# An Introduction to Radiation Effects on Electronics

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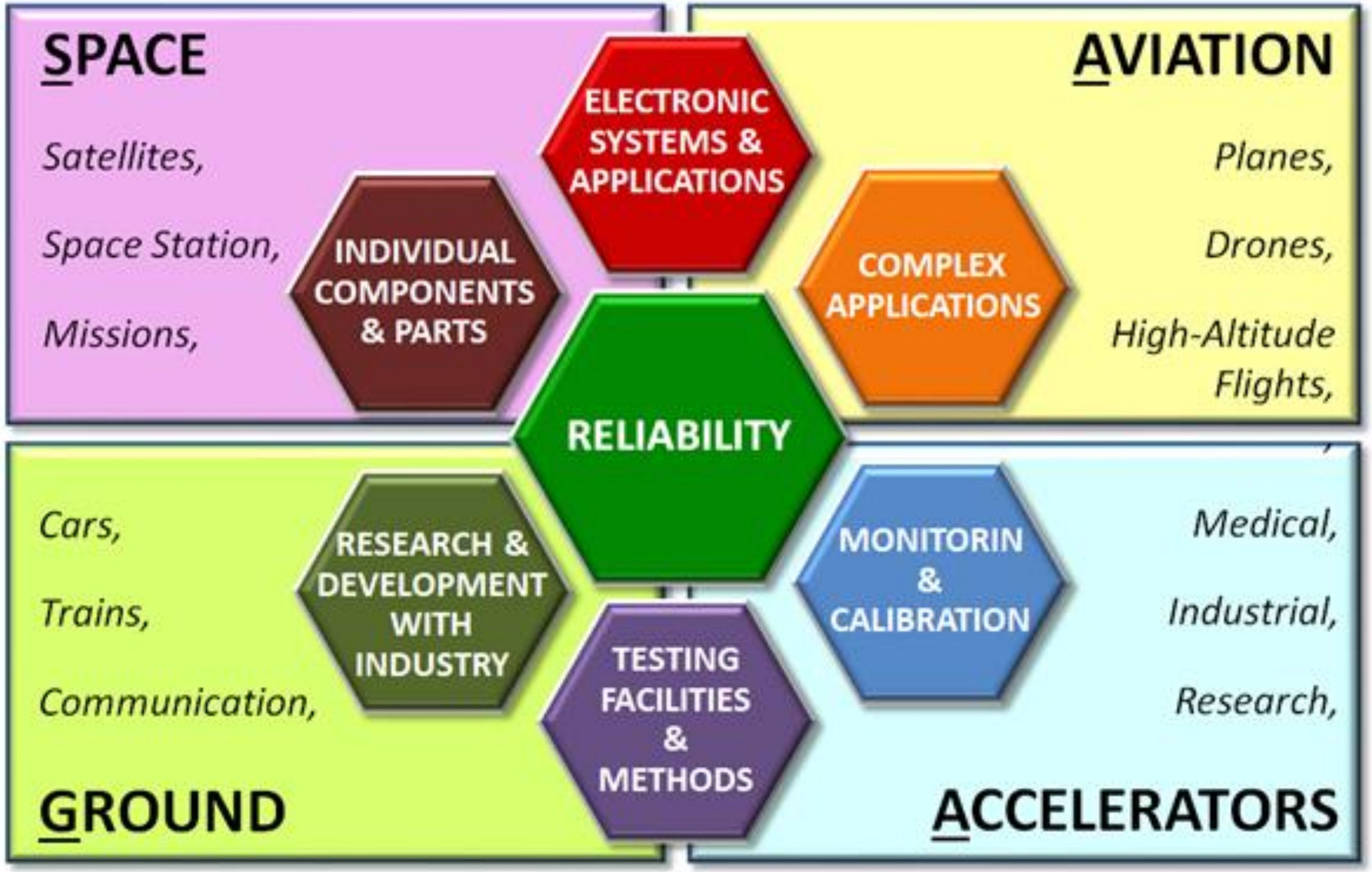
RADSAGA

European Commission

RADECS 2017
CERN, Geneva

# Reliability and Radiation Effects (RADSAGA)



**SPACE**

*Satellites,*

*Space Station,*

*Missions,*

**AVIATION**

*Planes,*

*Drones,*

*High-Altitude Flights,*

**GROUND**

*Cars,*

*Trains,*

*Communication,*

**ACCELERATORS**

*Medical,*

*Industrial,*

*Research,*

ELECTRONIC SYSTEMS & APPLICATIONS

INDIVIDUAL COMPONENTS & PARTS

COMPLEX APPLICATIONS

RELIABILITY

RESEARCH & DEVELOPMENT WITH INDUSTRY

MONITORIN & CALIBRATION

TESTING FACILITIES & METHODS

# Radiation Effects on Electronics
# A Mature Field of research and applications

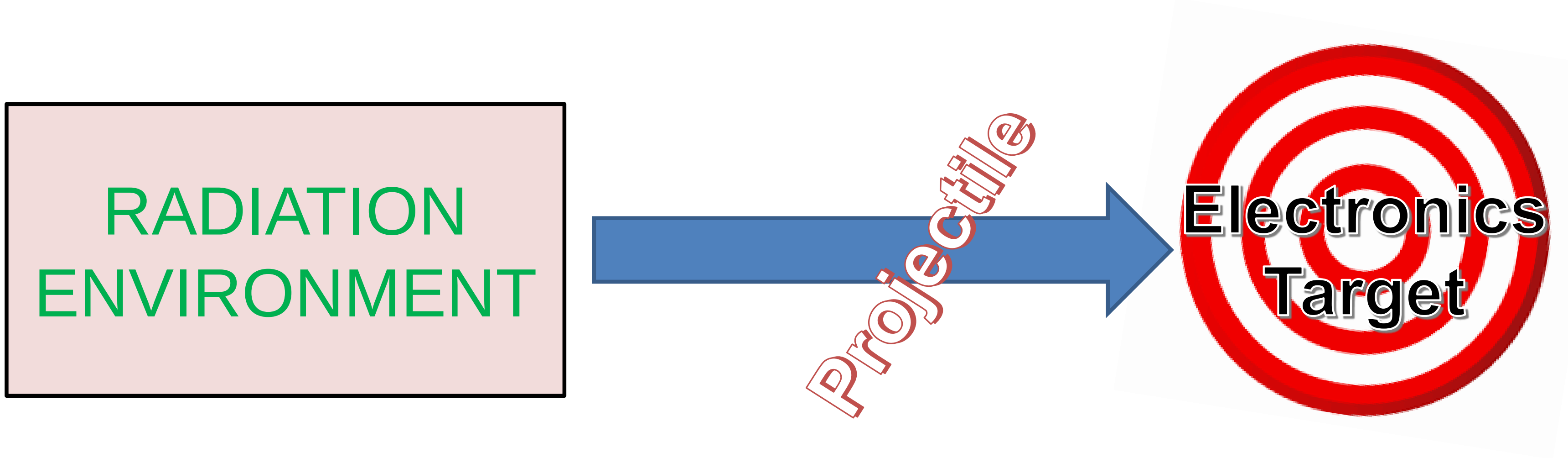
- NSREC 2017
- Basic Mechanisms of Radiation Effects
- Radiation Effects in Devices and ICs
- Single-Event Effects: Devices and ICs
- Hardness Assurance
- Space and Terrestrial Environments
- Hardening by Design
- Single-Event Effects: Mechanisms and Modeling
- Single-Event Effects: Transient Characterization
- Photonic Devices and Integrated Circuits
- Dosimetry

*Data workshop*

- RADECS2017
- Basic Mechanisms of Radiation Effects
- Radiation Effects in Devices and ICs,
- Single Event Effects in Devices and ICs
- Radiation Hardness Assurance at Device and System Level
- Radiation Environments (Space, Atmospheric, Terrestrial and Accelerators)
- Hardening by Design
- Single Event Effects Mechanisms and Modelling
- Single Event Transients and Laser testing
- Radiation Effects in Optoelectronics and optical fibers
- Facilities and Dosimetry
- *Analog and Mixed-Signal Integrated Circuits for use in Radiation Environments*
- *Radiation Effects on Materials*
- *In-Orbit Low-Cost Radiation Studies (Nanosat, Stratobus …)*

*Data workshop*

# Radiation Effects on Electronics
# The interaction of two complex universes
# How to enter in this world?



RADIATION ENVIRONMENT

Projectile

Electronics Target

EFFECTS
Damage
Material degradation
Loss of functionality
Upset Burnout…….

# Radiation environment: What, Where, How much, Energy, Flux of particles

Charged particles
- Electrons,
- Muons
- Protons
- alphas
- Heavy Ions

Neutral
- Neutrons
- Photons

**Fermions Bosons**

**Leptons Hadrons Gluons**

Energy
eV,
keV
MeV
GeV
TeV

Velocity

Rest Mass

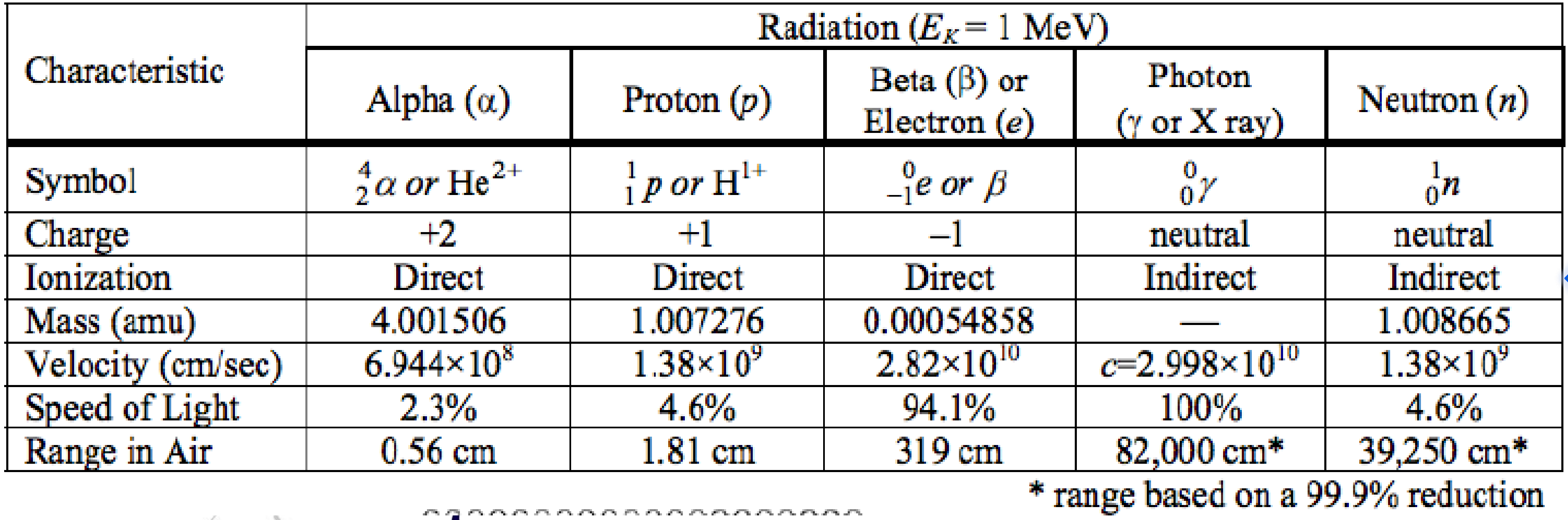
Lifetime

**Flux, Energy Incidence**

Particles/(cm2*s)
Mean, variability
Burst duration
Duty cycle

# Radiation:  charge, mass, interaction mode

- Example:  E=1MeV  alpha, proton, electron, photon, neutron



| Characteristic | Radiation ($E_K = 1$ MeV) | | | | |
|---|---|---|---|---|---|
| | Alpha ($\alpha$) | Proton ($p$) | Beta ($\beta$) or Electron ($e$) | Photon ($\gamma$ or X ray) | Neutron ($n$) |
| Symbol | $^4_2\alpha$ or $\mathrm{He}^{2+}$ | $^1_1p$ or $\mathrm{H}^{1+}$ | $^{0}_{-1}e$ or $\beta$ | $^0_0\gamma$ | $^1_0n$ |
| Charge | +2 | +1 | –1 | neutral | neutral |
| Ionization | Direct | Direct | Direct | Indirect | Indirect |
| Mass (amu) | 4.001506 | 1.007276 | 0.00054858 | — | 1.008665 |
| Velocity (cm/sec) | $6.944\times10^8$ | $1.38\times10^9$ | $2.82\times10^{10}$ | $c=2.998\times10^{10}$ | $1.38\times10^9$ |
| Speed of Light | 2.3% | 4.6% | 94.1% | 100% | 4.6% |
| Range in Air | 0.56 cm | 1.81 cm | 319 cm | 82,000 cm* | 39,250 cm* |

* range based on a 99.9% reduction

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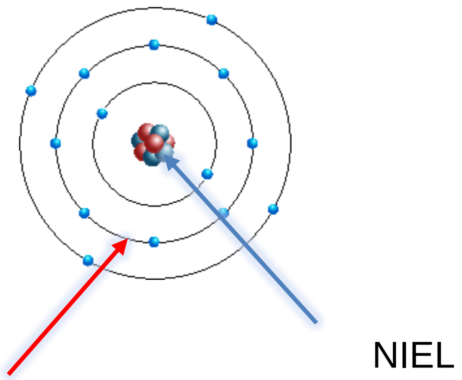
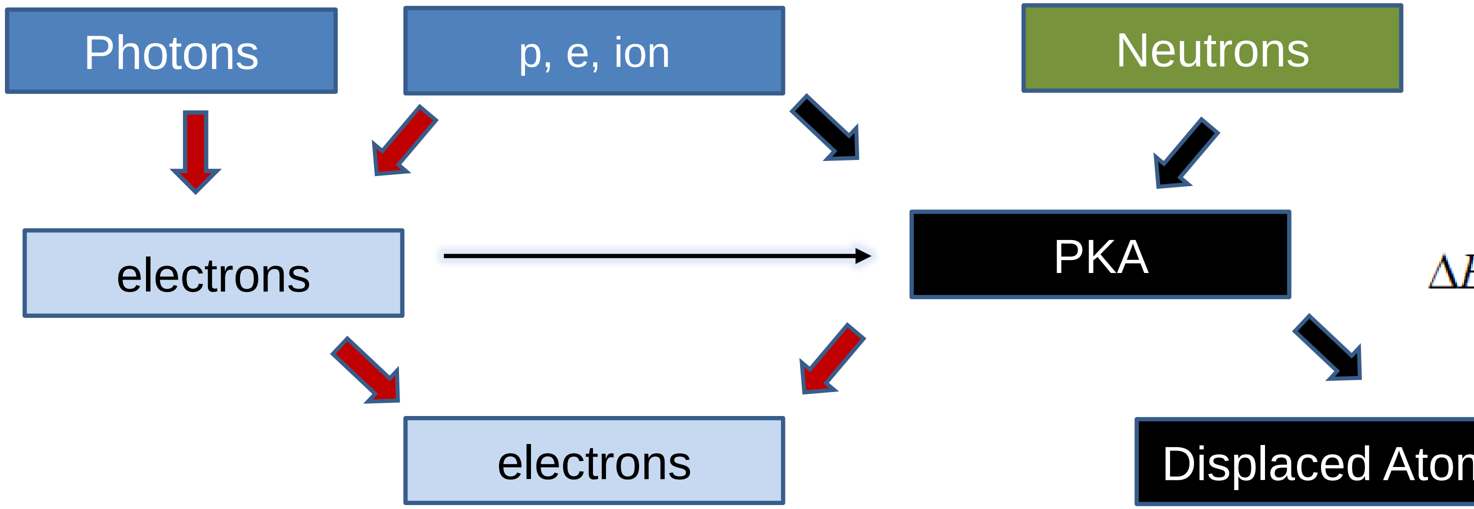
# IEL and NIEL



- IEL: electron interaction from primary knock-on electron (PKE) to electron-hole pairs
- NIEL: from PKA (Primary Knock on Atom) to stable defects



Photons

p, e, ion

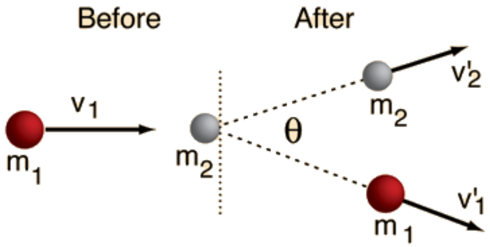
Neutrons

electrons

PKA

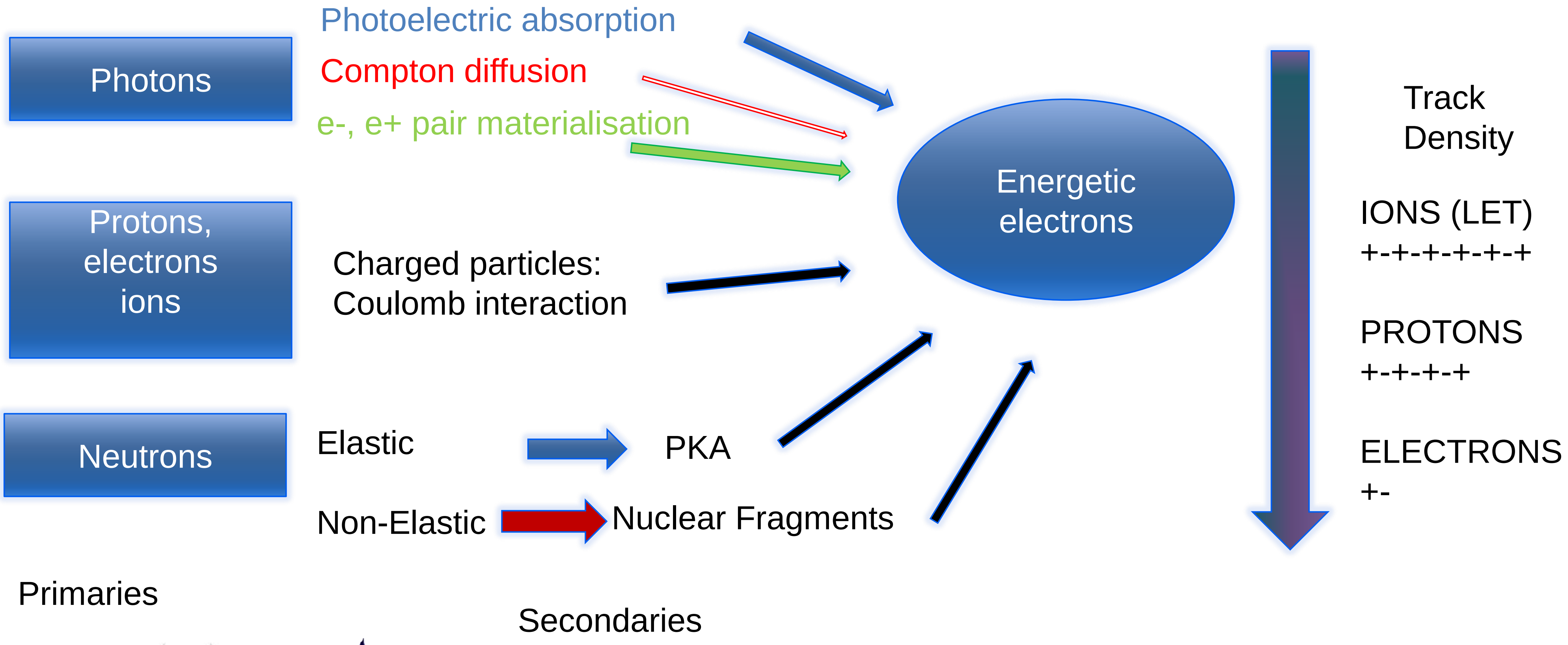
electrons

Displaced Atoms



$$\Delta E = 4\frac{m_p M_{Si}}{(m_p + M_{Si})^2}\sin^2\left(\frac{\vartheta}{2}\right)\cdot E_p$$

# IEL Mechanism: creation of Energetic Electrons



Photons

Photoelectric absorption

Compton diffusion

e-, e+ pair materialisation

Protons, electrons ions

Charged particles:
Coulomb interaction

Neutrons

Elastic

PKA

Non-Elastic

Nuclear Fragments

Energetic electrons

Track Density

IONS (LET)
+-+-+-+-+-+

PROTONS
+-+-+-+

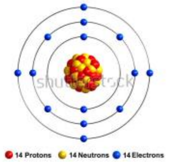
ELECTRONS
+-

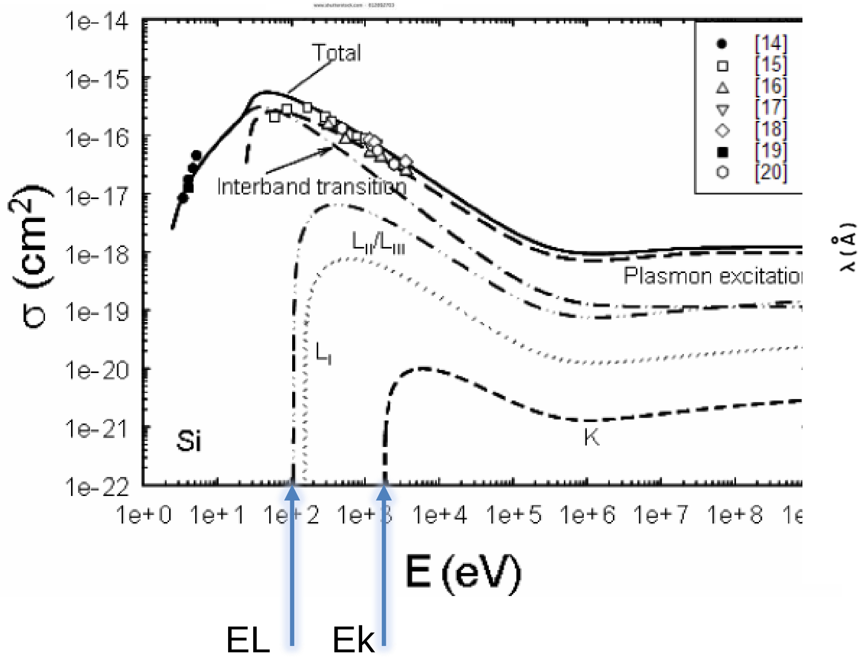
Primaries

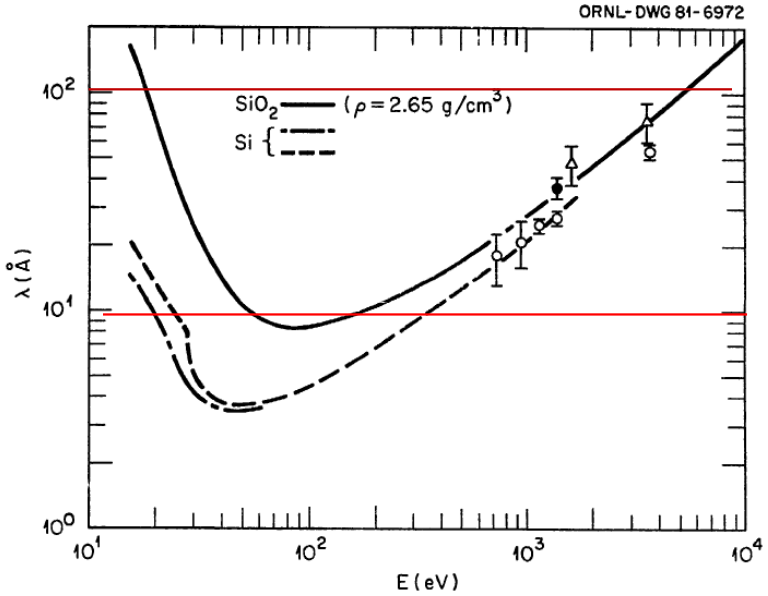
Secondaries

# IEL: Interaction, propagation, thermalisation

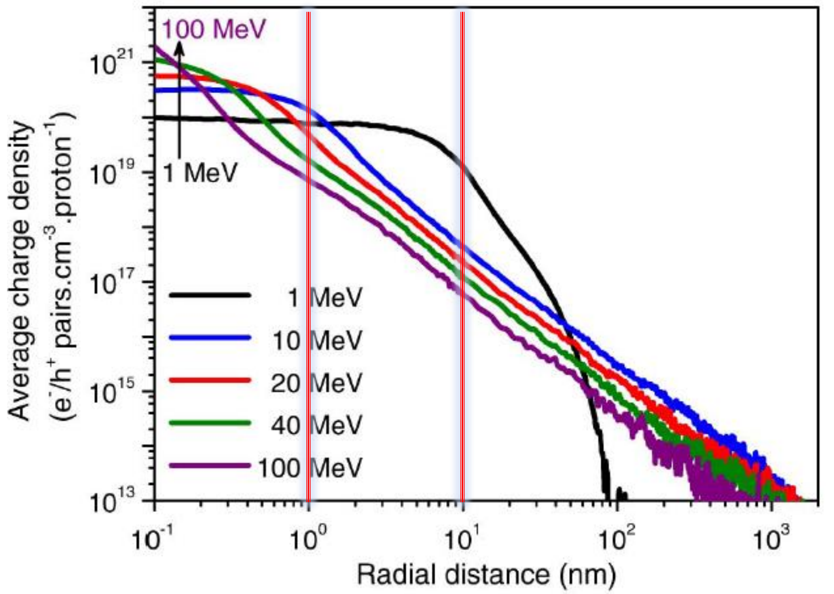
- Cross section of electrons in silicon





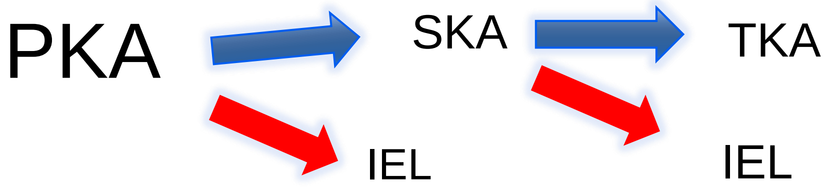


From: Ashley NS 1976



From: M. Raine et al. NS vol61 N°4 2014

# NIEL: Non Ionizing Energy Loss



PKA

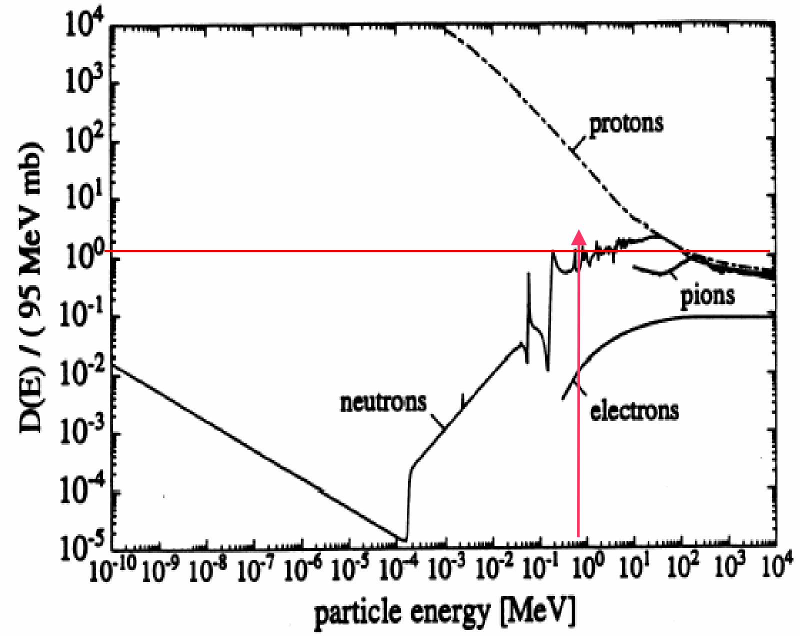
SKA

TKA

IEL

IEL

- NIEL Relative Energy Loss

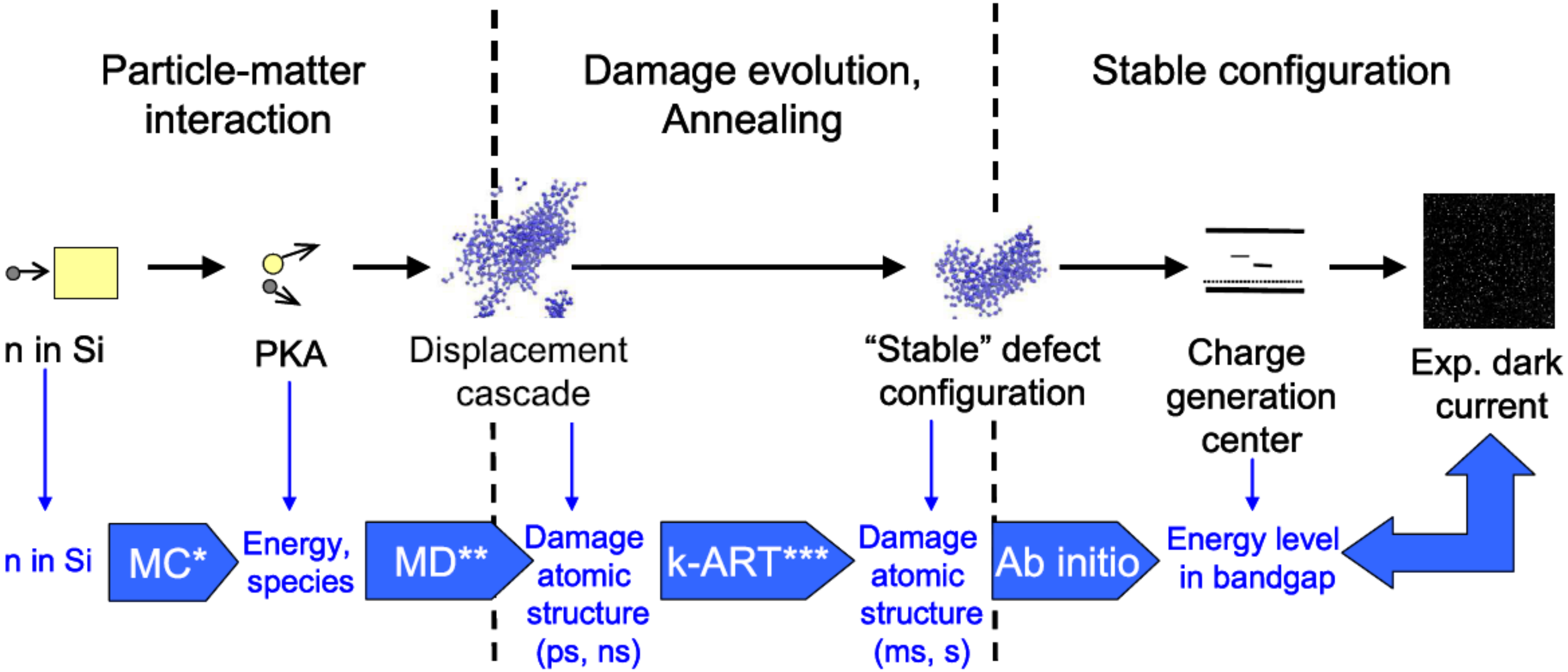


NIEL Factor: Product of cross-section of interaction by mean NIEL energy released in each interaction:

1 MeV neutron → 95MeV*mbarn per atom

(1mbarn= 1 E-27 cm2)

# Global approach of Displacement Damage Analysis: Successive steps and associated tools

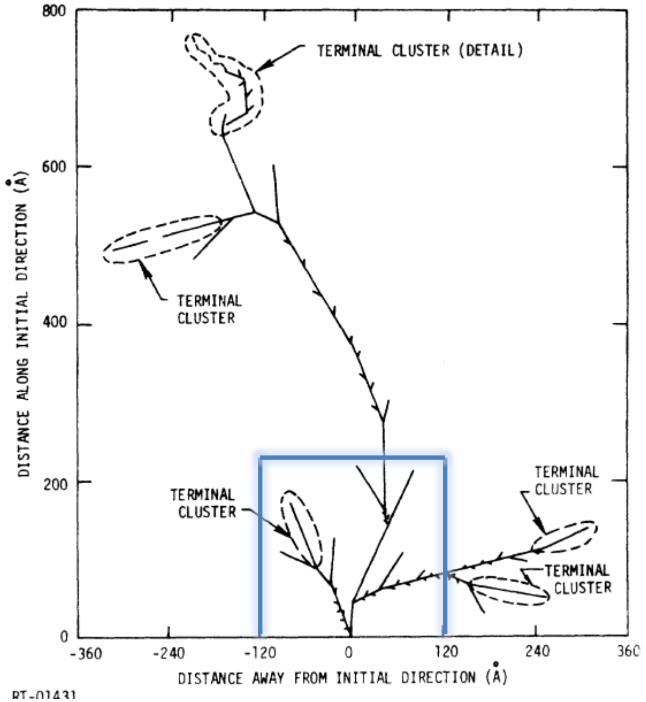


*MC = Monte Carlo (Binary Collision Approximation)
**MD = Molecular Dynamics
***k-ART = Kinetic Activation-Relaxation Technique

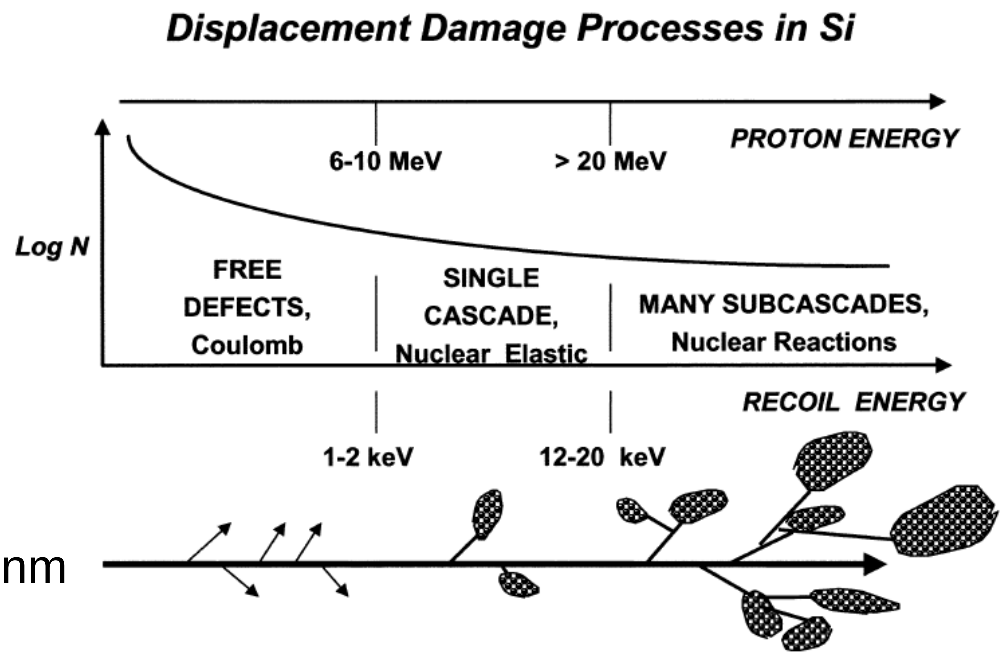
From: " Simulation of Single Particle Displacement Damage in Silicon–Part II: Generation and Long-Time Relaxation of Damage Structure" Antoine Jay,et Al NS, VOL. 64, NO. 1, JAN 2017 p141

# Displacement cascade: clusters and subclusters

- Neutron 1 MeV in Silicon (Van Lint NS 1972)

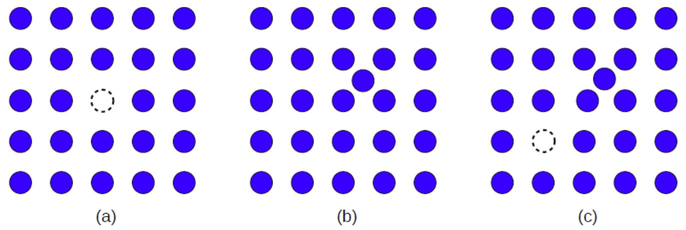


— 24nm*24nm

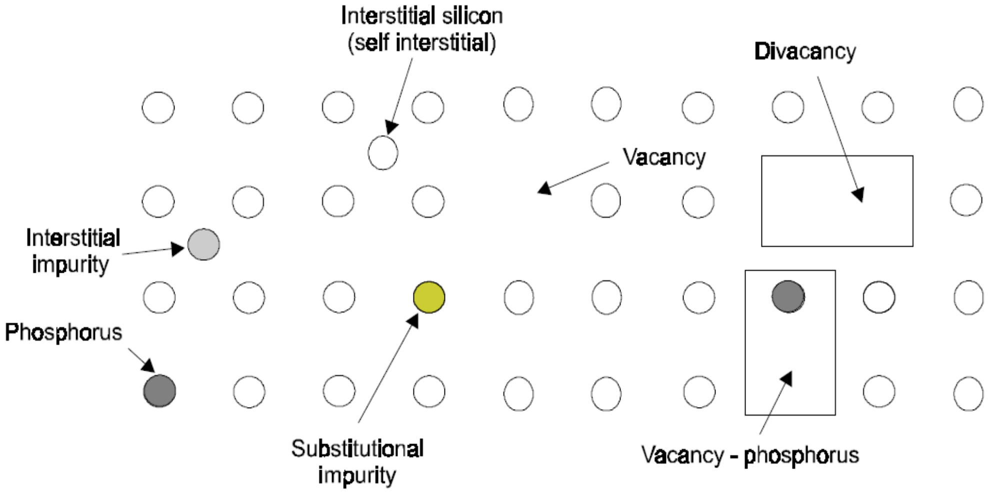


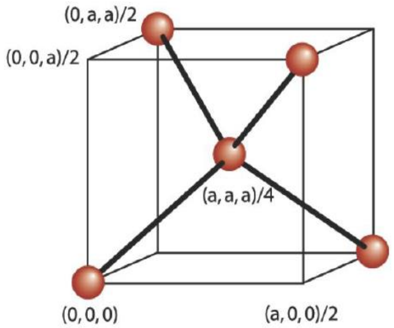
S. Wood, N. J. Doyle, J. A. Spitznagel, W. J. Choyke, R. M. More, J. N McGruer, and R. B. Irwin, "Simulation of radiation damage in solids," *IEEE Trans. Nucl. Sci.*, vol. 28, pp. 4107–4122, Dec. 1981.

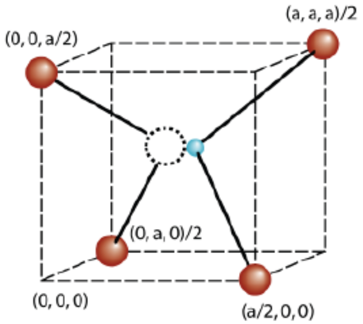
# Defects structures : Frenkel Pairs, Complex defects



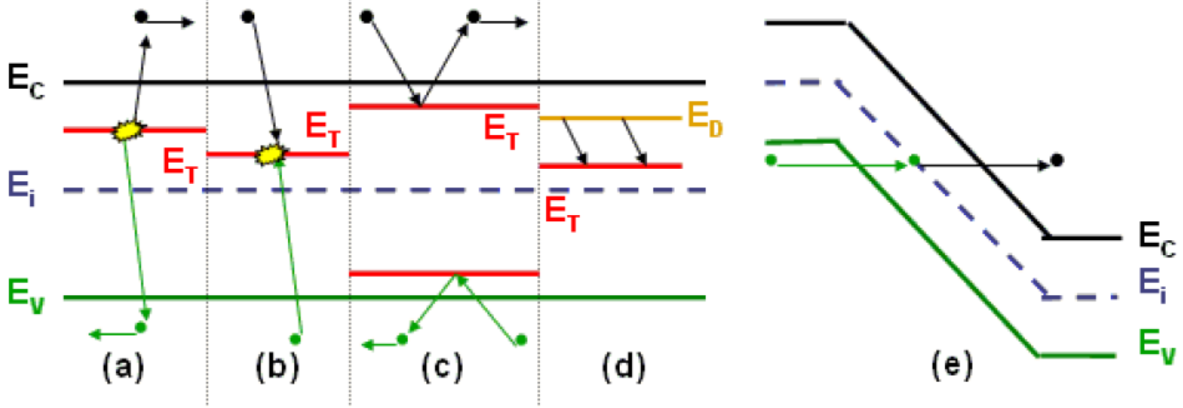
(a) Vacancy (b) intersticial (c) Frenkel Pair IV)







**(b)** In the VO defect an $O_i$ and a V share an Si substitutional site



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# The Target: Electronic world

## From Applications, systems, circuits, elementary devices, crystals and atoms

## *The Different abstraction levels*

**Semiconductor materials**
Silicon, Germanium
SiC, siGe, GaN, GaAs, InGaAs, InP,…….
CdTe, HgCdTe
**Insulators:**
$SiO_2$ $Si_3N_4$ $HfO_2$
Dopants B,P,As,..
Silicides (Co,Ti)
**Metals:**
Cu, Al

**Active Elementary Devices**
**Diodes :**
PN PIN Schottky Zener LED VCSEL
**Transistors**:Bipolar BJT, MOS, HEMT, IGBT, JFET
Thyristors, GTO

Passive devices:
resistors, capacitors (MIM)
Power, RF, Analog

**Integrated circuits**
Digital: Memory,FPGA processors, ASICS …
Analog: Amplifiers, Ref Voltage, comparators,
Mixed Analog-digital, smart Power,..)
Optronics

SOC
3D Integration

Subsystems
Systems
MegaSystems

S
A
G
A

# Multi abstraction Levels in Simulation and modeling electronics: from atoms to system

- Atomic level modeling: detailed atomic structures.
- *Numerically Solving Schrodinger’s equation using Hartree-Fock (HF) or Density Functional Theory (DFT)*
- Technology level modeling
- layer structures, doping profiles, resulting electrical characteristics.
- *numerically solving process and transport differential equations for a single transistor.(TCAD)*
- Device level modeling : description of transistor terminal characteristics *expressed in compact closed-form equations. (SPICE)*
- System Level Modeling and EDA tools description and synthesis of global functions
- *Each level of abstraction outputs are inputs to the following level of abstraction*

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# Radiation effects: how to classify?

Bulk defects: Displacement Damage (NIEL)

- Carrier-generation and recombination GR
- Density of carriers (for high resistivity material)
- Leakage current (related to Generation by defects)
- Mobility of carriers (defects diffuse free carriers)

Trapped charges in insulators and at SC-Insulator Interface (IEL-TID)

- Modify threshold voltage of MOS devices
- Induce inversion channels and leakage between devices
- Induce noise

Hole-electron pairs in Semiconductors (IEL)

- Transient currents

- Cumulative Effects
  - The observed effects increase when the number of impinging particles increases
  - The effects are mostly stable at the time scale of the irradiation
  - Some annealing may exist
  - Failure will appear for a given fluence ($\int_0^t Flux\ dt$)
- Single Event Effects
  - Effect produced by One incident particle
  - Events may appear as soon as irradiation begins. Frequency of events is proportional to the flux of particles

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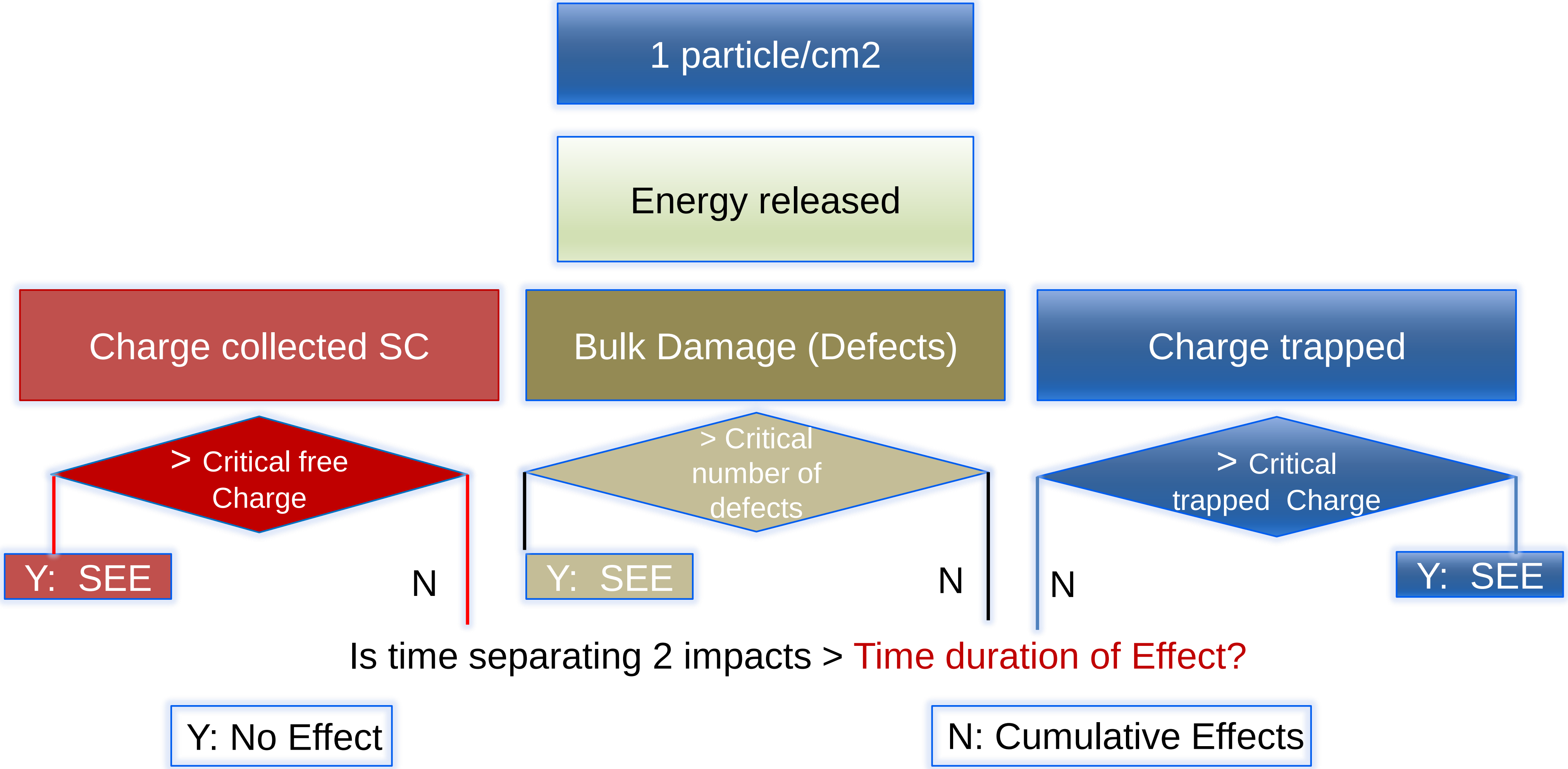

1 particle/cm2

Energy released

Charge collected SC

> Critical free Charge

Y: SEE

N

Bulk Damage (Defects)

> Critical number of defects

Y: SEE

N

Charge trapped

> Critical trapped Charge

N

Y: SEE

Is time separating 2 impacts > Time duration of Effect?

Y: No Effect

N: Cumulative Effects

# Electronic circuits and reliability

- The reliability is a main concern and different parameters are defined
  - MTBF : mean time between failure (for recoverable of soft errors )
  - MTTF : mean time to failure for a destructive effect

- FIT (Failure in Time)
  - 1 FIT = one failure for 1 E9 hours,
  - →1FIT = 1 failure for 1.14 E5 years!!!

- System FIT= $\sum_{i=1}^{n} FIT(i)$
- FIT value is related to a particular environment: At Ground level JESD89A Standard

- Reliability is related to external and internal environments and device sensitivity to these environments (Temperature, Humidity, Vibrations, Radiation, Aging
- Radiation must be considered if the global FIT value is significantly increased by radiation

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# Example of Electronic systems:
# Titan Supercomputer - modular structure

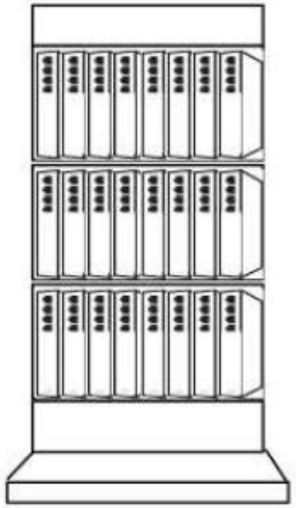
**1 node**= CPU 16 core Opteron 6274  32GB DDR3,
NVIDIA GPU K20X Kepler 6GB DDR5,  Router
1 **Blade=** 4 nodes
**1 Cage**= 8 blades
**1 cabinet** =3 Cages
**TITAN=200 cabinets**

= 4*8*3*200 nodes =19200 nodes

Compute Node

Blade

Cage



Cabinet

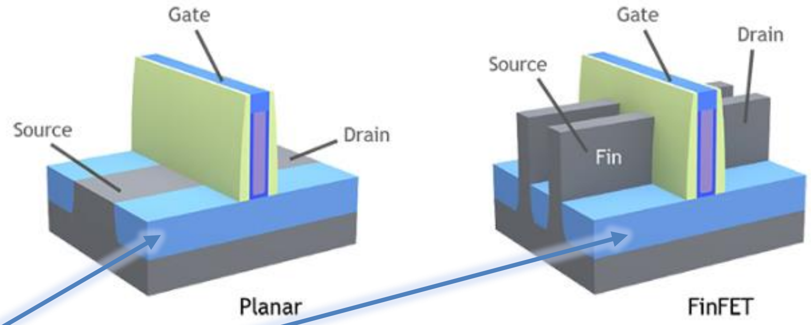
200 Cabinets (25 rows x 8 columns)

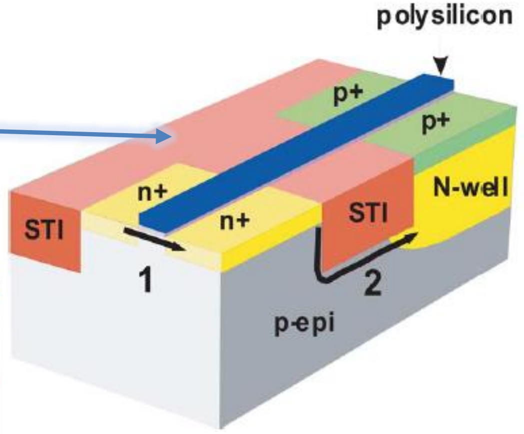
# Insulators in Integrated Circuits

- Gate of MOSFET **EOT**

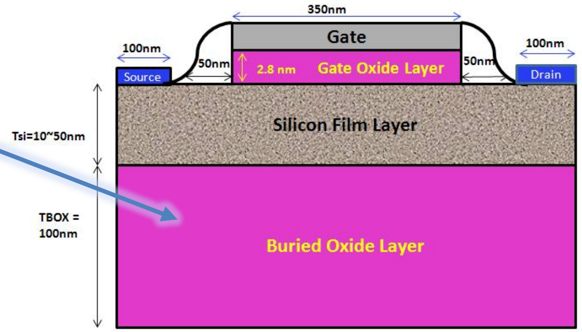
14nm Stack HfO2 45nm SiO2 130nm

- Isolation between devices STI
- BOX (Buried Oxide) in SOI
- Passivation of bipolar devices
- Inter-metal levels separation
  - Low k dielectric



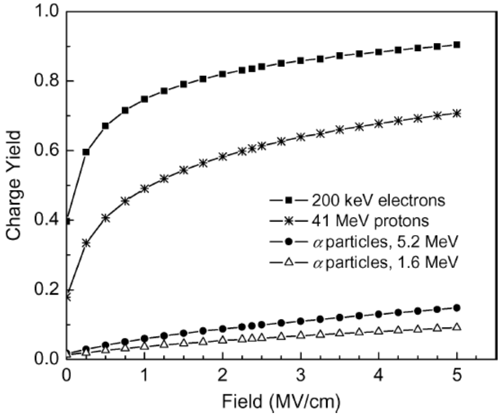


From Schwank NS08

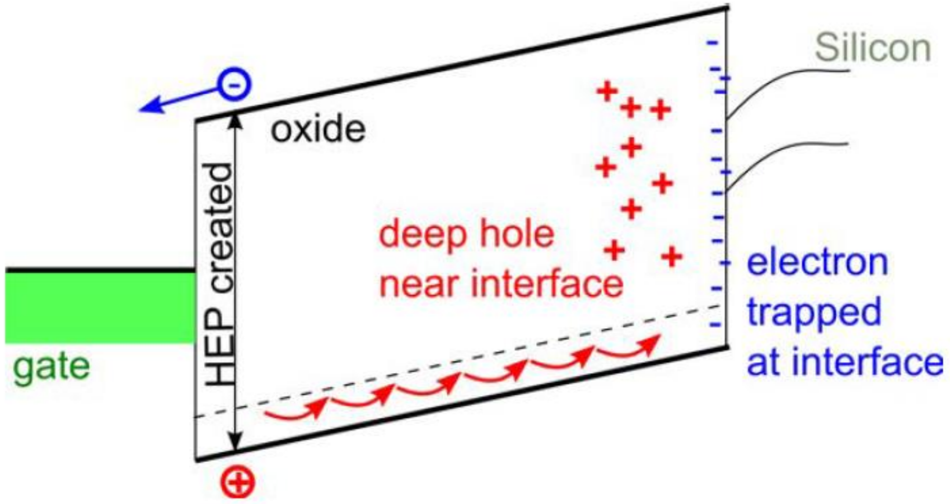


# Total dose mechanisms: Trapped charge in insulators

- Ionisation (Creation of Hole-electron pairs) Ep=17eV in SiO2
- Recombination in ionised column (geminate or columnar),
- Separation of carriers e- h+ by Electric Field (yield).
- Fast Evacuation of e- (high mobility)
- Slow transport of holes (hopping, Multiple-Trapping-Detrapping in shallow traps)
- Trapping in deep traps
- Compensation by electrons tunnelling from Si

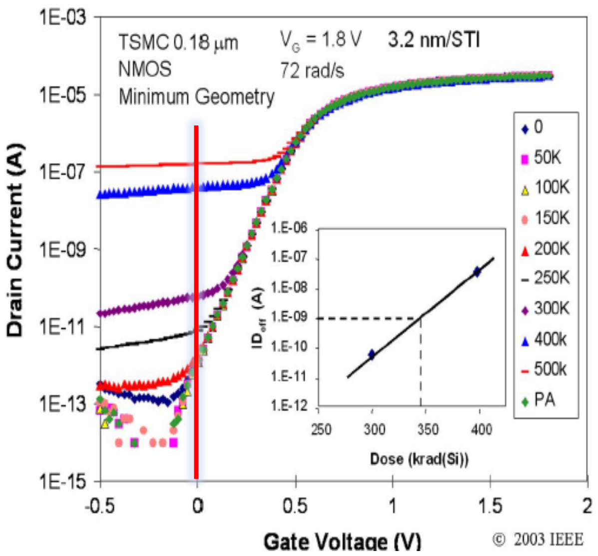


Yield is a function of the Electric Field and of the incident particle (e-, X-Ray, p, ion)



# TID Effects

- MOS Transistors:
  - Negative Shift of threshold voltage  NMOS easier to turn ON, PMOS more difficult to turn ON
  - Decrease of subthreshold slope for NMOS, leakage current at VGS=0V ↑
- PN junction: inverse current ↗
- Bipolar transistor: gain ↘
- Integrated circuits: static power supply current ↗



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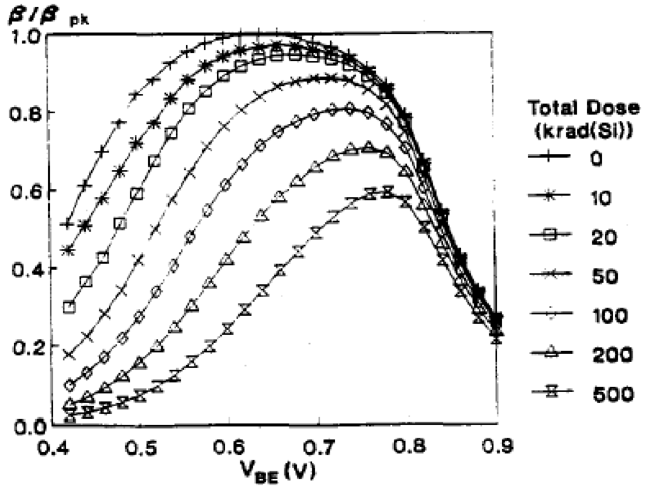
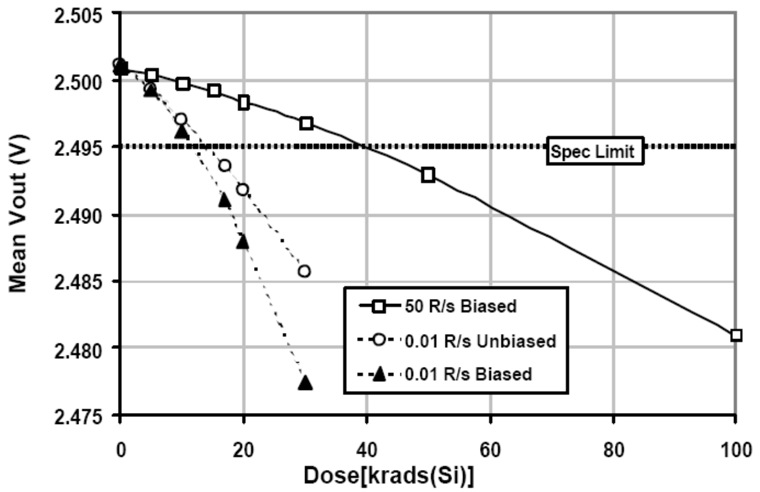


# TID: Influence of Dose rate

For CMOS worst case is obtained at high dose rate.

Experimental Test simulates years of life by a week or less of irradiation followed by annealing at room temperature or high temperature.

ELDRS (Enhanced low dose rate sensitivity) in some bipolar devices is **a challenge for testing.**



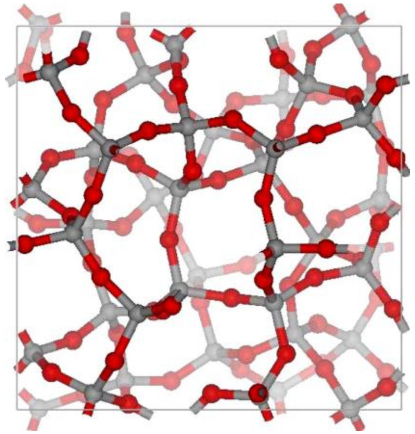
LT1019 Reference Voltage

**0.01 Rad/s: 36rad/h**

**100krad→ 116 Days of irradiation**

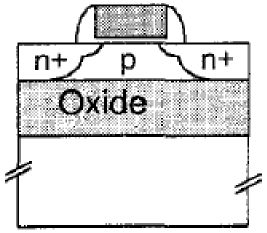
# Simulation of TID effects

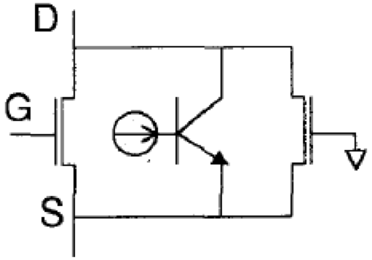
- Insulator: Atom level description of traps and interface states, charge transport, trapping, annealing,
- Devices: TCAD, Variation of electrical parameters
  - MOS: (VTh, Ileakage, transconductance)
  - Bipolar: Gain at low current, Emitter-collector leakage
- Inter-devices leakage
- Gates, complex circuits: SPICE : Power supply current, dynamic parameters (Tr, Tf, Td), functional failure
- System?

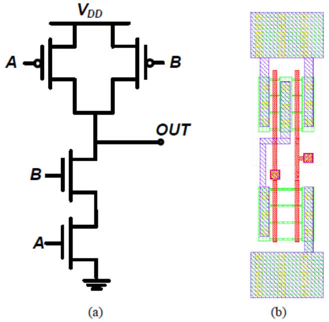


SiO2

Tuttleet al NS 2010







# Single Event Effects

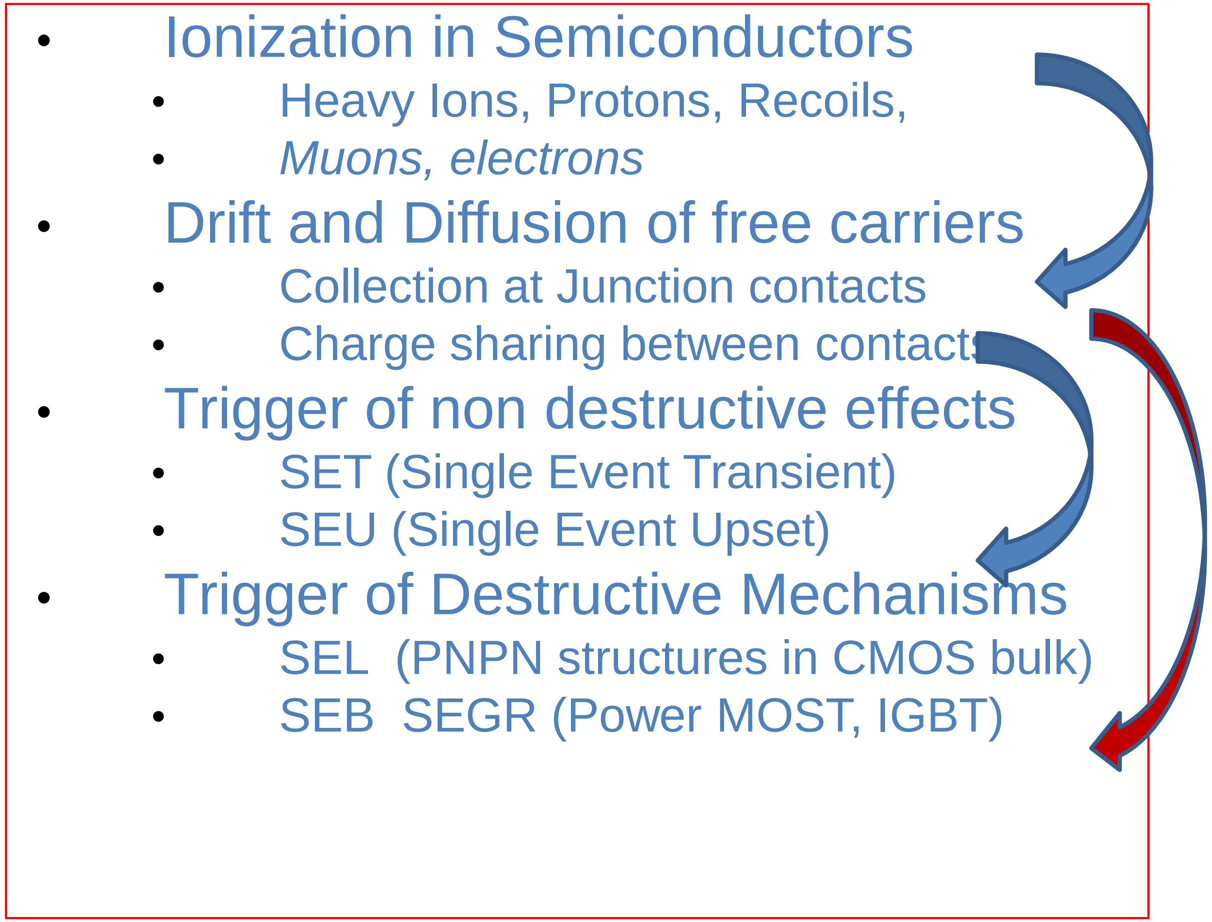
## Effects related to the interaction of a single particle

Ionization in Insulator

- Trapping of charges in Deep Traps
- SHE (Single hard error)
- Microdose effects

Displacement Damage in Semiconductor

- Recombination-Generation-Centers (SRH)
- Dark Current (CCD, APS)
- Leakage current (Junction)
- SDRAM stuck bits
- Gain degradation in BJT



- Ionization in Semiconductors
  - Heavy Ions, Protons, Recoils,
  - *Muons, electrons*
- Drift and Diffusion of free carriers
  - Collection at Junction contacts
  - Charge sharing between contacts
- Trigger of non destructive effects
  - SET (Single Event Transient)
  - SEU (Single Event Upset)
- Trigger of Destructive Mechanisms
  - SEL (PNPN structures in CMOS bulk)
  - SEB SEGR (Power MOST, IGBT)

# Single Particle: Charge carrier Generation (IEL)

- **Generation:** Tools Geant4 SRIM
  - Energy loss per unit length: dE/dx
  - LET (Linear Energy Transfer)
  - Unit of LET: MeV/(mg/cm2) (Practical unit to get values from 1 to 100)
    - when charge generation is considered : pC/µm
    - For silicon: d=2.33g/cm3, Ep=3.6 eV, 1µm→0.233mg $q=1.610^{-19}$ C

Result: 1pC/µm →97 MeV*cm2/mg

| | | |
|---|---|---|
| Avogadro | 6,02E+23 | |
| Mass | 28 | g |
| | 2,33 | g/cm3 |
| Volume | 12,02 | cm3 |
| Density | 5,01E+22 | Atoms/cm3 |
| available electrons =4* | 2,00E+23 | electrons/cm3 |

Density of Silicon atoms
Available electrons in Valence band

**Generation and available electrons in valence band:**

Silicon Z=14 A=28 2.33g/cm3 M layer 2 E23e-/cm3

Charge Density : track radius 10nm, LET: 1pC/µm density: 2 E22 e-/cm3 10% ionized

# Collection and Models of Current Transients

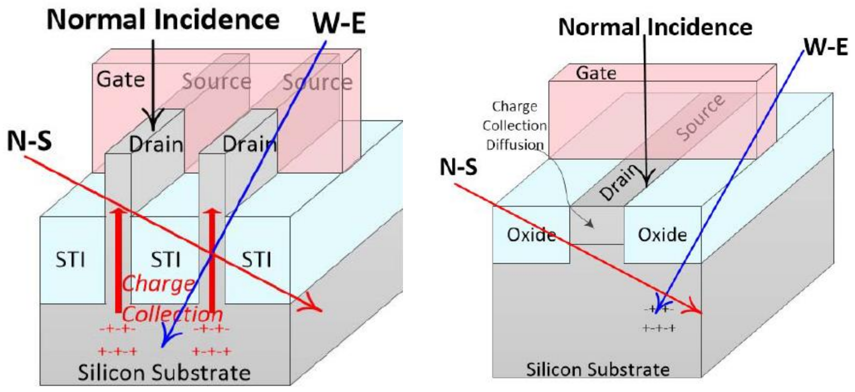
## **Collection of Charges** : TCAD 3D

Generation across a space charge layer:

Electric Field E

Drift of carriers v=µE or v= vlim

Modification of Electric Field



Generation in neutral region:

Ambipolar diffusion : high density of carriers (>majority carriers)

Cohesion of the track maintained by lateral electric field

Collection: Diffusion to junction and contacts

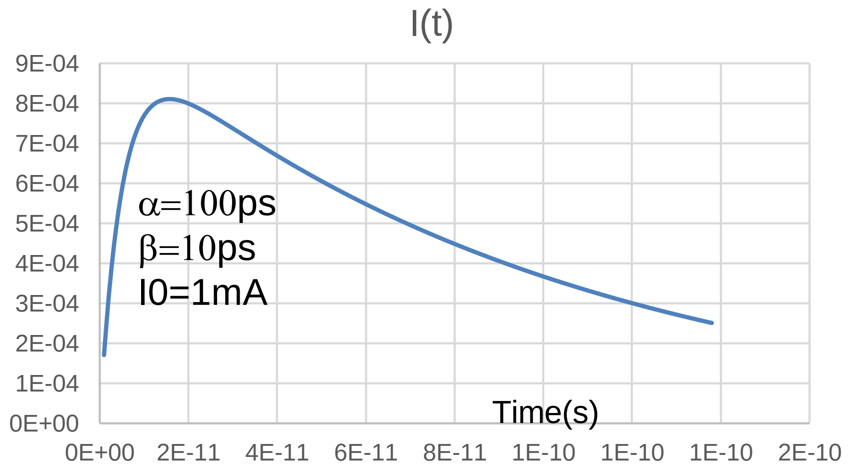
→ **Transient current**

Orders of magnitude: Qcollected=1pC, T=1ns Ipeak=Qc/T=1mA

Simple analytic formula I(t)=I0 (exp(-t/α)-exp(-t/β))

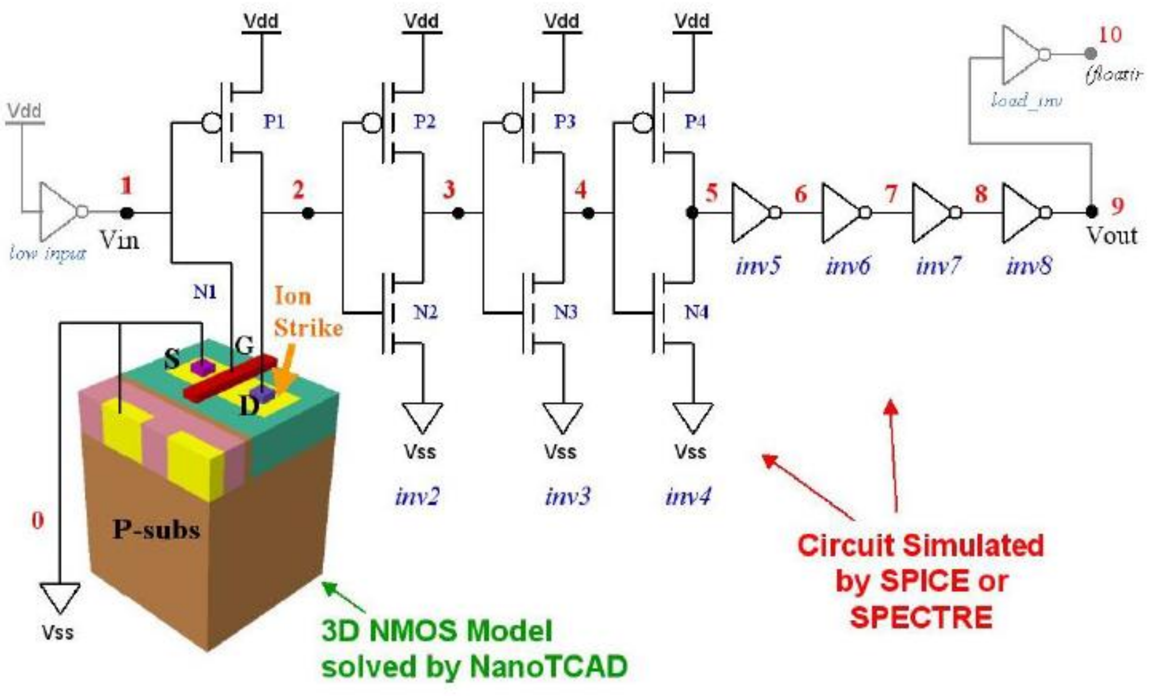
β: time constant to establish the generation

α: collection time



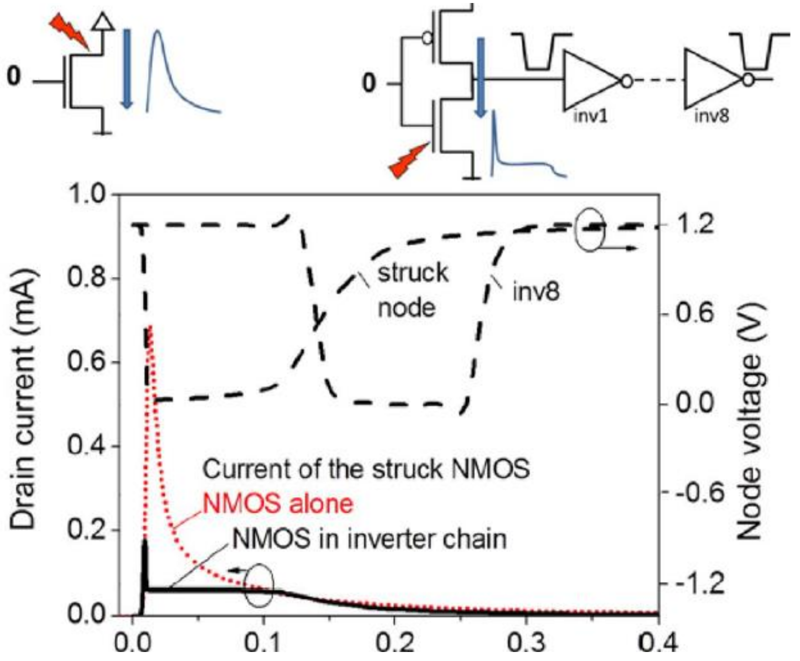
# SET in digital circuits (DSET) Propagation

Review:V. Ferlet-Cavrois et al NS 2013)



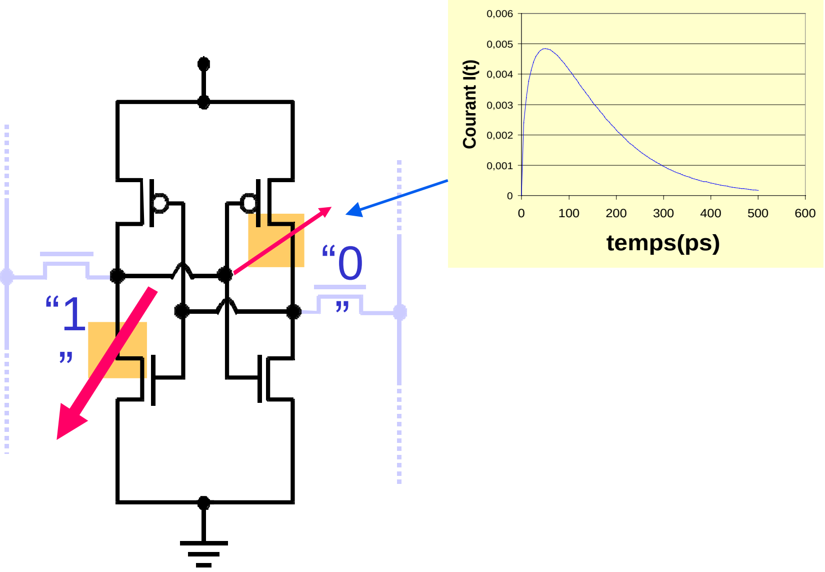
**Circuit Simulated by SPICE or SPECTRE**

**3D NMOS Model solved by NanoTCAD**



# SEU: Single Event Upset

- Change of state (0→1, 1→0 of the output of a latch, Flip-Flop, SRAM cell… due to an impact in an elementary device (MOST, BJT)
  - In bulk CMOS Drain junctions of Off Transistors (Drain-substrate or Drain Well) are the most sensitive nodes



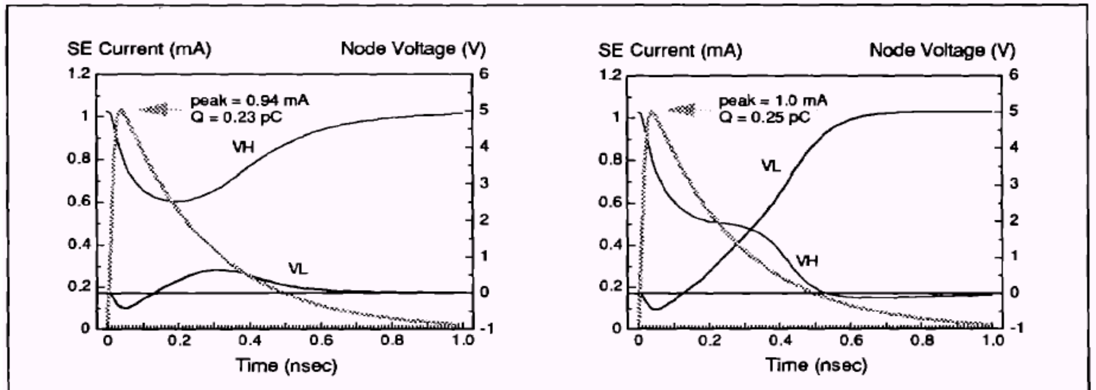


**Fig. 4.26** Simulation results showing noupset (left) and upset (right) of the cross-coupled information nodes in a CMOS SRAM cell. In this case, the critical charge is 0.25pC.

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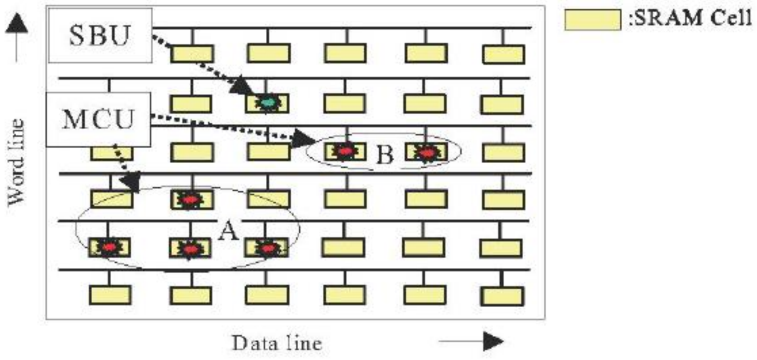
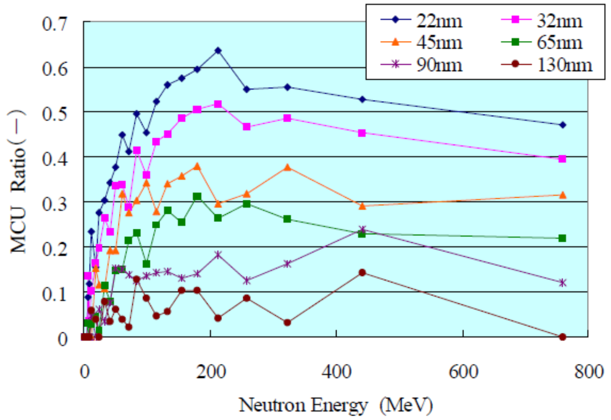
# MCU: Multi Cell Upsets

- Jedec: « A single event that induces several bits in an IC to fail at the same time. NOTE: The error bits are usually, but not always, physically adjacent”.
- MCU/SEU ratio increases when technology node decreases (R=0.1 at 130nm, R=0.5 at 32nm)
- Multiplicity increases

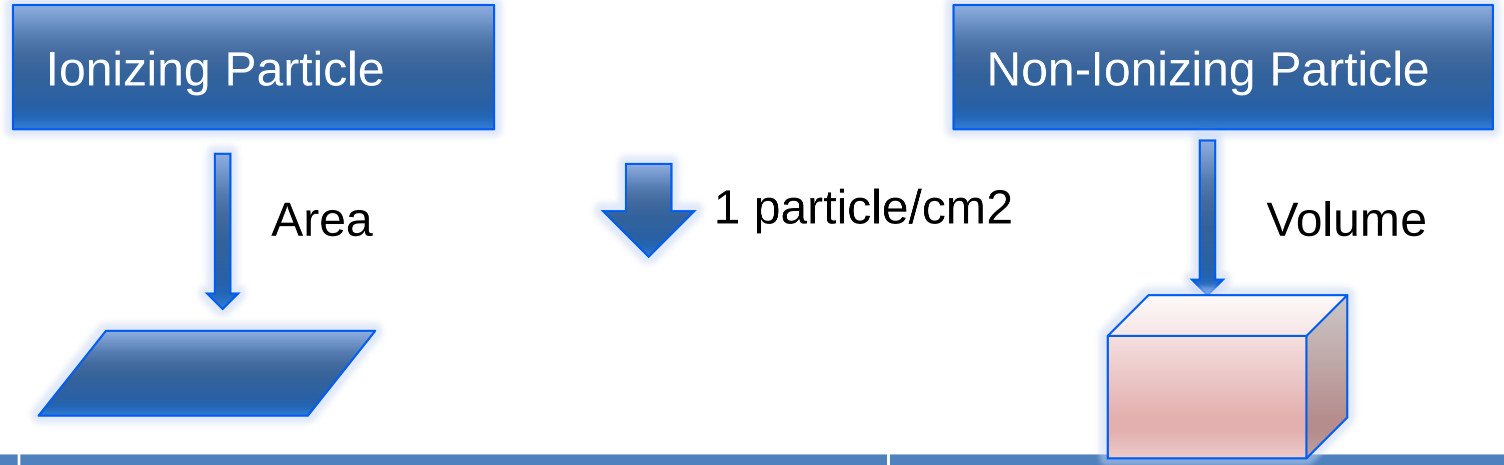


Multiplicity B:2 C:4

- Problem for ECC (Hamming Code: Detect 2 correct 1)
- Scrambling of bits in same word ( MCU but not MBU)



# Single Event cross-section

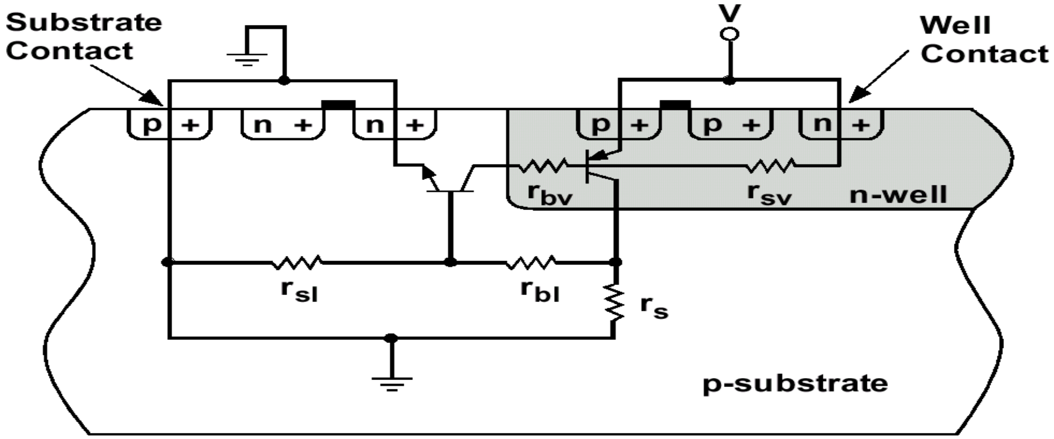


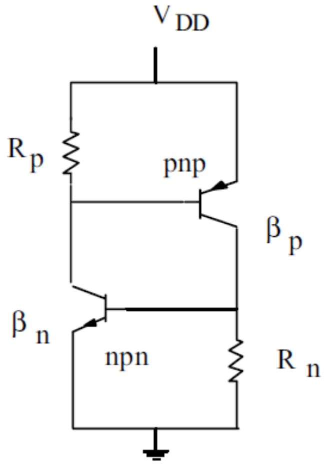
| Dimensions | Probability (to cross-area) | Probability of interaction in Volume (s=1barn/atom = 1 E-24cm2/atom) |
|---|---|---|
| 1µm*1µm | 1 E-8 | 5 E-14 |
| 100nm*100nm | 1 E-10 | 5 E-16 |

Saturated cross-Section /bit: HI neutrons

# Potentially destructive Effects: Single Event Latchup

- **Parasitic** structures in CMOS bulk
- Trigger of a PNPN Thyristor parasitic structure switching from Off-state to ON-state
- Condition of SEL:
    - *Existence* of PNPN Structure (SOI SEL free)
    - *Activity* of the Structure (influence of Wells Contact density on Rp Rn)
    - *Minimum bias voltage* >Vhold
    - Available current >Ihold
    - More important at high temperature (gain of bipolar transistors increases)





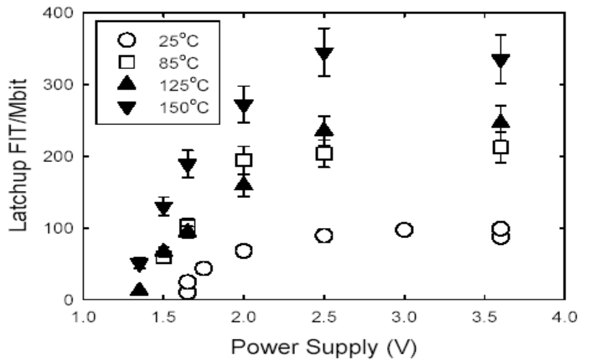


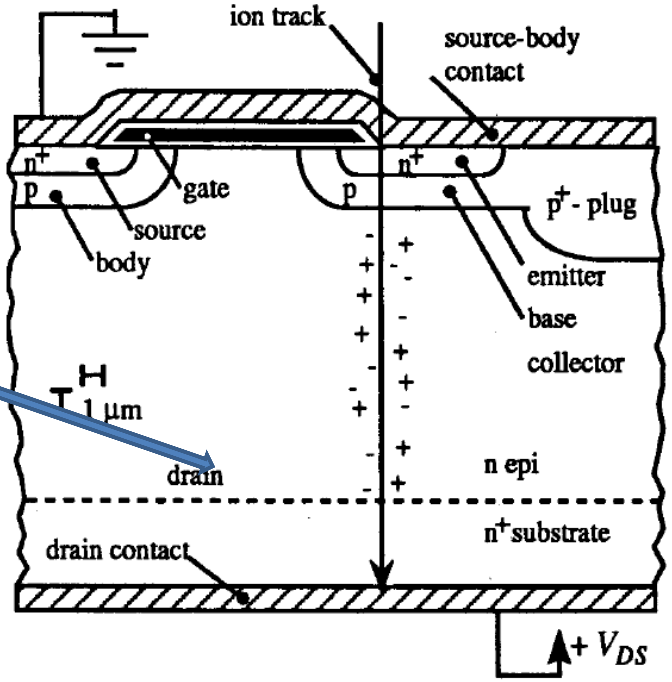
Figure 5. Neutron-induced latchup rate in 3.3-V SRAMs from Vendor B as a function of power supply voltage and operating temperature.

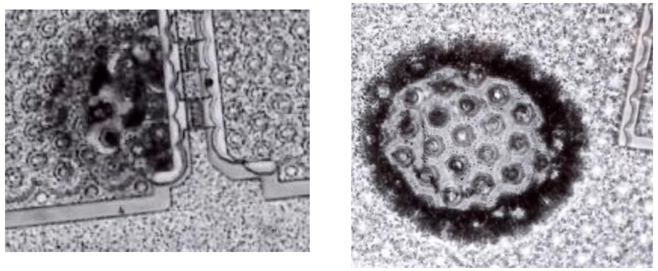
# Destructive Effects:  Power MOST and IGBT

SEB:Single Event Burnout

- Parasitic NPN transistor (normal state: blocked) is switched ON.
- Electrical Field profile modified by current in space charge layer
- Electric Field z extension limited to NN+ homojunction
- Peak electric field
- Carrier multiplication at critical Efield
  - Hole current (Base current)
  - Emitter current

- Local Heating and localised burnout





IRF240
VDS=190V HI

# Parasitic structures-Mitigation

- Parasitic structures inherent to the process may influence strongly the radiation response. Some technological mitigation is possible.
- NPN parasitic structure in Power MOST: SEB
  - Modify the NN+ doping profile to extend the E field zone and limit Epeak
  - Reduce the Rbe resistor value (increase doping, modify thickness,…
- PNPN structure in CMOS bulk : SEL
  - suppress the structure (SOI),
  - reduce Rn, Rp values
  - Reduce gain of BJT (doping profile, deeper STI for lateral BJT,…..
- SOI: open base parasitic bipolar transistor
  - Add body ties

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# Hierarchy of priority of REE to be solved

(Atmel, GlobalTCAD, Project Desmicrex)

## *Requirement for Radiation Effects Analysis and Priority*

1. *Single event latch-up*
   - *Effects of angle, impact position, temperature*
2. *Single event transients / DSETs + Multiple Transients*
   - *Effects of angle, position, clock-freq, cross-talk, temperature*
3. *Single event upsets / multiple-cell upsets*
   - *Effects of angle, position, temperature*
4. *Single event hard error (stuck bits)*
5. *Total ionising dose*
   - *Intra- and inter-device leakage across STI*
6. *Dose enhancement effects*
   - *Use of Cu and other high-Z materials*

**Decreasing priority**

# Radiation Hardening:
# To improve performance under irradiation

Radiation Hardening by Process: (RHBP)

Identify the mechanism of failure and its relation with a process step. Examples:

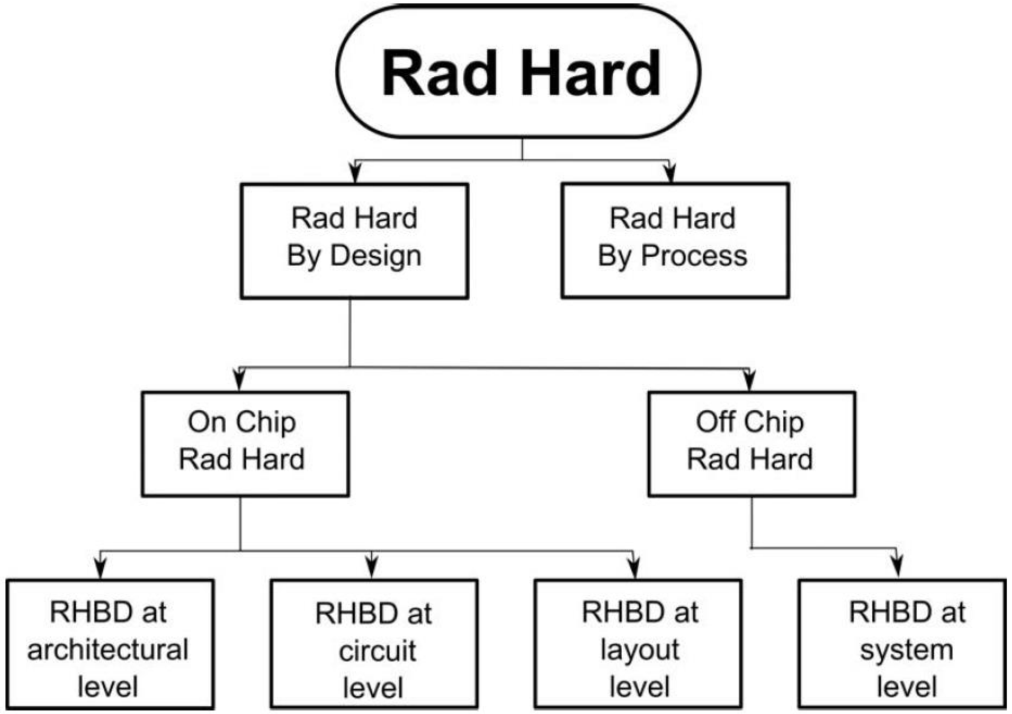
thermal treatment of oxides: limit density of traps

Limit or suppress 10B (SEU by thermal neutrons)

Limit oxygen content in silicon (V-O recombination center)

Radiation hardened by design (RHBD)

- Circuit level hardening (feedback loops)
- Architectural level hardening (TMR)
- Layout considerations (guard rings, closed NMOS)



**Rad Hard**

Rad Hard By Design

Rad Hard By Process

On Chip Rad Hard

Off Chip Rad Hard

RHBD at architectural level

RHBD at circuit level

RHBD at layout level

RHBD at system level

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# Specifications of Radiation environment

- Radiation environment is given in specific units related to the effects considered
  - TID:  deposited energy
    - RAD: Radiation Absorbed Dose = 1 E-5 J/g  GRAY: (Gy)  1 Gy=1J/kg = 100 rad
    - Dose relative only to a given material  Gy(Si),    Gy(SiO2)
    - Knowledge of Origin and energy spectrum is lost
    - LET can be converted to dose in rad
  - DD: Fluence (particles/cm2)
    - 1 MeV neutron Equivalent Fluence  (NIEL )
  - SEE: Flux (particles/(cm2*s)
    - Heavy Ions : LET spectrum, Flux
    - Hadrons: Flux   (E>E0)   or differential Flux (dn/dE)
    - Thermal neutrons (25meV equivalent)

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# Radiation Effects Testing: Reproduce the effects but not the real environment

TID : Co60, electrons, protons

- Parameters: Dose rate, Electrical bias, temperature, dynamic or static
  - *Identify worst case conditions*
- On line measurements

- Off-line (irradiation steps):

Two different approaches are needed for preliminary characterisation and qualification ( follow standards ESA and MIL Std 883 Method 1019)

DD: Fluence expressed in 1 MeV-neutrons equivalent

- Electrical conditions not important
- Low annealing after defect stabilisation
- Neutron reactors (E<6MeV),
- neutrons generators (14 MeV)

(DD+TID )

- Proton beams
- Mixed beams

*Importance of initial measurements and choice of samples (mean values of the population, no maverick) with a sufficient number (dispersion in a Lot and between different Lots)*

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# Single event effects testing : Facilities

**Heavy ions:** (UCL, RADEF, Tamu,..

- Flux variation
- LET values, HI Range

**Proton:**

- Energy  and Flux
- Beam area, Flux uniformity

**Neutrons:**

- monoenergetic (D-T 14 MeV, D-D 2.3 MeV)
- quasi-monoenergetic (UCL)
- broad spectrum (Lansce, Anita,…)

**Mixed environment** (Charm)

**Microbeams** (spatial localisation)

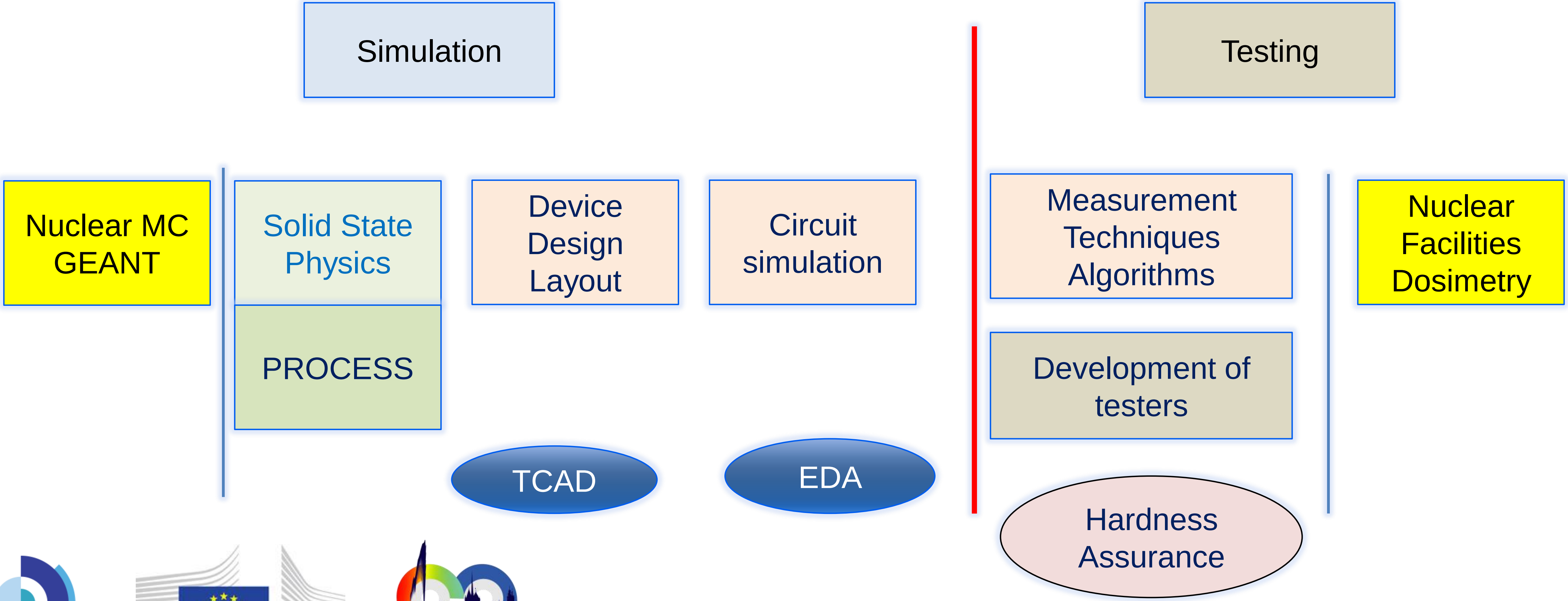
**Laser Testing** (ps duration, focused, single shot or pulse rate)

- *Spatial Localisation*: identify sensitive zones, X-Y scanning
- *Temporal Localisation:* Possible synchronisation with electrical signals
- No Metallisation penetration (backward testing)

**X-Ray focused** ps Pulse

- A solution to metal penetration ?

# REE: SKILLS



Simulation

Testing

Nuclear MC
GEANT

Solid State
Physics

PROCESS

Device
Design
Layout

Circuit
simulation

TCAD

EDA

Measurement
Techniques
Algorithms

Development of
testers

Hardness
Assurance

Nuclear
Facilities
Dosimetry

# Drivers for Reseach and studies on REE

**Failures in applications**

Task Force

SEE, DD in low earth orbits, Memory bit-flip in avionics,
SEL in automotive,
SEE at ground level: Routers, Computers :
Radioactive contamination:

**Obsolescence**

Need for new devices: sensors,..

**Anticipation of new Effects**

Moore Law, Shrinking: p direct ionization,
SEE e,µ,
3D technology

**New Needs**
**New Systems**
**High Radiation**

Power (SiC, GaN) Frequency (HEMT), Robotics

Test facilities

Simulation tools

COTS Hardness Assurance

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# Radiation Effects on Electronics community (RADECS, NSREC) and other scientific communities

- Radiation and reliability:  IRPS (International Reliability Physics Symposium)
- Radiation and testing methods (IOLTS)
- Radiation and electronic circuits design (VLSI )
- Specialized conferences : (see IEEE)
- Useful to meet other communities and apply some of their methods and models
  - Environment  (Radioactivity, cosmic rays, Radon, IAEA,
  - Physics (nuclear, solid-state, semiconductor and insulators)
  - Electronics (technology, TCAD, EDA, circuit design, simulation and testing)
  - Accelerators, Reactors, dosimetry

# Conclusion

- Radiation Effects on Electronics is a mature field of research
- New studies are much more efficient than in the past with the strong benefice of methodology and tools developed for Electronic Industry. Virtual simulation from ab initio to system modeling helps to understand and predict effects.
- But there exist still a need to reinforce this community in order to take into account the different problematics (space, atmosphere, ground, nuclear energy, medical and even military), to improve simulation tools and to develop industrial standards for testing and qualifying.
- A driving force is semiconductor technology with a broad spectrum of high reliability applications at ground level that takes radiation effects into account

There is much room for working on Radiation Effects on Electronics in research and industry and to find pleasure and satisfaction in this work.

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# Useful Lectures (only a few references, much more available)

- Defects in Materials and Devices Microelectronic
  - Edited by Daniel M. Fleetwood, Sokrates T. Pantelides, Ronald D. Schrimpf
- Ionizing Radiation Effects in MOS devices and circuits
  - T. P. Ma P. V. Dressendorfer
- Reliability and Radiation Effects in compound semiconductors
  - A. Johnston
- Soft Errors From particles to circuits
  - J.L Autran and D. munteanu
- The Effects of Radiation on electronic systems
  - G.C Messenger
- Physics of semiconductor devices
  - S. M. SZE

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# Acknowlegments

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- Many Thanks to Prof Paul Leroux and Dr Ruben Garcia Alia for reviewing the presentation
- Many thanks to you that attend this talk early in the morning before an important conference day.
- All comments and questions are welcome:

  remi-gaillard@orange.fr

# Additional slides