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ESTIMATION OF HEAVY ION BEAM PARAMETERS DURING SINGLE EVENT EFFECTS TESTING

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Abstract

During flight mission onboard electronic equipment of spacecraft exposed to outer space radiation. Impact of charged particles leads to errors and failures in electronic components (EC). The most critical problem for spacecraft engineers is heavy ions influence which cause single event effects (SEE) in EC [1,2]. To be assure that spacecraft electronics will work properly during the mission ground SEE testing is needed. For these purposes heavy ions accelerators are used. In this paper, we present facility for SEE testing including requirements to heavy ions beams, techniques and equipment used for control heavy ion beam parameters during SEE testing.

BASIC PRINCIPLES OF SEE TESTING

SEE are such effects, the cause of which is the interaction of the single charged particle with active area of semiconductor device. Such effects have a probabilistic nature and are not related to radTatTon “history” of the device. SEE can be classified into Destructive, Residual and Transient effects, by types of failures. Destructive SEE are Single event latch up (SEL) - inclusion of the parasitic four- layer p-n-p-n structure leading to harsh increase circuit current; Single event burnout (SEB) - secondary induced breakdown of p-n junction leading to its destruction; Single event gate rapture (SEGR) - breakdown of gate insulator along nuclear track of particle; Single event snapback (SESB) - secondary induced breakdown, determined the performance spurious bipolar structure in MOS transistor. Residual SEE are Single event upset (SEU) - inversion of logical state of memory unit or trigger circuit; Multiply byte upset (MBU) - inversion of logical state of several neighboring memory unit or trigger circuit; Single event functional interruption (SEFI) - inversion of logical state of memory unit or trigger circuit operation leading to violation of program progress (for example, program hangup). Transient SEE are analogue and digital Single event transient (ASET, DSET) - Short- time pulse in output element of linear or digital semiconductor devices.

General SEE testing foundation is The principle of equivalence thresholds LET for space heavy charged particles and monoenergetic ions, in which the electronic components having SEE :equality thresholds LET under the influence of space heavy charged particles, containing ions of different chemical elements with different spectral and energetic characteristics and any monoenergetic ion having a given value of LET, under the influence of which in electronic components appears SEE. Main SEE hardness characteristics are following: Threshold LET; Effect cross-section (saturation); Dependence of effect cross-section from ions LET, usually Weibull curve (see example on Fig. 1).

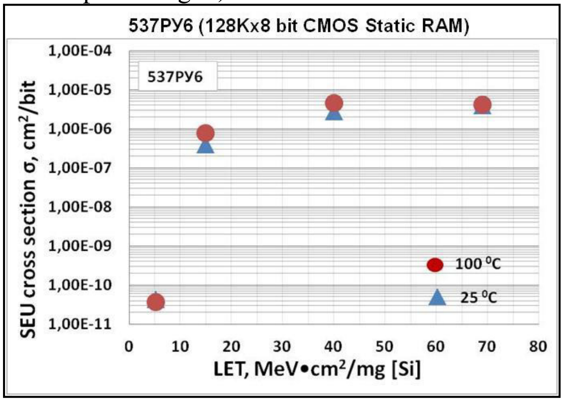

Figure 1: Dependence of SEU cross-section from ions LET for Russian-made SRAM at different temperatures.

TEST FACILITIES

A number of heavy ion test facilities are created under TCe BrancC of JSC “UnTted Rocket and Space Corporation” – “Institute of Space Device Engineerng” authorizing on the base of cyclotrons U400 and U400M (Flerov Laboratory of Nuclear Reactions (FLNR), Joint Institute for Nuclear Research (JINR), Dubna city, Moscow region) which have differential in the composition of output ions and their energy, the radiation area, range of temper-atures, by changeover time from one ion to another, vacu-um pumping time (see Table 1 for details). Currently our test facilities provide test operations of all EC functional classes on hardness to all types of SEE. Since 2010, by the effort of the five testing laboratories have been tested more than 3000 EC part types All test facilities are avail-able to carrying out tests (on request); there are no re-strictions for foreign organizations. Some pictures of test facilities are shown on Figs. 2-4.

Figure 2: Low energy test facility (IS OE PP).

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Figure 3: High energy test facility (IS OE VE).

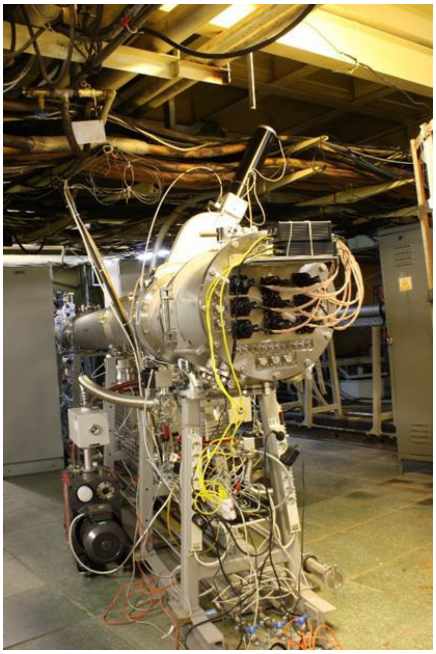


Figure 4: Low energy test facility (IS OI 400-N).

Device under test (DUT) mounted in test chamber is shown at Fig· 5.

Figure 5: Example of DUT in test chamber.

Table 1: The Technical Characteristics of the Test Facilities

Technical features	Low energy facilities	High energy facilities
Ion source	Cyclotrons U-400/U-400M	Cyclotron U-400M
Initial energy, MeV/nucleon	3 .. 4 (up to 6 on request)	15 .. 40 (>60 for light ions) Tunable with using degraders
Flux density, particle/(cm^2×s)	10 .. 10^5	10 .. 10^5 (10^4 for Bi)
Nonuniformity, %	± 10	± 15
Suit of ions	C, O, Ne, Ar, Fe, Kr, Xe, Bi	Ne, Ar, Kr, Xe (O, Fe, Bi)
LET (material), MeV × cm2/mg	0.5…99 (Depends on material of electronic component, type of ion and energy)	
Range in material, μm	≥30 (Depends on material of electronic component, type of ion and energy)	
Irradiation area, mm	150 x 200/ 200 x 200	Ø 60 (Ø 40 for Bi)
Operational pressure	Vacuum	For vacuum/ atmosphere
Charge overtime for gaseous ion, hour	6	6
Charge overtime for metal ion, hour	18	18
Vacuum pumping time, min	6 / 8	5
Temperature range, °C	-40 .. +125	-40 .. +125
Tilt, °	0 .. 90	0 .. 90

TEST PROCEDURE

The task of test is obtaining experimental cross section dependence of SEE from linear energy transfer (LET) of heavy ions energy in the wide range of LET. For this purpose it is needed to register not less than four points with effects during test campaign. With the facilities of low initial energy we have to use four different types of ions with specific LET for obtaining four experimental points. The most common combination of ions is Xe; Kr; Ar; Ne with LET approximately 69; 40; 15; 6 MeV cm^2/mg. The exact values of LET for each ion are determined on the basis of initial energy which is measured after the output of each ion.

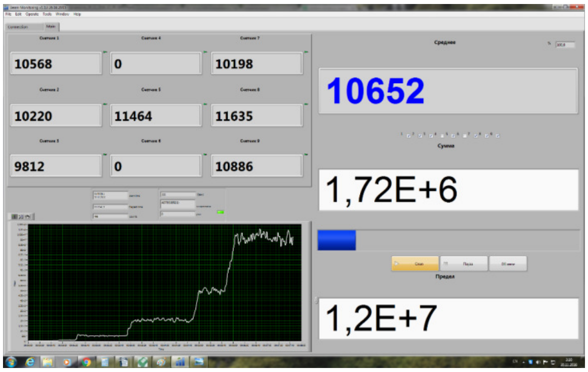
The peculiarity of testing with low energy ion beams is necessity to vacuum ion guide tube and test chamber. This is a prerequisite for the delivery of ions from source to device under test with no loss of energy. Thus, by measuring initial energy in vacuum tube (channel) we obtain the data to following LET calculation. Another feature of systems with low energy is low range of ions in materials of electronic components (30-40 mkm). Therefore, decapsulation of electronic devices is needed for SEE testing in order to ensure impact of heavy ions to open die (with no package). For most of modern electronic components such range of ions is sufficient to achieve sensitive volume of chip, since the thicknesses of the passive layers (passivation, metallization, etc) no more than 15 mkm. The information about type of ion and it initial energy is used for LET calculation. For LET estimation SRIM software is applied. A significant disadvantage of low energy facilities is long changeover time from one ion to another (from 6 hours for gaseous to 24 for metals), which increases the cost of tests.

The test bench with high initial energy is differs from low-energy facilities in that more powerful ion injector. With increasing of initial energy, the increasing of ion range while reducing of LET is observed. However, reducing the initial ion energy we can achieve similar values of LET in comparison with low energy facilities and a significant increase in particle range (from 200 to 2000 mkm for different LET). This allows us to test devices with a deep depth of sensitive volume or samples which cannot be fully decapsulated. Moreover, for obtaining several values of LET we do not need to change type of ion, so, for getting four experimental points we need only two ions. Since the change of initial energy in accelerator in short time is impossible, special thin foils (or stack of foils) are used. In this case, the information about type and initial energy (in channel) and also about material and thickness of energy absorber is used for LET calculations with SRIM software.

The EC irradiation is carrying out until the registration level is reached more than 100 SEE or until the destructive failure is occurred or until the fluence is 1E+7 cm^{-2}.

TECHNIQUES & EQUIPMENT FOR CONTROL BEAM PARAMETERS

Beam fluence and flux control system is based on joint application of scintillators based detectors and track membrane technique. Ion fluence is controlled by using polycarbonate or polyethylene terephthalate track detectors placed in close vicinity of any testing device in all irradiation runs. The result usually available in one hour after irradiation. Scintillators based detectors allow us control stability of the beam in online mode and used as reference point to metrologically certified track detectors. Interface of online fluence control system is shown on figure 6. Based on this data test engineer decides on the end of irradiation session for given DUT. At the backside of test chamber you can see scintillation detectors (Fig. 7). Photomultipliers for scintillators based detectors is located outside vacuum chamber (Fig. 8). An example of SEM micrograph of polymer track detector is shown on Fig. 9. Value of fluence is determined by counting holes in a certain area.


10568
0
10198
10220
11464
11635
9812
0
10886

Среднее
10652

Сумма
1,72E+6

Предел
1,2E+7

Figure 6: Online fluence control.

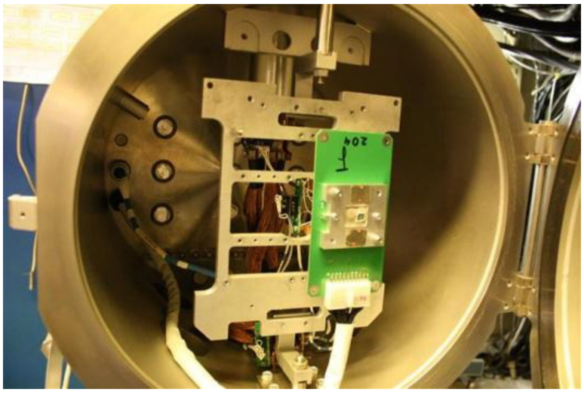


Figure 7: Scintillators on the back of chamber.


Figure 8: Photomultipliers for scintillators based detectors.

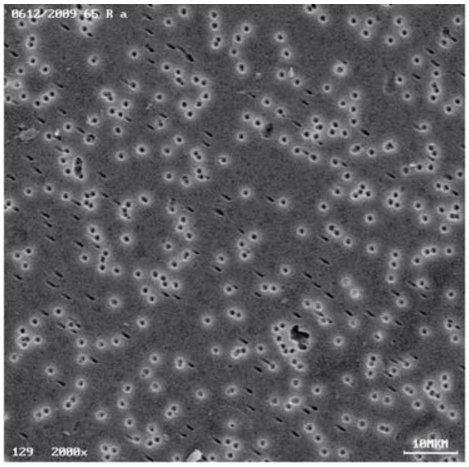


Figure 9: Picture of track detector after irradiation.

The main energetic parameters of the ion beam during SEE testing:

- Energy of ion in vacuum tract
- Energy of ion in test chamber
- LET in material of EC
- Range of ion in material of EC

Table 2: Applied Techniques for Estimation of the Main Ion Beam Parameters During SEE Testing

Characteristic	Low energy facility	High energy facility
Initial energy of ion	Measurements (TOF technique)	Measurements (TOF technique)
Energy of ion on DUT		Calculation (SRIM)
LET	Calculation (SRIM)	Calculation (SRIM)
Range of ion	Calculation (SRIM)	Calculation (SRIM)

Typical LETs and ranges in Si (as most common semiconductor) are shown in table below.

Table 3: LET and Ranges in Si at Test Facilities

Low energy facility (vacuum, energy of ion on DUT 3.5 MeV/nucleon						
Ion	C	O	Ne	Ar	Fe	Kr
LET (Si), MeV × cm2/mg	2.7	4.4	6.5	15.7	27.1	40.3
Range in Si, μ	50	43	39	37	34	38
High energy facility (forvacuum/atmosphere, energy depends of ion)						
Ion	O	Ne	Ar	Fe	Kr	Xe
LET (Si), MeV × cm^2/mg	0.5/ 0.5	0.9/ 1.0	4.5/ 4.8	9.7/ 11.2	18.0/ 21.9	42.2/ 57.9
Range in Si, μ	4720/ 4550	2800/ 2680	788/ 657	445/ 316	368/ 238	232/ 100
Energy of ion in vacuum tract, MeV/ nucleon	64	54	34	29	28.5	24.5

CONCLUSION

Facilities for SEE testing based on ion accelerators are presented. All of these test facilities are included in the Compendium on the international irradiation test facilities [3]. Described SEE Test Facilities were rewarded in the 2014, 2016, 2017 at International Exhibitions “Inventions Geneva”, “Archimedes” and “IPITEX”.

The standard practice of SEE testing implies using of heavy ions accelerators. Discussed test procedure is wide-ly used to determine the EC parameters of sensitivity to SEE.

The main directions of development these facilities are following: online control of beam parameters with accuracy increasing; creation of microbeam line; improvement and verification of energetic parameters calculations for ions after degraders and energy measurements on DUT.

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