What is changing in radiation hardness assurance?

THE CHALLENGE OF TECHNOLOGY EVOLUTION

R. Ecoffet, CNES
Introduction and some in-flight feedbacks
Radiation effects on electronics

Destructive

Cumulative

All technologies

Electron-hole pairs

Ionizing dose

Parametric drift
Functional failure (lifetime)

Vacancies - interstitials

Displacement damage

Single event

Optoelectronics
Bipolar

CMOS bulk, power MOSFETs, Power diodes

Short-circuit or dielectric breakdown
SEL, SEB, SEGR

Possible immediate destruction
Radiation effects on electronics

Non destructive

Analog

False signal SET

Disjunction
Redundancy swapping
De-synchronization
Gain change,…

Digital

False information SEU, MBU

False data
Program errors
Processor crash,…

Detectors Imaging

False pixel

False stars
Degraded images
Saturated pixels
Oscillating pixels,…

Single event effects
Hazard zones in low Earth orbit

Increased risk from solar events and cosmic rays

Increased risk from trapped protons
Low Earth Orbit in-flight feedback

1078 “anomalies”, 12 LEO satellites, 11 types of units
Low Earth Orbit in-flight feedback
Low Earth Orbit in-flight feedback
Low Earth Orbit in-flight feedback
## Lifetime

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Built for - by</th>
<th>Designed for</th>
<th>Survived</th>
<th>Received vs Specification</th>
<th>End of service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot-1</td>
<td>CNES – Matra Espace</td>
<td>5 years</td>
<td>17 years</td>
<td>x3</td>
<td>Not because of radiation</td>
</tr>
<tr>
<td>Hipparcos</td>
<td>ESA – Matra Espace</td>
<td>5 years in GEO</td>
<td>5 years in GTO</td>
<td>x7</td>
<td>Because of radiation</td>
</tr>
<tr>
<td>Inmarsat-2 F1</td>
<td>Inmarsat – Matra Espace British Aero.</td>
<td>10 years</td>
<td>22 years</td>
<td>x2</td>
<td>Not because of radiation</td>
</tr>
<tr>
<td>Jason-1</td>
<td>CNES - TAS</td>
<td>5 years</td>
<td>11 years</td>
<td>x2</td>
<td>Not because of radiation</td>
</tr>
<tr>
<td>Integral</td>
<td>ESA – Alenia Spazio</td>
<td>5 years</td>
<td>15 years</td>
<td>x3</td>
<td>Still in operation</td>
</tr>
</tbody>
</table>

x2, x3 mission levels → can survive  
x7 mission level → failure  
Gives an idea of the real safety margin  
- At least for satellites built with 1980-2000 technologies -
Dose calculations - yesterday

GEO
~20 krad / year
15 years : 300 krad

Outer electron belt

Proton belt and inner electron belt

Center of a 1 g/cm² (3.7 mmAl) solid sphere

AE8 Max / AP8 Min - Circular Orbits
Dose calculations - today

GEO
~1 krad / year
15 years : 15 krad

Outer electron belt

Proton belt and inner electron belt

MEO Navigation

PMOS dosimeter
CARMEN-2
JASON-2

LEO Constellations

LEO Observation Constellations

AE8 Max / AP8 Min - Circular Orbits

GALILEO
GPS
GLONASS
O3B
GLOBALSTAR
JASON

PMOS dosimeter
CARMEN-2
JASON-2

Dose calculations - today
Lessons learned

- **Ionizing dose**
  - Hidden margins: environment models, shielding description, application temperature, annealing
  - In Earth orbit, except in very particular cases, there is always a solution to dose

- **Single event effects**
  - Are an issue – one of the major causes of spacecraft “anomalies”
  - And new technologies may bring additional challenges (next slides)
Electronic technologies today and in the near future
Miniaturization

- Steady trend
  - Up to now, every prediction of a limit has been contradicted

http://www.spinograph.org/blog/why-nanoelectronics-better-microelectronics
About the same scale of structuration than elementary living matter

This virus (bacteriophage) is about 200 nm tall and 65 nm wide
Compared dimensions

280 MeV Fe

28 GeV Fe

scale. 5 μm
Dimensions

Width of DNA helix ~2 nm

Cascade from 20 keV PKA

Intel 22 nm node gate fin

Investigation of point and extended defects in electron irradiated silicon—Dependence on the particle energy: Journal of Applied Physics: Vol.117, No 16

http://www.edn.com/Home/PrintView?contentItemId=4395587
“New” materials : elements

- A large part of the periodic table is now used in technology
  - May become a strategic procurement issue (+ ethical and environmental issues)
  - Large part of non tabulated interactions

US Securities and Exchange Commission
https://www.sec.gov/Archives/edgar/data/1101302/000119312516645958/d225180dex991.htm
“New” materials: compounds

Micro-structuration: example of transistor gate evolution

Adapted from: http://semimd.com/applied/files/2013/12/Transistor_Blog_2.jpg
Micro-structuration : today

- Intel 22 nm node
- 9 Cu metal layers, W contacts, Ge and C implants

Those technologies are already in your smartphone

Micro-structuration: foreseen future

Quantum well transistors

M. Radosavljevic et al. (Intel), Non-Planar, Multi-Gate InGaAs Quantum Well Field Effect Transistors with High-K Gate Dielectric and Ultra-Scaled Gate-to-Drain/Gate-to-Source Separation for Low Power Logic Applications, Fig. 1: Evolution of InGaAs QWFET from planar to non-planar, multi-gate architecture, IEDM10-126, 978-1-4244-7419-6/10/$26.00 ©2010 IEEE
Complexity: interconnections

Intel 22 and 14 nm processes

80 nm minimum pitch
9 interconnection layers

52 nm (0.65x) minimum pitch
11 interconnection layers

Complexity: 3D patterns

Traditional Planar Transistor

22 nm Tri-Gate Transistor

22 nm Tri-Gate Transistor

22 nm Tri-Gate Transistor

22 nm Tri-Gate Transistor

https://electroiq.com/2012/09/horizontal-channels-key-to-ultra-small-3d-nand/
https://www.notebookcheck.net/Micron-intros-its-first-3D-NAND-memory-for-mobile-devices.171198.0.html
**Complexity: 3D patterns**

Intel’s 22-nm embedded DRAM stack

Stanford’s Nano-Engineered Computing Systems Technology (N3XT)

MEMS

[http://chipworksrealchips.blogspot.fr/2014/02/intels-e-dram-shows-up-in-wild.html](http://chipworksrealchips.blogspot.fr/2014/02/intels-e-dram-shows-up-in-wild.html)
Impacts on radiation effects: more interactions

Courtesy Jean-Luc Autran, RADECS 2013 Short Course
Complexity: transistors per chip

Number of transistors in a microprocessor

http://www.spinograph.org/blog/why-nanoelectronics-better-microelectronics
Complexity: technology mixing

Core
New memory concepts (*)
- MEMS
- Quite hard
- CMOS imagers
- Transients
- Hot pixels, RTS
- TID
- DDD

Periphery: CMOS usually
Will drive the radiation performance
- Quite soft
- Latch-up, SET, SEU

(*) Magnetic RAM, Spin Transfer Torque RAM (STTRAM), Phase Change RAM (PCRAM), ReRAM (Redox or Resistive RAM), Valence change memory (VCM), Electrochemical memory (ECM), Thermochemical memory (TCM),…
Complexity: event signatures

SEU signature in logic addressing space – MEMORY 1

Same «technology node», different circuit architecture
Complexity : event signatures

SEU signature in logic addressing space – MEMORY 2

(a) = row errors
(b) = column errors (groups of 8 columns)

Same « technology node », different circuit architecture
More transistors now in a single chip than in whole 1980’s spacecraft designs

(GALILEO Jupiter probe for example)
Consequences for radiation hardness assurance
New elements

- Recoil of heavy elements
  - Max recoil LETs in MeV/mg/cm² in Si: Si = 15, Cu = 31, W = 83
  - Proton SEUs can be induced on high-LET threshold devices, incl. rad-hard (seen in space)

- Physical sciences – radiation / matter interaction
  - As surprising as it may appear, proton NIEL for example is still largely unknown for elements such as As, Ga, In,…
Smaller dimensions

- Particle track larger than device features
  - Multiple node collection will generalize
  - MBUs (incl. SOI), possibly SEFIs or other conflicts in the state machine

- Induced defects comparable or larger than device features
  - Could in principle completely jam a DSM gate oxide

- High electric field across oxides
  - Electric field across a gate oxide of 2 nm under 1 V is about 5 MV/cm closing SiO2 minimum dielectric breakdown field, such as for power MOSFETs in the past
  - This has lead to the introduction of high-k dielectrics (e.g. HfO2)
  - But still possible impact on RILC (radiation induced current leakage) or even SEGR
Smaller SEE thresholds (critical charge)

- **SEEs induced by proton direct ionization**
  - Observed in testing for nodes smaller than 45 nm
  - From estimations would contribute to a few 10% of in-orbit LEO rate, to date
  - But still no agreed test method and a fortiori flight rate estimation technique

- **SEEs induced by electrons**
  - First observed through MBUs in SOI technologies, which was supposed impossible
  - Due to high-energy electrons ejected along ion track and ballistic crossing of the oxide between two cell
  - Would also possibly be created by primary electrons from the space environment
  - CNES and ESA studies on <=45 nm devices: really appears above 10 MeV from nuclear reactions, not an issue now for Earth orbit
Smaller dimensions and SEE thresholds

- Some proton–substrate nuclear reactions can produce several recoils
  - In the past, only the heavier one was of significant importance (classical proton SEE)
  - The thresholds being lower now, the lighter ones may also deposit enough energy for an SEE
  - The distances being shorter many of the recoils may reach a sensitive volume
  - Another possible source of multi-node charge collection
  - The multiplication of chemical elements implies more interaction possibilities
Single event functional interrupts (SEFI)

- SEFI is a functional manifestation, not a physical effect
- The term extends to any “critical effect”, and has to be detailed in test reports: a SEFI cross section curve without description of the “SEFI” is of little use
- Tends to generalize to about any digital or digital/analog circuits
- Complex signatures, possibly very harmful events (e.g. μP erases its EEPROM array)
- It is not impossible that multi-node charge collection plays a role in the generalization of SEFI because it may induce strong disturbances into the state machine
Some still unexplained effects

- **Weakened cells**
  - Observed in space after the first mission days, observed in testing
  - Cell is intermittently stuck at 0 or 1, may defeat classical mitigation techniques
  - Occurs in SDRAMs, DDR
  - Still badly understood, likely to be due to DDD
  - No agreed test method and a fortiori in-orbit estimation technique
  - RTS and possibly weakened cells are supposedly due to DDD, but the link between microcosm (energy states of defects) and the macrocosm (current measured in the laboratory) is still not understood

- **High current events (HCE)**
  - Observed on some FPGAs, FlashEPROM, MRAM,…
  - Micro-latch-up ? Damage and induced leakage ? Internal bus conflicts ?
  - May be resettable, may need ON/OFF, may not anneal
Discussion: test challenges

- Most of heavy-ion tests are made on delidded devices and normal incidence
  - More and more difficult and expensive to open parts to expose the die
  - Will become nearly impossible with 3D technologies
  - Particles coming sideways may be more harmful (tri-gate FinFET, “tower” Flash,..)
  - Roll and tilt testing will probably be necessary
  - Access to very high energy ion beams not easy, especially in Europe

- Possible test artifacts
  - High flux / fluence experiments may induce “new” artifacts
  - E.g. gate oxides can be damaged by $10^7$ heavy ions / cm², but in space the real fluence will be a couple or a few tens of these ions → ???
  - Or, beam degraders and everything that is in the ion beam path can generate neutrons, but there will not be a significant ion-induced neutron generation in space

- Testing a billion transistor circuit is a challenge by itself
Conclusions

- Device features are now comparable or smaller than radiation interaction characteristics, this complicates very much the problem.

- In terms of electrical testing, complexity becomes a real challenge (testability, test coverage).

- Tests procedures and facilities may need to be revisited to avoid artifacts (flux, fluence) and improve representativeness (high energy beams, tilted irradiation).

- R&D still needed in physics (radiation / matter interaction, physics of defects) and in understanding of basic mechanisms (RTS, weakened cells, HCE).

- The generalization of SEFI, HCE, weaken cells will impact on mitigation techniques.

- The paradigm of “we don’t care about radiation effects, a priori mitigation works” of the good old days of simple SEUs and easily detected latch-up is over.

- Links between radiation, component and system engineers more than ever needed.