LASER TECHNIQUE OF SINGLE EVENT LATCHUP THRESHOLD ESTIMATION

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Abstract

Radiation-induced latchup in various CMOS test structures was analysed by software simulation. Correlation between single particle induced and dose rate latchup was found. Latchup experimental research was performed at laser wavelength of 1.06 μm and 0.53 μm, pulse duration of 10 ps and 10 ns, various locations of focused laser beam and spot sizes. The possibility of single event latchup threshold energy prediction based on the results of nanosecond uniform laser irradiation tests was analysed.

1. 1. INTRODUCTION

Single event latchup (SEL) is one of the dominant failure effects of CMOS ICs under irradiation by high energy nuclear particles [1, 2]. The probability of single particle-induced latchup depends on SEL cross-section and threshold linear energy transfer (LET). Sometimes it is necessary to estimate only the fact whether there would be SEL in CMOS IC or not under certain radiation environment. In this case only threshold LET should be estimated.

SEL threshold prediction by software simulation requires taking into account various parasitic structure characteristics (gains of parasitic bipolar transistors, effective values of substrate and wells resistances, etc.), which are very difficult to identify. The estimation of SEL parameters using direct experimental approaches, are rather complex and expensive. For examples, picosecond focused laser simulation tests for SEL latchup threshold evaluation of real IC is rather difficult because of interconnection metallization shadowing and necessity to scan the whole IC chip surface using various pulse laser energy for each laser beam location [3]. This approach can be successfully used for investigation of test structures.

The main issues of this work are to perform experimental research and software simulation of radiation-induced latchup in various CMOS test structures and to reveal latchup threshold dependencies on:

- irradiation pulse duration;
- location of ionized region and its dimensions;
- charge distribution in the ionized region;
- power supply voltage.

Computer simulation was performed using "DIODE-2D" software. Laser simulators with pico- and nanosecond laser pulse durations and relatively long (wavelength λ=1.06 μm) and short (λ=0.53 μm) laser energy absorption lengths were used for experimental research. The devices under test were special test structures and commercial CMOS RAMs.

2. COMPUTER SIMULATION

"DIODE-2D" software simulator was used for investigation of common SEL mechanisms under various ionization conditions.

Two dimensional 40 μm x 100 μm p-n-p-n structure was chosen for simulation. Schematic diagram of the test structure is presented in Fig.1. The lateral transistor's base width W was 7 μm. The radiation influence was either uniform within the whole structure or local. In the latter case it was simulated with a narrow ionization strip.

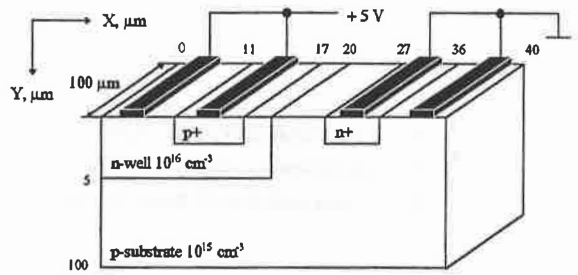

Fig.1. Schematic diagram of simulated test structure.

Simulation of the test structure was performed under various conditions: location and size of ionization strip, power supply voltage, irradiation pulse duration and bulk or surface ionization along the strip. Bulk and surface ionization corresponds to laser irradiation wavelength of 1.06 μm and 0.53 μm respectively.

The software simulation results (Fig.2 and Fig.3) represent SEL threshold vs. ionization strip location and width as well as power supply voltage.

The position of the most sensitive to latchup region was determined as a function of ionization strip width in the simulated test structure (Fig.2) and correlates with experimental fact that the most sensitive region is located near well-substrate junction [1, 4]. Similar dependencies were also obtained for λ=0.53 μm and for other base widths. The calculations were performed for twice larger separation distance between the well contact and the anode of parasitic structure. The results were found to be practically the same while the threshold energy values differ from initial ones for not more than 25%. It should be noted that a charge funnelling effect is not essential because there is practically no difference of latchup threshold energy when laser beam crosses well-substrate p-n junction or is located near depletion region.

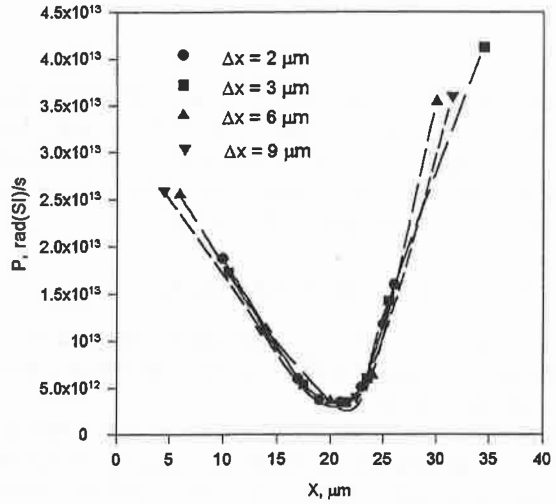

Fig.2. Calculated latchup threshold dose rate vs. ionization strip width (Δx) and its position (x) for wavelength λ=1.06 μm and pulse duration T_p=60 ps

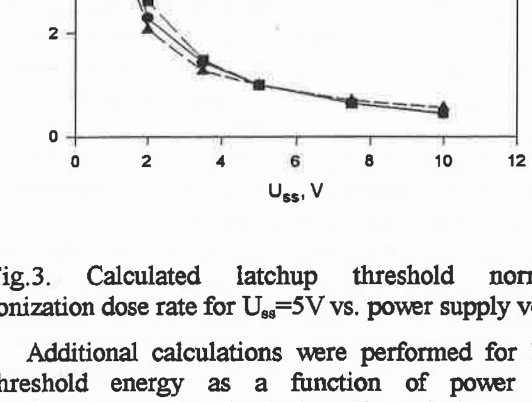

Fig.3. Calculated latchup threshold normalized ionization dose rate for U_{ss}=5V vs. power supply voltage.

Additional calculations were performed for latchup threshold energy as a function of power supply voltage U_{ss} (Fig. 3). Analysing Fig. 3 it is possible to conclude that normalized curves obtained for various irradiation conditions practically form one and the same dependence. Therefore these dependence can be experimentally estimated using uniform laser irradiation only.

The calculated latchup thresholds under the local irradiation were performed for various conditions. The difference in latchup threshold energy for two wavelengths can be attributed to strong dependence of laser radiation absorption factor vs. wavelength: with the decrease of wavelength from 1.06 μm to 0.53 μm the absorption factor in Si increases from ~14 to ~7000 cm^{-1}. Consequently volume ionization distribution changes from practically uniform to that localized within the 1.4 μm from the chip surface. Thus for focused laser beam with λ=1.06 μm the latchup sensitivity can be characterized by LET threshold dE/dx_{th}:

$$dE/dx_{th} \approx (1-R_{1.06})\, E_{1.06}\ \alpha_{1.06}\,(\varepsilon_i/\varepsilon_{1.06}); \qquad (1)$$

while for focused laser irradiation with λ=0.53 μm - by total absorbed energy (or charge) threshold $E_{a\ th}$:

$$E_{a\ th} \approx (1-R_{0.53})\, E_{0.53}\,(\varepsilon_i/\varepsilon_{0.53}) \qquad (2)$$

Here E is laser energy, R is a reflection factor; ε_i is a electron-hole generation energy (ε_i = 3.6 eV in Si); ε is a photon energy; α is a laser radiation absorption factor and "$_{1.06}$", "$_{0.53}$" indexes relate to the corresponding wavelengths.

The correspondence between latchup thresholds at various wavelengths and the dependence of laser energy on LET and absorbed energy in Si (expressions 1, 2) gives us the possibility to determine the latchup effective charge collection length L_{th}:

$$L_{th}=E_{a\ th}/(dE/dx_{th}) \approx 0.5\cdot(E_{0.53}/E_{1.06})\cdot(1/\alpha_{1.06}) \qquad (3)$$

Estimation of L_{th} gives the value of about 13 μm for the simulated test structure. Taking into account the results shown in Fig. 2 and estimated value of L_{th} we conclude that the charge collection length is determined by both drift and diffusion processes.

Additionally, software simulation of the test structure showed that the latchup occurrence is determined by the pre-latchup power supply current value (Fig. 4) and is independent of charge generation conditions in the test structure sensitive volume. Therefore, non-focused laser irradiation can be applied for SEL threshold estimation.

The latchup triggering time for typical CMOS ICs is about 10 ns (that corresponds to the carrier collection length about 10 μm and more) due to relatively large switching delay of parasitic structure which depends on the inertial switching characteristics of parasitic transistors. Thus, any temporal ionization is assumed to be "instant" if its time duration is less than the mentioned value.

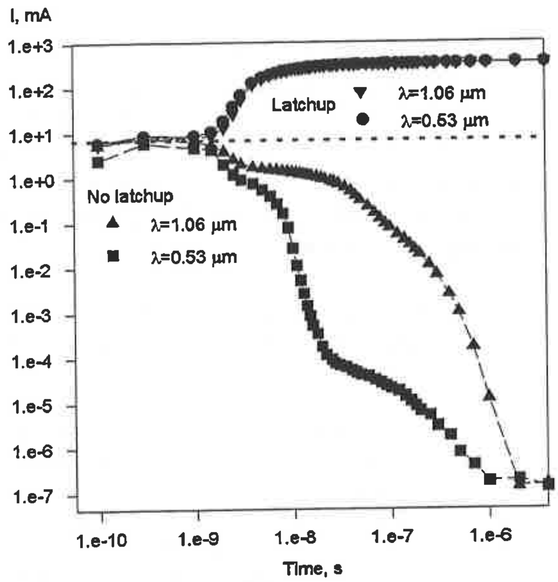

Fig.4. Pre-latchup and latchup transient power supply currents vs. time dependence under local laser irradiation with pulse duration T_p=12 ns.

3. SEL THRESHOLD ESTIMATION

We have analyzed the latchup conditions for various irradiation procedures. According to the analysis of simulation results it should be noted that the power supply transient current amplitude of a single parasitic structure at pre-latchup point does not essentially depend on pulse duration, wavelength and beam width (Fig. 4). Thus, the rough estimation of dE/dx_{th} can be written as [3]:

$$dE/dx_{th} = k_{lt} I_{ssl} P_{th} L_{th} / P_{il} ; \qquad (4)$$

where k_{lt} is a proportionality coefficient. The value of L_{th} in this formula can be estimated from laser test results (3). Taking into account that $P_{th0.53}/P_{th1.06} \approx$ const (from completes simulation) we can write the following relation:

$$dE/dx_{th} = k_{lt} I_{ssl} P_{th1.06} / P_{il1.06} , \qquad (5)$$

The proportionality coefficients can be estimated either from computer simulation or experimental results for special test structure. We calculated the latchup threshold LET from 2D-simulation results for local laser irradiation. Then we obtained the values of I_{ssl}, $P_{th0.53}$, $P_{th1.06}$ and $P_{il1.06}$ from calculations for uniform nanosecond laser irradiation. The predicted values of latchup threshold LET based on uniform nanosecond laser irradiation were obtained from formula (5) with k_{lt}=3 MeV/(mg·mA/cm^2).

It should be noted that the laser energies ratio P_{th}/P_{il} is used in the above relations. Therefore, the influence of optical effects, metal shadowing etc. is assumed to be rather small.

4. EXPERIMENT

Two types of laser simulators have been used as the radiation sources [5]. "PICO-2E" pulsed solid-state laser simulator (Nd^{3+} passively mode-locked, wavelength λ=1.055 μm) was used to generate picosecond pulses with the duration $T_p \approx$ 10 ps. "RADON-5E" portable pulsed solid-state laser simulator ($YAlO_3$:Nd^{3+}, wavelength λ=1.064 μm) was used to generate nanosecond laser pulses with the duration T_p=12 ns [6]. For both laser simulators the wavelength conversion to the second harmonic was performed by non-linear KTP crystal.

The devices under test were specially designed test structure TSCLU and CMOS RAM of two types 537RU6 (4Kx1, 3μm p-well process) and 537RU16 (8Kx8, 2 μm n-well process). The test structure consisted of several p-n-p-n structures of the same type with different shadowing of sensitive region by metallization (Fig. 5).

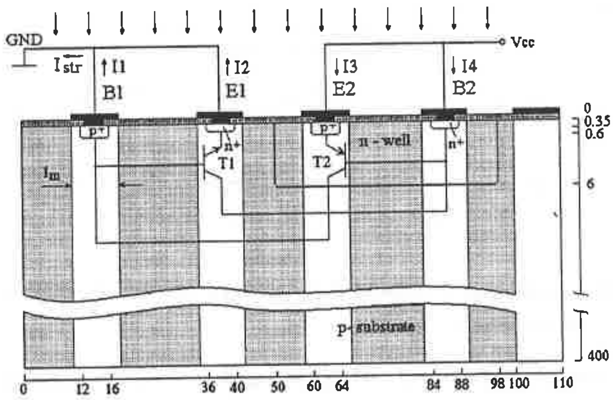

Fig.5. Schematic diagram of test structure TSCLU

During the experiment latchup threshold laser energy was estimated for focused and uniform irradiation as a function of power supply voltage, wavelength pulse duration and beam location (for focused irradiation).

Experiment (Fig. 6) and software simulation (Fig. 2) gave nearly the same position of the most sensitive region of investigated test structure TSCLU is in agreement with software simulation results. Also, there is obvious similarity between latchup threshold laser energy vs. supply voltage dependence for test structure TSCLUXX (Fig. 7) and the results obtained by software simulation (Fig. 3).

Measured 537RU6 and 537RU16 latchup threshold energy values under the focused beam irradiation for two laser wavelengths and two pulse durations are presented in Table 1. According to expression (3) $L_{th} \approx$21 μm for 537RU6 and $L_{th} \approx$6 μm for 537RU16. If $T_p < \tau_{th}$ (Fig.7), where τ_{th} is a latchup threshold time constant, then this irradiation can be considered as "instant", and for any "instant" irradiation the latchup threshold energy is the same (Table 1) within 20 % measurement errors.

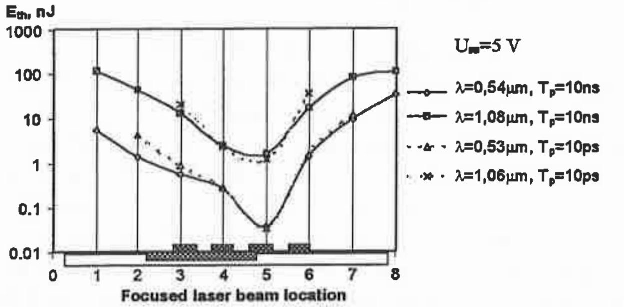

Fig.6. Experimental threshold laser energy vs. focused laser beam location for different wavelengths and pulse durations.

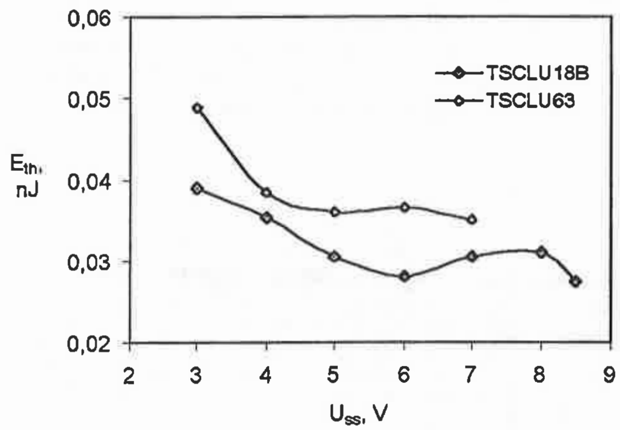

Fig.7. Latchup threshold laser energy vs. supply voltage for test structure TSCLU.

Table 1. Measured 537RU6 and 537RU16 latchup threshold energy E in nJ under the focused beam at various laser wavelengths and pulse durations

Type of RAM	λ=1.06 μm		λ =0.53 μm	
	T_p=10 ps	T_p=12 ns	T_p=10 ps	T_p=12 ns
537RU6	3.36	2.23	0.2	0.21
537RU16	2.38	2	0.045	0.063

The latchup threshold estimation for p-well 4K (537RU6) and n-well 64K (537RU16) CMOS SRAMs was performed (Table 2). Predicted values dE/dx_{th} are based on formula (5) using experimentally obtained values of power supply current I_{ssl} for relatively low dose rate P_{il} and latchup threshold laser intensity P_{th}. The ratio I_{ssl}/P_{il} for uniform laser irradiation with T_p=12 ns and λ=1.06 μm are shown in third column. Values of P_{th} were determined for λ=0.53 μm and λ=1.06 μm laser beams. Rather high predicted latchup threshold values were obtained for λ=0.53 μm laser radiation (sixth column). Such values can be explained by high absorption factor of IC surface polysilicon layers at λ=0.53 μm. Absorption is essentially higher in 537RU16 due to additional polysilicon layer. Therefore it is more preferable to use λ=1.06 μm. In this case we have obtained correlation with Cf^{252} experimental results: latchup took place in 537RU16 while it was not observed in 537RU6. It is necessary to point out that heavy particles of Cf^{252} have small ranges in device volume (R_o≤10μm in Si). Therefore for devices with L_{th}≤R_o the charge collection is nearly total and we can not use LET approach.

Table 2. Predicted RAM latchup threshold values in MeV/(mg/cm^2) using the uniform laser irradiation with T_p=12 ns.

		Uniform laser irradiation tests			Prediction	
Type of RAM	n_s	I_{ssl}/P_{il}, mA/(mJ/cm^2) (λ=1.06 μm)	P_{th}(12 ns), mJ/cm^2		dE/dx_{th}, MeV/ (mg/cm^2)	
			0.53 μm	1.06 μm	0.53 μm	1.06 μm
RU6	64	22/0.73	6.2	50	145	70
RU16	256	18/0.28	7.1	20	89	15

5. CONCLUSION

Latchup threshold comparative research using focused and unfocused laser beam, pico- and nanosecond laser pulse; bulk (wavelength 1.06 μm) and "surface" (0.53 μm) laser ionization was performed experimentally and by software simulation. Single event to dose rate latchup correlation was found. The approach was proposed for SEL threshold energy prediction using the dose rate laser simulation test results based on the independence of power supply current amplitude for single parasitic structure on pulse duration and irradiation spot width at pre-latchup point. For real IC this power supply current is proportional to the total number of parasitic structures.

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