Conference Paper

The Laser-only Single-event Effects Test Method for Spacecraft Electronics Based on Ultrashort-pulsed-laser Local Irradiation

O. Mavritskii, A. Chumakov, A. Egorov, A. Pechenkin, and D. Savchenkov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse 31, Moscow, 115409, Russia

Corresponding Author:
O. Mavritskii
oleg.mavr@gmail.com

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Abstract

The substantive laser method for studying the radiation hardness of semiconductor devices, not requiring calibration by ions, called "local irradiation", is described. The essence of the local approach is in irradiating the sample sensitive volume with the ultrashort-pulsed laser beam at some distance from its focus plane, where the beam becomes rather wide and divergent. Assuming the single-photon absorption, the relationship between the laser pulse energy and the excess charge actually generated in irradiated sensitive volume is obtained by accurate measurement of the electrical response, that makes possible to take into account non-uniform optical losses and avoid additional calibration by ions. Some results, obtained using both the front-side and the backside local irradiation of devices, are presented. Comparison with results obtained by traditional methods using focused laser radiation with subsequent calibration by ions showed that laser-only measurements, based on described local irradiation, give the correct estimates of radiation hardness parameters.

Keywords: Ultrashort laser pulse, single-event effect, local laser irradiation, semiconductor device, integrated circuit.

1. INTRODUCTION

Single event effects (SEEs) induced by ions, protons and neutrons in integrated circuits (ICs) significantly decrease the reliability of electronic components and systems, especially for space applications. The usual way to estimate SEE sensitivity of ICs is based on ion beam irradiation of the device under test (DUT).

The alternative way to investigate SEEs is to utilize ultra-short pulses of light from pico- or femtosecond laser beam, focused onto the active IC layer [1-9], to initialize effects similar to that, induced by heavy particle transition. In principle we can choose appropriate laser wavelength for any semiconductor material, for example, Si or GaN.

For a correct simulation of heavy ion interaction by focused laser beam we must provide a nearly uniform distribution of generated charge along the depth of sensitive layer L_{ef}. The results of the calculations of the charge-collection when an ion passes through a CMOS IC showed [1] that L_{ef} does not exceed 5 μm for the single event upset (SEU) and 20 μm for single event latchup (SEL).

Taking into account the dependence of the linear absorption coefficient and the corresponding penetration depth on the laser wavelength, a satisfactory radiation-absorption uniformity over the entire depth of the sensitive region can be attained for most silicon ICs at laser wavelengths in the range of 800–1100 nm. The most used wavelength for front-side (the side of the IC active layer) irradiating ICs is 1064 nm.

Laser technique has two main obvious benefits:

- by varying the laser pulse energy, we can obtain any effective value of linear energy transfer (LET), thus allowing to determine SEE cross section near the threshold LET;
- it is possible to localize by scanning the SEE sensitive points and find the most critical elements.

The use of laser irradiation allows location of SEE sensitive areas on IC's chip with submicron-scale accuracy (that is very difficult to achieve with ion beams); mapping of SEE sensitive nodes; measuring of current-voltage characteristics of parasitic p-n-p-n structures; studying the dynamic sensitivity of ICs to single-event upsets (SEUs) in different operating modes; providing "survival" tests of ICs in laser-initiated SEL mode; checking the effectiveness of various methods of radiation-hardening and so on.

Laser technique allows to simulate SEEs originating from laser ionization of semiconductor media, but not dielectric structures. It can't reveal spikes in CCD or micro-dose failures in SRAM. Laser light is also unable to pass through the metallization layers, but this problem in many cases can be solved using backside irradiation through the substrate. These are the main limitation of laser approach.

It should be noted that focusing laser to a spot close to the diffraction limit does not always lead to an increase in the accuracy of radiation hardness parameters estimates due to specific non-uniform laser energy absorption in IC structure.

This work presents some results in providing tests of different IC types using developed laser facilities and measuring techniques. Advances of modern "local laser irradiation" (LLI) technique, allowing to avoid ion calibration of laser obtained data for both front side and backside IC crystal irradiation geometries are discussed. Verification of LLI testing by and ion results is also presented.

2. EXPERIMENTAL TECHNIQUE

While executing SEE tests of semiconductor electronic devices with pico- and femtosecond laser facilities for both front-side and backside geometries we use two main laser irradiation techniques: focused [1–3] and local, [4–9]. There is also third approach based on two-photon absorption (TPA) [10], however, due to the complexity of LET estimation, TPA technique is being primarily used for scientific research but not for qualification tests.

Traditional focused laser technique is widely used for experimental simulation of SEE in ICs. It is based on utilization of pulsed laser beam sharply focused to a spot as small as possible at one of the possible planes, primarily at the crystal surface. Assuming single-photon absorption we can use linear correlation between laser pulse energy J_l and LET (L_z): $L_z = K_z \cdot K_s \cdot J_l \ / \ K_l$, where K_z is the proportionality coefficient between laser energy J_l and linear energy transfer (L_z) in the absence of optical losses. K_l is the coefficient of optical losses, which may change from 1 to ∞ and K_s is the coefficient of charge collection.

Obviously, the value of K_l can't be estimated, if we don't have full information about the optical parameters of IC structure. Calculated coefficient has been obtained only for simple ICs with the rather large distance more than 2 μm between adjacent metallization layers. Unfortunately, for modern VLSI ICs it is impossible to determine the proportionality coefficient between laser pulse energy and LET using calculation only.

Ion-beam calibration measurements seem to be the only correct way to obtain coefficient for equivalent LET correlation. However, in this case it must be assumed that for every sensitive area this coefficient has the same value. As a rule, it gives correct results for the same SEE, but for the different type SEEs the values of correlation coefficient may significantly differ and must be separately measured. The benefit is in the fact, that this particular coefficient has the same value for all IC samples in the batch and we can use it to calculate parameters of SEE sensitivity for different electrical and functional modes of DUT operation, obtained from laser technique application only.

Thus, the focused laser technique has a lot of applications, but can be applied for official qualification VLSI IC tests *only together with ion-beam calibration* for each SEE [8, 11]. It is clear that the front-side focused laser technique has a serious limitation for modern VLSI with multilevel metallization layers, which covers 99% of chip surface and even more. In most of modern IC only *a little part of chip surface* may be available for focused laser testing.

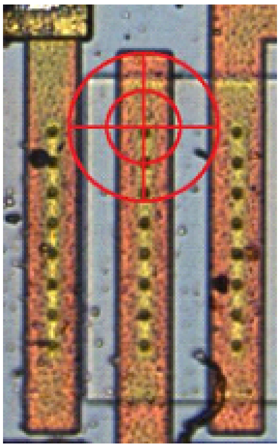
Nevertheless, except for the direct passage, due to the divergence of laser beam and such optical effects as single or multiple reflections, scattering, diffraction, secondary reflections from air-SiO_2 boundary, interference, partial absorption in n^+/p^+/poly-Si layers and reflection from bottom side of substrate there is a possibility for the fraction of laser radiation to reach sensitive volume. It is clear that this time we have some kind of "local", rather than focused laser irradiation. So, it's quite probable that there're some "holes" in metallization allowing some part of "large spot" laser radiation penetrating through them.

Depending on the type of DUT in our testing experience we use either front-side or backside geometry for both focused laser and LLI techniques. The procedure of backside focused laser irradiation of VLSI through the substrate has been actively used [7, 12] due to promising possibility to eliminate significant limitation of laser testing associated with the influence of multilayered metallization. But, instead of metal layers screening, there are a lot of reasons which must be taken into account: optical radiation is partially absorbed in silicon substrate; refraction and partial reflection of laser radiation at the upper surface of VLSI crystal; there can be n^+ buried layers or epitaxial layers that absorb laser light rather strongly. The application of backside focused laser technique again has the same limitations caused by the uncertainty and heterogeneity of optical losses during the passage of the substrate. In order to estimate the proportionality coefficient between LET and the energy, ion-beam calibration is still necessary, but in many practical cases it is very difficult because of short ion penetration ranges, that requires additional substrate thickness W_s thinning. Fortunately, the algorithm of evaluation of equivalent values of LET for backside LLI technique will be the same as for front-side case.

Fig. 1 shows an example application of LLI for simplest large scale p-n junction test structure having several metallization layers, having several semitransparent holes in test structure. In this configuration, a part of sensitive area is irradiated with various laser spot sizes and ionizing response is observed. The results of the simplest simulation are also shown (Fig. 1, b) taking into account only geometric factors. Lower experimental points are close to the noise level (~10 mV).

However, we can see that calculation curve satisfactorily corresponds to experimental data even in this approximation.

LLI technique is highly applicable for tests of ICs with large sensitive areas. Variable "large spot" laser irradiation provides a natural averaging of the optical losses making the account of their influence quantitatively more accurate.



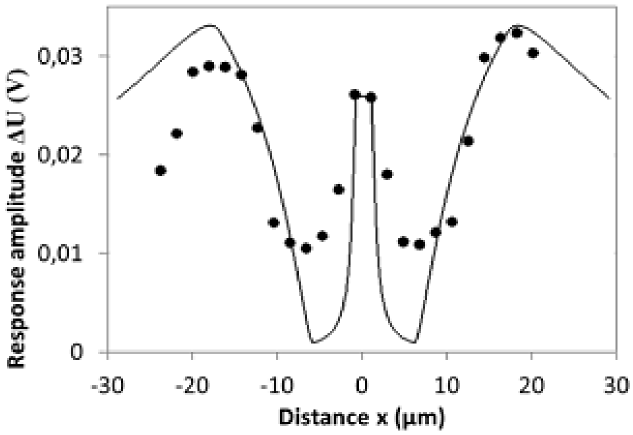


Figure 1: Local laser irradiation of test structures: symbols are the experimental data;line is the simulation curve.

For SEL effect, these large areas are the well-substrate p-n junctions. In contrary, when you investigate SEU the sensitive areas are drains of MOS-transistors, which are much smaller than even focused laser beam's spot. However, even for SEU tests, we prefer LLI to reduce the probability of missing an event due to the better coverage of the crystal area with a larger spot during scanning [7].

The algorithm of applying LLI technique for equivalent LET determination includes the following main procedures:

a. Scanning of the IC crystal using divergent "large spot" (from 30 µm to 100 µm) irradiation for SEE most sensitive point(s) localization.

b. Determination of SEE threshold energy values $J_{th}(0)$ of the laser radiation extrapolated to sharply focused in each selected sensitive point [5, 13, 14]. $J_{th}(0)$ can be estimated asymptotically from experimental SEE threshold laser energy J_{th} vs. laser spot diameter D (Fig. 2b).

c. Determination of the optimal diameter D_{IR} of the laser spot for the subsequent ionization response measurement in the 10…30 µm range, where the approximating curve has the best fit to the experimental points.

d. Measurement of the waveform *U(t)* and amplitude $U_{\max}$ of the ionization response in power supply circuit, when irradiating previously selected sensitive points with laser spot diameter D_{IR} in order to determine the equivalent parameters resistance R and capacitance C of the measurement circuit. It is very important to obtain ionization response irradiating the same SEE sensitive point, providing conditions at which optical losses are practically the same for both focused and local irradiation.

e. Numerical evaluation of the effective charge collection length L_{e_max} using RC obtained in p. (d).

f. Calculation of effective LET value L_z using data from pp. (b)-(e):

$$L_z = \frac{1}{qg_0} \cdot \frac{J_{th}(0)}{J_{th}(D_{IR})} \cdot \frac{C \cdot U_{\max}}{L_{e\_\max}(RC)},$$

where q is the charge of electron and g_0 is speed of the charge carrier generation in silicon.

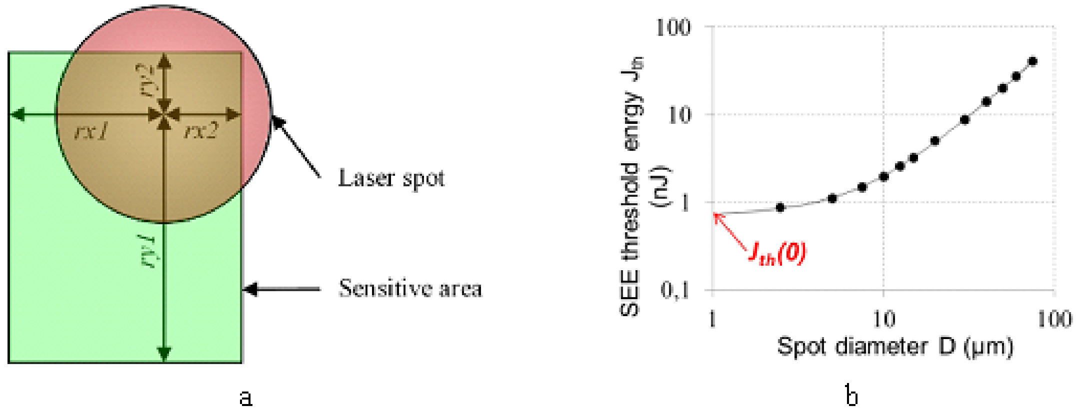


Figure 2: Model of IC sensitive area and typical experimental SEL threshold laser pulse energy vs. laser spot diameter dependence.

For proper backside LLI technique application it is necessary to provide relatively uniform absorption of laser radiation (passing through substrate) in a sensitive volume of VLSI. In used laser facilities it is effectively obtained by using laser radiation with wavelengths from the range of 0.95–1.08 μm, allowing to avoid the excessive energy losses of laser radiation in up to 1 mm thick substrates. It is also very useful to minimize the uncertainty of laser beam focus position and spot size at active layer by using IR camera, incorporated into focusing unit [1, 15] providing a simple and reliable way of DUT positioning and DUT tilt correction during backside scanning. Additional fine tuning of laser focus position can be obtained by precise shifting focusing lens by the value determined from measuring ionizing response vs. distance between DUT surface and focusing lens [7].

3. RESULTS AND DISCUSSION

Independent full range front-side LLI testing, including accurate measurement of the ionization response and SEE threshold laser pulse energy vs. laser spot diameter dependence, are shown in Fig. 3. The results, calculated from only laser data, shown in the inserts, gave the value of L_z = (10±5) MeV·cm^2/mg, which is in a good agreement with experimental cross-section curve.

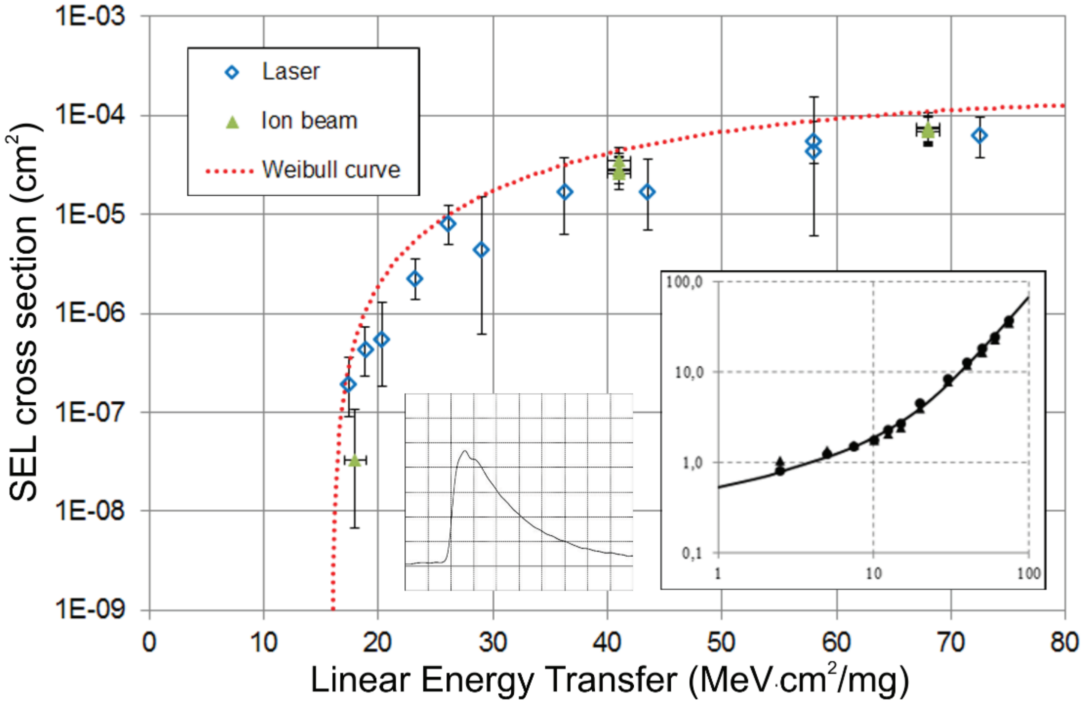
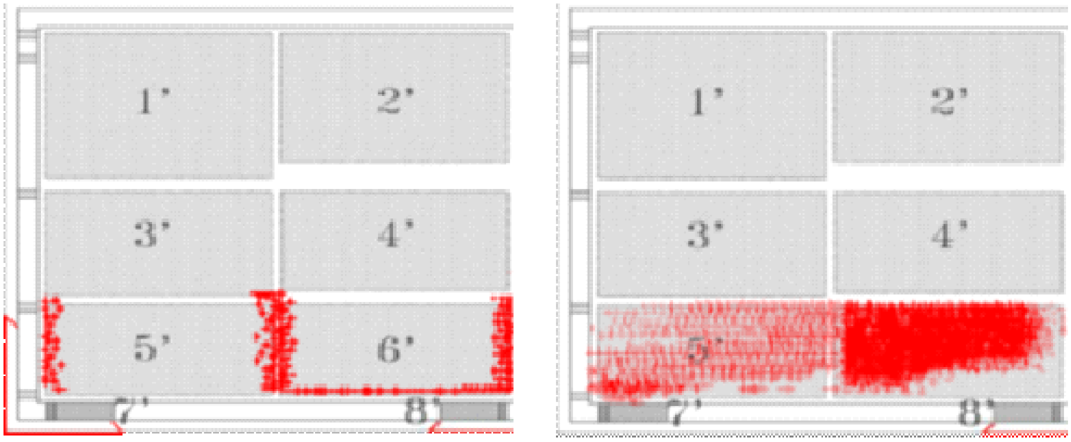


Figure 3: Front-side LLI-technique validated by ion-beam measurementson NS 8-channel 12-bit A/D convertor.

Fig. 4 shows the results for 90-nm SRAM test structure (8 blocks with different topology of 6T memory cells). SELs detected with front-side focused laser technique were located only along the edges of the 5th and 6th blocks (Fig. 4, a), probably due to the strong inhomogeneity of metallization coating. Then the same DUT was front-side irradiated by accelerated ions with LET values of 6 and 16 MeV·cm^2/mg, and again SELs were registered in blocks 5 and 6. Further laser tests were performed using backside LLI technique. One can see in Fig. 4, b that the same memory blocks appeared to be sensitive to SEL in the most part of their aria. It seems evident that backside approach provides more uniform distribution of optical losses then front-side.

The threshold LET value calculated from "front-side focused laser + front-side ion beam" data $L_z \approx 5$ MeV·cm^2/mg agrees well with the result L_z = (4 ± 2) MeV·cm^2/mg obtained by (only laser) backside LLI technique (Fig. 5).



a b

Figure 4: Front-side (a) and backside (b) SEL map for 90-nm SRAM structure.

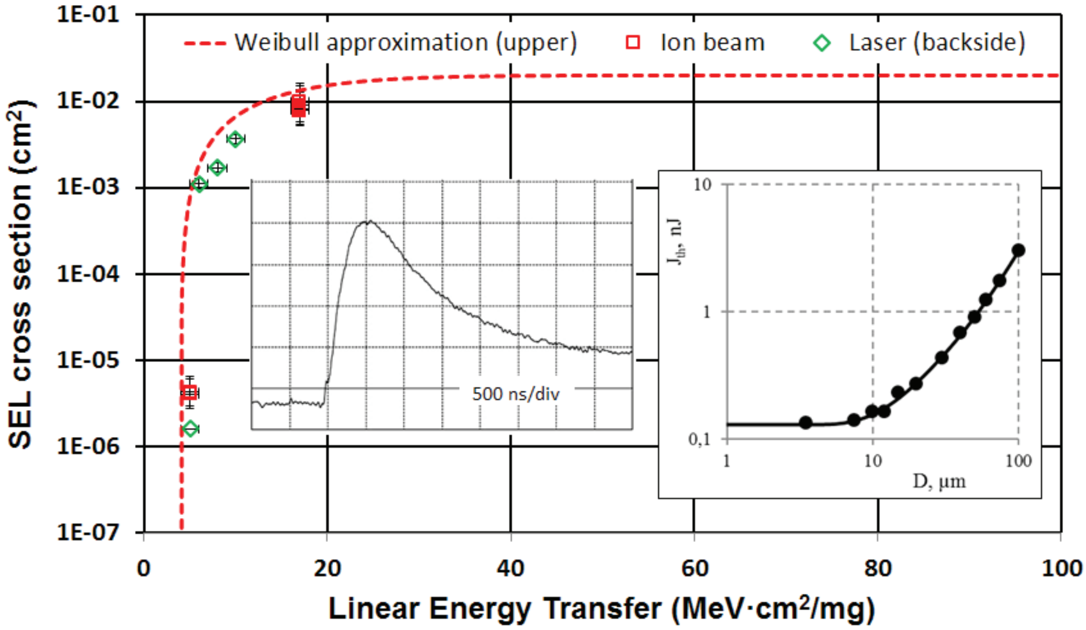


Figure 5: Results of “front-side focused laser + front-side ion beam” effective LET determination with backside LLI technique application data on inserts.

4. CONCLUSIONS

The backside local laser irradiation technique is the most acceptable for official laser testing of VLSI ICs. It allows to estimate the proportional coefficient between LET and laser energy using only laser experimental data. A reasonable combination of two described techniques on the same laser facilities made it possible to carry out a verification of the test results with ion-beam measurements.

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