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About the Probability of Destructive Failure Occurrence of 8–Gbit Samsung NAND-Flash Memory Devices in Space.

May, 6, 2009
May, 13, 2009
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Contents

1.Introduction

NAND-Flash memory devices irradiated with heavy ions, suffer from Destructive Failures (DF). It has been shown that DFs originate from ions hitting the control circuitry region of the die, in particular the High Voltage Generator [1, 2].

Based on few DF related tests in the course of the January RADEF campaign we developed three hypothetical models:

1. At Kr (LET = 32) DFs are preceded by a characteristic step wise growth of the write and erase current pulses.
   The stepping up of these pulses prepares the DF occurrence.
   A DF occurs after a critical (saturation) pulse waveform is reached.
   At Xe (LET = 60), but not at Kr we observed also some instantaneous DFs, i.e those where the critical pulse waveform still was not reached.

2. Accordingly the idea was developed that the steps of the write and erase current pulses are connected to separate multiple hits of the sensitive (HV generator) region. At Kr always and at Xe mostly several hits of the sensitive region are needed to initiate a DF.

3. Another presumption, introduced by Daniel Peyre, was that the occurrence frequency DFs decreases with decreasing flux, and that possibly no DFs are possible at the low flux in space.

The April RADEF campaign was focused onto two tasks:

i. To characterize the Heavy Ion response of Micron 8-Gbit NAND-Flash for comparison with the Samsung device, and

ii. To study the occurrence of DFs more thoroughly and in more detail, and to probe the ideas 1. – 3.
   For that purpose prior to the test
   (a) the waveform catching feature of the test bed was improved and dedicated to this task and
   (b) provisions to measure the write / erase time spectrum were built in.

The test showed that the Micron device and the Samsung device behave very similar.
In particular both experience DFs at comparable fluence.

2. DF Related Test Runs

Fig. 1 gives a brief overview of the DF related test runs. Green marks “still alive at the given fluence”, and red “DF” at the given fluence.
In the mode column “array” indicates irradiation of only the cell array including driver bars inside the array region”, and “peri” the complementary case, irradiation of only the control circuitry outside the array region. “3 holes” indicates irradiation of the the cell array excluding the driver bars, and “large” is very similar to “array”.

We verified that no DFs occur if the control circuitry along the array region is masked. If the driver bars inside the array region are masked, then the current pulses remain unchanged during the irradiation.
If the driver bars are not masked, then the current pulses increase up to the saturation waveform, but no DF occurs.
If the array region is masked and the control circuitry open, then DFs occur, and also the current pulses grow up.

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Manufacturer Part Number Size	Device ID	Mode	Ion / Angle / LET [MeV/mg/cm^2] / Temp./Flux																
			Kr										Xe						
			0° vac. 32,1 30°C					0° vac. kapton ≈38 30°C					0° vac. 60 30°C, 3.3V						85°C, 3.6V
			1000	2000	3000	6000	20000	100	200	300	3000	6000	10	30	100	300	1000	3000	30
Samsung	SA-292a	M5	3,01E+05	6,02E+05		7,52E+06						7,28E+05							
K9FWG08U1M	SA-293a	M5	1,50E+05																
4x1Gx8 (32GBit)	SA-294a	M5	3,00E+05		6,00E+05	1,21E+07 *						6,80E+05							
	SA-295a	M5										6,53E+05							
	SA-296a	M5						6,00E+05				1,40E+06							
	SA-297a	M5 array										1,32E+07							
		M5 peri										5,00E+05							
	Sa-298a	M5 peri										6,00E+05							
	Sa-299a	M5 peri										3,00E+05							
	SA-300a	M5							3,50E+05										
	SA-301a	M5							7,25E+05										
	SA-302a	M5						7,66E+05											
	SA-303b	M5				8,90E+06						3,59E+05							
	SA-304b	M5						1,31E+06											
	SA-306b	M2R												2,00E+04					
		M3a												2,00E+04					
		M1																	2,80E+04
		M5																	1,00E+05
	SA-307b	M5												5,00E+04					
	SA-308b	M5												1,00E+05	1,00E+05	1,00E+05	6,00E+04		
	SA-309b	M5												3,50E+04					
	SA-310b	M5											4,70E+04		4,70E+04				
	SA-311b	M5 3 holes															2,00E+06		
		M5 1 large															2,00E+06	5,00E+06	
	SA312b	M3a																1,10E+06	
		M3b																1,10E+06	
		M2R																1,50E+06	
Micron	MC2-3	M5	3,01E+05	6,02E+05		1,30E+07													
MT 29F8G08AAA	MC2-4	M5				1,00E+07													
1Gx8 (8Gbit)	MC2-5	M5				1,21E+07	1,05E+07												
	MC2-6	M3a									1,10E+06								
		M2R									1,50E+06								
		M5										?							
	MC2-7	M5										1,50E+06							
	MC2-9	M5				1,00E+07						1,40E+06							
	MC2-10	M5				2,10E+06													
	MC2-11	M1				5,31E+05													
	MC2-15	M5				1,00E+07						6,00E+05							
	MC2-16	M2R												2,00E+04					
		M3a												2,00E+04					
		M1																	4,00E+03
	MC2-17	M3a													4,00E+04				
		M2R													2,00E+04				
		M5													4,40E+04				
	MC2-19	M1												8,30E+04					
	MC2-20	M3a													2,00E+04				
		M2R													2,00E+04				
		M5													7,79E+04				
	MC2-21	M1													2,80E+04				

*: SA-294: Erase and Program operations with limited functionality after last irradiation step

Fig. 1: Overview of DF Related Test Runs

3. Test of Hypothetical Models

The validation of all three hypothetical models failed.

At Kr we were confronted with all three situations:

a) DF before the saturation current waveform was reached,

b) DF roughly coincident with the time (fluence) where the current pulses reach their saturation waveform (upper write / erase time limit).

c) DF substantially at a later time (larger fluence).

If the saturation waveform (write / erase time limit) is reached, the device can be remain still functional for a rather long time (large fluence increment).

From these observations we conclude that the growth of the write / erase current pulses and the DF occurrence are independent processes. An impending DF can not be predicted by observation of the growth of the write / erase current pulses, e.g. by monitoring the growth of the write / erase time.

To study a potential flux dependence of DF occurrence we performed test runs between 100 and 6000 cm^{-2} s^{-1}. At low flux of 100 or 200 cm^{-2} s^{-1} we observed DFs at roughly the same fluence as at 6000 cm^{2} s^{-1} (3E+5 – 2 E+6 cm^{-2}).
From this finding we are inclined to assume that no flux dependence does exist. Apparently we can not exclude this possibility for much lower fluxes. But this can not be proved within reasonable beam time.

4. DF Threshold Energy

The Kr-irradiation was performed in vacuum. Most of the DUTs experienced no DF, in clear contrast to the previous campaign, where the irradiation was performed in air. Therefore we simulated the increase to about LET = 38 by 5 mm distance in air by a thin kapton foil above the die surface. Then 11 out of 12 DUTs experienced a DF. From this we conclude that the DF Threshold LET is situated at about LET = 30.

5 .Size of the Sensitive Die Region

In consequence of the fact that all three hypothetical models failed, we have to assume that the DF occurrence is a pure statistical single particle effect.
The occurrence probability depends only on the fluence and is determined by the Poisson statistic. The probability density is:

$$f(x,\mu) = \frac{\mu^{x} * e^{-\mu}}{x!} \qquad \mu = n * p;\ \ p << 1, n >> 1$$

In this equation p is the probability of success (= DF occurrence),
and p is the probability that the tiny sensitive region of the die area is hit,
i.e. p is the relative share of the sensitive region in the total die area.
The count of ions hitting the die area A is n = A * fluence F,
and the count of ions hitting the sensitive region until DF occurrence is x.
Here p is a fixed value, and the mean value μ = n * p is in proportion to the fluence F.

Fig. 2 shows the differential probability f(x, n*p) versus n *p, and Fig. 3 the integral probability

$$f_{\text{int}}(x,\mu) = \int_{0}^{\mu} f(x,u)\,du$$

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Fig. 2: Differential Probability f(x, n*p)

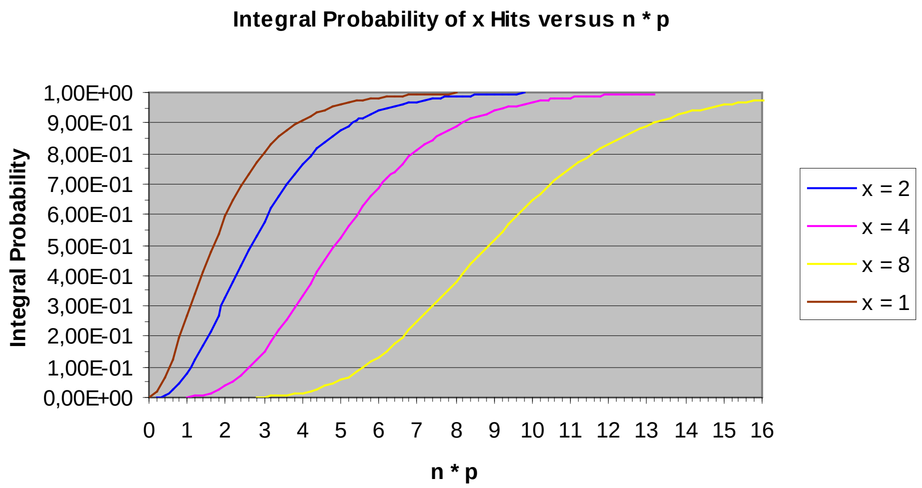

Fig. 3: Integral Probability f_{Int} f(x, n*p)

Device Type	ID	F [cm^{-2}]	F [cm^{-2}]	Remarks
Samsung 4 x 8-Gbit	SA-292a	7.28E5		
	SA-293a	1.50E5		LET = 32
	SA-294a	6.80E5		
	SA-295a	6.53E5		
	SA-296a	2,00E6		
	SA-297a	5,00E5		

	SA-298a	6,00E5		
	SA-299a	3,00E5		
	SA-200a	3,50E5		
	SA-301a	7,25E5		
	SA-302a	7,66E5		
	SA-303b	3.59E5		
	SA-304b	>1.31E6		
Micron 1 x 8-Gbit	MC2-7		1,50E6	
	MC"-9		1,40E6	
	MC2-10		2,10E6	
	MC2-15		6,00E6	
F_average		**7.0E5**	**2,8E6**	

Tab. 1: DF generating fluence F, Krypton, DUT in vacuum, Kapton foil, LET about 38 MeV cm^2 mg^{-1}

According to Tab. 1 the average fluence until DF occurrence is F_{av} = 7.0E5 cm^{-2} for the Samsung die and F_{av} = 2.8E6 cm^{-2} for the Micron die.

The total die area A is about 1 cm^2, and in consequence

$n = F * cm^2$

$n_{av} = F_{av} * cm^2 = 7.0E5$ @ Samsung
$= 2.8E6$ @ Micron

$f_{int}(x, \mu_{av}) = 0.5$ defines μ_{av}:

$\mu_{av} = n_{av} * p$ =1.67 @ x = 1 according to Fig 3
= 2.67 @ x = 2
= 4.67 @ x = 4
= 8.66 @ x = 8

$p = \mu_{av} / n_{av}$ = 1.67 / 7.0E5 = 2.4E-6 @ Samsung, x = 1
= 2.67 / 7.0E5 = 3.8 E-6 @ Samsung, x = 2
a.s.o.

For x = 1, i.e. in case a single hit of the sensitive region generates a DF, the sensitive region occupies a relative share of 2.4 E-6 of the total die area, in absolute figures about 240 μm^2.

6. Destructive Failure Probability in Space

6.1 Example Radiation Environments

The following coarse assessment of the DF probability P_{DF} is based on the LET spectra given in Fig. 4 and 5. It shall illustrate only the order of magnitude of DF probability. More precise assessments have to be based on mission specific LET spectra.

The LET spectra in Fig. 5 are regarded to be calculated for a shielding of 1.5 mm Al.

The mission duration of 10 years is assumed, including ten large flare days distributed over five “worst weeks”.

Fluence of “LET ≈ 30”-Ions in GEO

Fig.4:	GCR:	F = 1E-4 cm^{-2} d^{-1} = 3.6E-1 cm^{-2} / 10 y
	Max. Solar Flare 2.5 mm Al	F = 2E-3 cm^{-2} d^{-1} = 2.0E-2 cm^{-2} / 10 flare days
Fig.5:	GEO, quiet	F = 1.0E-5 m^{-2} s^{-1} str^{-1} = 3.9E0 cm^{-2} / 10 y
	GEO, worst week, 1.5 mm Al ?	F = 1E-4 m^{-2} s^{-1} str^{-1} = 3.8E-1 cm^{-2} / 5 worst weeks

Fluence of “LET ≈ 30”-Ions in LEO

Fig.5:	LEO, quiet	F < 1E-8 m^{-2} s^{-1} str^{-1} = < 3.9E-3 cm^{-2} / 10 y
	LEO, worst week:	F = 1E-6 m^{-2} s^{-1} str^{-1} = < 3.8E-3 cm^{-2} / 5 worst weeks

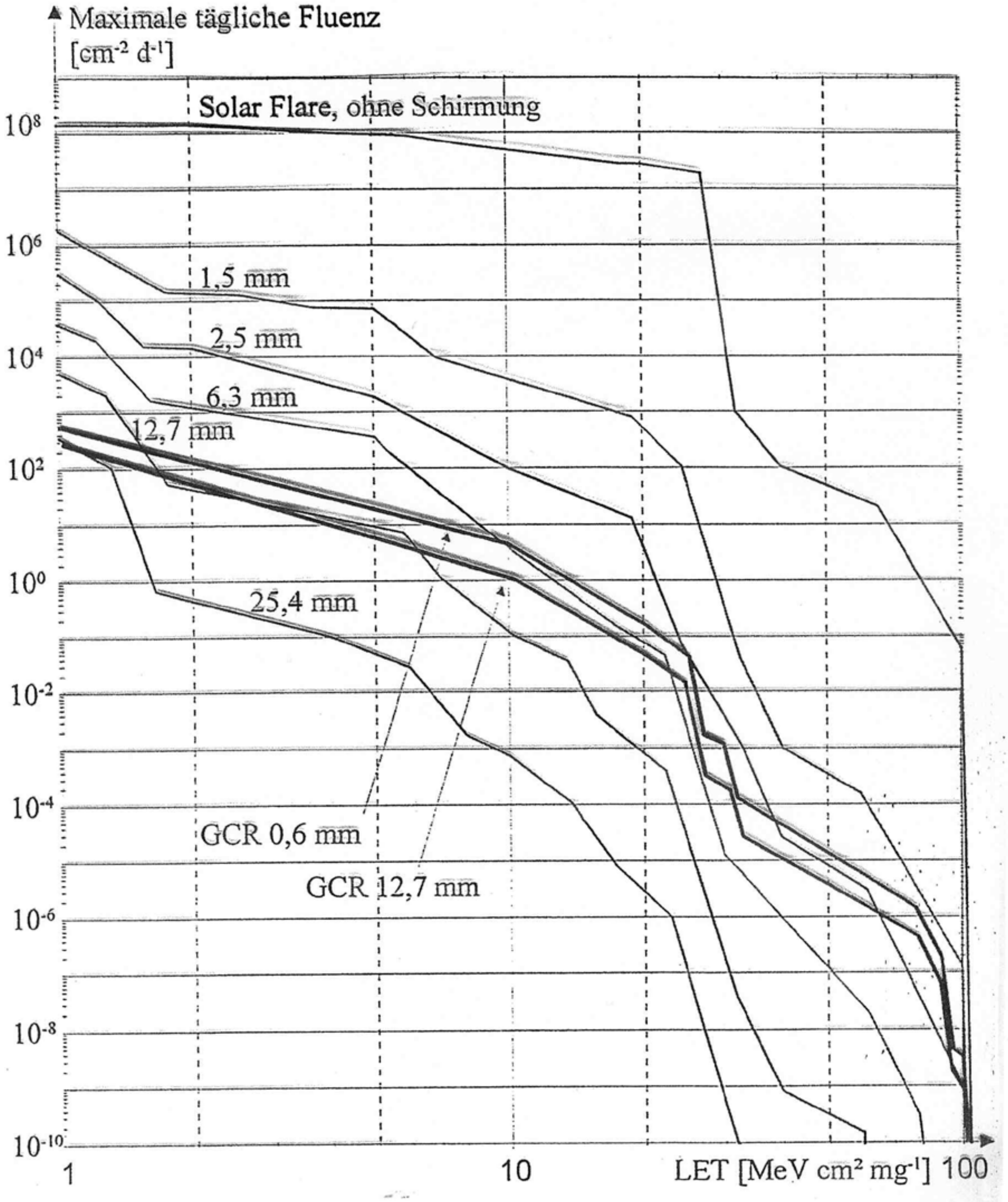

Fig. 4: LET Spectrum at 1 AU [3]

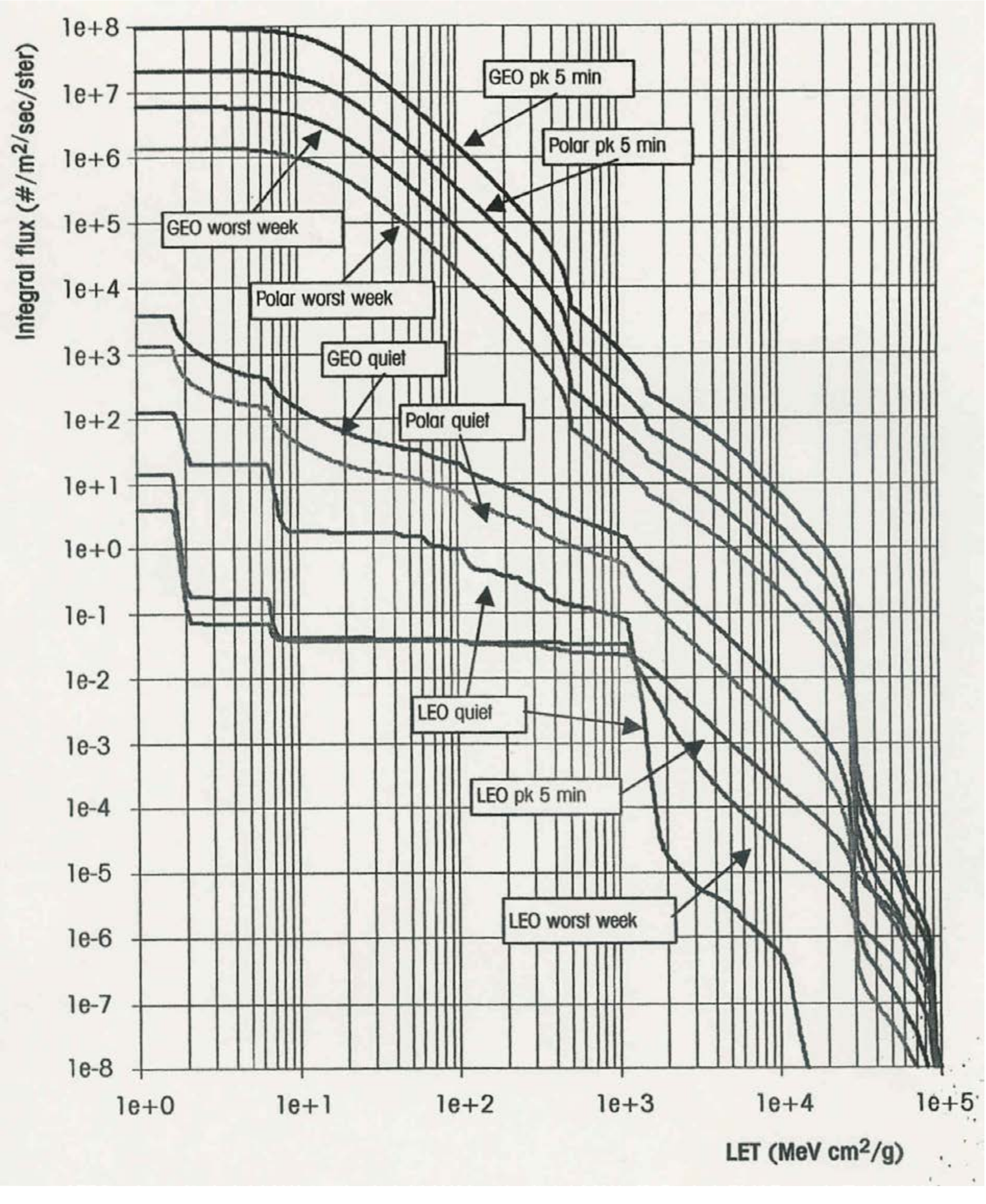

Fig.5: LET Spectrum in GEO and LEO [4]

6.2 DF Probability

$p_{DF} = p * F\ cm^2$

GEO, GCR: p_{DF} = 2.4E-6 * 3.6 E-1 = 8.6 E-7 / dev / 10y

= 2.4E-6 * 3.9E+0 = 9.4E-6 /dev / 10y

GEO, Flare: = 2.4E-6 * 2.0E-2 = 4.8E-8 / dev / 10 flare days

= 2.4E-6 * 3.8E-1 = 9.1E-7 / dev / 5 worst weeks

GEO, Total: p_{DF} **< 1.1E-5 / dev / 10 years**

This value is in rather good agreement with the very coarse assessment in [5] of 3.4E-10 h^{-1} = 3.0E-5 / 10 years.

LEO, GCR: p_{DF} = 2.4E-6 * 3.9E-3 = 9.4E-9 / dev / 10 y

LEO, Flare: = 2.4E-6 * 3.8E-3 = 9.1 E-9 / dev / 5 worst weeks

LEO, Total: p_{DF} **1.9 E-8 / dev / 10 y**

The DF probabilities assessed above do not take into account that the device is sensitive to DFs only during Write and Erase operations.
Within a large memory only a small fraction of Flash devices will be powered at a time, and again only a fraction of them will be operated in Write or Erase mode.
Therefore the figures given above should be multiplied by an application specific duty cycle of write / erase operations, which typically will be less than 0.01.

For comparison, the typical failure rate of memory devices is in the order of 1 Fit = 1E-9 h^{-1} = 8.6E-5 / 10 years. Accordingly at GEO the DF rate and the failure rate are in the same order of magnitude. At LEO the DF rate is negligible against the failure rate.

7. Summary

The relative size of the sensitive die area has been assessed based on the results of the last SEE test at RADEF. Every ion of LET > 30 MeV $cm^2\ mg^{-1}$ is regarded to create a DF. Then the DF in GEO is in the order of 1E-5 / 10 years and therefore, comparable to the typical failure rate of state of the art memory devices. In LEO the DF rate is negligible against the failure rate.

8. References

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