PROTECTION OF READ-OUT ELECTRONICS FROM IONIZING RADIATION

Lappeenranta–Lahti University of Technology LUT

Master`s thesis

2022

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Examiner(s): Professor Panja Luukka

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ABSTRACT

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This paper examines basic ways to protect electronics from ionizing radiation. This topic became relevant in the last century, with the development of astronautics. Then for the first time the question arose about the mechanisms of electronics degradation under the influence of ionizing radiation and, accordingly, about the protection methods. In this work, the main mechanisms of the interaction between radiation and individual semiconductor components were studied in order to understand exactly how alpha, beta and gamma radiation affect the properties of semiconductors.

Moreover, the case for the device under DeNuSa project was also designed. To make sure of its reliability, the passage of particles through the material is simulated in the GEANT4 program. Based on the research, various options have been proposed to protect this device from ionizing radiation.

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SYMBOLS AND ABBREVIATIONS

Roman characters

V_{TH} threshold voltage [V]

V_{GS} voltage difference between the gate and source terminal [V]

K_s screening coefficient

Greek characters

φ_n neutron fluence [neutron/cm^2]

τ charge carrier lifetime [s]

ρ density [g/cm^3]

Abbreviations

MIS metal-insulator-semiconductor

MOSFET metal–oxide–semiconductor field-effect transistor

SRAM static random access memory

SSPM solid-state photomultipliers

FDSOI fully depleted silicon-on-insulator varactors

FOXFET field-oxide field-effect transistors

FGMOS floating gate MOSFET

PMT photomultiplier tubes

LET Linear energy transfer

ADC analog-to-digital converter

LPE liquid-phase-epitaxy

SEU Single Event Upset

IC integrated circuits

RPS radiation protection screens

HCP heavy charged particles

TCE temperature coefficient of expansion

ERB Earth's radiation belts

VAC volt-ampere characteristics

SRIM Stopping and Range of Ions in Matter

TRIM Transport of Ions in Matter

1 Introduction

Protecting electronics from ionizing radiation is very important topic for space, nuclear and other physics fields. DENUSA project is developing a device that allows to remotely assess the level of alpha, beta and gamma radiation. The purpose of this work was to design and test a protective case for this device, which would protect the read-out electronics as much as possible, but at the same time the detectors could receive a sufficient amount of radiation for measuring it. To achieve this task, it is necessary to understand the mechanisms of ionizing radiation and to assess how particles affect certain types of semiconductor electronics. In the practical part, several variants of this case were designed, as well as the optimal material was selected. To assess the reliability of this device, it was tested in the TRIM, SRIM and GEANT4 software package.

2 Sources of radiation

Semiconductor materials inside various devices quite often encounter ionizing radiation. Most of the radiation comes from outer space, but the impact of radiation from extra-terrestrial sources is significantly diminished due to the interaction with atmosphere and its magnetic field. The main source of radiation on earth is a high-energy neutron flux, which is formed during nuclear interactions between protons and atmospheric elements. Another significant source is considered to be alpha particles emitted from the natural radioactive isotopes and local impurities present in individual parts of electronic devices (such as chip packages) [1]. Other sources of radioactive radiation are artificial, that is, made by man, such as nuclear power plants, medicine, etc. The main radiation types from these sources are X-rays, gamma radiation, heavy ions and high-energy protons.

2.1 What is ionizing radiation?

Ionizing radiation is a stream of particles that can cause ionization of matter. During ionization, an electron is detached from a molecule or atom, which turns into a positively charged ion. Despite the variety of phenomena occurring in a substance under the action of ionizing radiation, irradiation can be characterized by a single quantity, called the radiation dose.

Living organism cannot directly sense ionizing radiation, and thus being exposed to too large amount of radiation can have dangerous consequences. Thus, it is important to develop measurement devices that can detect radiation, before the radiation dose has become too large.

3 Effect of ionizing radiation on electronics

There are two main mechanisms of high-energy radiation interaction with semiconductor device: atomic collisions and electron ionization. Importance of these mechanisms in semiconductor structure depends on the device nature and radiation type. For electron, proton and γ-environments, most of the deposited energy is spent on ionization processes, i.e., excitation and pair production. For fast-neutron environments, on the contrary, a certain fraction of the deposited energy (up to ~50%) results directly in atomic displacement damage from collisions. Changes in the device caused by radiation can be different and depend on the relative sensitivity to ionization and volume displacement damage. For example, let's take surface-controlled metal-insulator-semiconductor (MIS) devices, this type is limited by the ionization produced, since radiation leads to charge accumulation in the layers of the insulator and to an increase in the density of surface states at the insulator-semiconductor interface.

If we consider bulk effect in semiconductors, performance is usually degraded by bias damage, since such damage can reduce the collected carrier concentration, as well as their mobility and lifetime. The carrier concentration is reduced by trapping, the mobility is lowered by scattering, and the lifetime is decreased by recombination. The incident radiation type is important since it determines “primary” introduced defects nature. As an example, initially appeared defect for ^{6o}Co by γ irradiation or electron irradiation is elementary, perhaps a single supplanted lattice atom and it is connected vacancy. Otherwise, fast neutrons irradiation is assumed to the formation of damage areas or “clusters”, each of which contains up to around several hundred supplanted atoms. Because defects in their original form are not thermally stable in the temperature range in which semiconductor devices usually operate, it is also required to understand the processes of defect reordering. Material factors and irradiation conditions such as resistivity, impurity content, irradiation temperature, and minority carrier injection level are quite important, influencing not only the reordering processes but also the basic nature of the final damage. In this work, we will consider the main mechanisms of the interaction of radiation with semiconductors [2].

4 Failure mechanisms in devices

In Figure 1, the authors of article [3] listed the most significant semiconductor devices and identified the degradation mechanisms leading to the failure of this device. It is worth mentioning that devices whose operation depends on the resistivity, or the concentration of the main carriers fail mainly due to the removal or capture of charge carriers. For example, semiconductor resistors, diodes, and others.

Devices based on the injection of minority carriers, such as photodiodes, bipolar transistors, and most switching and optoelectronic devices lose their functional properties due to the shortening of the lifetime of their majority charge carriers. Surface controlled devices, such as, MIS field effect transistors and capacitors fail primarily because of oxide charge build up and superficies effect. Radiation-produced changes in lifetime, carrier concentration, and mobility are the result of lattice atom displacements (atomic disorder), whereas the oxide and surface effects are caused by the ionization dose received. In addition to the permanent degradation's mechanism shown in Figure 1, radiation creates electron-hole pairs in materials during the exposure. For nuclear environments, ionization generated by neutrons is much less than made by x-ray and gamma photons. Charge carriers formed in the depletion zones of the device or within the diffusion length of these areas can create photocurrents at the terminals of the device [2]. Such photocurrents could cause serious transients in linear circuits and can generate errors in the information stored by logic circuits.

Device type	Failure mechanisms			
	Lifetime degradation	Carrier removal and trapping	Mobility Degradation	Oxide charge and surface effects
Semiconductors Resistors		P	S	
Diodes (Breakdown voltage, depletion capacitance)	S	P		
Diodes (Leakage, forward current, photocurrent)	P	S		S
Microwave Diode Sources (IMPATT,TRAPATT)	S	P		
Junction field effect devices	S	P		
MIS field effect devices& Capacitors				P
Microwave Bulk Oscillators(Gunn, LSA)		P	S	
Bipolar Transistors	P	S		S
Switching Devices (SCR)	P	S		
Optoelectronic Devices	P			
P- primary S-secondary				

Figure.1. Primary and secondary radiation failure mechanisms for semiconductor device.[3]

4.1 Fast neutron effects

The meaningful effect of fast neutrons on semiconductors is the change in the electrical properties of the device bulk material. The neutron sensitivity of mobility, carrier concentration, and minority carrier lifetime is presented by the authors of the article in Figure 2 for 1 Ω·cm silicon. The mobility data [4] show that degradation does not become severe until the neutron fluence (φ_n) exceeds 10^{15} neutron/cm^2. With such a particle flow density, the concentration of charge carriers drops to almost zero. The range of curves for charge carrier lifetime ratio (τ/τ_0) against φ_n coincide relatively to the range of lifetime values and injection conditions found in this type of devices. The low-injection (LI) curve for $\tau_0 = 10^{-6}$ s would characterize the behavior in solar cells at low injection. Here the lifetime has decreased by 50% at $\varphi_n = 5\cdot10^{10}$ neutron/cm^2. At the other extreme, the high-injection (HI) curve for $\tau_0 = 10^{-9}$s might typify the behavior observed in a modem, gold-doped transistor. In this case, a fluence of approximately $5\cdot10^{15}$ neutron/cm^2 is required for a 50% lifetime reduction [2].

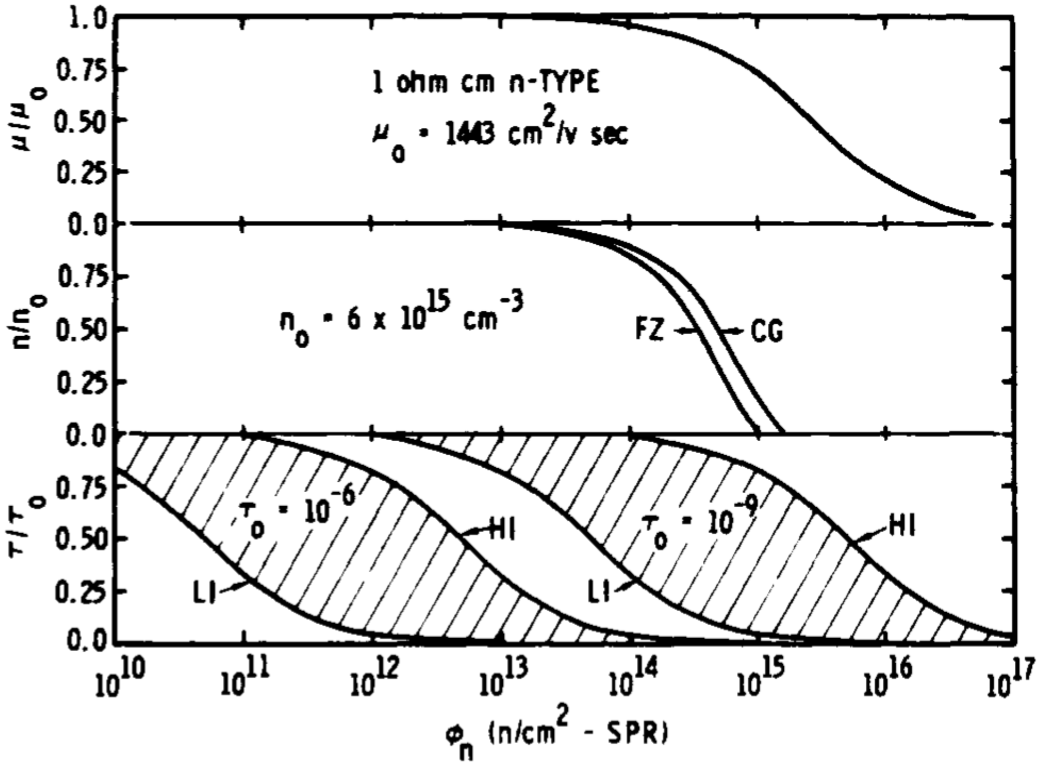


Figure 2. Calculated parameter degradation for 1 Ω·cm silicon near room temperature. [5]

4.2 Ionization effect

Radiation-induced ionization, which leads to failures in semiconductors, differs from neutron damage, which was discussed in the previous passage. In the study [5] the authors have shown that ionizing radiation causes failure of silicon devices due to two mechanisms: 1) trapped charge build up in the silicon dioxide passivation layer and 2) an increase in the density of surface states at the Si-SiO_2 interface. In MOSFETs, as well as planar bipolar transistors, these two mechanisms play a key role in determining the effects of ionization.

5 Radiation measurement techniques

The radiation interactions considered in this paper are related to the Poisson distribution. In active mode, radiation sensors can respond both to a single quantum (particle detection) and to a group of particles within a certain period of time (dose measurement). In passive mode, if no bias voltage is supplied to the sensors, energy can be accumulated due to particle irradiation. Then, after connecting the sensor to the power source, you can find out the dose of radiation. In the active mode, the sensors can operate both in pulse and integral methods.

In the case of Si-diode or Si-photodiode based detectors, the radiation induced burst of currents are monitored by the readout electronics. The resulting charge is the integral of the current from the detection time. The data obtained for a given period of time are used for indirect measurement of the radiation dose. In the pulse counting mode, the number of received signals is compared with a predetermined threshold. According to this principle, in random access memory (SRAM), the critical charge required to switch bits in memory elements works as a threshold for particle detection. A more complex version is implemented on the basis of 3-D NAND flash memory, in fact it represents several variants of threshold comparison, also makes it possible to evaluate the energy spectrum with particle detection.

Dosimeters are sensors operating in an integrated mode. The dosimeters measure cumulative values and emissions (TID, kerma, dose rate and exposure time) [6]. The integration of information can be carried out by the readout electronics (Si-diodes) or by the sensing devices themselves (MOSFET based sensors). The principle of operation of such devices can be implemented by various methods, for example, by measuring the threshold voltage V_{TH} or voltage reference sensing and time-domain (frequency) output. They can be qualified according to the principle of using a sensitive element, such as silicon diodes, solid-state photomultipliers (SSPM), fully depleted silicon-on-insulator varactors (FDSOI) and MOSFETs, as well as field-effect transistors (RADFET), field-oxide field-effect transistors (FOXFETs), floating gate MOSFET (FGMOS).

Particle detectors operating in pulse counting mode help to detect radiation, even small errors in integrated circuits. These methods essentially provide data on current or voltage or read operations from memory in digital memory structures [1].

5.1 Silicon diode based radiation sensors

In this type of sensor, the reverse biased pn-junction is used for measuring the radiation. Generated carriers arising due to interaction with ionizing radiation in the depleted region are swept away by drift in the presence of an electric field over the junction. As illustrated in Figure 3, the excess charge carriers are collected with an external electric field and amplified using a charge-sensitive pre-amplifier [1]. The resulting current or voltage transient from the amplified charge is compared with a threshold and shaped into a pulse to cause a trigger to the digital counter. Thus, sensors based on Si diodes, in the pulse counter mode, are used as detectors. However, such devices can also work in integrated mode, then the circuit measures voltage or current transients. It is possible to estimate the received energy by the integral of time from the received radiation. Thus, this information gives an indirect idea of the total accumulated radiation dose on the sensor device. In this case, the diodes are configured in reverse bias mode, which leads to a wide depleted layer and a decrease in leakage current, thus providing higher radiation detection efficiency with a linear relationship between the deposited charge and the integrated dose. Si-diode based position sensitive detectors such as single-sided silicon strip detectors [7] and active pixel detectors [8] are moderately sensitive and suitable for high-dose radiation measurement as in pulsed radiation fields (X-rays, electron linear accelerators) [9]. Over time, the sensitivity of these diodes decreases due to radiation, and they need to be calibrated again for effective measurements.

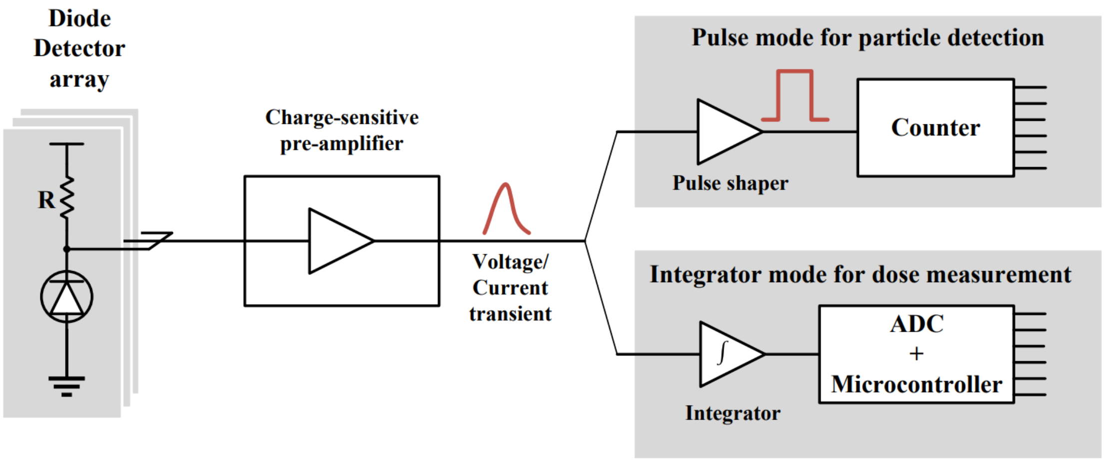


Figure 3. Illustrations of different methods (pulse mode and integral mode) of radiation detection of the Si-diode based radiation sensors.[1]

5.2 Silicon photodiodes based radiation sensors

This type of sensor uses Si photodiodes as a sensor. There are only four types of them: a photodiode with a p-n junction [10], a PIN (p-type, embedded, n-type) photodiode [11], an avalanche photodiode [12] and a Schottky photodiode [13]. Unlike a standard photodiode with a pn-junction, PIN photodiodes have better sensitivity. The width of the inner layer ensures that there is a high probability of absorption of incoming photons by this layer, and not by p- or n-type regions. The inner layer has a high resistance because there are no free charge carriers in it. The highest sensitivity to radiation among photodiodes is usually obtained in Avalanche photodiodes due to the Avalanche breakdown action. However, the Avalanche photodiode based detectors need larger bias voltage and produce higher levels of noise. When a beam of light with a suitable energy hits the inner layer, it creates an electron-hole pair, lifting an electron from the valence band into the conduction band and leaving a hole in its place. The bias voltage causes these charge carriers (electrons in the conduction band) to rapidly shift out of the transition zone, creating a current proportional to the incident light.

Detectors that work on the principle of Schottky photodiodes consist of semiconductor structures (e.g., SiC) and give a fast response time due to a small working capacity. Sensitivity in detectors with Schottky barriers to radiation occurs when electrons (or holes) with energy exceeding the height of the potential barrier are excited in the quasi-metallic layer of the barrier (during absorption of radiation quanta) [14]. The photodiodes could be embedded with SSPMs and be as an alternative for vacuum-based photomultiplier tubes (PMTs) can be used in various fields, in space or in high energy physics research [15].

SSPMs are fabricated using an array of Geiger-mode photodiodes on custom CMOS technology. A radiation sensitive scintillator material is coupled to the fabricated SSPM device. Scheme of the CMOS SSPM connected with scintillation material shown in Figure 4 [1]. When a charged particle hits the surface of the dosimeter, the scintillator absorbs the energy of this particle and re-emits it in the form of light. The generated photons fall into the pixels of the SSPM matrix. The ingress of radiation from a low LET (Linear energy transfer) activates several pixels, and from a high LET a larger number of pixels. Due to the incident radiation, the scintillation coupled SSPM device generates an equivalent amount of transient current. After that, transients are recorded to count the pulses of radiation. Just as with analog-to-digital converter (ADC), the time integral of the current can be digitized. The number of activated photodiodes is proportional to the energy released due to incident high-energy radiation. Compared to PMTs, SSPM-based detectors are compact, lightweight and can be integrated with built-in CMOS read-out circuits [15]. The digitized output data provides an estimate of the spectrum of the absorbed dose and the released energy, as well as the liquid-phase-epitaxy (LPE) of the radiation particle.

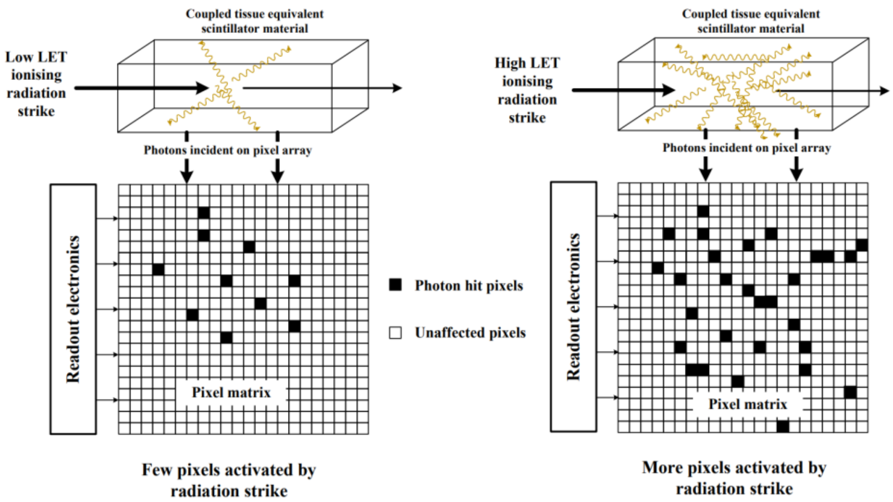


Figure 4. Illustration of working principle of scintillator coupled solid-state photomultiplier (SSPM) based dosimeter.[1]

5.3 Radiation sensitive MOSFET devices

The characteristics of MOSFET devices, especially mobility and V_{TH} threshold voltage, vary greatly when exposed to high-energy radiation. By studying the shift of the threshold voltage V_{TH}, it is possible to estimate the received radiation dose, such use of pMOS in a diode configuration was proposed by the authors in reference [16] to measure the radiation dose in space. A scheme was devised to change the voltage difference between the gate and source terminal (V_{GS}). The authors of the article [17] showed that the magnitude of the V_{TH} shift is proportional to the square of the thickness of the gate oxide (t^2_{OX}). However, MOSFET-based sensors have a number of disadvantages, one of them is low sensitivity. If you use field oxide instead of gate oxides, you can get a higher sensitivity, such devices are called FOXFET (field-oxide field-effect transistor) this type of device is shown in Figure 5 [18]. The wider width of the oxide layer contributes to the generation of more charges. Also, like MOSFET-based devices, FOXFET is just as strongly temperature dependent.

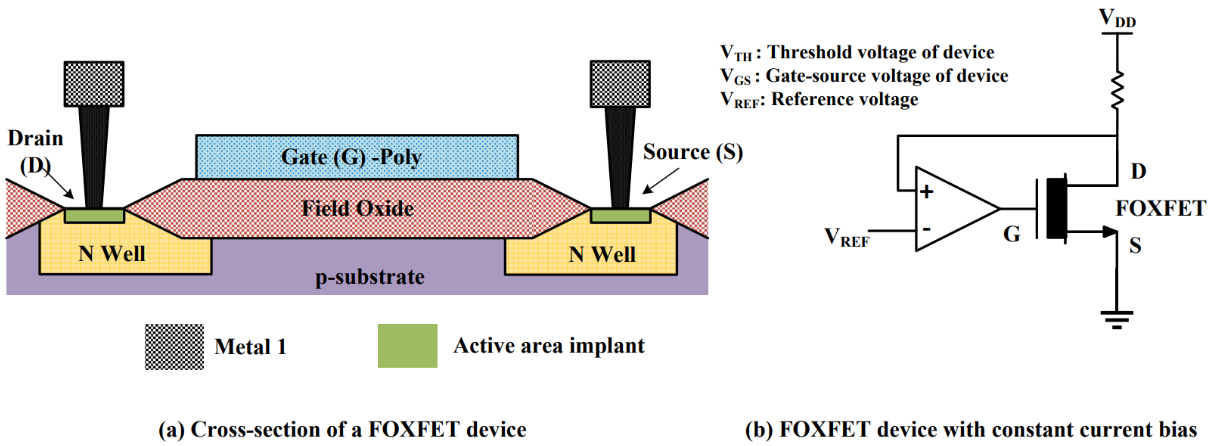


Figure 5. (a) Cross-section of a field-oxide field-effect transistor (FOXFET) device used in dosimeter and (b) readout circuit for threshold voltage measurement of a FOXFET based dosimeter. [1]

Alternatively, we can consider FGMOS devices. Floating gate structures (FG) can be implemented by connecting a polysilicon gate of a MOSFET capacitor to the gate of a sensitive MOSFET device using standard CMOS technology [19], as shown in Figure 6a, or using an additional isolated polysilicon gate in a special two-polymer CMOS process [20], as shown in Figure 6b. Thus, a capacitor is formed in the process. This capacitor is used for pre-charging FG before irradiation by injection of carriers by an avalanche process or by tunnelling through a gate-oxide [21]. When exposed to ionizing radiation, charges are generated that accumulate in the oxide region and neutralize the initial charge on the FG. This leads to a change in V_{TH}, and the reading circuit integrated on the chip with sensors measures the V_{TH} shift and provides a proportional output voltage or current [22]. Such dosimeters are very sensitive to the radiation dose, they also show good resolution, but their use is limited by a low dose level.

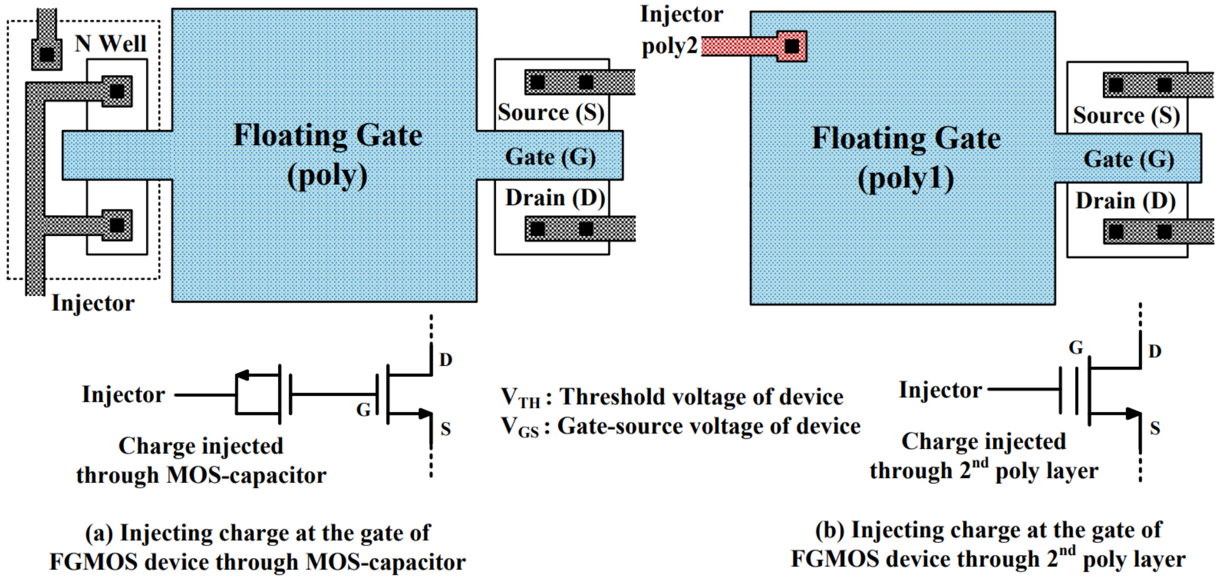


Figure 6. (a) Top view of the floating-gate MOSFET (FGMOS) device integrated with MOS-capacitor for charge injection into gate-oxide and (b) top view of the FGMOS device with an additional poly layer used for charge injection [1].

5.4 SRAM based radiation monitor

SEUs (Single Event Upset) in the presence of radiation can affect data storage circuits, RAM. SRAM (Static Random Access Memory) is the most used circuit for SEUs monitoring in electronic systems. This circuit consists of two cross-coupled inverters that create a two-state structure as shown in Figure 7.

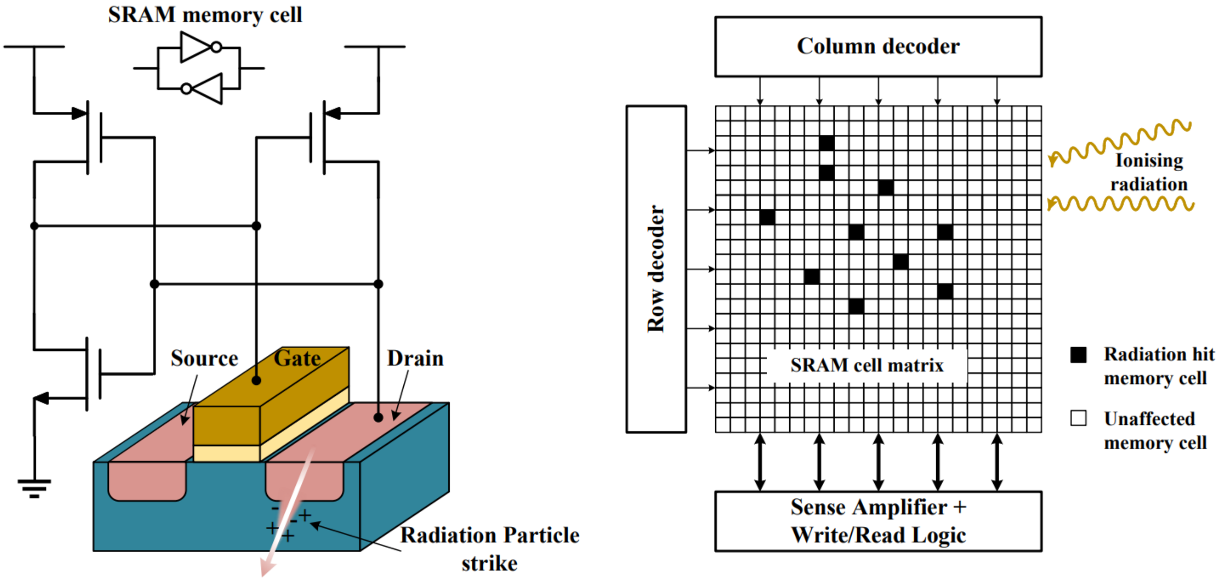


Figure 7. Mechanism of radiation strike and memory bit-flips on static random access memory (SRAM) nodes.[1]

6 Specialized radiation protection enclosures for microelectronics products.

Several approaches are used to increase the radiation resistance of electronic equipment:

- technological (application of specialized technological processes and materials in the manufacture of integrated circuits (IC) and other components of on-board equipment) [23,24];
- constructive (specialized buildings IC, methods of local protection) [23];
- circuit engineering (methods of majorization, etc.) [23];
- simulation of radiation effects (at the IC design stage) [23].

Structural protection is not an alternative to the listed methods but serves an additional way to reduce the radiation load on all objects, e.g., on board of the spacecraft. However, when using standard structural protection materials (aluminum and its alloys), a sufficiently high level of radiation exposure is maintained, therefore local protection is recommended for the most vulnerable elements.

6.1 Local protection

Local protection is an additional shielding designed to protect critical components and hardware elements. The use of such a screen does not entail a serious increase in the mass or dimensions of the spacecraft units, it is one of the most effective and economical approaches to providing radiation protection. A promising direction for the development of methods of local protection of IC is the creation of new types of enclosures with integrated radiation protection screens (RPS).

Application of commercial IC chips and semiconductor devices in military and civilian space systems became possible after the effectiveness of shielding using protective materials was experimentally proven [25]. Local IC shielding was proposed in 1979, and studies confirming its effectiveness were conducted in the 80s in the USA [25-27].

The effect of radiation on the elements and equipment of the spacecraft is determined by the type of radiation, energy, intensity and penetrating ability of primary and secondary particles in the volume of matter. RPS are effective for protecting electronic equipment from the effects of a soft component of cosmic radiation (electrons, protons), unable to penetrate deeply into matter.

As for ionizing radiation with a higher penetrating power (X-ray radiation, gamma radiation, muons, heavy charged particles, etc.), the protection of electronic systems by means of screens is less effective. It should be noted that by using one method it is impossible to provide a sufficient level of protection of spacecraft equipment from the entire spectrum of cosmic radiation. RPS protect the elements of spacecraft from the cumulative (dose) component of the radiation load, while at the same time high-energy particles, including heavy charged particles (HCP), creating single radiation effects, have a probabilistic nature of exposure and require other ways to increase radiation resistance.

6.2 Modern materials and designs of protection screens

Materials and technologies for RPS are developed by many deep tech manufacturers. the names of these technologies and their manufacturer are listed below: RAD-COAT ((Space Electronics Inc., USA), RAD-PAK (Maxwell Technologies, USA), WALOPACK (3D-Plus, France), X-Ray (Actel, USA) [28-29]. To protect the IC in the spacecraft from the effects of ionizing radiation, companies offer several housing designs (Figure 8).

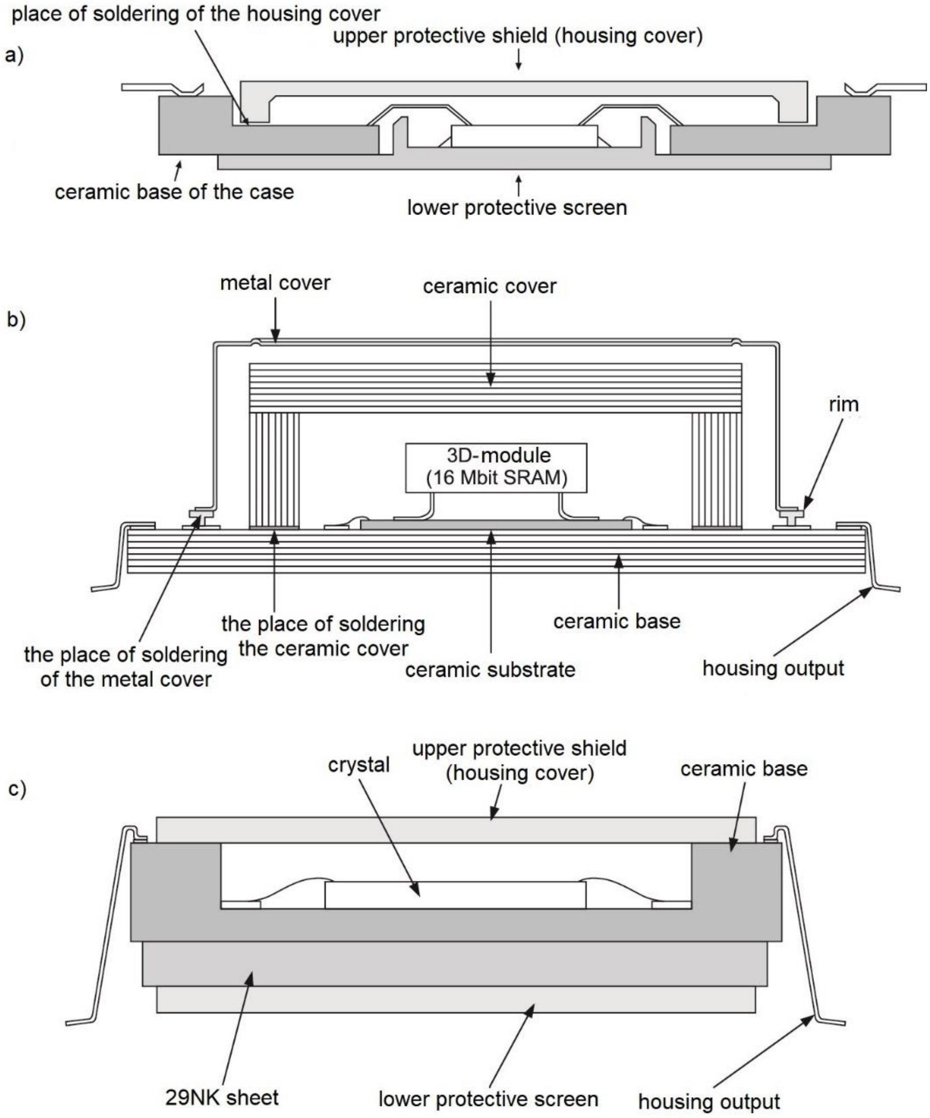


Figure 8. Housing designs MIC with integrated protective screens of a number of foreign companies.

According to Maxwell Technologies, the RAD-PAK technology provides a radiation resistance level of at least 100 krad in relation to the effect of the absorbed dose [29]. It is fundamentally important that the effectiveness of such protection takes into account the parameters of the orbit, the service life and the layout of the spacecraft.

As recent studies have shown, multilayer structures and composite materials have the most protective properties against radiation exposure, which allow reducing the dose loads on the elements of the spacecraft equipment by several times while reducing the weight of the overall characteristics [29, 30]. Such RPS materials include WALOPACK, which are structures with alternating layers of Al_2O_3 ceramics and powdered tungsten. It was shown in that for a geostationary orbit (GSO), a three-layer protection composition is most effective, in which a material with a high atomic number Z is located between layers of a material with a low Z, in particular, the A1-W-A1 composition.

The configuration and dimensions of the RPS should correspond to the standard MIC housing. From this point of view, the universal technology is application of RAD-COAT protective coatings, which, unlike RAD-RAK and WALOPACK technologies, is not tied to the design of a standard case MIC. RAD-COAT type coatings are made on the basis of a plastic matrix with a filler in the form of tungsten powder. However, taking into account the density of these coatings (13 g/cm^3), it can be assumed that they are inferior in efficiency to RAD-PAD and WALOPACK type protection.

6.3 Studies of RPS samples based on various materials

Since this area is very relevant, a number of other companies have produced their own protective enclosures with integrated radiation shields. For example, the company «TESTPRIBOR» in 2014. At the first stage, studies of promising materials for RPS were carried out, providing maximum protection efficiency with optimal weight and size characteristics and consistent in terms of temperature coefficient of expansion (TCE) with materials used for the manufacture of metal-ceramic IC housings (alloy 29NK and ceramics Al_2O_3). The results of computer calculations of the coefficients of attenuation of proton and electron fluxes RPS for a number of space orbits were compared with experimental data.

For research, RPS samples were made in the form of plates of different thicknesses based on pure metals (tungsten, tantalum, copper and aluminum), composites of the W-Cu system, as well as coatings of Bi-Al alloys, Al_2O_3 ceramics and an alloy of the Fe-Ni-Co (29NK) system. Samples of the screens were tested for electrons and protons of the Earth's radiation belts (ERB) on modeling installations. Electron irradiation was carried out on electron accelerators ELU-4 (electron energy 4 MeV) (NPC of the National Academy of Sciences of Belarus for Materials Science, Minsk), as well as U-31/33 (2.2 MeV) and "RELUS" (3.6 MeV) (CJSC "ENPO SPELS", Moscow). To reduce the electron energy to 1.6–1.8 MeV at the ELU-4 accelerator between an aluminum plate with a thickness of 5 mm was installed as a target and an electron output window. Proton irradiation was carried out on a proton accelerator with tunable energy (Protvino). The following values of the proton energy were used: 50, 70, 100, 150 and 200 MeV.

The absorbed dose was determined both by the IS-7 detectors and by changes in the volt-ampere characteristics (VAC) of p-channel MOSFETs. IS-7 detectors are standard dosimetry tools in JSC "ENPO SPELS" when conducting radiation resistance tests. Their error does not exceed 15%. Transistor MOSFET structures (elements of IN74AC04N logic CMOS ICS) manufactured in PC (Public corporation) "Integral" according to standard epi-planar technology with induced p-type channels (channel length L=2.0 microns, width W=50.0 microns) were used as test samples.

The parameters of the test MOS structures were measured before and after each dose of irradiation with the help of a semiconductor parameters meter for STIS-1/6. The measurement error was ± 5%. The efficiency of shielding was determined by the change in the VAC, in particular, the threshold voltage of the U_{vol} of the MOSFETs located behind the screen and without the screen. The values of the screening coefficient of K_s test structures were calculated from the ratio:

$$K_s = D_p / D_{p0}$$

where D_p is the dose of parametric failure of the test instrument structure behind the protective screen, D_{p0} – the dose of parametric failure of a test device of a new structure without a screen. Parametric failure was recorded when the threshold voltage ΔU_{vol} = 0.1 B.

When using IS-7 dosimeters, the screening efficiency was also determined by the ratio of the absorbed dose measured without the screen to the absorbed dose behind the screen.

To convert the fluence (integral flux density) of electrons into the accumulated dose, the following ratios were used: 1 krad=3×10^{10} el/cm^2; 1×10^{12} el/cm^2 =33 krad.

The GEANT4 program was used to calculate the absorbed radiation dose in a silicon crystal located behind protective screens and without a screen, irradiated with protons with an energy from 0.04 to 500 MeV. As the results of the RPS study based on various materials have shown, in terms of overall and cost parameters, tungsten is the most suitable material [31]. To change the TCE of its impurities of other metals, in particular, copper, are added. The W-Cu composite obtained in this way has the necessary technological qualities for the manufacture of RPS integrated into MIC metal-ceramic housings.

Studies of the protective properties of RPS samples based on composite material W-Cu, Al_2O_3 ceramics and an alloy of the Fe-Ni-Co (29NK) system, when irradiated with electron fluxes with an energy of 1.6–1.8 MeV, test structures of p-channel MOSFETS showed that as the thickness of the elements of metal-ceramic housings increases, MIC increases the screening efficiency coefficient.

W-Cu (ρ=16,6 g/cm^3)						
d, cm	0,06		0,09	0,12		0,15
d_m, g/cm^2	1,06		1,51	2,01		2,47
K_s	96		130,8	142,3		155,8
Al_2O_3 (ρ=3,62 g/cm^3)						
d, cm	0,093	0,181	0,271	0,364	0,456	0,545
d_m, g/cm^2	0,337	0,655	0,981	1,317	1,651	1,973
K_s	2,3	6,9	36,2	103,8	126,9	140,3
29NK (ρ=8,4 g/cm^3)						
d, cm	0,05	0,075	0,10	0,15	0,20	0,25
d_m, g/cm^2	0,42	0,63	0,84	1,26	1,68	2,1
K_s	4,2	9,6	21,9	115,4	130,7	138,5

The calculation of Ks is performed for D_{p0} =2.6×10^{12} cm^{-2}; d_m =p×d [g/cm^2], where d is the thickness of the sample, d_m is the mass thickness, and p is the density of the material.

Figure 9. Protective properties of radiation shield samples based on W-Cu composite material, Al_2O_3 ceramics and Fe-Ni-Co (29NK) alloy system.

Screens based on Al_2O_3 ceramics can provide the required level of electronic equipment products protection with a thickness of more than 3 mm, screens made of 29NK alloy – more than 1.5 mm. However, an increase in the thickness of the ceramic housing in most cases is not possible both in terms of dimensions and the required level of heat removal.

More efficient is to integrate into microchips housing screens based on composite material W-Cu (Figure 9). Even with a thickness of RPS d = 0.6 mm, significantly higher radiation-protective properties are achieved than those of screens made on the basis of 29NK alloy or Al_2O_3 ceramics. However, an excessive increase in the thickness of Cu plates also does not give a significant gain in the radiation-protective properties of RPS from both electron and proton irradiation. Most likely, this is due to an increase in Bremsstrahlung, which has a high penetrating power. It has been established that for protection against electrons and protons of the RPS, the optimal thickness of screens based on W-Cu is in the range of 0.9–1.2 mm.

In the results of computer simulation of the efficiency coefficient of screening RPS based on W-Cu with a thickness of 1.2 mm from electrons and protons with different energies, it was shown that this type of RPS very effectively weakens the emission of RPS electrons in the entire energy range – the order of magnitude of the K_s varies in the range of 10 to 104.

Electrons		Protons			
E_e, MeV	K_s	E_p, MeV	K_s	E_p, MeV	K_s
0,5	Max.	3	38214695,96	28	10586,32
1,0	39524,3	5	2918577,01	30	7554,69
1,5	4753,6	7	1113847,86	31	34,92
2,2	1385,1	10	606568,38	32	0,90
2,5	948,5	12	264503,06	33	0,46
3,0	460,0	15	184863,02	34	0,33
3,6	324,3	17	110060,02	35	0,30
4,0	202,3	20	38051,11	36	0,39
5,0	34,3	22	22194,03	38	0,50
6,0	5,9	26	12995,70	40	0,57

Figure 10. Results of computer simulation of the screening efficiency coefficient RPS based on W-Cu with a thickness of 1.2 mm from electrons and protons with different energies. The maximum value of the attenuation coefficient means that not a single electron with such energy passes through the protective shield

For protons of outer space (OS) with an energy of less than 30 MeV, the protective shield provides attenuation of the absorbed dose in 103-106 times, for protons with energy in the range of 30-100 MeV, an increase in the absorbed dose behind the protective screen is observed by two to three times. It is inefficient to use a protective shield for proton radiation with an energy of more than 100 MeV. The specific energy losses of protons increase as the energy of the particles decreases, and especially sharply before stopping in the substance [26]. This is due to the observed decrease in the value K_s that is below unity for protons with an energy in the range of 30-100 MeV (Figure 10).

From the results of calculating the values of the efficiency coefficient of the shielding of the K_s for the RPS based on the W-Cu composite with a thickness of 1.2 mm for electron and proton flows of the OS on various types of orbits, it can be seen that the protective shield reduces the total absorbed dose from charged particles by at least an order of magnitude. At the same time, RPS are the most effective for GSO, GLONASS and VEO orbits (highly elliptical orbit) with a large contribution of electrons. The use of RPS for orbits with a large contribution of protons (the ISS orbit and the circular polar orbit) is less effective.

6.4 Enclosures for MIC with RPS based on W-Cu composite material

According to the results of research made by some companies (e.g., TESTPRIBOR), the enclosures could be designed and manufactured for MIC with radiation protection screens made on the basis of composite material W-Cu that are integrated into them.

The authors have proposed two variants of the metal-ceramic housing, which differ in methods of sealing the subcorpus space (Figure 11). In the first case, sealing it is carried out by soldering (figure 11a), and in the second – by seam-roller welding (Figure 11b).

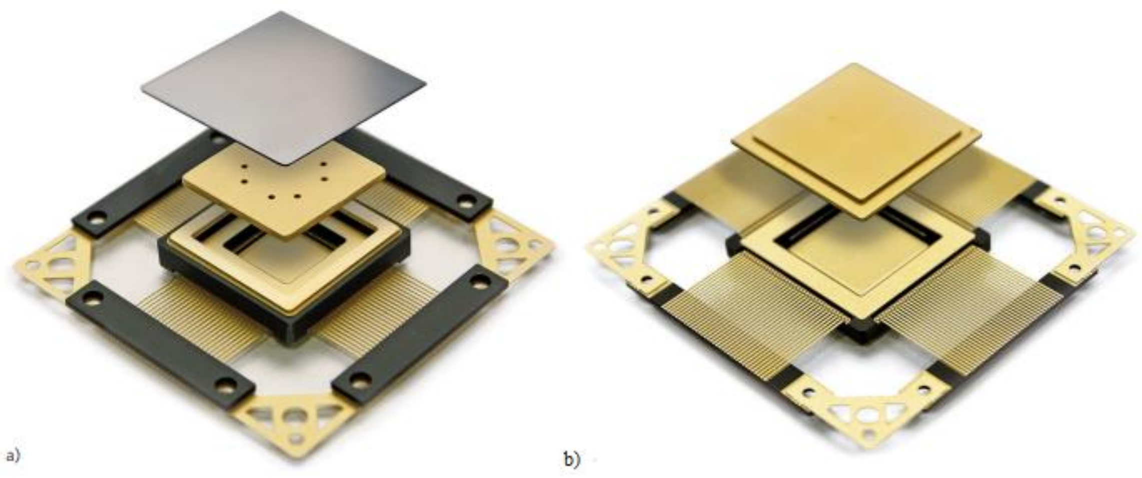


Figure 11. Variants of the metal-ceramic housing with integrated RPS based on W-Cu composite material: a) 100-lead planar housing with sealing by soldering, b) 144-lead planar housing with sealing by seam-roller welding.

The TESTPRIBOR company has developed materials and technology that can be used for the manufacture of a new generation of electronic component base cases used in rocket and space technology equipment to ensure increased requirements for radiation resistance.

The use of enclosures with integrated radiation protection will allow:

- increased radiation safety of MIC, electronic components and equipment;
- usage of commercial and industrial grade electronic components for space applications;
- to expand the range of MIC used and thereby reduce the cost of equipment in the production of space equipment;
- to ensure a reduction in weight and overall parameters in comparison with standard methods of structural protection.

7 Radiation shielding materials

7.1 Materials used in radiation shielding

At nuclear power facilities, in industrial or medical X-ray systems, in radioisotope projects, when working with particle accelerators and in a number of other circumstances, radiation protection is very important because radiation can be very dangerous and pose a serious threat [31]. A very important part of the operation of equipment that emits potentially dangerous radiation is the containment of the dangerous radiation in order to prevent it from causing any harm to employees, patients etc. No less important goals are to preserve both human safety, which can be affected by radiation, as well as photographic film, electronic devices, protection of sensitive materials, structural materials, because they can also suffer from radiation exposure.

The degree of penetration of the radiation, as well as the process of controlling the impact, varies depending on the type of radiation that is used. Different types of shielding radiation materials are most suitable for specific types of radiation than others, which is determined by the interaction between specific particles and the elementary properties of the shielding material.

7.2 General radiation shielding properties

Protection against radiation, which should consist of the ability to reduce the effects of the incident radiation by reflecting or blocking particles through a barrier material, is based on the principle of attenuation. Charged particles can be attenuated by energy loss from reactions in the electron barrier at the moment gamma and X-ray radiation are attenuated by photoemission, scattering, or pair production. Neutrons can be made the least harmful due to a combination of elastic and inelastic scattering, because most neutron barriers are made of materials that stimulate these processes. In industrial projects, these types of radiation are most often encountered:

- Gamma and X-rays Shielding: electromagnetic radiation, which is detected with a higher level of energy than those manifested by ultraviolet or visible light.

- Neutron Protection: Neutrons are particles that have no charge and thus use a wide range of energy and mass levels that need to be blocked.
- Alpha and Beta particles: Alpha particles are positively charged helium nuclei, they are also relatively easy to block. Beta particles are negatively charged electrons, which are harder to defend against [31].

Speaking about radiation protection, the main methods of radiation protection or radiation safety include time, distance and shielding. By time, it means to limit exposure to the lowest possible level. Distance means that the best option is to be as far away from radiation sources as possible. The distance from the radiation source by twice the distance reduces the radiation intensity by one-fourth of the magnitude. Also, if we talk about using effective protection, this is another way to manage the effects of radiation. What materials best protect against radiation? Of course, concrete, lead, and water are most often used.

7.3 X-ray and gamma radiation shielding materials

Most often, materials that have a higher density are more effective than materials with a lower density to contain or reduce the intensity of radiation. Materials that have a low density can compensate for the discrepancy with an increased thickness. This is just as important as the density when shielding. Lead is very well suited for less exposure to gamma and X-rays due to its high atomic number. A lead atom has a relatively large number of protons along with a corresponding number of electrons. Electrons stop a large number of gamma and X-ray particles that are trying to pass through the lead barrier, and the degree of protection can be increased due to thicker shielding barriers. It is very important to remember that there is a possibility that certain X-rays can penetrate the shielding and that an absolute barrier may become impossible in certain cases [31].

7.4 Alpha and beta shielding

What are the requirements for shielding alpha particles? When density remains an important characteristic for blocking alpha and beta radiation, thickness is of the least concern. To protect from the alpha particles, just one centimeter of plastic or one sheet of paper will be enough. Sometimes lead is ineffective to stop beta particles, because they can produce secondary radiation when they pass through elements with high atomic number and density. When negatively charged beta particles come into contact with a material that has a higher density, such as tungsten, the electrons are blocked, but the target that the barrier is supposed to protect may be exposed to radiation. Beta particles of the highest energies in the air can travel up to two meters, or even more [31].

7.5 Neutron shielding

To block neutron radiation, lead is not suitable, because neutrons are not charged and can easily pass through dense materials. Materials consisting of elements with a low atomic number are desirable to stop this type of radiation, because they have a high probability of the appearance of cross-sections that will interact with neutrons. Materials that are based on hydrogen are suitable for such a task. Compounds that have a high concentration of hydrogen atoms, such as water, form effective neutron barriers in addition to being relatively inexpensive protective substances. A low-density material can release gamma rays that block neutrons, meaning that neutron radiation protection is most effective when it includes elements with both low and high atomic numbers. A material that has a low density can scatter neutrons due to elastic scattering, and segments with a high density block subsequent gamma rays due to inelastic scattering [31].

7.6 Radiation shielding design and selection considerations

There are a number of factors that influence the choice, as well as the use of radioactive protective materials. Certain factors such as strength, damage resistance, attenuation, thermal properties and cost-effectiveness can affect radiation shielding in various ways. For example, metals are strong and also resistant to radiation damage, however they change their mechanical properties and also in a certain way they are degraded under radiation exposure. Just like metals, concrete is strong, durable, not particularly expensive to produce, but their disadvantage is that they become weaker when the temperature rises and are less effective at blocking neutrons. The following are certain considerations about the choice of material for radiation shielding [31]:

- The function of the effective cross-section of the shielding material is neutron attenuation. It shows the probability that the energy level of incident neutrons as a result of the nuclear reaction will be reduced.
- It is worth taking into account that the secondary effects of radiation from the protective material result, for example, from the absorption of gamma rays, which are generated as a result of neutron absorption.
- The energy that is absorbed in the protective material can lead to the formation of condensation. In this regard, it is necessary to note that the choice of materials with optimally high thermal conductivity is another factor that needs to be taken into account.
- When choosing a material, it is necessary to evaluate how the absorption of radiation affects the properties of the materials that are used and how these changes will affect the characteristics of the screen.
- Important points that should be taken into account when deciding which materials to use are manufacturing methods, weight, purchase cost, transportation costs, as well as installation costs, associated waste and the final cost of scrap material

7.7 Lead radiation shielding products

Knowing that lead is a heavy element, which is about 80% heavier than others from the periodic table, it is often used to make products that protect against radiation. Lead is manufactured in various product forms to provide radio protection, and which includes the following types: lead sheets, plates, slabs and foils; lead epoxies; lead shot; lead wools; lead putties; lead pipe; lead bricks; lead-clad pipe; lead-clad tubing; lead sleeves; lead-polyethylene-boron composites; lead glass.

For use in the construction of walls, lead can be added to concrete or cinder blocks. If you add non-perforated sheets of lead to the blocks and push the sheet over the edge of the concrete block, then you can build a lead screen into the wall with an overlap, in order to obtain a very effective radiation barrier, using a continuous lining from a lead sheet. This approach can also be used to create lead-coated doors and folding frames. It is important, as in the case of a wall structure, to overlap the lead that is used in the door frame with the lead that is used in the wall structure in order to provide a continuous lead barrier that will work as an effective screen.

For example, for viewing windows that are used in X-ray rooms, lead glass can be used and added in several layers as a means of creating a very effective radiation barrier. If you are looking for an alternative for lead glass, then you can take acrylic sheet materials containing 30% lead by weight, which have already been added to the acrylic resin during the manufacturing process.

7.8 Lightweight radiation shielding products

Light radiation protection equipment was developed to ensure personal protection and personal radiation protection. One such product in the form of flexible fabric is called Demron®, which can be fabricated into hazmat suits, Demron® blankets, Demron® tents, and other personal protection products such as tactical vests. Testing by the United States Department of Energy (DoE) has demonstrated the effectiveness of the material to reduce the levels of high energy alpha and beta radiation as well as to reduce low energy gamma radiation. The lightweight and flexible nature of these types of products makes them well suited for personal protective equipment that is wearable. An additional advantage is that they can be easily cleaned, stored and maintained.

8 Design case

In the previous chapter, we analyzed the most radiation-resistant materials that, with sufficient tightness and the right thickness, are able to protect electronics from ionizing radiation. However, do not forget that the detectors must receive a sufficient dose of radiation to achieve good measurement resolution. Therefore, to begin with, it was decided to study the most easily accessible materials for the electronic casing.

The simplest and most affordable material for making a case is ABS plastic, which is used in 3D printing. Therefore, it was decided to use this type of plastic for the prototype. The Fusion 360 program was used for case design. For the detection of alpha particles with energies characteristic of radioactive decay, it is necessary to ensure a small surface density of the screen separating the sensitive volume of the detector from the environment, therefore there is a through hole in the upper part of the case.

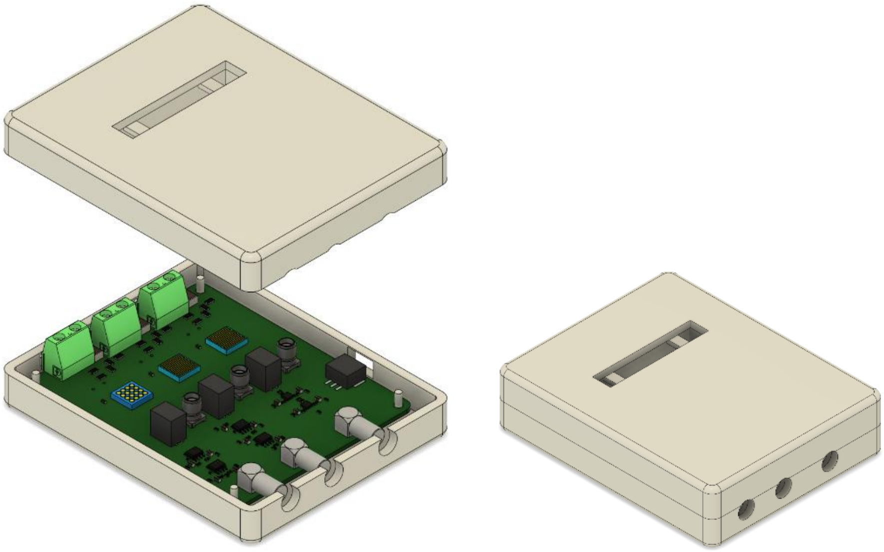
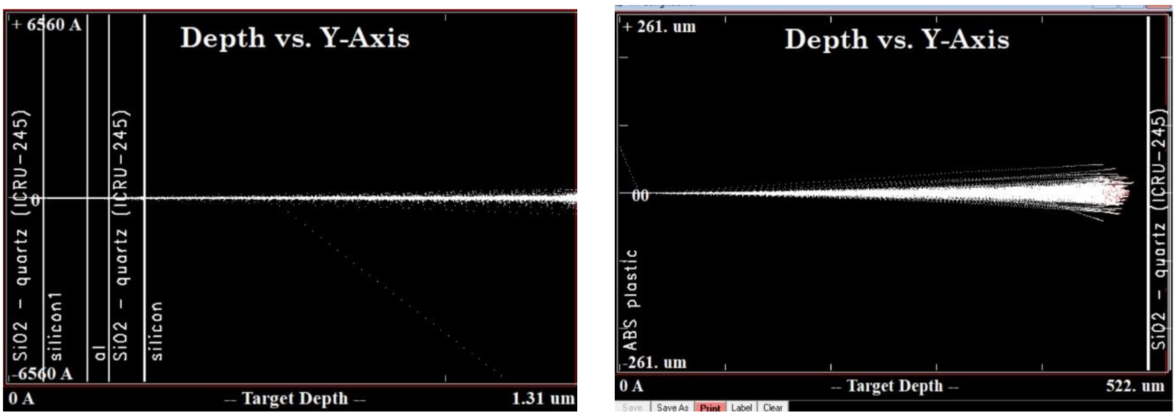


Figure 12. Plastic case for our device.

9 The case test in the SRIM and TRIM program

To fully understand how suitable our plastic is for these tasks, it was decided to test it experimentally in the SRIM program, which simulates the passage of heavy ions through a substance of a given thickness. Stopping and Range of Ions in Matter (SRIM) is a group of computer programs that calculate interactions between ions and matter. The core of SRIM is a program called Transport of Ions in Matter (TRIM). SRIM is popular in the scientific and technical community in the field of ion implantation and is also widely used in other fields of materials science.

For this analysis, five most frequently encountered ions with specified energies were selected. As a semiconductor element, I created a multilayer structure with alternating layers of SiO_2 and Si. Many simulations were carried out, and oxygen, hydrogen, carbon, silicon and chromium with different energies were used as ion sources. If we do not use any protective layers, then we can observe that oxygen ions easily penetrate our semiconductor and cause damage to our structure (figure 13A). The deepest passage was in hydrogen with an energy of 6 MeV, it penetrates into our plastic by 500 micrometers (Figure 13B).



A) B)

Figure 13. A) with case. B) without case

Having modeled various ions with different energies, it can be argued that our enclosure with a wall thickness of 5 mm is enough to prevent damage to the semiconductor structure when exposed to heavy ions.

In the following pictures you can observe how deep various ions pass into ABS plastic with a thickness of 5 mm.

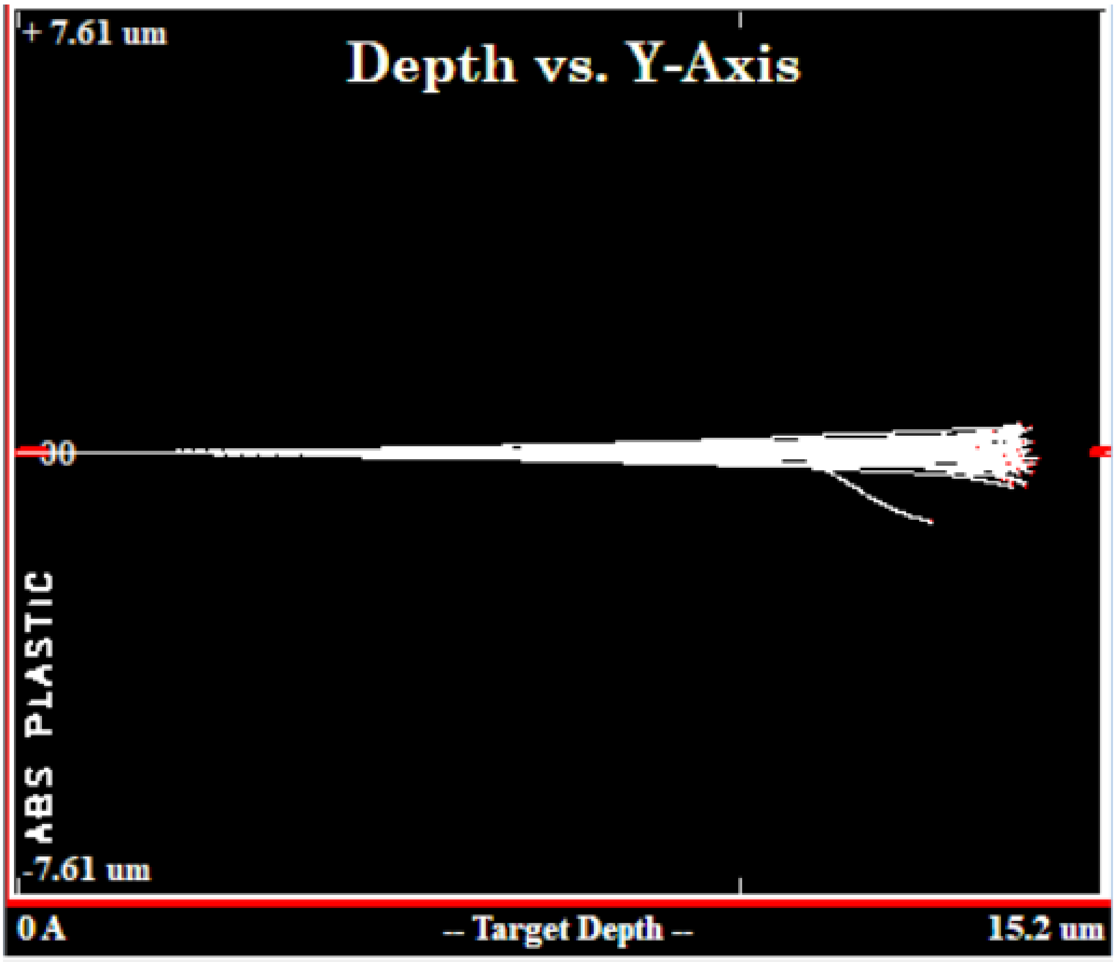


Figure 14. Oxygen 16000keV into ABS pl ± 15 um

Oxygen with an energy of 16000keV passes inside the ABS plastic to a depth of 15 um.

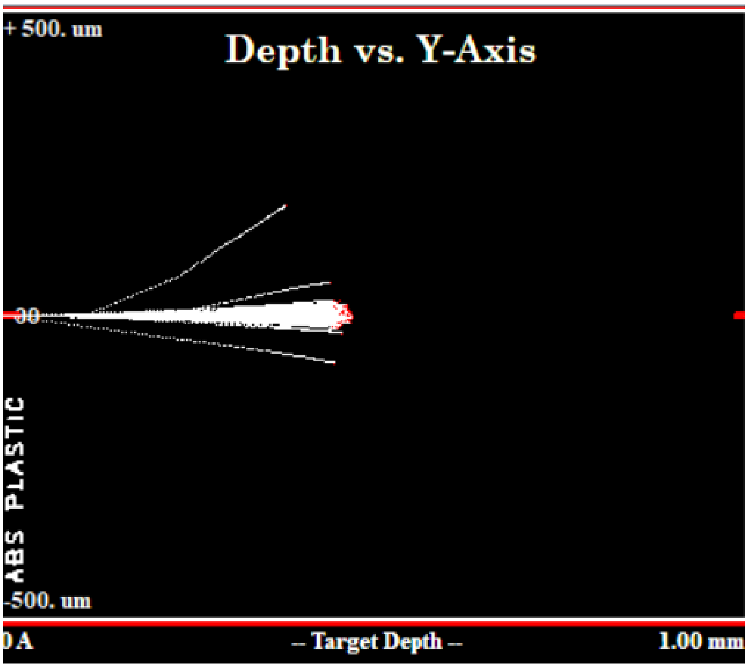


Figure 15. Hydrogen 6000keV ± 500um

Hydrogen with an energy of 6000keV passes inside the ABS plastic to a depth of 0.5mm.

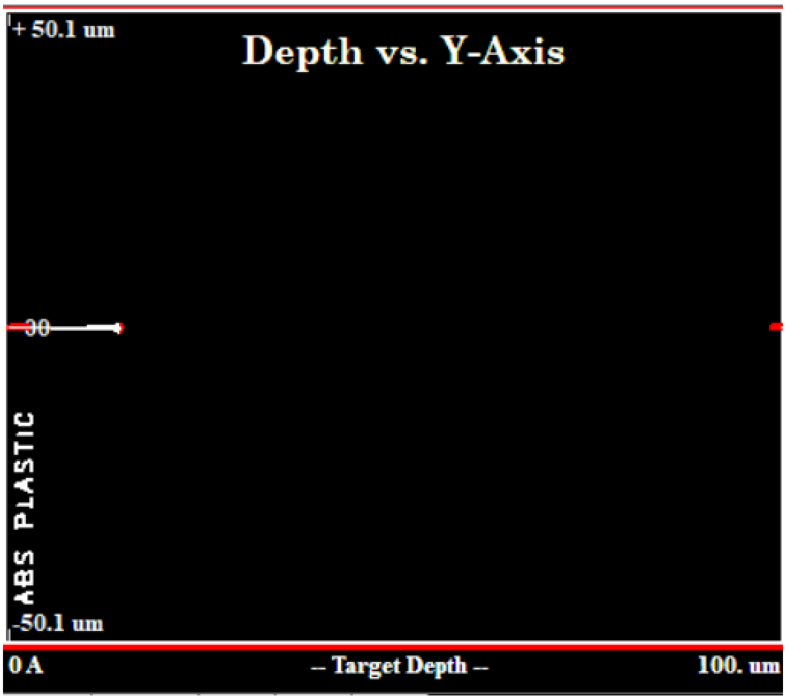


Figure 16. Carbon 12000keV ± 20um

Carbon fiber with an energy of 12000keV passes inside the ABS plastic to a depth of 20um.

10 A program for modelling the passage of radiation through a material (GEANT4)

To simulate the passage of particles through the detector, the best option is the GEANT4 software package. GEANT4 is an object-oriented set of software tools for modelling the passage of particles through matter. The toolkit provides a diverse, wide, but assembled set of software components that can be used for various purposes. It ranges from simple one-time studies of basic phenomena and geometries to full scale simulation of detectors for experiments at the CERN (The European Organization for Nuclear Research) and other objects.

When defining and implementing the software components, all aspects of the modelling process were taken into account: system geometry, materials used, main particles of interest, description of primary particles, events, tracking of particles passing through materials and external electromagnetic fields, physical processes, particle interactions, response of sensitive detector components, generation of event data, storage of events and tracks, visualization of the detector and particle trajectories, as well as subsequent analysis of simulation data at various levels of detail.

One of the most important tasks in the physics of the atomic nucleus and elementary particles is the study of the transport of various particles through matter. Knowledge about the interaction of electrons and gamma quanta with matter has now reached a high level. Due to previous extensive tests that have provided the base for the simulations, usually there is no need to conduct expensive research and experiments, you can get the necessary data using computer simulation of particle passage to solve fundamental and applied problems. Particle transfer modelling is used for quantitative analysis in electron microscopy, electron spectroscopy of surfaces, electron probe microanalysis and positron spectroscopy. It is also possible to use modelling for the design of detection systems and calibration of detectors, when determining radiation sources for the radiographic method of non-destructive testing. The use of computer modelling methods is sufficiently accurate for assessing the effect of radiation on the electronics.

10.1 Description of the GEANT4 package

The internal tools implemented in GEANT4 allow us to fully describe the physical experiment: the geometry of the system, the chemical composition of the materials forming it, the types of particles involved in the experiment, and the physical processes governing the interaction of particles.

The object-oriented programming technology allows achieving a high level of transparency when describing various modules of the modelling program. For example, the method by which interaction sections are calculated is implemented completely separately from the way in which these sections are used, which makes it possible to easily change or expand the interactions necessary for the experiment [32].

GEANT 4 is a set of libraries and classes that can be used to describe the following aspects of computer modelling:

1. The type and properties of the particles used. For example, the G4ParticleDefinition class allows you to set particle properties such as mass, spin, decay modes, etc., and using the G4DynamicParticle class it is possible to implement such dynamic characteristics of particles as energy, momentum, polarization, etc. [33].

2. Generation of primary particles. The G4PrimaryGeneratorAction class is responsible for creating primary particles, in which it is possible to set the type, properties, as well as the shape of the beam.

3. Physical processes that cause particle interactions. The G4PHYSICSLIST class is responsible for this aspect. All particles are created in it, as well as the processes that can occur with them. Since the creation of such a package is a very complex procedure, where a lot of details need to be taken into account, ready-made packages are usually used, specialized for certain purposes.

4. Getting information about each event, tracks and storing it. The G4Event class contains information about each event in the simulation process. The G4Step class allows you to get information about each step of the simulation. Specifying system geometry: G4DetectorConstruction. This class allows you to create computer model of a real object, given its size, material, relative arrangement of parts, etc.

5. Materials of the components of the experiment system. GEANT4 has the ability "create" substances and elements (G4Element, G4Material). Material can be created in various ways: to create a molecule of a substance from elements or to create a substance as a mixture of several elements with certain weighting factors.

6. Setting the sensitive areas, when particles hit, which will be analysed their movements: G4SensitiveDetector.

7. Visualization. GEANT4 has the ability to visualize geometry and particle tracks in the process of modeling using the following graphic systems: OpenGL, OpenInventor, HepRep, DAWN, VRML, RayTracer, ASCIITree.

All classes of the program implement the initial functionality programmed in them. This allows the developer using the GEANT4 program to make changes only to those classes that do not fit their initial functionality to the task being solved. In practice, this means that it is almost always necessary to change the classes responsible for the geometry of the system, the materials used, the description of particles and their interactions, the collection of modeling data, but it is not necessary to change the classes that implement the most complex (in terms of programming) process – the direct process of passing particles and their interaction with matter. The following physical processes are taken into account in GEANT4:

1. Electromagnetic interactions:

- Processes involving gamma quanta: photo effect (G4PhotoElectricEffect), Compton scattering (G4ComptonScaterring), formation of electron positron pairs (G4GammaConversation), formation of muon pairs (G4GammaConversationToMuons), Compton scattering of linearly polarized gamma quanta (G4PolarizedCompton), Rayleigh scattering).
- Processes common to all charged particles: multiple scattering (G4multiplescattering), transient radiation (G4TransitionRadiation), scintillation effect (G4Scintillation), Cherenkov effect (G4Cerenkov), photoabsorption ionization model (G4PAIModel).
- Processes involving electrons and positrons: ionization (G4eIonisation), bremsstrahlung (G4eBremsstrahlung), annihilation of positrons into gamma quanta

(G4eplusAnnihilation), annihilation into muons (G4eplusAnnihiToMuPair), synchrotron radiation (G4SynchrotronRadiation).

- Processes involving muons: ionization (G4MuIonization), bremsstrahlung (G4MuBremsstrahlung), muon photonuclear interactions, formation of electron positron pairs (G4MuPairProduction).
- Processes involving charged hadrons: ionization (G4hIonisation)

2. Processes involving hadrons, strong interaction (lepton-hadron interactions, cross sections of photonuclear and electronuclear reactions, coherent elastic scattering, interactions of inhibited particles), as well as many highly specialized models of specific physical processes.

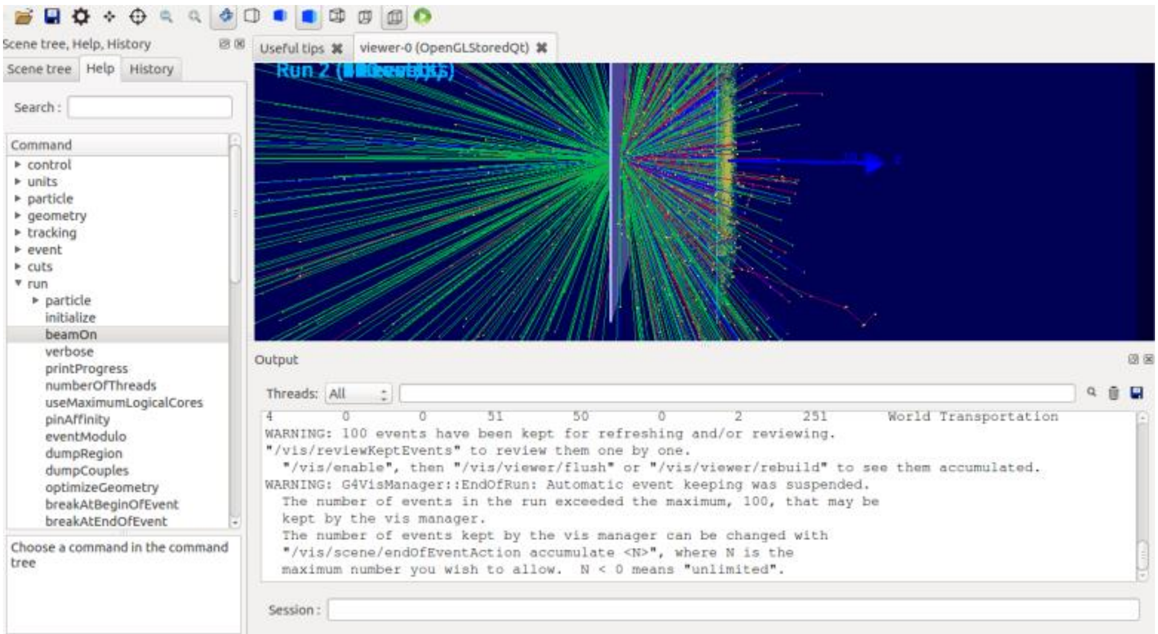


Figure 17. Graphical visualization of the experimental setup and particle tracks.

10.2 Simulation results

Theoretically, we can predict that plastic does not protect electronics from protons and high-energy electrons. For experiments with this program, lead with a thickness of 2, 3, 4 and 5 mm and an energy of 50 MeV was selected. The movement of particles is divided by the program into events. One event is the minimal advance of a particle, taking into account the processes occurring with it. Such as loss of energy, collision with matter and separation of a new particle. The interaction of proton and lead begins at the step edge on the graph (Figure 18).

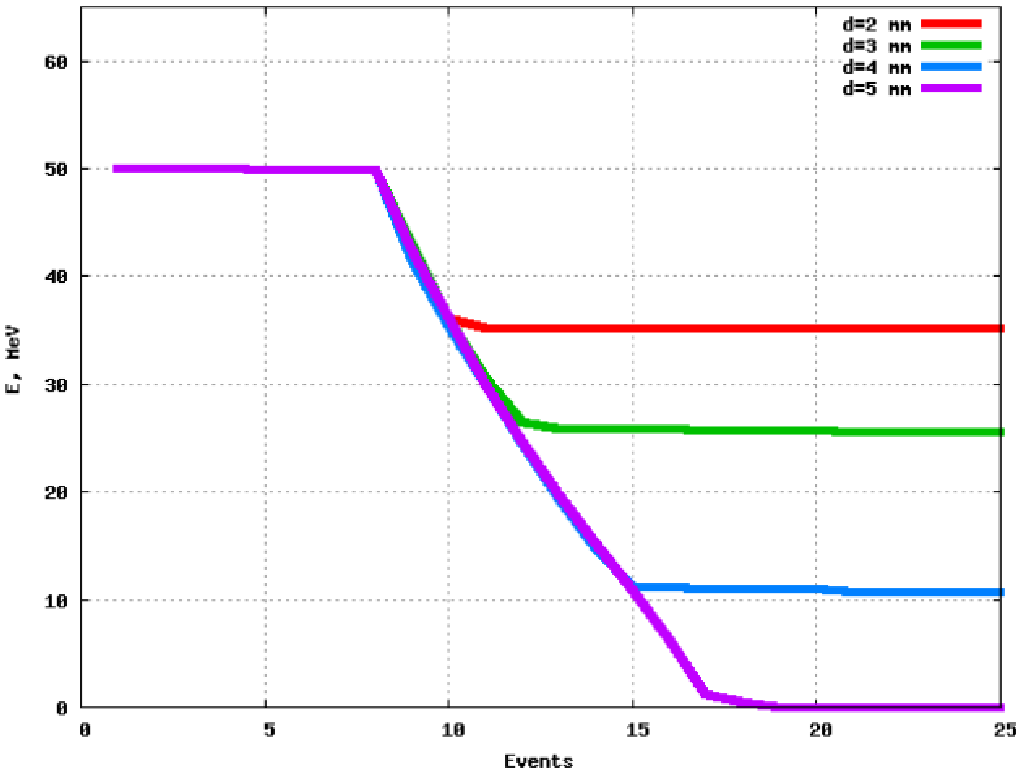


Figure 18. Energy losses by protons during the passage of the target.

Dependence of the amount of energy lost by the proton on the movement in the lead block.

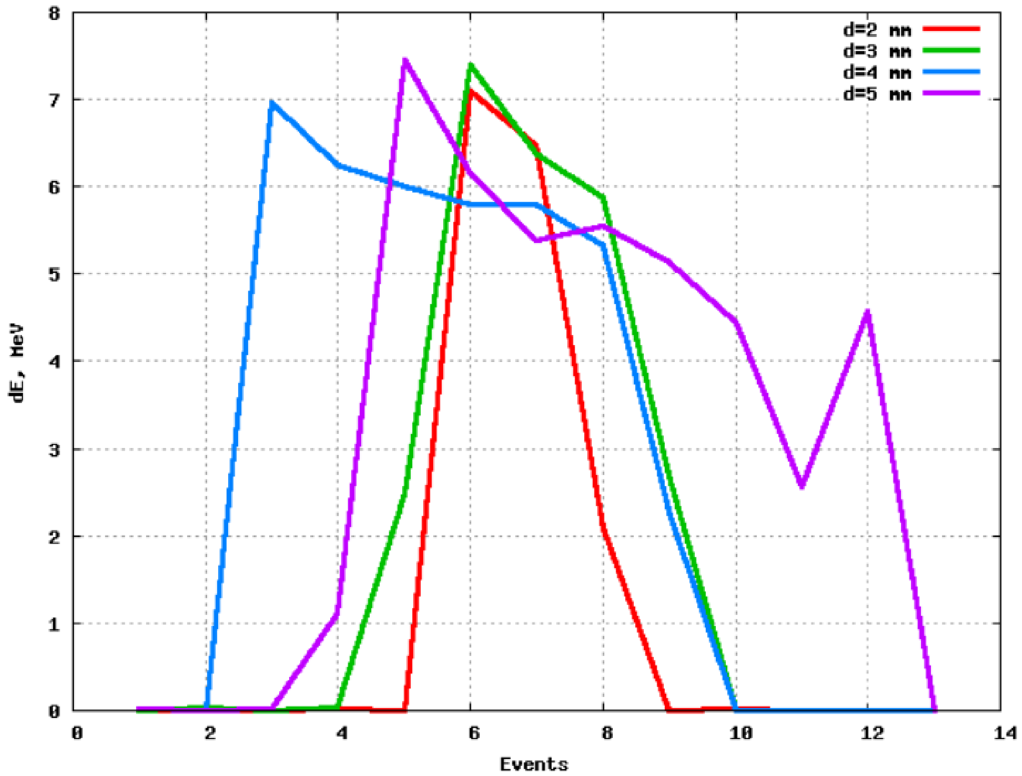


Figure 19. The amount of energy expended during the proton passage of the target.

To construct angular distributions, protons and electrons were chosen as the source of particles, and lead was chosen as the material of the target and detector. The simulation was carried out with proton particle energies of 50, 70 and 100 MeV.

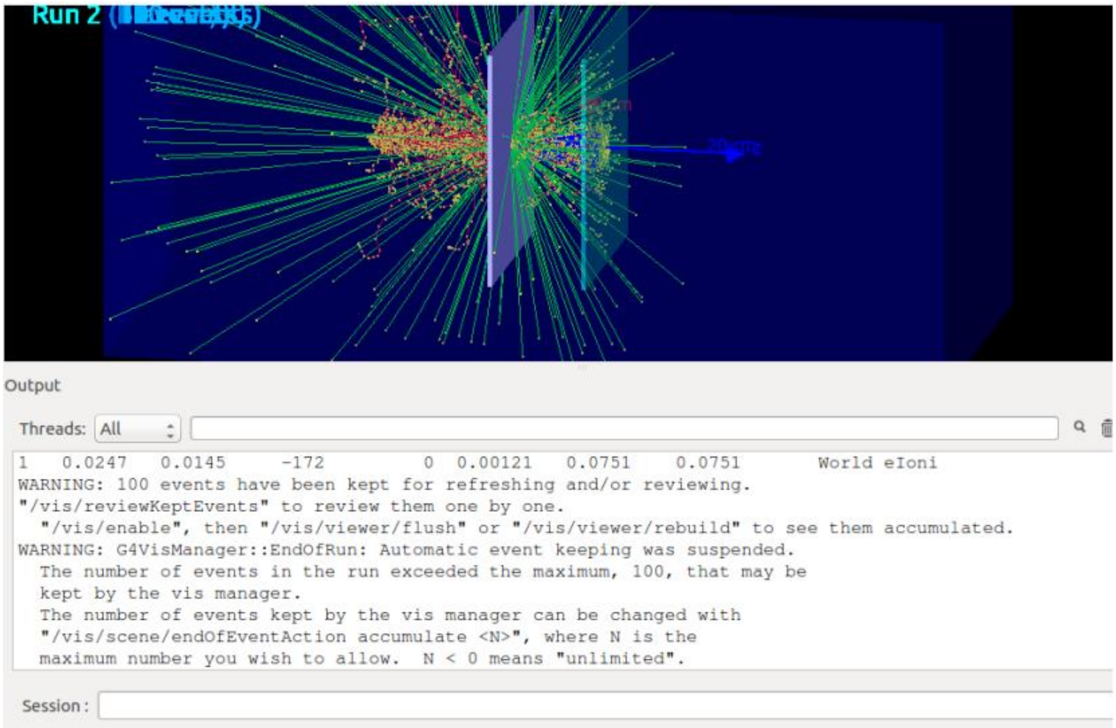


Figure 20. Visualization of the passage of a target by protons.

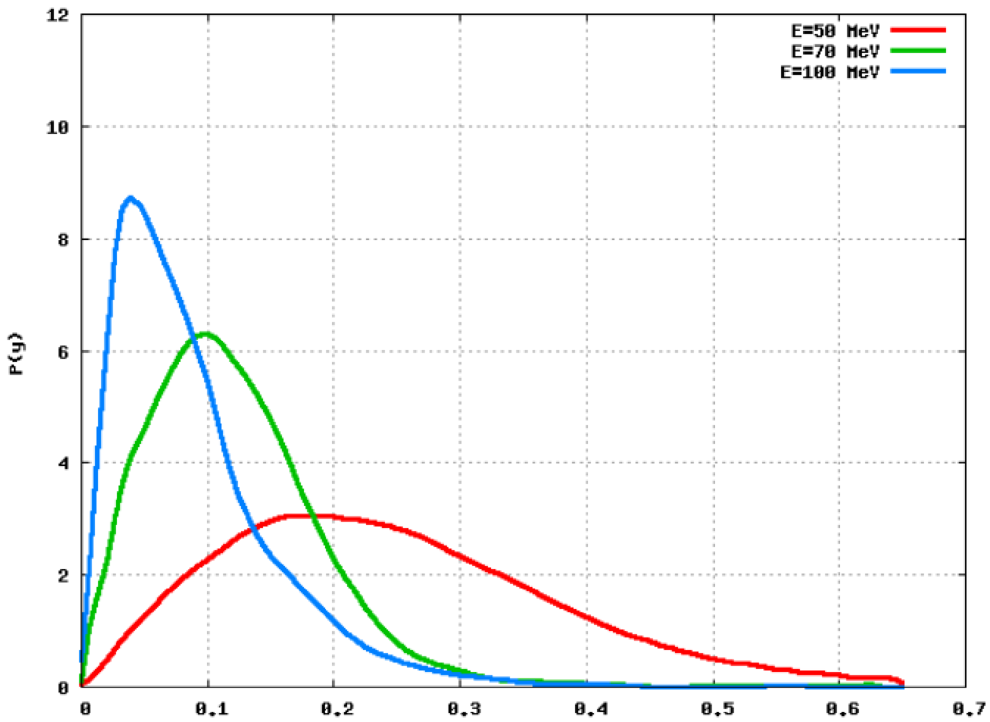


Figure 21. Graph of angular distributions for protons.

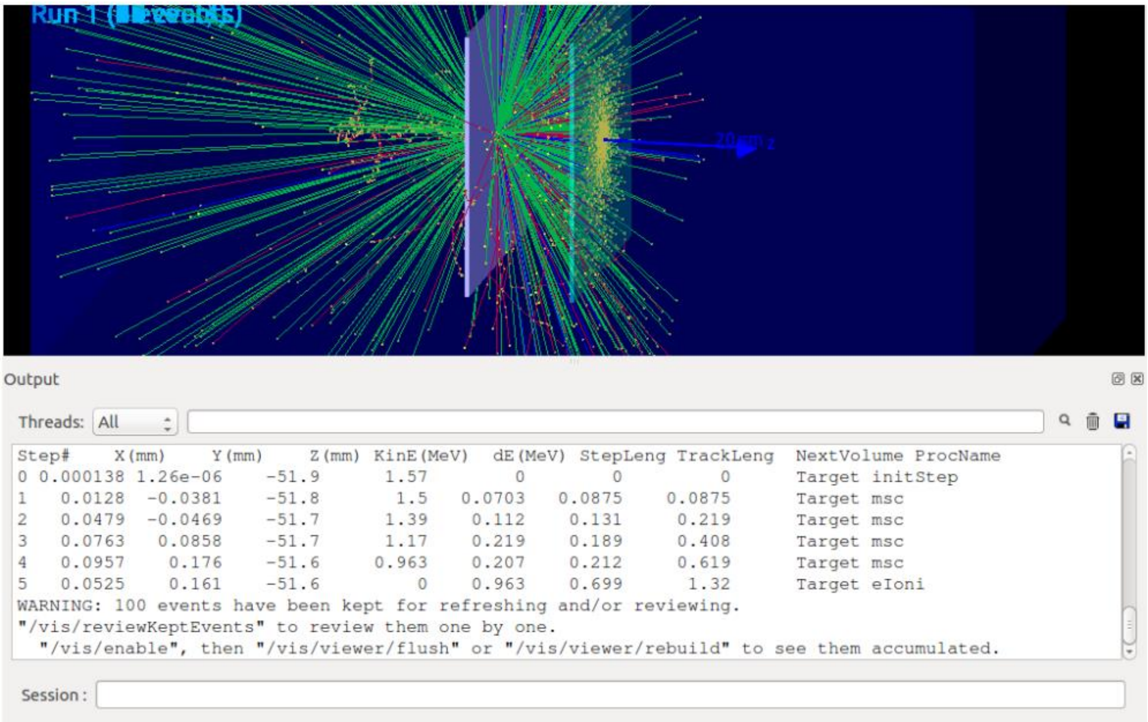


Figure 22. Visualization of the passage of the target by electrons.

The energies of 300, 1000 and 1800 MeV were taken for the electrons.

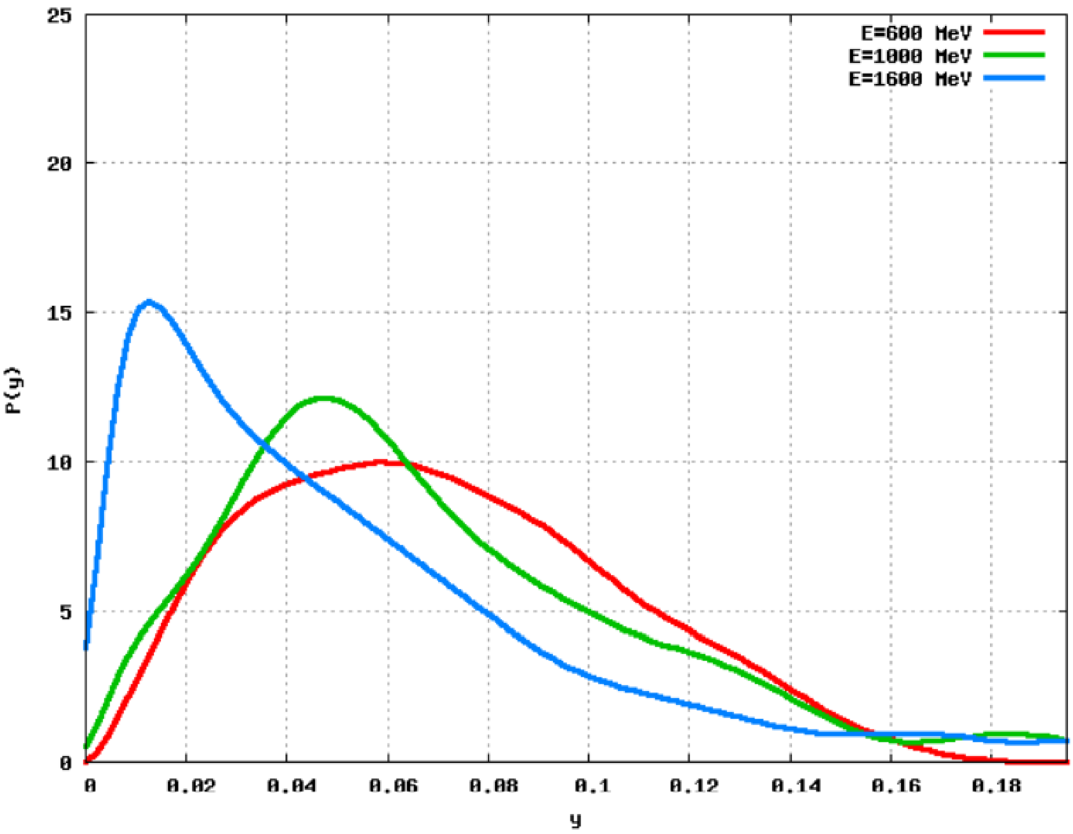


Figure 23. Graph of angular distributions for electrons

11 Conclusions

During the writing of the master's thesis, the nature of ionizing radiation and the processes of interaction of matter with it were studied. A model of a protective case for the DeNuSa project was proposed, as well as available materials from which protective casing can be made. It can be argued that the protective case made of ABS plastic with a wall thickness of 5 mm is able to protect the read-out electronics from heavy ions, but it is not able to cope with protons and electrons. The case made of lead with a thickness of 5 mm resists ionizing radiation much more strongly, however, this type of material will negatively affect the mass of the device, and problems with sealing may also appear. A protective box with local protection is not a bad option, but the price of the device will increase significantly. Experts from the DeNuSa project can use the proposed options and choose the best protective housing for the project purposes. After choosing a suitable design and material to cover all the tasks of the project, it will be possible to simulate the case again, as well as to conduct a full analysis in the GEANT4 program with the necessary energies.

12 Summary

The aim of this master's thesis *Protection of read-out electronics from ionizing radiation* is to create a case for a chip from the DeNuSa project to protect it against ionizing radiation and simulate the interaction of radiation with the case. Based on the analysis of the literature, the most radiation-resistant materials for protecting the microcircuit were installed. Based on the data obtained, various variants of protective cases were developed and tested using specialized software. It has been established that plastic protects only from heavy ions, which is an insufficient condition for a chip from the project. In this connection, it was proposed to make the case from the most radiation-resistant material – lead, however, this could lead to price increase. After all, experts from the DeNuSa project can use the proposed options to choose a suitable design and material to cover all the tasks of the project, and finally conduct a full analysis in the GEANT4 program with the necessary energies.

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