

PACS numbers: 42.62.–b; 82.53.Mj
DOI: 10.1070/QE2014v044n12ABEH015519

Correlation of the ionisation response at selected points of IC sensitive regions with SEE sensitivity parameters under pulsed laser irradiation*

A.V. Gordienko, O.B. Mavritskii, A.N. Egorov, A.A. Pechenkin, D.V. Savchenkov

Abstract. **The statistics of the ionisation response amplitude measured at selected points and their surroundings within sensitive regions of integrated circuits (ICs) under focused femtosecond laser irradiation is obtained for samples chosen from large batches of two types of ICs. A correlation between these data and the results of full-chip scanning is found for each type. The criteria for express validation of IC single-event effect (SEE) hardness based on ionisation response measurements at selected points are discussed.**

Keywords: *single event effects, femtosecond laser pulses, ionisation response.*

1. Introduction

Currently much attention has been paid to radiation hardness of integrated circuits (ICs) used in spacecraft equipment. An analysis of the causes of malfunctioning of spacecraft equipment has made urgent the problem of testing the radiation hardness of all electronic components intended for operation in space environment. One of the main reasons of malfunctioning is the use of electronic components with insufficient hardness to the effect of space heavy charged particles (heavy ions) in on-board equipment.

Under terrestrial conditions, the most appropriate instruments for estimating the parameters of IC sensitivity to single-event effects (SEEs), caused by heavy ions, are ion and proton accelerators. The main drawback of such tests is their laboriousness and high cost. At the same time, the number of ICs that must be tested for radiation hardness constantly increases. Therefore, more available methods, allowing for operative tests of many ICs of different types, must be developed. One of alternative approaches [1] is the use of pulsed laser radiation.

Laser tests are based on the fundamental possibility of generating an excess charge in a local volume of the IC element, which is equivalent to a charge generated by heavy ions passing through the element. This approach is valid if the spatial distributions of the electrons generated by heavy ions and laser pulse are nearly the same at the beginning of electric response formation. This condition is satisfied when ultrashort pulsed laser radiation focused into a micrometre-sized beam is used. It was shown in [2] that, applying this beam, one can produce a charge density, which is characteristic of any existing heavy ion and, therefore, leading to consequences similar to those of SEEs caused by passage of space heavy ions.

This approach removes one of limitations typical of the tests based on the use of ionised particles: the impossibility of analysing ICs produced by flip-chip technology. Moreover, the methods based on application of focused picosecond laser beams have revealed radically new possibilities [3]. For example, the spatial resolution provided by modern laser systems makes it possible to localise IC sensitive elements with high accuracy (to few micrometres), and their time resolution allows one to study the dynamic sensitivity to SEEs in different IC operation modes.

It should be emphasised that the use of laser systems to study the effects caused by passage of heavy ions through ICs is aimed at modelling the electric effects from heavy ions striking the IC sensitive region rather than the heavy ion – matter interaction itself. Indeed, the spatial distributions of the generated charge and ionisation energy loss are significantly different for the effects of real heavy ions and focused laser radiation on ICs.

First, the lateral sizes of the charge track formed in a semiconductor immediately after passage of a particle is much smaller than the focal diameter for a focused Gaussian laser beam, which, in turn, is limited by diffraction. Second, the energy loss of a heavy ion passing through a thin semiconductor layer is negligible; this does not hold true for laser radiation, the absorption of which depends strongly on the laser wavelength.

Nevertheless, a correct choice of a laser wavelength makes it possible to model both long-range particles (the penetration depth of near-infrared laser radiation in silicon is several hundreds of micrometres) and short-range particles (the corresponding depth in the visible range is several micrometres or several tenths of micrometre). With the wavelength dependence of the laser radiation absorption coefficient and different charge collection mechanisms taken into consideration, one can state that an equivalent generated charge is accumulated in the IC active layer by the moment of the IC electric response formation; hence, a laser beam can cause effects similar to heavy ion-induced effects.

However, one must take into account that laser radiation cannot ionise insulators; therefore, laser methods are inappropriate for simulating effects related to ionisation of IC insulating layers.

* Presented at the III International Conference on Photonics and Information Optics, Moscow, Russia, January 2014.

A.V. Gordienko, O.B. Mavritskii, A.N. Egorov, A.A. Pechenkin, D.V. Savchenkov National Research Nuclear University MEPhI, Kashirskoe shosse 31, 115409 Moscow, Russia;
e-mail: alexgordya@gmail.com, oleg.mavr@gmail.com

Received 7 April 2014; revision received 4 June 2014
Kvantovaya Elektronika **44** (12) 1173 – 1178 (2014)
Translated by Yu.P. Sin'kov

The adequacy and advantages of applying ultrashort laser pulses to test IC sensitivity to HCPs, which were justified in numerous studies (see, for example, [3–7]), give grounds to consider laser methods as a high-power tool for majority of tests. In this context, the role of ion accelerators may be reduced to calibration measurements, necessary for quantitative estimation of the IC sensitivity parameters based on the results of laser tests.

The aforementioned necessity of testing constantly increasing numbers of ICs of the same type calls for ways to reducing testing time for large IC batches. Recently a technique based on measuring the ionisation response signal (IRS) amplitude at selected points of sensitive regions of ICs from one batch was proposed in [8]. In this paper, we report the results of successful approval of this technique.

2. Experimental setup

The choice of an appropriate laser system depends on the type of a specific IC. We performed all measurements in CMOS structures with an automated FEMTO-T laser complex, the block diagram of which is shown in Fig. 1. A distinctive feature of this complex is the use of an MPAP-2500 laser system (Avesta Ltd, Russia), which generates femtosecond pulses with a wavelength of 870 nm and is characterised by high energy stability and beam quality ($M^2 < 1.6$). The pulse width can be varied from 150 fs to 3 ps.

Initial femtosecond pulses are generated by a TiF-50 Ti:sapphire master oscillator to be transmitted through a stretcher, regenerative amplifier (RA) and additional multipass amplifier (MPA). The pulse picker based on Pockels cells makes it possible to obtain pulses with energies up to several hundreds of microjoules with a controlled repetition rate (including the single-pulse mode) at the output. The amplifying subsystem was pumped by the second-harmonic radiation of an additional Nd^{3+} : YAG Q-switched diode-pumped laser. The width of the amplified pulse is reduced in an adjustable compressor to a value (from the aforementioned range) necessary to carry out tests for IC hardness to SEEs. A beam expander, installed at the output of the laser source, increases the beam diameter to implement subsequent alignment with the entrance aperture of the focusing objective and form a spot of minimally possible diameter on the object under study. The width and shape of the output pulse were monitored by an ASF-200 optical autocorrelator.

The rest of the optical scheme is basically similar to that described in [7]. It includes an adjustable laser-energy attenuator, a focusing system (a microscope with a telecentric illuminating system), a CCD video camera, a three-coordinate system for positioning objects and a control PC with all necessary interfaces. It should be emphasised that careful fitting of laser-beam parameters, including alignment of its divergence and effective diameter with the input pupil of infinity corrected objective (Mitutoyo Plan Apo NIR 20$^{\times}$ with an extra large working distance), provided a focusing spot diameter of 1.2 μm at a level of 1/e, which is close to the diffraction limit.

The parameters of this system ensure sufficiently uniform absorption of laser radiation in the material over the sensitive region depth, which is similar to uniform distribution of the energy loss of heavy ions passing through IC semiconductor materials.

Electric signals from the IC under study were recorded by a high-speed TDS-3034C digital oscilloscope, connected to the functional-control system (connected, in turn, to the control PC).

3. IC ionisation response signal maps

It is convenient to present the results of laser-based study of heavy-ion-induced SEEs in the form of maps of different response parameters of the IC crystal, comparing them with the IC topology (or an optical crystal photograph). IRS maps hold a particular position among other obtained maps.

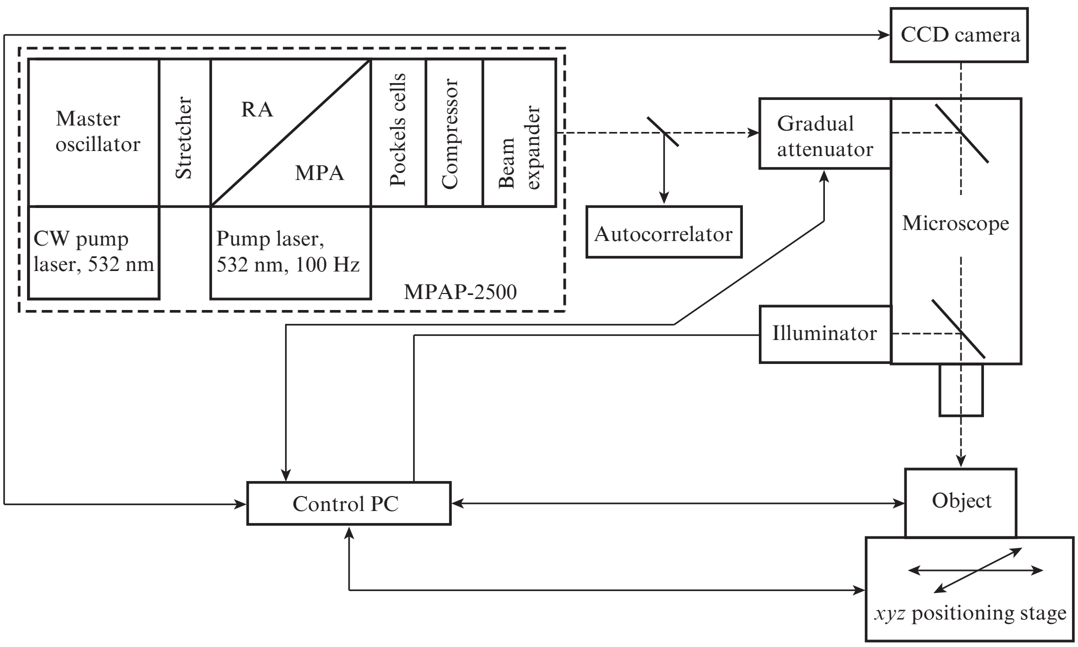

Figure 1. Block diagram of the laser system.

Generally, IC ionisation response signal is considered to be an electric pulse formed on the current-collecting resistor in the IC power supply circuit under pulsed laser irradiation of the IC sensitive region.

When choosing the nominal resistance of the current-collecting resistor, one must take into account that, on the one hand, an increase in resistance leads to a rise in the amplitude of the IRS and thus increases the signal-to-noise ratio. On the other hand, it increases the *RC* value of the integrating circuit formed by this resistor and intrinsic capacitance of the IC crystal and measuring accessories. With an excess increase in the *RC* value of the integrating circuit, the shape of the IRS pulse characterises to a greater extent the IC rather than the dynamics of ionisation processes.

We obtained maps by recording IRS pulses from an IC operating in non-biased photodiode mode. Figure 2 shows an IRS map of a BU61580 IC recorded on the FEMTO-T laser system (irradiation from the front side) and a panoramic photograph of the same IC. The map of the entire crystal area was recorded with a step of 30 μm and the same size of focusing spot. Even with this resolution one can clearly see differences in the IRS pulse amplitudes in regions with different unit-packing densities; metal buses can be observed. A decrease in the scan step and focusing spot size leads to an increase in the spatial resolution, which is limited in the system used by the minimum spot size. However, the scan time increases as well and may reach 5–6 h at a scan step of 5 μm.

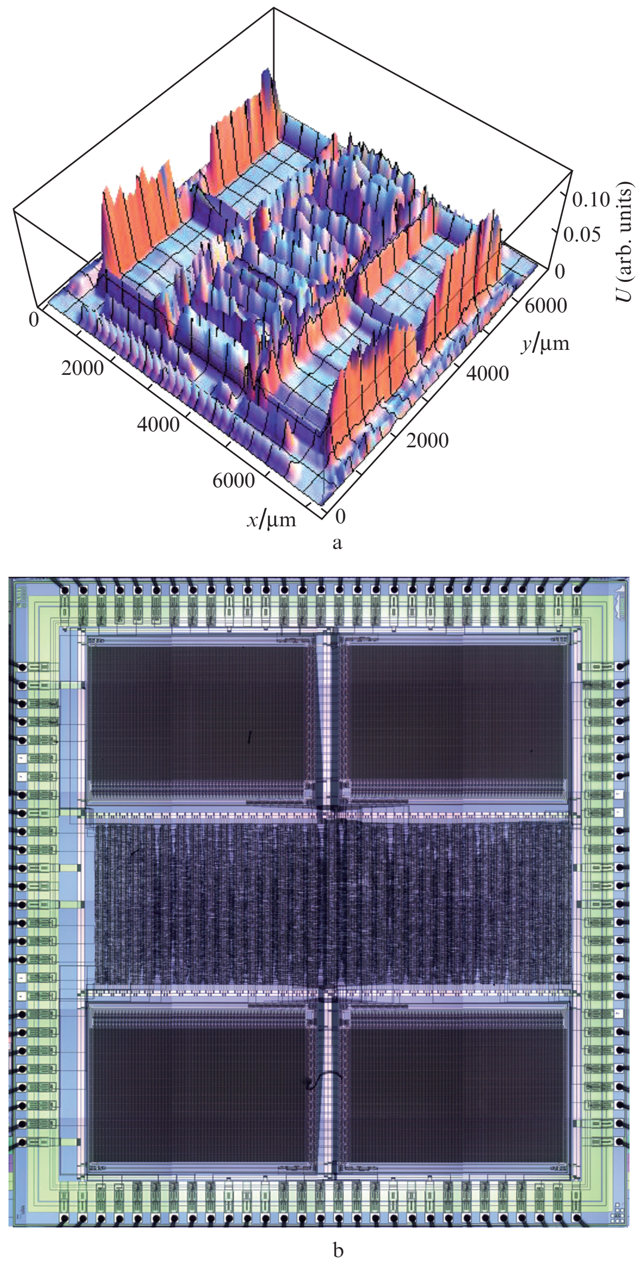

Figure 2. (a) IRS map of the IC irradiated from the working side and (b) a panoramic photograph of the same IC, obtained on the same system.

By analogy with the laser failure-detection methods [9], IRS maps can also be used to study specific microregions in order to gain additional information about the IC topological features, which affect the energy thresholds of effects in the vicinity of specific point. These measurements often revealed a correlation between the energy thresholds of effects and the IRS amplitude in specific IC regions.

In some experiments it would be enough to obtain high-resolution maps for small regions (micromaps). Our measurements yielded such IRS micromaps for ICs of the same type and with the same level of SEE hardness. Moreover, the differences in the IRS maps for ICs that are considered to be from the same batch give grounds to expect that a specific IC has some local defect or belongs to another batch.

Based on these observations, we proposed an express technique for rejecting ICs, which is expected to reduce significantly the testing time for large IC batches. It is based on the suggestion that the parameters of sensitivity to heavy-ion-induced SEEs for ICs from the same batch are identical if the IRS amplitudes for selected regions of these ICs are equal. Potentially, this technique may reduce the testing time of one IC batch by a factor of more than 10.

4. Express technique for rejecting ICs

This technique includes the following stages.

(1) Several ICs from a batch are scanned, and the regions sensitive to SEE-caused upsets are determined. When there are several such regions, three or four of them are chosen (with different unit-packing densities, if possible). The coordinates of the point intended for monitoring the IRS pulse amplitude are set for each chosen region.

(2) To obtain micromaps of the vicinities of the chosen points in a specific sample, square areas, centred at the chosen points and having a side of ~10 μm, are sequentially scanned. The diameter of the focused laser beam is chosen to be 10–15 μm; the scanning step is 1–3 μm. The IRS amplitude, averaged over several laser pulses (to reduce the error to a level of 2% or lower), was recorded at each scanning point and stored in the micromap data array.

(3) Stage 2 is repeated for all ICs from the tested batch according to the unified template of square areas around chosen points.

(4) According to the results of mathematical processing of the data array for IRS micromaps (see below), the coordinates of the chosen points to which the IRS amplitude correspond are corrected for each sample from the batch. The spread of values at each isolated point over all samples of the batch is determined.

(5) If the difference between the IRS amplitudes for the samples and the average value does not exceed some specified value (for example, 10%), it is assumed that that all ICs of the batch have identical sensitivity parameters to specific SEEs.

In the aforementioned difference for some samples is larger, the sensitivity parameters of these samples are considered as differing from the corresponding parameters of the other samples of the batch; these samples must be subjected to additional analysis.

The coordinates of chosen points (stage 4) must be corrected for the following reason. Manual fixing of samples and technological tolerances for their location in the housing do not allow one to perform measurements exactly at the same chosen point for each subsequent sample from the batch. Therefore, we developed an additional technique for correcting coordinates, which made it possible to reduce significantly the measurement error related to the positioning error. To this end, the IRS was recorded not at an individual point but within some microregion in its vicinity. Note that this technique is a mathematical procedure and does not require additional time for repeated scannings. The correction principle is similar to the well-known approach applied to create a large panoramic picture by stitching small images. The micromap of one of the samples is considered as a basic one, and the values of coordinate shift and rotation providing the best partial coincidence of maps are chosen for each next sample. This procedure is repeated for each sample with respect to the basic one. The intersection regions, as well as rotation and shift coefficients, are remembered for each sample. Then mathematical correction of coordinates is performed, and the IRS amplitude and its spread are found at the point belonging to all intersection regions.

The efficiency of coordinate correction technique was verified in the following way: one of the samples was multiply reinstalled and micromaps were recorded at a chosen point. After the correction the spread of IRS amplitudes was reduced to 5%. We also estimated the statistical dispersion, observed under conditions of multiply repeated scanning without reinstalling a fixed sample. It was found to be ~4%; apparently, it is due to the laser energy instability and mechanical precision of the system positioning.

5. Experimental results

The above-described technique was approved on two samplings from test batches (12 samples in each). The samples from batch I were fast CMOS logic structures: four 2-to-1 selectors–multiplexers with three states at the output. This batch was tested for single event upsets (transients). The criterion for sensitivity to this SEE type was considered to be the achievement of certain critical values of voltage pulse amplitudes at the outputs, caused by these transients.

The samples from batch II were test structures in the form of parallel I/O octal registers. In these samples, we investigated single malfunctions leading to switching logical states of register triggers.

To estimate the parameters of IC SEE sensitivity to heavy ions in tests with ion sources, it is generally used to present measurement results in the form of a dependence of the SEE cross section on the linear energy transfer (LET) of the ion striking the IC semiconductor material. It is also convenient to present the results of laser tests as a dependence of the SEE cross section on the laser pulse energy (Fig. 3), which is proportional to the ion LET [2]. To this end, the entire surface of the IC crystal is successively scanned by laser pulses with different fixed energies. Each point in the dependence $\sigma(J)$ corresponds to the ratio of the number of IC points where the SEE upset occurred to the total number of pulses multiplied by the scanning area. A similar procedure with a successive decrease in energy was performed when searching for IC sensitive regions.

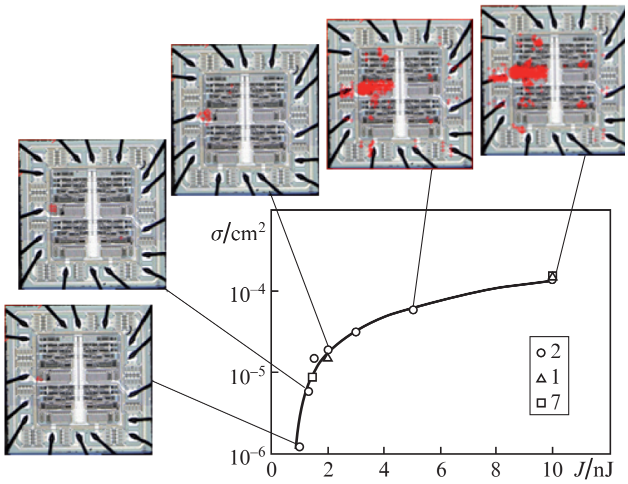

Figure 3. Dependence of the cross section of single event upsets, σ, on the laser energy J for the basic sample (2) and two other samples from batch I (1 and 7).

Four regions were chosen in an IC from batch I (Fig. 4). The cross hairs of the cross-shaped mark with an external circle radius of 20 μm indicates the position of the laser beam (10 μm in diameter) at the centre of the region under study. The range within which the dependence of the IRS amplitude on the laser energy is linear was previously determined for each chosen point in the basic sample. Then all scannings of point surroundings were performed at fixed energy values from the linearity range.

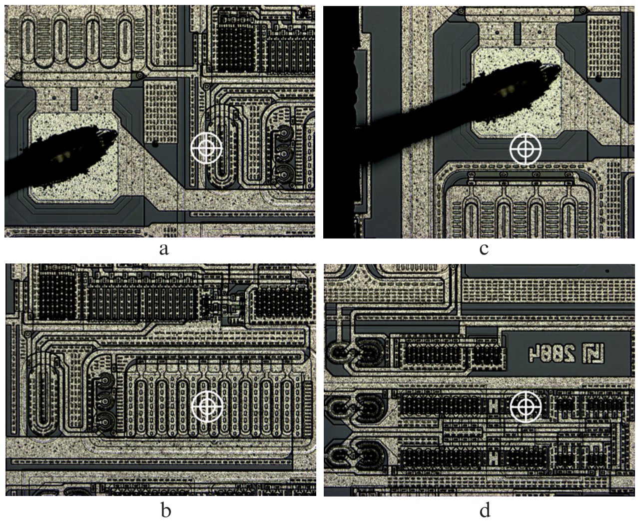

Figure 4. Photographs of the surroundings of chosen points on a sample from batch I. The cross hairs of the cross-shaped mark indicates the laser beam position (10 μm in diameter) at the chosen point.

Figure 5 shows the results of scanning the first region before and after mathematical correction of coordinates. Note that the IRS pulse amplitudes measured before the coordinate correction at the point differ by more than 50%. However, correction significantly reduces the amplitude

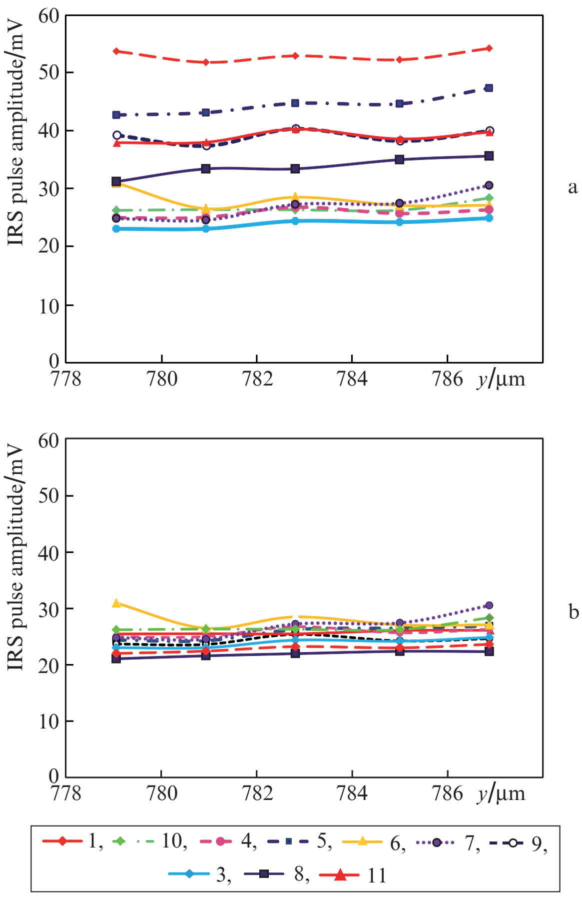

Figure 5. Dependences of the IRS pulse amplitudes on a shift over coordinate y from the check point (a) before and (b) after coordinate correction for a sample from batch I. The error of the averaged IRS pulse amplitude at each point does not exceed 2%.

spread. Measurements showed that the spread of IRS amplitudes for the samples selected from a batch of 12 ICs does not exceed 10%. Hence, one might expect these ICs to belong to the same group with respect to the SEE hardness.

To verify this suggestion, we performed additional complete scannings of all samples at two laser pulse energies: a minimum energy leading to single event upsets and an energy close to the plateau in the dependence $\sigma(J)$. Each point presented in Fig. 3 is the result of scanning the entire IC crystal at certain energy. It can be seen that all pairs of points are in good agreement with the dependence of the cross section of upsets on the laser energy for the basic sample.

Similar measurements at three sensitive points were performed for samples from batch II. Figure 6 shows dependences of IRS pulse amplitudes on the shift in coordinate x from the check point after coordinate correction for some samples. An interesting feature of these results is that the IRS pulse amplitudes for samples 9 and 2 differ from the pulse amplitudes for other samples from the batch by about 40% at all three chosen points. The results of complete scanning of all ICs from the batch showed (Fig. 7) that the SEE cross sections for the aforementioned samples also significantly (by more than 70%) differ from the cross sections of other samples of the batch at the same laser pulse energies; therefore, all parameters of SEE sensitivity with respect to heavy ions for the selected samples differ from the corresponding parameters for the other samples from batch II. An additional analy-

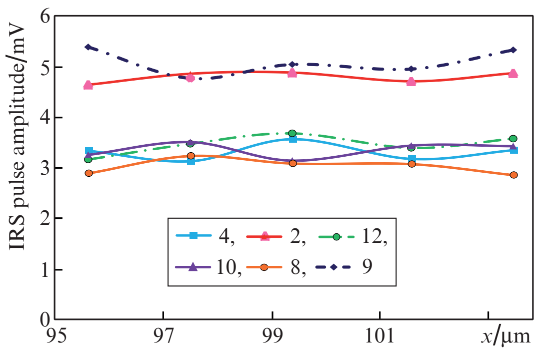

Figure 6. Dependences of the IRS pulse amplitudes on a shift over coordinate x for samples from batch II. The error of the averaged IRS pulse amplitude at each point does not exceed 2%.

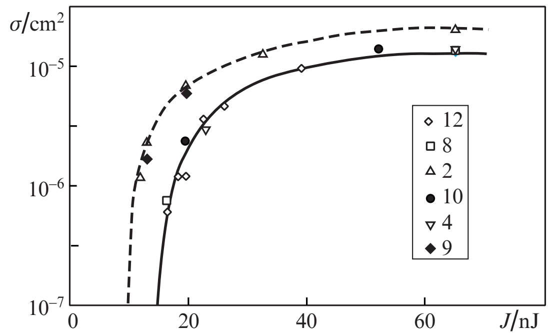

Figure 7. Dependences of the cross section of single event upsets, σ, on the laser energy J for samples from batch II.

sis of samples 2 and 9 on the presence of defects or deviations in the batch production must be performed to explain these differences. Nevertheless, we have grounds to state that the proposed technique can be used to reveal individual ICs in the batches with differing levels of SEE hardness.

Thus, the proposed express rejection technique was experimentally verified on small batches of different-type ICs. The approval result can be considered as positive. However, confident application of this technique calls for confirmation of the obtained result on other IC types. The experiment reported in this paper can be considered as a step in the way to improve the methods of large-scale laser tests of ICs and semiconductor devices on their basis.

Acknowledgements. This work was supported by Government Contract No. 1540.2014/K of the Ministry of Education and Science of the Russian Federation.

References

1. Buchner S.P., Wilson D., Kang K., Gill D., Mazer J.A. *IEEE Trans. Nucl. Sci.*, **34** (4), 1228 (1987).
2. Chumakov A.I. *Deistvie kosmicheskoi radiatsii na integral'nyee skhemy* (Effect of Space Radiation on Integrated Circuits) (Moscow: Radio i Svyaz', 2004).
3. Buchner S.P., Miller F., Pouget V., McMorrow D.P. *IEEE Trans. Nucl. Sci.*, **60** (3), 1852 (2013).
4. Chumakov A.I., Vasil'ev A.L., Kozlov A.A., Kol'tsov D.O., Krinitskii A.V., Pechenkin A.A., Tararaksin A.S., Yanenko A.V. *Mikroelektronika*, **39** (2), 85 (2010).

5. Yanenko A.V., Chumakov A.I., Pechenkin A.A., Savchenkov D.V., et al. *Spetstekhnika i Svyaz'*, **4–5**, 4 (2011).
6. Egorov A.N., Mavritskii O.B., Chumakov A.I., Nikiforov A.Yu., Telets V.A., Pechenkin A.A., Yanenko A.V., Kol'tsov D.O., Savchenkov D.V. *Spetstekhnika i Svyaz'*, **4–5**, 8 (2011).
7. Chumakov A.I. *Mikroelektronika*, **35** (3), 184 (2006).
8. Gordienko A.V., Mavritskii O.B., Egorov A.N., Pechchnkin A.A., Savchenkov D.V. *Sb. nauch. tr. Nauchno-tekhnicheskoi konferentsii-seminara 'Fotonika i informatsionnaya optika – 2013'* (Proc. Sci.–Tech. Conference–Seminar 'Photonics and Information Optics – 2013') (Moscow: NIYaU MIFI, 2013) p. 207.
9. Essely F., Guitard N., Darracq F., Pouget V., Bafleur M., Perdu P., Touboul A., Lewis D. *IEEE Trans. Device Materi. Reliability*, **7** (4), 617 (2007).