CERN Training

Radiation effects on electronic components and systems for LHC

Radiation effects on devices : Total Ionizing Dose, displacement effect, single event effect

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by

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Acknowledgments : Laurent Dusseau, G. Hubert, E. Lorfèvre. Many of the view graphs come from original works developed in our team.

OUTLINE

- Introduction
- Radiation field & dosimetry
- Total ionizing dose
- Displacement
- Single event effect
- Conclusion

Introduction

Radiation effects on electronic devices are observed :

Nuclear applications

- **civil**
  - **high Dose**
  - **gamma, electron, neutron**
- **Military**
  - **Dose and photocurrents in SC**
  - **X-ray flash**

Accelerators

- **high dose, displacement and single event**
- **hadrons**

Space

- **dose, displacement (LEO) and single event**
- **heavy ions, electrons protons**

Commercial LSI at ground level

- **single event**
- **neutron and material contamination**

Introduction

Radiation failure classification in devices :

Cumulative effects :

Long term cumulative effect

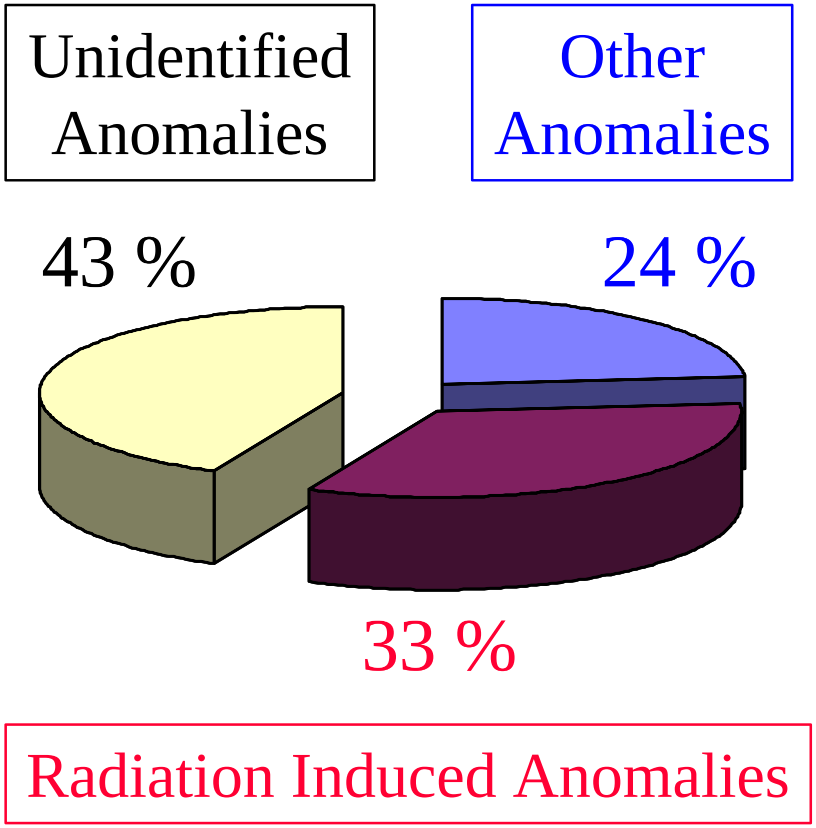
- **Dose (TID, Total Ionizing Dose) and Dose rate**
  - **Ionization and trapping in insulators, bulk and interface**
- **Displacement damage**

Single Event Process (SEP)

Short time response resulting from the energy transfer of a particle to the device.

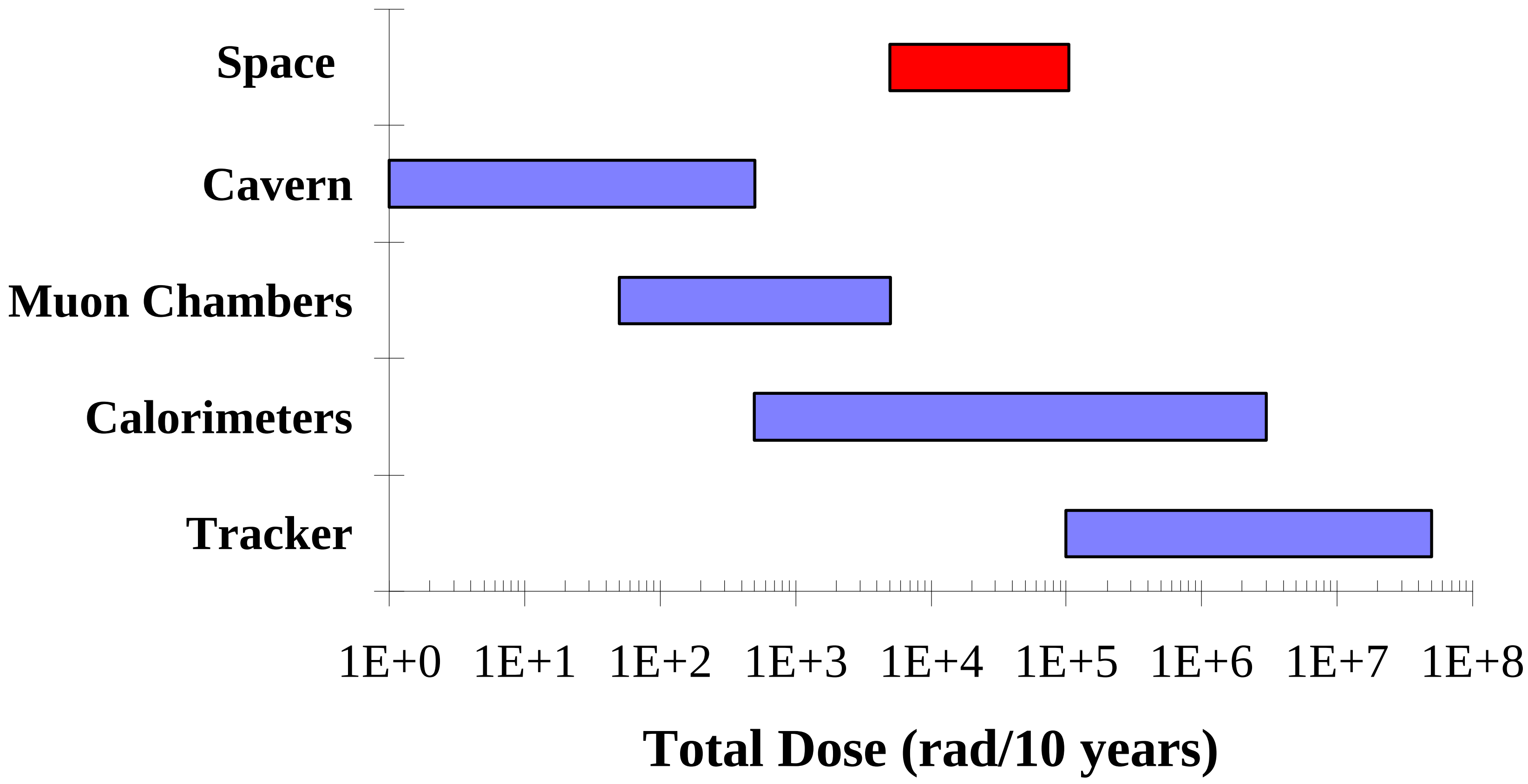
Introduction

Space anomalies



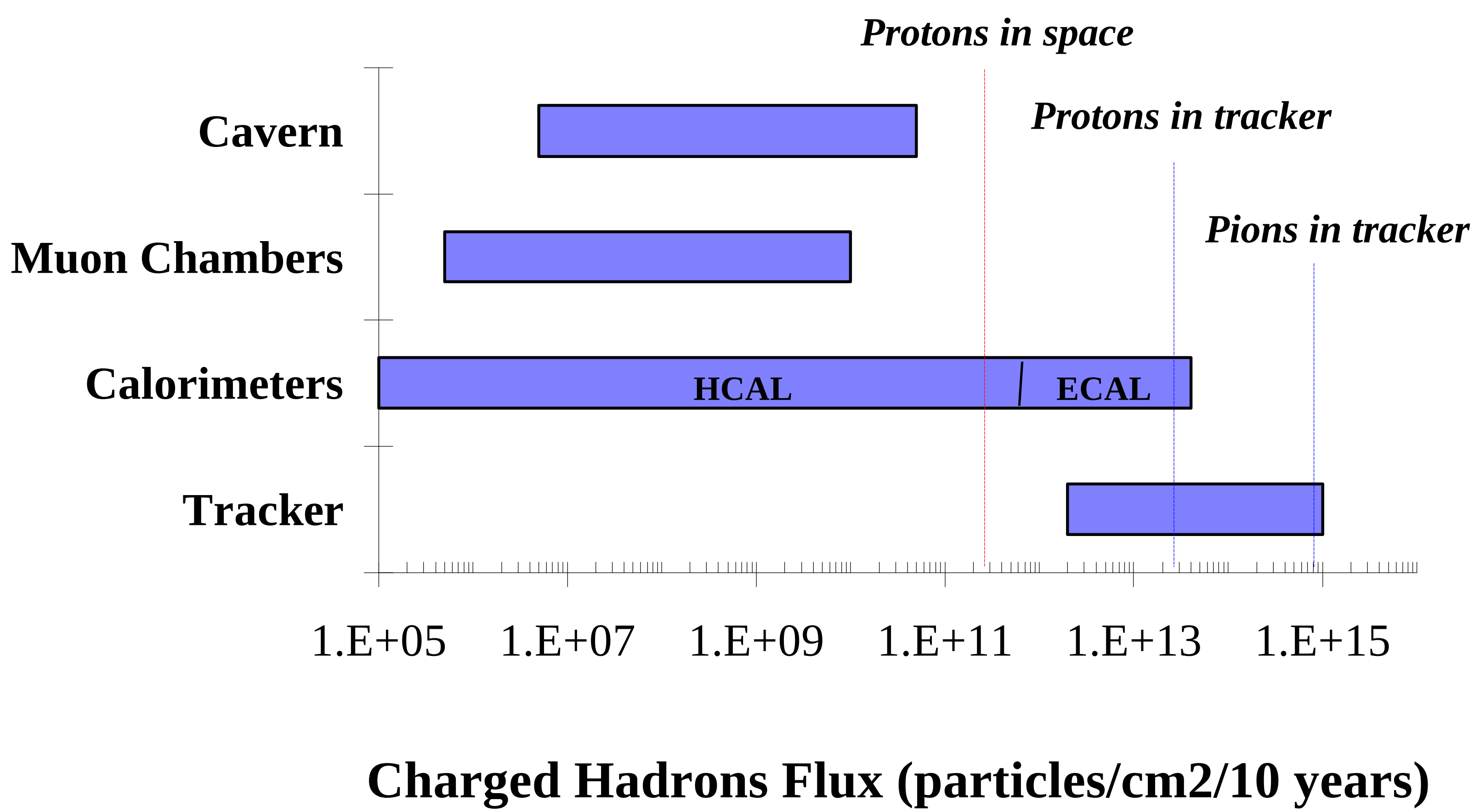
Comparison with space environment

Total Dose in Space and CMS



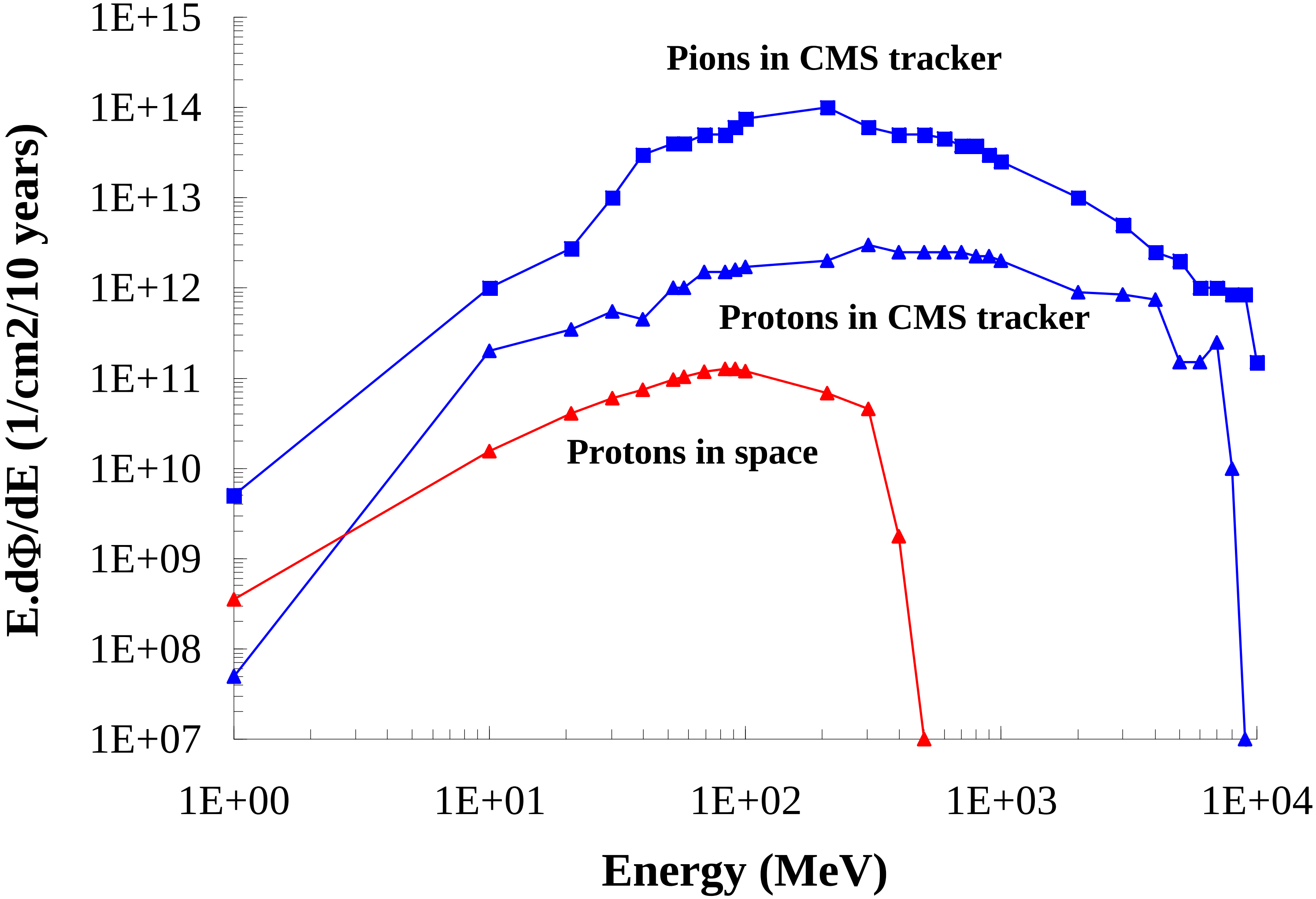
Comparison with space environment

Charged Hadron Flux in space and CMS



Comparison with space environment

Charged Hadron Diff. Energy Spectrum



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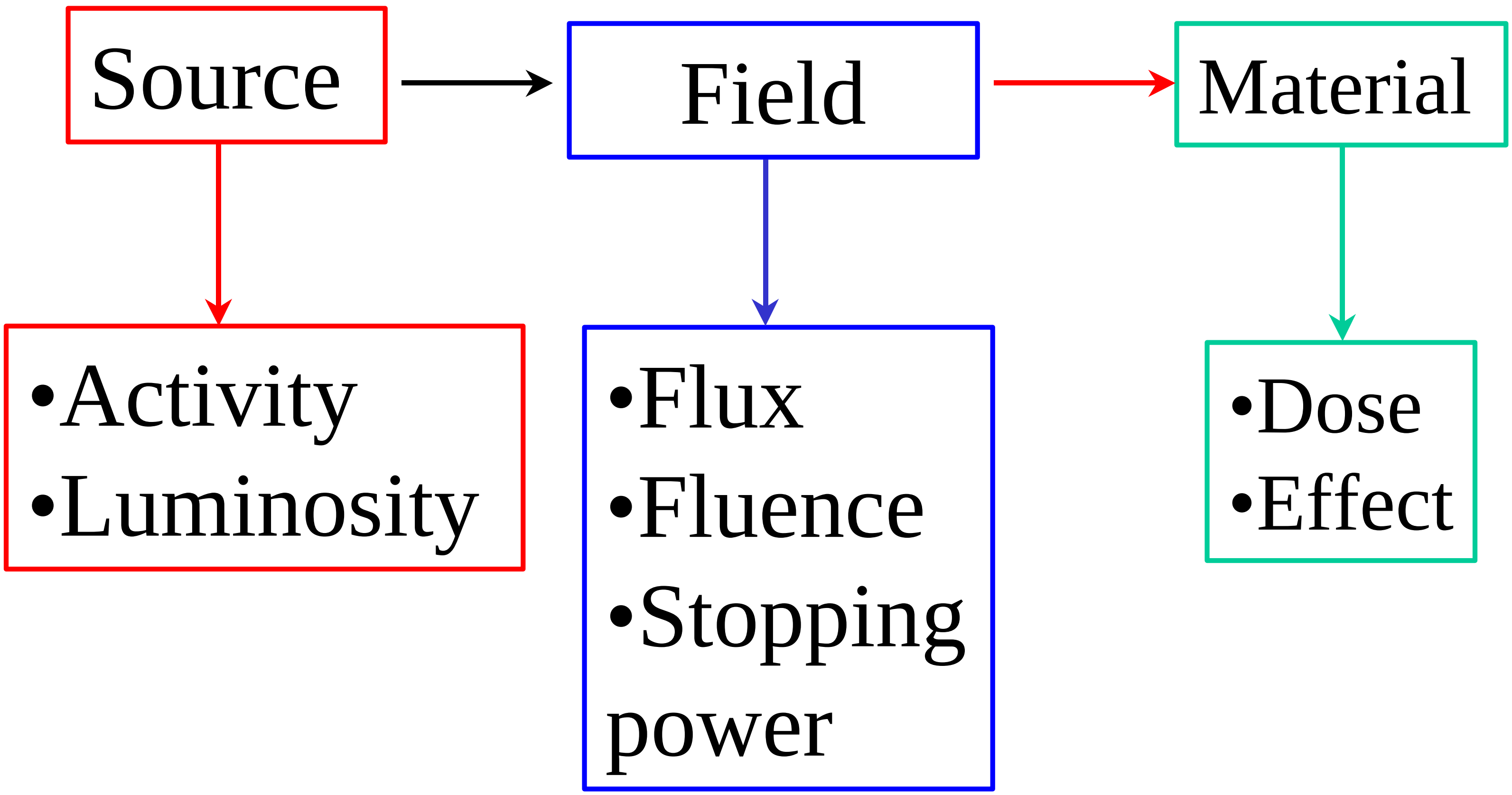
Radiation field & dosimetry



Radiation source

Source

- Activity

Unit: Ci, Bq (s^{-1})

1 Ci=3.7 10^{10} Bq (disintegrations . s^{-1})

$$L = \frac{N_1 N_2}{S} fk$$

- Luminosity

  N_1,N_2 number of particles

  S: Interaction surface

  f: Collision frequency

  R: Activity

  s_i:cross section

$$R = \sum_i s_i . L$$

- Typical activity :

  Co60 radiotherapy k Ci

  Geological sample 0.1 Bp/g

Radiation field

Field

• Φ Flux	$cm^{-2}\ s^{-1}$
• Ψ Fluence	cm^{-2}

Typical values :

- neutron at ground level : 0,1 $cm^{-2}\ s^{-1}$
- protons in space, belts (E > 10 MeV) : $10^5\ cm^{-2}\ s^{-1}$
- Electrons in space belts (E > 1 MeV) : $10^6\ cm^{-2}\ s^{-1}$
- heavy ions in space (Geo, 10 years) : $10^6\ cm^{-2}$

Radiation field

Field : particle energy loss

For a charged particle beam, the average energy loss is characterized by (ICRU) :

- Stopping power, S (MeV/μm): average energy loss per unit path length of a charged particle traversing a material

- resulting from coulomb interactions with

- Electrons (Collision) S_{col}

- Atomic nuclei (nuclear) S_{nuc}

- Mass stopping power (1/ρ) S

The energy may not be transferred in the surrounding path area.

Nuclear reactions are not considered.

Dosimetry

Material

Physical measurement

- Macroscopic : Dose Gy (J.kg^{-1})
- Microscopic : LET, NIEL

Effect

- **Macroscopic :**
  - radiation protection Sv
  - in Si e-h production
  3.7 10^{15} e-h /Gy
- **Microscopic : MeV g^{-1}**
  LET : charge deposition around the track
  NIEL :energy transferred to recoil atoms

Dosimetry

Material : energy deposition

Dosimetry is concerned by the determination of the energy deposited in the area of interest.

As direct a measurement is most of the time impossible, a dosimeter is used.

There are two levels

- The physical characterization
- The effect on a property of the considered. device :

Measuring a dose at the first level on expect to obtain the second.

Macroscopic physical data :

The average energy deposited in a material per unit of mass at the point of interest is called Dose, Absorbed Dose, or Total Dose :

- Gy ($J.kg^{-1}$)   (1 Gy = 100 rad)

Macroscopic effect :

In personal dosimetry the effect unit is the Sv (Sievert)

1 Gy gamma is 1Sv

1 Gy neutron or proton correspond to several Sv

Dosimetry

Material : energy deposition

Typical doses :

Ground level, population : 0,5 rad/year

Lethal dose : 4 Sv (4 Gy gamma whole body)

Space mission 10 y : GEO 10 krad

Constellation 100 krad

Nuclear reactors : D >> 1 MGy

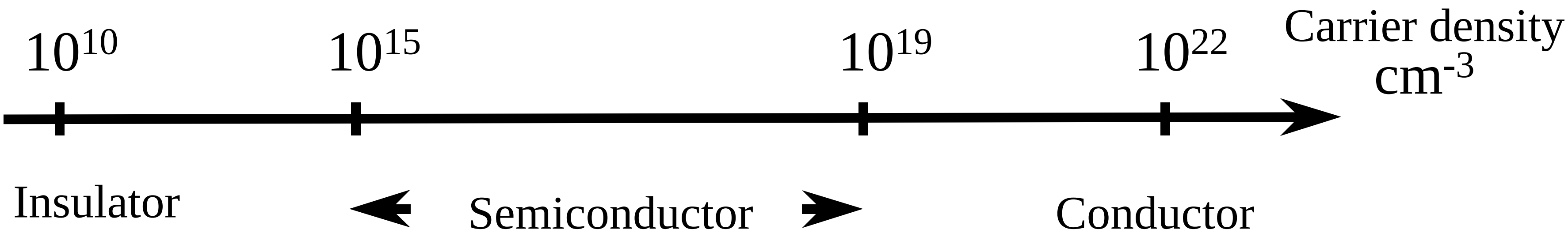
PARTICLE EFFICIENCY FOR TOTAL DOSE IN Si

Even if this kind of data must be used with care, its an interesting first response (order of magnitude).

- Fluences (cm^{-2}) that produces 1 Gy (TOTAL IONISATION DOSE) in Silicon (Particle energy : E = 14 MeV)

Iron	**10^4**	**max TID is close**
Proton	**10^6**	
Electron	**10^7**	
Photon	**10^8**	
Neutron	**10^9**	**long discussions**

Radiation Effects



- Transient Phenomenon :
  - ⇨ Photo-currents
- Permanent or semi-permanent Phenomenon :
  - ⇨ Displacements
  - ⇨ Trapped charges + annealing

C/Gy ~ 10^{15} cm^{-3} ⇨ $\Delta V = 3{,}6\ d^2\ D$

for d =100 nm and D=10 Krad ΔV=3,6 V

D, dose
d, oxide thickness

Dosimetry

Material

- Linear Energy transfer LET (MeV.cm^2. g^{-1}) :
Energy deposition related to Ionization along the particle path

$$\frac{1}{r}\left(\frac{d\Phi}{dx}\right) = LET$$

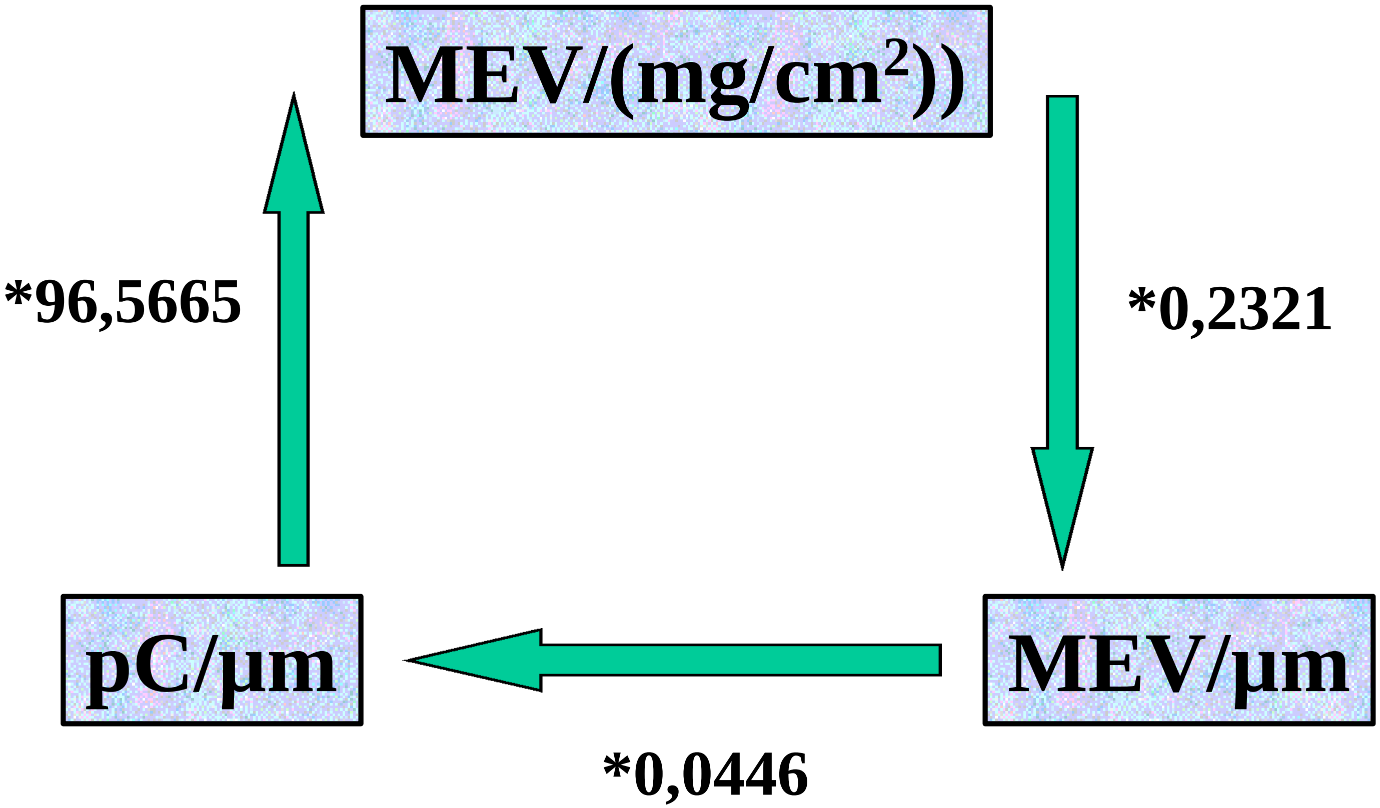
Others convenient units are used :

- **MeV.µm $^{-1}$**
- **C.µm $^{-1}$**

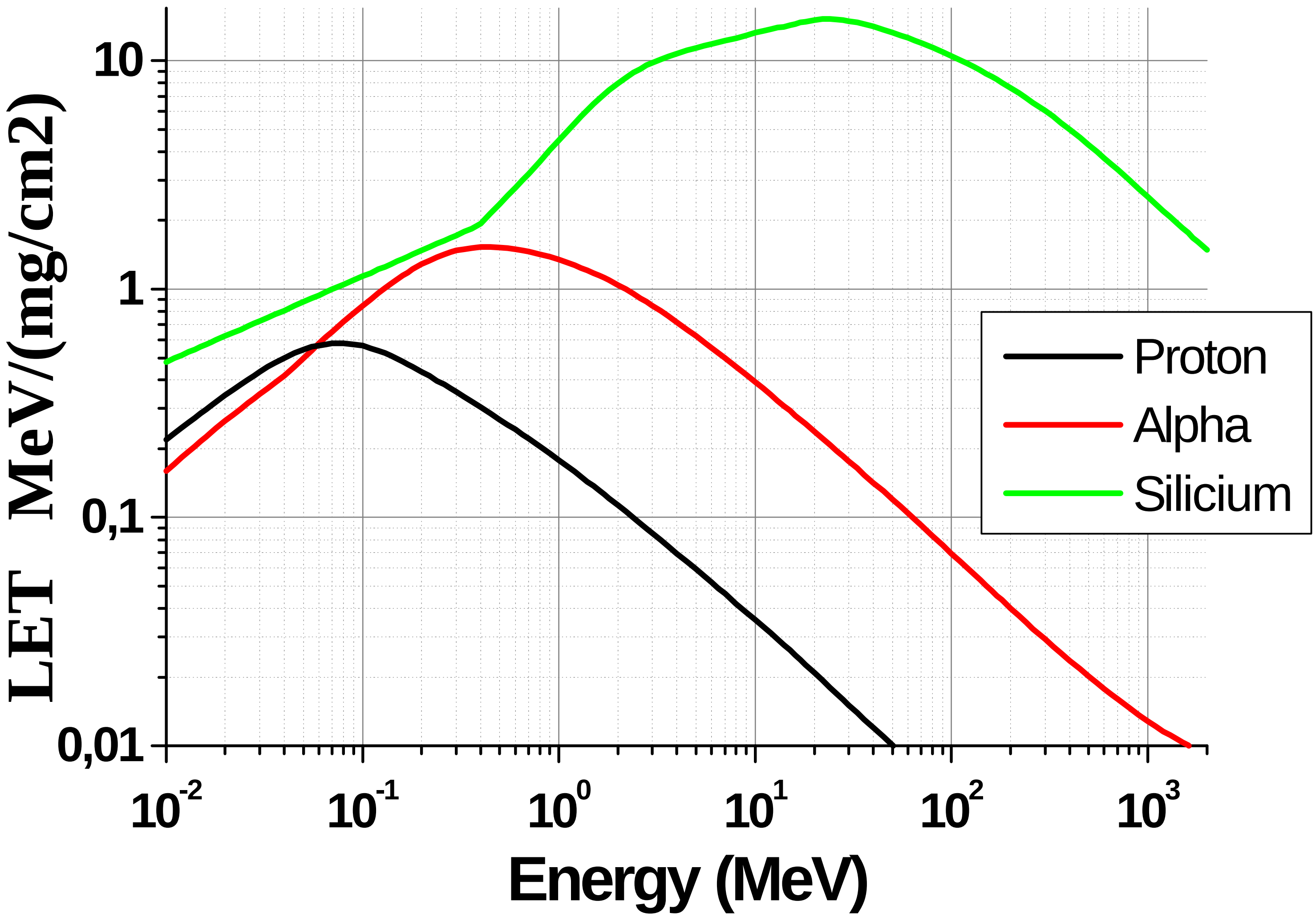
Usual parameter for Single Events

- Non Ionizing Energy Loss NIEL (MeV.cm^2. g^{-1}) :
Energy deposition related to recoil atoms along the particle path
Usual parameter for displacement damage

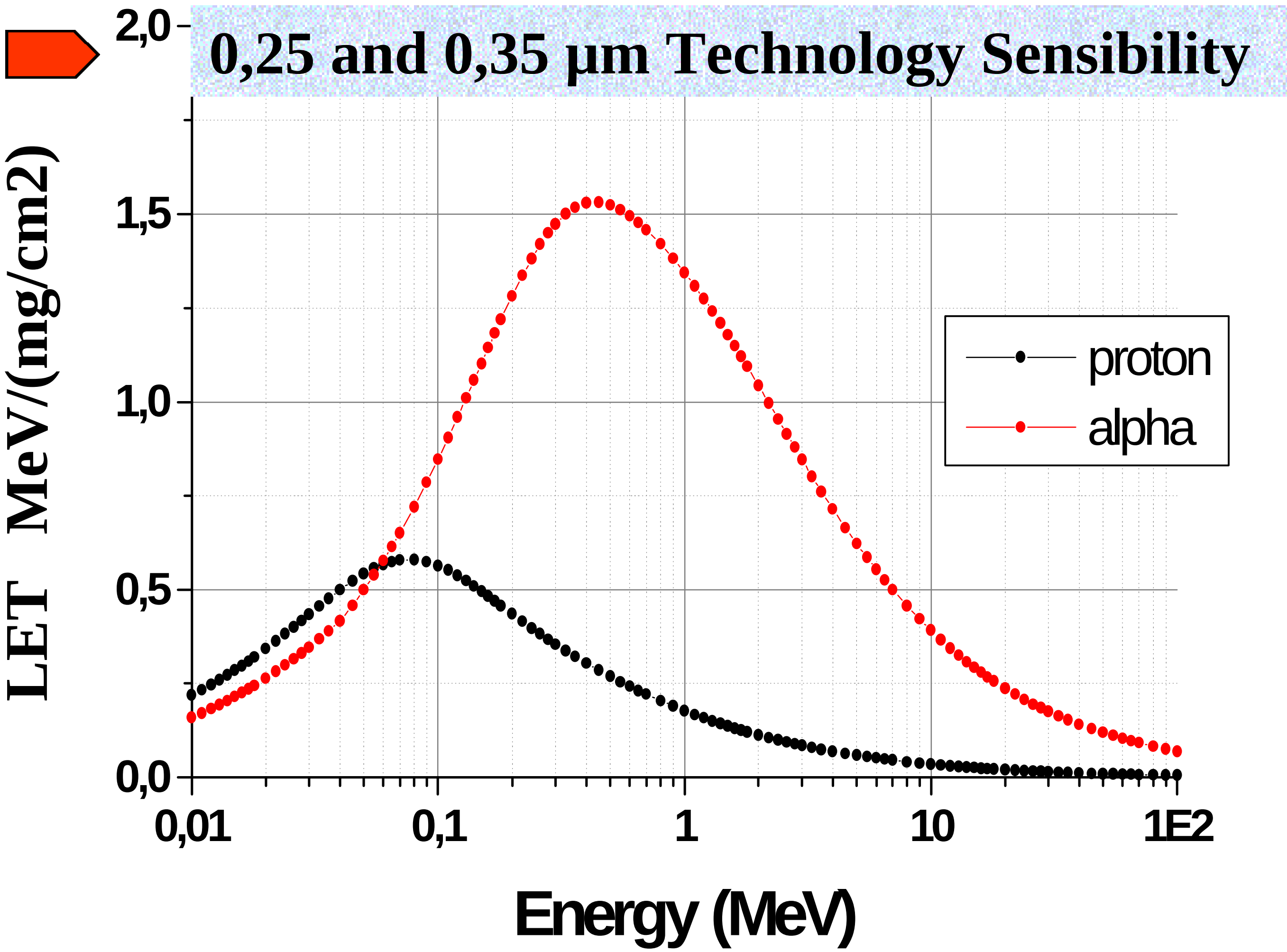
Linear Energy Transfer Units in Silicon



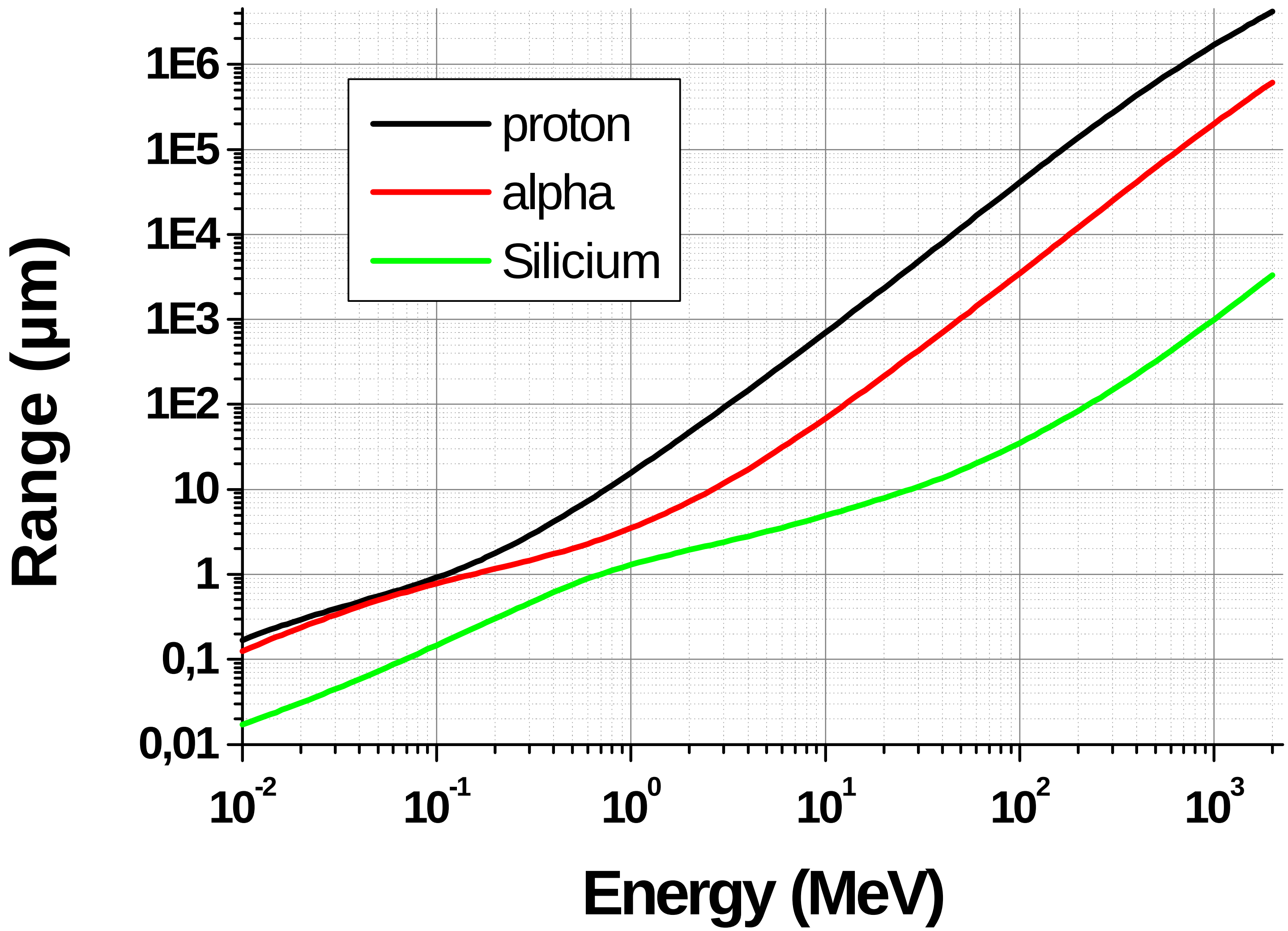
LET in Silicon



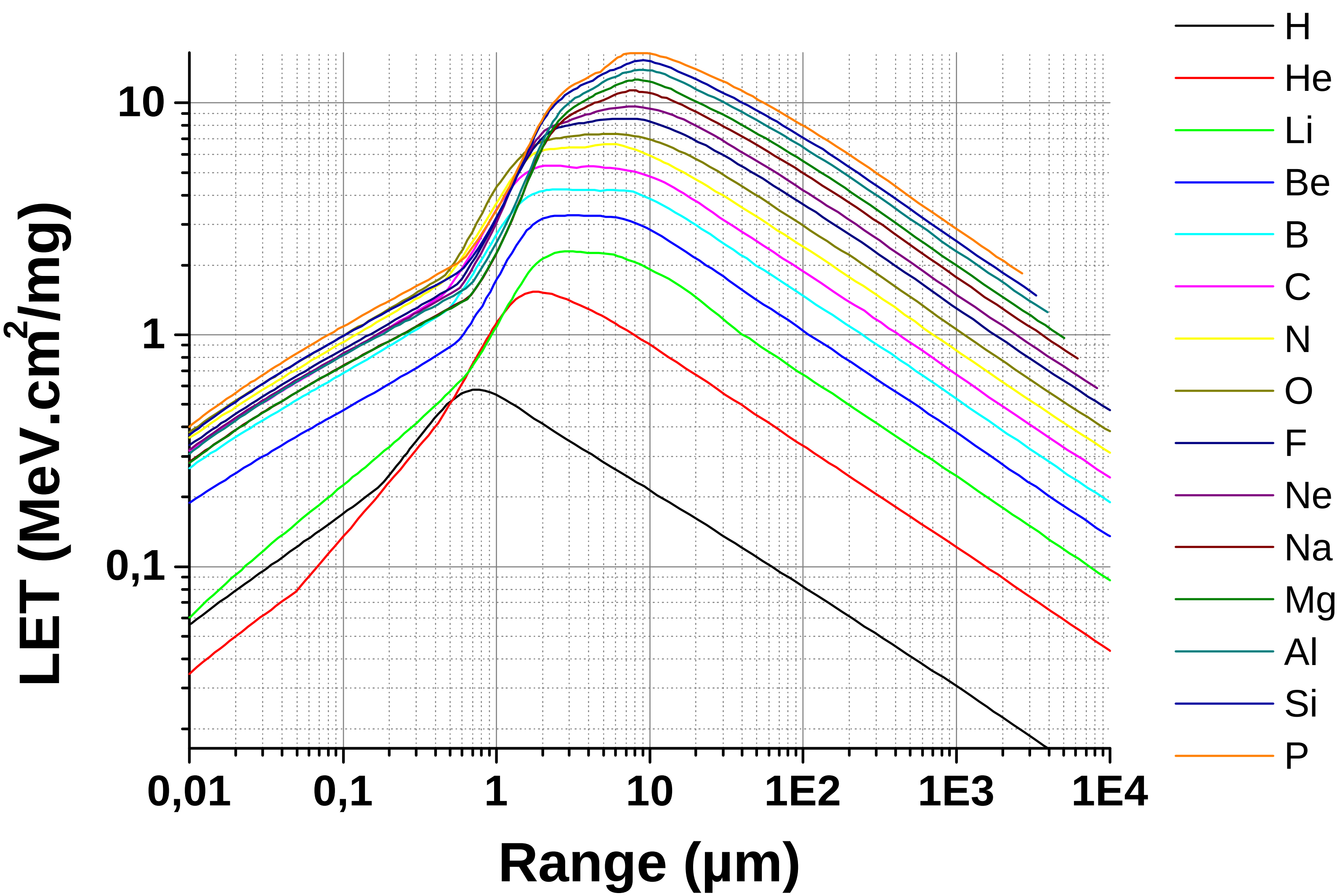
SEU Sensibility



Range in Silicon

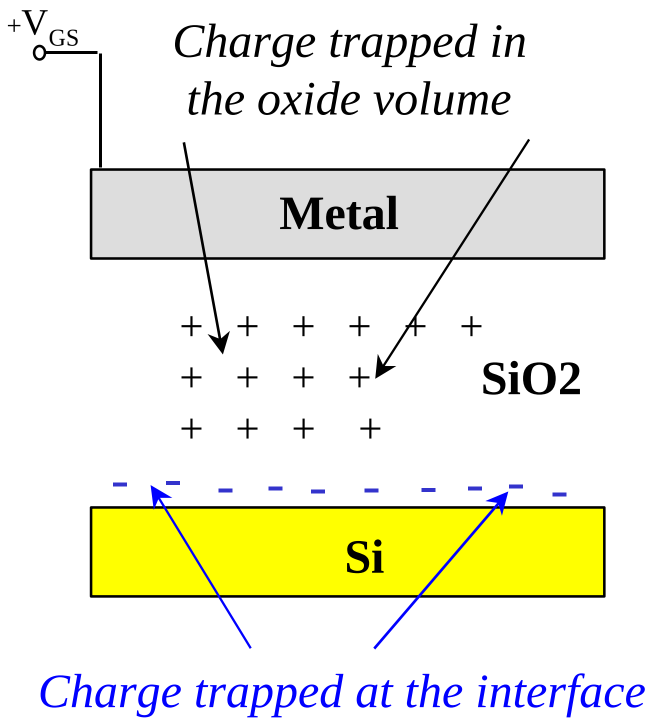


LET and Range in Silicon



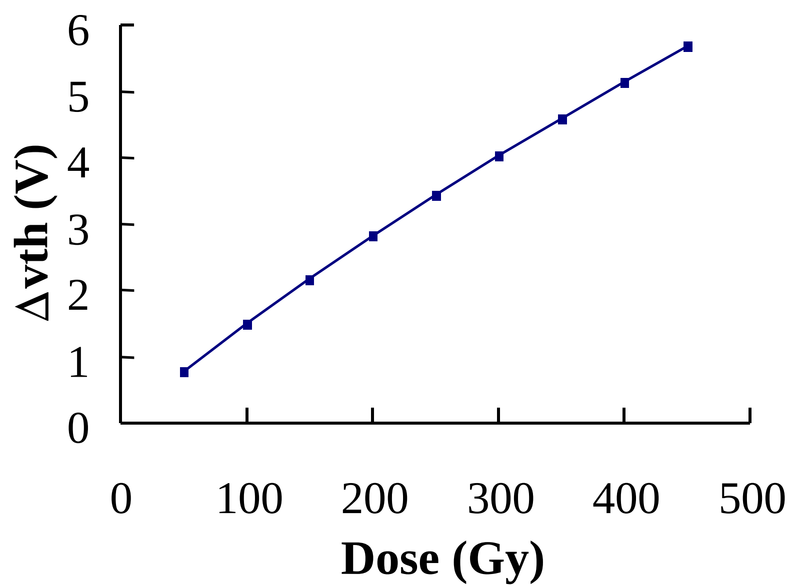
Total dose Effects

Charge Trapping



Charge trapping after irradiation

NMOS



Threshold voltage degradation as a function of the total Dose

Radiation Effects

Heavy Ions and Protons

- Single Event Effects (Semiconductor / Oxide)

CMOS technologies	Single Event Latch up Single Event Upset
Power devices	Single Event Burnout Single Event Gate Rupture Single Event Latchup

- Total dose effect (Oxide)
- **Displacement damage** (Semiconductor)

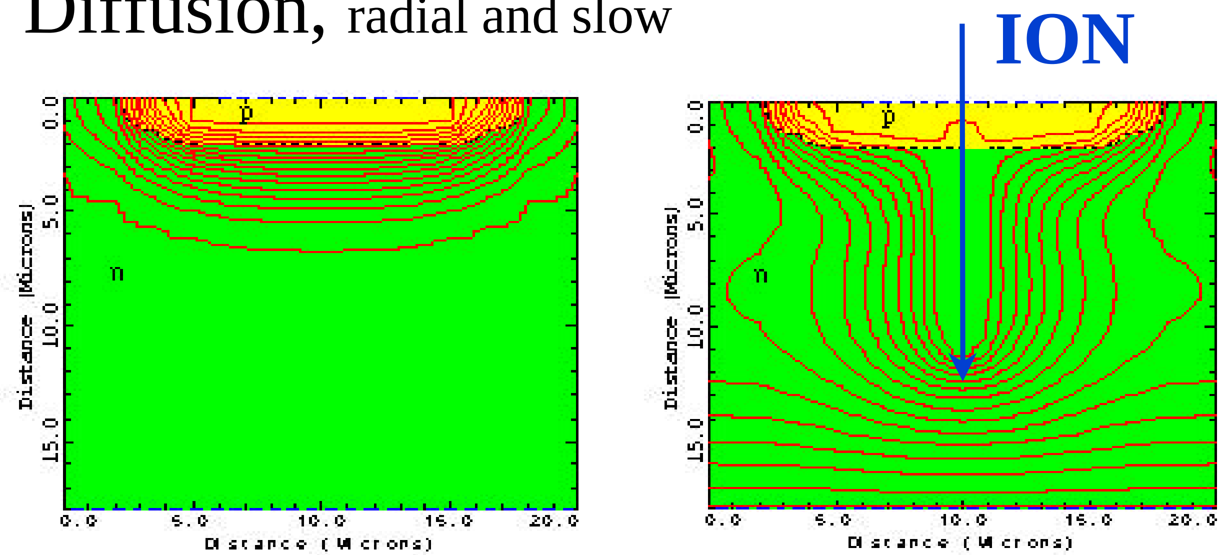
Radiation Effects

Heavy ion - Semiconductor interaction

Generation of electron-hole pair → Collection

❶ Drift, Field funneling

❷ Diffusion, radial and slow



Reverse biased junction

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TOTAL IONISATION DOSE EFFECT (TID)

Total Ionizing Dose (TID) induces :

charge trapping in the oxide

new states at the Si-SiO_2 interface.

- TID may change the device electrical characteristics

for a dose as low as 10 Gy

- Long term behavior, interface state density and bulk charge, depend on the device history.

– Important parameters are :

- Dose
- Dose rate
- Applied voltage
- Temperature
- Time.

- These parameters must be taken into account in the device selection.

TOTAL IONISATION DOSE IN : Si and SiO_2

- In Si (r = 2,3 g cm^{-3}, pair creation energy = 3,8 eV)

In Si N = 3,7 10^{15} (electron-hole pairs) cm^{-3} Gy^{-1}

- In SiO_2 (r = 2 g cm^{-3}, pair creation energy = 17 eV)

In SiO_2 N = 7,6 10^{14} (electron-hole pairs) cm^{-3} Gy^{-1}

- To obtain this result, it is supposed that the energy is mostly transferred to electrons.

- The density of electron-hole pairs for one Gy is very low, unless high dose and dose rate :

- No effect on metal

- No effect on Si or others SC (for low dose rate < 10^5 Gy^{-1} s^{-1})

- Possible effect on insulator - Trapping (starting at 10 Gy)

Very high dose rate may affect the semiconductor : starting with low carrier concentrations (military applications)

TOTAL IONISATION DOSE IN SiO_2 (BULK)

Typical Silicon oxide capacity behavior under irradiation :

- 1 - In SiO_2 during irradiation e-h pairs are created

- 2 - As electron and hole mobility are quite different ($\mu_e >> \mu_h$)

- Most electrons may get out

- Most holes can be trapped

- 3 - The charge positive induced by D in the capacitor (S, a) is given by :

$$\Delta Q = f\ a\ S\ N\ e\ D$$

f is a collection efficiency ($0 < f < 1$).

f = 0 hard oxide

f= 1 dosimeter

ΔQ can be considered as the equivalent charge near the surface.

TOTAL IONISATION DOSE IN SiO_2 (BULK)

- With a proper electric field holes may be trapped near to the Si-SiO_2 interface, it's the worst case :

$\Delta Q = a\ S\ N\ e\ D$

The capacity is $C = \varepsilon\ S/a$ ($\varepsilon_r = 3{,}9$)

The voltage drop is : $\Delta V(\text{Volt}) = 3{,}5\ \ a^2(\mu m)\ D(Gy)$

High dose, bad quality (f = 1) thick oxides (a^2) develop important voltage.

- At the device level :

MOS Gates - not a problem for LSI

All devices - Thick Oxide next to the SC may induce, leakage, ...

Total ionizing dose at the Si-SiO2 interface

Typical Silicon-silicon oxide interface behavior under irradiation :

In device fabrication, interface states density are kept as low as possible.

Electron injection occurs in the interface states, charges are exchanged with Si.

Interface state charge can be positive or negative depending on the fermi level position in regard to the state energy location.

- n channel - acceptor - (negative)

- p channel - donor - (positive)

Interface states charge changes with polarization (time constant).

Total ionizing dose at the Si-SiO2 interface

- 1 - At Si-SiO_2 interface <u>during irradiation</u> chemical bonding are changed, hole trapping at interface, some hydrogen migration have been observed....

- <u>New interface states are formed.</u>

- Interface state density vs. energy is changed.

- Interface charge is more important.

As a result : static and dynamic electrical response of the Si-SiO_2 is altered.

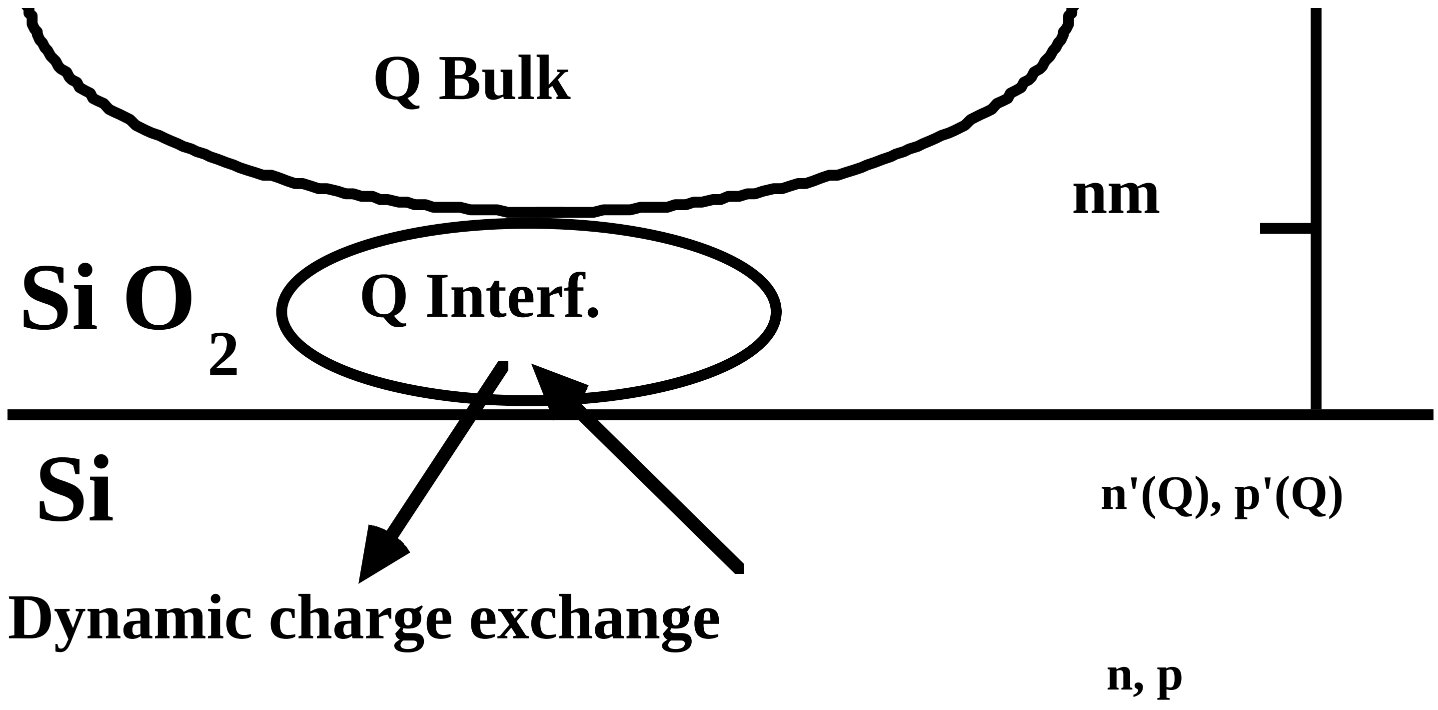
- 2 - Si-SiO_2 interface state density evolution with time after irradiation :

- <u>Interface state density changes with time</u>.

- Construction after irradiation.

- Effect of annealing, hole trapping at interface.

TOTAL IONIZATION DOSE AT THE Si-SiO_2 INTERFACE



Interface state charge and bulk trapped charge will play an important role :

changing the free carrier density n and p next to the interface

possible inversion layer

modifying the carrier mobility and life time

TOTAL IONIZATION DOSE EFFECTS IN DEVICES

MOS

Total ionization dose effects in MOS devices result from both, bulk charge and Silicon-silicon oxide interface charge :

- Induced mobility degradation

- Threshold voltage changes

- Induced leakage

Device characteristic changes :

- V_{th} (threshold voltage). Interface and bulk contribution.

- Q Trapped oxide charge (density)

- Q Interface trap charge (density and E distribution)

- μ Mobility in the channel.

- I_D Channel output drive (n or p)

TOTAL IONIZATION DOSE EFFECTS IN DEVICES

BIPOLAR

Total ionization dose effects in Bipolar devices result from silicon oxide (protection, isolation, non active) layers proximity with Si active device area :

- Induced mobility degradation

- Induced leakage

Device characteristic changes :

- Gain b.

- Leakage

IC - Integrated circuits

Frequency operation

Access and delay time

Power supply current

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Displacement

- Displacement damage is related to lattice defect density induced by (secondary) particle collision with atoms, in the target, that are ejected from their initial position.

- Lattice defect density will increase with irradiation, inducing a degradation of the material characteristics.

- For the semiconductor, introducing new defects means :

- **- diminution on the carrier life time (minority),**
- **- carrier charge density change,**
- **- reduced mobility**

The electrical characteristics degradation of the semiconductor will affect the device performances.

Displacement

The NIEL, S_d , is a target oriented parameter : average energy loss inducing displacement in the target.
NIEL simple expression for a mono atomic target :

$$S_d = (N/A)\ \Sigma\ \sigma_i(E)\ T_i(E) \qquad \text{MeV g}^{-1}\ \text{cm}^2$$

N is the Avogadro number, A is the atomic number of the target.
$\sigma(E)$ is the interaction cross section. T(E), the average part of the energy of the recoil atom that will induce displacement. The various possible interactions (i) are taken into account.

Particle interaction is a stochastic process, the NIEL is just an approximation that get sense when the number of events is quite large in the considered area.
high energy particles :
- 1 GeV muon will induce a shower that will affect billions of particles.

Displacement

Role of (relatively) low energy particles in displacement damage.

Collision with atoms :

- Elastic

- Inelastic

- Protons and heavy ions are important at low momentum.

- Electrons induce displacement at high energy.

- Photons do not have any effect if their energy is lower than 10 MeV - wavelength above 10^{-13} m.

- Neutron behave almost like protons at high energy (100 MeV and up).

Displacement damage is important at low energy. Inelastic collisions are of particular interest.

Displacement

The energy threshold for atom displacement is in the range of 6 to 25 eV.

- One 100 MeV electron, Si recoil 0,77 MeV, 0,1 MeV in displacement

2 500 Frenkel pairs (90 % recombine in a minute).

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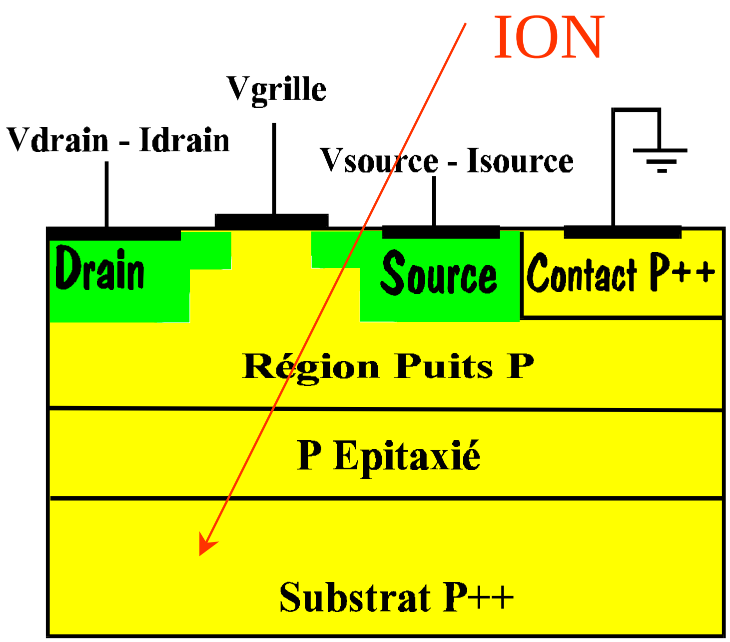
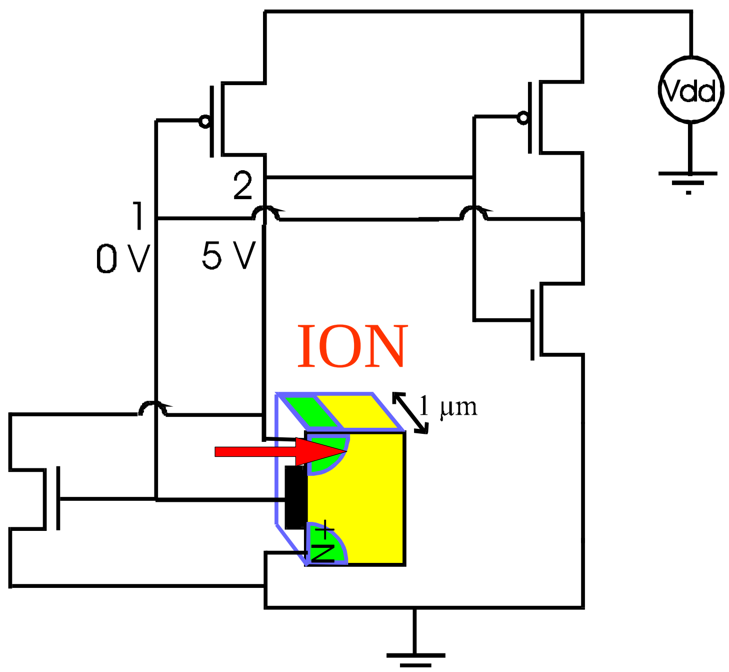
Effects in CMOS technologies

Single Event Upset

SRAM structure struck by an ion





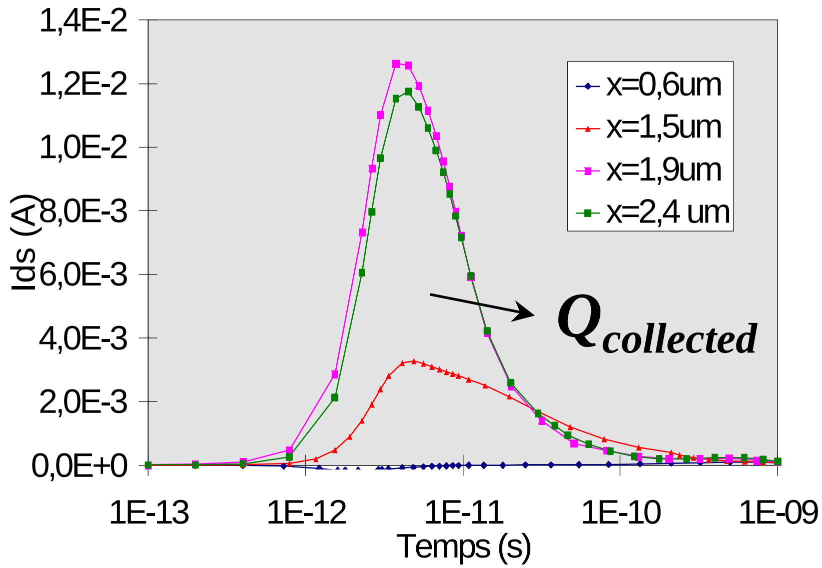
Device level

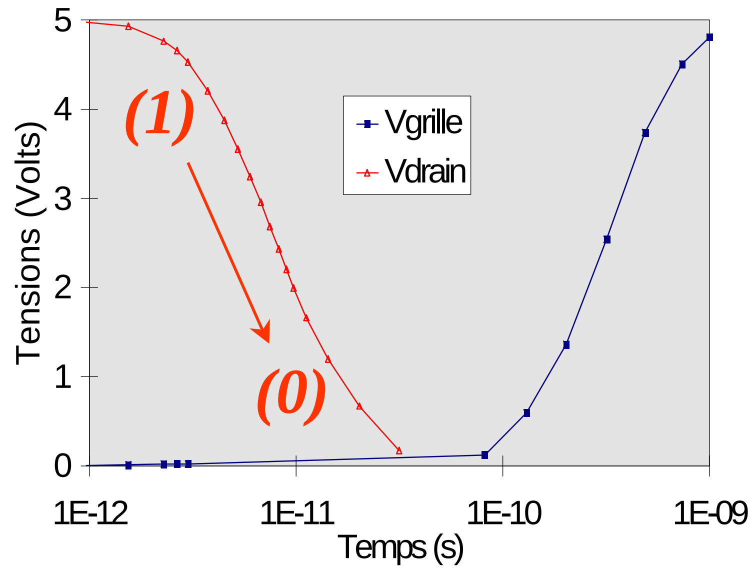
Circuit level
(memory cell)

Effects in CMOS technologies

Single Event Upset

For impacts in or close to the drain





Drain current

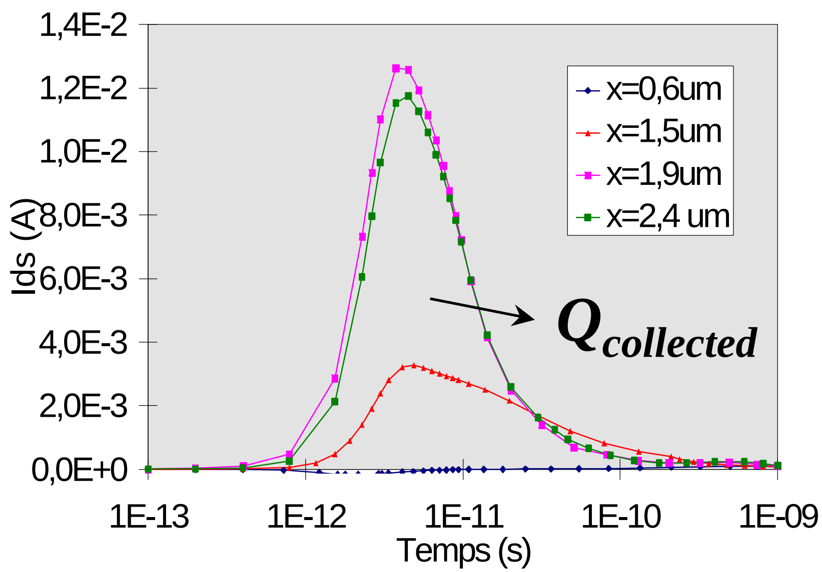
Evolution of the node voltage

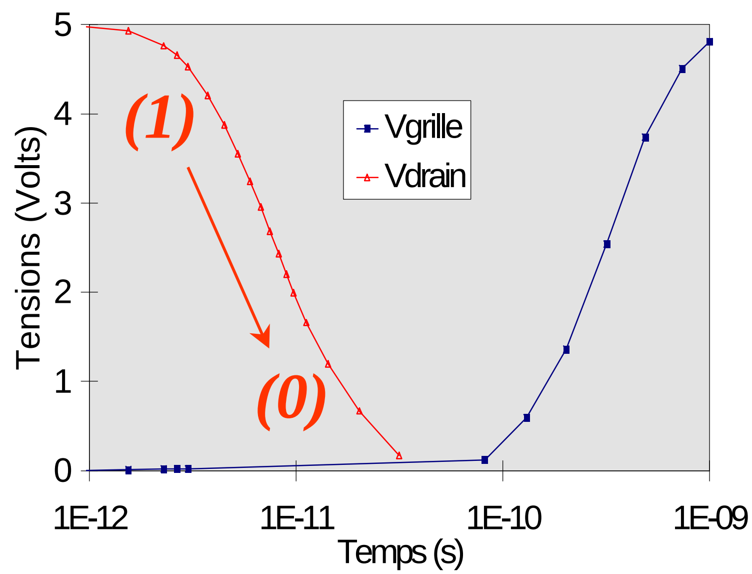
If $Q_{collected} > Q_{critical} \longrightarrow$ SEU

Effects in CMOS technologies

Single Event Upset

For impacts in or close to the drain





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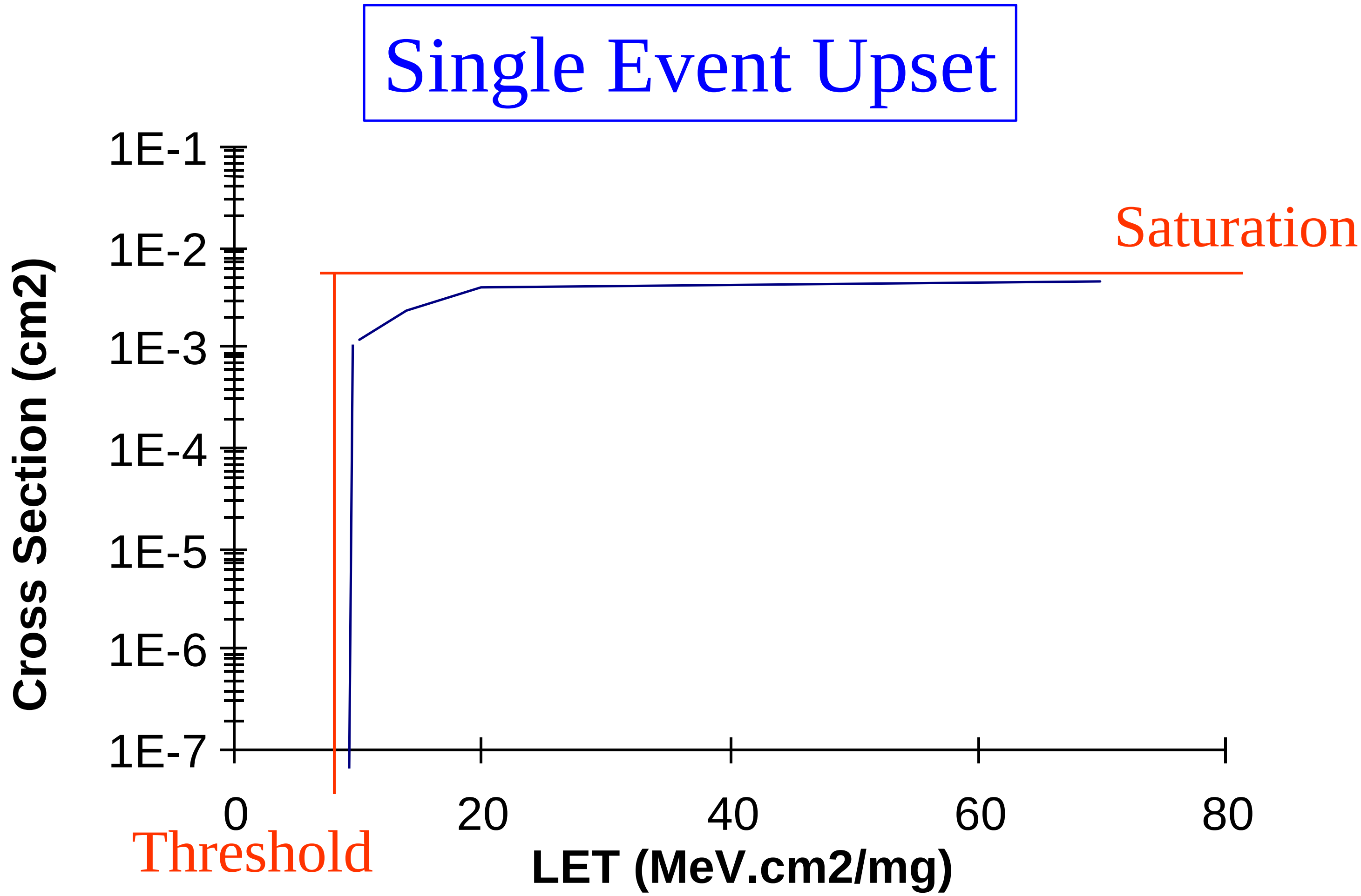
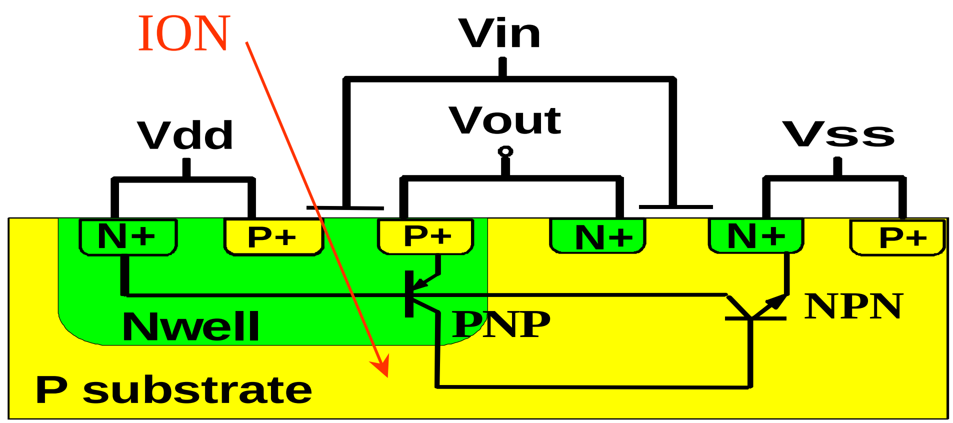


Cross Section of a 0.6 µm CMOS technology

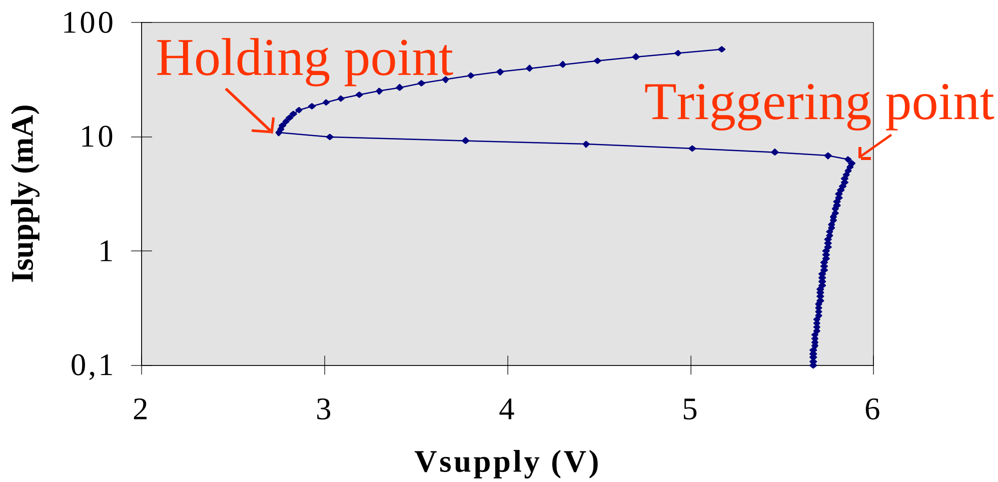
Effects in CMOS technologies

Single Event Latchup



Destructive Failure

Schematic representation of the parasitic NPNP structure

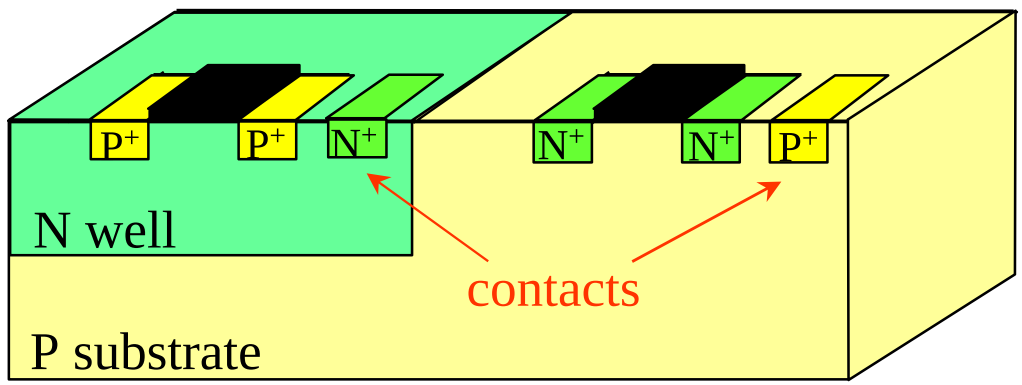


Example of latchup characteristic

Effects in CMOS technologies

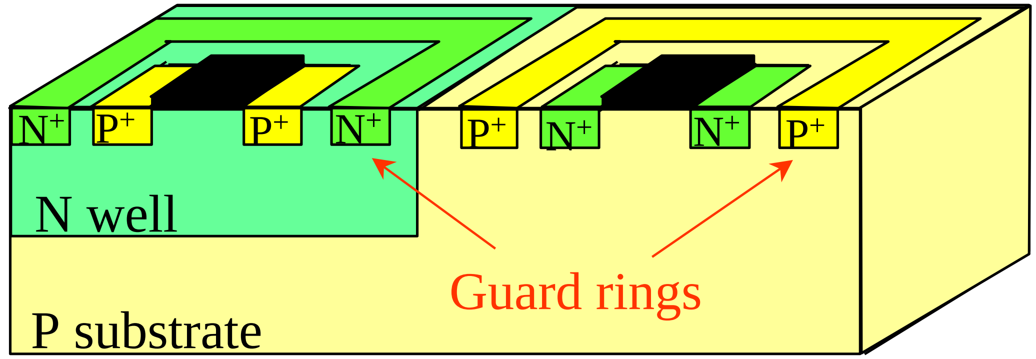
SEL Hardening

- Geometric dimensions



- Adding contacts, body ties

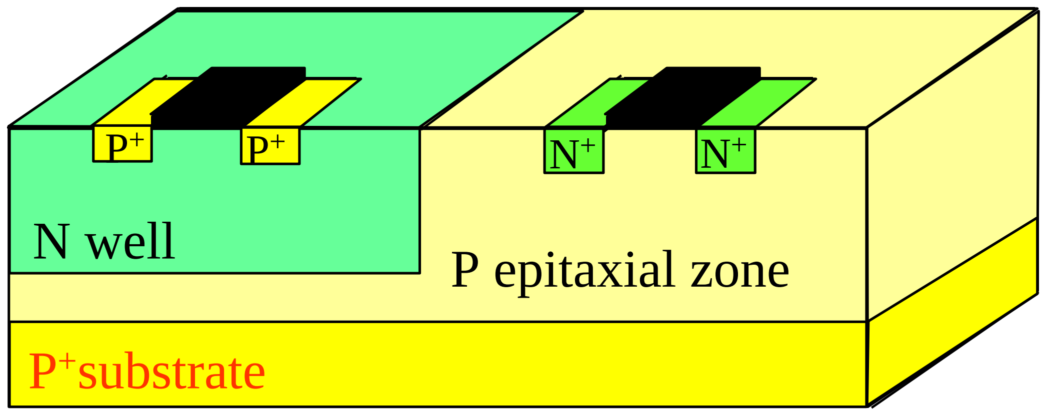
- Guard rings

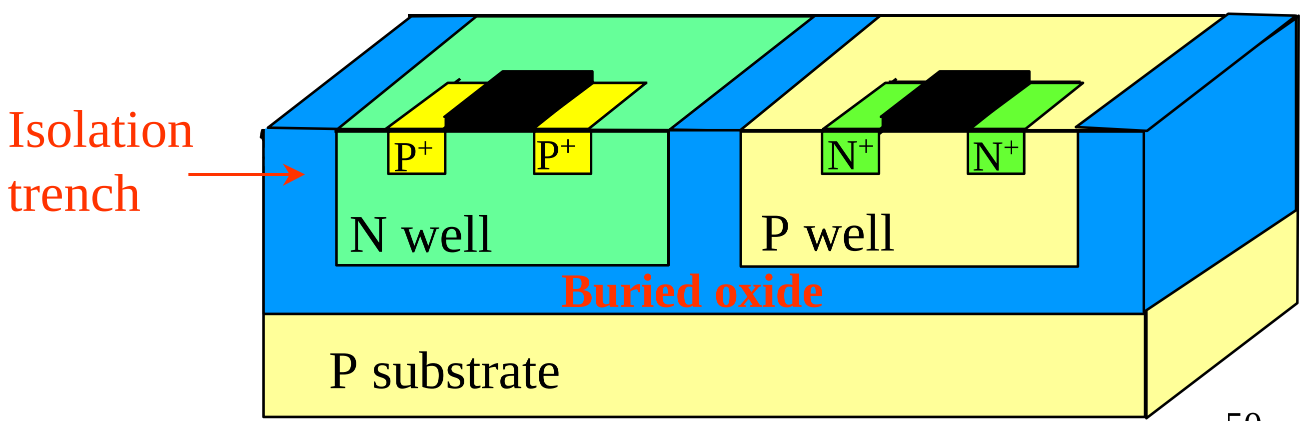


Effects in CMOS technologies

SEL Hardening

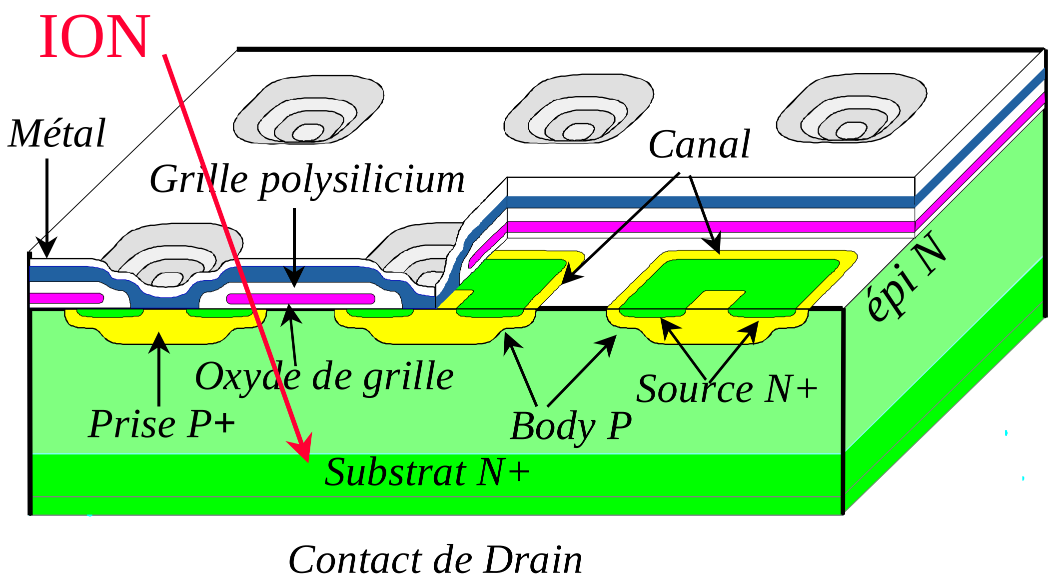
- Epitaxy
- Doping
- SOI

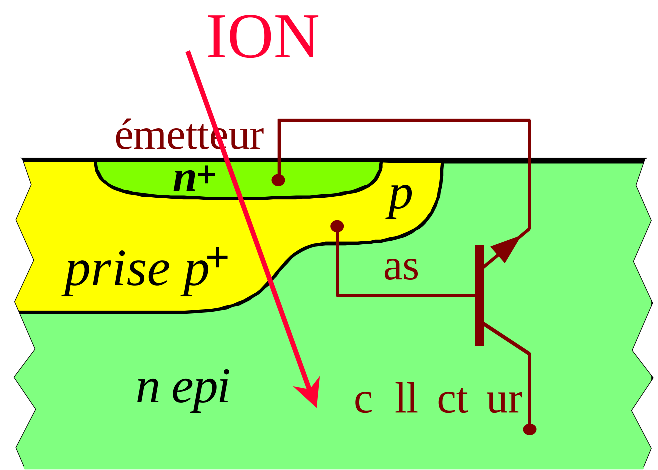




*Effects in Power Devices : **MOSFET, VIP***

Single Event Burnout

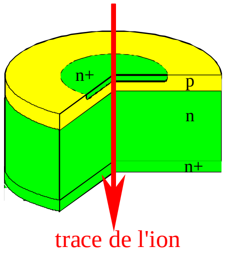




Power MOSFET (VDMOS) = 15000 cells in parallel

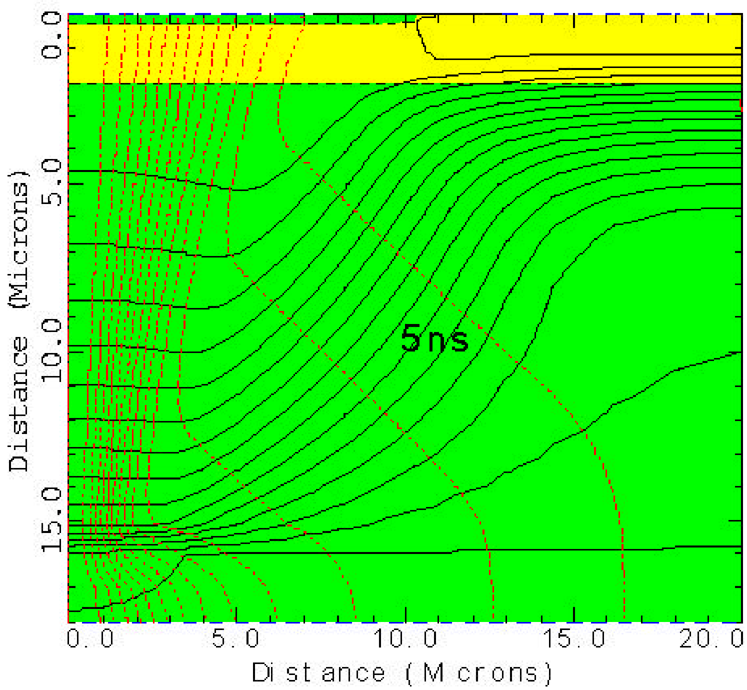
Triggering of the parasitic bipolar transistor ⟶ Burnout

Effects in Power Devices :

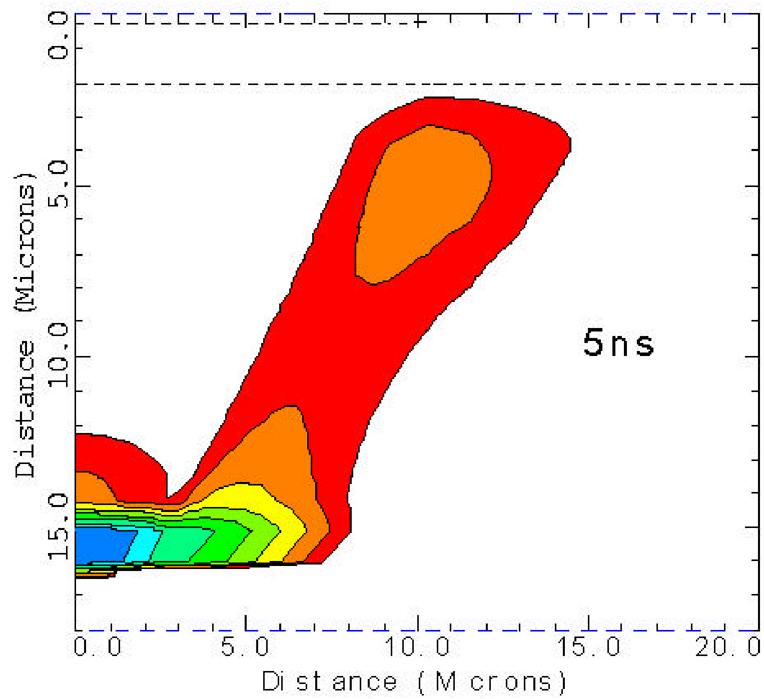


Single Event Burnout

5 ns after the ion's passage



Potential and current lines

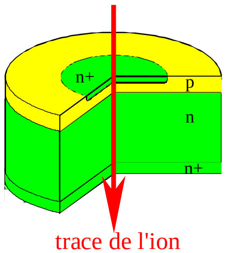


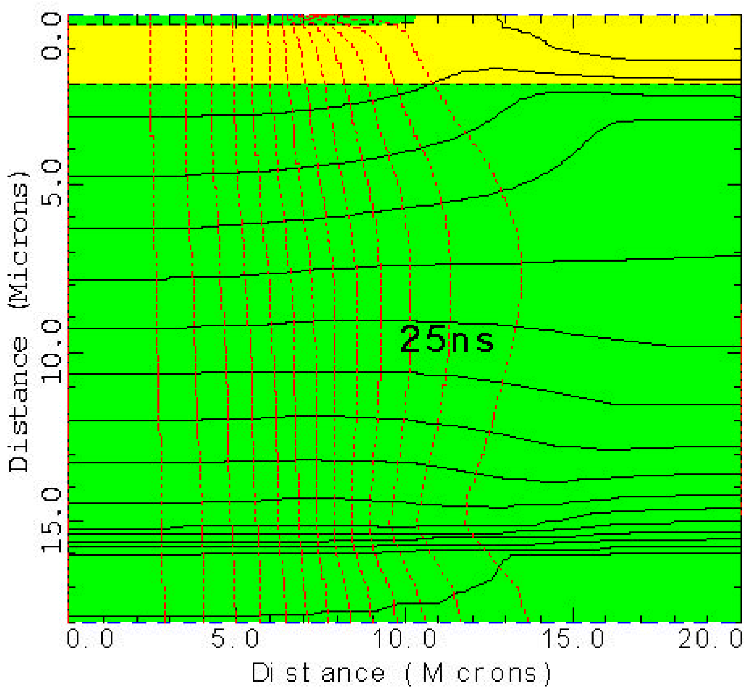
Generation rate

MOSFET, VIP

Single Event Burnout

25 ns after the ion's passage





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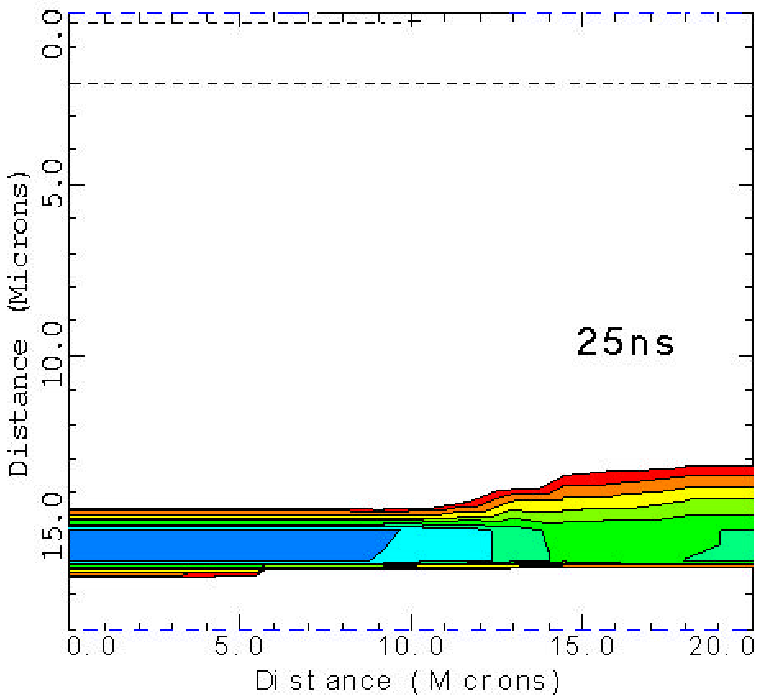
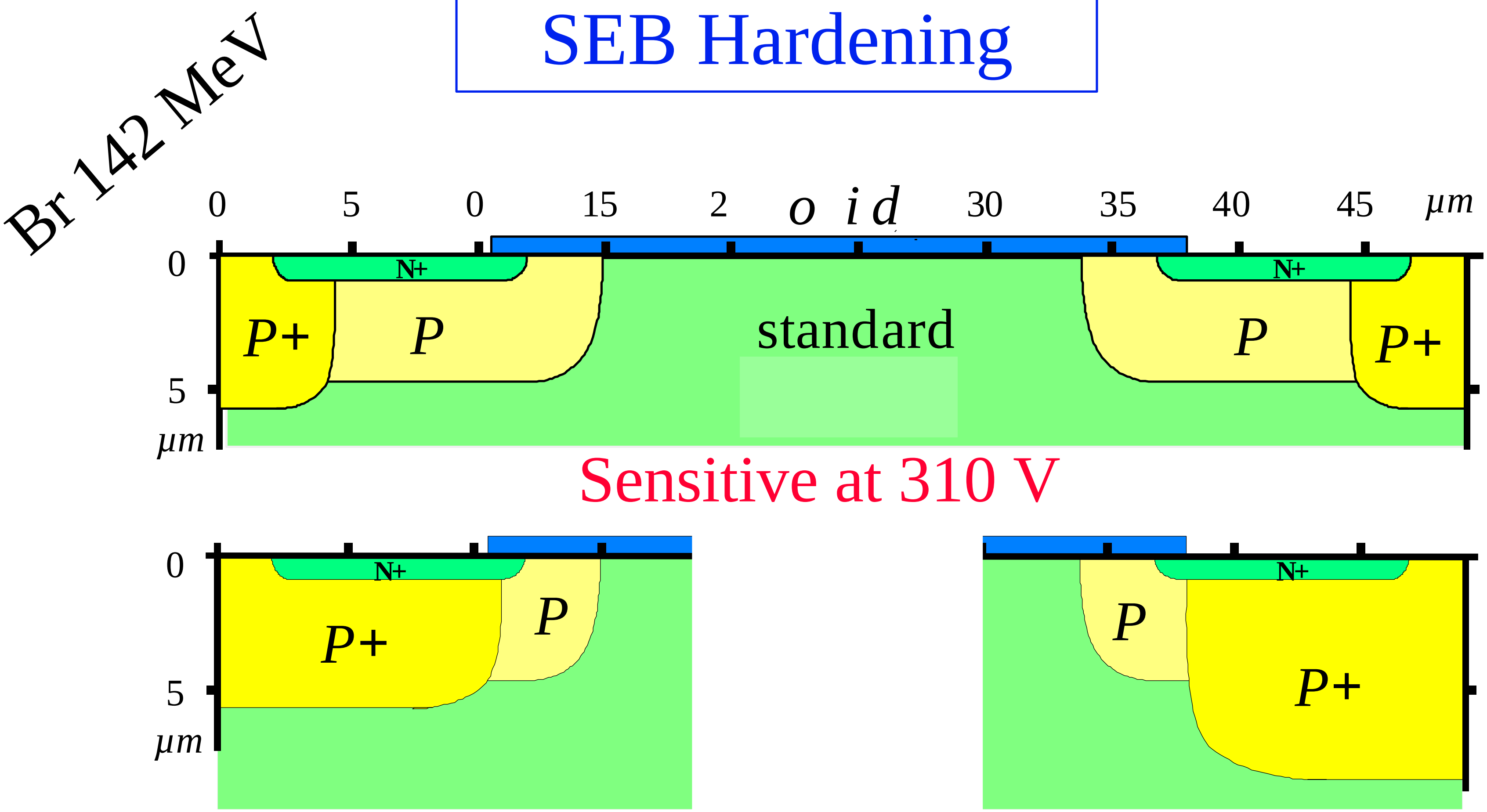


Generation rate

Effects in Power Devices : ***MOSFET, VIP***

SEB Hardening



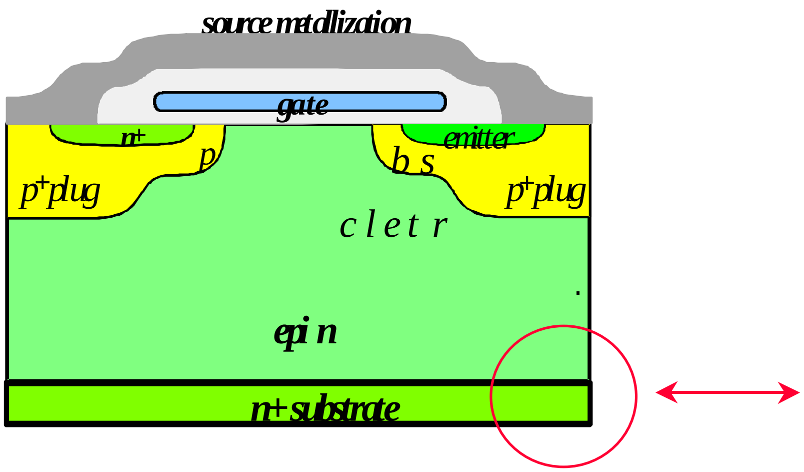
Sensitive at 310 V

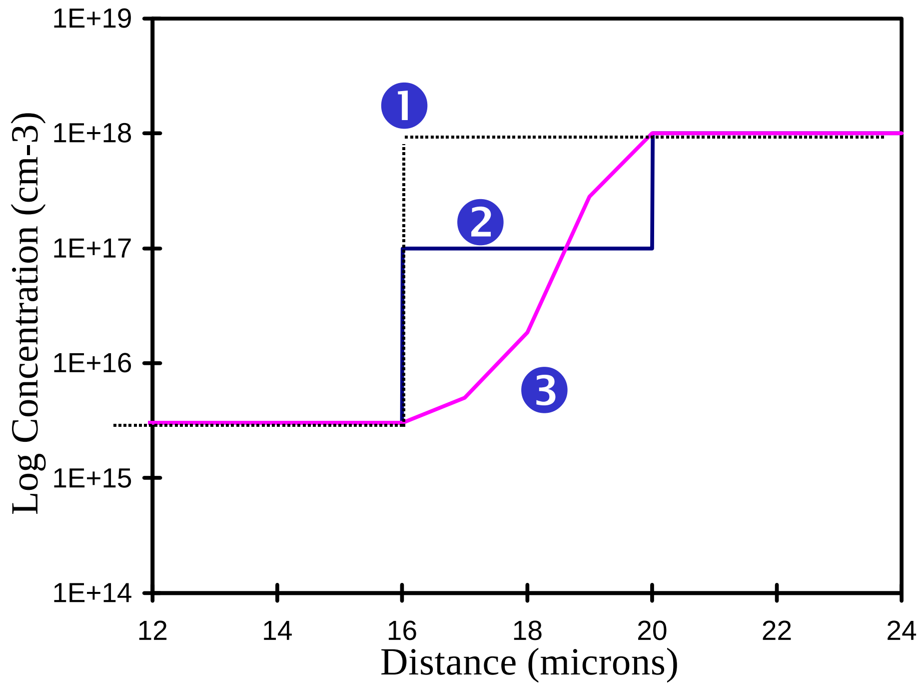
Sensitive at 380 V

Sensitive at 460 V

Effects in Power Devices : ***MOSFET, VIP***

SEB Hardening



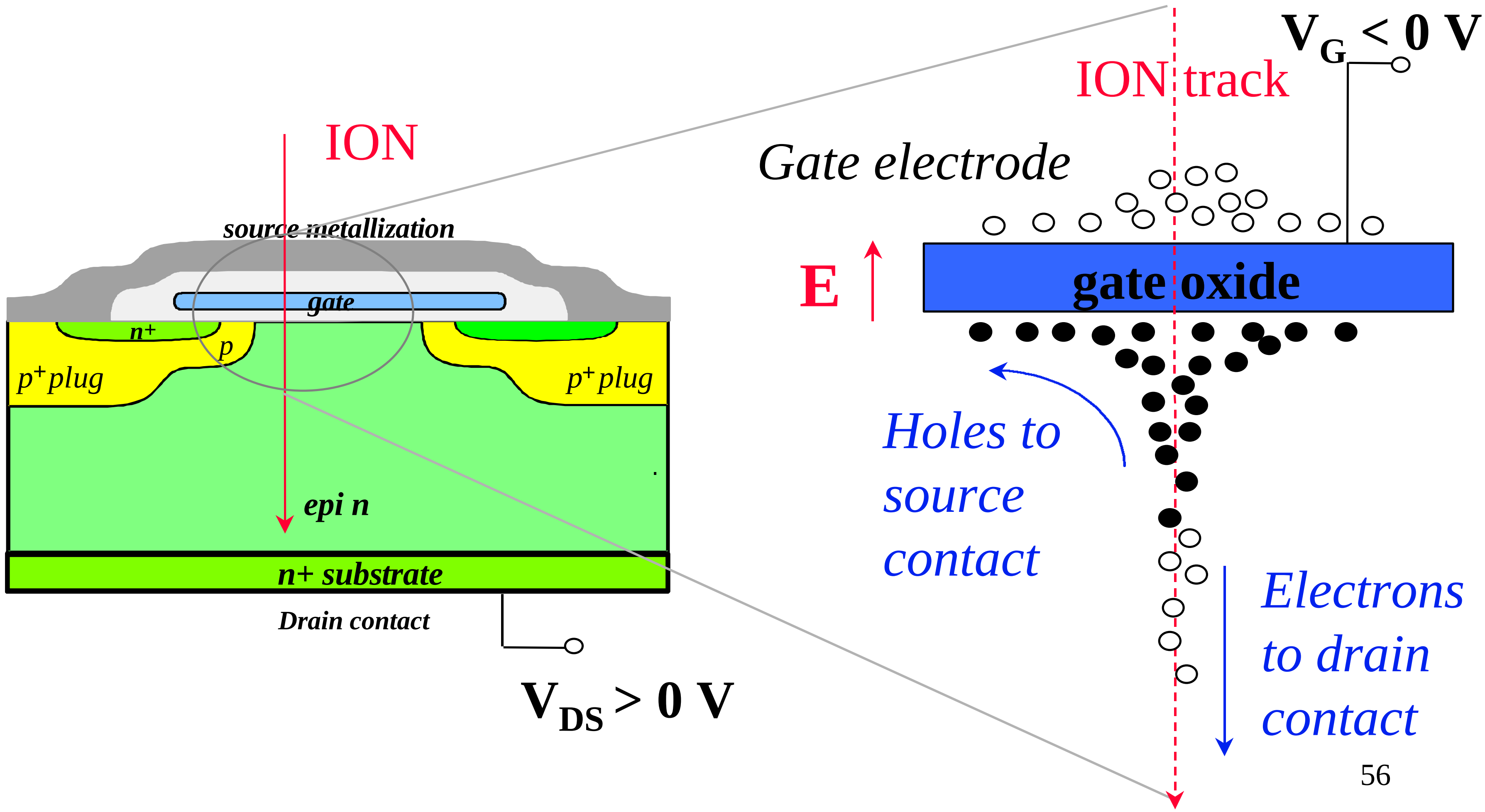


Doping Profile at the epi-substrate junction

LET Sensitivity	
❶ Standard	1
❷ Stepped profile	1/6
❸ Gradual profile	1/30

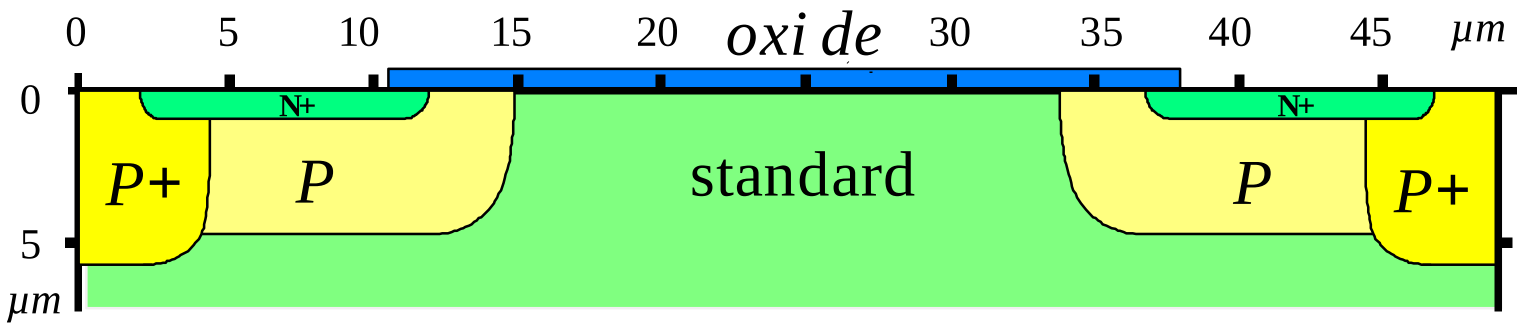
Effects in Power Devices : ***MOSFET, VIP***

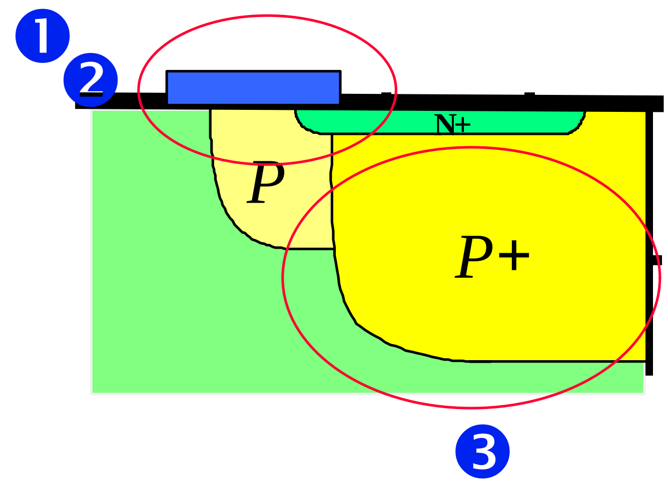
Single Event Gate Rupture



Effects in Power Devices : ***MOSFET, VIP***

SEGR Hardening

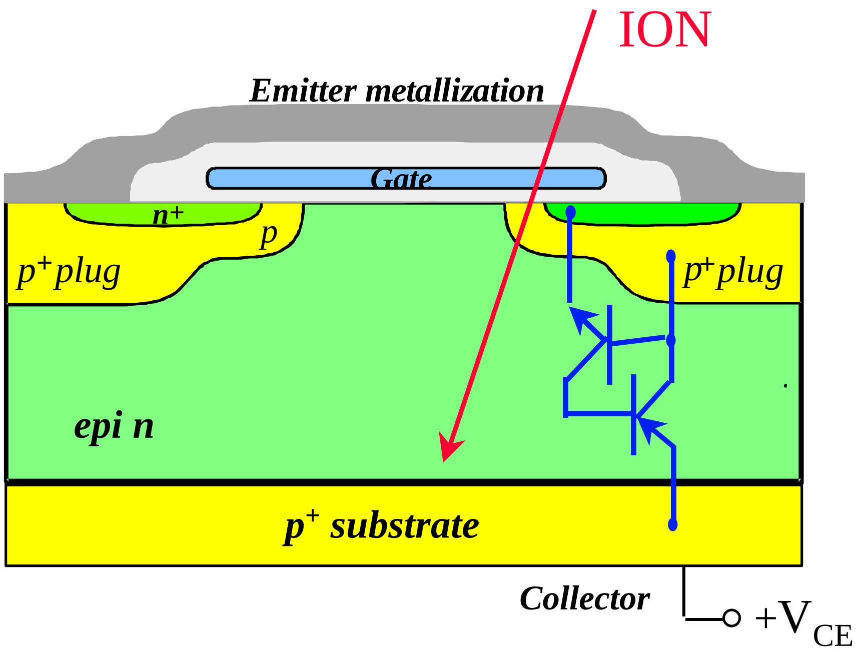


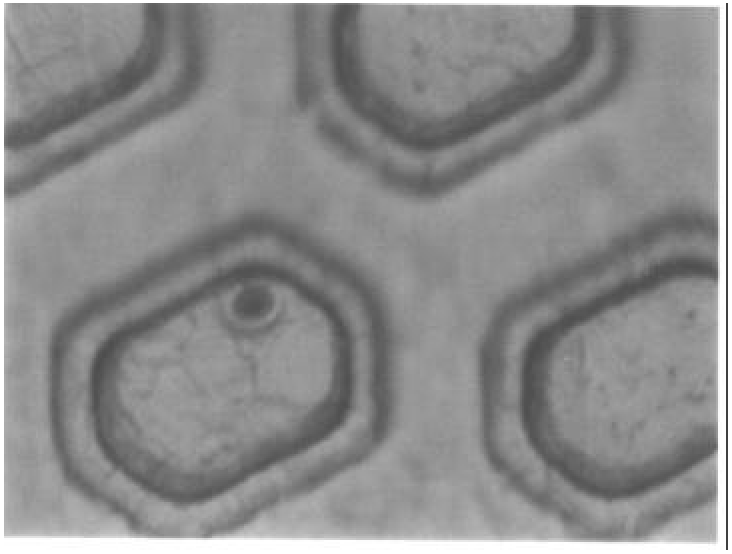


❶ Oxide thickness optimization
❷ Reduced area of gate oxide
❸ Extended plug

Effects in Power Devices : ***IGBT***

Single Event Latchup





Parasitic thyristor

Example of Latched cell

Hardening solutions comparable to SEB

Conclusion

Development of an Electronic systems

Evaluation of the constraint

- **Radiation field**
- **Working conditions (time, temperature, ..)**

Testing conditions

System evaluation

Radiation hardening level :

Device

- **technology**
- **design**

Circuit

- **design**

System

- **redundancy**
- **Soft correction**
- **Shielding**