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DESCRIPTION OF MICROCIRCUIT SINGLE EVENT UPSETS BY INTEGRAL EQUATION

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1. SINGLE EVENT UPSETS DESCRIPTION

Let us consider the accumulation of upsets to be a Poisson stochastic process with rate $\lambda(t,E)$ which depends on the true value of energy E deposited in a small sensitive volume of a cell, and the time t. Therefore, $\lambda(t,E)$ must be proportional to the number of cells $N(t,E)$:

$$\lambda(t,E) = m \cdot N(t,E), \tag{1}$$

where m is the mean number of interactions per unit time.

If the initial number of cells is $N(E)$, λ may be expressed as

$$\lambda(t,E) = m \cdot \left[N(E) - \int_0^t \lambda(\tau, E)\, d\tau \right]. \tag{2}$$

The solution of this equation gives:

$$\lambda(t,E) = m \cdot N(E) \cdot \exp(-mt). \tag{3}$$

According to (3) the number of SEU at time t is:

$$N(t,E) = N(E) \cdot (1 - \exp(-m \cdot t)). \tag{4}$$

Let us assume that the spectrum of the energy deposited in the small sensitive volume of a cell is $F(E)$. This leads to the expression

$$N(t) = \int [1 - \exp(-m \cdot t)] F(E) N(E)\, dE. \tag{5}$$

Since the upset is generated from the individual interaction of a particle with the cell which occurs very rarely ($m \cdot t << 1$), the expression $[1 - \exp(-m \cdot t)] \cdot F(E)$ is approximately equal to $m \cdot t \cdot \exp(-m \cdot t) F(E)$. It represents a single event spectrum of the energy deposited from the interaction and consists of two multiplicands, the prabability of interaction and the probability of energy deposition from ionizing collisions. Therefore, in order to describe the accumulation of SEUs in memory cells it is necessary to take into account both the single event spectrum and a «response function» $N(E)$.

The expression (5) has a microdosimetric character and permits the following approximations:

1. Target model: $N(t) = N \cdot [1 - \exp(-m \cdot t)]$.
2. Modified target model: $N(t) = N(E_r) \cdot [1 - \exp(-m \cdot t)]$.
3. Edge effect: $N(t \to \infty) = N(E_{\max})$.

The last expression allows the calculation of the «response function» energy dependence.

The validity of Eq.(2) as well as the single event spectrum of the energy deposited in a small sensitive volume was examined in experiments with various types of microcircuits. Particles were generated by the cyclotrons of the Flerov Laboratory of Nuclear Reactions of JINR (Dubna) in the energy range from 1 MeV/amu up to 5 MeV/amu as well as by the JINR Synchrophasotron at 3.65 GeV/amu. B, O, Ne, Ar, and Kr ions were used in the cyclotron experiments and p, He, O — and their mixtures with the same energies — in the experiments at the Synchrophasotron.

The ion beam characteristics presented in Table 1 include those of the LBL-88 cyclotron, for comparison.

Table 1. Parameters of heavy ions accelerated by the JINR and the LBL cyclotrons

Cyclotron or source	Ion	E, MeV	(dE/dx), MeV · cm^2 /g	Path length* mkm	Data from [1—3], mkm
IC-100	Ar	46.3	$1.9 \cdot 10^4$	12	12.1
	Ne	26.7	$1.1 \cdot 10^4$	11	13.1
	O	19.3	$8.0 \cdot 10^3$	13	14.5
	B	13.6	$3.8 \cdot 10^3$	14	13.6
U-400	Kr	210	$3.9 \cdot 10^4$	25	25
LBL-88	Kr	250	$4.2 \cdot 10^4$	34	–
	Ar	160	$1.4 \cdot 10^4$	42	–
	Ne	58	$6.8 \cdot 10^3$	27	30.2
	C	380	$5.1 \cdot 10^2$	1803	1810
	O	424	$1.0 \cdot 10^3$	943	969
	He	11.8	$3.7 \cdot 10^2$	83	88
Pu-239	α	5.15	$6.7 \cdot 10^2$	23	23.5
Am-241	α	5.48	$6.4 \cdot 10^2$	25	26.4

*Calculated in accordance with ME & PhI code for HEZ particles

From this Table it follows that the Russian and American approaches differ because the obtained ionization profiles are distinctly different. The experiments at JINR were designed for full energy loss within the sensitive volume. In contrast, the USA investigators attempted to achieve uniform ionization along the particle trajectory through the sensitive volume.

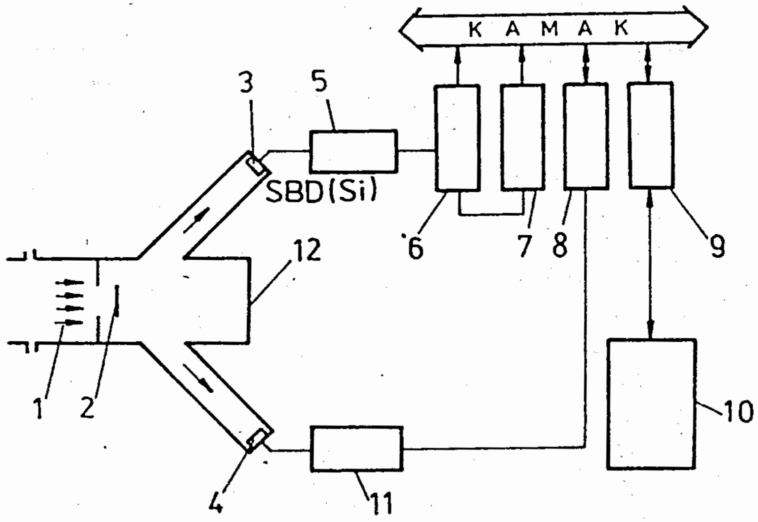

Fig.1

An attempt was made [1] to consolidate the LET response and nuclear reaction (induced by protons) data for I2164A DRAM. This attempt gave a technique of fitting the thickness, which is not based on the real direct measurements of it. We cannot illuminate this problem completely, but we can investigate — when all ions are slowing down within the sensitive volume.

The obtained results are in good agreement with the predicted theoretical ones. We have studied the most common devices made in Russia with the different technologies: n-MOS, CMOS, CMOS/SOS, TTL. All circuits, except for CMOS/SOS only, were sensitive to the energy loss created by ^{40}Ar, accelerated by the IC-100 accelerator. Figure 1 shows a schematic diagram of the experimental equipment used in the study. Figure 2 contains the dependence of the SEU number on time and its predicted behaviour according to Eq.(5). Figure 3 shows the energy dependence of the chips response function obtained using n-MOS, CMOS and TTL curcuits.

To calculate the rate of SEU a different form of Eq.(5) is used. One can derive it assuming $N(E) = N \cdot \eta(E - Q \cdot \varepsilon)$ and $m \cdot t << 1$. The value of $N(t)$ for this special case is

$$N(t) = \Sigma\, V\, \Phi\, Nt \cdot \int F(E)dE = \sigma_{\mathrm{SEU}} \Phi\, Nt, \qquad (6)$$

where

$$\sigma_{\mathrm{SEU}} = \Sigma\, V \cdot \int_{\varepsilon Q}^{\infty} F(E)dE,$$

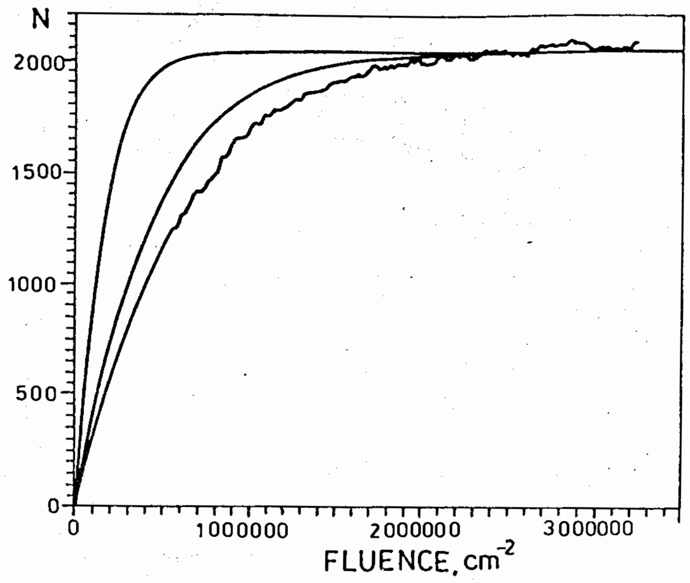

Fig.2.

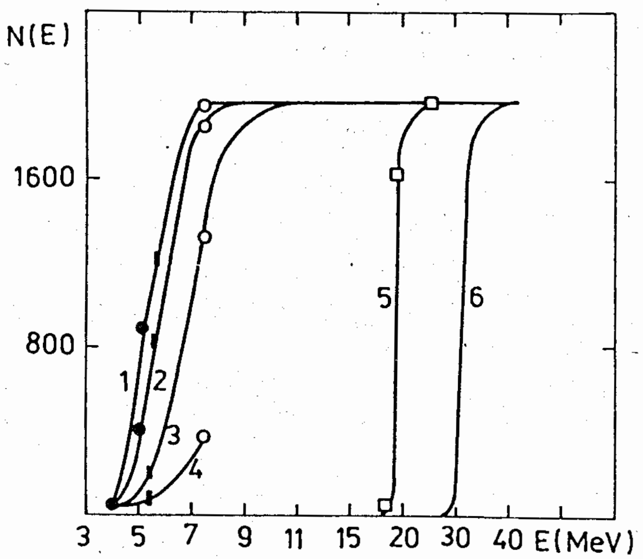

Fig.3

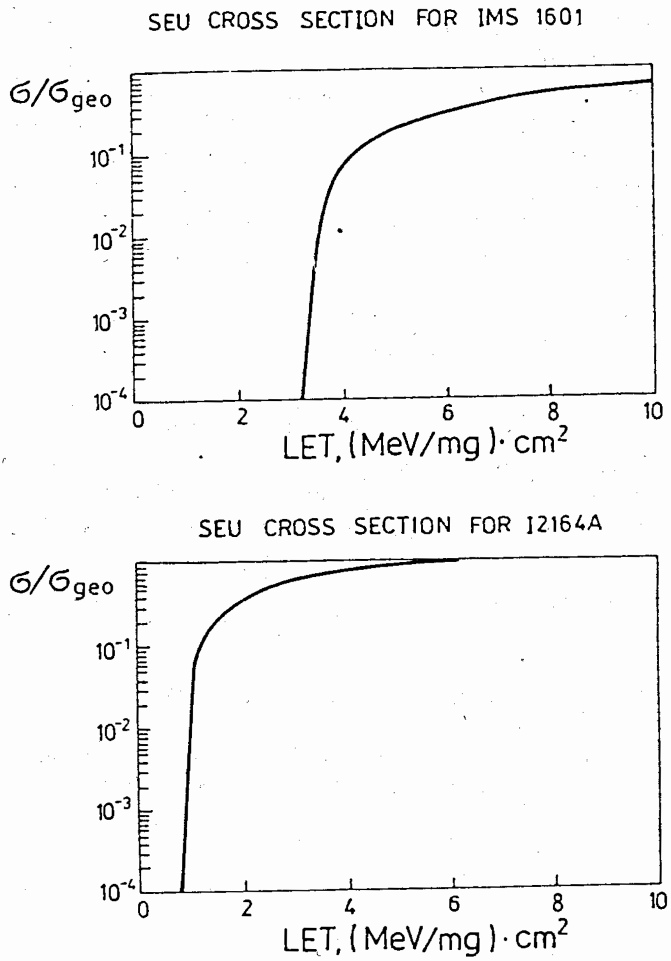

Fig.4

Φ is the flux of particles, Σ is the microscopic cross section, V is the sensitive volume, Q is a critical charge, ε is the energy of electron-hole pair generation and N is the total number of sensitive cells. The product V is an effective cross section of a cell.

If the distribution of energy loss concentrates far from the low integration limit in Eq.(6), σ_{SEU} is approximately equal to the effective geometical cross section of a cell, otherwise a strong dependence of σ_{SEU} on the LET energy is obtained. The main cause of such dependence is a diviation of the collected charge deviations, because of various conditions of the electron-hole field —assisted at the drift and diffusion from element to element.

Let us consider the element similar to that of I2164A DRAM, and the element of IMS1601EPI SRAM*. Using the model developed above, we can calculate the LET response for each circuit. The values of the critical charge or energy needed for the SEU trigger used in our computations, were 3.3 MeV and 10 MeV for I2164 and IMS1601, respectively. Figure 4 shows that two curves have been computed within the interval of LET from 0 to 10 MeV · $\mathrm{cm}^2/\mathrm{mg}$.

2. COSMIC RAYS EFFECTS

Generalization of Eq.(5) makes it possible to calculate the yield of SEU for any radiation environment, for example, during an orbital flight. Cosmic rays are a mixture of particles; a partial contribution to the SEU rate can be expressed in the following way (only electromagnetic interactions are included):

$$N_i(t) = \int dl dT dE \cdot P(l) \cdot \delta\left[E - \int_0^l dE/dx(T)dx\, \Phi_i(T)N(E)(1 - \exp(-m_i t) \right]. \qquad (7)$$

Here $P(l)$ is the distribution of a path length l, $\Phi(T)$ is the normalized flux of particles and $\delta(\ldots)$ is the delta function.

The total SEU rate is the sum of the rates of all kinds of particles presented in the Cosmic rays. Integrating over E in Eq.(7) and amplifying the result, assuming that $P(l) = \delta(1 - a)$, $N(E) = N \cdot \eta(E - E_0)$, one obtains:

$$N_i(t) = N \cdot (1 - \exp(-m_i t)) \int_{T_{1_i}}^{T_{2_i}} \Phi(T)dT. \qquad (8)$$

Here T_1, T_2 are the solutions of the inequality

$$\int_0^a dE/dx(T)dx \geq E_0, \qquad (9)$$

they may not exist, because the particles of that kind give no contribution to the SEU rate.

Inequality (9) gives more strict requirements than the simple LET $\geq E_0/a$, because it deals with both the LET and energy criteria. For example, a proton in the maximum of its own ionizing ability posseses a value of LET of about 1000 MeV · cm^2/g and it can only lose about 100 keV on the residual path. If the particle projected range of $R(T_{2_i}) \leq a$, then $T_{1_i} = E_0$ and min $\{T_{2_i}\} = E_0$. In general, T_{2_i} is equal to the maximum of energy in the primary spectrum. The dependence of T_2 on particle charge, widely present in the Cosmic rays ($Z \in [1—26]$), is

$$T_2(Z, E_0) = C \cdot (Z - Z_0)^2. \qquad (10)$$

Let us assume that E_0 is 10 and 20 MeV ($a = 10$ mkm); C is about 0.15 MeV/amu, Z_0 is equal to 6 and 11, respectively.

The estimation performed by means of the analytical approach has shown that the key problem for the Cosmic rays investigation is to obtain both the «response function» and flux of particles of the Cosmic rays near the chips location in the medium range of energy in particular. Available LET spectra can be used, provided that small changes of LET *vs* energy are observed ($Z \gg 1$, $T_1 = 0$).

3. NUCLEAR INTERACTIONS OF HEAVY IONS

In order to take into account nuclear interactions, Eq.(5) must be transformed into the following expression:

$$N_i = \Sigma_i \Phi_i V_{\mathrm{eff}} t \cdot \int_0^\infty F_1(E)N(E)dE, \qquad (11)$$

where $F_1(E)$ is the single event spectrum for nuclear interactions.

Assuming as before that $N(E) = N_0\eta(E - E_0)$ and integrating over E, Eq.(11) can be written as follows:

$$N_i = \Sigma_i \Phi_i V_{\mathrm{eff}} t N \cdot \int_{E_0}^{c(Z-Z_0)^2} F_1(E)(dE. \qquad (12)$$

For comparison of the number of SEUs produced by the electromagnetic and nuclear interactions we introduce the parameter $R = N^{\mathrm{el}}/N^{\mathrm{nucl}}$. Having summed the partial contributions of the number of SEUs for all kinds of particles, the value of R may be expressed as

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*We are primarily interested in this part because it is used in General Purpose Computers (GPC) of the Space Shuttle

Table 2. Product $\Sigma_i\,\Phi_i$ and the volume which contains an interaction in a one-day flight (free space location)

Ions	$\Sigma_i\,\Phi_i$, $\mathrm{cm}^{-3}\mathrm{c}^{-1}$		V_0, cm^3	
	Sol-min	Sol-max	Sol-min	Sol-max
1. Beyond the Earth magnetosphere				
H	$8.6\cdot10^{-2}$	$4.5\cdot10^{-2}$	$1.4\cdot10^{-4}$	$2.6\cdot10^{-4}$
He	$1.5\cdot10^{-2}$	$9.1\cdot10^{-3}$	$7.7\cdot10^{-4}$	$1.3\cdot10^{-3}$
O	$6.3\cdot10^{-4}$	$3.8\cdot10^{-4}$	$1.8\cdot10^{-2}$	$3.1\cdot10^{-2}$
Si	$1.2\cdot10^{-4}$	$7.6\cdot10^{-5}$	$9.5\cdot10^{-2}$	$1.5\cdot10^{-1}$
Fe	$1.3\cdot10^{-4}$	$8.1\cdot10^{-5}$	$9.2\cdot10^{-2}$	$1.4\cdot10^{-2}$
2. Inclination 57.7°, $h = 250$ nmi				
H	$2{,}1\cdot10^{-2}$	$1.4\cdot10^{-2}$	$5.4\cdot10^{-4}$	$8.3\cdot10^{-4}$
He	$4.9\cdot10^{-3}$	$3.5\cdot10^{-3}$	$2.4\cdot10^{-3}$	$3.3\cdot10^{-3}$
O	$2.1\cdot10^{-4}$	$1.5\cdot10^{-4}$	$5.4\cdot10^{-2}$	$7.6\cdot10^{-2}$
Si	$4.3\cdot10^{-5}$	$3.1\cdot10^{-5}$	$2.7\cdot10^{-1}$	$3.7\cdot10^{-1}$
Fe	$5.0\cdot10^{-5}$	$3.7\cdot10^{-5}$	$2.3\cdot10^{-1}$	$3.2\cdot10^{-1}$
3. Inclination 28.5°, $h = 250$ nmi				
H	$5.0\cdot10^{-3}$	$4.4\cdot10^{-3}$	$2.3\cdot10^{-3}$	$2.6\cdot10^{-3}$
He	$1.5\cdot10^{-3}$	$1.3\cdot10^{-3}$	$7.5\cdot10^{-3}$	$8.6\cdot10^{-3}$
O	$7.1\cdot10^{-5}$	$6.2\cdot10^{-5}$	$1.6\cdot10^{-1}$	$1.9\cdot10^{-1}$
Si	$1.5\cdot10^{-5}$	$1.3\cdot10^{-5}$	$7.6\cdot10^{-1}$	$8.6\cdot10^{-1}$
Fe	$1.9\cdot10^{-5}$	$1.6\cdot10^{-5}$	$6.3\cdot10^{-1}$	$7.2\cdot10^{-1}$

$$R = \frac{\sum\limits_{i>z_0}^{28} s_{\mathrm{eff}}\Phi_i\, t \cdot \int\limits_{E_0}^{c(z-z_0)^2} \Phi(T)dT}{\sum\limits_{i=1}^{28} \Sigma_i\,\Phi_i V_{\mathrm{eff}}\, t \cdot \int\limits_{E_0}^{\infty} F_1(E)dE}. \qquad (13)$$

The product $\Sigma_i \cdot \Phi_i$ is a reciprocal volume which contains an interaction per unit time. It is presented in Table 2 for *p*, He, O, Si, and Fe for the solar-min and solar-max periods. Microscopic cross sections were calculated for protons and heavy ions using the simple formulas:

$$\sigma_p = 0.043 \cdot A^{0.69} \quad \text{and}$$

$$\sigma_I = 0.0688 \cdot (28^{1/3} + A^{1/3} - 1.32)^2. \qquad (14)$$

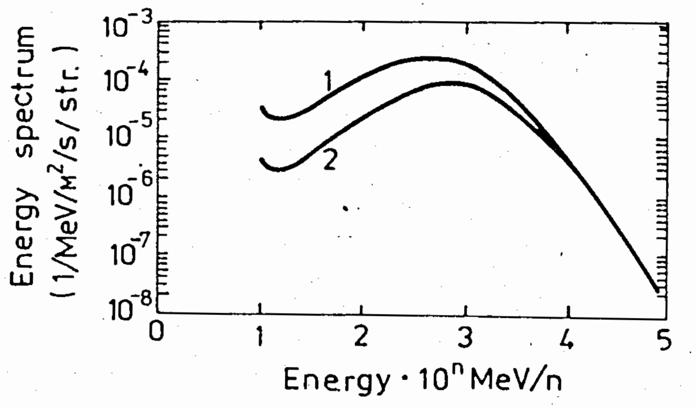

Fig.5

Fluxes of GCR were computed according to the Russian standard [4], improved at the ME & Phl, by summing the geometrical cutoff effects and ordit penetration factors. The code gives the data concerning the near Earth environment including SAA protons, Solar flashes particles along the orbital movement of the vehicle. The most valuable data are in good agreement with the data of NASA. For example, Fig.5 illustrates the main features of these data as well as shows a difference between the iron spectra beyond the Earth magnetosphere (1) and in it (2), when the vehicle orbit inclination is 57.7°.

We have studied in detail the single spectrum $F(E)$ created by high-energy heavy ions in nuclear interactions with Si nuclei both from the theoretical and experimental points of view [5]. It has been observed out that its shape is practically independent of the type of ions, and the values are strongly affected by the chips environment.

Estimates made for different cases of space flights indicate large difference in a *R*-values, which depend upon

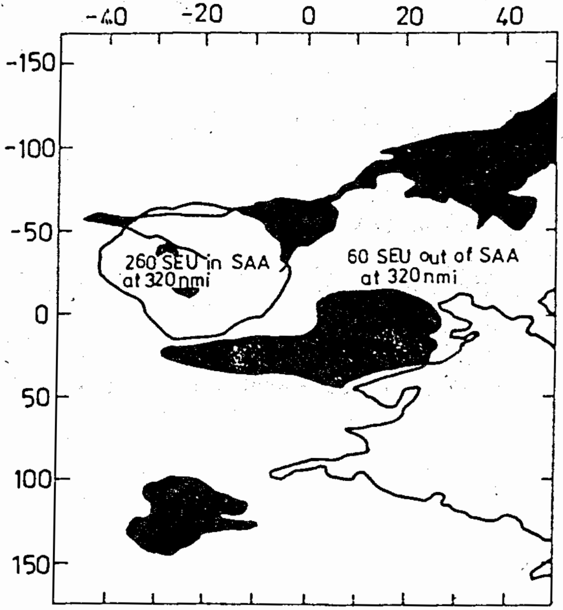

Fig.6

various conditions of a mission. For example, beyond the magnetosphere *R* is equal to 3.4 and 1.2 within the Solar-min and Solar-max periods, correspondingly; but at the 57.7° orbit inclination the corresponding values are 0.65 and 0.27. Therefore, for SEU predictions must take into account both electromagnetic and nuclear interactions of heavy ions for the missions into the Earth magnetosphere.

The method discribed in this paper was used for the prediction of the SEU yield in the GPC of the Space Shuttle. The value of SEU is practically independent of the altitude when the vehicle is out of the SAA region. Thay are caused by the nuclear interactions in general (inclination 28.5°). In the SAA region the number of SEU varies due to strong fluctuations of the protons flux. The presented values are not the maximum ones, but it is a rather accurate estimation of the contribution at the altitudes of 320 nmi (see Fig.6) (we have proposed a 50% duty cycle for each GPC).

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