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SOFT UPSETS IN 16K DYNAMIC RAMs INDUCED BY SINGLE HIGH ENERGY PHOTONS*

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Abstract

Soft upsets have been observed in dynamic random access memories (RAMs) that can be attributed to single high energy photon interactions. In the experiments, bremsstrahlung produced by the interaction of 40 MeV electrons with a thin tungsten converter has been found to produce soft upsets at flux levels well below those where photocurrent generation of upsets dominates. The number of upsets observed at low photon fluxes depends on the total number of photons which have been incident on the device but is independent of the dose rate. This behavior is consistent with preliminary calculations which assume that the upsets are caused by alpha particles produced in the silicon chip by the nuclear reaction $^{28}Si(\gamma,\alpha)^{24}Mg$. In these calculations the bremsstrahlung spectrum and the reaction cross section were integrated over the range from 15 to 22 MeV.

Introduction

The observation of soft upsets in microcircuits due to single ionizing particles or events has opened up serious questions regarding the reliability of integrated circuits as ever smaller feature sizes are achieved. The causes of soft upsets have been identified as alpha particles emitted by trace amounts of radioactive impurities in device packaging materials[1,2] and as cosmic rays.[3,4] Because cosmic rays are always present, the possibility exists that single event radiation effects may prove to be a more fundamental limitation on reducing device dimensions than the limitations associated with device fabrication. In view of the obvious importance of the single event soft upset phenomenon, the amount of research in this area has increased rapidly over the past two years.

Random-access-memories (RAMs) have served as convenient devices for testing soft upset susceptibility in various radiation environments. To date, soft upsets have been observed upon irradiation with protons at both MeV and GeV energies,[5,6,7] neutrons,[5,6] alpha particles,[1,2] and heavy ions.[8] In the case of protons and neutrons, the production of highly ionizing particles via nuclear reactions is the intermediate mechanism necessary for soft upsets since the protons or neutrons themselves do not produce enough electron-hole pairs in a small enough volume to cause upset.

Because the photodisintegration of an atomic nucleus by a single photon can also lead to the emission of energetic alpha particles and thereby to upset, in the present experiment, dynamic RAMs were irradiated with high energy bremsstrahlung to see if this type of soft error could be observed. Upsets due to alpha particles from a nuclear (γ,α) reaction must, of course, be separated from the well known upsets due to photocurrents produced by the dose rate of the incident ionizing radiation. In order to produce this separation, 16K dynamic RAMs were exposed to a bremsstrahlung field where the dose rate was below that necessary for photocurrent upsets. Based on the experimental values for the $^{28}Si(\gamma,\alpha)^{24}Mg$ cross section[8-11] in the energy range from 15 MeV to 22 MeV, the incident bremsstrahlung radiation was chosen to be as "hard" (i.e. to have as few low energy photons as possible) as was available from the NRL Linac in order to emphasize the effects due to nuclear reactions as against those due to photocurrents.

The present work demonstrates a new mechanism for single event soft upset production in microcircuits: namely, that upsets can be caused by alpha particles, and perhaps other particles as well, which are emitted from nuclear reactions induced by single high energy photons. These experiments are also the first observation of a deleterious radiation effect produced in an electronic device by a single photon.

Experimental Set-up

A 40 MeV electron beam from the NRL Linac was directed at a thin (.005") tungsten converter. The high-Z material insured that an efficient production of bremsstrahlung was obtained.[12] A graphite absorber (10cm long) between the converter and the RAMs under test stopped the electron beam. This low-Z absorber is used to minimize secondary electrons and neutrons which might be produced in the beam stop and to remove the low energy end of the bremsstrahlung. A long beam dump, beyond the RAMs under test, ensured than any neutrons produced in the dump could not reach the device. The system was originally designed and is used for photactivation analysis so the purity (i.e. lack of neutrons) of the bremsstrahlung radiation was known.[13]

The radiation field has been characterized with CaF_2 thermoluminescent dosimeters (TLDs). In the region where the devices were irradiated (about 60cm from the converter), the field intensity varied as the inverse square of the distance from the converter. To preserve the purity of the radiation, the devices were irradiated in a free field geometry. It was therefore necessary to measure the bremsstrahlung field behind the devices and to use the inverse square variation to calculate the field at the devices.

For calculations of the yield of alphas given in a following section, it was necessary to measure the total bremsstrahlung field. This was accomplished by placing the TLDs behind 3" of aluminum to obtain charged particle equilibrium. In order to measure the absorbed dose at which device failures occurred, a separate calibration experiment was performed in which TLDs in just an aluminum foil were irradiated at the same time as when the total field was being measured and at the same position as that in which the devices would be placed. The aluminum foil is thinner and of a different material than the lids on the devices, but its use does give a measure of the absorbed dose better than do the measurements behind 3 inches of aluminum. It is also the way the total dose for hard failure was measured on similar devices in a Co-60 cell. The TLDs in the aluminum foil measured doses a factor of three less than the TLDs behind 3 inches of aluminum, indicating that the absorbed doses in the devices were also a factor of three below the free field values. The values of dose shown in this paper are the doses measured behind 3 inches of aluminum except in the case where the total dose failure level is given, and this is the absorbed dose or the free field dose divided by three.

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The minicomputer system used to test the dynamic RAMs consists of a Zilog Z-80 system with 36K of memory of which 16K is reserved for the testing program. The system operates with a 4 MHz clock and a refresh period of approximately 100 micro-seconds. All three voltages on the chip were within 1 percent of the typical recommended values. The devices were placed about 1 meter from the computer system on twisted pair cables with load matching resistors at the signal transmitting ends. Decoupling capacitors were placed at all three power supply pins at the device end of the cable.

Four devices were tested together in sockets mounted on a common board, but all of the electrical connections to the computer were separate for each device. Errors were matched to devices by the unique bit position among the 8 bits available. The computer system was shielded from the radiation and received no measurable dose according to the TLDs placed on it. The exposure on the four devices was measured to be uniform within 20 percent.

The testing procedure consisted of filling the devices alternately with all 0's or all 1's and then exposing them to the bremsstrahlung field. After a predetermined number of Linac pulses, the RAMs were checked for upsets by comparing the entire memory to the fill character and printing out the address and contents of any mismatches. The memory space was then filled with the opposite character and checked to make sure no hard upsets had occurred. The memory space was then refilled and the system was exposed again.

The Linac pulses were 1 microsecond long, had a repetition rate of 180 pulses per second and average currents on the converter which were adjusted from about .1mA to 10mA. Dose rates, as measured with the TLDs behind 3 inches of aluminum, varied from about .05 Rad(CaF_2) per pulse to about 5 Rad (CaF_2) per pulse. In all cases, preliminary runs determined the dose rate level above which the upset rate increased rapidly, thus indicating that the photocurrent upset threshold had been reached. This photocurrent or dose rate threshold varied from device to device.

All of the 16K dynamic RAMs tested are divided internally into two 8K parts (separated by sense amplifiers) one of which stored data in an inverted form. Such a division means that when the program places a single character in the devices, half the device stores that character as a 1 or 0 and the other half stores the inverse character. Information supplied from the manufacturers of the devices allows a determination of which addresses store data in an inverted way. Thus, from the address of each upset, the internal nature of the upset (0 to 1 or 1 to 0) could be determined. For all but one manufacturers devices, this determination was made for the data presented.

Results

Table 1 lists the 23 devices used in this study and identifies them by number. Included are device type, date code, and lid material.

The results of the upset measurements on the devices are separated by manufacturer and are presented in Tables 2-5. Presented also are the device number, the average dose per Linac pulse as measured with the CaF_2 behind 3" of aluminum, the number of upsets, identified by state change where possible, and the total number of upsets observed divided by the total dose in kilorads. The total number of observed upsets is also given so that the statistical behavior of the data can be understood.

For each device, a plot of the upsets per kilorad versus dose rate shows that at low dose rates upsets per kilorad are constant and do not depend on dose rate. In the model to be developed in the next section it will be seen that, if the upsets are produced by single photon interactions, the number of upsets per kilorad is expected to be constant. Where the upsets per kilorad will increase rapidly is after the dose rate threshold for upsets has been exceeded. This behavior can be seen in some of the data above 1 Rad(CaF_2) per pulse, i.e. above approximately $1X10^6$ rads(CaF_2) per sec.

The variation in results among devices and manufacturers is real even though the statistics are poor.

The large majority of the upsets, where identifiable, correspond to transitions from the 1 to the 0 state, or from a state where the cell's potential well is empty to one where it is filled.

Eventually, most of the devices failed during the tests and were replaced. Since the total dose on the devices was known, and because these total dose failure levels may be of value to the radiation effects community they are included in Table 6; values for the devices which did not fail are shown as greater than the total dose accumulated when the experiment was terminated. In order to obtain the total absorbed dose in the device, the hard failure levels given in Table 6 were taken to be those measured behind the 3" of aluminum and divided by 3. Two device types we also tested for hard failure in a Co-60 test cell and failed at levels comparable to those in Table 6. Two Hitachi devices both failed at 2.1 Krad(CaF_2) and two Mostek devices failed at 3.3 Krad(CaF_2) and 3.9 Krad(CaF_2) in the Co-60 experiment. Note that 1 rad(CaF_2) is approximately equivalent to 1 rad(Si).

The statistical variations shown in Tables 2-5 are due to the relatively small accumulated number of upsets which in turn was limited by the low total dose failure levels of the devices. Large exposures were necessary for improved statistics and these took up a large fraction of the device's total dose failure level, thus limiting the number of different dose rates that could be investigated. Thus the data in these tables reflect a trade-off between obtaining better statistics and obtaining measurements for more dose rate values.

Calculations

In order to explain the results of these experiments, a mechanism has been postulated whereby the interactions of single high energy photons with silicon nuclei produce ionizing particles via nuclear reactions. These ionizing particles are then assumed to produce enough electron-hole pairs close to sensitive areas of the device, so that they are capable of causing upsets. Protons and alpha particles are produced by bremsstrahlung interactions with silicon,[9,10,11,14] but the protons are not capable of depositing enough energy in a small enough volume to produce upsets. Cross sections for the $^{28}Si(\gamma,\alpha)^{24}Mg$ reaction have been measured[8,9,10,11,14] in the range of bremsstrahlung energy from about 15-22 MeV. Because the Q-value for this reaction is -9.99 MeV in this photon energy range, alpha particles are produced with energies from about 4 to 10 MeV, and such alpha particles are known to be capable of producing upsets. In the 15-22 MeV range and for the above named reaction an average value of the integral cross section of 5.3×10^{-27} cm^2 MeV has been adopted[8,9,10,11,14] in the calculations which follow.

One way to test the validity of the single photon induced upset model is to calculate the number of alphas produced in a 16K RAM per rad(Si) of bremsstrahlung absorbed by it and to compare this number with the measured number of upsets. In these calculations, the bremsstrahlung spectrum may beapproximated with the analytical expression of Kramers[15] with 0.1 MeV assumed to be the lower energy cutoff due to self absorption in the converter and the 40 MeV upper cutoff. According to Kramers:

$$I(k) = \begin{cases} I_0, & 0.1 < k \leq 40 \text{ MeV} \\ 0, & \text{elsewhere} \end{cases}$$

where $I(k)$ and I_0 are bremsstrahlung fluences in ergs cm^{-2} MeV^{-1} and k is the energy of the bremsstrahlung photons. Now the absorbed dose in silicon is

$$R_{Si} = \int_0^\infty \mu_{en}(k) I(k) dk$$

where $\mu_{en}(k)$ is the mass energy absorption coefficient. For the conditions of the present experiment it is reasonable to assume that

$$R_{Si} = I_0 \overline{\mu_{en}} \Delta k$$

where $\overline{\mu_{en}}$ is an effective absoption coefficient in the range 0.1 to 40 MeV. Since μ_{en} does not vary a great deal, the value of 0.02 cm^2/gm was chosen.[16] Then

$$I_0/R_{Si} = 1.25 \text{ ergs cm}^{-2} (\text{erg gm}^{-1})^{-1} \text{ MeV}^{-1}$$

Since R_{Si} is measured in rads(Si), we have for this assumed bremsstrahlung spectrum

$$I_0/R_{Si} = 1.25 \times 10^2 \text{ ergs cm}^{-2} (\text{rad(Si)})^{-1} \text{MeV}^{-1}$$

The yield of alphas from silicon is now given by

$$Y = \int_0^\infty \sigma(k) \phi(k) dk$$

where $\sigma(k)$ is the reaction cross section in cm^2 atoms^{-1} MeV per incident photon per cm^2 of energy k and $\phi(k)$ is the bremsstrahlung spectrum expressed in photons cm^{-2} MeV^{-1}. It has already been assumed that the bremsstrahlung spectrum is of the form $\phi(k) = I_0/k$, with I_0 = constant and we will further assume the cross section is zero outside the 15-22 MeV region, and an effective value $\bar{\sigma}$ inside.[8,9,10,11,14] Hence

$$Y = \bar{\sigma} I_0/\Delta k \int_{k_1}^{k_2} dk/k$$

where $k_1 = 15$ MeV, $k_2 = 22$ MeV, $\Delta k = 7$ MeV, and $\bar{\sigma} = 5.3 \times 10^{-27}$ cm^2 MeV atom^{-1}. Thus

$$Y/R_{Si} = 3.8 \times 10^{-26} \text{ ergs MeV}^{-1} \text{atom}^{-1} \text{rad(Si)}^{-1}$$

and to rationalize the ergs and MeV^{-1} the above quantity must be divided by 1.6×10^{-6} ergs MeV^{-1}. Thus

$$Y/R_{Si} = 2.4 \times 10^{-20} \text{ alpha atom}^{-1} \text{ rad(Si)}^{-1}$$

This dose is distributed over all atoms in a gram and therefore

$$Y/R_{Si} = 516 \text{ alphas rad(Si)}^{-1}$$

However, the target is all 16K cells of the device with an assumed cell size of 20 microns X 20 microns with a depletion depth of 1 micron. If it is assumed that any alpha particle entering this region will cause an upset, then, on the average, one-half of the alphas produced in a layer whose thickness is equal to the range of the alpha particles will cause upsets. Assuming all ground state transitions and a normal resonance shape to the cross section, the average alpha energy will be around 7 MeV with a range of 40 microns.[20] Hence the volume of significant alpha production will be 8.0×10^{-9} cm^3 or 1.8×10^{-8} per cell. For all cells in a 16K RAM this gives 3.0×10^{-4} g and an alpha yield of

$$Y/R = .15 \text{ alpha rad(Si)}^{-1} \text{ (16K RAM)}^{-1}$$

$$= 150 \text{ alphas Krad(Si)}^{-1} \text{ (16K RAM)}^{-1}$$

Conclusions

The measurements reported here have shown that single high energy photons can cause soft upsets in 16K dynamic RAMs. The evidence for this new mechanism is the observation that at low dose rates the number of soft upsets produced is proportional to the total dose delivered, but is independent of the dose rate. These experiments are also the first observation of the production of a deleterious radiation effect in an electronic device by a single high energy photon. The most probable cause of the upsets are alpha particles emitted from the $^{28}Si(\gamma,\alpha)^{24}Mg$ nuclear reaction.

In order to characterize differences between devices, the average value for the number of upsets per kilorad and the standard deviation have been calculated for each device. These values are given in table 7. Values of the upsets per kilorad which were at or near the photocurrent limit were not included. Also shown in table 7 is the average number of upsets per kilorad for a particular manufacturer's devices along with the associated standard deviation. The table demonstrates differences in devices and differences between manufacturers greater than the statistical fluctuations.

The calculations for a model 16K dynamic RAM and the $^{28}Si(\gamma,\alpha)^{24}Mg$ nuclear reaction resulted in a value of 150 upsets per kilorad (Si). In view of the magnitude of the statistical variations, the average values in table 7 for upsets per kilorad (CaF_2) are in reasonable agreement with these calculations especially in view of the additional uncertainties in alpha particle upset sensitivities. Yaney, Nelson, and Vanskike[2] have, for example, reported variations in sensitivity to alpha upset that vary by an order of magnitude between two different devices, and these results were obtained with relatively monoenergetic 4.9 MeV alphas incident the device surface. Yaney, Nelson, and Vanskike[2] also measured upset rates which, when calculated for the incident alpha flux they reported, ranged from 2.5 to 1000 alphas per upset. May and Woods[1] used a value of 67 alphas per upset to fit theoretical calculations with measured upset rates for 4K dynamic RAMs. In the present case, the sensitive volumes of the device are being bombarded by alphas from a greater variety of directions and with a greater variety of energies than in the case of alpha source surface bombardment, and so greater variations in results can be expected. The predominance of upsets from the 1 to the 0 state or from the empty cell state to the full cell state observed in the present experiment is in agreement with the model of May and Woods[1] used to explain upsets under alpha bombardment, and this fact also supports the mechanism that has been postulated.

Other possible sources of upsets from nuclear reaction products must also be considered. More protons are produced by the bremsstrahlung than alphas.[9] Although the possibility of direct proton upset at energies around 1 MeV has been postulated,[17] for present day 16K RAMs, the ionization density produced by such protons is too low to produce upsets. Aluminum metallizations could contribute alphas via the $^{27}\mathrm{Al}(\gamma,\alpha)^{23}\mathrm{Na}$ reaction.[18] The proximity of metal contacts and storage cell sensitive volumes enhances the importance of this upset mechanism. Oxygen in the passivation layers also can contribute alphas via the $^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ reaction.[19] Again, this mechanism can not be entirely ignored. These two reactions and reactions with the device lid notwithstanding, it is estimated that the silicon reaction will be the largest source of alphas and therefore the most likely cause for the observed upsets.

The existence of high energy photons such as were used in these experiments is rare in a nuclear or space environment, but the discovery of this new soft upset mechanism is nevertheless of fundamental significance to the field of radiation effects in electronic devices.

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Table 1: 16K dynamic RAMs tested, including manufacturer, device type, date code, and lid material.

Manufacturer	Device No.	Device Type	Date Code	Lid Material
Texas Instruments (TMS)	25	TMS 4116-25JL	7902	Metal
"	26	"	"	"
"	27	"	"	"
"	21	"	"	"
"	24	"	"	"
"	5	"	7917	"
"	6	"	7845	"
"	2	"	7840	"
"	7	"	7845	"
"	22	"	7902	"
"	23	"	"	"
"	9	"	7845	"
Mostek (MK)	16	MK4116J-2	7940	Ceramic
"	15	"	"	"
"	17	"	"	"
"	18	"	"	"
Hitachi (HM)	3	HM4716A-3	8F1	Ceramic
"	1	"	"	"
"	2	"	"	"
Motorola (MCM)	2	MCM4116AC-25	7917	Ceramic
"	1	"	"	"
"	5	"	"	"

Table 2: Dose rate, upsets, and number of upsets per kilorad for TEXAS INSTRUMENTS TMS 4116-25JL 16K dynamic RAMs.

Device	Rad(CaF$_2$)/pulse	Number of Upsets			Number of Upsets/Krad(CaF$_2$)
		0 to 1	Total	1 to 0	
25	.058	0		1	1.7
25	.35	0		11	3.1
25	.44	0		3	2.3
25	1.1	1		15	13.
26	.058	0		0	0
26	.35	0		2	.57
26	.44	0		0	0
26	1.1	1		2	2.3
27	.058	0		2	3.5
27	.35	1		8	2.6
27	.44	3		4	5.3
27	1.1	0		36	28.
28	.058	0		1	1.7
28	.35	3		3	1.7
28	.44	2		3	3.9
28	1.1	0		4	3.1
21	.25	3		5	3.2
21	.27	2		5	2.4
21	.33	0		1	0.61
24	.25	0		0	0
24	.27	0		1	.33
24	.33	0		1	2.4
5	.57	5		14	2.8
5	.75	0		3	13.
5	.88	0		2	5.7
6	.57	3		10	1.9
6	.75	0		97	430.
2	.66	0		9	2.7
2	.86	1		14	4.9
2	1.7		97		1400.
2	3.1		7994		6.5×10^4
7	.66	1		2	1.4
7	.78	2		0	.99
7	1.0	1		2	2.7
7	1.7	2		1	1.2
7	2.6	0		9	69.
7	4.7		69		750.

Table 2 continues on next page

Table 2 (continued):

		Number of Upsets			
Device	Rad(CaF_2)/pulse	0 to 1	Total	1 to 0	Number of Upsets/Krad(CaF_2)
22	.75	2		71	13.
22	.88	2		4	2.1
23	.75	2		39	7.9
23	.88	1		3	1.5
9	.77	0		1	1.1
9	1.2	0		2	.80
9	1.7	0		5	.77

Table 3: Dose rate, upsets, and number of upsets per kilorad for <u>MOSTEK</u> MK 4116J-2 16K dynamic RAMs.

		Number of Upsets		
Device	Rad(CaF_2)/pulse	0 to 1	1 to 0	Number of upsets/ Krad(CaF_2)
16	.57	0	4	.58
16	.75	0	0	0
16	.88	0	0	0
15	.57	0	2	.29
15	.75	0	0	0
15	.88	0	0	0
17	.66	0	1	.43
17	.86	0	0	0
17	1.2	0	0	0
17	1.7	0	3	3.5
17	2.6	0	10	19.
18	1.7	0	0	0
18	2.6	0	0	0
18	4.7	0	1	.27

Table 4: Dose rate, upsets, and number of upsets per kilorad for <u>HITACHI</u> HM 4716A-3 16K dynamic RAMs.

Device	Rad(CaF_2)/pulse	Number of Upsets	Number of upsets/ Krad(CaF_2)
3	.25	2	.80
3	.27	3	1.0
3	.33	0	0
1	.27	3	2.2
1	.63	1	1.6
1	.71	12	2.8
2	.27	1	.74
2	.63	2	0
2	.71	13	3.1

Table 5: Dose rate, upsets, and number of upsets per kilorad for <u>MOTOROLA</u> MCM 4116AC-25 16K dynamic RAMs.

		Number of Upsets		
Device	Rad(CaF_2)/pulse	0 to 1	1 to 0	Number of upsets/ Krad (CaF_2)
2	.25	0	49	39.
2	.27	3	50	39.
2	.63	0	44	70.
2	.71	8	205	50.
2	.75	1	372	71.
1	.25	7	35	17.
1	.27	0	11	8.2
1	.63	0	8	13.
1	.71	11	83	22.
1	.75	14	161	33.
5	.27	2	30	11.
5	.33	1	8	5.5

Table 6: Absorbed total dose hard failure levels for Texas Instruments, Mostek, Hitachi, and Motorola 16K dynamic RAMs. Devices which did not fail are shown at the highest exposure level reached.

Device	Failure Level (Krad(CaF_2))
TMS 25	>2.2
TMS 26	>2.2
TMS 27	2.2
TMS 28	2.2
TMS 21	>2.4
TMS 24	>2.0
TMS 5	2.5
TMS 6	2.3
TMS 2	1.8
TMS 7	2.8
TMS 22	2.7
TMS 23	2.6
TMS 9	2.8
MK 16	3.3
MK 15	>3.3
MK 17	2.4
MK 18	4.5
HM 3	2.4
HM 1	2.1
HM 2	>2.1
MCM 2	4.0
MCM 1	4.4
MCM 5	>1.5

Table 7: Average values for the number of upsets per kilorad(CaF_2), A, and the standard deviation, S, for the devices tested. Also given are averages by manufacturer ($\bar{A}$, upsets per kilorad(CaF_2)) with standard deviations ($\bar{S}$).

DEVICE	A	S	MANUFACTURER	$\bar{A}$	$\bar{S}$
TMS 25	5.0	4.7			
" 26	.72	.94			
" 27	9.9	10.			
" 28	2.6	.95			
" 21	2.1	1.1			
" 24	.91	1.1	TEXAS INSTRUMENTS	3.9	2.9
" 5	7.2	4.3			
" 6	-----	-----			
" 2	3.8	1.1			
" 7	1.6	.67			
" 22	7.6	5.5			
" 23	4.7	3.2			
" 9	.89	.15			
MCM 2	54.	14.			
" 1	19.	8.5	MOTOROLA	27.	20.
" 5	8.3	2.8			
HM 3	.60	.43			
" 1	2.2	.49	HITACHI	1.4	.66
" 2	1.3	1.3			
MK 16	.19	.27			
" 15	.10	.14	MOSTEK	.34	.37
" 17	.98	1.5			
" 18	.09	.13			