Compendium of SEE comparative results under ion and laser irradiation

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***Abstract*— Compendium of SEU, SEL, SET, SEB and SEGR comparative results under ion irradiation and focused laser beam are presented. The possible sources of discrepancies between ion and laser results and the ways of data correction are discussed.**

***Index Terms*— heavy ions, laser, SEU, SEL, SET, SEB, SEGR.**

I. Introduction

THIS WORK reports results of SEE investigation under focused laser and ion beams. We compared the main single event effects (SEU, SEL, SET, SEB and SEGR) in three types of devices: microcontroller ATMEGA128-16, video operational amplifier AD829JRZ and N-MOS transistor IRF3710SPBF. Ion accelerator tests are the usual tool for DUT SEE sensitivity determination [1, 2]. SEE cross-sections are determined as a function of Linear Energy Transfer (LET). Focused lasers are powerful tools for studying SEEs in device. SEE cross-sections can be estimated as a function of laser energy [3, 4]. Assuming the availability of correlation between laser energy and LET as well as between SEE cross-sections obtained under laser and ion irradiation it is necessary to find out corresponding correlation coefficients. The values of these coefficients are mostly due to the laser beam optical losses in multilayer metal/dielectric/semiconductor structures. Sometimes it is possible to estimate this correlation only from laser tests using local laser technique [5,6]. The most reasonable way is to obtain this correlation using both laser technique and ion tests, but it is possible for these correlation coefficients to differ from various effects in the same device. The similar techniques (equipment and software) for testing of the same DUT type under ion and laser beams were used. We try to explain differences in correlation coefficients between laser energy and LET for various effects in the similar DUT.

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II. Experimental technique

A. Heavy ion irradiation

Heavy Ion experiments were conducted at Roscosmos test facility IS OI-A based on cyclotron U400M of the Joint Institute for Nuclear Research (JINR, Dubna, Russia). LET values of the used ions are presented in Table 1 [7]. Ion irradiation area was about 200 mm x 200 mm. Polycarbonate terephthalate track detectors were used to measure ion flux.

Table I
Summary of ions

Ion	Energy of ions, MeV	*LET*, $Mev{\cdot}cm^2/mg$	Range (in Si), μm
^{20}Ne	81	≈ 6	45
^{40}Ar	146	≈ 15	38
^{84}Kr	269	≈ 40	35
^{136}Xe	435	≈ 69	37

A common test procedure included the following steps:

1) DUT decapsulation and operation test;
2) DUT installation in vacuum chamber and operation test;
3) DUT ion irradiation;
4) Change of the ion beam angle or ion type.

B. Laser technique

Laser SEE tests were performed using two pulsed picosecond facilities PICO-3 (SPELS) and PICO-4 (MEPhI) (Table 2). "PICO-3" and "PICO-4" were designed according to similar general block schemes (see Fig. 1) [8]. They consist of the following major parts: laser source, variable attenuator, focusing unit (microscope) with illuminator, CCD camera, DUT positioning system (XYZ-stage) and control equipment.

The laser source PICO-3 is a diode-pumped solid state picosecond laser, which generates 70 ps pulses with 1064 nm or 532 nm wavelength. The laser source PICO-4 is based on a diode-pumped solid state picosecond laser, which generates 25 ps pulses with 532 nm wavelength to pump optical parametric generator (OPG). This combination of pump laser and OPG allows output wavelength tuning in 700…1000 nm

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or 1150…2100 nm ranges, depending on a specific SEE simulation technique used.

Laser test of DUTs were carried out for two wavelengths 1064 nm (PICO-3) and 900 nm (PICO-4). Devices under test were scanned by randomized focused laser beam.

TABLE II
MAIN CHARACTERISTICS OF THE LASER FACILITIES

Laser facility type		PICO-3	PICO-4
Wavelength, nm		1064/ 532	700…1000 or 1150…2100
Pulse duration, ps		70	25
Pulse energy (max), μJ		7.8/3.0	20
Energy attenuation coefficient		$1…5·10^4$	
Focused spot diameter		2.2/1.2	2.5
Optical resolution of the microscope		0.5 μm*	
Camera type		Near-infrared/ Color CCD	Color CCD
Device positioning system:	Travel range, μm	horizontal - 100 vertical - 25	
	Minimum step, μm;	horizontal - 0.13 vertical - 0.16	

*in visible optical range

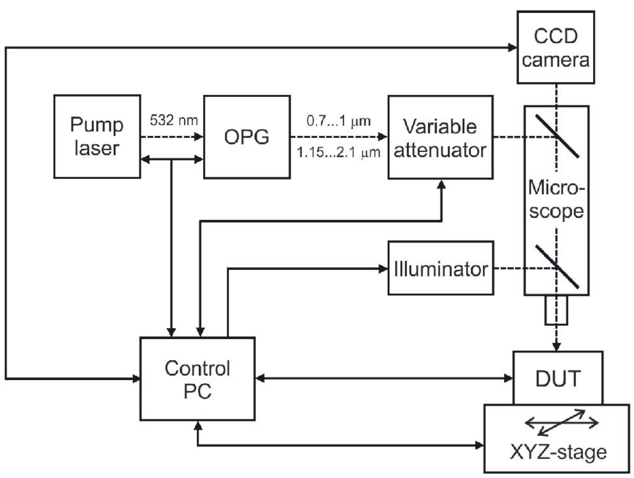


Fig. 1. Block scheme of “PICO-4” laser SEE simulation facility

Laser tests of video operational amplifier AD829JRZ and microcontroller Atmega128-16 were performed with front side irradiation with 1064 nm and 900 nm wavelengths respectively. N-MOS transistor IRF3710SPBF was covered with a continuous metallization layer making front side laser irradiation impossible. Back side laser irradiation technique with wavelength of 1064 nm was used for IRF3710SPBF testing.

C. Correlation coefficients estimation technique

The correlation coefficients estimation technique is based on the known linear ratio between laser energy and LET and assuming that the ratio between SEE cross-sections obtained under laser and ion irradiation is linear as well. So the objective is to estimate two correlation coefficients Kj and K_σ in the following relations:

$$L_{ie} = K_j \cdot J \tag{1}$$

$$\sigma_{ie} = K_\sigma \cdot \sigma_l(J) \tag{2}$$

where L_{ie} is equivalent LET, J is pulse laser energy (focused irradiation), σ_{ie} is equivalent ion SEE cross-section, $\sigma_l(J)$ is the SEE cross-section obtained using laser technique at a given value of J.

Assuming the correlation mentioned above we expect the σ_l versus J (or L_{ie}) to be described by Weibull function:

$$\sigma_l(J) = \sigma_{sl} \cdot \left\{ 1 - \exp\left[-\left(\frac{(J - J_0)}{W} \right)^s \right] \right\} \tag{3}$$

where J_0 is SEE laser threshold energy, σ_{sl} is laser SEE saturation cross-section, W, and s is approximation shape parameter.

To perform the correlation coefficient estimation we should perform both laser and ion SEE tests. Through the laser SEE test we obtain a function $\sigma_l(J)$ using the fact that laser technique provides almost continuous series of pulsed laser energy in contradiction to ion tests. To match both laser and ion data we should get at least two cross-sections σ_{i1} and σ_{i2} at different ion LETs (LET_1 and LET_2) so that one of cross-section values corresponds to saturation region and the other lies at the near-threshold region of the Weibull curve.

Estimation of the correlation coefficient Kj is to be performed by solving the equation:

$$\frac{\sigma_{i1}}{\sigma_{i2}} - \frac{\sigma_l(LET_1/K_j)}{\sigma_l(LET_2/K_j)} = 0\,. \tag{4}$$

The correlation coefficient K_σ is to be estimated from the relation:

$$K_\sigma = \frac{\sigma_{i1}}{\sigma_l(L_{i1}/K_j)} \tag{5}$$

Finally the estimated cross-section curve (3) can be determined.

III. EXPERIMENTAL RESULTS

A. Atmega128-16

ATmega128-16 is a CMOS 8-bit microcontroller with 128K bytes in-system programmable flash. It contains 32 x 8 general purpose registers with peripheral control registers, 128K bytes of in-system reprogrammable flash, 4K bytes EEPROM and 4K bytes internal SRAM.

SEU, SEFI and SEL were studied under ion and laser irradiation. The number of SEUs was determined by comparing the data read from internal SRAM during irradiation with that previously written. A criterion for SEFI was defined as malfunction of microcontroller without latch-up. Observed latch-up corresponded to 50 mA peak current in power circuit.

Comparison of experimental results for SEU and SEL effects under laser and ion irradiation is shown in Fig. 2 and Fig. 3.

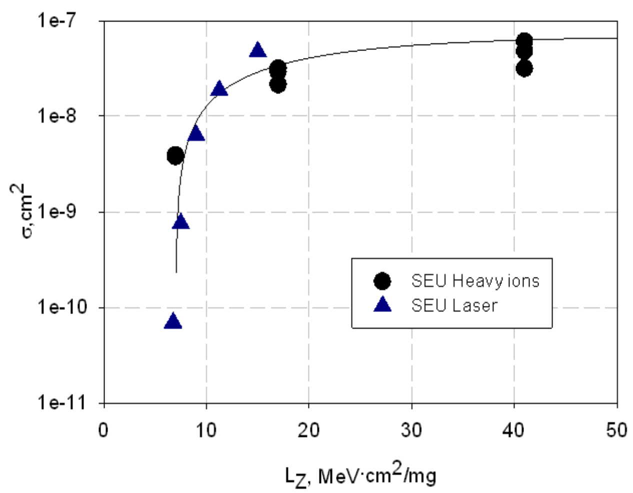


Fig. 2. SEU cross-section curve for ATmega128-16 by heavy ions and laser irradiation.

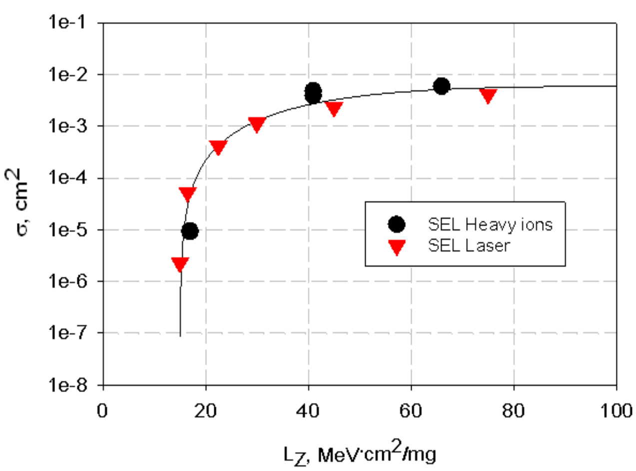


Fig. 3. SEL cross section curve for ATmega128-16 by heavy ions and laser irradiation.

We obtained different correlation coefficients between LET and 900 nm laser energy:

$K_{j.SEL} \approx$ 150 MeV·cm^2/(mg·nJ) for SELs and

$K_{j.SEU} \approx$ 75 MeV·cm^2/(mg·nJ) for SEUs.

No differences for cross section values in the laser and ion tests were obtained ($\sigma_{laser}/\sigma_{ion} \approx 1$) for both SEUs and SELs and so there was no correction needed for values of SEU and SEL cross-section ($K_{\sigma.SEL} \approx K_{\sigma.SEU} \approx 1$). We considered that the difference between $K_{j.SEL}$ and $K_{j.SEU}$ is concerned with various optical losses in SEU and SEL sensitive areas of ATmega128-16. This assumption was confirmed by the differences in values of ionizing response under local laser irradiation [5].

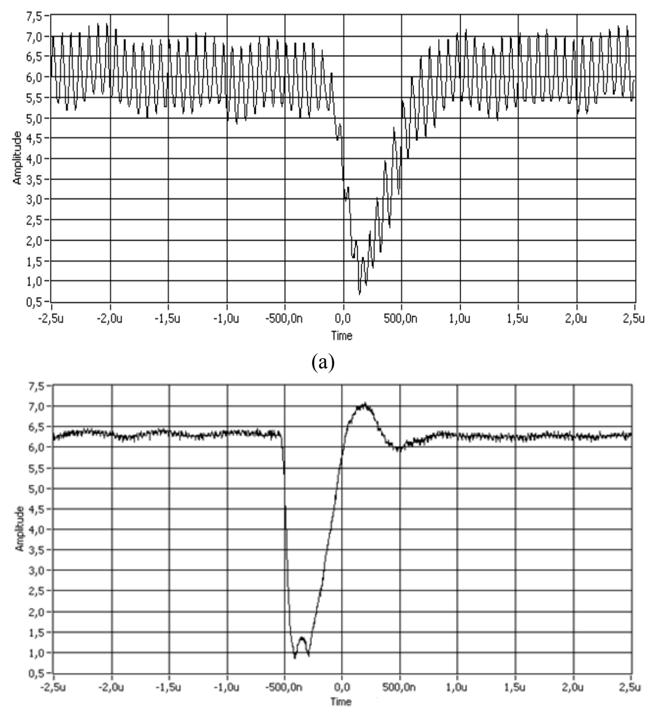
No SEFI was observed under ion and laser irradiation. We suppose that SEFIs were masked by high SEL sensitivity.

B. AD829JRZ

Video operational amplifier AD829JRZ SET investigation was performed under focused laser and ion irradiation. AD829JRZ is fabricated under Analog Devices complementary bipolar process. All samples were biased in non-inverting, low-gain, closed-loop configuration with different supply voltages (±10V, ±18V). Biasing and control DUT was provided by automated measurement systems (AMS). AMS is based on NI PXI platform measurement modules (power sources, ADC/DAC, digitizers/oscilloscopes) and provides SET count and waveforms storing in-files.

First samples were investigated under ion irradiation (^{22}Ne, ^{40}Ar, ^{84}Kr, ^{136}Xe) at IS OI-A (400M). Typical SET waveforms are presented in Fig. 4(a). Unfortunately, strong electromagnetic interference took place at cyclotron. No SELs were observed.

At the next step, the samples were scanned by focused picoseconds laser PICO-3. Laboratory conditions were provided to obtain clearly noiseless SET waveforms presented in Fig. 4(b). SELs were observed with equivalent values of LET above 69 Mev·cm^2/mg. Unfortunately, we observed laser induced SEL after ion experiments and cannot confirm this effect under ion beam with large values of LET.



(a)

(b)

Fig. 4. Typical SET waveforms of AD829JRZ under (a)ion beams and (b) focused laser beam

SET cross-section comparison is presented on Fig. 5. Correlation coefficients for SETs between LET and laser (wavelength 1064 nm) energy is $K_{j.SET} \approx$ 8 MeV·cm2/(mg·nJ) and $K_{\sigma.SET}$ = 0.1 between cross-sections. The correlation coefficient value shows that the SET effectiveness of laser spot influence is much higher than that of ion. It may be due to laser spot diameter as well as relatively larger and deeper SET sensitive volume than for other SEE such as SEU and SEL.

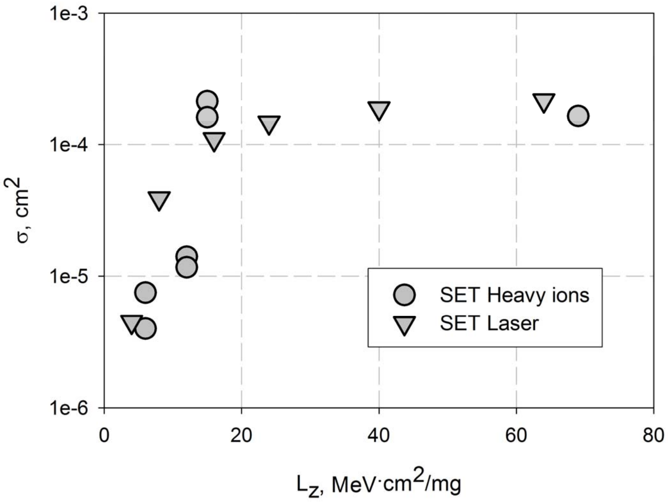


Fig. 5. SET cross-sections of AD829JRZ.

C. IRF3710SPBF

International Rectifier 100V N-Channel MOSFET IRF3710SPBF was tested using both laser and heavy ion beams.

The same test circuits were used for both laser and heavy ion irradiation. As a first step, heavy ion irradiation (^{40}Ar, ^{84}Kr, ^{136}Xe) took place. At the next step, samples were scanned with focused picoseconds laser PICO-3 with 1064 nm wavelength from backside. For instance, SEB cross section for laser and heavy ions irradiation is presented in Fig.6.

Correlation coefficients obtained for SEB were $K_{j.SEB}$ = 2 MeV·cm^2/(mg·nJ)) and $K_{\sigma.SEB} = 5$.

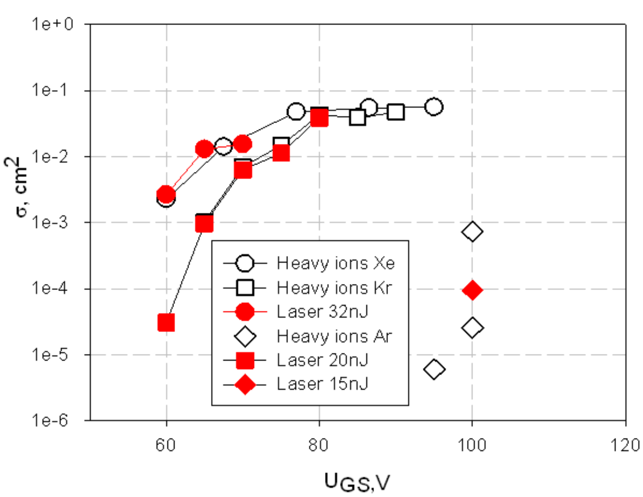


Fig. 6. SEB cross sections of IRF3710SPBF.

The same correlation coefficient was obtained for SEGR. We observed SEGR in IRF3710SPBF under laser beam with energy 20 nJ and ^{84}Kr ion beam for the biases U_{DS} = 65 V and U_{GS} = 0. SEGR cross section under laser irradiation was about 10 times higher than under heavy ions. Apparently, this cross-section difference relates to the size of the laser spot.

IV. Conclusion

The comparison of the laser and ion SEEs was carried out. All types of SEE observed under ion beam (SEU, SEL, SET, SEB and SEGR) took place under focused laser irradiation. The choice of any specific laser technique (wavelength, front or back side irradiation) depends on the DUT manufacturing technology, namely, due to optical losses because of the metallization and polysilicon layers influence. Correlation coefficient between laser energy and LET may be different for various SEEs in the same DUT due to non-uniformity in optical losses on chip's surface.

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