ISSN 1063-7397, Russian Microelectronics, 2011, Vol. 40, No. 3, pp. 149–155. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © A.I. Chumakov, 2011, published in Mikroelektronika, 2011, Vol. 40, No. 3, pp. 163–169

RESISTANCE OF MICROELECTRONIC DEVICES TO THE EFFECT OF SEPARATE NUCLEAR PARTICLES

Interrelation of Equivalent Values for Linear Energy Transfer of Heavy Charged Particles and the Energy of Focused Laser Radiation

A. I. Chumakov

National Research Nuclear University MEPhI, Kashirskoe sh. 31, Moscow, 125080 Russia

OAO ENPO Specialized Electronic Systems, Kashirskoe sh. 31, Moscow, 115409 Russia

e-mail: Aichum@spels.ru

Received August 3, 2010

Abstract—The estimations of equivalent values for linear energy transfer of heavy charged particles based on the results of experimental investigations of sensitivity of LSICs to local radiation effects with the use of the procedure of local laser irradiation are presented. The possibility of recalculation of the energy of laser radiation into equivalent values of linear energy transfer with the use of the measurements of the ionization reaction in the supply circuit of LSIC is substantiated. Uncertainties caused by the characteristics of the interaction of optical radiation with semiconductor structures are eliminated in the suggested procedure.

DOI: 10.1134/S1063739711030036

1. INTRODUCITON

The wide use of modern microelectronic devices in the electron equipment of spacecrafts makes the problem of evaluating their sensitivity to the effects of the influence of single charged particles (SCPs) from low-intense flows of high-energy protons and heavy charged particles very actual [1–4]. The appearance of local radiation effects such as failures and faults, despite their low probability under space environment, in some cases nevertheless leads to functional faults in the operation of a spacecraft.

As a rule, a minimal set of sensitivity parameters for each type of the local radiation effect in a large integrated circuit (LSI) involves such parameters as the saturation section and threshold values of linear energy losses (LET). Conventional methods of the evaluation of sensitivity parameters are based on tests with the use of ion or proton accelerators [4, 5]. However, these methods are laborious and expensive, and do not allow one to purposefully investigate separate LSI fragments by virtue of the stochastic nature of the interaction of the ionizing radiation with the substance.

The methods based on the use of focused laser radiation are alternative means [6–8]. To a first approximation, an equivalent LET value not taking into account the effects of two-phonon absorption can be evaluated as follows [4]:

$$L_z \approx \alpha_0 (1 - R_\lambda) \frac{J_{\mathrm{lr}}}{K_m} \frac{\varepsilon_i}{h\nu} \frac{1}{\rho} = \frac{K_\lambda}{K_m} J_{\mathrm{lr}}, \quad (1)$$

where α_0 is the coefficient of the band-to-band absorption of laser radiation; J_{lr} is the energy of laser radiation; R_λ is the reflectance from the IC surface; K_m is the coefficient of losses of laser radiation on optical nonuniformities (layers of metallization and polysilicon), ρ is the semiconductor density; ε_i is the energy of the formation of one electron–hole pair (3.6 eV is silicon); $h\nu$ is the photon energy of the laser radiation; and K_λ is the proportionality coefficient between LET and energy of laser radiation, which in general depends on the wavelength of laser radiation and parameters of the semiconductor structure.

The application of the methods based on the use of focused laser radiation has substantial limitations for LSIs because they have multilayered metallization, which covers a considerable part of the crystal surface. There is a relatively high probability of “blanks” of laser radiation, when optical radiation is almost completely absorbed/reflected in protective oxide and metallization layers. In this case, the procedure of a local laser effect is more effective [8].

The procedure of applying the local laser radiation is based on scanning the whole surface of the LSI crystal and counting the total amount of occurring local radiation effects N_{lz}. Due to a wider optical spot, it is

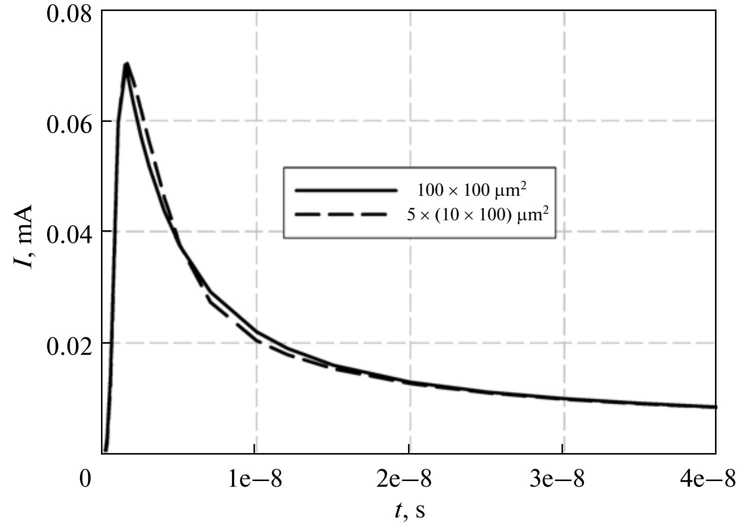

Fig. 1. Ionization current in a separate *p*–*n* junction and in the structure with five *p*–*n* junctions uniformly arranged on the crystal surface under the effect of the pulse of the ionizing radiation 70 ps wide.

possible to integrate optical inhomogeneities and to use any averaged coefficient of optical losses. By the experimental results, we can determine equivalent linear energy losses (LET) L_z and cross sections of the observed effects σ_{lz} from the following relations:

$$L_z \approx K_\lambda J_{\text{li\_l}}/K_m, \quad (2)$$

$$\sigma_{ez} = A_{is} N_{ez}/N_l, \quad (3)$$

where $J_{\text{li\_l}}$ is the energy of laser radiation reduced to the focused value, A_{is} is the area of the LSI crystal, and N_l is the total number of pulses of laser radiation during scanning the whole surface of the LSI crystal. Thus, the necessary condition for the evaluation of equivalent LSI values is the determination of the coefficient of optical losses K_m.

2. INTEGRATED REACTION OF SEMICONDUCTOR LSIs

The procedure of the local laser effect is more effective in studying the sensitivity of the LSI with multilayered metallization compared with the procedure of focused radiation because it ensures a more correct evaluation of radiation losses at various optical inhomogeneities, particularly, metallization and polysilicon layers. During the local irradiation, due to repeated reflection, diffraction, etc; optical radiation still partially reaches active semiconductor structures forming the ionization reaction. However, the actual semiconductor structure of the LSI consists of multitude *p*–*n* junctions, which leads to the formation of a complex distribution of currents and potentials inside the structure, which does not correlate very strongly with the actual physical pattern that occurs in the presence of the ionization path. Nevertheless, if we consider a summary ionization reaction in the supply circuit, we can assume that it will be formed in the LSI in the form of an integrated reaction as if one large *p*–*n* junction is irradiated [9].

In order to verify this assumption, we numerically modeled the formation of the ionization reaction under the irradiation of a multitude of *p*–*n* junctions arranged at different distances from one another. At the first stage, we evaluated the variations in the ionization reaction in a semiconductor structure 100 × 100 × 300 μm³ in size in the presence of one large transition and several *p*–*n* junctions uniformly distributed over the crystal surface. Simulation was performed under the effect of the pulses of ionizing radiation at different distances between the *p*–*n* junctions.

The performed analysis revealed that right up to distances between the junctions of about 10 μm, no noticeable distinctions is observed in the reaction of the structure. The results of modeling the ionization current under the effect of the pulse of ionizing radiation 70 ps long for a separate *p*–*n* junction with an area of 100 × 100 μm² and five *p*–*n* junctions 100 μm in length and 10 μm wide, with distances between them also of 10 μm, are shown in Fig. 1. We can see that both these reaction almost coincide with each other. There are small distinctions only in the initial point of time (at times less than 1 ns). However, this portion exerts no substantial influence on the conditions of the formation of failures and faults in the LSI because the ionization current is integrated during the formation of the ionization reaction of a separate element in this range of time intervals.

The influence of distancing *p*–*n* junctions from one another on the parameters of the ionization reaction can be roughly evaluated based on the introduction of the effective collection length of minority carriers L_d

$$L_d \approx \sqrt{D_d \tau_d}, \quad (4)$$

where D_d is the diffusivity of minority carriers and τ_d is the effective collection time of the carriers by the junction due to the diffusion processes. It follows from the results presented in Fig. 1 that as τ_d, we can accept the value of 1 ns, at which the effective length is larger than 2 μm. Taking into account the presence of neighboring *p–n* junctions, we obtain the absence of a noticeable influence between neighboring junctions at distances up to 4 μm. It is absolutely evident that these distances are substantially smaller for modern submicron LSI.

It should be also noted that the conditions of switching the LSI elements under the effect of separate charged particles are determined by the attainment of the voltage pulse of a certain critical value rather than by the equivalency of the parameters of the characteristics of ionization current pulses. Therefore, in the region of small times, the current is integrated at internal and external LSI capacitors, due to which the processes of the formation of the ionization reaction are leveled.

A second possible cause of distinctions in the character of the ionization reaction is caused by possible nonuniformities of the bulk ionization of the semiconductor structure due to the shadow effects induced by the ionization strips. The influence of this nonuniformity also manifests itself at large values of effective length (1). Previous investigations of the adequacy of laser imitation methods [10] studied this problem in more detail and revealed that the problem is formally reduced to the introduction of the coefficient of losses of optical radiation because of the presence of shades under the metallization layers.

An important result, obtained through computational modeling, is associated with the independence of the characteristics of the integrated ionization reaction of the LSI on the local irradiation area under the condition that the nonlinear effects caused by both the absorption of optical radiation in materials and the nonlinear ionization effects are absent.

The results were confirmed in investigations when the surface of crystals of various LSIs was scanned by a pulse beam with a diameter of 1 mm. No noticeable distinctions in the character of the ionization reaction upon varying the diameter of the region of influence and depending on the arrangement on the LSI crystal were found. It is evident that this result is valid only for LSIs with approximately uniform elements fulfilled by submicron technology. In the presence of nonuniformity elements occupying a considerable area, for example, capacitors and powerful output transistors, the character of the ionization reaction can vary in these regions.

3. EVALUATION BY THE REACTION IN THE SUPPLY CIRCUIT

The above-presented results allow us to use the assumption of independence of the ionization reaction in the supply circuit on the arrangement of the irradiation zone when evaluating the coefficient of optical losses. In this case, we can evaluate the coefficient of losses of laser radiation K_m from the comparison of the calculated and experimental amplitude–temporal characteristics of the ionization reaction in the supply circuit under the local irradiation of a part of the LSI crystal. In the linear approximation, the current in the supply circuit is determined by charge collection from the substrate, and its amplitude–temporal characteristics under the local effect of the laser pulse are almost independent on the diameter of the spot:

$$\Delta I(t) \approx q g_o (1 - R_\lambda) \frac{J_u}{T_p} \frac{\alpha_0}{K'_m} \frac{\varepsilon_i}{h\nu} \frac{10^{-2}}{10^{-7}\rho} L(t), \quad (5)$$

where ΔI is the ionization current in the supply circuit, g_o is the generation rate of carriers in silicon, T_p is the duration of the pulse of the laser radiation, J_u is the energy of laser radiation, K'_m is the coefficient of losses of laser radiation on optical inhomogeneities upon measuring the ionization reaction in the supply circuit, $L(t)$ is the effective length of carrier collection from the substrate, and t is the current time.

Under the local effect of the pulse of laser radiation less than 100 ps wide on the surface of the LSI RAM crystal, relation (5) is transformed to form [8]:

$$\Delta I(t) \approx 10^5 q g_o (1 - R_\lambda) \frac{J_u}{T_p} \frac{\alpha_0}{K'_m} \frac{\varepsilon_i}{h\nu} \frac{1}{\rho} \left[\frac{\exp(-t/\tau) \cdot T_p}{\sqrt{\pi t / D_d}} + f(t) W_{pn} \right], \quad (6)$$

where τ is the lifetime of nonequilibrium charge carriers, W_{pn} is the width of the depleted region of the p–n junction in the substrate, D_d is the diffusivity of minority carriers in the substrate, and $f(t)$ is the normalized form of the laser radiation pulse.

Due to the integration on the internal and external IC reactive elements, the form of the ionization reaction on a current-collecting resistor can be evaluated from the relation

$$\Delta U(t) \approx \frac{R_t}{R_{in} + R_t} \frac{\exp(-t/RC)}{C} \int_0^t \exp(x/RC) \Delta I(x) dx, \tag{7}$$

where R_t is the value of the current-collecting resistor, R_{in} is the value of the equivalent IC internal resistance, $C = C_{in} + C_l$ is the summary IC capacitance and measuring set (external circuits), C_{in} is the value of the equivalent internal IC capacitance, C_l is the equivalent capacitance of the external measuring circuits, and $RC = (R_{in} + R_t)$, C is the equivalent time constant. It should be noted that the value of C_{in} in modern LSIs can be several nF; therefore, its influence cannot be neglected.

Taking into account relations (5)–(7), evaluation of the ionization reaction can be presented as follows:

$$\Delta U(t) \approx 10^5 q g_o (1 - R_\lambda) \frac{R_t}{R_{in} + R_t} \frac{J_u}{C} \frac{\alpha_0}{K'_m} \frac{\varepsilon_i}{h\nu} \frac{1}{\rho} L_e(t), \tag{8}$$

where $L_e(t)$ is the effective collection length of charge carriers determined allowing for the integration of the ionization current on internal and external reactive elements:

$$L_e(t) \approx \frac{\exp(-t/RC)}{T_p} \int_0^t \left[\frac{\exp(-t/\tau) \cdot T_p}{\sqrt{\pi x / D_d}} + f(x) W_{pn} \right] \exp(x/RC) dx. \tag{9}$$

The results of modeling the variation in the effective carrier collection length in time for a p-type substrate with a doping level of 1.5×10^{15} cm^{-3}, minority carrier lifetime of 2 μs, and external voltage at the p–n junction of 0 under the effect of an ionizing radiation pulse with the effective duration of 70 ps are presented in Fig. 2 as an example. The results of modeling show that the amplitude–temporal characteristics are largely determined by parameters of the equivalent RC circuit; at identical values of the time constant, the shapes of pulses do not vary from one another.

Thus, we can evaluate a series of necessary parameters from the analysis of the ionization reaction. For example, carrying out the measurements of the ionization reaction of the LSI under local laser irradiation and various external elements R_t and C_l, we can determine the internal equivalent capacitance and resistor from the pulse duration (Fig. 3) and thereby carry out the computational evaluation of $\Delta U(t)$.

The acquired results in turn allow us to determine the maximal value of the effective collection length of the charge from the substrate $L_{e\_\max}$ (Fig. 4). Based on the obtained parameters, from a comparison of the computed and experimental amplitudes of the ionization reaction in the supply circuit, we can evaluate the coefficient of optical losses K'_m. As it follows from the dependences presented in Fig. 4, uncertainty in the substrate type can give a considerable error in the value of K'_m, although for most of modern submicron LSI, the p-type substrate is used. In the case of the absence of the data on the type of the used substrate, it is recommended to apply the average value, at which the error of evaluations can be about 30% (Fig. 4, the dash-and-dotted line).

The results of the computational–experimental simulation allow us to evaluate the equivalent values of LET using the following relation:

$$L_z = \frac{J_{\text{li}}}{J_{\text{i}}} \frac{\Delta U_{\max}}{L_{e\_\max}} \left(1 + \frac{R_{in}}{R_t}\right) \frac{C}{10^5 q g_o} \frac{K'_m}{K_m} \approx 9.1 \times 10^9 \frac{J_{\text{li}}}{J_{\text{i}}} \frac{C \Delta U_{\max}}{L_{e\_\max}} \left(1 + \frac{R_{in}}{R_t}\right) \frac{K'_m}{K_m}, \ \left[\text{MeV cm}^2/\text{mg}\right]. \tag{10}$$

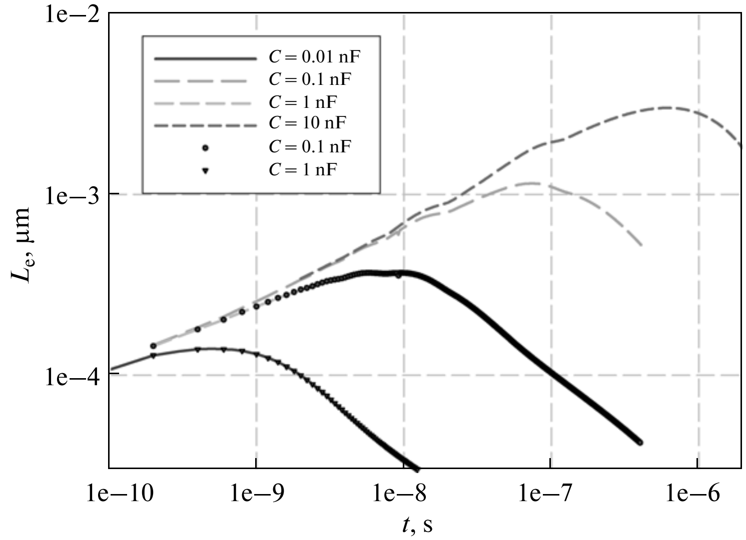

Fig. 2. Variation in the effective length in time for the semiconductor structure under the effect of the ionizing radiation pulse 70 ps wide and different values of C: curves $R = 100\ \Omega$, symbols $R = 10\ \Omega$.

Characteristic features of the presented relation should be noted. If we evaluate the equivalent values of LET by the procedure of local irradiation, then the values of K_m and K'_m are equal to each other. Moreover, the results of scanning the crystal surface show that for many submicron LSIs, variations in the coefficient of optical losses are insignificant, and they can be neglected. The second feature lies in the fact that the ratios of the energies of laser irradiation are in relation (10); therefore, the errors in determining the absorptance and reflectance do not affect the results of the evaluation of LET values. It is only important that the values of the absorption length of laser radiation should exceed the maximal value of the effective collection length of carriers.

Recently, the procedure of irradiation of LSIs from the back side has been actively used [6]. This makes it possible to eliminate one of the significant limitations of the use of laser methods associated with the influence of multilayered metallization. Not taking into account the optical effects leading to variations in the sizes of the local irradiation zone, radiation is partially absorbed in a silicon substrate in this case. Therefore, these losses and the possibility of the partial reflection of laser radiation from the upper surface of the LSI crystal should be taken into account in relations (1) and (5). Taking this fact into account, relations for the evaluation of equivalent values of LET and characteristics of the pulse of the ionization current upon the irradiation from the bottom side of the LSI crystal are transformed to the form

$$L_{zb} \approx \alpha_0 (1 - R_{\lambda b}) J_{\text{li}} \frac{\varepsilon_i}{h\nu} \frac{1}{\rho} [\exp(-\alpha W_s)(1 + R_{\lambda t})], \tag{11}$$

$$\Delta I_b(t) \approx q g_o (1 - R_{\lambda b}) \alpha_0 [\exp(-\alpha W_s)(1 + R_{\lambda t})] \frac{J_u}{T_p} \frac{\varepsilon_i}{h\nu} \frac{10^{-2}}{10^{-7}\rho} L(t), \tag{12}$$

where α is the coefficient of the losses of laser radiation in a silicon substrate with thickness W_s. It is evident that in this case the parameter equivalent to the coefficient of optical losses K_m is the quantity that characterizes partial losses of laser radiation in silicon substrate. Therefore, when carrying out the transformations similar to those mentioned above, we also obtain relation (10). From this viewpoint, the suggested procedure is insensitive to the procedure of irradiation of the LSI from the active or back side of the LSI crystal. An important limitation is only the necessity to provide a relatively uniform absorption of laser radiation in a sensitive region of the LSI, i.e., the fulfillment of condition

$$\alpha L_{e\_\max} < 1. \tag{13}$$

Taking into account that typical values of $L_{e\_\max}$ do not exceed 10 μm, it follows from relation (13) that the absorptance of laser radiation should not be larger than $\alpha > 10^3$ 1/cm. Thus, we obtain that this procedure can be effectively applied for using laser radiation with wavelengths from a range of 0.8–1.08 μm. In this case, when irradiating from the back side, in order to avoid

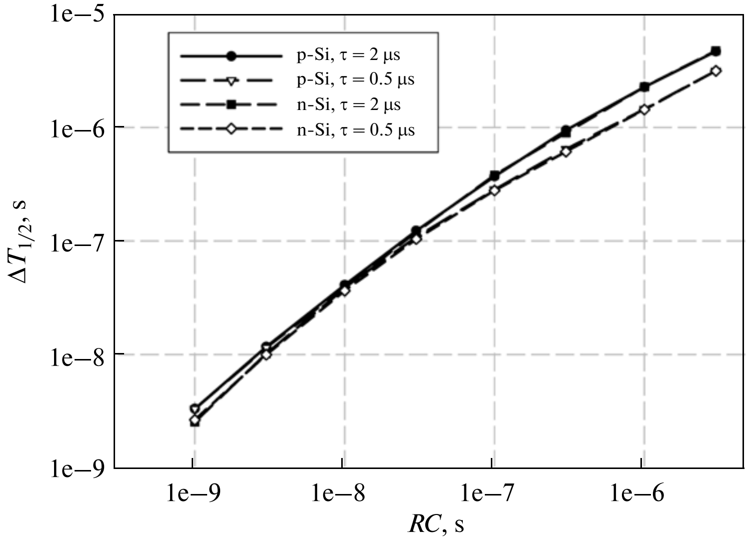

Fig. 3. Variations in the pulse width of the ionization reaction at a half-height in *n*-type and *p*-type substrates against the equivalent time constant *RC*.

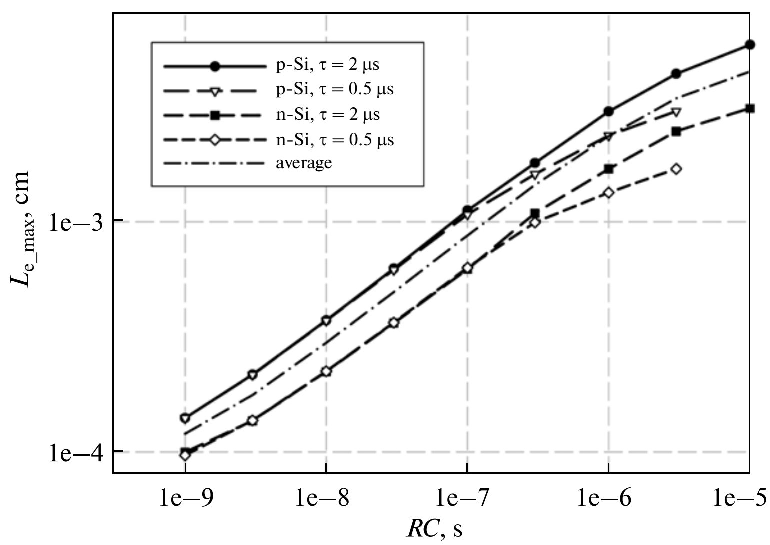

Fig. 4. Variations in the maximal collection length in *n*-type and *p*-type substrates against equivalent time constant *RC*.

the excessive energetics of laser radiation, it is useful to apply laser radiation with a wavelength of 0.95–1.08 μm.

Thus, the suggested procedure for determining equivalent values by the results of local laser radiation is reduced to the fulfillment of the following main operations:

(i) scanning of the LSI crystal by the procedure of local laser irradiation with the purpose of determining the sensitivity regions;

(ii) determination of threshold values of laser radiation reduced to the focused effect in sensitive regions [8, 11];

(iii) measurement of the ionization reaction in LSI regions under study under the local effect of laser radiation at several values of external resistors and/or capacitors in order to determine the equivalent of capacitances and resistances;

(iv) evaluation of the effective collection length by the results of measurements;

(v) evaluation of the value of LET from relation (10).

4. CONCLUSIONS

In this work, we substantiated the procedure of evaluation of equivalent values of linear energy losses by the results of irradiation of the LSI crystal by the local laser radiation. The procedure is based on the conversion of the energy of laser radiation into equivalent values of LET using the results of measurements of the ionization reaction in the supply circuit of the LSI. The uncertainties caused by the characteristics of the interaction of optical radiation with semiconductor structures are eliminated in the suggested procedure.

ACKNOWLEDGMENTS

I thank A.L. Vasil'ev, A.N. Egorov, A.A. Pechenkin, and A.V. Yanenko, collaborators of Specialized Electronic Systems, for their discussion and help in the experiments.

REFERENCES

1. Messenger, G.C. and Ash, M.S., *Single Event Phenomena*, New York: Chapman&Hall, 1997.
2. *The Radiation Design Handbook. European Space Agency* Noordwijk: ESTEC, 1993.
3. Pickel, C., Single Event Effects Rate Prediction, *IEEE Trans. Nucl. Sci.*, 1996, vol. 43, no. 2, pp. 483–495.
4. Chumakov, A.I., *Deistvie kosmicheskoi radiatsii na IS* (The Effect of Space Radiation on the ICs), Moscow: Radio i Svyaz', 2004.
5. Allen, G.R., *Compendium of Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory*, 2008 IEEE Radiation Effects Data Workshop Record.
6. Pouget, V., *Fundamentals of laser SEE testing and recent trends*, Suresnes: RALFDAY, 2009, EADS France, Suresnes, 11th September.
7. Jones, R. et al., Comparison Between SRAM SEE Cross-Section from Ion Beam Testing with Those Obtained Using a New Picosecond Pulsed Laser Facility, *IEEE Trans. Nucl. Sci.*, 2000, vol. NS-47, no. 4, pp. 539–544.
8. Chumakov, A.I., Egorov, A.N., Mavritskii, O.B., and Yanenko, A.V., Evaluation of Moderately Focused Laser Irradiation as a Method for Simulating Single-Event Effects, *Mikroelektronika*, 2004, vol. 33, no. 2, pp. 128–133 (*Russian Microelectron.* (Engl. Transl.), 2004, vol. 33, no. 2, pp. 106–110).
9. Chumakov, A.I., Modeling Rail-Span Collapse in ICs Exposed to a Single Radiation Pulse, *Mikroelektronika*, 2006, vol. 35, no. 3, pp. 184–190 (*Russian Microelectron.* (Engle. Transl.), 2006, vol. 35, no. 3, pp. 156–161).
10. Nikiforov, A.Yu. and Skorobogatov, P.K., Physical Principles of Laser Simulation for the Transient Radiation Response of Semiconductor Structures, Active Circuit Elements, and Circuits: A Linear Model, *Mikroelektronika*, 2004, vol. 33, no. 2, pp. 91–107 (*Russian Microelectron.* (Engl. Transl.), 2004, vol. 33, no. 2, pp. 68–79).
11. Chumakov, A.I., Pechenkin, A.A., Egorov, A.N., Mavritskii, O.B., Baranov, S.V., Vasil'ev, A.L., and Yanenko, A.V., Estimating IC Susceptibility to Single-Event Latchup, *Mikroelektronika*, 2008, vol. 37, no. 1, pp. 45–51 (*Russian Microelectron.* (Engl. Transl.), 2008, vol. 37, no. 1, pp. 41–46).