SEE Under Laser Radiation with Different Pulse Durations and Wavelengths

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***Abstract*— The results are presented of experiment-calculated simulation of radiation-induced SEUs and SELs. Experimental simulation was carried out using laser pulse durations from 25 ps up to 10 ns and wavelength from 0.85 µm up to 1.064 µm. Numerical estimation results are in good agreement with obtained experimental data.**

***Index Terms*— very large scale integration, radiation effects, measurement by laser beam**

I. Introduction

Single Event Effects (SEE) are known to be a serious problem for advanced space microelectronics [1-3]. This especially concerns Single Event Latchups (SEL) and Single Event Upsets (SEU). Usually the minimum set of the sensitivity parameters for each type of SEE includes the saturation cross-section and the threshold linear energy transfer (LET). The traditional methods of SEE sensitivity estimation are based on the tests using ion and proton accelerators. The methods based on the use of the focused laser radiation are the alternative means [1, 3-5]. We think that the local laser irradiation technique allows one to overcome some common laser methods' limitations [6, 7]. In this work we compare SEL and SEU threshold LET values estimated with the help of the local laser irradiation technique with different laser radiation parameters (pulse duration and wavelength).

Threshold LET value estimation (in $MeV{\cdot}cm^2/mg$) can be carried out by means of the measurement of the focused laser beam threshold energy and the ionization response in power supply circuits under local laser irradiation [6, 7]:

Manuscript received April 11, 2012.

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$$L_z \approx 9.1\cdot 10^9 \frac{J_o}{J_u}\cdot \frac{C\cdot \Delta U_{\max}}{L_{e\_\max}}\left(1+\frac{R_{in}}{R_t}\right)\cdot \frac{K_m^{'}}{K_m} \qquad (1)$$

where J_o is the energy of the sharply focused laser beam; J_u is the laser irradiation energy when measuring the amplitude ΔU_{max} (in V) of ionization response on the resistor R_t; $C=C_{in}+C_l$ is the total capacitance of the IC and the external measuring circuits, C_{in} is the value of IC equivalent internal capacitance; C_l is the equivalent external circuits capacitance (in F); R_{in} is the equivalent internal IC resistance; K'_m is the factor of optical losses caused by optical heterogeneities when measuring ionization response of the IC; K_m is the same factor when estimating focused laser energy; L_{e_max} is the maximum charge collection length (in cm).

An important question is whether it is possible to extrapolate these results to the cases of the use of laser radiation with different characteristics namely different wavelengths and pulse durations. To solve this question the experiment-calculated modeling of radiation-induced SEUs and SELs was carried out.

II. Experimental Simulation

The experimental simulation was carried out using three types of laser facilities providing the range of pulse duration from 25 ps up to 10 ns and the range of wavelength from 0.53 um up to 1.064 µm (Table 1).

In this work laser simulators RADON-9F and PICO-3 were used with wavelength 1.064 µm. PICO-4 operated with wavelengths 1.0 µm, 0.95 µm and 0.85 µm.

Table 1 – Main characteristics of the applied laser simulators

Laser simulator type	PICO-3	PICO-4	RADON-9F
Wavelength, µJ	1.064/0.532	0.7…1.0	1.064
Pulse duration, ns	0.07	0.025	7…10
Pulse energy, µJ	7.8/3.0	20	7.1
Focused spot diameter	2.2/1.2	2.5	2

Two types of SEE were studied: SEU in a SRAM MMDJ-6560 and SEL in a digital data converter (DDC) IC (AMI_R).

Fig. 1 shows SEL sensitive areas' map obtained by the local laser irradiation with 50 µm optical spot diameter for the DDC AMI_R using PICO-3 laser facility. It should be noted that SEL maps obtained by the other laser simulators had the same view. The equivalent threshold LET values were estimated in three most sensitive points marked on Fig.1.

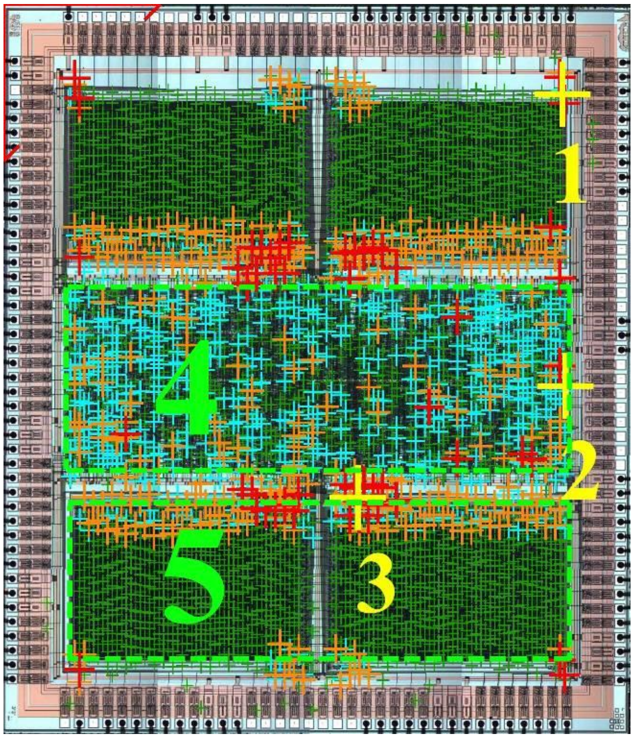

Fig. 1. SEL map for DDC AMI_R. Scanning was performed with 50 µm spot diameter. Scanning energy values were: 640 nJ (green), 160 nJ (blue), 60 nJ (orange), 30 nJ (red). The most sensitive areas are yellow.

The results of the SEL study for different laser radiation parameters are presented in Table 2. Obviously SEL threshold laser energy values and ionization response characteristics differ from each other for different laser facilities. Nevertheless all the results give close threshold LET values. A noticeable difference for estimated LET only takes place in the first sensitive area. We suppose that this difference is caused by some inaccuracy of the positioning into a certain point.

The comparison between SEL cross-section dependencies on LET for laser and ion accelerator tests is shown on Fig. 2. Without going into details one can see that there's satisfactory agreement between laser and ion accelerator results. Laser simulation methods enable us to obtain SEE cross-section dependencies for particular chip areas. Those dependencies can differ from each other significantly.

The most interesting result is that LET values obtained for 70 ps and 10 ns pulse durations are the same. Indeed one can see that SEL switching time duration is more than 100 ns (Fig.3). Therefore any laser pulse with the duration shorter than 10…20 ns can be considered as a very short one.

Table 2 – SEL study results for the DDC AMI_R

Parameter	RADON-9F			PICO-3		
	Area number			Area number		
	1	2	3	1	2	3
J_o, nJ	1.6	1.2	1.1	1.8	1.2	1.2
$\Delta U_{max}/J_u$, mV/nJ (50 Ohm)	0.7	0.5	0.6	0.6	0.5	0.4
$T_{1/2}$, ns	320	310	440	330	320	470
L_{zo}, MeV·cm^2/mg	20	10	10	20	10	10
Parameter	PICO-4					
	0.85 µm			0.95 µm		
	Area number			Area number		
	1	2	3	1	2	3
J_o, nJ	0.05	0.06	0.07	0.09	0.08	0.11
$\Delta U_{max}/J_u$, mV/nJ (50 Ohm)	13.1	11.3	10.2	7.0	6.5	5.8
$T_{1/2}$, ns	280	270	340	270	260	330
L_{zo}, MeV·cm^2/mg	10	10	13	10	8.0	11

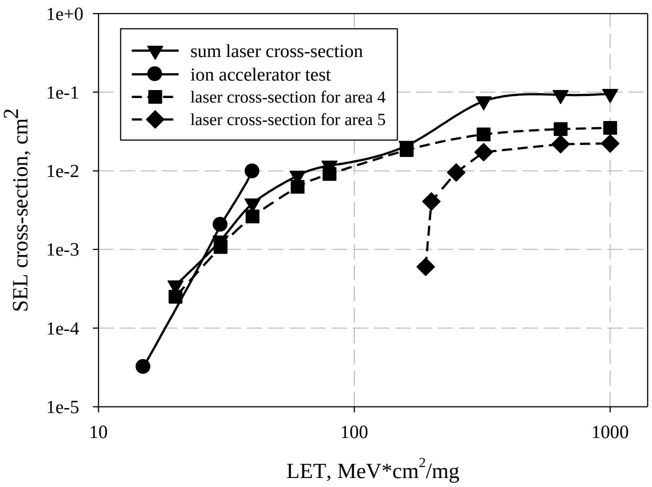

Fig. 2. DDC AMI_R SEL cross-section vs. LET for ion accelerator test and laser simulator PICO-3. ▼ – total laser cross-section, ● – SEL cross-section by ion accelerator test, ■ – laser cross-section for area 4, ♦ - laser cross-section for area 5.

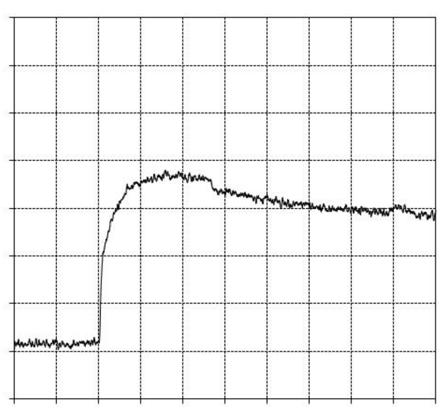

Fig. 3. SEL evolution waveform for DDC AMI_R. Scales: 50 mA/div, 50 µs/div.

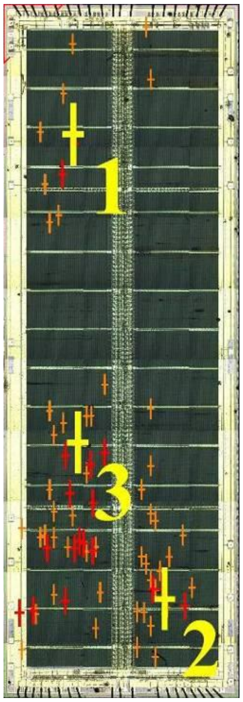

Fig. 4. SEU map for MMDJ-6560. Scanning was performed with 50 μm spot diameter. Scanning energy values were: 600 nJ (orange), 550 nJ (red). The most sensitive areas are yellow.

Table 3 – SEU study results for MMDJ-6560

Parameter	RADON-9F					
	Area number					
	1		2		3	
J_o, nJ	14		14		18	
$\Delta U_{max}/J_u$, mV/nJ (20 Ohm)	0.037		0.040		0.029	
$T_{1/2}$, ns	256		254		258	
L_{zo}, MeV·cm^2/mg	19		20		20	
Parameter	PICO-3			PICO-4 0.85 μm		
	Area number			Area number		
	1	2	3	1	2	3
J_o, nJ	1.4	1.4	2.7	0.4	0.3	0.6
$\Delta U_{max}/J_u$, mV/nJ (20 Ohm)	0.058	0.059	0.042	0.73	0.71	0.52
$T_{1/2}$, ns	300	300	370	270	270	280
L_{zo}, MeV·cm^2/mg	4.4	4.4	4.7	3.5	2.4	3.1
Parameter	PICO-4					
	0.95 μm			1.0 μm		
	Area number			Area number		
	1	2	3	1	2	3
J_o, nJ	0.8	1.0	0.9	2.5	2.9	4.0
$\Delta U_{max}/J_u$, mV/nJ (20 Ohm)	0.33	0.34	0.22	0.13	0.13	0.093
$T_{1/2}$, ns	280	270	280	290	280	260
L_{zo}, MeV·cm^2/mg	3.9	3.3	4.1	5.3	3.4	4.4

Similar results for SEU threshold LET estimation in SRAM MMDJ-6560 are presented in Table 3. SEU maps for all facilities were practically the same (Fig. 4).

III. Numerical Simulation

The numerical simulation was carried out with the help of two-dimensional simulation application "DIODE-2" [8]. A singe p-n junction was taken as the basic structure. The junction had the area of 100×1000 μm^2, was made in the depth of 1 μm in the p-substrate with the 3·10^{15} cm^{-3} doping level and 300 μm thickness. Fig. 5 shows the results of ionization response simulation for various laser wavelengths and pulse durations. These results are in satisfactory agreement with the experimental data. One can see a decrease of ionization response pulse amplitude and a raise of laser pulse duration when the wavelength is increased.

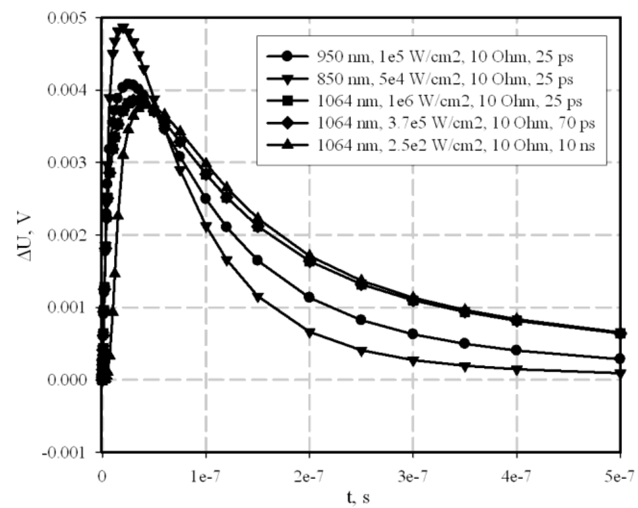

Fig. 5. Calculated ionization response pulse for external resistor of 10 Ohm with an external capacitor of 5 nF.

● – 950 nm, 1e5 W/cm^2, 10 Ohm, 25 ps;
▼ – 850 nm, 5e4 W/cm^2, 10 Ohm, 25 ps;
■ – 1064 nm, 1e6 W/cm^2, 10 Ohm, 25 ps;
♦ – 1064 nm, 3.7e5 W/cm^2, 10 Ohm, 70 ps;
▲ – 1064 nm, 2.5e2 W/cm^2, 10 Ohm, 10 ps.

This result has a simple physical explanation associated with the strong influence of the wavelength on the laser radiation absorption coefficient in silicon. That coefficient grows by about 70 times [9] when the wavelength is decreased from 1.064 μm to 0.85 μm. It is natural that this decrease leads to more intense semiconductor structure's ionization, i. e. significantly greater ionization response.

Ionization response pulse duration decrease for shorter wavelengths is associated with the fact that the processes of inhomogeneous charge generation along the semiconductor structure begins to affect on the charge collection length L_{ef} (Fig. 6). The presence of the contrary excited carriers concentration gradient leads to decrease of L_{ef} and decrease of the ionization response pulse duration. In this case such change will be only noticeable on conditions that

$$RC \le L_{ef}^2 / D_n \quad (2)$$

where D_n is the excited carriers' diffusion constant.

The value of RC characterizes the SEE equivalent switching time duration. If the pulse duration is significantly shorter than this switching time then its value won't affect the SEE threshold energy. As we noticed earlier, in AMI_R SEL switching time is more than 100 ns (Fig. 3) as it is associated with parasitic bipolar transistors performance. Therefore any laser pulse with pulse duration shorter than 10 ns can be considered as a δ pulse for this effect.

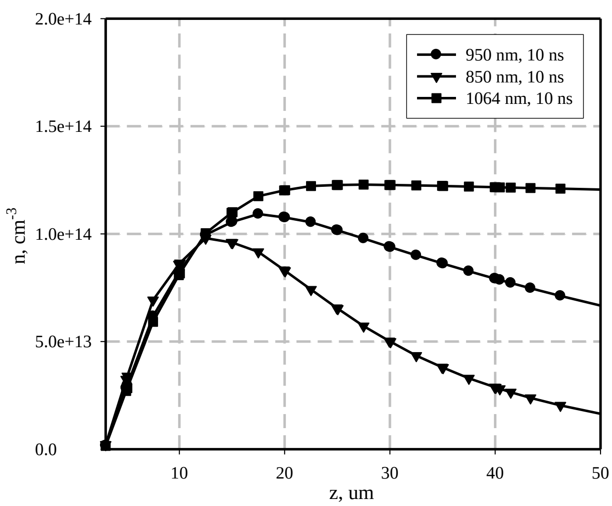

Fig. 6. Calculated excited carriers density distribution vs. depth for the moment 10 ns after the pulse. Pulse duration is 25 ps.

SEUs evolve in a completely different way. This effect is associated with the switching of active elements whose speed is about 1 ns and less. Therefore the laser pulse with the duration of 10 ns cannot be considered as δ pulse. In this case more energy is needed for SEU appearance.

The LET dependencies on laser wavelength are explained in a similar way. As the effective charge collection length L_{ef} can be estimated using SEE switching time τ_{ef}

$$L_{ef} \approx \sqrt{D_n \cdot \tau_{ef}}\ , \quad (3)$$

the decrease of this time leads to the decrease of L_{ef} . Accepting that SEU L_{ef} doesn't exceed several microns one can see that there will be no influence of the laser wavelength in the range analyzed.

The case of SEL is completely different. The absorption length for the wavelength 0.85 µm and the effective charge collection length become commensurable in this case. Thus the dependence of the effective LET on the wavelength must become apparent.

IV. Conclusion

Use of 10 ns laser pulse is possible for study of the SELs with switching times more than 50…100 ns. When SEL switching time is shorter than 10 ns the picosecond laser pulses must be used only. The wavelength for SEL investigation must be from 0.85 µm to 1.08 µm as the laser absorption in silicon begins to affect for shorter wavelengths. In case of SEU laser pulse length must be about picoseconds and the wavelength can be decreased up to 0.8 µm.

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