EN Engineering Department

RADECS 2011 Résumé

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- ***"Synergy of non-ionizing and ionizing processes in the reliability degradation of Power MOSFETs oxide" M. Naceur et al., (University of Montpellier 2)***
- A breakdown is considered to occur when the gate current (leakage current) drastically increases (insulator between gate and channel stops performing as such).
- Charge breakdown reduction after electric stress is observed after heavy ion irradiation at two energies exhibiting a similar LET value.

PA-12

- Two main type of radiation induced failures have been identified on Power MOSFETs: Single Event Gate Rupture (affecting the functionality of the gate dielectric) and Single Event Burnout (resulting in a drain to source shortening).
- Devices that do not exhibit oxide breakdown (SEGR) during irradiation tests might however exhibit a lifetime decrease due to the creation of latent defects within the oxide layer.

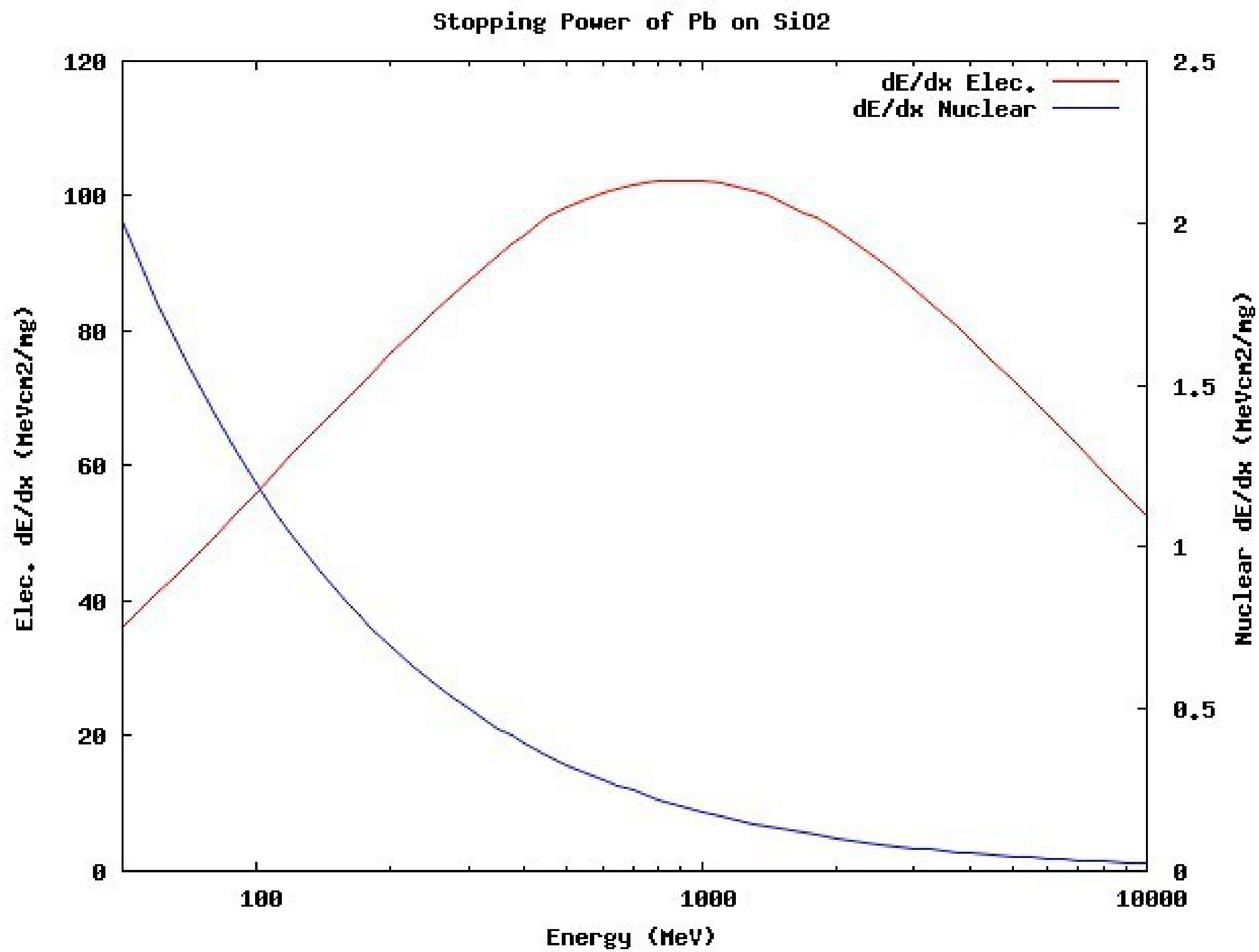
- Limitations of the LET concept as a parameter for radiation damage:
  - For the same ion, the same LET can be achieved with very different energies (different sides of the Bragg peak).
  - Considering only the initial LET value of the beam neglects the energy loss through upper layers with respect to the active zone.
- The current work concentrates on the gate oxide layer degradation (grounded devices during irradiation) as opposed to the effects on the active area of the operating device (biased devices).

PA-12

- Experimental procedure: Irradiation at the GANIL Facility with ^{208}Pb ions of ~110 MeV and ~6 GeV (LET~60-70 $MeVcm^2/mg$).
- High Electrical Field Stress tests were performed after irradiation, measuring the charge to breakdown value of the oxide.
- The charge to breakdown reduction is more important lower energy for similar LET values (contrary to what is observed in devices under bias) ☒
- The electronic *dE/dx* is decreased of a factor ~2 between the surface and the oxide layer for $E(^{208}Pb)$=108 MeV ☒

- The enhanced degradation at low energies can be attributed to higher energy loss due to nuclear reactions within the oxide layer. The nuclear stopping power is 50 times larger for the low energy case (5% of total energy loss). ☑
- These non-ionizing processes can lead to non-trivial densities of atomic displacements which can act as an extra contribution favoring early breakdown.
- NIST definition of Nuclear Stopping Power: average rate of energy loss per unit path length due to the transfer of energy to recoiling atoms in elastic collisions.

PA-12


Stopping Power of Pb on SiO2
dE/dx Elec.
dE/dx Nuclear
Elec. dE/dx (MeVcm2/mg)
Nuclear dE/dx (MeVcm2/mg)
Energy (MeV)
120
100
80
60
40
20
0
2.5
2
1.5
1
0.5
0
100
1000
10000

PA-4

- ***"Rediscovery of Single-Event Gate Rupture Mechanism in power MOSFETs" Satoshi Kuboyama et al. (Japan Aerospace Exploration Agency)***
- Suggestion of a new possible mechanism for SEGR in power MOSFETs.
- SEGRs are detected by abrupt increase in the gate and drain currents during heavy ion irradiation under reverse bias conditions and are attributed to the gate dielectric breakdown between the gate and the drain.
- Testing: 768 MeV Kr ions (LET=32 $MeVcm^2/mg$) at the RADEF facility in Finland.

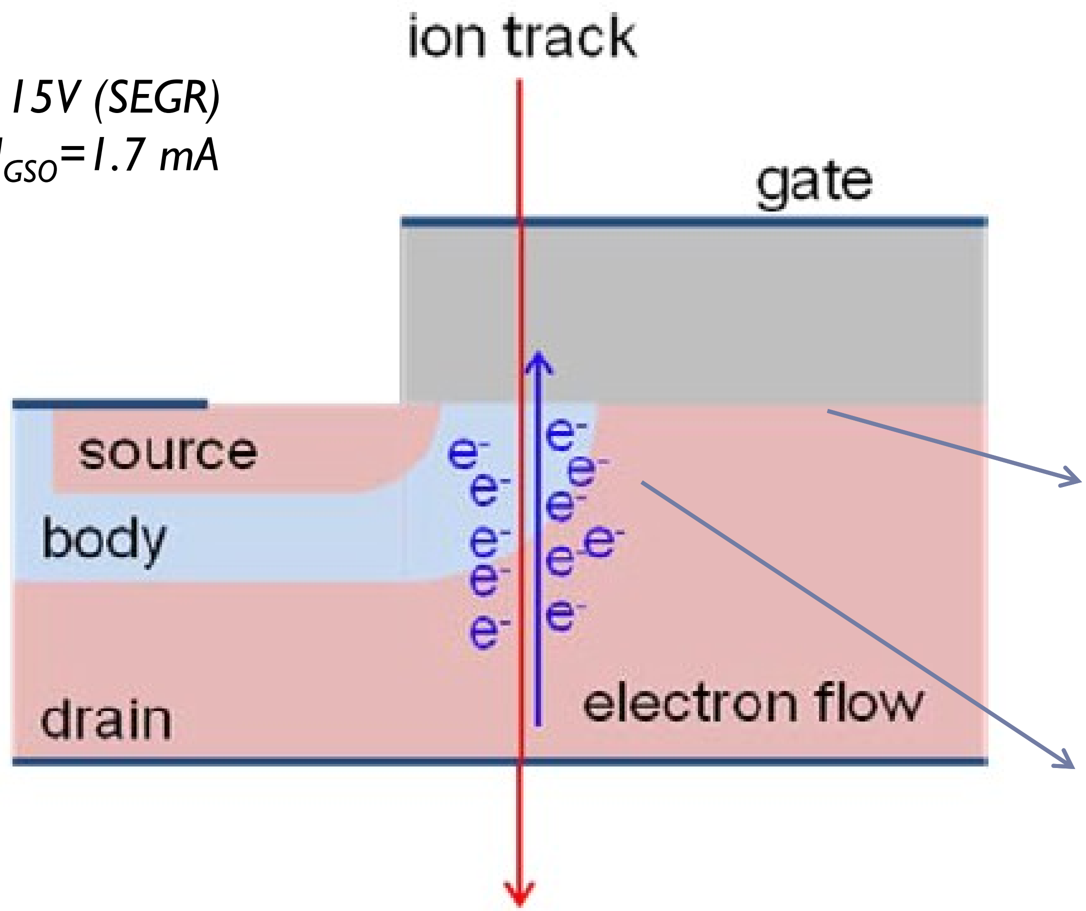
PA-4

- Traditionally, SEGR are associated to damages located inside the oxide faced on the drain region, where the maximum electric field is generated when an incident ion perpendicularly passes through the region (the body is usually grounded).
- However, the I_{GDO} value measured experimentally during the SEGR is too small if the oxide between the gate and the drain was damaged by the event. ☒
- Because the charge to breakdown depended on the energy of the electrons injected as opposed to the oxide field, the SEGR was located inside the oxide faced on the body region. ☑
- The drain current pass through the body-drain region where no damage was observed even after the SEGR might be explained by minority carrier injection effect in an analogous way than bipolar transistors.

PA-4

p-channel power MOSFET
for space applications

V_{GS}=12.5V → 15V (SEGR)
I_{GDO}=2.3nA I_{GSO}=1.7 mA



highest electric field region

damaged region observed experimentally

A3

- ***"GEANT4 Analysis of n-Si Nuclear Reactions from Different Sources of Neutrons and Its Implication on Soft-Error Rate" S. Serre et al. (University of Aix-Marseille)***
- GEANT4 simulations in order to compare different testing facilities and atmospheric environments, and their impact in the soft error rate of a widely characterized 65nm SRAM.
- Terrestrial neutron radiation now recognized as one of the primary sources of ground soft-errors in microelectronics.
- The capability of the test source to reproduce natural neutron spectra is fundamental in the estimation of the SER.

A3

- Creation of a large database of n-Si interactions.
- Neutron sources compared: terrestrial spectrum at NY, TRIUMF Neutron Facility, neutron source of the LANSCE ICE House + 4 additional mono-energetic values (1, 10, 100 and 1000 MeV).
- Considered Geant4 processes for neutron interactions: elastic, inelastic, fission and capture.
- For each neutron source, 5.10^8 particles are generated incident on a 20 μm thick silicon perpendicular to its surface ($1 cm^2$). All the resulting recoil nuclei with a kinetic energy above 40 keV and secondary charged particles (except electrons and pions) are recorded.

A3

- Mono-energetic results: 1 MeV neutrons exclusively induce silicon recoil nuclei whereas 1 GeV neutrons produce the most numerous fragments (notably protons and ions ranging from $_{3}Li$ to $_{11}Na$), including the production of $_{15}P$ by capture of a secondary proton by $_{14}Si$ nuclei.
- Importance of the low energy part [1-10 MeV] producing the largest part of silicon recoil nuclei that should induce a non-negligible part of soft-errors.
- Analysis includes secondary ion production, energy histogram of produced ions, nuclear reaction-induced shower multiplicity and ratio of elastic/inelastic processes.

A3

- For the SER estimation part, the database files were inputted into the TIARA simulation code.
- Upset occurrence criteria: if the ionizing product directly impacts a sensitive drain, a critical LET value is considered; otherwise, the transient current collected by the contact is computed following a collection-diffusion model.
- Experimental SER rate obtained as ASTEP in very good agreement with estimated values.

A3

TABLE II
CHARACTERISTICS OF THE DATABASES GENERATED FROM THE IRRADIATION OF A 20 μM THICK SILICON LAYER WITH 5×10^8 NEUTRONS.

Neutron source	Total number of events[1]	Total number of generated products[2]
1 MeV	86,682	86,682
10 MeV	79,228	101,016
100 MeV	49,961	90,808
1 GeV	39,731	106,493
JEDEC	66,364	93,715
LANSCE	71,054	92,935
TRIUMF	61,077	84,509

[1] Elastic+inelastic events
[2] Silicon recoil nuclei (E>40keV) + secondary ions

from the original paper "1 MeV neutrons exclusively induce silicon recoil nuclei whereas 1 GeV neutrons produce the most numerous fragments"

from FLUKA .out file

E_n(MeV)	λ_{inel} (cm)	λ_{el} (cm)	N_{inel}	N_{el}
1	~1E+30	~1E+30	-	-
10	18,25	28,74	54800	34700
100	43,10	31,24	23200	32000
1000	43,78	91,10	22800	11000

PA-7

- ***"Influence of the manufacturing process on the radiation sensitivity of fluorine-doped silica-based optical fibers" A. Alessi et al. (Université Jean Monnet, Saint-Etienne, France)***
- Increasing need for radiation-tolerant optical fibers operating in the ultraviolet and visible range of wavelengths for diagnostics of the future facilities devoted to fusion studies, both by inertial or magnetic confinement.
- Dopants (Ge, P, N, F) are added to silica to allow optimizing the refractive-index profile in order to adjust dispersion.

PA-7

- F-doped silica represents a key material for the production of optical fibers with enhanced and stable transmission properties in the spectral range for IR to UV.
- Its presence decreases the number of strained bonds resulting in an increase of the radiation hardness.
- The purpose of the work is to investigate the Radiation Induced Absorption (RIA) origins in the fluorine-doped fibers for different deposition techniques.
- After gamma and X-ray radiation, evidence was found of the strong impact of the chlorine on the radiation induced losses at ~ 3.5 eV (355 nm).

C1

- ***"Influence of proton elastic scattering on soft error generation of SRAMs" M. Kosmata et al. (Helmholz-Zentrum Dresden)***
- Influence of elastically scattered protons at energies well bellow the Coulomb barrier for p-Si inelastic reactions (4.2 MeV).
- For the component tested, a 32 nm SRAM cell, the LET threshold value was evaluated through He ions and found to be 0.3 MeVcm^2/mg (Q_{crit}=25 fC, E_{crit}=5.6 keV). For protons, SEU generation from direct ionization is only possible if the protons enter the sensitive volume with an energy between 9 and 400 keV.

- For *E<4.2 MeV*, nuclear reactions can be neglected. For *E>0.4 MeV*, the direct ionization is not enough to cause an upset. Errors deriving from protons in the energy window bellow these two values are attributed to elastic backscattering.
- The energy of the backscattered projectile after collision with respect to the initial energy is reduced by a factor *K*:

$$K = \frac{\sqrt{M^2 - m^2 \sin^2\theta} + m\cos\theta}{M + m} \;\Rightarrow\; \begin{aligned} K\left(\theta = \frac{\pi}{2}\right) &= \frac{M - m}{M + m} = 0.93 \\ K(\theta = \pi) &= \left(\frac{M - m}{M + m}\right)^2 = 0.87 \end{aligned}$$

C1

- For normal incidence, the residual energy of the backscattered proton is calculated analytically:

$$E_R(z) = K.\left[E_{inc} - \int_0^z S(E)dx\right] - \int_0^{\frac{z}{\cos\theta}} S(E)dx$$

- With this, the expression of the Rutherford cross section and some geometrical considerations, the yield of backscattered protons reaching the device with *9 keV < E < 400 keV* can be calculated for a given incident energy and compared experimentally though the measured SEU rate.
- Because of the $1/\sin^4(\theta/2)$ scaling of the cross-section, most backscattered protons hit the sensitive volume at angles nearly parallel to the surface, increasing the probability of MBU.
- Analytical results are in good agreement with measurements.

C7

- ***"Impact of total ionizing dose on the electromagnetic susceptibility of a single bipolar transistor" A. Doridant et al. (IES-UM2 and TRAD)***
- Space and military electronic components are subject to both electromagnetic fields and total ionizing dose. It is important to study the synergy between TID and EMI on integrated circuits.
- Electromagnetic interferences were introduced at frequencies of aggression between 100 MHz and 1.5 GHz for a bipolar transistor with a peak transition frequency of 200 MHz, before and after irradiation of 150 krad. Substantial differences were observed and need to be explained.

PC-3

- ***"Terrestrial Neutron-Induced Single-Event Burnout in SiC Power Diodes" H. Asai et al. (High-Reliability Engineering & Components Corporation)***
- Tolerance against single-event burnout (SEB) caused by terrestrial neutrons is one of the urgent issues in practical applications of power devices.
- The SEB is initiated by energetic secondary ionizing atoms induced by neutrons within the semiconductor substrate.
- In the high-electric field region of a reverse biased power device, the initial charge deposited by a secondary atom is amplified.

PC-3

- Silicon carbide (SiC) has been said to have far more suitable characteristics for high voltage and high temperature device applications than silicon.
- A transportable proton recoil detector (TPRC) to measure strong high neutron fluence used for SEE testing was developed and used in LANSE/WNR (Los Alamos Neutron Science Centre) and RCNP (Research Centre for Nuclear Physics) in Japan.
- The DUT was reverse biased during neutron irradiation. The measurements detected abrupt increases in reverse current caused by the SEB.

PC-3

- At RCNP, in order to reproduce the terrestrial neutron environment, the 392 MeV protons are injected into a W target and spallation neutrons are collimated into a beam. Charge particles are removed by a clearing magnet.
- The shape of the RCNP spallation neutrons from 5-300 MeV reproduces the terrestrial spectrum times $1{,}5.10^{8}$.
- The new TPRD method is accurate enough to provide us a practical reference of the integral flux of RCNP spallation neutrons for SEE testing purposes.
- The dependence of the SEB rate with applied voltage was measured (as V_{DS} increases there is a higher chance of SEB)

PC-3

- Manufacturer difference affects strongly on neutron SEB tolerance of SiC power diodes.
- By applying PHITS simulations, the type of nuclei, energy and yields of the secondary particles generated by the nuclear reactions between terrestrial neutrons and substrates of Si and SiC devices were calculated.
- The amount of C secondary atoms generated in the SiC device is much larger, and these energetic C ions may increase the SEB cross-section because they have higher energies and ranges than the Si.

PC-10

- ***"Neutron-Induced Multiple Bit Upsets on Dynamically-Stressed Commercial SRAM Arrays" P. Rech et al. (UM2)***
- Experimental data demonstrate that the dynamic-stress increases SRAMs sensitivity and MBU occurrence.
- Memories are becoming the main responsible of the overall Silicon on Chip error rate.
- This paper intends to analyze the occurrence of MBUs due to neutrons in memory arrays.
- TSL facility in Uppsala (Sweden) with neutron beams between 50 and 180 MeV.
- Neutron-induced error rate of SRAM arrays can increase if operations are continuously applied to the memory.

PC-10

- Different chips of commercially available SRAMs of 4Mbit and 32Mbit built in a 90nm technology by the same vendor were tested.
- A controller was used that continuously applied write or read operations to the array and detected radiation-induced errors. Stimuli could be sent at 20 MHz.
- In a static test, a known pattern is written in the whole memory and the array is read back after a predefined accumulation time to detect mismatches.
- In a dynamic test, the array is continuously accessed and the memory-bot cells stimulated at speed.

PC-10

- This sequence of operations realistically describe the typical utilization of memories in which the same location is usually read or modified very frequently.
- For realistically evaluating the SER of SRAMs in operation it is not sufficient to perform static or traditional dynamic tests.
- The novelty of this work is the application of the dynamic-stress test in order to measure the occurrence of MBU in the array under operating conditions.
- Results: both memory types have a higher cross section when dynamic-stress test is applied.

E-5

- ***"A Monte-Carlo Engineer tool for the prediction of SEU proton cross section from heavy ion data" C. Weulersse, F. Wrobel et al. (EADS, IES-UM2)***
- Energetic protons typically cause failures through the ionization of secondary particles from a nuclear reaction with a material nucleus.
- Usually no proton tests are scheduled if the threshold LET is larger than 15 $MeVcm^2/mg$.
- In order to reduce costs and time, several attempts have been proposed to derive proton cross section from HI data by making several assumptions.

E-5

- PROFIT:
  a) Deterministic model that assumes that each cell has a different critical energy and that all interactions are elastic.
  b) The inputs are the device depth and the average diffusion angle for protons (2 μm and 90° by default).
  c) The shape of the HI cross section is now attributed to intra-cell sensitivity variations.
  d) Koga et al have shown discrepancies larger than an order of magnitude between profit results and proton experimental data on DRAMs and SRAMs.
- SIMPA is semi-empirical and convolutes the HI cross section with the measured energy deposition spectra (in diodes).

- PROFIT formalism (LET criteria):

$$\sigma_p(E_p) = \int \sigma_{HI}(L)\, p_{Ep}(L)\, dL$$

analytical (example from J. Barak 2006)

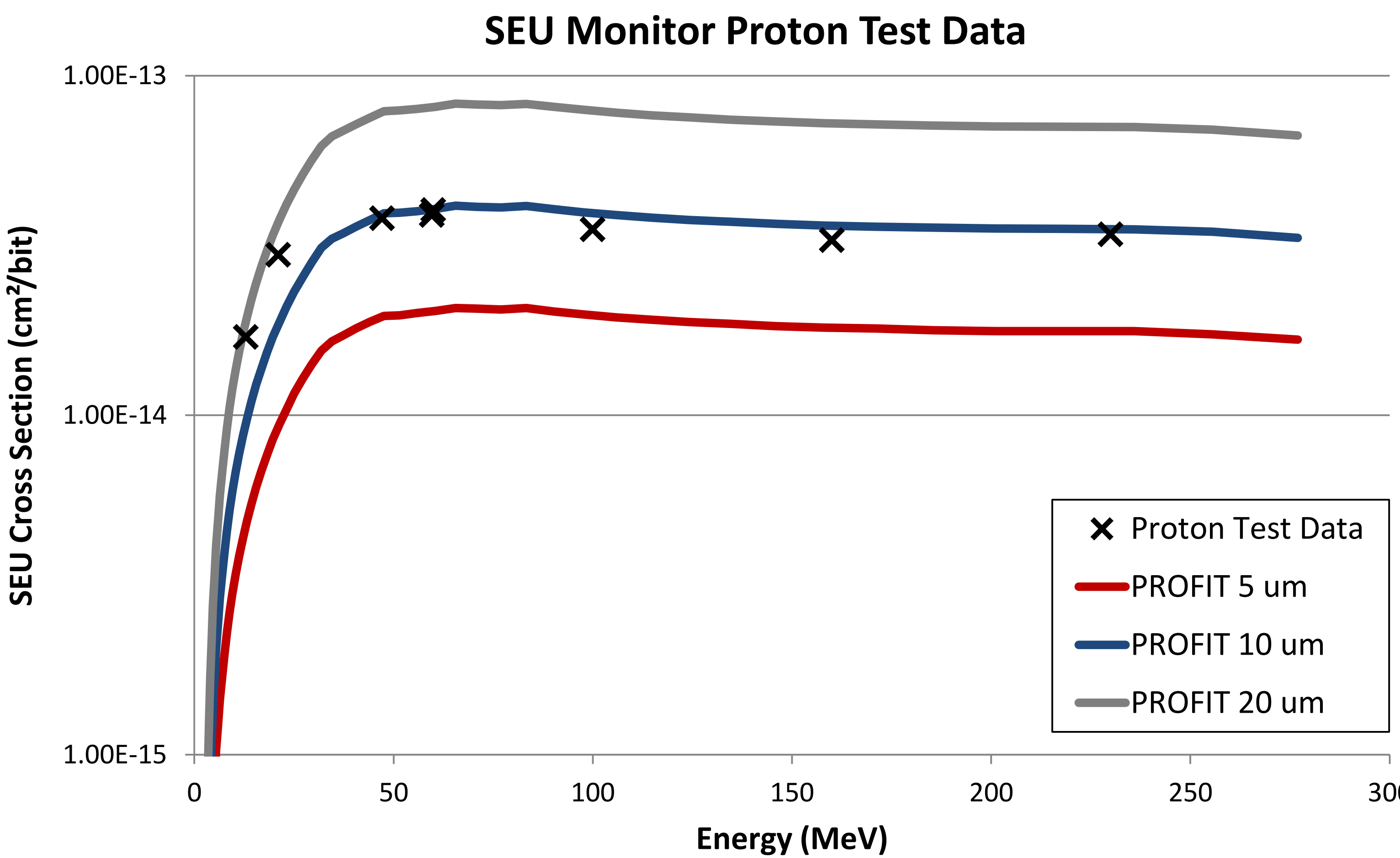
$$p_{E_p}(L) = 4x10^{-6} \exp[-(0.134 + 9E_p)/L]$$

- SIMPA formalism (Deposited energy criteria)

$$\sigma_p(E_p) = \int \sigma_{HI}(E_d)\, p_{Ep}(E_d)\, dE_d$$

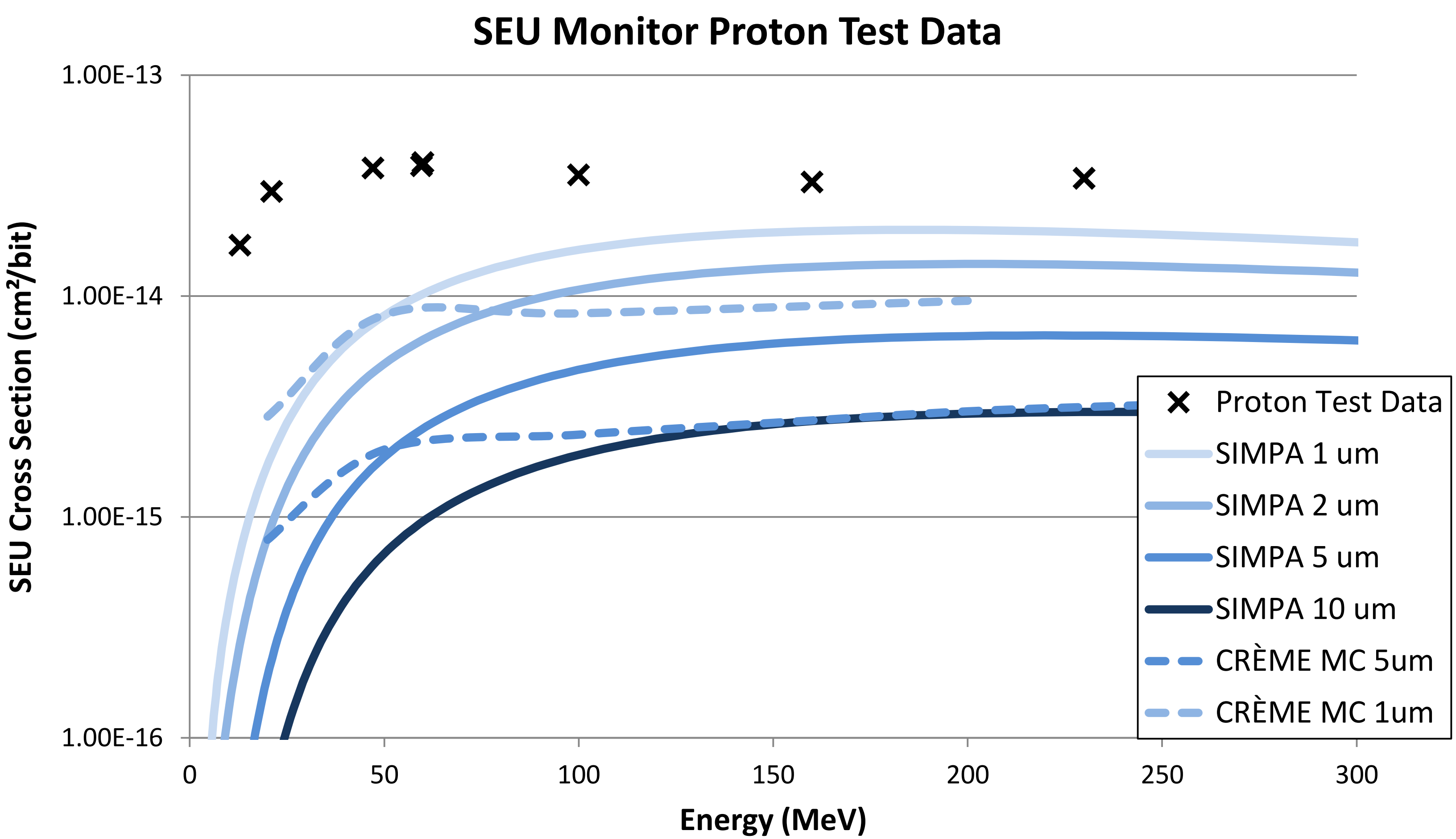
measured (in METIS, obtained through library of physical MC simulation)

Results from tool-application in house: PROFIT output compared with proton test data for the ESA SEU monitor for different device thicknesses.



(E-5)

Results from tool-application in house: SIMPA output compared with proton test data for the ESA SEU monitor for different device thicknesses.



E-5

- Monte-Carlo methods use a physical description that follows each secondary ion and calculates the collected energy in sensitive regions.
- Combined with a detailed description of the device, they could avoid HI data.
- Deterministic (analytical) models which use simplified criteria are applied for simple structures and seem not to be relevant for advanced process devices.
- The MC approach remains the only solution to take the effect of secondary particle into account. MC based tools are more time consuming.

E-5

- An MC prediction tool is proposed which uses the same expression as the SIMPA methodology as a connection between HI and proton data:

$$\sigma_p(E_p) = \int \sigma_{HI}(E_d) p_{Ep}(E_d) dE_d$$

- The probability for energy deposition is not approximated by an analytical expression but is calculated using a MC selection of nuclear interactions from a pre-calculated database.
- In order to explain the HI cross section shape in terms of intra-cell variation, it is assumed that the greater the LET is, the larger is the sensitive area.

- For each reaction given by the precompiled nuclear database (validated experimentally), the energy deposited by the secondary ions is calculated through SRIM.
- The deposited energy is compared to the critical energy.
- The procedure is repeated for a large number of reactions (~1e5).

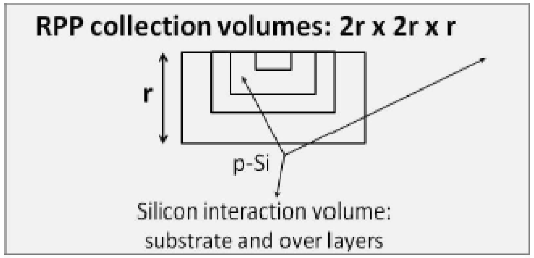


Fig. 1. Schematic of the sensitive and interaction volumes used in METIS, $(2r)^2$ is the surface of a sensitive volume and is equal to the heavy ion cross section, the thickness of Silicon material above the sensitive volumes is 20 μm.

$$E_{crit} = LET_i t_i$$
$$SV = 2r \times 2r \times r = \sigma_i^{1/2} \times \sigma_i^{1/2} \times \sigma_i^{1/2}/2$$

- Nuclear databases contain elastic scattering and nuclear reactions and provide a detailed history of secondary ions.
- For each reaction given by the pre-compiled database the deposited energy by the secondary ions is calculated analytically (using the different sensitive volumes).
- Advantages:
  a) It is able to treat isotropic or anisotropic environments
  b) It is possible to simulate to SVs in order to consider the two OFF state drains (relevant for SRAMs, but similar results are obtained)
  c) Using a neutron database, atmospheric environments can be used.
  d) It can easily consider nuclear interactions with other elements that Si
  e) Estimation of multiple bits is feasible
  f) The other methods mostly underestimate the experimental data

PH-7

- ***"PROBA-II Technology Demonstration Module in-flight data analysis" R. Harboe-Sorensen et al (ESA)***
- The orbital parameters of the PROBA-II satellite are an altitude of 700-800 km (inner radiation belts) and an inclination of 98 degrees.
- The TDM is on since Feb. 2010 and consists of 4 different radiation effects experiments:
  1) SEUs in the Reference SEU Monitor (4 SRAM devices)
  2) Latch-up events in 4 different SRAM devices
  3) In-flight tech. demonstration of FLASH memories
  4) RADFET dosimeters for total ionizing dose measurements

PH-7

- The two RADFETs have been manufactured employing two different lids. As RADFET degradation with TID is sensitive to temperature, this value is measured by sensors.
- Even if the temperature only changes between +41°C and +54°C (average of +49°C) major variations are observed in the RADFETs performance.
- No differences between both RADFETs were observed, which had an initial V_{th} of 1.366V.
- When the temp. increases to 54°C decreasing values of V_{th} are recorded.
- Strong RADFETs increases are clearly visible when temp. decreases (the radiation environment is excluded as a cause of the variations as it is fairly constant over this period).
- 80 mV change in 18 months resulting in a TID measurement of 450 Rads, consisted with what was expected for the orbit.

PH-7

- Most SEEs are observed in the South Atlantic Anomaly and therefore induced by protons.
- The TDM SEU experiment is performed on the Atmel AT68166 MCM, selected due to its substantial SEU characterization available.
- 849 SEUs observed occurring over 403 days. The rates in terms of SEUs per day are:
  - 2.1 SEU per day for the Proba-II orbit (2.8 with CREME96 sim.)
  - 620 SEU per day for the H4IRRAD env. (650 with FLUKA sim.)
- The SRAMs in the SEL experiment are protected with current limiting circuits. It is performed on 4 different memory types having very different SEL characteristics.

Sum-up

Paper	Comments
PA12	Enhanced oxide degradation in non-biased power MOSFETs for low-energy ions attributed to the synergetic effect of nuclear displacements and charge deposition. Limitations of LET formalism that only considers direct ionization.
PA4	Gate dielectric breakdown observed in gate-body region as opposed to gate-source region (where expected due to highest electric field generated by ion strike)
A3	n-Si interaction library and interface with calculation of upsets due to sencodaries considering LET criteria when impacting sensitive drain and transient model otherwise.
C1	Proton-induced upsets can be due to the reduction of the energy of the primary due to the trajectory in the substrate and the changing in direction due to elastic backscattering, resulting in higher LET value and higher MBU probability.

Sum-up

Paper	Comments
PC3	SiC is more suitable than Si for high-voltage, high-temperature power diodes. C secondaries are more abundant and energetic that those from Si, making new devices potentially more prone to SEB.
PC10	Both SEU and MBU are increased when memories are accessed dynamically during testing.
E5	MC approach to obtain proton XS from HI data that produces better predictions than previous analytical and semi-empirical tools.
PH7	Observed on-board (proton induced) SEU rate consistent with analytical simulations. High dependence of RADFET response with temperature.