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Determination of the upset dominant mechanism in the $0.18\,\mu$m microcontroller's RAM exposed by pulsed low-energy protons

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Received July 12, 2023
Revised November 13, 2023
Accepted December 6, 2023

Upsets in the embedded RAM of a microcontroller exposed by pulses of low-energy protons are investigated. Experiment features at the laser-plasma source are examined. The estimation of linear energy losses from direct ionization by protons in the sensitive volume and absorbed dose rate calculation with account of the structure and chemical composition of the microcontroller crystal are presented. Experimental results are compared with previously obtained data from X-rays exposure experiments and upset bitmaps are analyzed. It is shown that failures in the microcontroller RAM are caused by single event effects.

Keywords: Proton radiation, X-rays, microcontroller, single event upsets, low-energy protons, pulsed exposure, laser-plasma acceleration.

DOI: 10.21883/0000000000

Introduction

Currently, about 40–50% of the total volume of radiation tests carried out in the interests of space industry enterprises falls on the subject of single event effects (SEEs) [1].

One of the manifestations of SEEs is violation of the logical state of memory element under the influence of individual particles, the so-called single event upsets (SEUs).

Until recently, it was believed that SEUs in outer space was caused only by heavy ions and high-energy protons. Failures due to direct ionization by protons were first predicted in 1982 [2] and subsequently experimentally confirmed in 2007 for low energy protons generated at Van de Graaff electrostatic generator [3]. Subsequently, in the work of various authors on a electrostatic generator and on facilities operating in quasi-static modes, it was confirmed that direct ionization by protons can be the cause of SEUs [4,5]. Moreover, in these studies, the cross section for SEUs under the influence of low-energy protons was several orders of magnitude higher than the value for high-energy protons.

A special feature of the experimental setup in this work is the use of a pulsed proton source based on a laser-plasma source. Despite the fact that the idea of laser acceleration of particles is not newly [6,7], the authors are not aware of any work in which such a source would be used to study the response of microelectronic devices to the impact of individual nuclear particles. In our opinion, such a source is promising, however, there is a question related to the relatively high proton flux density of the laser-plasma source (of the order of $10^{13}-10^{16}\,\mathrm{cm^{-2}\cdot s^{-1}}$), as a result of which volumetric ionization effects may occur. A similar problematic situation was considered earlier using a pulsed proton source, but with different parameters and high energies [8]. According to RD 134-0191-2011 [9] to eliminate the effects of volume ionization: „... the average proton flux density in one pulse of proton radiation of any duration should not exceed $5\cdot10^{10}\,\mathrm{cm^{-2}\cdot s^{-1}}$“. Those in this case, it is necessary to evaluate the correctness of modeling low-energy proton radiation of outer space using a laser-plasma generator.

In this regard, the problem of this work was to determine the dominant failure mechanism of the sample under study when exposed to a pulse of low-energy protons.

1. Measurement procedure

The object of study was a $0.18\,\mu$m bulk microcontroller (MC) with an ARM core. The object reaction to gamma and neutron exposure was previously studied in [10,11]. The metal cover of the MC with a thickness of ~ 0.5 mm is opaque to low-energy protons generated at the laser-plasma accelerator, therefore, before the experiments, the MC was decapsulated.

During the experiments, the occurrence of failures in the built-in 32 kB memory of the MC was investigated. Before each laser shot, all random access memory (RAM) cells were initialized to 0xAAAAAAAA. Writing and reading information from RAM was carried out using the built-in debug interface [10].

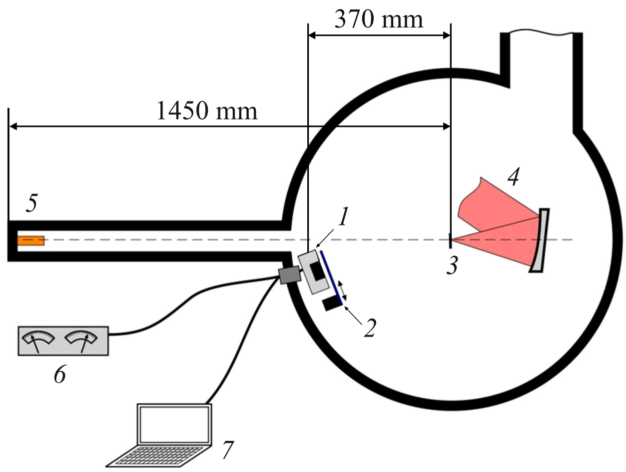

Figure 1. Experiment geometry: *1* — MC in a contact device, *2* — remote-controlled shutter, *3* — target, *4* — laser pulse , *5* — silicon detector FDUK 1UVSKM, *6* — power supply, *7* — personal computer.

The proton source was an aluminum foil target 6 μm thick, onto which a powerful Ti:Sa laser pulse with an energy of up to 2 J and an ultrashort duration $\sim$ 25 fs was focused.

The object under study was installed in a contact device inside a vacuum target chamber in the path of a proton beam emitted from the rear surface of the foil at the moment of irradiation by a laser pulse. A power source and a personal computer for writing/reading data were connected to the contact device via a vacuum connector.

The energy spectrum and proton fluence were monitored using the time-of-flight technique, the detector of which was a pin diode (silicon detector FDUK 1UVSKM), located normal to the target (at an angle 0°) at a distance of 1450 mm from its surface. The MC was located at an angle10°relative to the target normal at a distance of 370ṁm from its surface (Fig. 1).

The maximum energy of protons in the beam when the detector is located at an angle 0° and 10° relative to the target normal was positively correlated with the energy of laser radiation (Fig. 2, *a*). However, an increase in the laser pulse energy led to an increase in the spread in the maximum proton energy.

Fig. 2, *b* shows the dependence of the proton fluence on the energy of laser radiation when the pin diode is located at an angle 10° (i.e., at the location of the object). It can be seen that the maximum energy of laser-accelerated protons was about 6 MeV. Despite some scatter of values, the dependence is satisfactorily described by a power function. Also, from the oscillograms from the pin diode, the duration of the proton pulse at the location of the sample was determined. It amounted to $\sim$ 40 ns.

To take into account the differences in the fluence of particles incident on the pin diode and on the MC, a fluence coupling coefficient was introduced, which was determined experimentally from the ratio of the dependences of the proton fluence on the pin diode at an angle 0° and the proton fluence on the MC on the energy of laser radiation.

2. Experimental results

During the experiments, upsets in the MC RAM were recorded. The dependence of the number of upsets on the energy of laser radiation is presented in Fig. 3, *a*. When a certain threshold of laser energy is exceeded, approximately 0.55 J (Fig. 2, *b*), an increase in the number of errors in the MC memory is observed.

Also in the experiments, the radiation-induced (integral ionization reaction of the MC) was recorded. Fig, 4 shows the characteristic shape of the MC ionization current at a laser radiation energy of 1.78 J — pulse with amplitude $\sim$ 100 mA and decay time $\sim$ 250 ns.

To determine the effect of accompanying electromagnetic radiation (EMR) on the reaction of the MC, experiments were carried out with a lavsan screen, which absorbed protons, but was transparent to EMR. With this screen, no upsets were recorded, therefore, the main cause of upsets is ionizing radiation, and not EMR.

3. Discussion

As noted in the problem, the main issue of the work is to assess the possible influence of volume ionization effects on the reaction of the object under study. To do this, it is necessary to determine the absorbed dose (through linear energy transfer (LET)) from proton radiation in the sensitive volume (SV) of the object, for which it is necessary to know its structure.

3.1. Specifying the MC simulating structure

To determine the simulating geometry, the silicon crystal was examined in the transverse direction, for which a high-resolution optical microscope was used, as well as an electron microscope. It has been established that the MC contains 6 metallization layers with a thickness of $\sim 0.7\,\mu$m, 6 layers with a thickness of $\sim 0.9\,\mu$m, a contact layer with a thickness of $\sim 1\,\mu$m and an sensitive layer with a thickness of $\sim 0.5\,\mu$m (Fig. 5, *a*).

Mass spectroscopy and electron microscope were used to determine the elemental composition. It was revealed that the metallization layers consist of Al and Ti, the insulating layers are made of SiO_2, and the contacts are made of W.

The structure used for calculations is shown in Fig. 5, *b*. In contrast to the real structure, the Al,Ti/SiO_2 metallization/passivation layers and the W layer were specified as continuous layers. The ratio of aluminum and titanium in the metallization layer was taken in proportion: Al:Ti = 4:1 This structure generally corresponds to the models of bulk technology silicon crystals presented in the literature [12,13].

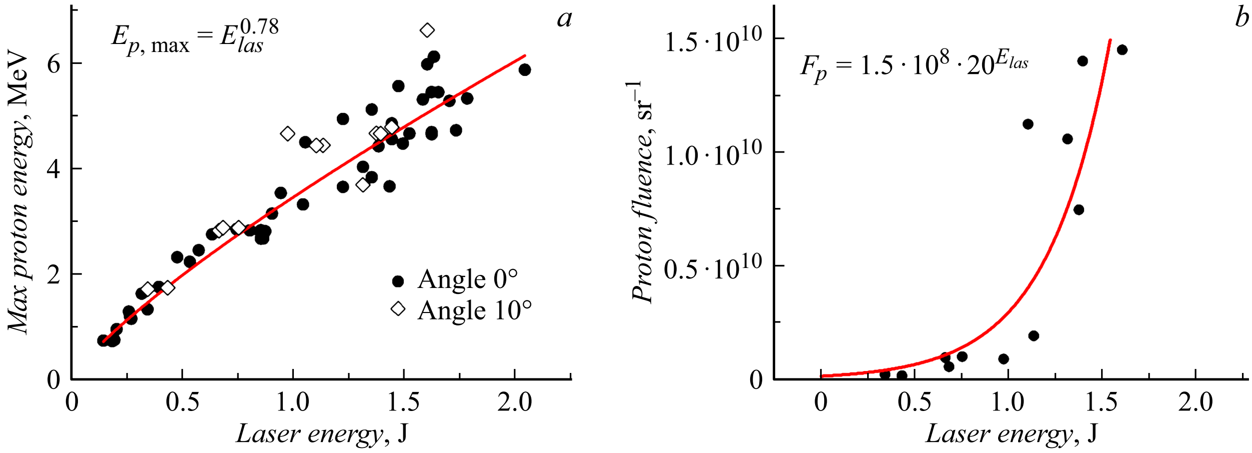

Figure 2. Dependences of the maximum energy of protons when the detector is located at angles 0°and 10° (a) and the fluence of protons with energies more than 0.6 MeV when the detector is located at an angle 10° (b) on laser radiation energy.

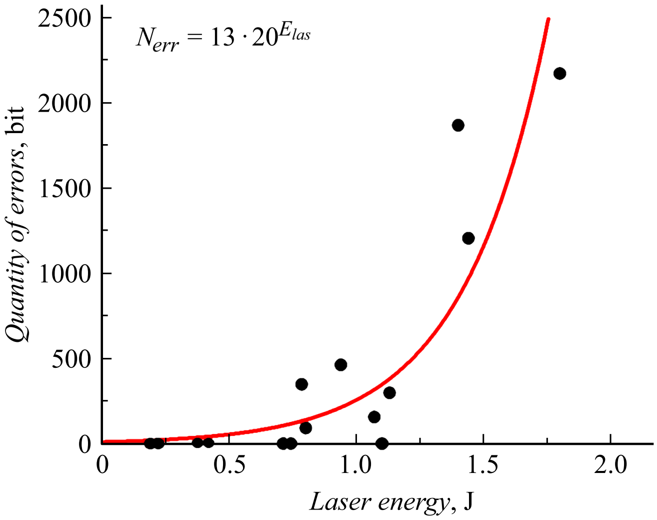

Figure 3. Dependence of the number of upsets in the MC RAM on the energy of laser radiation.

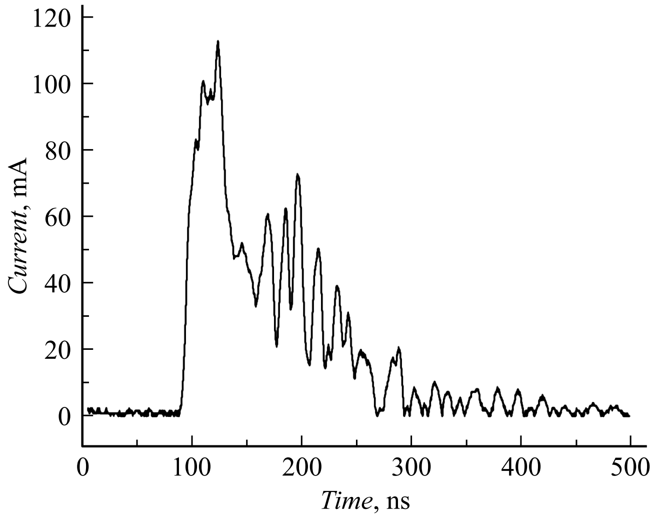

Figure 4. MC ionization current characteristic shape under the influence of protons.

3.2. Estimation of LET from direct ionization by protons

Let's consider the data processing procedure using the results of one chosen laser pulses. When processing waveform recordings of signals from a pin diode (an example is shown in Fig. 6, a) the differential energy spectrum of protons was reconstructed using the time-of-flight technique (Fig. 6, b).

From Fig. 6, b it is clear that protons energy is in range from 0.1 to 5.3 MeV. For further calculations, the spectrum was divided into 12 energy intervals, with its own average energy and fluence values.

The SRIM [14] was used to simulate the energy deposited in the SV of the MC crystal. For each energy corresponding to the middle of the dividing intervals of the differential spectrum (Fig. 6, b), the LET distribution in the layer-by-layer structure was obtained. Fig 7, a shows the such distribution.

Using the protons LET distributionsin a layer-by-layer structure, the LET value and the absorbed dose rate from protons in the MC SV were determined. When proton radiation passes through absorbing layers, that part of the energy spectrum whose Bragg peak fall with SV works most efficiently. For this structure, the maximum protons LET was observed for $\sim$1 MeV protons (Fig. 7, b) and amounted to 0.69 MeV$\cdot$cm$^2\cdot$mg^{-1}.

The maximum LET for direct ionization by protons is quite close to the LET threshold for the object under consideration (approximately 0.9 MeV $\cdot$cm$^2\cdot$mg^{-1} [15]). If we take into account that the LET threshold values are determined with a fairly large error, for example, $\pm$30%

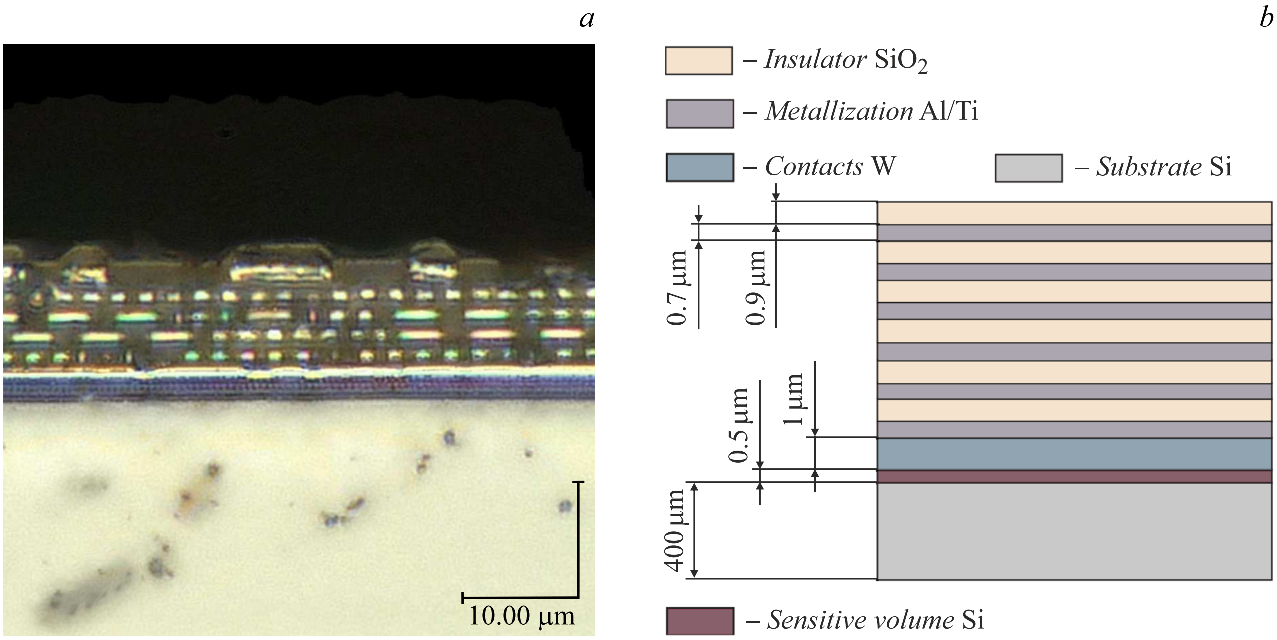

Figure 5. Real structure of MC (a) and structure used for calculations (b).

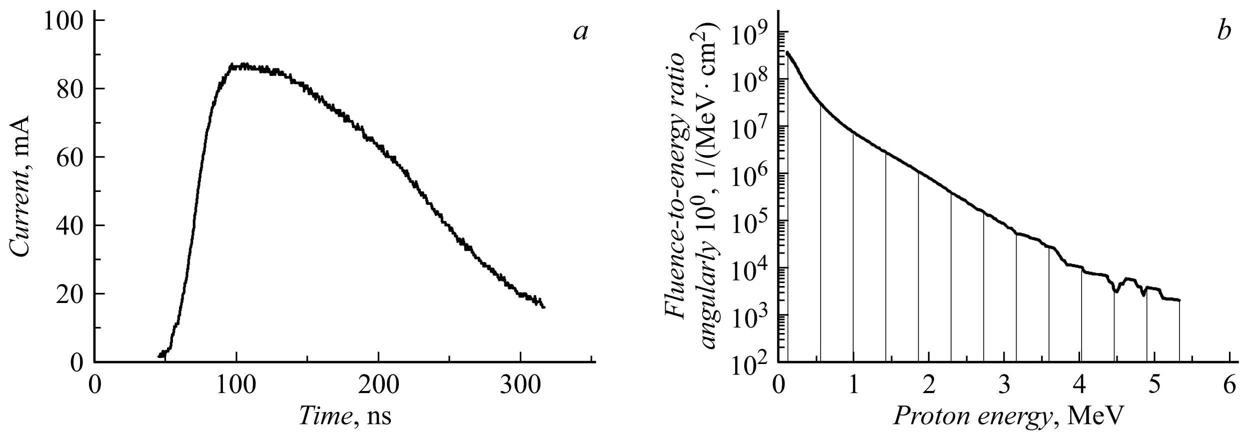

Figure 6. Typical waveform of the detector current (pin diode) under the influence of protons (a) and the corresponding differential energy spectrum of protons (b).

in the work [16], then upsets mechanism due to direct ionization by protons may occur. However, additional aspects need to be considered to confirm this hypothesis.

3.3. Estimation of dose rate from direct ionization by protons

The absorbed dose rate in the SV per pulse was calculated using the formula

$$P = \frac{\Sigma_j^{12} D_j}{t} = \frac{(\mathrm{LET}_{SV})_j \cdot F_j}{t \cdot \rho}, \quad (1)$$

where $(\mathrm{LET}_{SV})_j$ — protons LET with energy E_j in the SV, F_j — the corresponding fluence of protons, t — transit time of protons (~ 40 ns) from the target to the MC (according to Fig. 1), ρ — silicon density.

The energy values E_j and fluence F_j were taken from the energy differential spectrum (Fig. 6, b).

As a result of calculations using formula (1), it was found that the absorbed dose rate from protons in the SR is $\sim 10^9$ rad(Si)/s for laser radiation energy from 0.7 to 2 J.

3.4. Volume ionization effect contribution analysis

Previously this MC was exposed to bremsstrahlung pulses [10]. It has been shown that observed upsets in RAM caused by volume ionization effect. The dependence of failures in RAM on the level of exposure to bremsstrahlung

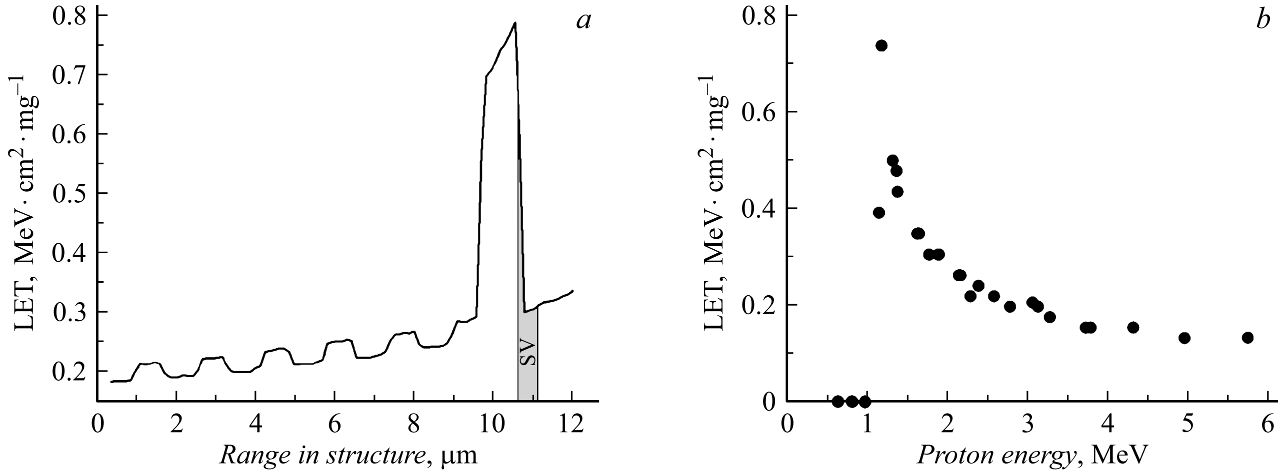

Figure 7. Simulating in SRIM the dependence of the protons LET on their range in the layer-by-layer MC structure (*a*) and the dependence of the protons LET in a SV on the initial energy of protons (*b*).

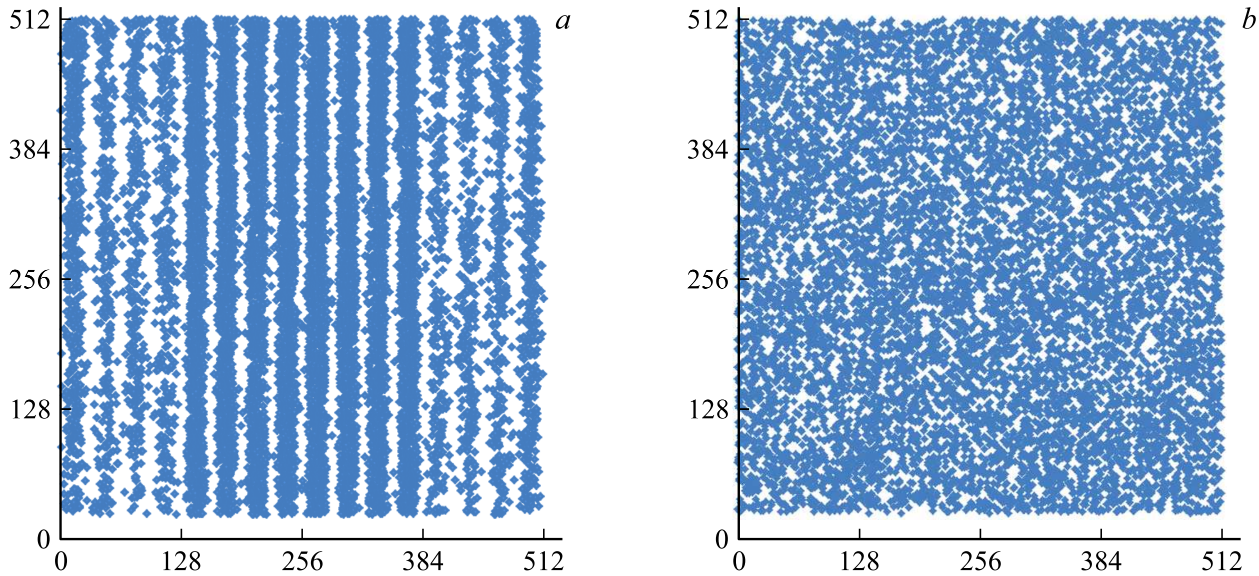

Figure 8. MC RAM upset bitmaps when exposed to bremsstrahlung (*a*) and proton radiation (*b*).

radiation has a threshold character, caused by a drop in the supply voltage on the MC internal power, which occurs when large radiation-induced currents flow [17,18]. A mass RAM upset was recorded at a dose rate $\sim 3 \cdot 10^9$ rad(Si)/s. The pulse durations and dose rate levels for the cases of bremsstrahlung and proton radiation of the laser facility were approximately the same. The calculated dose rates in the SV when exposed to proton radiation coincide in order of magnitude with the value of the dose rate from bremsstrahlung radiation, at which a massive RAM upset is observed. However, in our case, no mass upset was registered; the number of upset increases linearly with the proton fluence. Note that the MC ionization currents from proton ($\sim 10^2$ mA) and bremsstrahlung ($\sim 10^3$ mA) radiation differ by an order of magnitude. The difference in the amplitude of the ionization currents is due to the fact that the total charge of the generated charge carriers in the volume of the sample is not the same. In the case of exposure to bremsstrahlung radiation, the volume through which the current flows is limited by the entire thickness of the substrate (about 400 μm), while in the case of proton radiation, the volume of current flow is determined by the range of ~ 1 MeV protons, which create the largest dose in the SV with a depth $\sim 40\,\mu$m.

Upset bitmaps were used as an additional instrument to analyze the possible contribution of volume ionization effects. As shown in the work [19], visual analysis and digital processing of upset bitmaps (with a known arrangement of cells in the array) make it possible to unambiguously identify the presence of volume ionization effects. As noted above, when exposed to high-intensity ionizing radiation, in microcircuits significant radiation-induced currents flow through the internal power rails, and the voltage on individual cells can drop below the storage voltage, which will lead to loss of information. And due to the periodic distribution of power buses, such cells will also be located with some periodicity, which will appear on the upset bitmap in the form of „stripes", which is observed for the Current MC when it is irradiated by a bremsstrahlung pulse (Fig. 8, *a*).

The upset bitmap obtained during irradiation with a proton pulse is shown in Fig. 8, *b*. Its analysis shows a random upset distribution on the map, which indicates the absence of a contribution from volume ionization.

Conclusion

This work was the first to study the reaction of a MC to a pulse of protons generated on a laser-plasma source of charged particles. It is shown that when exposed to a proton beam, an inversion of the MC memory cells occurs. Based on the analysis of upset bitmaps, and radiation-induced currents of MC, obtained under various influences: a bremsstrahlung pulse and a proton beam, it was established that in the case of proton exposure, cell inversion occurs due to local ionization effects induced by individual protons. Additionally, based on microdosimetric calculations, it was shown that the SEUs is caused by the mechanism of direct ionization by protons, since the protons LET in the SV is close to the threshold value for this object. It should be noted that domestic regulatory documents do not establish test methods for the effects of low-energy protons.

The results of the work show that laser charged particle accelerators are promising test equipment for solving problems in the field of radiation research and testing.

Acknowledgments

The authors express their gratitude to P.A. Sannikova for assistance with mass spectrometric analysis and O.A. Filin for providing data on structure analysis using an electron microscope.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by V.Prokhorov