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RADIATION-EFFECT MODELING AND SIMULATION

Simulating Single-Event Effects Associated with High-Energy Neutrons for Different VLSI Technologies

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Abstract—A computer and a physical simulation are conducted of single-event effects associated with neutrons or protons of different energy for test VLSI circuits realized by modern technologies with a minimum feature size of 0.5 or 0.35 μm. The test specimens are found to be fairly susceptible to these effects. In particular, neutrons with an energy of order 1 MeV are shown to mainly cause single-event upsets with a threshold energy of about 1 MeV and a sensitive volume of order 1 μm^3. As the minimum feature size is reduced, the threshold is predicted to decrease sharply due to a growing amplifying effect of the parasitic bipolar transistor.

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INTRODUCTION

The ongoing reduction in circuit feature sizes is bound to lower the threshold energies of single-event effects associated with single nuclear particles, resulting in temporary or permanent failures of circuit elements [1–3]. For the last 25 years, the focus of hardness-assurance research concerning these phenomena has been on space environments [1–5]. However, single-event effects do occur near and on the ground as well, mainly due to neutrons being generated in the upper atmosphere [6, 7].

SINGLE-EVENT-EFFECT MECHANISMS

In very-large-scale-integration (VLSI) circuits, single-event effects arise due to a large energy deposition in the sensitive volume of a circuit element. Parameters of sensitive volume are determined by a type of single-event effects observed. For example, for single-event upset (SEU), this volume is determined by reverse-biased-drain-junction areas and adjacent base areas at distances no more than 3–7 μm at the expense of the electric field penetration effect into the track of nuclear particle [8]. The sensitive volume to the single-event latchup (SEL) is located near the well–substrate junction [9, 10].

A substantial neutron energy deposition in the sensitive volume occurs at the expense of secondary nuclear particles formed as a result of the elastic and inelastic scattering of the neutrons from the silicon atoms. An estimation of the energy deposition is made with the help of differential cross sections of scattering, the value of which is determined as a ratio of the particle number scattered in unit time within an infinitesimal solid angle to the flux of incident particles. One can suppose in most cases that the elastic scattering with energies less than a few megaelectronvolts occurs in compliance with the hard-sphere interaction law, which allows us to consider an isotropic distribution of the recoil nucleus relative to the center of mass. The concept of isotropic scattering of fast neutrons cannot be considered a precise one. In reality, neutrons with energies more than a few megaelectronvolts are scattered mostly forwards.

Similar energies occur at inelastic neutron scattering from the silicon atoms. The only distinction lies in the spectral characteristic of primarily knocked atom (PKA). If we neglect the possibility of a PKA excitation and suppose that the scattering is isotropic relative to the center of mass, the integral and differential spectra may be estimated analytically [1, 11].

Figure 1 shows, as an example, the energy deposition spectra for scattering of 14-MeV neutrons. It is evident that, at the expense of inelastic scattering mechanism, maximal energy does not exceed 1.9 MeV. If we take into account the nuclear reactions under neutron irradiation, the maximal energy deposition in the sensitive volume is increased almost twofold, but in the process the probability value of these events falls abruptly. Thus, one can say that, at the expense of the elastic and inelastic 14-MeV neutron scattering in active volumes of circuit elements, the effects with threshold energies below 1.9 MeV will occur (precisely, less than 1.65 MeV and 0.25 MeV regarding dose-rate effects and displacement damage, respectively). Taking into account a possibility of less probable nuclear reactions, this energy will be less than 3.5 MeV.

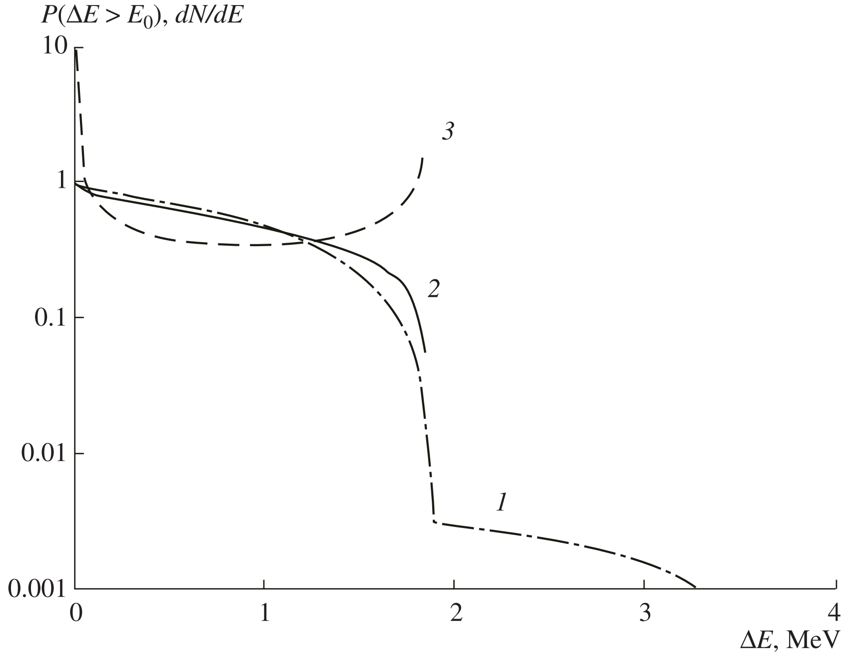

Fig. 1. Approximate energy-deposition spectra for 14-MeV neutron scattering from Si atoms: (*1*) total spectrum, (*2*) integrated spectrum at inelastic scattering, and (*3*) differential spectrum at inelastic scattering.

It is important to note that the spectrum estimations presented are for the energy deposition in relatively large volume, i.e., we assume that a heavy secondary particle has come into being in this volume and has lost all of her energy right there. It is evident that this is not quite correct since it is possible for both a secondary nuclear particle to be produced outside the sensitive volume and a secondary particle to partially leave the sensitive volume. Therefore, when elaborating the models of single-event effects, it is necessary to take into consideration the influence of geometrical factors and of materials surrounding the sensitive volume.

When estimating the single-event effects in VLSI elements, one can use, in most practical cases, a charge (energetic) model of single-event effects that arise. In such approximation a cross section of single-event effect, for example, the cross section σ_{SEU_n} of SEUs arising from the neutrons action, may be written in the following way:

$$\sigma_{SEU\_n} \approx V_a N_0 \sum_i \sigma_{n\_i} \mathrm{f}(\Delta E_i > E_o) = \sigma_{SEU\_p\_sat} \frac{\sigma_{tot\_n}}{\sigma_{tot\_p}} \sum_i \frac{\sigma_{n\_i}}{\sigma_{tot\_n}} \mathrm{f}(\Delta E_i > E_o), \quad (1)$$

where σ_{n_i} is the partial cross section for the *i*th neutron-scattering mechanism on silicon atoms, $f(\Delta E_i > E_o)$ is the probability of energy deposition in the sensitive volume from secondary particles above the threshold value E_o; σ_{tot_p} is the total cross section of nuclear reactions from the protons in silicon ($\sigma_{tot\_p} \approx 400$ mb), σ_{tot_n} is the total cross section of neutron–silicon interaction ($\sigma_{tot\_n} \approx 1.8$ b for 14-MeV neutrons), N_0 is the concentration of atoms in 1 cm^3 (for silicon, $N_0 = 5 \times 10^{22}$ cm^{-3}), V_a is the sensitive volume, and $\sigma_{SEU\_p\_sat}$ is the saturation cross section for SEUs under protons action.

In the limits of a simplest model, under influence of protons with relatively high energies, practically all heavy secondary nuclear particles that arise within the sensitive volume V_a cause temporary failures. Thus, one can write

$$\sigma_{SEU\_p\_sat} \approx \sigma_{tot\_p} V_a N_0. \quad (2)$$

EXPERIMENTAL

Table 1 shows basic characteristics of similar VLSI test circuits of domestic or foreign production by different technologies. Only the cache memory region was tested.

In the experiments, we counted SEUs and stuck-at bits in the cache memory and circuit malfunctions, and also checked the circuits for SELs. SEUs and stuck-at bits were detected by a specialized algorithmic functional test (AFT). In the AFT process, the test pattern 55555555h (checkerboard pattern) was written to the cache memory before cyclic readout, checking, and transmitting the result through an RS232 output. Nor-

Table 1. Basic characteristics of the test VLSI specimens

Parameter	Microprocessor				
	Type 1	Type 2	Type 3	Type 4	Type 5
Supply voltage, V	3.3	3.3	3.3	3.3	3.3
Cache memory	$1K \times 128$	$1K \times 128$	$1K \times 128$	$1K \times 128$	$1K \times 128$
Clock rate, MHz	33.0	33.0	33.0	82.5	82.5
Technology	Bulk, 0.5 μm	Bulk, 0.5 μm	SOI	Bulk, 0.35 μm	Bulk, 0.35 μm

mally, information about normal test fulfillment, absence of temporary failures, and the test time are transmitted. In the case of an SEU (readout information is not in compliance with the preliminary written one), the transmission was made through RS232 and recording of information as for the test number, initial and readout information, defective cell number, and the test time. Then, the second writing and second readout are made for checking for permanent failures (stuck-at bits). When the number of temporary failures exceeds 50, the inverse pattern, AAAAAAAAh, was written to the cache memory, and the testing was continued.

The sensitivity parameter (single-event-effect cross section σ_{le}) was determined by the relation

$$\sigma_{le} = N_{le}/\Phi; \quad (3)$$

where N_{le} is the number of single-event effects detected (temporary failures, functional failures, permanent failures, and SELs) under proton or neutron irradiation with total fluence Φ.

Experimental investigations were made on a proton synchrotron at energies in the range 180–1000 MeV, and also on 14-MeV neutron generator and on a Pu(Be) isotopic neutron source. Protons were used for the reason that substantial energy deposition in sensitive volumes from protons and neutrons at energies above 50–70 MeV are practically equivalent [11].

Permanent failures or functional failures were not observed in the course of the experimental investigations. The experimental results of the estimation of VLSI sensitivity to SEUs are summarized in Table 2.

Analysis of experimental results allows us to confirm the basic statements as for the models of single-event effects, namely, statistical character arising of the events and their mutual independence. Statistical character of SEUs appears most evidently through the distribution of SEU addresses and over data bits (Figs. 2, 3). Mutual independence appears most clearly through the experimental dependence of the SEU accumulation in time.

ESTIMATION OF PHYSICAL SENSITIVITY PARAMETERS

Experimental results presented allow us to apply Eq. (2) to the sensitive volume on the assumption that the effect of high-energy protons under inelastic scattering leads to formation of heavy secondary nuclear particles whose energy exceeds the threshold value.

Majority of the estimations presented correspond to the physical representations to the effect that, as the topology design standards are reduced, the sensitivity region value is also reduced. A sufficiently evident result was obtained that the least sensitivity volume occurs for the specimens produced by SOI technology. Increase of the sensitivity volume with the energy growth is explained by approximations used, in which a possibility of heavy nuclear particles forming outside the sensitive volume is not taken into consideration (Table 3).

At the same time, relatively unexpected results have been obtained at the proton energies 250 MeV and

Table 2. Experimental values of SEU cross section for the test VLSI specimens

Type	SEU cross section, cm^2					
	protons				neutrons	
	180 MeV	225 MeV	250 MeV	1 GeV	14 MeV	Pu(Be)
Type 1	7.5×10^{-9}	6.8×10^{-9}	2.2×10^{-9}	2.3×10^{-8}	6×10^{-9}	5.2×10^{-11}
Type 2	6.1×10^{-9}	–	–	–	6.3×10^{-9}	1.2×10^{-10}
Type 3	1.3×10^{-9}	1.2×10^{-9}	1.9×10^{-9}	5.0×10^{-9}	3.3×10^{-9}	2.1×10^{-10}
Type 4	3.5×10^{-9}	3.5×10^{-9}	5.4×10^{-9}	1.0×10^{-8}	5.1×10^{-9}	4.2×10^{-10}
Type 5	4.0×10^{-9}	–	–	–	6.2×10^{-9}	5.8×10^{-10}

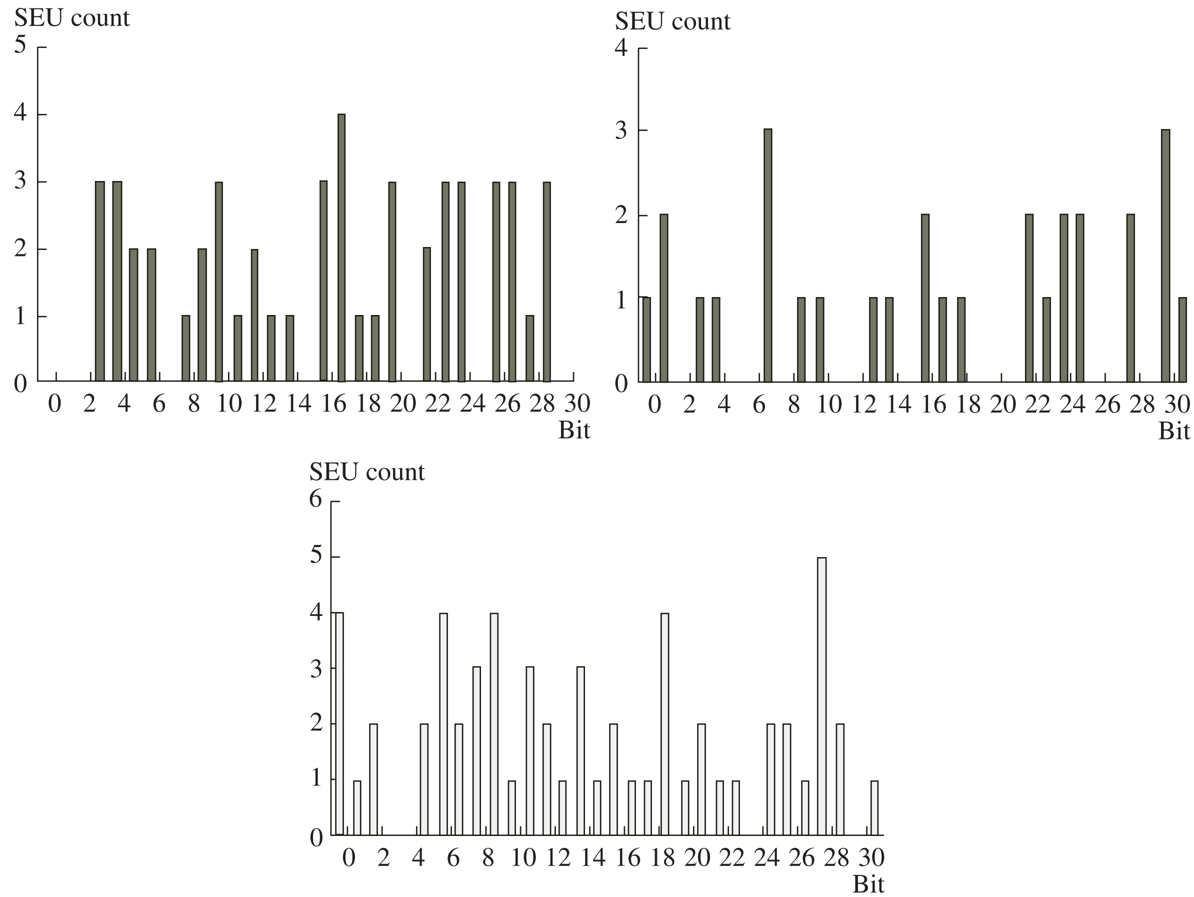

Fig. 2. SEU distribution over the bits for three sample ICs of type 1.

1 GeV. Most likely, this fact is explained by a small statistic and by possible missing of the proton beam at the energy 250 MeV (investigations were made with one specimen only).

For comparison, the estimations of the sensitive region parameters were carried out on the basis of topology analysis. The estimation data are presented in Table 4. It was supposed in the calculations that the sensitive region thickness was of order 0.5 μm (this value corresponds approximately to the depletion-region thickness of a reverse-biased drain junction), and the channel makes a half contribution to the saturation-section region (the second half belongs to collection of carriers by source junction). Thus, the two sensitive volumes should be about 4 and 1.5 μm^3 for the specimens of type 1–3 and 2 μm^3 and 0.75 μm^3 for the specimens of type 4 and 5, respectively. Analysis of the data presented allows us to notice that, first, there are two sensitive volumes instead of one volume for p- and n-channel transistors, and, second, the sensitive region of n-channel transistors is a dominant one.

It is easy to notice from comparison of the sensitive regions and cross sections of SEU that the threshold energy for all types of specimen under test lies below 1.5 MeV. Also, the threshold energies of SEU arising for specimens of type 1 are 1.5 to 2 times that for specimens of type 4. However, because of large sensitive volume values, a noticeable difference in the SEU cross sections under irradiation with 14-MeV neutrons is not observed. Indeed, two tendencies are there as the topologic dimensions are decreased. On the one hand, the decrease of topologic dimensions of active regions of devices results in a shift of integrated energy deposition spectrum into the region of lower energy levels, and in a threshold upset energy decrease due to lowering of effective values of load capacitances, which are less changed with the technology resolution standards decrease. However, the transition to lower values of the neutron energy will result in more abrupt lowering of SEU cross sections for specimens with relatively large threshold energies (Fig. 4). This explains the abrupt decrease in SEU cross section for specimens of type 1–3 in the experiments on the Pu(Be) source.

It should be noted that, aside from intrinsic dimensions of drain regions, the effect of the electric field penetration into the substrate, resulting in an increase in the effective collection length of charge carriers, also influences the collection region dimensions. This effect

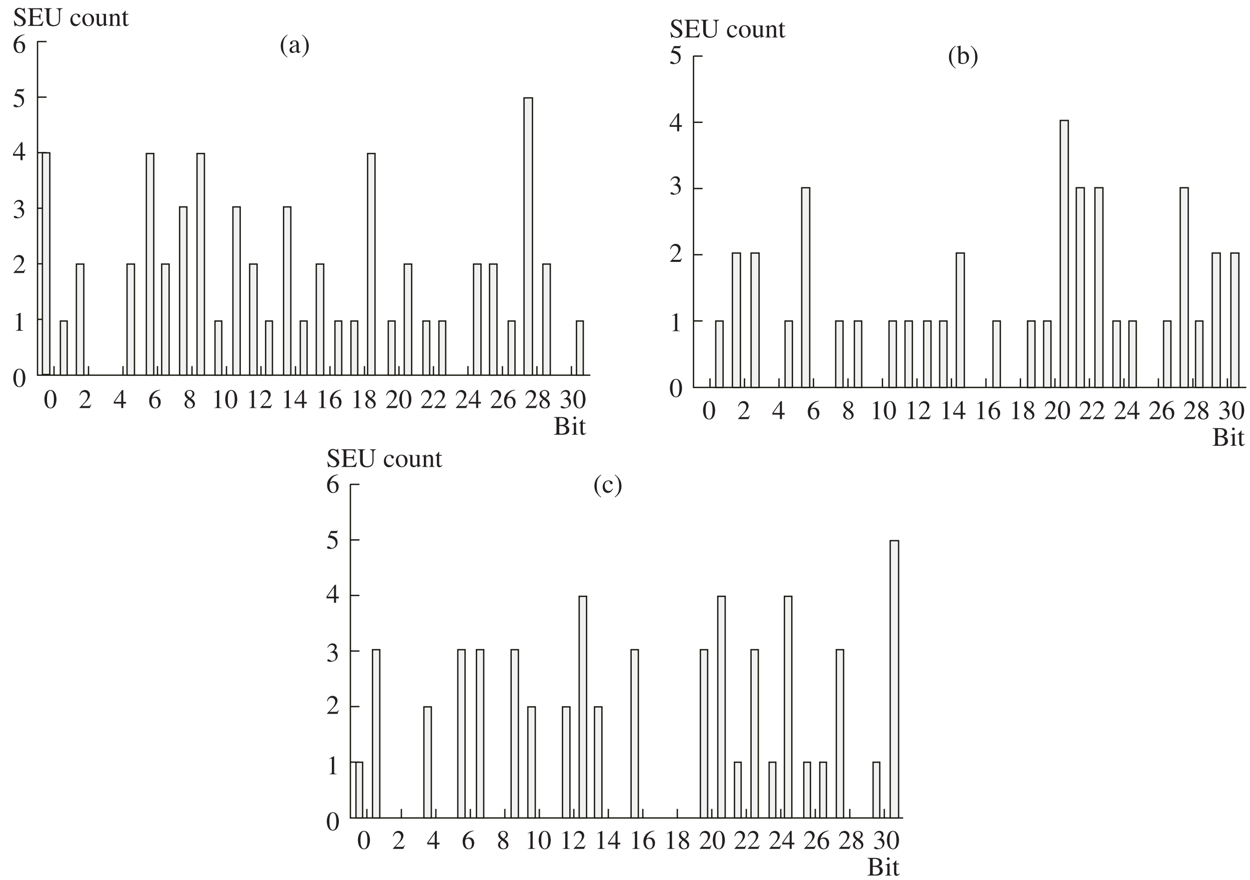

Fig. 3. SEU distribution over the bits of a sample IC of type (a) 1, (b) 2, or (c) 3.

will compensate partly the elements topological dimensions difference. This conclusion also follows from experimental study of the same VLSI circuits under irradiation with 14-MeV neutrons, namely, that the SEU cross sections of circuits produced by bulk technology are practically the same and lie within the range $(1–4) \times 10^{-14}$. More noticeable distinctions of threshold energies would increase the difference in the SEU cross section. Further, the effects of the electric field penetration into the track of nuclear particle under 14 MeV neutrons action are less significant due to a substantially smaller initial energy of secondary particles.

It is also necessary to note once again the limitations of the proposed models based on the estimation of the energy deposition in some sensitive volume. Specifically, the models neglect the following:

(i) the penetration effect of the electric field of pn junction into the track of a secondary nuclear particle, when it crosses the sensitive volume;

(ii) the possibility of a parasitic bipolar transistor action, even with bulk-technology circuits (this is also the case with SOI structures).

The penetration effect of the electric field results in an increase in sensitive volume. The most difficult task

Table 3. Values of sensitive volume (in μm^3) for the test VLSI specimens

Type	V_a, μm^3			
	E_p = 180 MeV	E_p = 225 MeV	E_p = 250 MeV	E_p = 1 GeV
Type 1	2.9	2.6	0.9	7.4
Type 2	2.3	–	–	–
Type 3	0.5	0.45	0.73	1.6
Type 4	1.3	1.3	2.1	3.2
Type 5	1.5	–	–	–

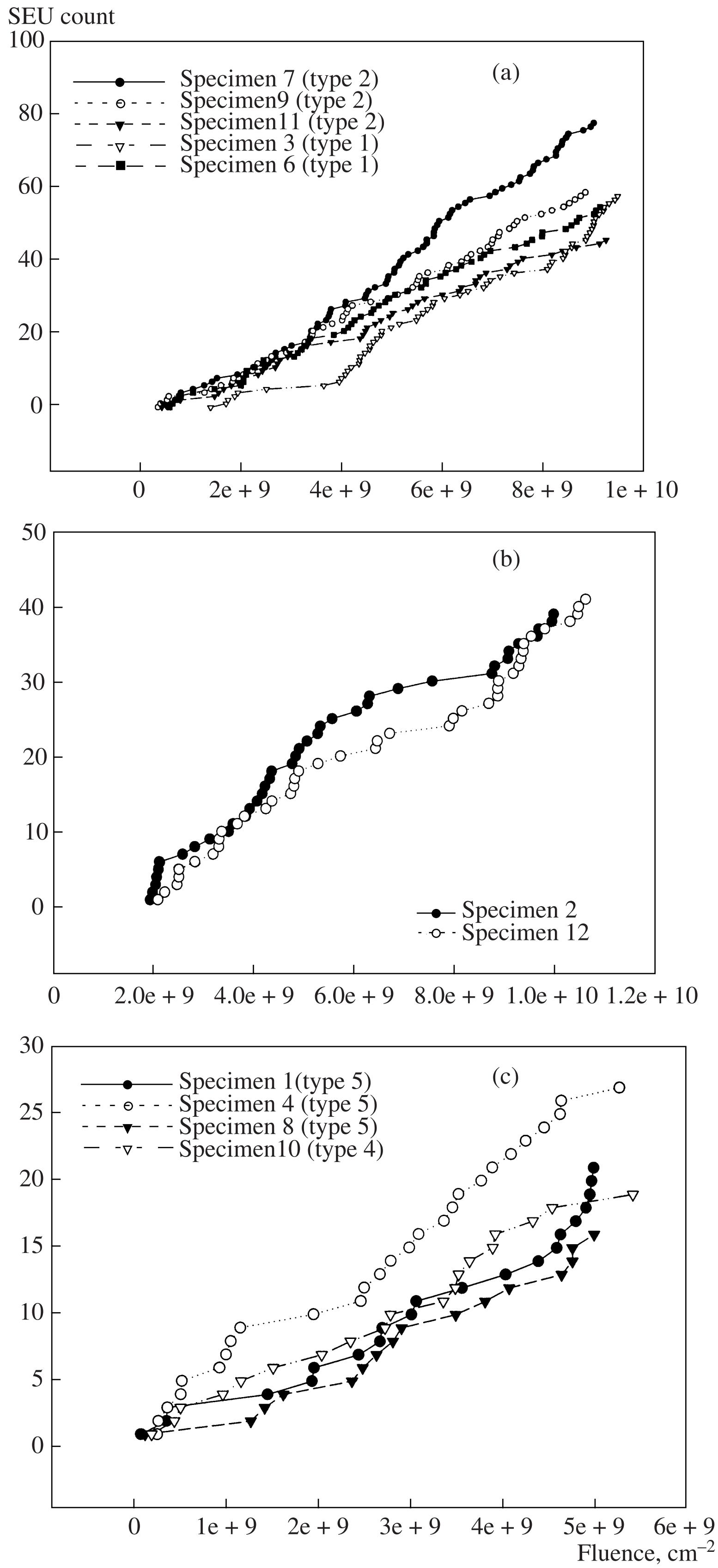

Fig. 4. SEU count vs. fluence for sample ICs of different type: (a) types 1 and 2, (b) type 3, or (c) types 4 and 5.

Table 4. Drain and channel areas of memory-cell transistors

Region	Area for specimens 1–3, μm^2	Area for specimens 4 and 5, μm^2
NMOS drain	7.1	3.6
NMOS channel	1.5	0.8
PMOS drain	2.3	1.2
PMOS channel	1.0	0.5

is to estimate the amplification effect of collected charge associated with the parasitic bipolar transistor. As an example, we performed a computer simulation of ionizing reaction of PMOS and NMOS transistors with a minimum feature size of 0.5 μm. Figure 5 shows the transistor structure in a two-dimensional geometry with a width of 5 μm.

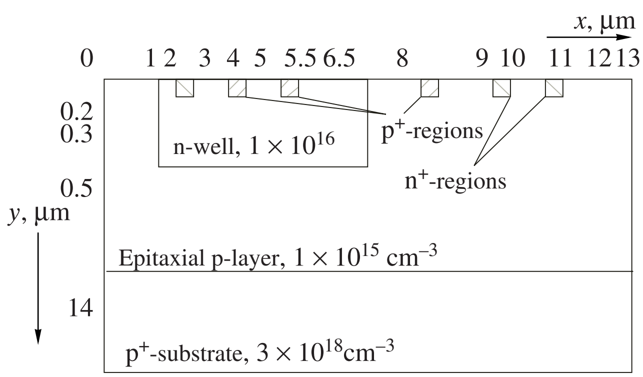

Fig. 5. Model structure for the computer simulation of ionizing-radiation response.

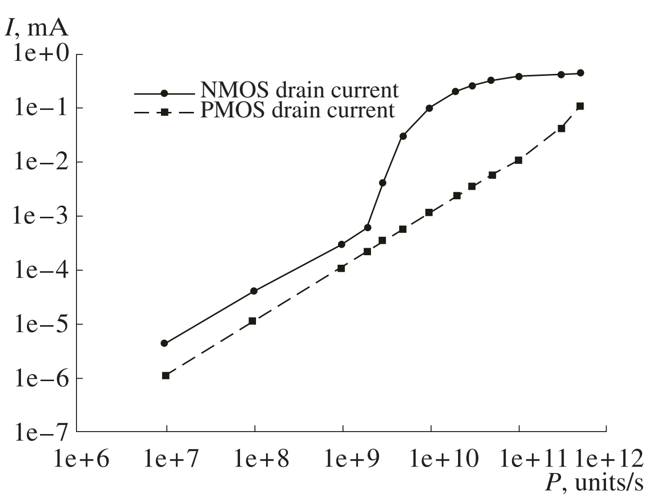

Fig. 6. Calculated PMOS or NMOS drain photocurrent vs. dose rate for a radiation pulse 10 ns wide.

Simulation results for photocurrents of drain junctions are presented in Fig. 6. One can observe easily that, in a PMOS transistor at levels of order of 2×10^9 units/s, a substantial growth in peak photocurrent is observed, which is explained by transition into the active region of the parasitic bipolar transistor. Despite the fact that the active base thickness of the PMOS transistor is almost one-third as large (its beta current gain factor is almost ten times as high), its influence occurs at action levels almost 100 times as high. This fact is explained by the fact that the currents through this transistor are about five times as strong, and the base resistance is almost one-tenth as great.

Thus, the results presented indicate that even in similar structures the threshold energies may differ substantially due to the influence of the parasitic bipolar transistor. The difference may attain two orders of magnitude (of the order of the beta current gain factor). To estimate accurately these values in practical structures seems to be impossible. Nevertheless, these processes may determine the threshold energies of single-event effects arising in the VLSI circuits. Further, one should expect an increasing role of this effect as the topological dimensions are decreased.

CONCLUSIONS

The computer simulation and the experiment have demonstrated that VLSI circuits in current use, made by different processes, are susceptible to single-event effects caused by neutrons with an energy of order 1 MeV; these are mainly SEUs with a threshold energy of about 1 MeV and a sensitive volume of order 1 μm^3. As the minimum feature size is reduced, the threshold is predicted to decrease sharply due to a growing amplifying effect of the parasitic bipolar transistor.

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