PANDA Lecture Week
Introduction into Front End Electronics
Part III: Radiaton Effects

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Outline

1. Introduction
   - Further reading
   - Dosimetry
2. Interaction Radiation – Matter
3. Radiation Effects on Semiconductor, Example MOS-Transistor
4. Literature

Introduction

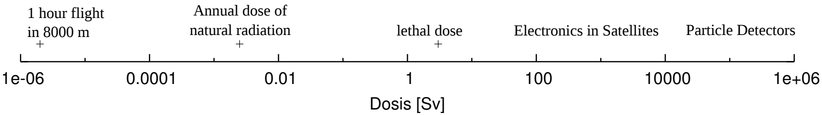
Further reading

- List of Literature at the end of the talk
- Textbooks
  - ?
- Journals
  - IEEE Transactions on Nuclear Science
- Conferences
  - Nuclear and Space Radiation Effects Conference (NSREC, USA)
  - Radiation Effects on Components and Systems (RADECS, Europa)
  - NSS, TWEPP, . . .

Introduction

Dosimetry

- Dose defines absorbed energy per mass
- Unit: 1 Gray [Gy] = 1 J/kg (obsolete unit: 1 rad = 0,01 Gy)
- For biological effects: 1 Sievert [Sv] = Dose in Gray rated with a quality factor q depending on type of radiation.



Outline

1. Introduction
2. Interaction Radiation – Matter
   - Charged Particles
   - Neutral Particles
   - Electromagnetic Radiation
3. Radiation Effects on Semiconductor, Example MOS-Transistor
4. Literature

Interaction Radiation – Matter

Radiation interacts with matter and leads to

- Ionisation
- Lattice displacement damage
- Nuclear reactions

Different modes of interaction

- Charged particles
  Protons, Myons, Ions, ...
- Neutral particles
  Neutrons
- Electromagnetic radiation
  Gamma-ray, Electrons

Interaction Radiation – Matter

Charged Particles

- Charged particles interact with orbital electrons of absorbing matter
- Energy transfer by Collision processes
    - Deceleration of projectile
    - Excitation of ionisation of absorber atom
- Description of deceleration by statistical collision processes with Bethe-Bloch-Equation

$$\frac{dE}{dx} \sim -\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{\beta^2}{1-\beta^2}\right) - \beta^2\right] \tag{1}$$

- Finite range of projectiles in absorbing matter

Interaction Radiation – Matter

Charged Particles

Interaction with nucleus possible.

- Electromagnetic interaction between charged particle and nucleus
  $\Rightarrow$ Rutherford scattering
- Similar masses $\Rightarrow$ momentum transfer to nucleus $\Rightarrow$ lattice displace damage

If Coulomb barrier is exceeded nuclear reaction is possible

- Fusion

$$^{4}\mathrm{He} + {}^{14}\mathrm{N} \rightarrow {}^{17}\mathrm{O} + {}^{1}\mathrm{H} - 1,2\ \mathrm{MeV}$$

$$^{1}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma + 5,49\ \mathrm{MeV}$$

- Induced fission

Interaction Radiation – Matter

Neutral Particles

Neutral particles do not interact with orbital electrons or nuclei by electromagnetic interaction

Thus

- Large range in matter
- No Coulomb barrier ⇒ low threshold for nuclear reactions

$$n + {}^{14}\mathrm{N} \rightarrow {}^{14}\mathrm{C} + \mathrm{p}$$

Influence on absorbing matter

- Collision: Lattice displace damage
- Nuclear reaction

  Example: Neutron Transmutation Doping

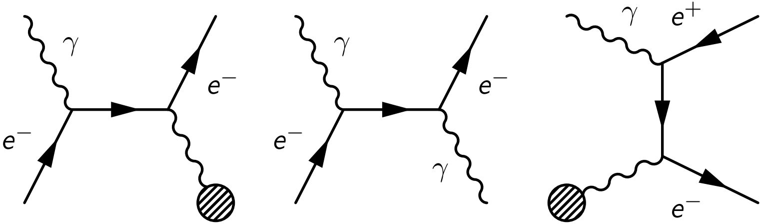
$$\begin{aligned} n + {}^{30}\mathrm{Si} &\longrightarrow {}^{31}\mathrm{Si} + \gamma \\ {}^{31}\mathrm{Si} &\xrightarrow{2{,}62\mathrm{h}} {}^{31}\mathrm{P} + e^- \end{aligned}$$

Interaction Radiation – Matter

Electromagnetic Radiation

3 basic interaction processes of electromagnetic radiation with matter

photo effect	Compton scattering	pair production
$E_\gamma < 0,5\ \mathrm{MeV}$	$E_\gamma \approx 0,5 \ldots 1\ \mathrm{MeV}$	$E_\gamma > 1\ \mathrm{MeV}$



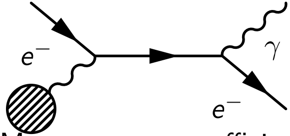
- Original photon disappeared after interaction
- Radiation intensity decreases exponentially
- Individual photon range not determined

Interaction Radiation – Matter

Electromagnetic Radiation

Special position of the electron:
Charged particle but :

- Energy loss by bremsstrahlung dominates ($\sigma \sim 1/m^4$)



- Momentum not sufficient for nuclear collisions
- Cross section for nuclear reaction small (Inverse beta decay)

Effect on matter comparable with photons
At high energies: Electromagnetic showers by alternating pair production and bremsstrahlung processes

Interaction Radiation – Matter

Summary

Effects on Matter (e.g. Semiconductors)

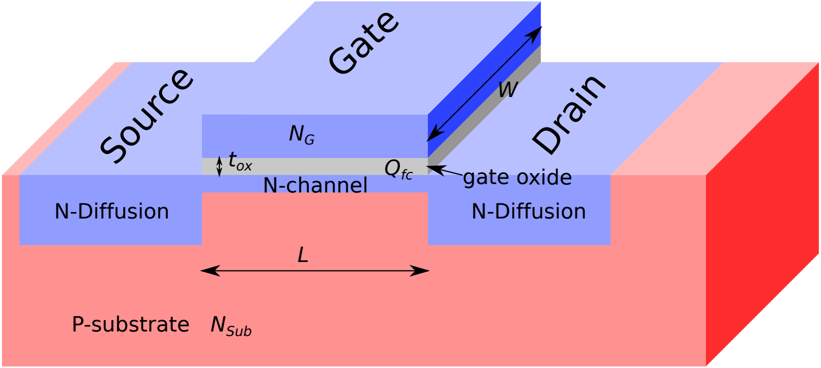
- Charged particles and electromagnetic radiation leads to ionisation
  - In oxides: charge accumulation, electric fields
  - In junction areas: electrical pulses, single event transients
- Lattice displace damages
  - Creating vacant states in energy gap: *Traps*
  - ⇒ Reduction of mean free path of charge carriers
- Nuclear reactions (charged particles, Neutrons)
  - Lattice displace damages
  - Doping

Outline

1. Introduction
2. Interaction Radiation – Matter
3. Radiation Effects on Semiconductor, Example MOS-Transistor
   - Reminder: Function of a MOS-Transistor
   - Effects of Oxide ionisation of MOS Transistors
     - Mitigation
   - Single Event Effects
     - Mitigation
4. Literature

Radiation Effects on Semiconductor

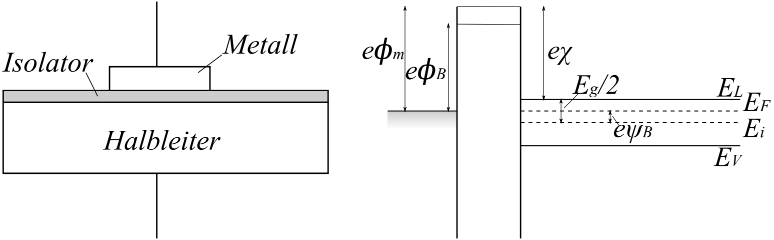
Reminder: Function of a MOS-Transistor



Cross section of a NMOS-Transistor

Radiation Effects on Semiconductor

Reminder: Function of a MOS-Transistor



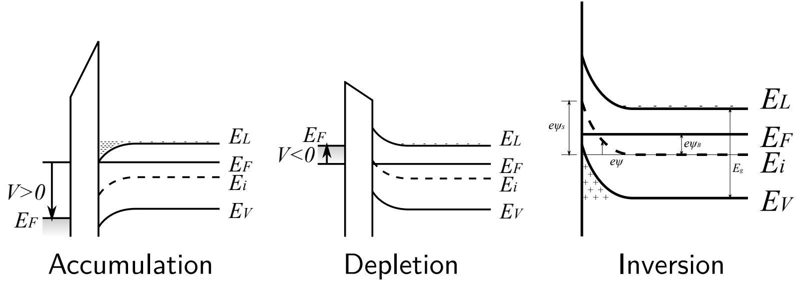
Cross section of a metal insulator semiconductor diode and band structure.

ϕ_m	work function (metal)	ϕ_B	potential barrier
χ	work function (sem.)	E_g	band gap
E_F	Fermi level	E_i	intrinsic Fermi level

Radiation Effects on Semiconductor

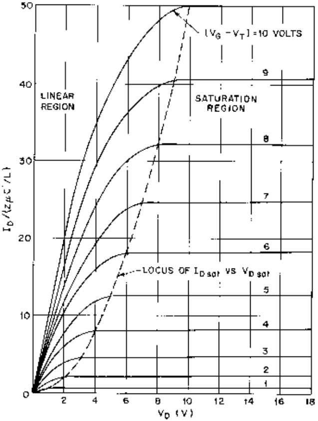
Reminder: Function of a MOS-Transistor

MIS diode with external voltage:



Radiation Effects on Semiconductor

Reminder: Function of a MOS-Transistor



$$I_{DS} = \beta\left(u_{GS} - V_T - \frac{u_{DS}}{2}\right)u_{DS} \tag{2}$$

With $\beta = \mu C_{Ox} W/L$.
Drain-Source current saturates at

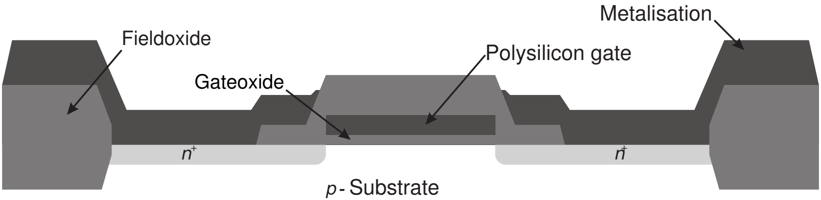
$$I_{DS_{Sat}} = \frac{\beta}{2}\left(u_{GS} - V_T\right)^2 \tag{3}$$

Characteristics of a MOS transistor from [Sze, 1981] and simple first order model.

Radiation Effects on Semiconductor

Effects of Oxide ionisation of MOS Transistors

- Ionisation leads to creation of electron hole pairs
- Partly recombination
- Transport of charge carrier across the oxide
- Hole capture in deep traps
- $\Rightarrow$ Accumulation of positive charge in oxide

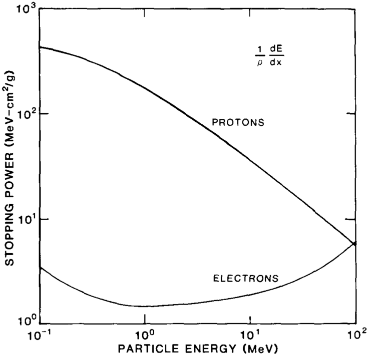


Of particular importance: Gate oxide, Field oxide

Radiation Effects on Semiconductor

Effects of Oxide ionisation of MOS Transistors

Creation of Electron Hole Pairs:



[Srour and McGarrity, 1988]

- Energy deposition by the penetrating particle
- Total ionising dose defined as energy per mass unit:

$$1\ \mathrm{Gy} = \frac{1\ \mathrm{J}}{1\ \mathrm{kg}} \qquad (4)$$

- Electron hole density:

$$n = D\frac{1}{E_p}\varrho \qquad (5)$$

Radiation Effects on Semiconductor

Effects of Oxide ionisation of MOS Transistors

Creation of Electron Hole Pairs:

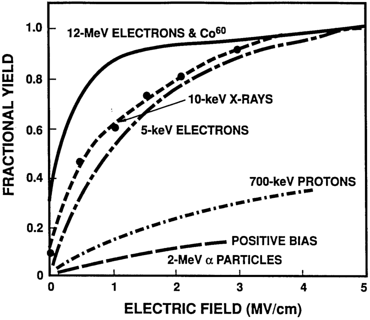
Material	Mean E_p	Density	Pair density by 1 Gy
	eV	g/cm^3	cm^{-3}
GaAs	4.8	5.32	$7 \cdot 10^{15}$
Silicon	3.6	2.328	$4 \cdot 10^{15}$
Silicon Dioxide	17	2.2	$8.1 \cdot 10^{14}$

[Schwank, 1994]

Radiation Effects on Semiconductor

Effects of Oxide ionisation of MOS Transistors

Electron hole recombination:



[McLean et al., 1989]

- part of the electron hole pairs recombine promptly
- Fraction of unrecombined pairs depends on projectile, energy and electrical field
- Two established models[Oldham, 1984]:
  - low LET: geminate model, Smoluchowski, 1917
  - high LET: columnar model[Jaffé, 1913]

⇒ TID tests of electronics always have to be done under bias conditions!

Radiation Effects on Semiconductor

Effects of Oxide ionisation of MOS Transistors

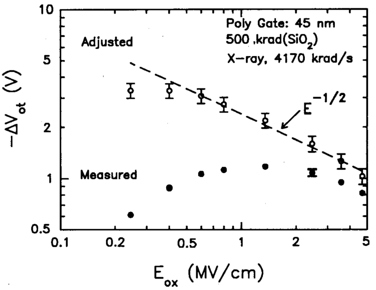
Charge Transport:

- Very high mobility of electrons in $\mathrm{SiO_2}$ $\rightarrow$ swept out of the oxide within picoseconds[Hughes, 1973]
- Hole transport more complex[Hughes, 1975]
  - Much slower (order of seconds)
  - Dispersive
  - Temperature and field activated
- Localised traps are involved, two Models:
  - Hopping transport[Boesch et al., 1975]
  - Multiple Trapping[Srour et al., 1976]
- Both can be mathematically described by Continuous-time Random Walk model

Radiation Effects on Semiconductor

Effects of Oxide ionisation of MOS Transistors

Positive charge trapping:



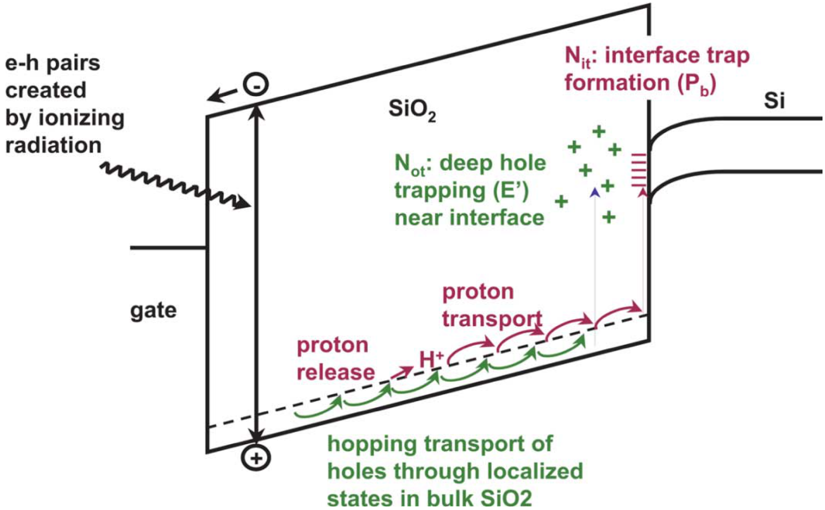
[Shaneyfelt et al., 1990]

- Highest trap density near interfaces
- Holes trapped depending on hole trap density and capture cross section
- Hole trapping efficiency $\sim 1/\sqrt{E}$
- Threshold voltage shift due to trapped holes:

$$\Delta V_{ot} = -\left(\frac{q}{\epsilon_{ox}}\right) t_{ox} \Delta N_{ot} \tag{6}$$

Radiation Effects on Semiconductor

Effects of Oxide ionisation of MOS Transistors



Radiation Effects on Semiconductor

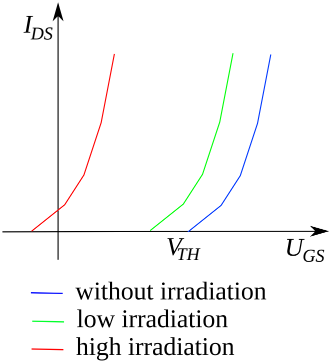
Effects of Oxide ionisation of MOS Transistors

- Charge accumulation leads to electrical field $\Rightarrow$ Band bending below oxide
- Gate oxide
  - Threshold shift
  - Strong ionisation: NMOS-Transistor gets conducting at zero gate source voltage
- Field oxide
  - Arising of parasitic transistor at the channel sides
  - Leakage currents

Radiation Effects on Semiconductor

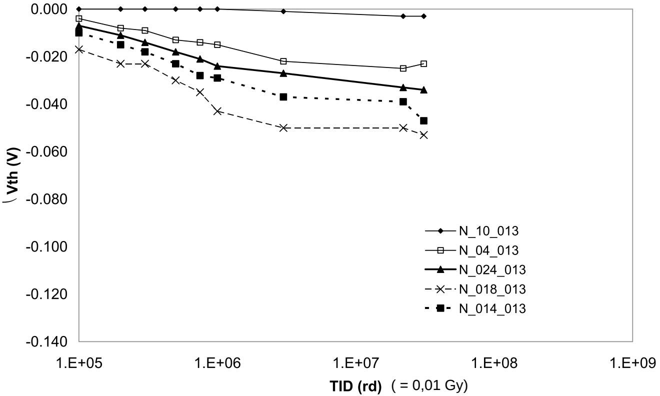
Threshold shift

- Effect of gate oxide ionisation: Threshold shift V_{Th}
- Change of operating points in analogue circuits
- In digital circuits: shift of switching points $\Rightarrow$ Changes of timing
- Strong ionisation: NMOS-Transistor gets conducting at zero gate source voltage



Radiation Effects on Semiconductor

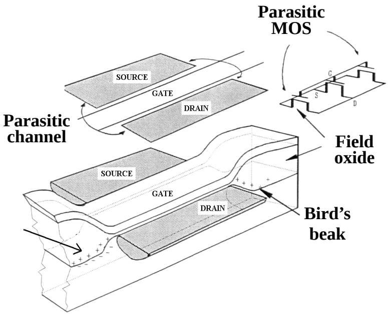
Threshold shift



Threshold shift measured on different transistors in 130 nm technology[Faccio, 2006].

Radiation Effects on Semiconductor

Parasitic MOS Transistors

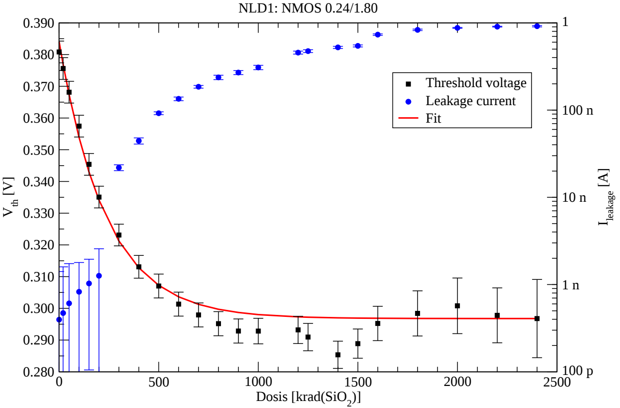


(*R. Gaillard et al., Short Course Notes of RADECS 1995*)

- Arising of parasitic transistor at the channel sides due to ionisation of Field oxide
- At NMOS-transistors $\Rightarrow$ parasitic channels
- $\Rightarrow$ Leakage current

Radiation Effects on Semiconductor

Effects of Oxide ionisation



Threshold shift and increasing of leakage current due to irradiation[Löchner et al., 2009]

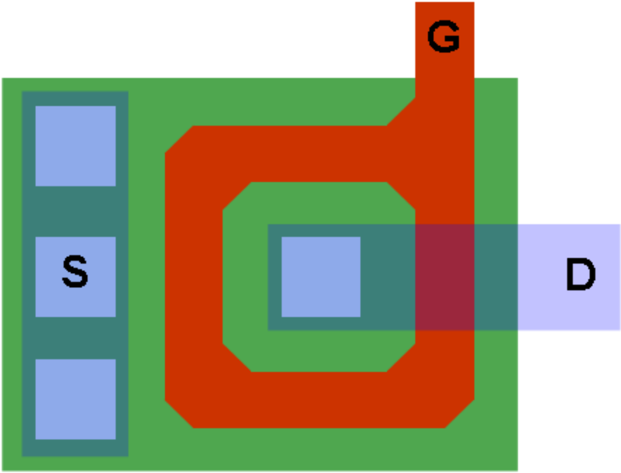
Radiation Effects on Semiconductor

Mitigation

- In principle
  - Selecting suitable process technology
    Technologies with smaller feature sizes are less sensitive against TID
  - Irradiation tests
- Ionisation of gate oxide
  - Smaller feature sizes ⇒ thinner gate oxide
  - Trapped holes neutralised by tunnelling electrons
- Ionisation of field oxide
  - Enclosed Gate Transistors (Hardness by Design)
  - Guard rings
  - parasitic channels can not arise
  - requires more area ⇒ increase of capacitance
    - ⇒ decrease of speed
    - ⇒ increase of power consumption

Radiation Effects on Semiconductor

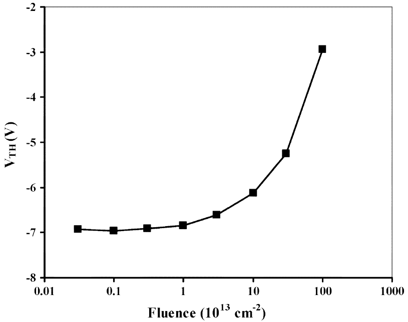
Counteraction



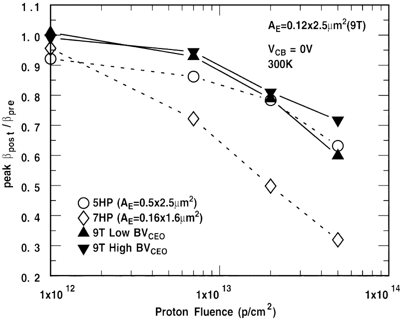
Layout of an enclosed MOSFET[Bruder, 2006]

Radiation Effects on Semiconductor

Other Examples



Threshold shift of a *High Electron Mobility Transistor (HEMT)*[Karmarkar et al., 2004]

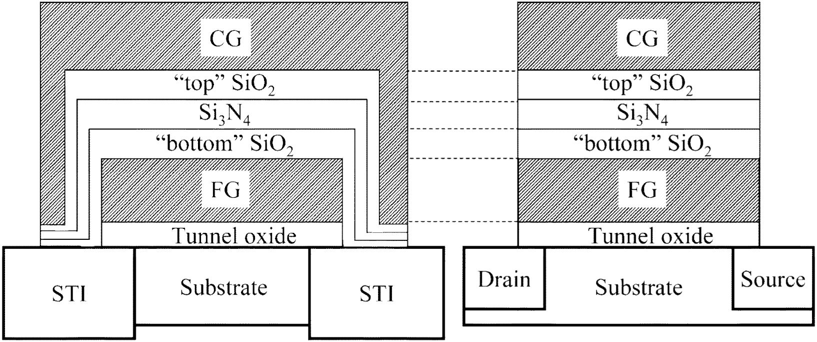


Decrease of current gain of SiGe HBTs of different generations[Sutton et al., 2004]

Radiation Effects on Semiconductor

Non-Volatile Memory

Non-Volatile Memories in most cases based on floating gate structures.

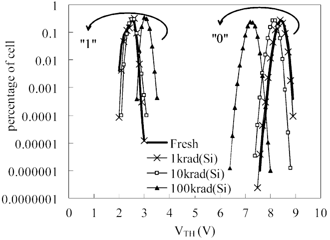


[Cellere et al., 2004]

Radiation Effects on Semiconductor

Non-Volatile Memory

Single Event Latch up:



[Cellere et al., 2004]

- Threshold of memory transistor defined by charging of FG
- Threshold shift due to TID observable
- Control circuit more sensitive to irradiation than memory cells[Nguyen et al., 1999] (finite state machine, charge pumps, output register...)

Radiation Effects on Semiconductor

Single Event Effects

Energy deposition due to ionising radiation

- Measure for energy deposition: *Linear Energy Transfer LET*
- Measured in MeV/cm or MeV cm^2 / mg
- Conversion by material density

$$LET/\frac{\mathrm{MeVcm}^2}{\mathrm{mg}} = LET/\frac{\mathrm{MeV}}{\mathrm{cm}}/1000 \cdot \varrho/\frac{\mathrm{g}}{\mathrm{cm}^3} \quad (7)$$

$$LET/\frac{\mathrm{MeV}}{\mathrm{cm}} = LET/\frac{\mathrm{MeVcm}^2}{\mathrm{mg}} \cdot 1000 \cdot \varrho/\frac{\mathrm{g}}{\mathrm{cm}^3} \quad (8)$$

- $\varrho_{Si} = 2,33\ \mathrm{g/cm}^3$

Radiation Effects on Semiconductor

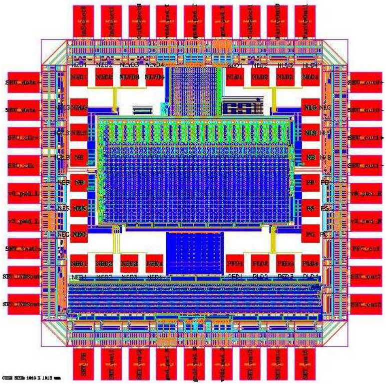
Single Event Effects

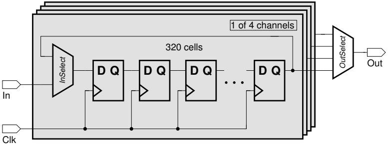
- LET of ^{12}C: 5 $\mathrm{MeVcm^2/mg} = 11,6\ \mathrm{GeV/cm}$
  LET of ^{58}Ni: 30 $\mathrm{MeVcm^2/mg} = 69,9\ \mathrm{GeV/cm}$
- Energy deposit in 1 µm Silicon:
  ^{12}C: 1,16 MeV
  ^{58}Ni: 6,99 MeV
- Ionisation energy: 2 - 3 eV $\Rightarrow$
  ^{12}C: 464000 Electron hole pairs $\approx 74\ \mathrm{fC}$
  ^{58}Ni: 2796000 Electron hole pairs $\approx 447\ \mathrm{fC}$
- For comparison typical charge in register cell:
  - Supply voltage 1,8 V
  - Node capacity: 10 fF
  - $\Rightarrow$ Charge : 18 fC
- **Deposited energy large enough to flip register**

Radiation Effects on Semiconductor

Single Event Effects

GRISU, A Test Device for SEE Cross section Measurement

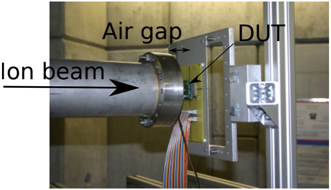




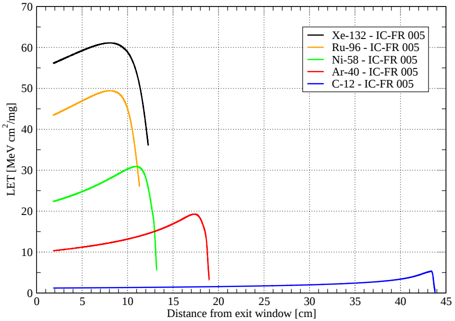
Radiation Effects on Semiconductor

Single Event Effects

Linear energy transfer for different ion beams at GSI linear accelerator



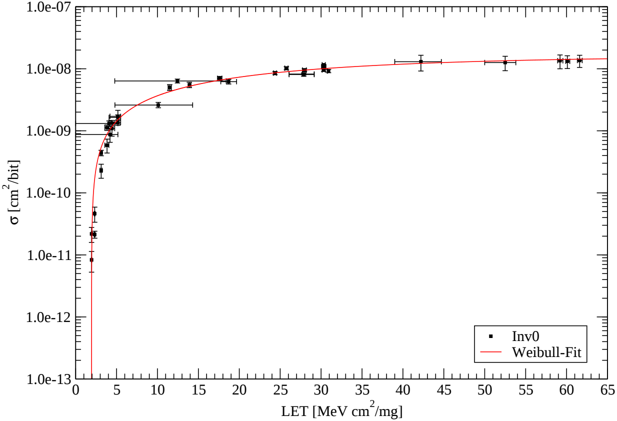
Irradiation setup @ GSI



[Löchner et al., 2009]

Radiation Effects on Semiconductor

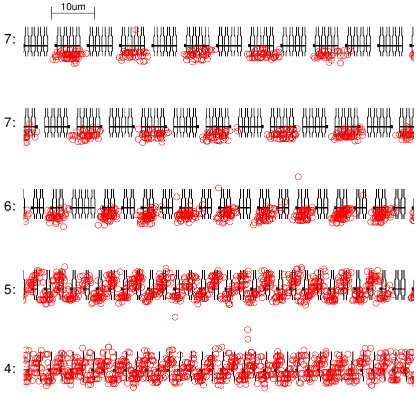
Single Event Effects



Cross section for single event transients in minimum sized CMOS inverter[Löchner et al., 2009]

Radiation Effects on Semiconductor

Single Event Effects



Intersection points of ion trajectories leading to SETs[Löchner et al., 2009]

Radiation Effects on Semiconductor

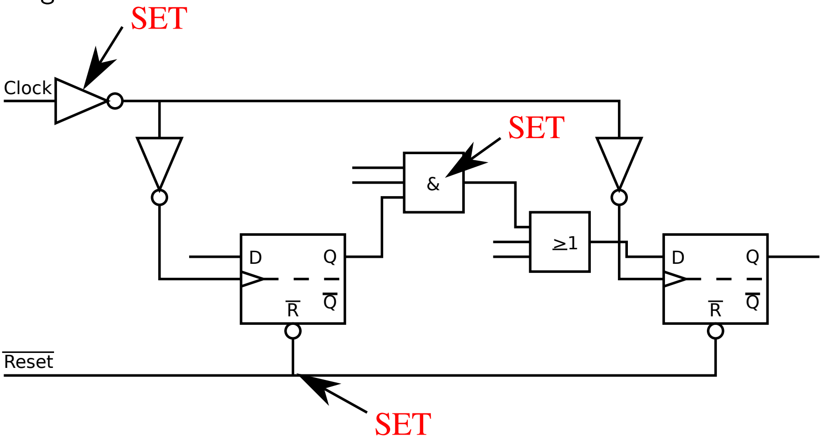
Single Event Effects

- Single Event Transients
  - Pulse transients due to charge injection by ionising particles
  - harmful for: combinational logic, analogue circuits
  - SETs close to clock edge ⇒ corrupted data stored in register
  - Probability increases with increasing clock frequency
  - Critical nodes:
    - Clock tree
    - Asynchronous reset
      On Nov. 11th 2001 an SET caused a RESET of NASA MAP (Microwave Anisotropy Probe)
      Satellite switched into safe hold mode. Reactivation needed several days

Radiation Effects on Semiconductor

Single Event Effects

Single Event Transients:



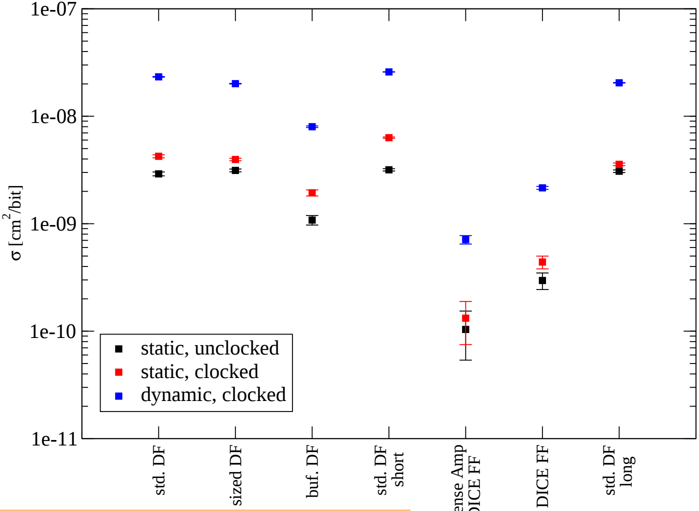
Radiation Effects on Semiconductor

Single Event Effects

- Single Event Upset
  - Bit flip of a register or SRAM cell
  - Corrupts data or processing code
  - SEUs in finite state machines might cause an undefined state $\rightarrow$ Chip system hang-up
  - Probability depends on process technology, layout, state, clocking etc.
  - Latest technologies with small feature sizes are more vulnerable
  - FPGAs: SEU in configuration LUT leads to functional change

Radiation Effects on Semiconductor

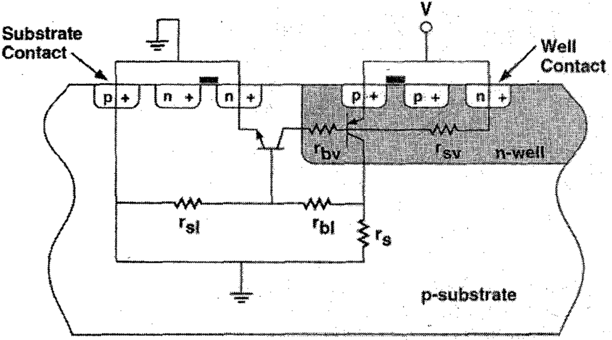
Single Event Effects



Radiation Effects on Semiconductor

Single Event Effects

Single Event Latch up:

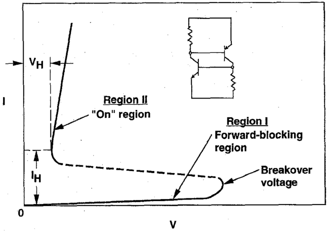


[Johnston, 1996]

Radiation Effects on Semiconductor

Single Event Effects

Single Event Latch up:



[Johnston, 1996]

- Latch up: low resistive condition in four region structures
- Triggering of Latch up: Transition from region I to region II
- Device restoring to normal operation only by decreasing supply voltage below V_H
- Current only limited by external supply resistance
- **Large current might cause over heating and permanent device damage**

Radiation Effects on Semiconductor

Single Event Effects

Mitigation

- Single Event Transients & Single Event Upsets
  - Redundancy
    - SEU: Triple redundant register, hamming coding
    - SET: triple redundant combinatorics, triple redundant registers with phase shifts
  - Larger node capacitance requires larger charges ⇒ SET and SEU less probable
- Single Event Latch up
  - Protection by Chip Layout
    - Guard rings
    - Sufficient density of substrate and well contacts
- **Component selection by irradiation tests!**

Outline

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2. Interaction Radiation – Matter
3. Radiation Effects on Semiconductor, Example MOS-Transistor
4. Literature

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