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Estimating IC Susceptibility to Single-Event Latchup

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Abstract—The results are presented of a computer and physical simulation concerned with the estimation of CMOS-circuit susceptibility to single-event latchup. A laser-simulation procedure is proposed and tested in which only the most sensitive areas are irradiated. The estimates are found to agree with the measurements.

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INTRODUCTION

The proliferation of high-density integrated circuits (ICs) over space systems makes it necessary to evaluate their resistance to single-event effects (SEE) of high-energy ions or protons, the most important ones being single-event upset (SEU) and single-event latchup (SEL) [1–3]. A solid methodological framework has been developed for simulating and predicting SEUs [3–5]. By contrast, actual measurements are still required to evaluate resistance to SELs, but this appears impossible in Russia as it is. Considering that SELs can lead to a catastrophic failure of the IC itself or its power supply, a real need exists to develop computer and physical simulation procedures that could work in the circumstances.

Picosecond pulses of focused laser radiation have been investigated as an alternative to ion beams of different linear energy transfer (LET) [6, 7]. This approach, however, involves scanning the laser beam across most of the chip surface; furthermore, adequate estimation of SEL threshold may not be possible when some sensitive regions are shielded by the metallization pattern.

This paper proposes a procedure for estimating SEL threshold by local laser irradiation [8], with the exposed area limited by rail-span collapse. The estimates are to be verified by proton-accelerator testing.

RESPONSE MECHANISM TO LOCAL LASER IRRADIATION

Standard procedures of the use of laser radiation for estimation of radiation susceptibility of ICs are based on random scanning of the surface of the chip and on determination of energies, at which the appearance of the local radiation effect takes place. Unfortunately, these procedures are applicable in the case of testing of ICs with a minimum feature size of 0.5–1 μm or greater. This circumstance is determined by restrictions in focusing of laser radiation (down to 1 μm) and by the presence of several metal layers in modern ICs. As feature sizes are decreased, an increase in diffraction losses of the focused laser radiation on metallization layers takes place. This effect is difficult to take into account. Therefore, the use of similar procedures for ICs with a minimum feature size of about 0.5 μm or less calls for the presence of calibration dependences for estimation of a constant of proportionality between equivalent values of LET and the laser radiation energy [9].

Changing to the local exposure, on the one hand, allows one to average the diffraction losses in the limits of the irradiation spot, and on the other hand, to estimate these losses. Indeed, the photocurrent through the supply circuit is integrated over all the pn junctions [10] and is directly proportional to the energy of laser irradiation in the linear region. In the linear approximation, the supply-circuit photocurrent ΔI is determined by the processes of collection of the charge from the substrate, and its time pattern under the local exposure are virtually independent of the spot diameter:

$$\Delta I(t) \approx q g_o \frac{J}{T_p} \frac{K_l}{K_m} L(t), \qquad (1)$$

where q is the electronic charge, g_o is the generation rate of charge carriers in the silicon, T_p is the laser-pulse duration, J is the energy of laser radiation, K_l is the coefficient of conversion of laser-radiation energy into equivalent dose rate, K_m is the coefficient of effect of optical inhomogeneities (metallization), $L(t)$ is the charge-collection length from the substrate, and t is time.

Figure 1 shows the variations in the charge-collection length in time under the effect of a 12-ns bell-

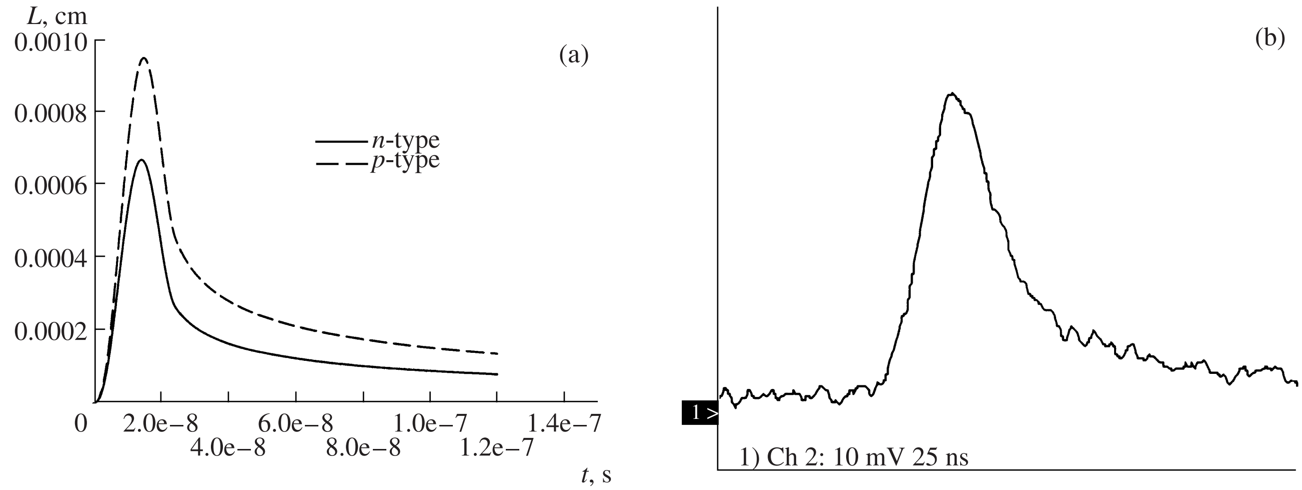

Fig. 1. (a) Calculated dependences of the charge-collection length for the n-type and p-type substrates, and (b) an oscilloscope trace of the current through the resistor $R = 100\ \Omega$ in the supply circuit under laser irradiation with a spot diameter of 100 μm and a pulse energy of $J = 69$ nJ.

shaped pulse of ionizing radiation in the substrate with the doping level 10^{15} cm^{-3}, and oscilloscope traces of supply current under the action of a laser pulse with the same duration and a spot diameter of 100 μm. Their time characteristics are in close agreement.

If the pulse duration is substantially smaller than the characteristic time constants of radiation response, the maximum value of $L(t)$ can be estimated by

$$L_{\max} \approx \sqrt{D_d T_p} + W_{pn}. \qquad (2)$$

Here, D_d is the minority-carrier diffusivity in the substrate and W_{pn} is the junction width (with CMOS circuits, this refers to the well–substrate junction).

It is noteworthy that, in some cases, the response pulse is broadened (Fig. 2). This effect is determined by both the bandwidth of the IC itself (Fig. 2b) and the presence of capacitors in the supply circuit (Fig. 2a) [11]. This effect is strongest in micromodules, which contain capacitors of order 0.1–1.0 nF to reduce noise. It is evident that the response height drops in this case. However, even in this case, it is possible to estimate K_m. If we know the value of the output resistor, the capacitance can be estimated from the time constant; knowing the response height, we then estimate the charge-collection length.

Values of K_m thus obtained vary over a wide range (Table 1) and correlate well with the specific features of the manufacturing process. Indeed, as the minimum feature size is decreased and the number of metallization layers is increased, K_m tends to grow. It is noteworthy that, in general case, K_m depends on the location on the chip.

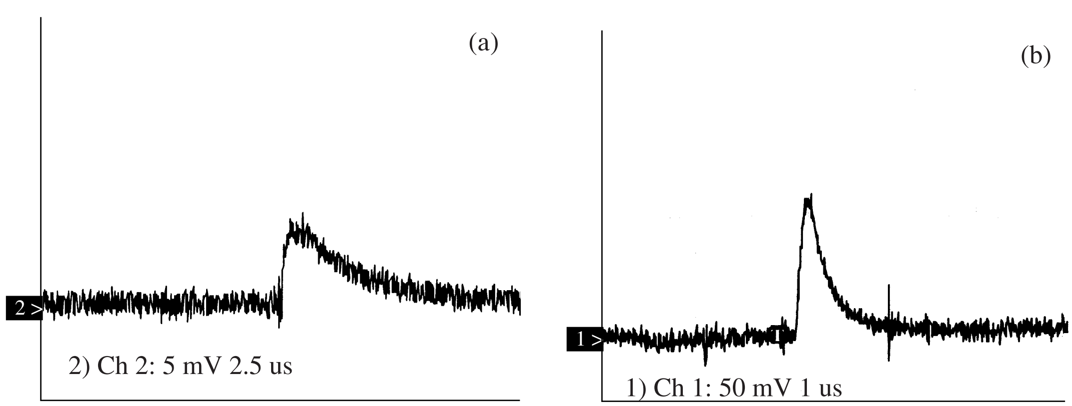

Fig. 2. Oscilloscope traces of the current through the output resistor in the supply circuit under local laser irradiation: (a) the KM684002 circuit, spot diameter = 50 μm, $R = 10\ \Omega$; (b) the MAX4508CSE circuit, spot diameter = 100 μm, $R = 4.7$ kΩ.

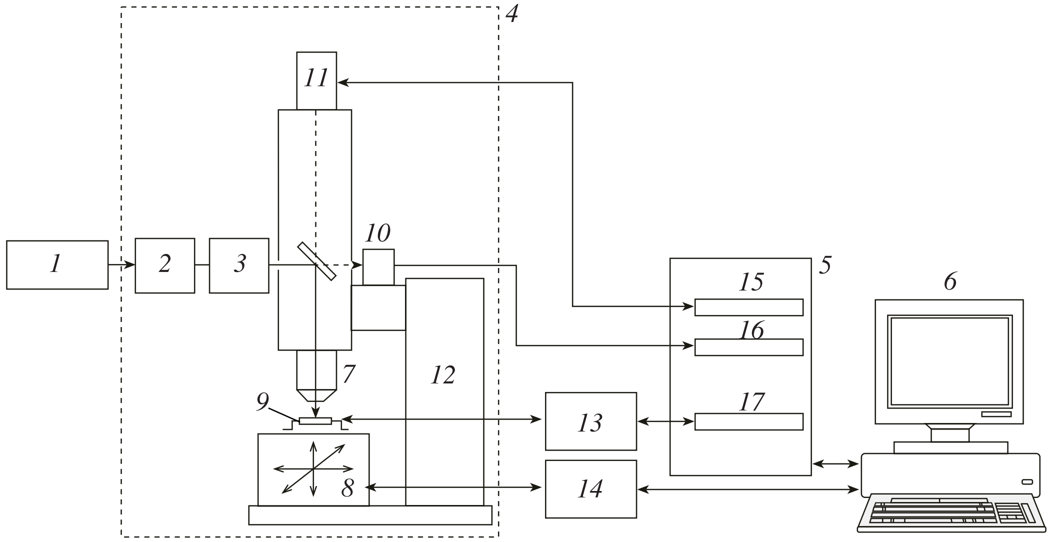

Fig. 3. Experimental arrangement for SEL laser simulations: (*1*) laser, (*2*) continuous attenuator, (*3*) step attenuator, (*4*) focusing unit, (*5*) expansion unit of the PC, (*6*) PC, (*7*) microobjective, (*8*) *X–Y–Z* stage, (*9*) chip under investigation, (*10*) pulse-energy meter, (*11*) color solid-state camera, (*12*) microscope, (*13*) interfacing-and-switching unit, (*14*) step-motor controller unit, (*15*) image-capture board, (*16*) interface unit for pulse-energy meter, and (*17*) universal parallel adapter.

LASER-SIMULATION PROCEDURE

Experimental investigations were carried out using a specially designed automated laser installation (see Fig. 3). The installation included a set of laser simulators: PICO, PICO-2, RADON-6, and RADON-9F. They have similar structural and optical arrangements and differ only in the maximum energy and the duration of laser pulses (see Table 2).

A laser pulse (1), whose energy was varied over a desired range in a continuous (2) or stepwise (3) fashion with a suitable attenuator, was introduced into an optomechanical focusing unit (4) based on a BIOLAM-I microscope (12), where the pulse was focused on a chip under test (9) with the use of removable microobjective (7). The chip was placed on a precision X–Y–Z stage (8), which was controlled with a personal computer (PC) (6) via the controllers of the step motors (14). The energy of a laser pulse was checked with a suitable unit (10), whose output signal was fed into the PC through an interface unit (16) located in a PC expansion unit (5). The expansion unit also contained an image-capture board (15) for a color solid-state camera (11) integral to the microscope. Functional checking of the chip and detection of radiation responses and SEL currents were performed using an interfacing-and-switching unit (13), which was connected to the PC through a universal parallel adapter (17).

The use of a set of laser sources was necessary at the first stage for estimation of the effect of duration of the laser radiation pulse on the SEL threshold. Although it is currently held that picosecond pulses are required to simulate SEE, longer pulses are also suitable in the case of SEL because the response is long enough [12]. Nevertheless, we used picosecond simulators at the first stage, namely, PICO (T_p = 7 to 10 ps), PICO-2 (T_p = 30 ps), and RADON-6 (T_p = 12 ns). Figure 4 shows the results of experimental investigations of the SEL threshold for an LSI RAM circuit. It follows from these results that taking into account distinctions in coefficients of absorption of laser radiation for the used laser simulators, the duration of the pulse of laser radiation does not

Table 1. Values of the coefficient of losses of optical radiation for some ICs

Make	AM29F010B-45E	KM684002	DS26LS32MW	IDT79RC64V474
K_m	3.0–3.5	2.8–3.5	1.0–1.5	50–140

Table 2. Main parameters of the laser simulators

Laser simulator	PICO	PICO-2	PADON-6	RADON-9F
Pulse duration, ns	0.007–0.01	0.03	12–14	7–9
Maximum energy per pulse, μJ	50	100	2000	100

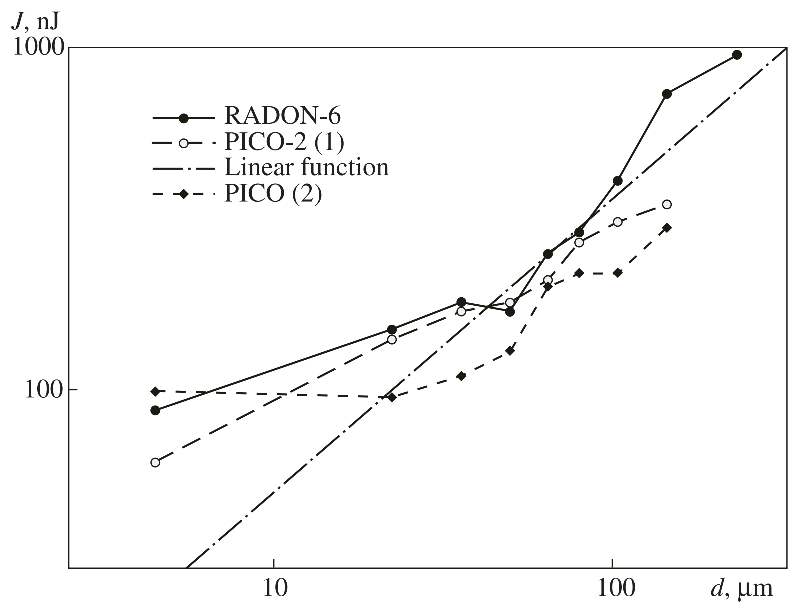

Fig. 4. SEL threshold pulse energy vs. spot diameter for the K6R4016C1D memory circuit.

exert a noticeable effect on the SEL threshold energy up to the values $T_p \sim 10$ ns.

Two important conclusions can be drawn from the dependences presented in Fig. 4. First, for the LSI under investigation, the dependence of the threshold energy on the diameter of the optical spot in the region larger than 20 μm is close to linear. This indicates that the sensitive region to the SEL in the LSI RAM lies along the well containing the memory cells. Therefore, large SEL cross sections should be also expected for this circuit. Second, as the diameter of the optical beam is decreased (the beam becomes focused), strong divergence takes place between the dependences of the same type. This indicates both a strong effect of local optical inhomogeneities on the results of experimental investigations and strong sensitivity to the arrangement since it is impossible to focus the radiation virtually to the same point.

During experimental investigations of a K6R4016C1D RAM, we obtained an interesting side result. For this IC, we found no SELs when the entire chip was irradiated, which confirms the absence of correlation between the levels of appearance of SELs in the IC under the action of pulsed ionizing radiation (gamma rays, x rays, laser radiation, electrons, etc.) and single high-energy nuclear particles [8].

It should be noted that the sensitive region may not be very large. This follows from the results of experimental investigations of a KM684002 RAM, for which the dependence of the SEL threshold energy on the spot diameter is almost linear (Fig. 5). For similar dependences, the sensitive region is small and, consequently, the SEL cross section will be small if there are few such regions. The data presented also show the point where the dependence starts to flatten out, indicating that the area of the optical spot becomes comparable with the area (cross section) of the sensitive region. In other words, the cross section of saturation by SEL for this region turns should be about 10^2 μm^2.

To summarize, the experimental procedure for estimation of radiation-susceptibility parameters is as follows:

(i) The chip surface is scanned by an optical beam of diameter 100–200 μm to identify the most sensitive areas;

(ii) Each of the sensitive areas is irradiated with a laser beam of variable diameter to determine the respective SEL threshold energies;

(iii) From these measurements, the values S_{lt} of the sensitive areas and the SEL threshold energy J_{lt} for focused radiation are estimated;

(iv) For the same areas, supply-circuit response is measured at laser-radiation energies well below the SEL threshold;

(v) From the results of step (iv), the K_{m} factor is determined;

(vi) The estimates thus obtained are substituted into the equations

$$\sigma_{lt} \approx \sum_{i}^{k} S_{lti}, \tag{3}$$

$$LET_{lto} \approx k_l J_{lt\_\min}/K_m, \tag{4}$$

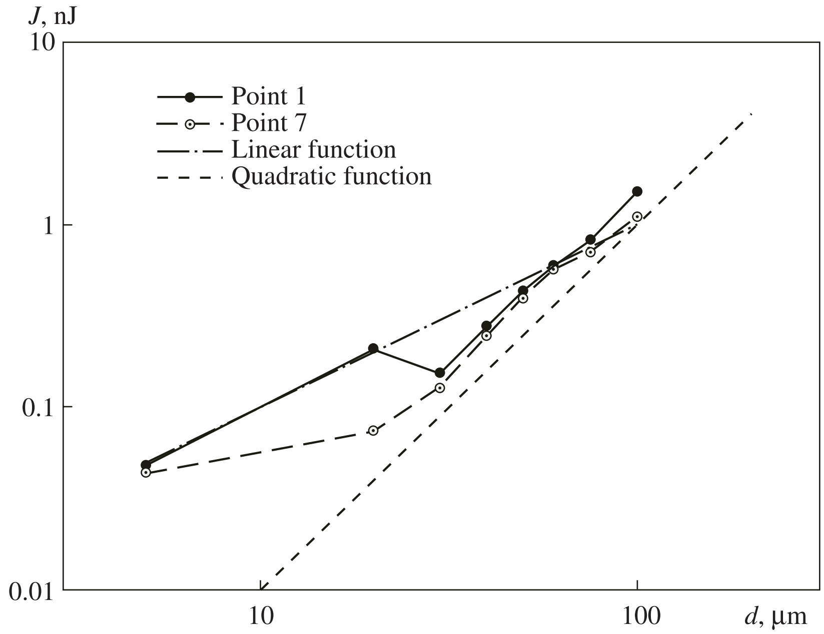

Fig. 5. SEL threshold pulse energy vs. spot diameter for the KM684002 memory circuit.

where σ_{lt} is the SEL saturation cross section for heavy charged particles, S_{lti} is the value of the ith sensitive area, k is the total number of sensitive areas, LET_{lto} is the threshold LET of SEL, k_l is the constant of proportionality between the laser radiation energy [3] expressed in nanojoules and the LET expressed in MeV cm^{2}mg^{-1}, and J_{lt_min} is the minimum value of J_{lt}.

EXPERIMENTAL RESULTS

Experimental investigations of ICs for various applications and with various minimum feature sizes were carried out using a RADON-9F laser simulator with a pulse duration of approximately 8 ns. The simulation results were verified by measurements using a proton accelerator with energies 250 MeV or 1 GeV and by comparison with published experimental results. Table 3 presents estimated threshold LETs and some experimental data.

The results of proton experiments allow one to carry out screening with respect to an LET of 14 MeV cm^{2}mg^{-1} (since energy deposition is by secondary particles in the case of protons). A comparison of the results obtained by the procedure proposed with the experimental data shows the predictions to be satisfactory.

Table 3. Comparison of threshold LETs of SEL evaluated by different approaches

IC make	LET_{lto} obtained by the procedure proposed, MeV cm^2 mg^{-1}	SEL cross section for a chip under proton irradiation, cm^2	LET_{lto} evaluated by measurement, MeV cm^2 mg^{-1}
AD7249	>100	no	
IDT79RC64	10 ± 5	1.0×10^{-10}	
98H02A	11 ± 3	3.8×10^{-10}	
7C1049B	12 ± 5	1.4×10^{-9}	>34 [13]
MT5C1008	13 ± 4	no	
KM616 4002C	25 ± 10	no	>34 [14]
K6R4016C1D	7 ± 3	1.7×10^{-9}	~2 [15]
KM684002	>100	no	>87 [16]
KM684002A	37 ± 10	no	>34 [17]

CONCLUSIONS

A pulsed-laser-simulation procedure for estimating SEL susceptibility is proposed and tested in which only the most sensitive areas are irradiated. Adequate agreement is achieved between estimated and measured threshold values of linear energy transfer.

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