Simulation of the Heavy Charged Particle Impacts on Electrical Characteristics of N-MOSFET Device Structure

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***Abstract*—The paper presents the results of simulation of the impacts of a heavy charged particle with a value of linear energy transfer equal to 1.81 MeV·cm²/mg, 10.1 MeV·cm²/mg, 18.8 MeV·cm²/mg, 55.0 MeV·cm²/mg, corresponding to nitrogen ions $^{15}N^{+4}$ with energy E = 1.87 MeV, argon $^{40}Ar^{+12}$ with energy E = 372 MeV, ferrum $^{56}Fe^{+15}$ with energy E = 523 MeV, xenon $^{131}Xe^{+35}$ with energy E = 1217 MeV, on electrical characteristics of n-MOSFET device structure when there are variations in the motion trajectory and ambient temperature.**

Keywords—MOSFET, device simulation, ionizing radiation, single event upset, linear energy transfer.

I. INTRODUCTION

The main factors of space environment that can cause damage to the electronics of spacecraft are the following [1-3]: ionizing radiation; cosmic plasma; thermal radiation of the Sun, planets and space environment; weightless state; etc. Ionizing radiation consists of a stream of primary charged nuclear particles - electrons, protons and heavy charged particles, as well as secondary nuclear particles - products of nuclear transformations associated with primary particles. The main effects of ionizing radiation on the electronics are associated with ionization and nuclear energy losses of primary and secondary particles in active and passive areas of semiconductor devices and integrated circuits (ICs). These effects can cause parametric failure of semiconductor devices and ICs as a result of accumulation of a dose of ionizing radiation, as well as single event effects (SEE), for example, a single event upset (SEU). SEU occurs when heavy charged particles are found in the IC, and is characterized by short-term strong ionization along the particle track [4, 5]. The current impulse caused by the recombination of ion-induced holes and electrons changes the state of the logic element. The value of ionizing charge, sufficient for SEU, depends on the voltage on the electrodes and linear energy transfer (LET).

The developers of aerospace and special-purpose ICs need to study the radiation exposure mechanisms on the element and component base and use design and technology solutions that simultaneously reduce the effects of radiation exposure and can be implemented within semiconductor technology. [6, 7].

II. MOS-TRANSISTOR DEVICE STRUCTURE

A typical device structure of an n-MOSFET is shown in Fig. 1. Silicon doped with boron with an impurity concentration of $2 \cdot 10^{17}$ cm^{-2} serves as the substrate. Insulation between elements is made under STI-technology. The drain and source areas are formed using phosphorus ion implantation through a mask. The maximum impurity concentration in the drain and source areas is $2 \cdot 10^{19}$ cm^{-2}. The depth of occurrence of the drain-source p-n-junctions is 0.65 μm. Polysilicon is used as the gate material. The contacts to the drain, source, and substrate areas are from aluminium.

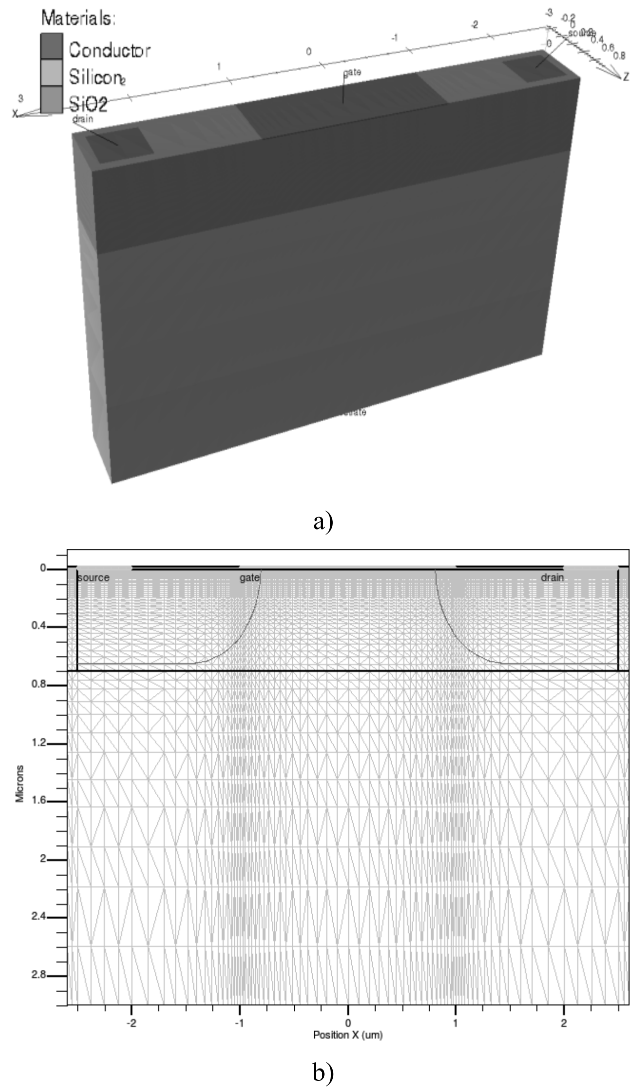


Fig. 1. Device structure of the n-channel MOS-transistor (a) and its cross section along the coordinate Z = 0.25 μm (b)

Table I presents the allowable values for the main design and technology parameters of the device structure under study.

TABLE I. BASIC PARAMETERS OF THE N-MOS-TRANSISTOR STRUCTURE

Parameter	Allowable values		
	Min.	Nom.	Max.
STI oxide depth, µm	0.5	0.7	0.9
STI oxide width, µm	0.1	0.2	0.5
Gate oxide thickness, nm	11	13	15
Contact window length and width to drain and source, µm	0.3	0.5	0.7
Window width (phosphorus implantation)	0.43	0.45	0.47
Gate length, µm	1.0	2.0	3.0
Gate width, µm	0.5	1.5	2.5

III. RESULTS

Impact simulation of a heavy charged particle with a value of LET equal to 1.81 MeV·cm^2/mg, 10.1 MeV·cm^2/mg, 18.8 MeV·cm^2/mg, 55.0 MeV·cm^2/mg, corresponding to nitrogen ions $^{15}N^{+4}$ with energy E = 1.87 MeV, argon $^{40}Ar^{+12}$ with energy E = 372 MeV, ferrum $^{56}Fe^{+15}$ with energy E = 523 MeV, xenon $^{131}Xe^{+35}$ with energy E = 1217 MeV, on electrical characteristics of n-MOSFET device structure using the Silvaco software system [8]. Simulation was performed at ambient temperatures values of 223 K, 303 K, and 383 K.

The study included the effect of the motion trajectory of a heavy charged particle, namely, the angles α and β to the normal to the surface of an n-MOS transistor in two perpendicular planes (Fig. 2). The entry point is the center of contact to the drain area (coordinates of the point are x = 2.25, y = 0, z = 0.25). At the time of impact, the voltage at the gate is V_g = 1.2 V, at the collector is V_c = 0.05 V. A heavy charged particle causes the generation of additional charge carriers, which results in an increase in the drain current I_D. In the future, there is a decrease in the value of the drain current I_D to the initial value.

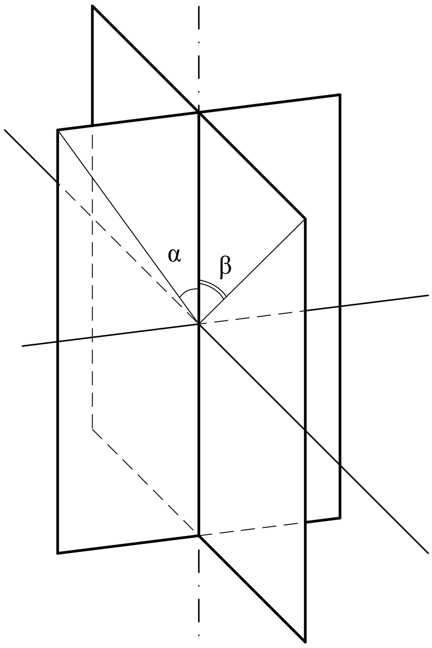


Fig. 2. Location of the angles α and β to the normal to the surface of an n-MOS transistor

Fig. 3 shows the dependencies of the drain current I_D on the simulation time when exposed to a heavy charged particle with LET equal to 1.81 MeV·cm^2/mg at an ambient temperature of 303 K and variation of the angle α. The angle β in the calculations is equal to 0°.

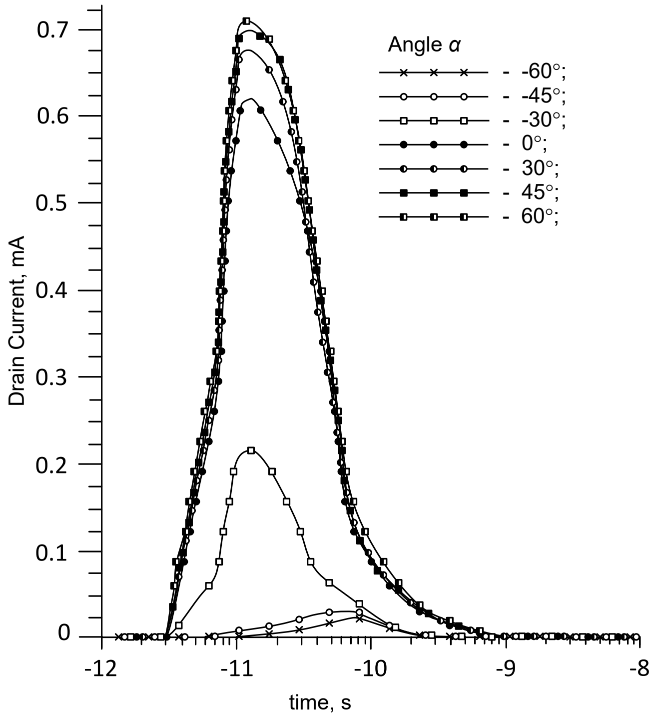
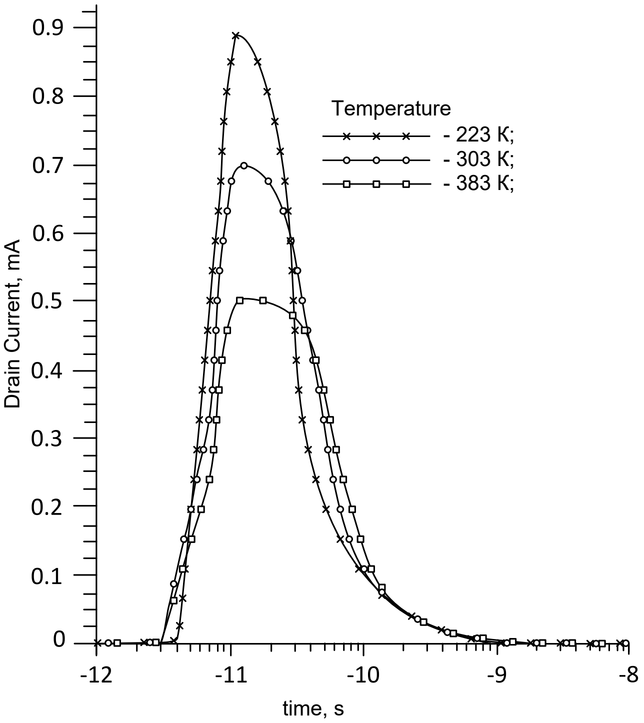


Fig. 3. Dependencies of the drain current I_D on the simulation time when exposed to a heavy charged particle with LET equal to 1.81 MeV·cm^2/mg at an ambient temperature of 303 K and variation of the angle α

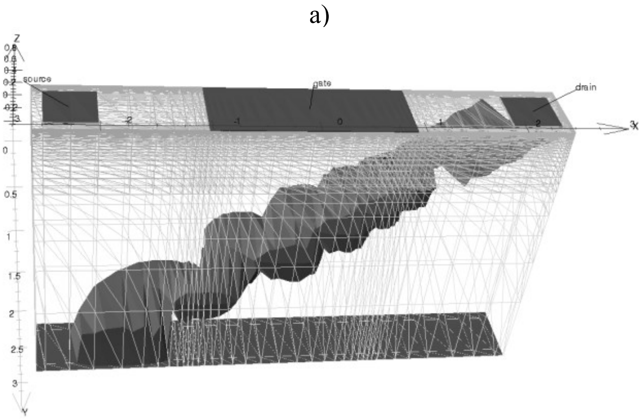
The simulation results showed that the value of the drain current I_D, caused by the effects of a heavy charged particle, is many times higher than the nominal value. Thus, when the angle α = 0°, the drain current I_D increases by 626.7 times (from $9.9 \cdot 10^{-7}$ A to $6.2 \cdot 10^{-4}$ A). Recovery of the drain current level I_D to the nominal value occurs at the moment of time t = 5.8 ns. With an increase in the angle α, there is an increase in the ratio I_{Dmax} / I_{Dnom} (for example, at α = 30°, the ratio I_{Dmax} / I_{Dnom} is 684.4; at α = 45° – I_{Dmax} / I_{Dnom} = 715.9; at α = 60° – I_{Dmax} / I_{Dnom} = 707.3). Wherein, the recovery time is less dependent on the angle α in the range from 0° to 60° (t = 5.4 ns at α = 30°; t = 6.7 ns at α = 45°; t = 5.2 ns at α = 60°).

The angle β has a strong influence on the magnitude of the peak drain current and the recovery time. Thus, at angles α = 0° and β = 60° the drain current I_D increases by 22.2 times (up to a value of $2.2 \cdot 10^{-5}$ A). Recovery of the drain current level I_D to the nominal value occurs when t = 7.72 ns. Wherein, an increase in the angle α hardly changes the values of the peak drain current, but decreases the recovery time (at α = 30°, the ratio I_{Dmax} / I_{Dnom} is 19.97, t = 7.66 ns; at α = 45° – I_{Dmax} / I_{Dnom} = 21.29, t = 7.44 ns; at α = 60° I_{Dmax} / I_{Dnom} = 23.32, t = 6.27 ns).

Fig. 4a shows the dependencies of the drain current I_D on the simulation time when exposed to a heavy charged particle with LET equal to 1.81 MeV·cm^2/mg at different ambient temperatures and α = 60°. Fig. 4b shows the generation rate distribution of charge carriers along the particle passage track (303 K).



a)



b)

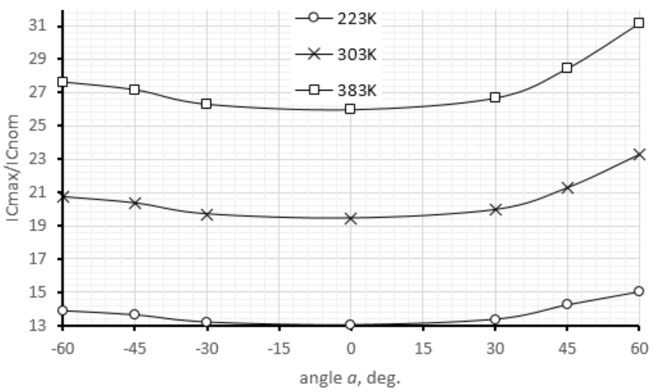
Fig. 4. Dependencies of the drain current I_D on the simulation time when exposed to a heavy charged particle with LET equal to 1.81 MeV·cm^2/mg at different temperatures and $\alpha = 60°$ (a) and the generation rate distribution of charge carriers along the particle passage track (b)

It is shown that the value of the drain current I_D, caused by the effects of a heavy charged particle, at temperatures above 300 K changes approximately the same number of times relative to the nominal value. Thus, at a temperature of 303 K, the nominal drain current I_{Dnom} is $9.9 \cdot 10^{-7}$ A, the maximum drain current I_{Dmax} is $7 \cdot 10^{-4}$ A (I_{Dmax} / I_{Dnom} = 707.3), at a temperature of 383 K – $7.2 \cdot 10^{-7}$ A and $5 \cdot 10^{-4}$ A respectively (I_{Dmax} / I_{Dnom} = 706.2). At temperatures below 303 K, a significant decrease in the I_{Dmax} / I_{Dnom} ratio is observed (592.4 at a temperature of 223 K). As in the case of the influence of the angle α, the recovery time of the value of the drain current to the nominal value shows a relatively weak dependence on temperature (t = 5.6 ns at T = 223 K; t = 5.1 ns at T = 303 K; t = 6.1 ns at t = 383 K).

Figure 5a shows the dependence of the ratio I_{Dmax} / I_{Dnom} on the angle α (angle $\beta = 60°$) at different temperatures.

It is shown that the dependencies qualitatively obtained by computer simulation coincide and have the smallest increase in the maximum drain current I_D at $\alpha = 0°$. When the angle increases to $\alpha = 60°$ or $\alpha = -60°$ there is an increase in the maximum drain current and in the I_{Dmax} / I_{Dnom} ratio by 1.2 %, 4.6 % and 6.55 % for angle values $\alpha = -30°$, -45° and -60°, respectively, and 2.5 %, 9.3 % and 15.4 % for angle values α = 30°, 45° and 60°, respectively. These values are valid for almost the entire temperature range under consideration, except for the angle $\alpha = 60°$. Thus, the ratio of I_{Dmax} / I_{Dnom} at a temperature of 223 K increases by 15.4 %, at a temperature of 303 K - by 19.9 % and at a temperature of 383 K - by 20.1 %.

Figure 5b shows the dependence of the recovery time on the angle α (angle $\beta = 60°$) at different temperatures. In contrast to the I_{Dmax} / I_{Dnom} ratio, the dependence of the recovery time on the angle α demonstrates a more complex character. It is shown that with an increase in the absolute value of the angle α, there is a decrease in the time, required to return the device structure of the MOS transistor to its original state. At high and low temperatures, the effect of this absolute value is almost the same. Thus, at a temperature of 383 K and an angle α equal to -60° and 60°, the recovery time decreases by 1.11 ns and 1.1 ns, respectively, and at 223 K, by 0.55 ns and 0.52 ns. However, at a temperature close to 303 K, the change in the angle towards the channel of the transistor (positive values of the angle α) has the greatest effect. Thus, at an angle α equal to -60° and 60°, the recovery time decreases by the value of 0.39 ns and 1.45 ns, respectively (the difference is 3.7 times).



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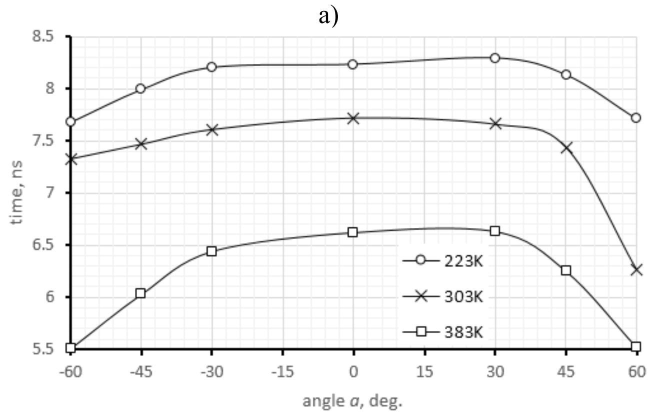
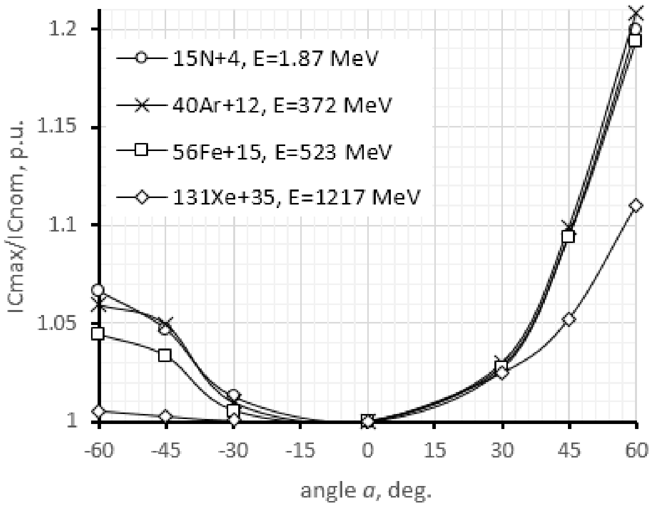


b)

Fig. 5. Dependence of the ratio I_{Dmax} / I_{Dnom} (a) and recovery time (b) on the angle α (angle $\beta = 60°$) at different temperatures

Figure 6a shows the dependencies of the ratio I_{Dmax} / I_{Dnom}, normalized to a value at $\alpha = 0°$, on the angle α (temperature T = 303 K, angle $\beta = 60°$) for particles represented by nitrogen ions $^{15}N^{+4}$ with energy E = 1.87 MeV, argon $^{40}Ar^{+12}$ with energy E = 372 MeV, ferrum $^{56}Fe^{+15}$ with energy E = 523 MeV and xenon $^{131}Xe^{+35}$ with energy E = 1217 MeV. These particles correspond to the value a linear energy transfer of 1.81 MeV·cm²/mg, 10.1 MeV·cm²/mg, 18.8 MeV·cm²/mg and 55.0 MeV·cm²/mg. It is shown that when LET of particles increases, the relative increase in the ratio I_{Dmax} / I_{Dnom} at a change in the angle α decreases. Thus, for nitrogen ions $^{15}N^{+4}$, argon $^{40}Ar^{+12}$ and ferrum $^{56}Fe^{+15}$ at an angle $\alpha = 60°$, the ratio increases by an average of 20 %, and for xenon ion $^{131}Xe^{+35}$ by 10.99 %. At the same time, the values of the ratio I_{Dmax} / I_{Dnom} are proportional to the LET value of the particle: 23.3 (maximum drain current I_D is $2.31 \cdot 10^{-5}$ A), 123.2 ($1.22 \cdot 10^{-4}$ A), 218.2 ($2.16 \cdot 10^{-4}$ A), 408.1 ($4.04 \cdot 10^{-4}$ A) in the case of exposure to nitrogen, argon, ferrum and xenon ions, respectively. It can also be noted that with positive values of the angle α, its influence on the ratio I_{Dmax} / I_{Dnom} is more than 3 times (and for xenon ion $^{131}Xe^{+35}$ in 20 times) higher compared to the negative values of the angle α.



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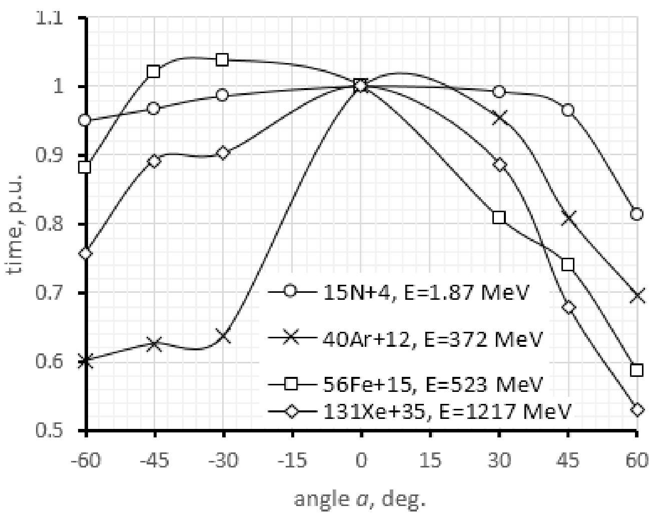

b)

Fig. 6. Dependence of the ratio I_{Dmax} / I_{Dnom} (a) and recovery time (b) on the angle α (angle $\beta = 60°$, temperature T = 303 K) for different particles

Figure 6b shows the dependencies of the recovery time, normalized to a value at $\alpha = 0°$, on the angle α (temperature T = 303 K, angle $\beta = 60°$) for particles represented by nitrogen ions $^{15}N^{+4}$ with energy E = 1.87 MeV, argon $^{40}Ar^{+12}$ with energy E = 372 MeV, ferrum $^{56}Fe^{+15}$ with energy E = 523 MeV and xenon $^{131}Xe^{+35}$ with energy E = 1217 MeV. Analyzing the results obtained, it is difficult to identify patterns in the dependence of the recovery time on LET of particles.

IV. Conclusion

We can conclude from the analysis of the results of simulation of the effects of a heavy charged particle on the n-MOS transistor device structure that the value of the drain current I_D, caused by the influence of a heavy charged particle, is many times greater than the nominal value of the drain current I_D (up to 700 times for nitrogen ion $^{15}N^{+4}$ with energy E = 1.87 MeV) and depends heavily on the angles α and β, which characterize the motion trajectory of the particle. At temperatures above 303 K, the ratio of the peak drain current to the nominal current remains almost constant. At temperatures below 303 K, a significant decrease in the I_{Dmax} / I_{Dnom} ratio is observed (to 592.4 at a temperature of 223 K). The recovery time is less dependent on the angle α in the range from 0° to 60° (t = 5.4 ns at $\alpha = 30°$; t = 6.7 ns at $\alpha = 45°$; t = 5.2 ns at $\alpha = 60°$) and temperature (t = 5.6 ns at T = 223 K; t = 5.1 ns at T = 303 K; t = 6.1 ns at T = 383 K), it largely depends on the angle β (t = 5.8 ns at $\beta = 0°$; t = 0.27 ns at $\beta = 60°$). For the remaining particles (argon ions $^{40}Ar^{+12}$, ferrum $^{56}Fe^{+15}$ and xenon $^{131}Xe^{+35}$), a qualitative coincidence of the dependences is observed, except for the case with the recovery time.

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