time, the observed reduction in the trend of alterations at the irradiation fluence growth above 10^{13} ion/cm^2 indicates the effect of structural damage saturation, characteristic of high-dose irradiation, in which case there is a change in the disordering mechanisms caused by the formation of complex defects. In turn, the observed changes in the optical spectra, as well as the induced absorption spectra in the case of high-dose irradiation, indicate the dominance of oxygen vacancies, as well as complex defects of the Mg + V_O type in the damaged layer at high irradiation fluences. Similar defects of the Mg + V_O type, arising at high irradiation fluences, were studied in detail in Refs. [37,38].

The observed fundamental absorption edge shift to the region of longer wavelengths at irradiation fluence growth indicates the effect of a change in electron density associated with the emergence of electron excitation processes, alongside the formation of cascade effects of electron redistribution associated with the effects of ionization electron losses of incident ions. Also, with an increase in the irradiation fluence, the observed optical spectra show the formation of a local maximum and minimum in the wavelength range of 200–250 nm, indicating the appearance of irradiation-induced absorption bands associated with the accumulation of F – centers, as well as oxygen vacancies (V_O^0 and V_O^{1+}) [39–41].

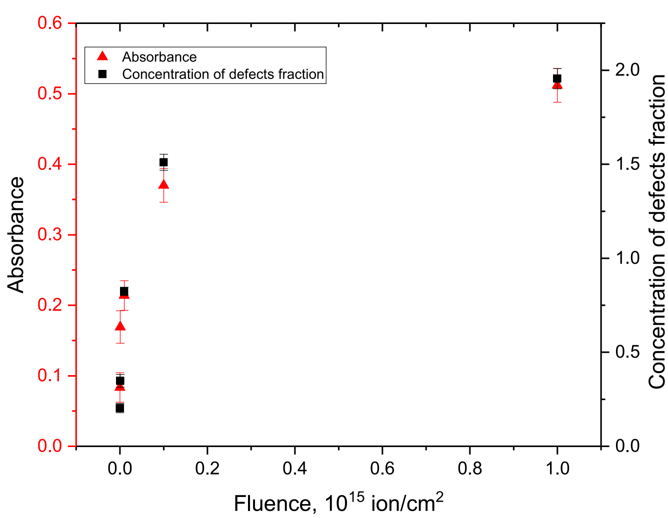

Fig. 4. Results of comparative analysis of alterations in the absorbance value, characterizing the change in the optical density of the irradiated material, caused by the accumulation of defects, and the concentration of the defect fraction calculated on the basis of changes in the structural parameters of irradiated MgO ceramics.

One of the ways to assess the irradiation effect on the relationship between structural and electronic characteristics depending on the irradiation fluence is to determine the relationship between changes in the band gap and its shift, which characterizes the electron density distribution. In this case, the band gap reduction as a result of external influences is primarily associated with the electron density redistribution, as a result of which additional electron transitions arise in the structure, and F^+ centers associated with oxygen vacancies (V_O^0 and V_O^{1+}) are formed. In the case of high-dose irradiation, the density of formation of such F^+ centers grows, which results in transmittance reduction, and the appearance of additional absorption bands in the optical spectra. A rise in the concentration of F^+ centers is indicated by an elevation in the intensity of the spectral bands characteristic of these spectra.

Based on the obtained absorption spectra of the studied MgO ceramics exposed to heavy ion irradiation, Tauc' plots were constructed, allowing one to estimate the change in the band gap, reflecting the change in the electron density distribution. These changes characterize the effects of ionization losses, as well as structural changes caused by the radiation damage accumulation in the damaged layer structure, the accumulation of which results in formation of additional absorption bands characteristic of F^+ centers [42,43]. The general appearance of the presented constructions is characterized by two types of changes: 1) shift of the fundamental absorption edge to the region of low energies; 2) appearance in the region of 4.6–4.9 eV of an additional absorption band, the formation of which is associated with the formation of F^+ centers in the damaged layer structure, as well as the formation of oxygen vacancies due to the rupture of chemical and crystalline bonds.

An analysis of the band gap values (E_g) depending on the irradiation fluence indicates a reduction in this value, with the most significant and clearly expressed changes observed at low fluences (10^{11}–10^{13} ion/cm^2), while at fluences of 10^{14}–10^{15} ion/cm^2 the change in the band gap value becomes smaller, which may be due to the so-called saturation effect of structural changes, as well as the dominance of the processes of formation of F^+ centers in the damaged layer at high irradiation fluences. At fluences of 10^{14}–10^{15} ion/cm^2, the intensity of the spectral absorption band at 4.6–4.9 eV increases sharply by more than 2 orders of magnitude, which indicates a rise in the concentration of absorbing optical centers associated with the formation of a large number of oxygen vacancies (V_O^0 and V_O^{1+}).

Results of changes in the optical characteristics such as Shift of the fundamental absorption edge, linear refractive index ($n^{optical}$), optical transmission ($T^{optical}$), refraction loss (R^{loss}), the static (ε^{static}) and optical permittivity ($\varepsilon^{optical}$) are shown in Table 1.

The general trend of changes in optical parameters in the case of

Table 1
Data on the change in optical characteristics of MgO ceramics depending on the irradiation fluence.

Fluence	*Parameter*					
	Shift of the fundamental absorption edge, eV	$n^{optical}$	$T^{optical}$	R^{loss}	ε^{static}	$\varepsilon^{optical}$
Pristine	0	1.98	0.108	0.108	3.92	2.93
10^{11} ion/cm^2	0.09	1.99	0.801	0.110	3.98	2.98
10^{12} ion/cm^2	0.17	2.00	0.798	0.112	4.03	3.03
10^{13} ion/cm^2	0.25	2.01	0.795	0.114	4.07	3.08
10^{14} ion/cm^2	0.33	2.03	0.792	0.115	4.13	3.13
10^{15} ion/cm^2	0.38	2.04	0.790	0.117	4.16	3.15

irradiated samples indicates a negative impact of accumulated structural damage caused by irradiation. In this case, the most pronounced changes are observed at fluences above 10^{13} ion/cm^2, for which the decrease in the ΔE_g value is about 0.25–0.4 eV, which indicates the formation of an anisotropic change in the distribution of electron density in the structure, arising as a result of ionization processes, as well as the associated redistribution of knocked-out electrons in the damaged layer structure. Moreover, the manifestation of this effect during high-dose irradiation is due to the increase in the probability of overlapping of defective areas caused by irradiation, which leads to the formation of complex defective formations with a highly disordered electronic structure. At the same time, the change in the $T^{optical}$ and R^{loss} values indicates a change in the nature of the optical transmission capacity in the damaged layer, the changes of which are caused by the effects of the appearance of a large number of oxygen vacancies, as well as anisotropic changes in the distribution of electron density.

4. Conclusion

As a result of the conducted studies, relationships between changes in optical properties and structural changes in the damaged layer of MgO ceramics caused by irradiation with heavy Xe^{22+} ions were established. It has been determined that the dominant mechanisms of the near-surface layer destruction in the case of high-dose irradiation are the formation of a large number of oxygen vacancies, as well as complex defects of the $Mg + V_O$ type. According to the experiments conducted, a direct correlation was established between alterations in the concentration of oxygen vacancies and the effects of the formation of structurally altered areas arising along the trajectory of ions in the damaged layer, as well as the associated effects of the overlap density during the irradiation fluence variation. At the same time, it was determined that a growth in the irradiation fluence, leading to a change in the density of structurally altered areas in the damaged layer, causes an elevation in the concentration of oxygen vacancies, the formation of which leads to a decrease in optical transmission.

The general concept of the observed connections between structural defects caused by heavy ion irradiation and changes in optical properties due to a reduction in transmittance, formation of absorption centers and vacancy defects makes it possible to determine the kinetics of damage characteristic of heavy ion exposure comparable to nuclear fuel fission fragments, which in turn will allow determination of the mechanisms of ceramic degradation and critically permissible doses at which these ceramics can be used. At the same time, the obtained dependences of the correlation of optical parameters and structural defects under high-dose irradiation in the case of the effect of deep overlapping of defective areas indicate the formation of more complex defects in the structure, the formation of which leads to a slowdown in the damaged layer disordering processes.

CRediT authorship contribution statement

Maxim V. Zdorovets: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Artem A. Kozlovskiy:** Writing – review & editing, Writing – original draft, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gulnaz ZhMoldabayeva:** Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Igor A. Ivanov:** Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Marina Konuhova:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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