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Original article

Comparison of the MOSFET Response at Exposed of the X-Ray and Gamma Radiation

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Abstract

Introduction. Electromagnetic or ionizing radiation has great penetrating power. Currently, in literature there is general opinion on complete radiation response of MOSFETs to various types of ionizing radiation. That is why radiation resistance of MOSFETs (metal–oxide–semiconductor field-effect transistors) and integrated circuits is of great interest.

Objective. The purpose of this study is to compare the radiation response of MOSFETs to gamma and X-ray irradiation and assess the effect of applying external gate-substrate potential on dose dependences of the threshold voltage change in MOSFETs.

Materials and methods. This study considers MOS transistors with a polysilicon gate with an oxide (silicon dioxide) thickness of 120 nm. Silicon dioxide acts as a dielectric in MOS structures. Cesium-137 radionuclides are the source of gamma radiation; an X-ray tube with a tungsten-rhenium cathode is a source of X-ray radiation . The change in the threshold voltage of n- and p-channel transistors is analyzed using dual transistor approach.

Results. Strong influence of gamma and X-ray radiation brings the same effects in structures under investigation. Voltage applied to the MOS structures during X-ray irradiation had a strong effect on their radiation response. The maximum radiation response of MOS transistors was observed at high positive gate – substrate potentials. Proportionality coefficients are introduced to ensure that the initial sections of the dose dependences coincide for various applied gate – substrate potentials. The coefficients allow comparing active and passive modes of operation of the X-ray emitter.

Conclusions. The values of the proportionality coefficients of the dependence between the threshold voltage change of the MOS transistor and the ionizing radiation dose are determined. A numerical correlation is established between the effects of gamma and X-ray radiation at doses up to $1.9 \cdot 10^4$ rad (the proportionality coefficient is 38.5). The proportionality coefficients are determined, which allow us to compare the passive gamma-ray irradiation mode (with no potential applied) and the active X-ray irradiation mode (with gate – substrate potential applied). The correction coefficients obtained depend on the polarity of the applied gate - substrate potential. For the negative potential the proportionality coefficient is 38.5. With positive polarity applied the coefficient does not depend on the applied potential and equals 120.

Keywords: MOSFET gate insulator, gamma and X-ray irradiation, space and surface charge, active and passive irradiation

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Introduction. Comprehensive development of defense, space and nuclear industries implies using semiconductor integrated circuits (SIC) based on MOSFETs (metal–oxide–semiconductor field-effect transistors) which must remain operational when exposed to various types of irradiation for a long period of time [1]. Various types of ionizing radiation with high penetrability (gamma and X-ray radiation) are of prime interest.

Gamma rays are produced in the decay of radioactive isotopes, and X-rays are produced when a cathode is bombarded with high-energy particles when high voltage is applied to an X-ray tube. Due to MOSFETs exposure to ionizing radiation short-term charge effects occur in metal and in the semiconductor, and long-term charge effects occur in the oxide [2, 3].

When the gate oxide is exposed to ionizing radiation, electron-hole pairs (EHPs) are produced which are later separated by oxide-charge-induced field. Due to their higher mobility, electrons leave the oxide in picoseconds and holes in accordance with the hopping mechanism move to the oxide phase interface, where they are captured by bulk traps, introducing a positive charge into the oxide [1, 4]. Due to radiation-induced holes and bulk traps interaction, hydrogen is released, which is involved in the depassivation of amphoteric surface states [5, 6].

When the threshold voltage is applied, surface states are charged positively for *p*-channel transistors and negatively for *n*-channel ones. The oxide net charge determines the total radiation response of the MOSFET, which is expressed in the shift of the threshold voltage due to radiation effects [3].

Currently in literature there exist different views on the radiation response of MOSFETs when exposed to different types of ionizing radiation. In [7], the radiation responses of MOSFETs when exposed to γ-radiation from ^{137}Cs and X-ray radiation at energy of 10 keV are compared. The authors have shown that under gamma exposure the proportion of EHPs that escaped the initial recombination, and the change in the parameters of the structures under consideration, are greater than under X-ray irradiation. Formulas are provided for calculating the proportion of EHPs that escaped recombination depending on the electrical intensity of the oxide. Formulas for gamma and x-ray irradiation are identical and only the coefficients differ. At the same time, radiation responses of the types of ionizing radiation under consideration are relatively equal at low doses. In [8], the results of comparing different types of irradiation are presented and the proportion of EHPs that escaped recombination is shown to be maximum for gamma radiation compared to other types of irradiation considered. The authors present universal formulas that make it possible to calculate this proportion depending on the electrical intensity for various ionization losses in the MOSFET's gate oxide. The results in [7, 8] are identical. However, the experimental results in [9] contradict the results obtained in [7, 8]. The authors studied the response of the threshold voltage of radiation sensors, which are p-channel MOSFETs with increased gate-oxide thickness when exposed to γ-ray quanta from ^{137}Cs and x-ray quanta at energies of 90 and 140 keV with gate potential of +5 V and with no potential during irradiation. It is shown that the maximum radiation response is obtained under irradiation with X-ray quanta at an energy of 90 keV. It should be noted that all the given literature data were obtained at low radiation doses. At present in the literature there is no general consensus on the radiation response of MOSFETs exposed to small doses of various ionizing irradiation types when gate-to-substrate potential is applied, therefore this problem requires further detailed consideration.

If the responses of MOSFETs to various types of radiation within the dose range under consideration are close, then it is the possible of replace γ-radiation with X-ray radiation when analyzing radiation resistance of MOSFETs without introducing significant errors. X-ray irradiation facilities have lower cost and smaller dimensions than γ-irradiation facilities. They also do not require special measures to dispose of radioactive waste and are safer during operation. In addition, X-ray research facilities make it possible to introduce potentials during irradiation directly to the MOSFET at intermediate stages of production (before packaging integrated circuits).

The implementation of the active mode of operation with the gate – substrate potential application on irradiation facilities containing radionuclide substances is problematic, while studying such operational modes of MOS integrated circuits is an essential part of predicting their radiation response, since when operating in an ionizing medium, the circuits are influenced by control potentials.

It is also known that the application of a positive potential to the gate during irradiation increases the radiation response of MOSFETs due to improved separation of electron – hole pairs and a decrease of the initial recombination [4].

Objective. The purpose of this study is to compare the radiation response of MOSFETs to gamma and X-ray irradiation and assess the effect of applying external gate-substrate potential on dose dependences of the threshold voltage change in MOSFETs.

Materials and methods. The radiation response is analyzed on *n*- and *p*-channel MOSFETs with a phosphor-doped polysilicon gate made using standard planar silicon technology with a gate oxide 120 nm thick.

Gamma irradiation of the MOSFET is carried out on the GOT facility. The gamma dose rate is 62.5 rad/s. The facility is a closed sarcophagus with a revolver load cell and 86 radionuclides of Cs-137 inside. The number and geometry of the sources allow creating a homogeneous floatation of gamma rays with an energy of 662 keV. Irradiation is conducted in a quasi-enclosed structure.

The X-ray irradiation of MOSFETs in both active and passive (without applying the gate – substrate potential) modes was conducted on a research X-ray emitter with a tube with a tungsten-rhenium cathode operating in the 40 kV and 90 μA modes. The facility contains a high-voltage block with an X-ray tube, a control unit, connecting cables and a ground bus. According to the passport data, it allows using X-ray tubes in 45 kV and 100 μA modes. The facility was equipped with a probe station and a voltage power supply, which made it possible to apply various potentials to the bonding pads of MOSFETs under study during irradiation (in the active mode). The potentials applied to the gate ranged from –3 to +10 V.

Measuring the coefficient of proportionality of the absorbed dose for various types of ionizing irradiation Transistors made in a single technological cycle on a common silicon plate with dielectric insulation (SWDI) were studied to compare the radiation response of MOSFETs under the influence of x-ray and gamma radiation. Irradiation was conducted in the passive mode. The change in the threshold voltage of the MOSFETs was analyzed. The characteristic quantity of this value was approximated within a model that excludes production of new bulk or surface defects. In the framework of this model, the process of trapping radiation-induced charge carriers onto one type of bulk or surface traps is described by the relation of the concentration of charged traps N_t and the radiation dose D of the form [8, 10–13]

$$N_t = N_{t0}\left[1 - \exp(-\beta D)\right],$$

where N_{t0} is the concentration of bulk or surface predefects in the oxide; β is a coefficient proportional to the capture cross-section.

The corresponding change in the threshold voltage is defined as:

$$\Delta U_{th} = \Delta U_{th_{max}}\left[1 - \exp(-\beta D)\right],$$

where $\Delta U_{th_{max}}$ is the steady-state value of the threshold voltage change.

In addition, in [2, 14] it is indicated that at least two types of trap centers with different capture cross-sections and concentrations are responsible for the formation of both space and surface charges. The main contribution is made by the trap centers (E'-centers $(-\mathrm{Si} \equiv \mathrm{O}_3)$ and P_b-centers $(-\mathrm{Si} \equiv \mathrm{Si}_3)$) in the oxide, passivated by hydrogen and hydroxyl groups. The change in the components of the threshold voltage associated with the space and surface charges formation in the dielectric can be described by the sum of at least two such exponential components.

The considered *n*- and *p*-channel MOSFETs were manufactured in a single technological cycle, and were exposed to the same radiation impact. As a result, on average, the same radiation-induced charge was introduced into the oxide layer of both types of MOSFETs. Taking into account the signs of charges formed in the oxide, the change in the threshold voltage can be decomposed which for the indicated MOSFETs provides system [9]:

$$\begin{cases} \Delta U_{th\,n} = \Delta U_{ot} - \Delta U_{it}; \\ \Delta U_{th\,p} = \Delta U_{ot} + \Delta U_{it}, \end{cases}$$

where ΔU_{ot} is the change in the component of the threshold voltage associated with the carrier storage of space charge; ΔU_{it} is a change in the component of the threshold voltage associated with the charge of surface states.

Densities of radiation-induced charges in the gate oxide and changes in the surface and volume components of the threshold voltage of MOSFETs correlate the following ratio:

$$\Delta N_{it} = \Delta U_{it} C_{ox}/q; \;\; \Delta N_{ot} = \Delta U_{ot} C_{ox}/q,$$

where $C_{ox} = \varepsilon_{ox}\varepsilon_0/d_{ox}$ is the specific capacity of the dielectric; q is the electron charge (ε_{ox} and ε_0 are the electrical permittivities of the oxide and vacuum respectively); d_{ox} is the thickness of the gate oxide.

Decomposing dose dependences for n- and p-channel transistors into components associated with space and surface charges was conducted using the dual transistor method [15]. Correlations (Fig. 1) were obtained considering the presence of two types of bulk and two types of surface trap centers in the insulator [2, 14].

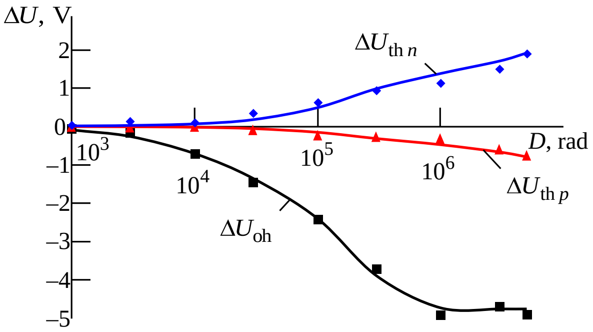

Fig. 1. Dose dependences of threshold voltage shift components associated with space and surface state charges for *n*- and *p*-channel MOSFETs.
Markers are measurement results, curves are approximation

The obtained dose dependences and their approximation are shown in Fig. 2. The approximation parameters used to analyze dose dependencies are given in the table. Coefficients β characterize the technology of growing the gate oxide.

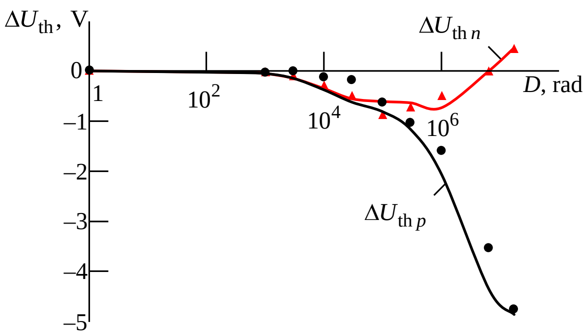

Fig. 2. Dose dependences of the threshold voltage shift for *n*- and *p*-channel MOSFETs under gamma irradiation.
Markers are measurement results, curves are approximation

They are proportional to the capture cross section of various trap centers in the oxide: β_{ot1}, β_{ot2} – to two types of bulk traps; β_{it1}, β_{it2} – to two types of surface traps, respectively. The concentrations of charged traps introduced by irradiation are indicated by the following parameters: N_{ot1}, N_{ot2} – bulk traps of two types; N_{it1}, N_{it2} – surface traps of two types, respectively. Maximum voltage change induced by traps in the oxide is represented by the values $U_{\text{ot max1}}$, $U_{\text{ot max2}}$ for two types of bulk traps; $U_{\text{it max1}}$, $U_{\text{it max2}}$ for two types of surface traps, respectively.

The correlations between the change in the threshold voltage and the lengh of X-ray radiation exposure for n- and p-channel MOSFETs are shown in Fig. 3.

The correlaions for X-ray and gamma irradiation presented in fig. 2 and 3 have a similar form. Therefore, the ionization effect caused in the gate insulator of MOSFETs by these types of

Approximation parameters

Charge type	Approximation parameter	
	Indication	Vflue
Bulk	$U_{\text{ot max1}}$, V	0.6
	N_{ot1}, cm^{-2}	$1.0 \cdot 10^{11}$
	$U_{\text{ot max2}}$, V	1.6
	N_{ot2}, cm^{-2}	$2.7 \cdot 10^{11}$
	β_1, rad^{-1}	$9.0 \cdot 10^{-5}$
	β_2, rad^{-1}	$7.0 \cdot 10^{-7}$
Surface state	$U_{\text{it max1}}$, V	2.6
	N_{it1}, cm^{-2}	$4.4 \cdot 10^{11}$
	$U_{\text{it max2}}$, V	0.1
	N_{it2}, cm^{-2}	$1.7 \cdot 10^{10}$
	β_1, rad^{-1}	$2.5 \cdot 10^{-7}$
	β_2, rad^{-1}	$5.0 \cdot 10^{-6}$

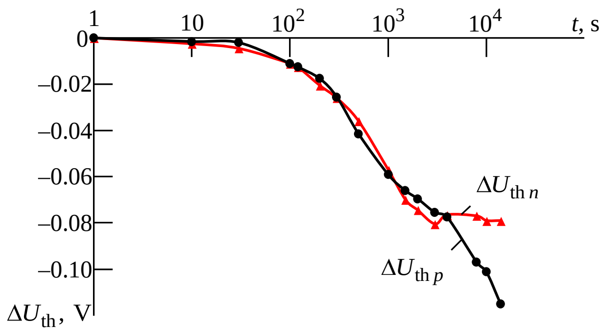

Fig. 3. Time dependences of the threshold voltage shift for *n*- and *p*-channel MOSFETs under X-ray irradiation.
Markers are measurement results

radiation is induced by the same physical phenomena in the oxide, which are associated with carrier capture in the same traps. The identical form of the correlations of the change in the threshold voltage allows one to introduce the coefficient of proportionality between the gamma radiation dose absorbed in silicon dioxide and the duration of the X-ray irradiation exposure. Based on the experimental curves, the value of this coefficient for the samples examined has been determined to be 38.5.

Assuming absolute coefficient ensures the agreement between dose dependences and the approximating curve built according to the table (Fig. 4). The obtained result makes it possible to determine the dose of X-ray radiation absorbed for a specific insulator (silicon dioxide).

The effect of the potential applied. The processes taking place in the oxide are of probabilistic nature. A positive potential shifts dynamic equilibrium towards the carriers capture into traps near the semiconductor – insulator interface. The probability of carrier capture increases due to an increase in the hole concentration in this region [16]. The application of a negative potential decreases the steady-state value ΔU_{th}, due to a shift in the dynamic equilibrium near the oxide – substrate interface towards the charge carriers release from traps when compared to the absence of an external field during MOSFET irradiation.

The value of the positive potential applied during irradiation significantly affects the dose dependences of the threshold voltage change. This is associated with the influence of both internal (built-in) and external electric field strength on the separation of electron-hole pairs generated during irradiation in the insulator. It also influences the change in the drift component of charge carriers mobility moving through the volume of the gate oxide to trap centers located near interface region.

The results of investigating the effect of the applied gate – substrate potential U_{gs} under X-ray irradiation for n- and p-channel MOSFETs are presented in Fig. 5. The applied negative potential practically does not affect the dose dependences within the experimental error. In contrast to the positive potential, the negative potential when applied changes the direction of the external electric field intensity, which causes a change in the direction of motion of the mobile charge carriers produced in the gate oxide during irradiation. In this case, the generated charges are removed from the oxide – substrate interface surface region. Thus, the main radiation-induced charge is formed at the gate – substrate interface, where it has practically no effect on the surface

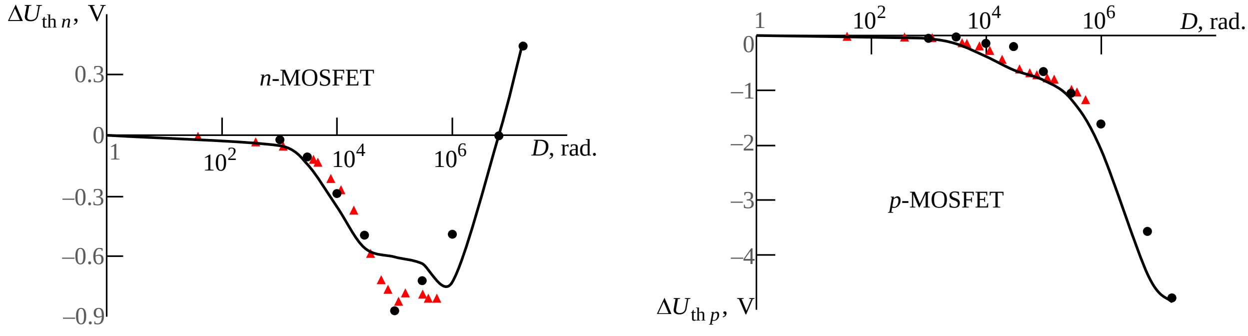

Fig. 4. Dose dependences of the threshold voltage shift for *n*- and *p*-channel MOSFETs. Markers are measurement results: black markers for gamma irradiation, red markers for x-ray irradiation. Curves are approximation for both types of irradiation

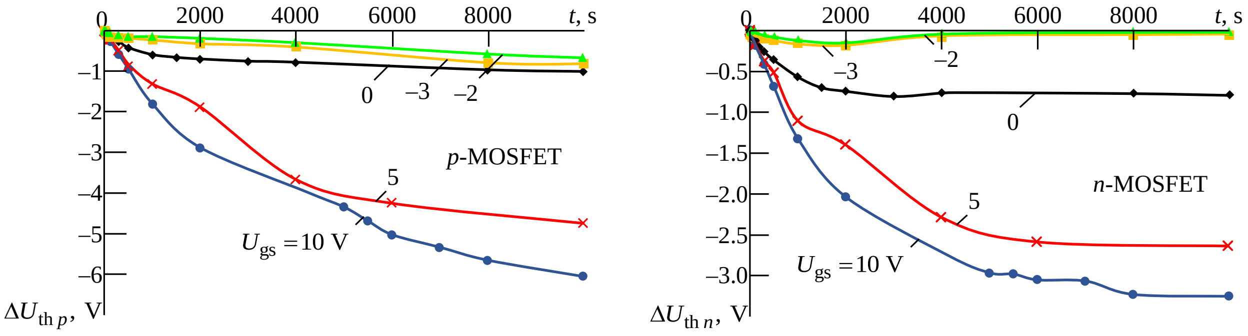

Fig. 5. Time dependences of threshold voltage shift for *n*- and *p*-channel MOSFETs with the gate-substrate potential applied during irradiation. Markers are measurement results

layer of the semiconductor substrate. Only holes generated directly in the surface region of the semiconductor – insulator interface participate in the formation of radiation-induced charges in the insulator.

Applying positive potential increases the steady-state value ΔU_{th}. The steady-state value observed in the dose dependence of the change in the threshold voltage of the MOSFET is associated with a state of dynamic equilibrium between the capture and release of various charge carriers from traps in the gate oxide [16]. Applying external potential of –2 V leads to overcompensation of the built-in insulator potential in the MOSFET structure induced by the contact gate – substrate potential difference and the built-in charge that occurred in the dielectric during the thermal oxidation of silicon. A further increase in the negative external gate – substrate potential does not significantly change the dose dependences of the threshold voltages shift of n- and p-channel MOSFETs.

The variations in ΔU_{th} with respect to the applied gate – substrate potential for different doses of gamma radiation (Fig. 6) tend to reach steady-state values. At low radiation doses (up to $1.9 \cdot 10^4$ rad) the change in the threshold voltage is slightly affected by the potential applied. At potentials of more than 5 V, the variations considered reach steady-state values due to a limited number of holes formed during irradiation that can participate in the formation of the bulk and surface charges near the silicon – silicon dioxide interface.

At large doses of irradiation, the number of generated electron-hole pairs increases significantly and the curve of the threshold voltage change with the respect to the gate voltage ap-

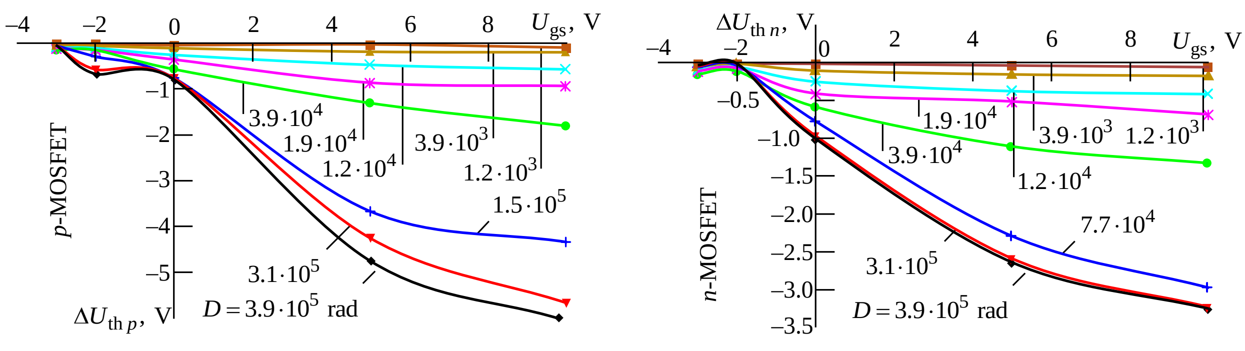

Fig. 6. Dependences of threshold voltage shift for *n*- and *p*-channel MOSFETs with gate-substrate potential applied during irradiation. Markers are measurement results

plied during irradiation has a greater slope. The steady-state values are not reached even at a gate potential of +10 V. This indicates that in the studied range of X-ray doses the number of available trap centers for charge capture exceeds the number of holes generated during irradiation that have reached the surface region of the semiconductor.

At negative gate potentials, the dependence of the threshold voltage change on the gate potential applied during irradiation will be weak in the entire dose range under study (as indicated earlier) due to the bulk and surface charges location at the outer oxide boundary. There this charges have minimum effect on the gate surficial region of MOSFETs substrates under study.

The effect of the voltage applied to the gate on the proportionality coefficient. The analysis of the dose dependences of the threshold voltage change when exposed to gamma and X-ray radiation in the passive mode, as well as to X-ray radiation in the active mode with gate-substrate potentials of different values and polarities applied, showed that at low radiation doses (less than $1 \cdot 10^4$ rad) it is possible to introduce the proportionality coefficient making it possible to equal the radiation responses of MOSFETs due to the exposure to active and passive modes of irradiation.

It should be noted that the obtained proportionality coefficient between passive modes of gamma and x-ray irradiation, which is equal to 38.5, coincides with the proportionality coefficient between passive gamma-irradiation and various active modes of X-ray irradiation with a negative gate – substrate potential.

In active modes with positive polarity the coefficient is about three times the indicated value and amounts to 120. For both negative and positive polarity in the active X-ray mode, the proportionality coefficient in the considered gate – substrate voltage range is independent of the potential.

Taking into account the correction proportionality factors, the dose dependences of the threshold voltage change with various potentials applied to the gate under X-ray and gamma exposure are shown in Fig. 7.

Results. Similar nature of dose dependences for gamma and X-ray irradiation, correlating with the data of the authors of [7], defines the relationships using a single approximating curve. This indicates the equivalence of parameters of formation, transfer and capture processes of mo-

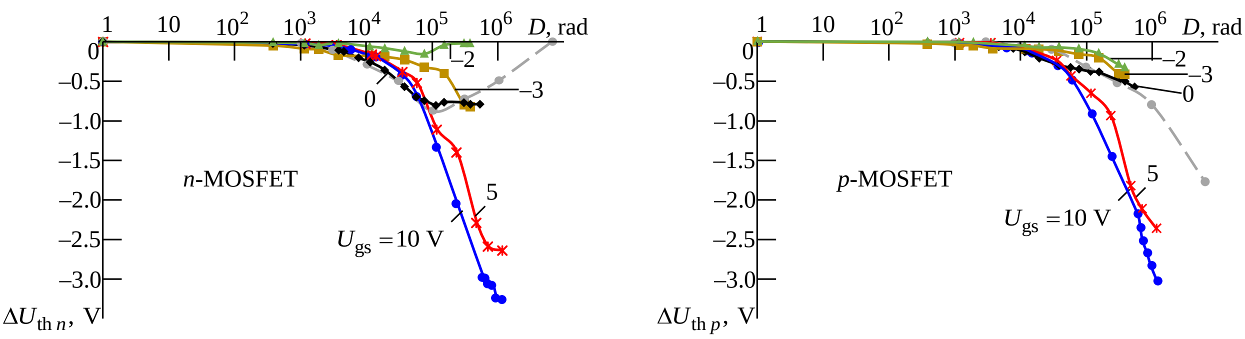

Fig. 7. Dependences of threshold voltage shift for *n*- and *p*-channel MOSFETs on the gate–substrate potential applied when exposed to irradiation, adjusted for the correction proportionality coefficient.
Solid curve is for X-ray irradiation, dashed curve is for gamma irradiation. Markers are for measurement results

bile charge carriers in the gate MOSFET insulator for different types of ionizig radiation. The approximation parameters depend on the production technique of MOSFETs. They are completely defined by the capture cross section and the concentration of trap centers. For the technology under study, dose dependences are accurately described considering two types of trap centers involved in the formation of a bulk charge and two types of trap centers involved in the formation of amphoteric surface states. The approximation parameters are presented in the table. The obtained values of parameter β somewhat differ from those calculated according to the model presented in [17]: for a bulk charge $\beta = 6 \cdot 10^{-6}$ rad^{-1}, for a surface states charge $\beta = 6 \cdot 10^{-7}$ rad^{-1}. However, it should be noted that in their model the authors of this work take into account the presence of only one type of trap centers for both bulk charge and charge of surface states.

The study of active modes shows a strong dependence of the radiation response of the MOSFET on the value and polarity of the potential applied. The external potential depending on the polarity result in the formation of a charge at one of the gate oxide interfaces. Holes take part in the formation of charges in the oxide during irradiation exposure; therefore, the main charge is formed at the more negative electrode (of the gate or the substrate). The charge formed at the gate – oxide interface practically does not effect surficial region of the substrate and the MOSFET parameters; therefore, MOSFETs irradiated at a positive potential at the gate have a higher radiation response.

For small doses of radiation (less than $1.9 \cdot 10^4$ rad), the correcting coefficient to transition from active to passive X-ray irradiation mode does not depend on the value of the applied gate – substrate potential, but is defined by its polarity only. When a negative gate – substrate potential is applied in the voltage range under study, it corresponds to the passive mode and amounts to 38.5. When a positive potential is applied, this coefficient does not vary and amounts to 120. Therefore, using active mode can reduce time of exposure to obtain the necessary radiation response at a constant dose rate, which reduces the test duration.

Conclusions. The study results and model analysis show that the dose dependences for gamma irradiation and time dependences for X-ray irradiation in the passive mode are of analogical form which allows introducing a correction coefficient of proportionality. This coefficient depends on the dose rate of the X-ray irradiation and it allows translating the time dependence into the dose one.

References

1. Tapero K. I., Ulimov V. N., Chlenov A. M. *Radiatsionnyye effekty v kremniyevykh integral'nykh skhemakh kosmicheskogo primeneniya* [Radiation Effects in Silicon Integrated Circuits for Space Applications]. Moscow, *BINOM. Laboratoriya znaniy*, 2012, 305 p. (In Russ.)

2. Pershenkov V. S., Popov V. D., Shal'nov A. V. *Poverkhnostnyye radiatsionnyye effekty v elementakh elektronnykh mikroskhem* [Surface Radiation Effects in Elements of Electronic Microcircuits]. Moscow, *Energoatomizdat*, 1988, 256 p. (In Russ.)

3. Gurtov V. A. *Vliyaniye ioniziruyushchego izlucheniya na svoystva MDP-priborov* [The Effect of Ionizing Radiation on the Properties of MIS Devices]. Reviews on Electronic Technology. Moscow, *TSNII Elektronika*, 1978, iss. 14, no. 595, pp. 3–31. (In Russ.)

4. Chumakov A. I. *Deystviye kosmicheskoy radiatsii na IS* [The Effect of Cosmic Radiation on Integrated Circuits]. Moscow, *Radio i svyaz'*, 2004, 320 p. (In Russ.)

5. Aleksandrov O. V., Mokrushina S. A. Model for Charge Accumulation in n- and p-MOS Transistors during Tunneling Electron Injection from a Gate. Semiconductors. 2018, no. 52 (6), pp. 783–788. doi: 10.1134/S1063782618060027

6. Aleksandrov O. V. On the Effect of Bias on the Behavior of MOS Structures Subjected to Ionizing Radiation. Semiconductors. 2015, no. 49 (6), pp. 774–779. doi: 10.1134/S1063782615060020

7. Benedetto J. M., Boesch H. E. The Relationship Between ^{60}Co and 10 keV X-Ray Damage in MOS Devices. IEEE Trans. Nucl. Sci., 1986, no. 6, pp. 1318–1923.

8. Sogoyan A. V., Zebrev G. I., Nikiforov A. Yu., Pershenkov B. S., Chumakov A. I. *Poverkhnostnyye radiatsionnyye effekty v integral'nykh skhemakh* [Surface Radiation Effects in Integrated Circuits]. Space model. Vol. 1. Ed. by L. I. Panasyuk, L. S. Novikov. Moscow, *KDU,* 2007, pp. 466-493. (In Russ.)

9. Pejovic M., Ciraj-Bjelac O., Kovacevic M., Rajovic Z., Ilic G. Sensitivity of P-Channel MOSFET to X- and Gamma-Ray Irradiation. International Journal of Photoenergy. 2013, № 158403, pp. 1–7. doi: 10.1155/2013/158403

10. Chzho Ko Vin. The Use of Ionizing Radiation for Accelerated Testing of MOS Integrated Circuits. Electronic Engineering. Series 2. Semiconductor Devices. 2012, no. 1 (228), pp. 54–56. (In Russ.)

11. Chumakov A. I., Vasil'yev A. L., Kozlov A. A., Kol'tsov D. O., Krinitskiy A. V., Pechenkin A. A., Tararaksin A. S., Yanenko A. V. Prediction of Local Radiation Effects in Integrated Circuits under the Influence of Outer Space Factors. Microelectronics. 2010, vol. 39, no. 2, pp. 85–90. (In Russ.)

12. Baraban A. P., Bulavinov V. V., Konorov P. P. *Elektronika sloyev SiO_2 na kremnii* [Electronics of SiO_2 Layers on Silicon]. Leningrad, *Izd. Leningradskogo universiteta*, 1988, 304 pp. (In Russ.)

13. Romanov N. M., Mokrushina S. A. Gamma Irradiation Effect to MOS Structures with Thin Al_2O_3 Oxide. Prospective materials. 2018, no. 2, pp. 17–24. (In Russ.) doi: 10.30791/1028-978X-2018-2-17-22

14. Korshunov F. P., Bogatyrev Yu. V., Vavilov V. A. The Effect of Radiation on Integrated Circuits. Minsk, Science and technology, 1986, 254 p. (In Russ.)

15. Fleetwood D. M. Dual-Transistor Method to Determine Threshold-Voltage Shifts Due to Oxide-Trapped Charge and Interface-Traps in MOS Devices. Appl. Phys. Lett. 1989, no. 55, pp. 466–468. doi:10.1063/1.101854

16. Oldham T. R. Total Ionizing Dose Effects in MOS Oxides and Devices. IEEE Trans. Nuclear Physics. 2003, no. 50 (3), pp. 483–499. doi: 10.1109/TNS.2003.812927

17. Lazar' A. P., Korshunov F. P. *Modelirovaniye radiatsionnoy stoykosti elementov logicheskikh KMOP integral'nykh skhem* [Modeling the Radiation Resistance of Elements of Logical CMOS Integrated Circuits]. *Doklady BGUIR,* 2013, no. 5, pp. 17–23. (In Russ.)

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