中国科学院大学
University of Chinese Academy of Sciences

Remedies in Design for Reliability

RadHard in SoC Design

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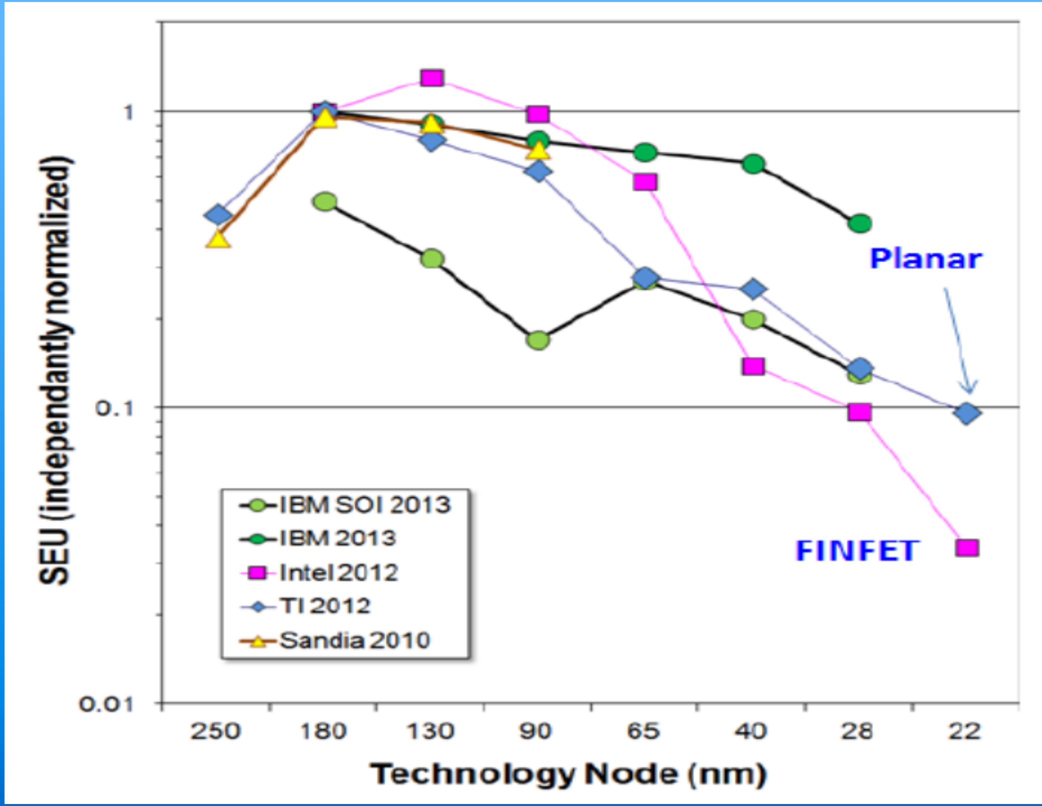
RadHard in SoC Design

Causes of Chip Failures and Remedies for Reliability

- Design Bugs
- Excess Temperature
- Rush Current
- Manuf. Defaults
- ESD Issues

- Verification
- Library Corners
- Electro-migration
- DFT/ATE
- ESD Protection

SEU Sensitivity for SRAM



Reported SER (or SEU) values of SRAM products

Table 5: The reported SER (or SEU) values of SRAM products influenced by various neutron fluence conditions

Products	*fluence*	*SER (SEU)*	Vendor Ref.
0.6um, 0-11MeV, 14MeV	$(5\text{-}86)\times10^9$	0	Xilinx 1998
FPGA 0.35um, 100 MeV	0.3×10^9	(5)	Xilinx 1998
1Gb 130nm@3889m	3.69×10^6	(4000)	[2] 2012
2x1Gb 90nm@2885m	3.5×10^6	(3000)	[2] 2012
16Mb 65nm, 20-250MeV	$(2\text{-}3)\times10^9$	838	Cypress 2017
Virtex-6 RAM, 40nm	$\sim1\times10^9$	83	Xilinx 2009

Source: Chen & Hu, 2018, CSTIC

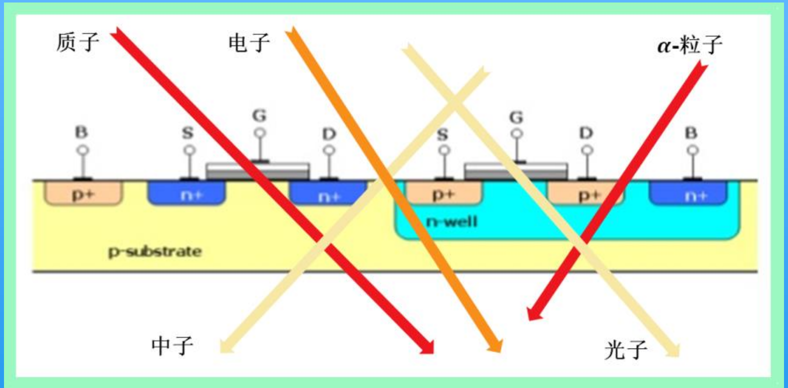
RadHard Topics

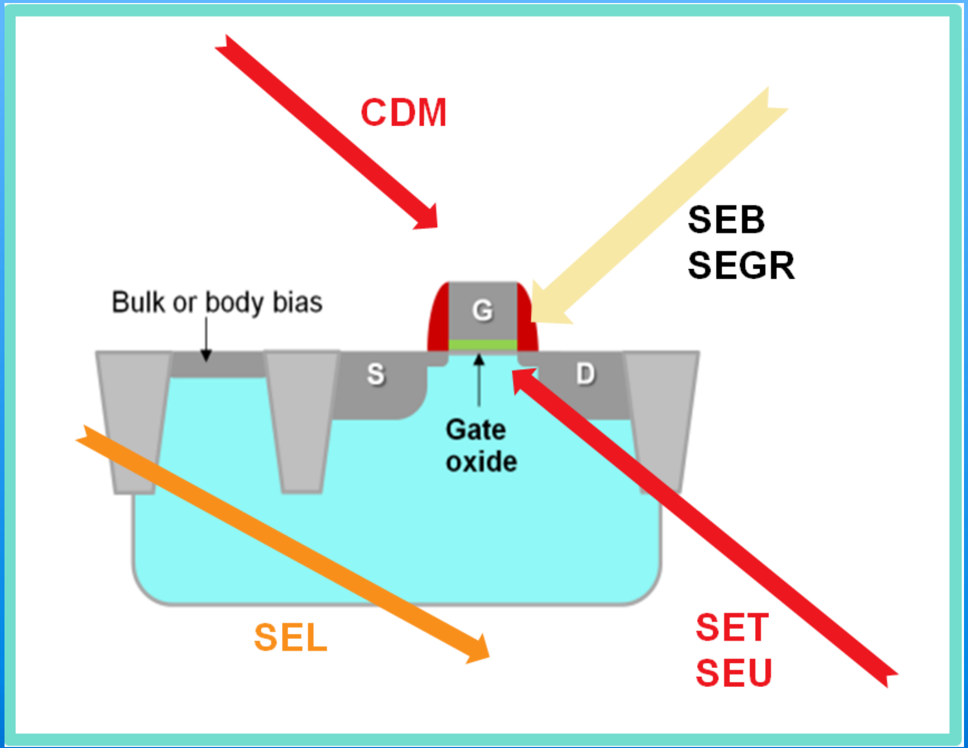
- SEE/SEU and RadHard/TID
- FPGA chips
- SRAM
- SOI
- Stopping Power and Range
- Variable factors

Study of Radiation-Induced Effects

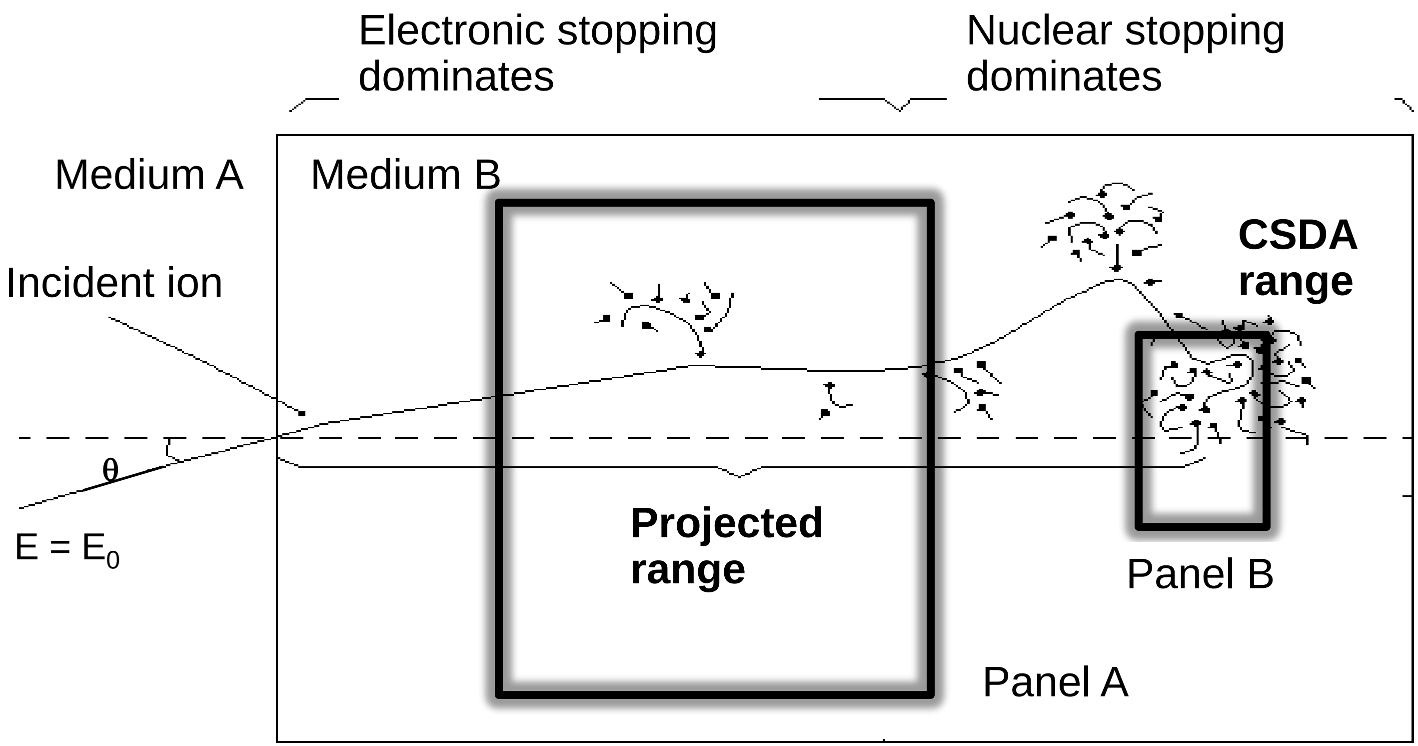
- TID – total ionizing dose
- SEE – single event effects (SP/ρ)
  - *SEU, single event upset*
  - *SET, single event transient*
  - *SEL, single event latchup*
  - *SEB, single event burnout*
  - *SEGR, single event gate rupture*

ESD and SEE on Bulk CMOS, FD-SOI, FinFET

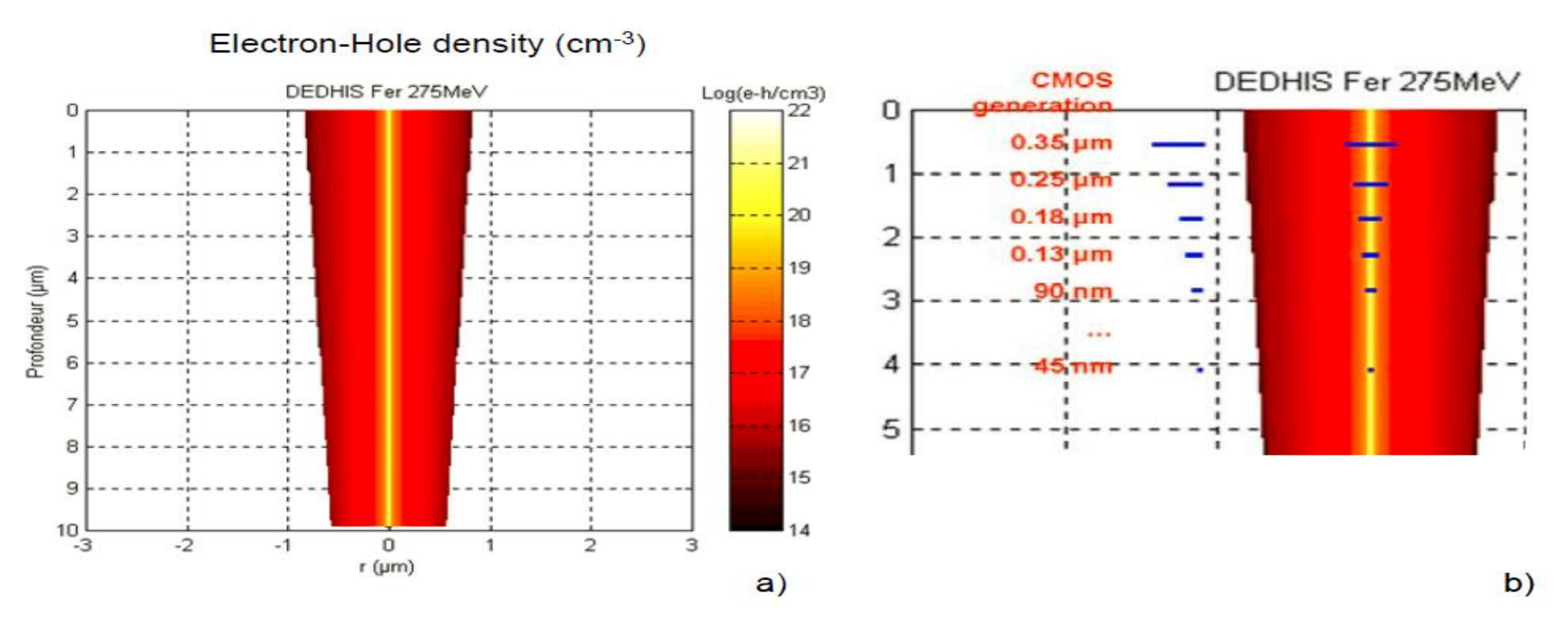




Proton Interaction and CSDA/Projected Ranges



Heavy Ions Induced Secondaries and Tertiaries



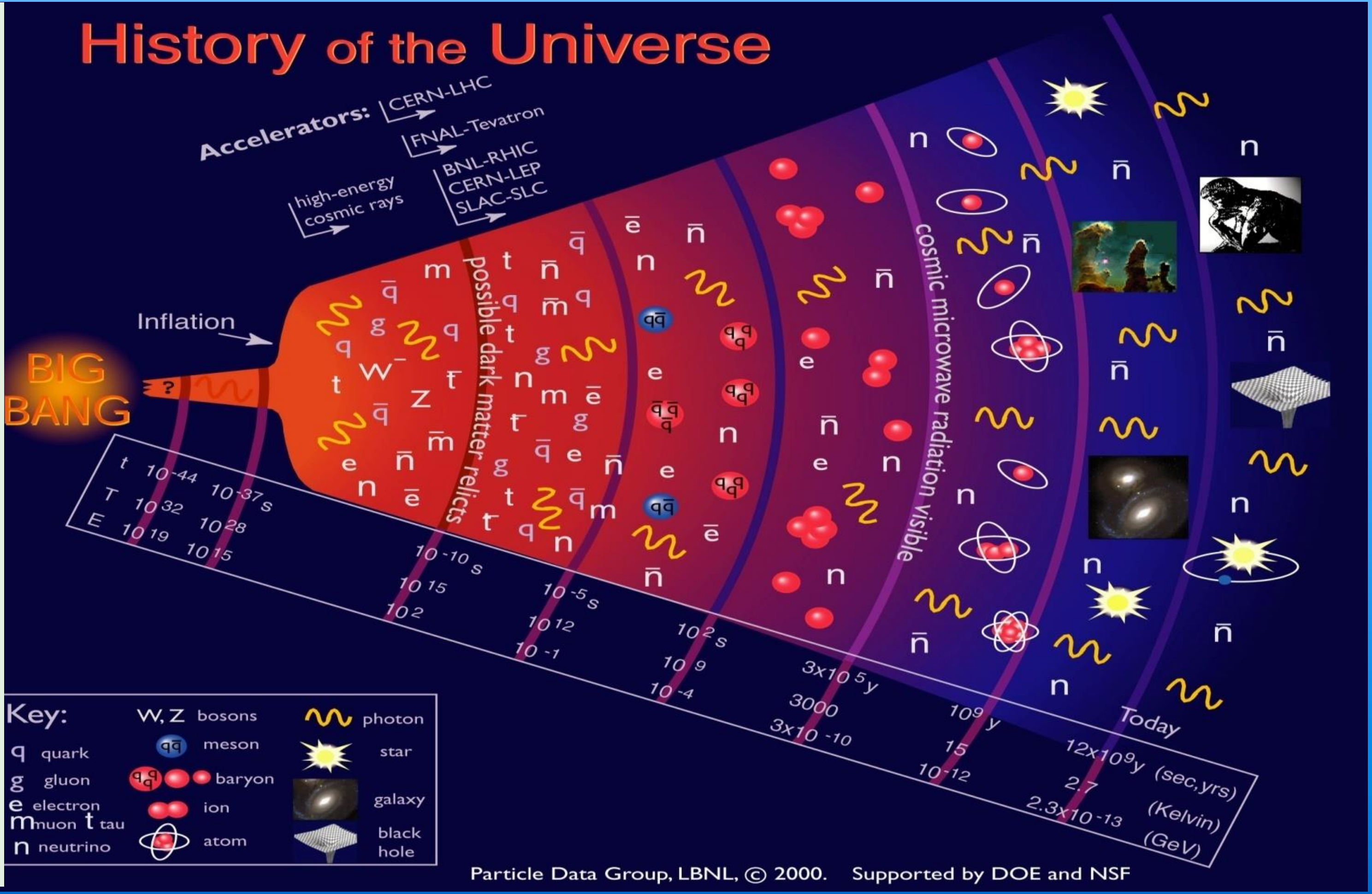
a) Trajectory path of heavy ions at 275 MeV (LET= 24 MeV-cm^2/mg);
b) Comparison with CMOS node sizes (45-350 nm)
Ref.: Griffoni Alessio, 2009

RadHard in SoC Design

- **SEE and RadHard:** SEE/SEU, RadHard/TID/SP
- **Cosmic Rays & Charged Particles:** *p, e , α, ions*
- **Cosmic Rays & Neutrons:** cross-section, range, fluence
- **RadHard Remedies:** TID, SOI
- **Discussion**

Big Bang Higgs Boson Supernova Van Allen Belt

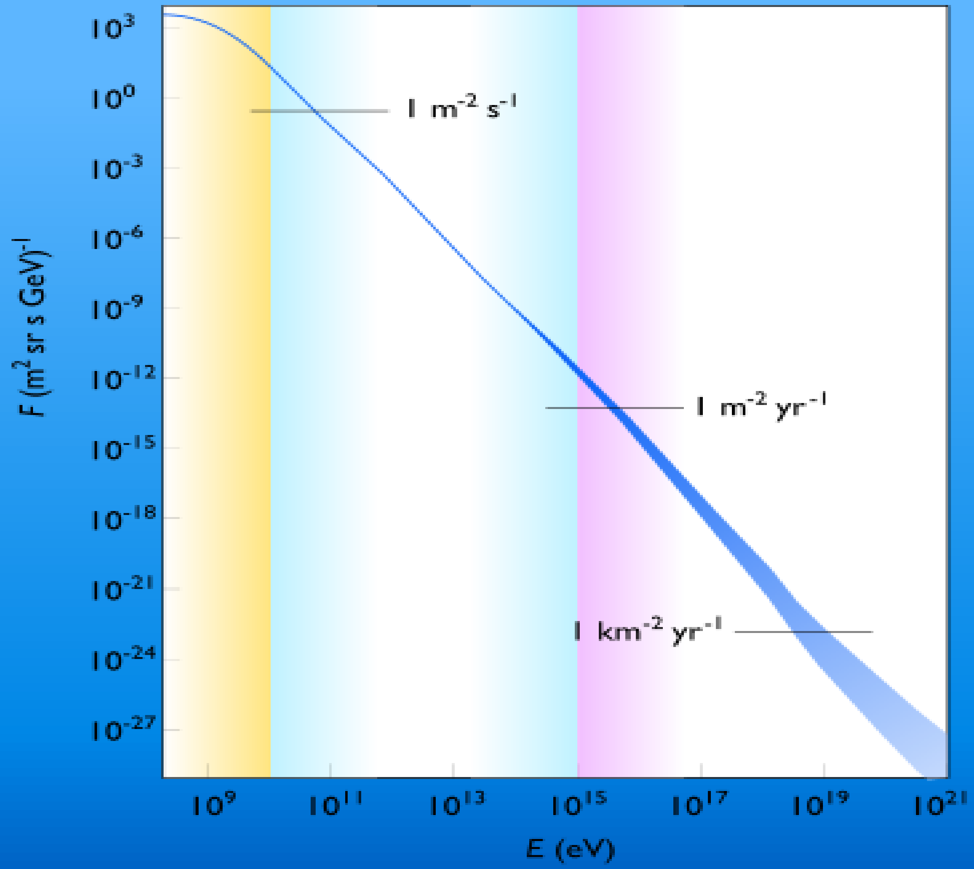
… particles and their large effects …



Gravitational Wave Observatory

- Predicted by Albert Einstein in general relativity in 1916: G-wave → G-radiation similar to EM
- LIGO, Feb 2016
  - includes more than 900 scientists worldwide, as well as
  - 44,000 active Einstein@Home users
-
- A Brief History of Humankind - Homo Sapiens

Cosmic ray – high-energy radiation



Space Radiation

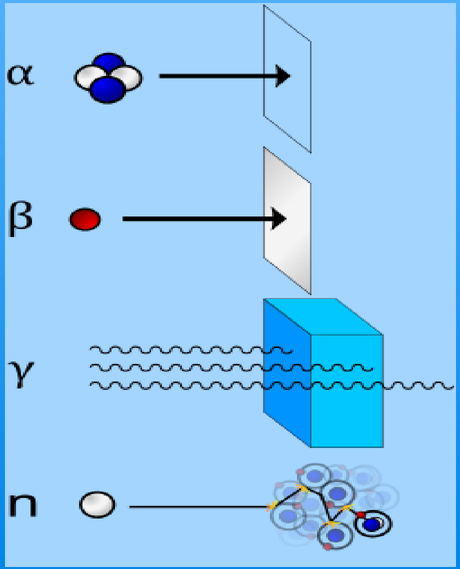
- Radiation Particles in Van Allen Belts and Solar/Galactic Cosmics

Environment	Composition	Energy	Flux, $1/(cm^2 \cdot s)$
Inner Van Allen belt Alt. (1,000-6,000) km	protons (99%) electrons (1%)	10-50 MeV $\geq$100 keV	$(1-2)\times10^5$ ($\geq$50MeV) 3×10^6 ($\geq$1 MeV)
Outer Van Allen belt Alt. (13,000-60,000) km	protons (1%) electrons (99%)	1 MeV (0.1-10) MeV	2×10^6
Solar/Galactic cosmics At Earth's surface	protons (90%) alphas (9%) HZE ions (1%) photons (x-, γ-)	1×10^9 (1 GeV) 1×10^{12} (1 TeV) 1×10^{16} (10 PeV) 1×10^{20} (100 EeV)	1×10^4 1×10^0 1×10^{-7} [a] 1×10^{-9} [b]

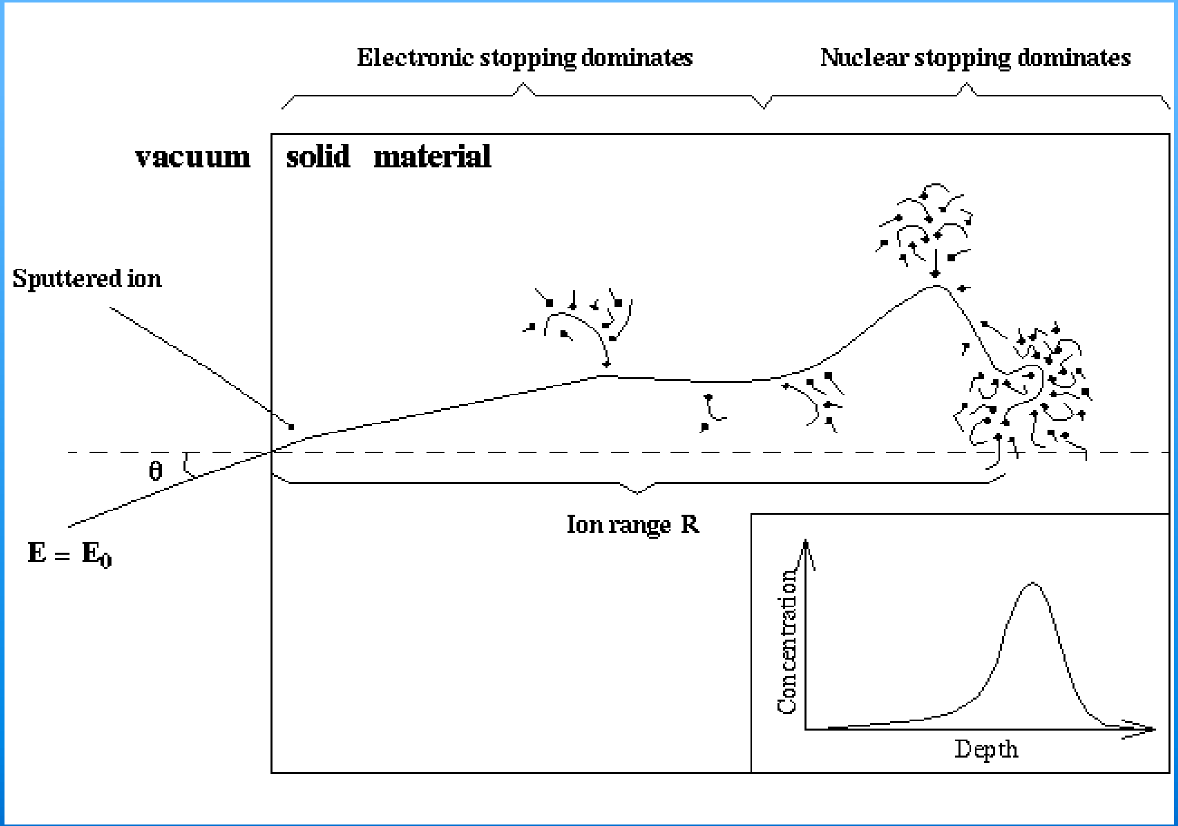
[a] a few times a year; [b] once a century

Cosmic Rays and Ionization Radiation

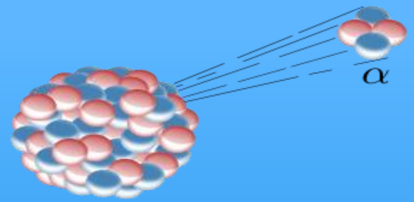
- **Types** of Ionizing Radiation
  - Charged Particles:
    - p, e, α (He^4), β (e^-, e^+), ions
  - Non-charged particles: n, X-rays, γ-rays
    - X-rays, γ-rays are EM radiation
- Interactions of Ionizing Radiation
  - Interaction process: Ionization events
  - Ionization products
    - Secondary, tertiary particles are produced



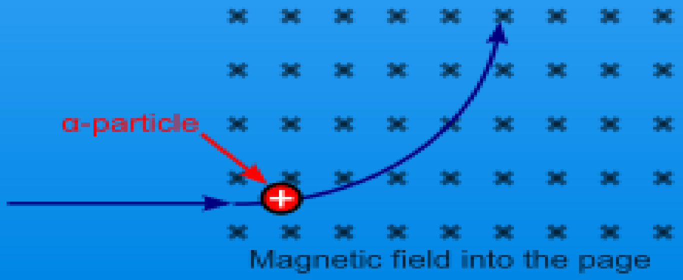
Interactions via Secondary Particles

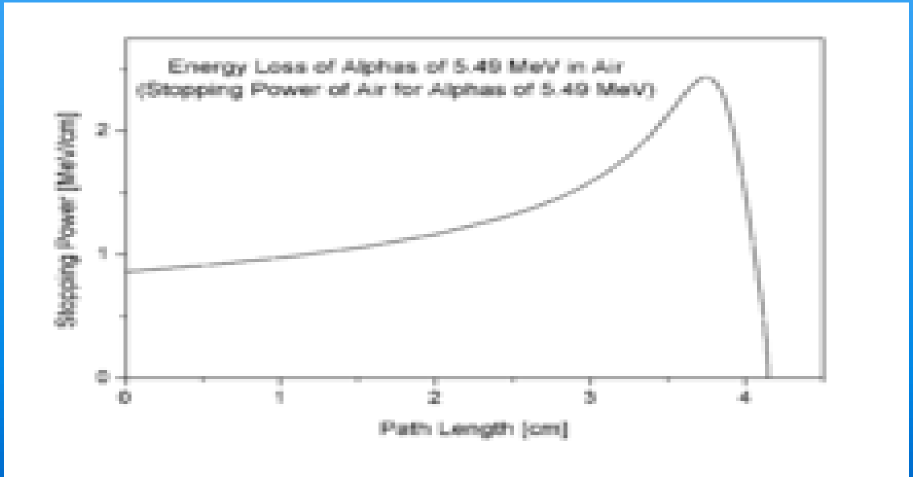


Alpha Particles – 2 protons, 2 neutrons



- Symbols: α, α^{2+}, He^{2+}, or ${}^{4}_{2}H^{2+}$
- Process: alpha decay
- In general >5MeV, speed is about 5% of C
- In cosmic, 10-12%





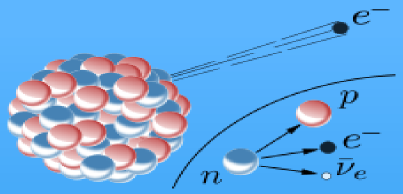
Ex.: ${}_{92}^{238}U \rightarrow {}_{90}^{234}Th + {}_{2}^{4}He$

Beta Particles

- Beta particles are either β^- or β^+
- Electron emission, β^- decay

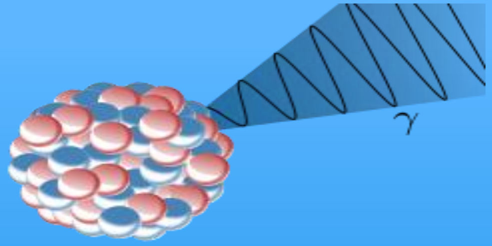
  $n \rightarrow p + e^- + \bar{\nu}_e$
- Positron emission, β^+ decay

  $p \rightarrow n + e^+ + \nu_e$
- Decay via EM and may give off bremsstrahlung x-rays.
- Detection and measurement
  - ion chambers,
  - Geiger-Muller counters, and
  - scintillation counters



Blue Cherenkov radiation light being emitted from a TRIGA reactor pool is due to high speed beta particles traveling faster than the speed of light (phase velocity) in water (which is 75% of the speed of light in vacuum).

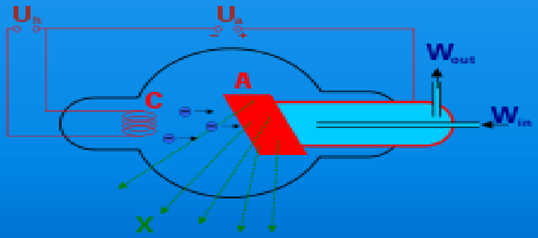
Gamma rays (Paul Villard, 1900)



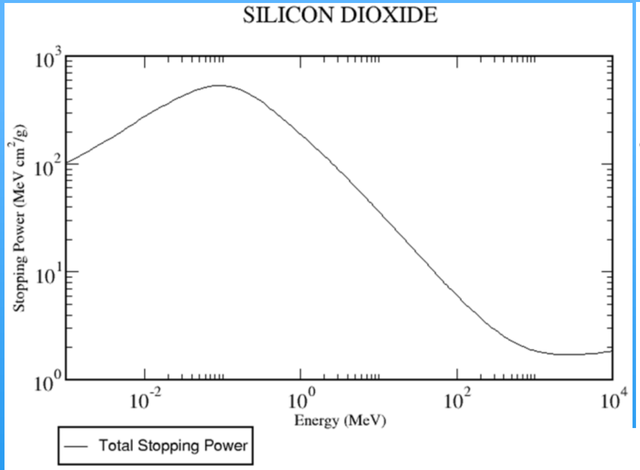
- Nuclear radiation: γ-rays
  - Villard (Fr.) discovered in Radium,
  - named as γ-rays by Rutherford in 1903
- Non-nuclei γ-rays
  - from lighting strikes,
  - terrestrial γ-ray flashes
- Characteristics of γ-rays
  - f >10 exahertz (or $>10^{19}$ Hz), <10 pm ($<10^{-11}$nm, or 0.1 Å)
  - typically >100 keV; astronomical >10 TeV

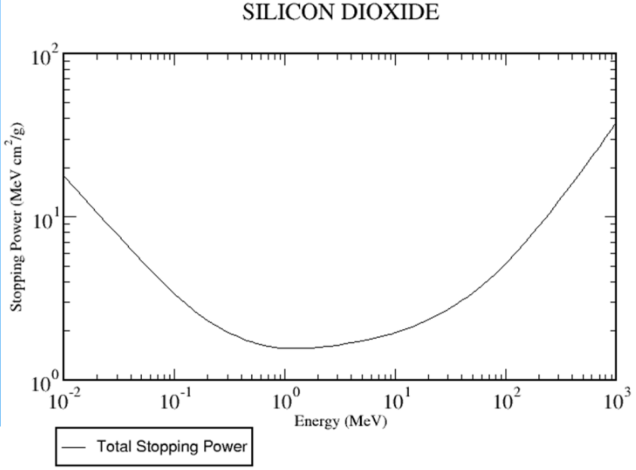
X-ray (Röntgen radiation) 1895

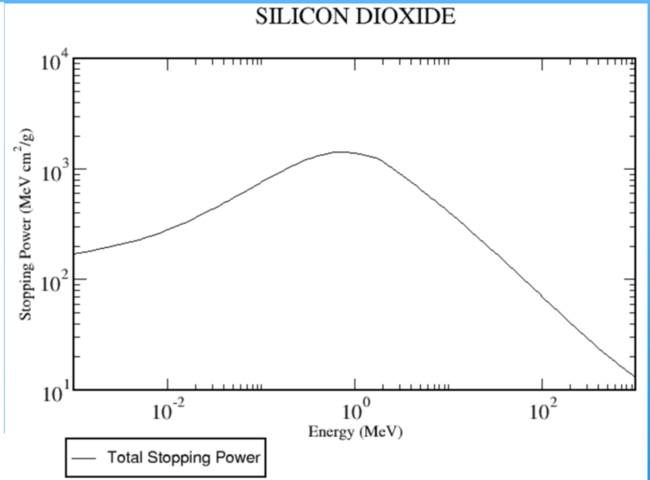
- 1901 The First Nobel Prize, Wilhelm Röntgen
- Characteristics of X-ray
  - wavelength 0.01-10nm ($3x10^{16}$ Hz - $3x10^{19}$ Hz)
    - between UV and γ-ray
  - Energy range: 100 eV – 100 keV
    - hard X-ray >5-10 keV (0.2-0.1nm);
    - soft X-ray <5 keV
  - Medical radiotherapy;
    - linear accelerators 6-20 MeV

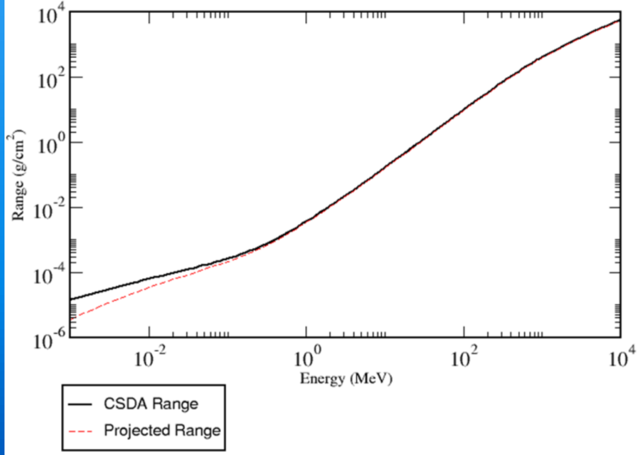


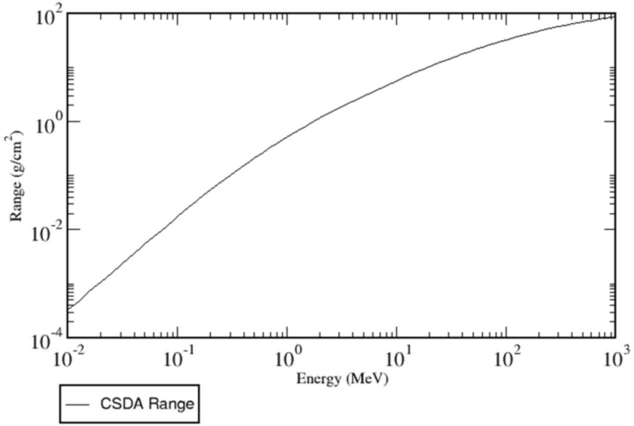
Selected Results of SP and Range for e, p, α Particles

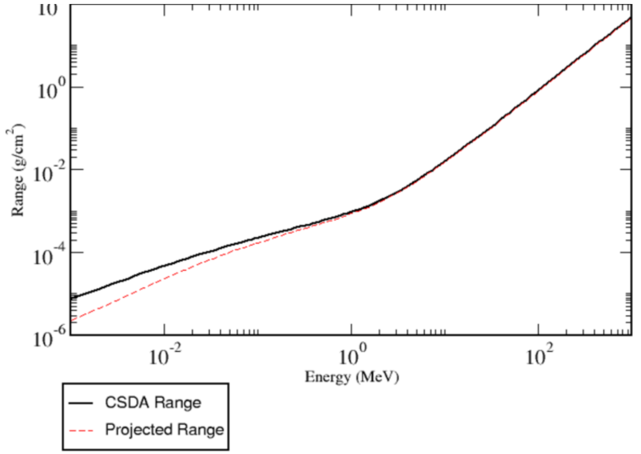












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- Cosmic Rays & Charged Particles: *p, e , α, ions*
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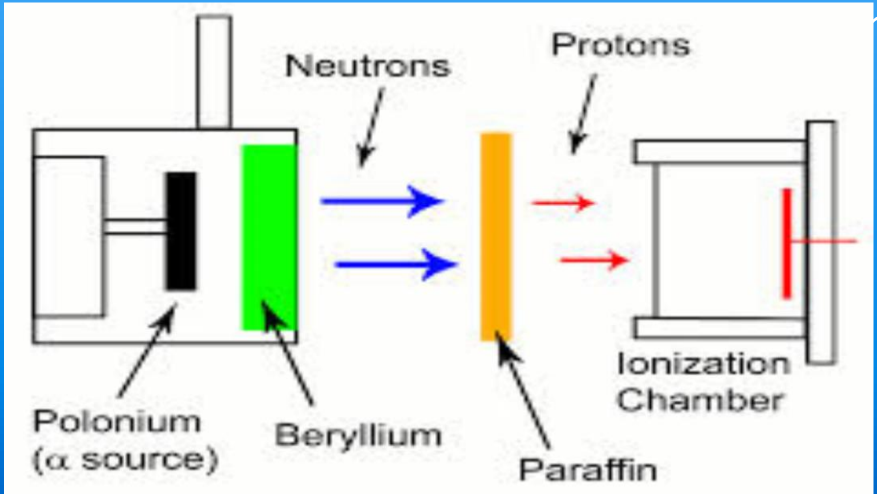
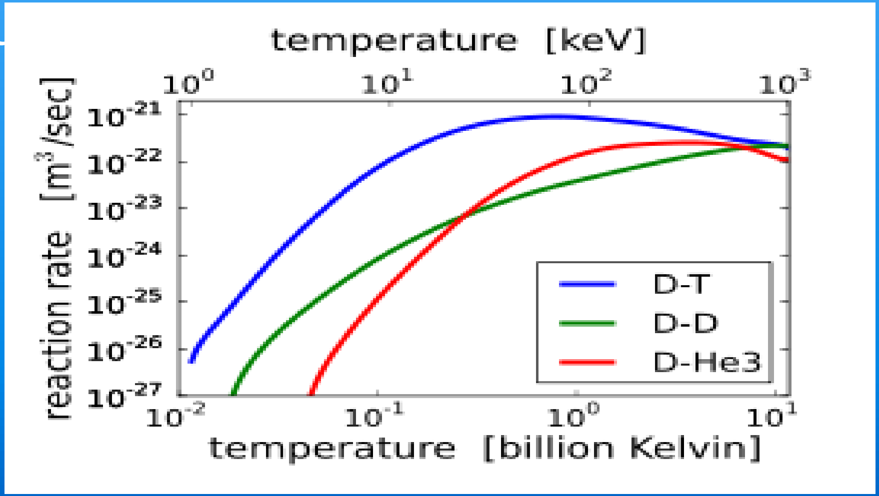
Big Bang Higgs Boson Supernova Van Allen Belt

Discovery of the Neutron (1932)

- Sir James Chadwick, 1935 Physics Nobel Prize
  - Cavendish Lab., Cambridge University
- Atomic number (Z, # of p), and (atomic) mass number (A),



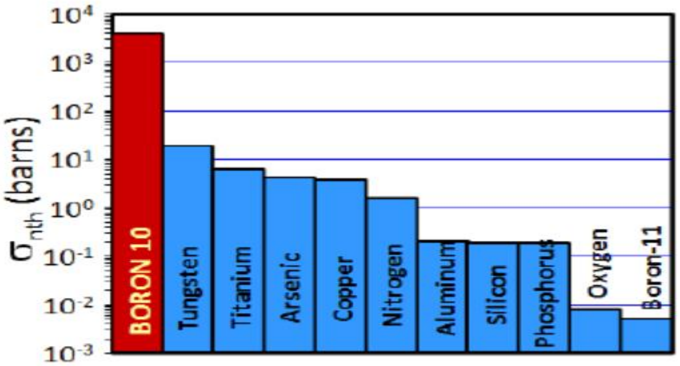


Neutron Temperature

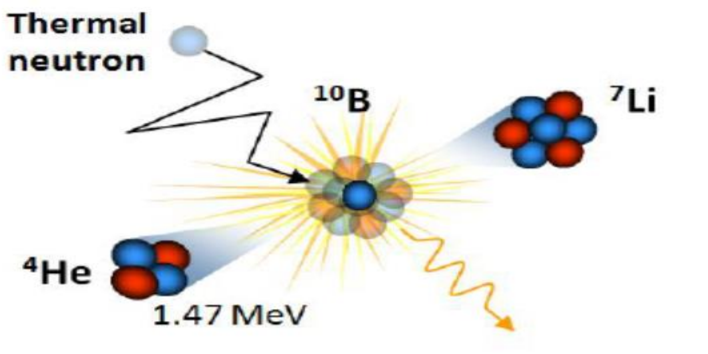
- Thermal neutrons, free with kT=0.0253 eV, speed 2.2km/s
- Cold neutrons, equilibrated w/ deuterium, for scattering exp.
- Ultracold neutrons,
  - a few kelvins w/ solid deuterium or superfluid helium
- Fission energy (fast) neutrons (0-14MeV)
  - close to 1 MeV (1.6×10^{-13} J), hence of ~14000 km/s
- Fusion neutrons, D-T fusion, 14.1MeV
- Intermediate-energy neutrons, ex. epithermal
- High-energy neutrons,
  - by particle accelerators or from cosmic rays

Interactions of Neutrons with Matter

Thermal neutron



(a) Thermal neutron cross section of some nuclei



(b) Nuclear reactions caused by thermal neutron in boron nucleus

Thermal neutron, or free neutron, larger effective cross-section (higher probability for interaction with nuclei)

kT = 0.0253eV (4.0x10^{-21}J) @RT,
if absorbed → fusion, → isotope → SEE

Cross Section, Probability of the Reaction

- Probability, σ [counts cm^2/particles]

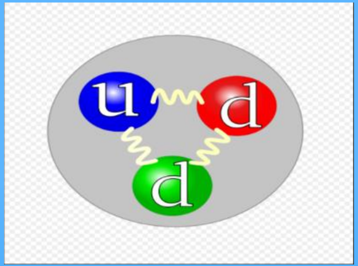
$$\sigma = N_{counts} /(N/A) = N_{counts} / \Phi$$

$$N_{counts} = N\left(\frac{\sigma}{A}\right) = \frac{N}{A}\,\sigma = \sigma\,\Phi$$

- Numbers of Damage
  - In a SRAM study of the configuration memory, the cross-section is σ_{SEU}, then

$$N_{counts} = N_{SEU}$$

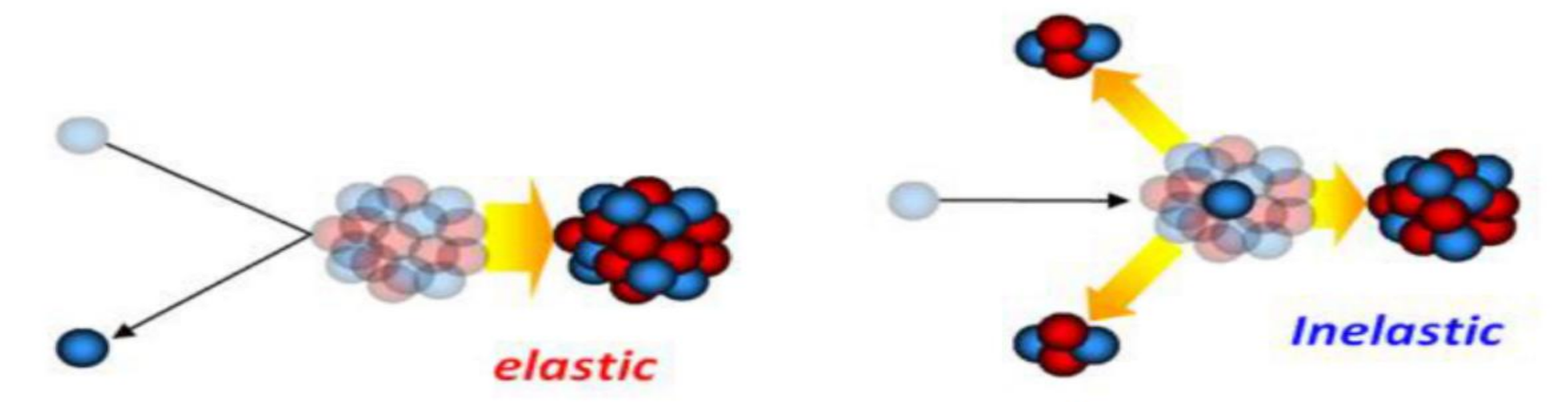
Neutron Flux



- Neutron $fluence,\ \Phi = \int_0^t \varphi dt\ \ \left(\frac{neutrons}{cm^2 s}\right)$
- Natural neutron fluence
  - F_{star}: 10^5-10^{11}; After a supernova, 10^{22};
  - in a thunderstorm $3 \cdot 10^2$-$5 \cdot 10^2$ $\left(\frac{neutrons}{cm^2 s}\right)$
- Artificial neutron fluence
  - research reactor, nuclear power plant over 40yrs:
    - $3{,}5 \cdot 10^{19}$ n/cm^2 (E>1MeV)
  - weaponry:

Interactions of Neutrons with Matter

Elastic and Inelastic Scatterings



(a) Elastic scattering (b) Inelastic scattering

Concerns:
For SRAM using 45nm process, the Q critical is about 1fC,while a 60eV neutron, in an elastic scattering process, can be a critical SEE.

$$\mathbf{E}_{k,Si} = \mathbf{0.13\ E}_{k,n}$$

Neutron Generation

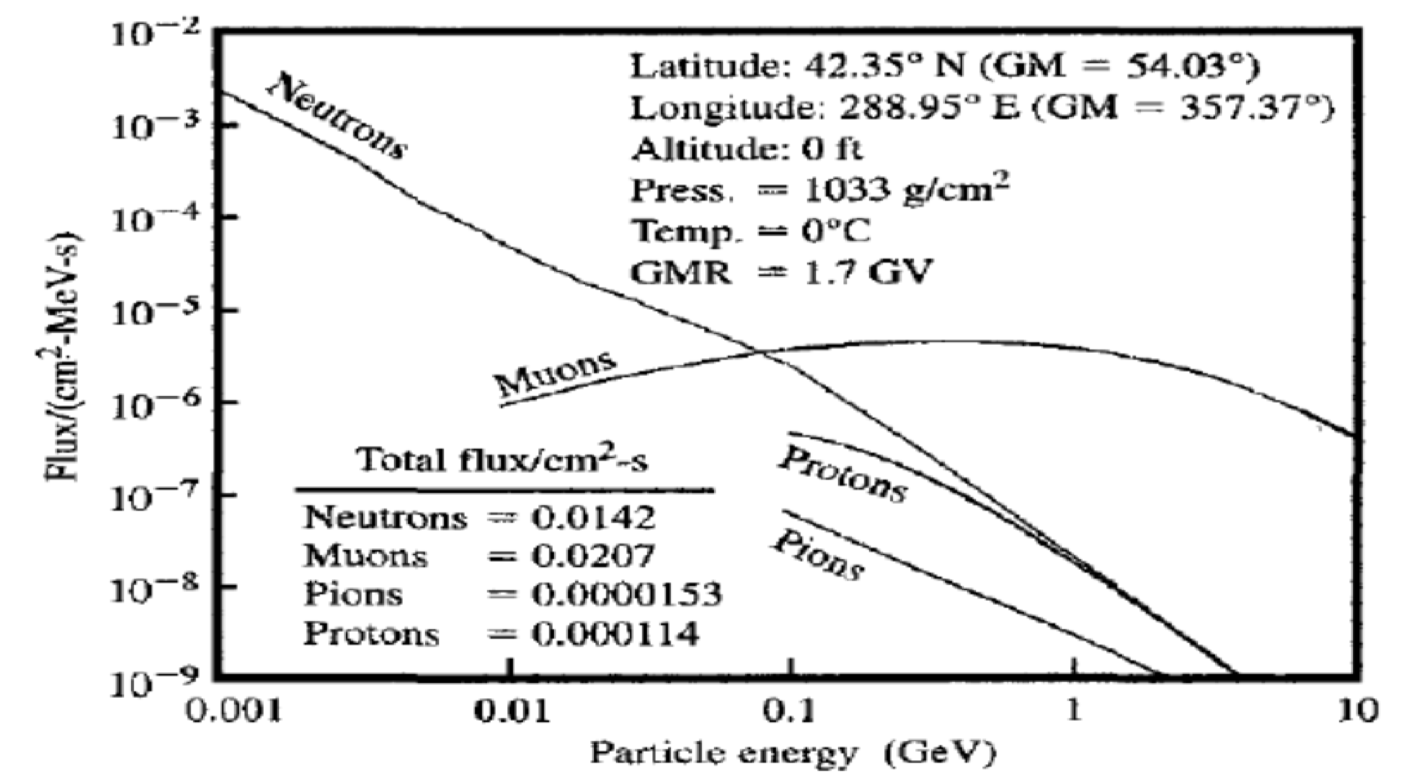
Neutron generation for Biology Studies –

US 13,000 individuals receive measurable n doses
WW 1,000,000 airline crew members (1994)
RBE of 10-100keV n, which has a range of 2um

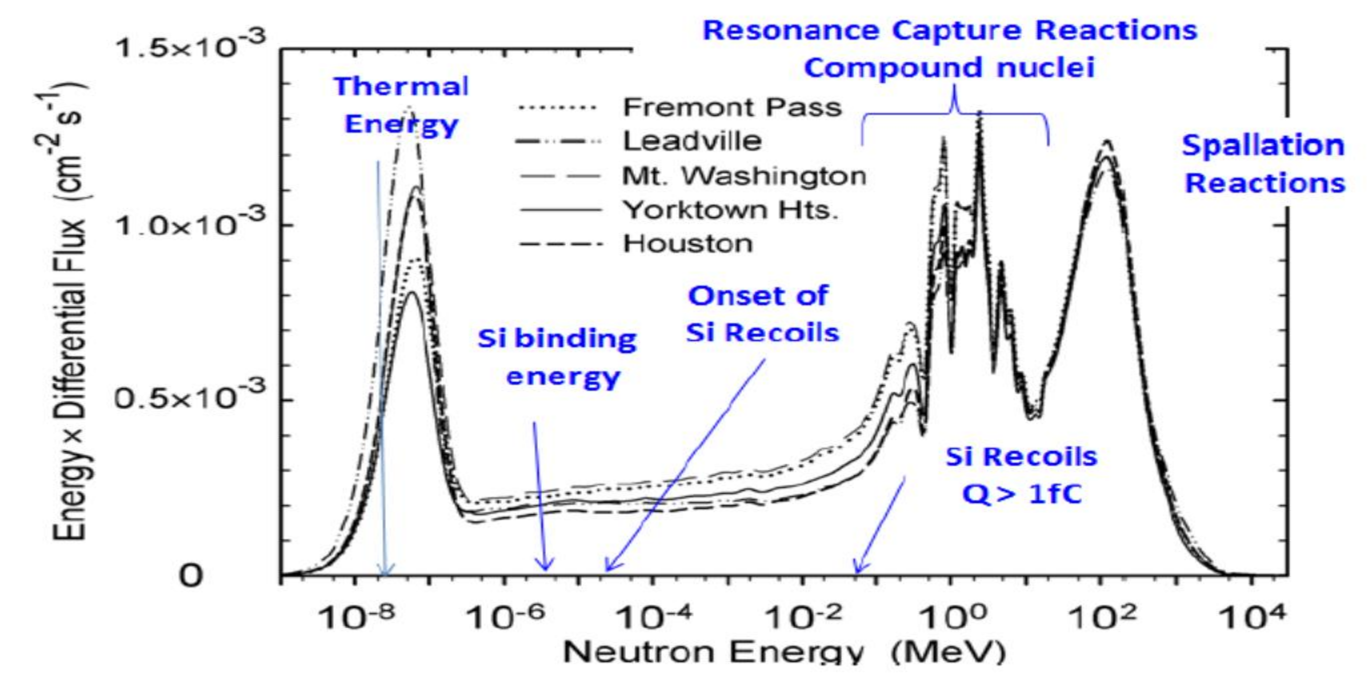
For the interest of RadHard on IC?

Incident P (1.92-2.00 MeV),
Reaction: $^{7}Li(p, n)^{7}Be$ (threshold 1.88MeV)

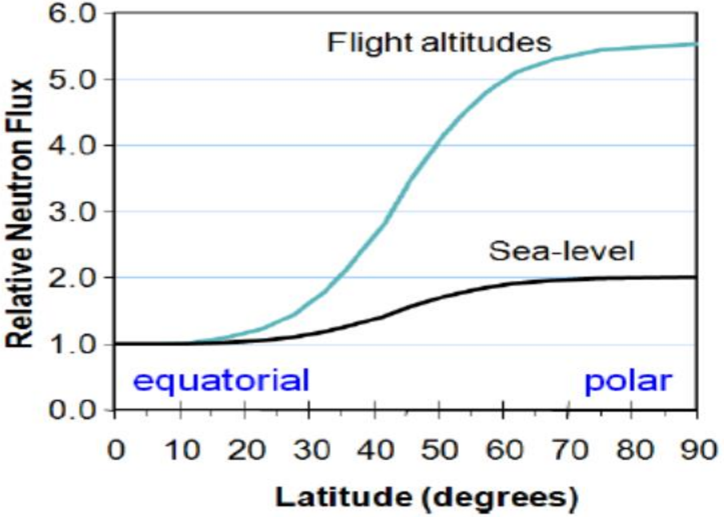
Neutrons in Terrestrial Particles



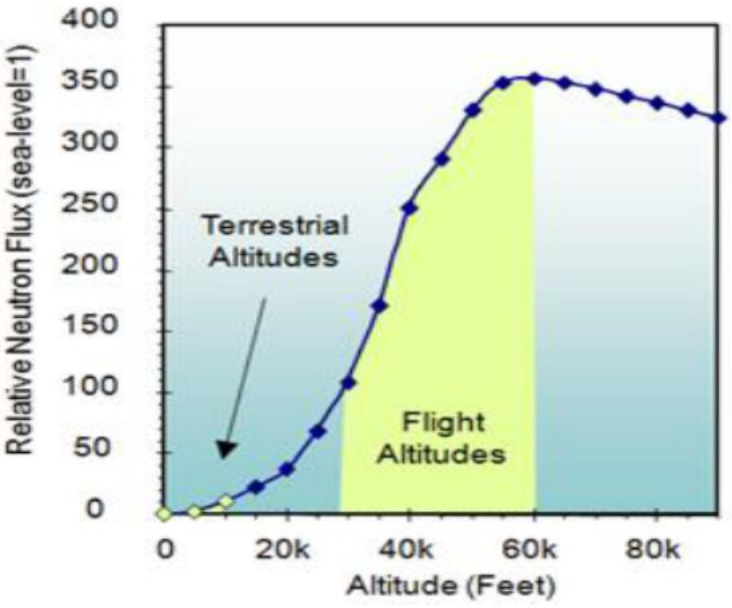
Neutron Flux at Known Geographical Sites



Neutron Flux at Various Latitude and Altitude



(a) Neutron flux variation with latitude

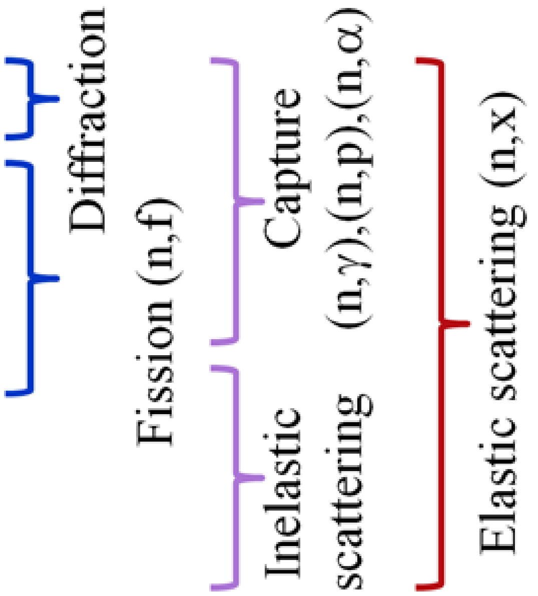


(b) Neutron flux variation with altitude

Neutron sources and types of interaction

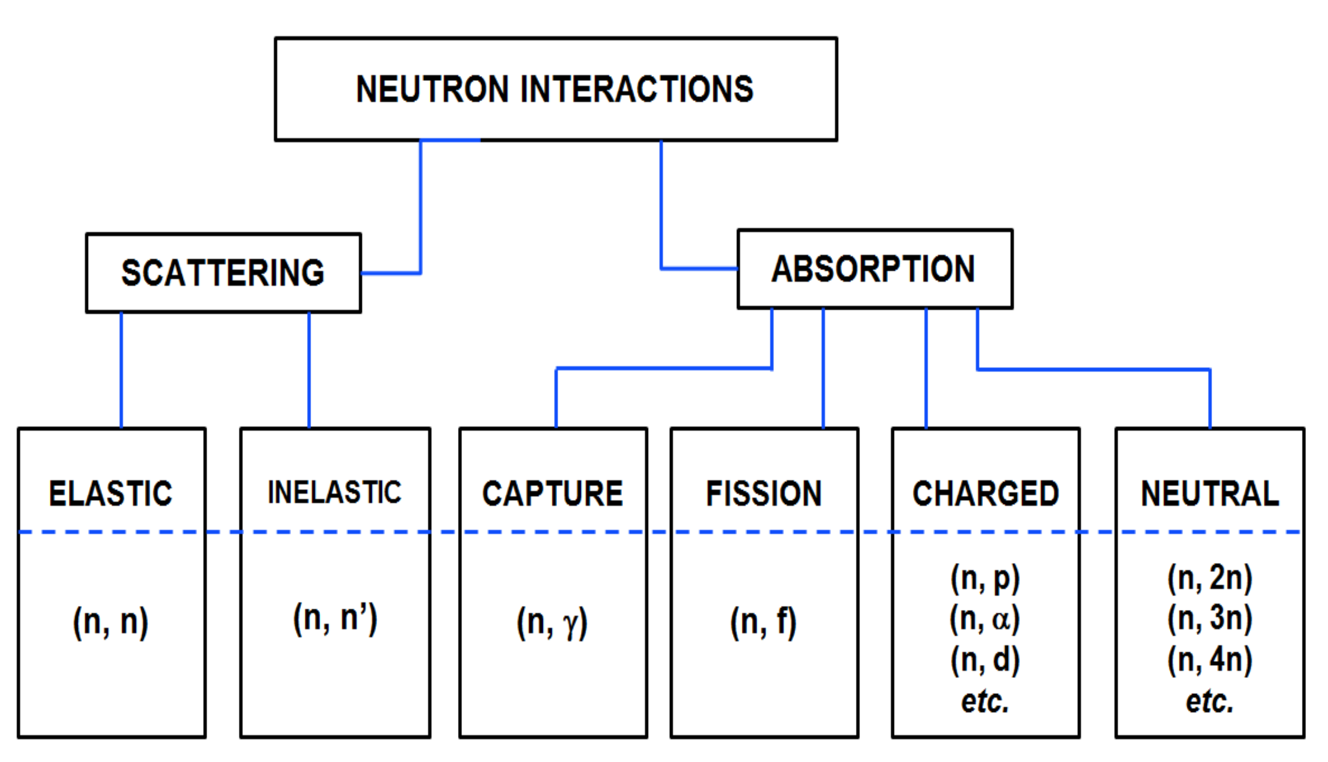
Neutron Types	Energy
Slow neutron	0 ~ 1 keV
Cold neutron,	*≤ 0.002 eV*
Thermal n,	*≈ 0.025 eV*
Epithermal n,	*≥ 0.5 eV*
Resonance n,	*1 eV ~ 1 keV*
Medium energy n	1 ~ 500 keV
Fast neutron	0.5 ~ 10 MeV
Very fast neutron	10 ~ 50 MeV
Cosmic neutron	50MeV~10GeV
Relativistic neutron	> 10 GeV

Interactions

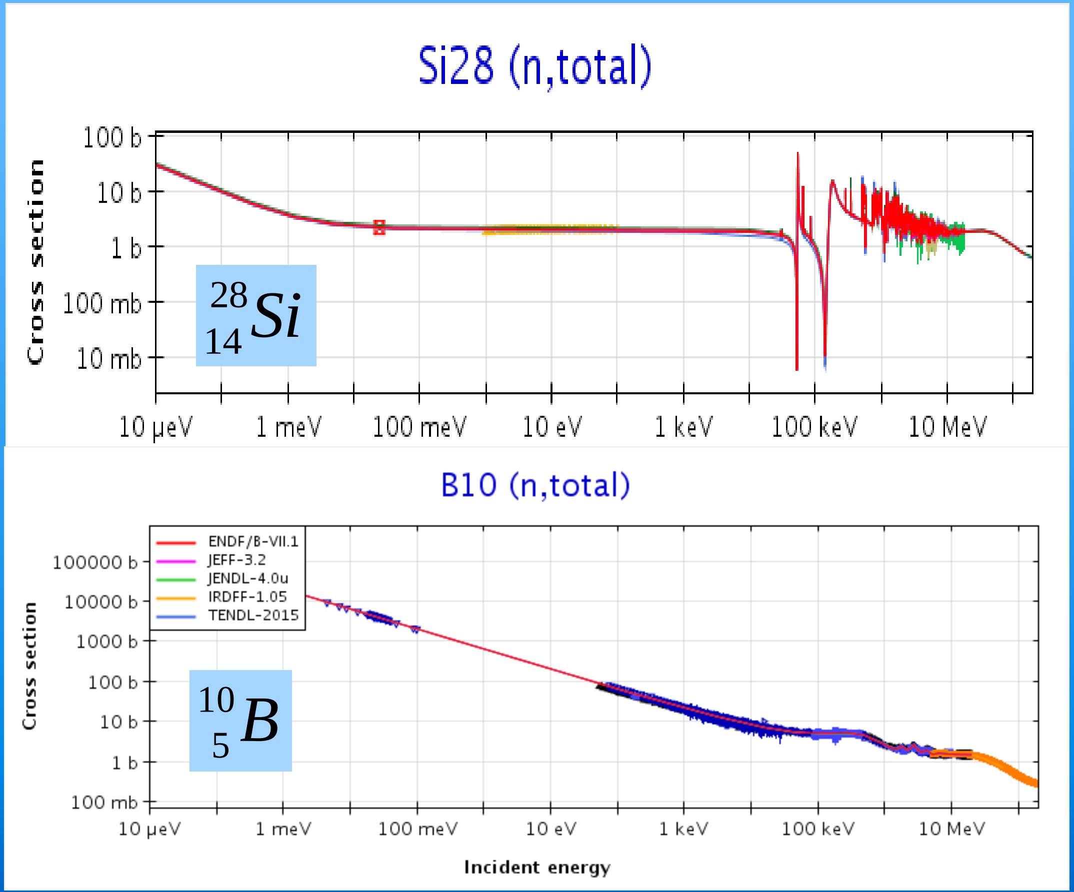


Source: Chen & Hu, 2018, CSTIC

Neutron Interactions – Scattering and Absorption



Total neutron cross section (microscopic) σ



The macroscopic cross section Σ & the mean free path λ

Table 3: The macroscopic *cross section and the mean free path of CMOS transistor compounds for 10 MeV neutrons*

Compound	ρ	M	σ_1	σ_2	Σ_{comp}	λ
SiO_2	2.27	60.08	1.90	1.32	0.103	9.709
GaAs	5.32	144.6	3.65	3.80	0.165	6.061
SiC	3.16	40.10	1.90	1.18	0.146	6.849
Si	2.329	28.08	1.90	N/A	0.095	10.53

Table 4: The macroscopic *cross section and the mean free path of SiO_2 and Si at various neutron energies*

E, MeV	*0.001*	*0.01*	*0.1*	*1*	*10*	*100*
SiO_2, Σ_{comp}	0.217	0.213	0.189	0.478	0.103	0.053
SiO_2, λ	4.608	4.695	5.291	2.092	9.709	18.87
Si, Σ_{comp}	0.097	0.087	0.050	0.230	0.095	0.055
Si, , λ	10.31	11.49	20.00	4.348	10.53	18.18

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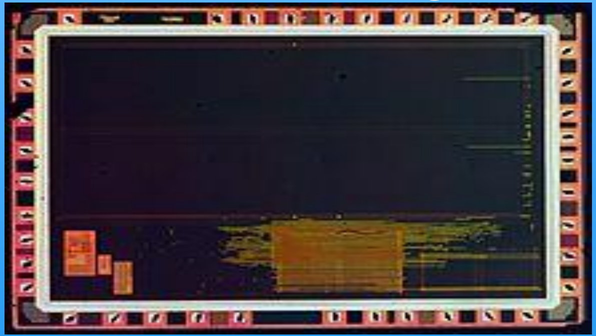
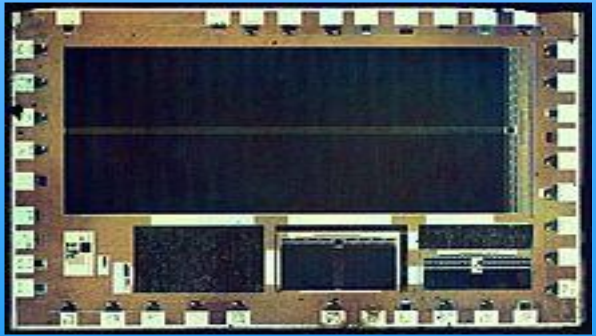
Radiation Hardening Technique

- After metalization etching



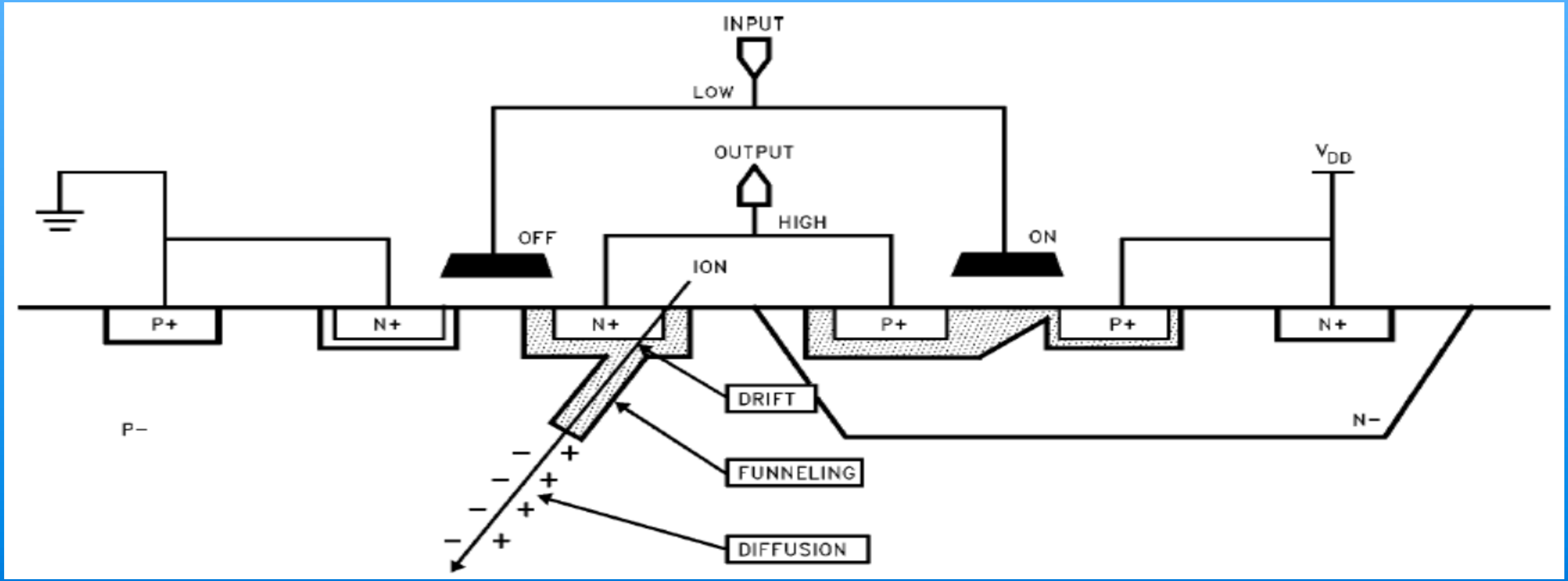


Radiation hardened die of the 1886VE10 microcontroller prior to (a), and after (b) a metalization etching process

- Embedded SEU Protection in FPGA Chip by Atmel (2005)

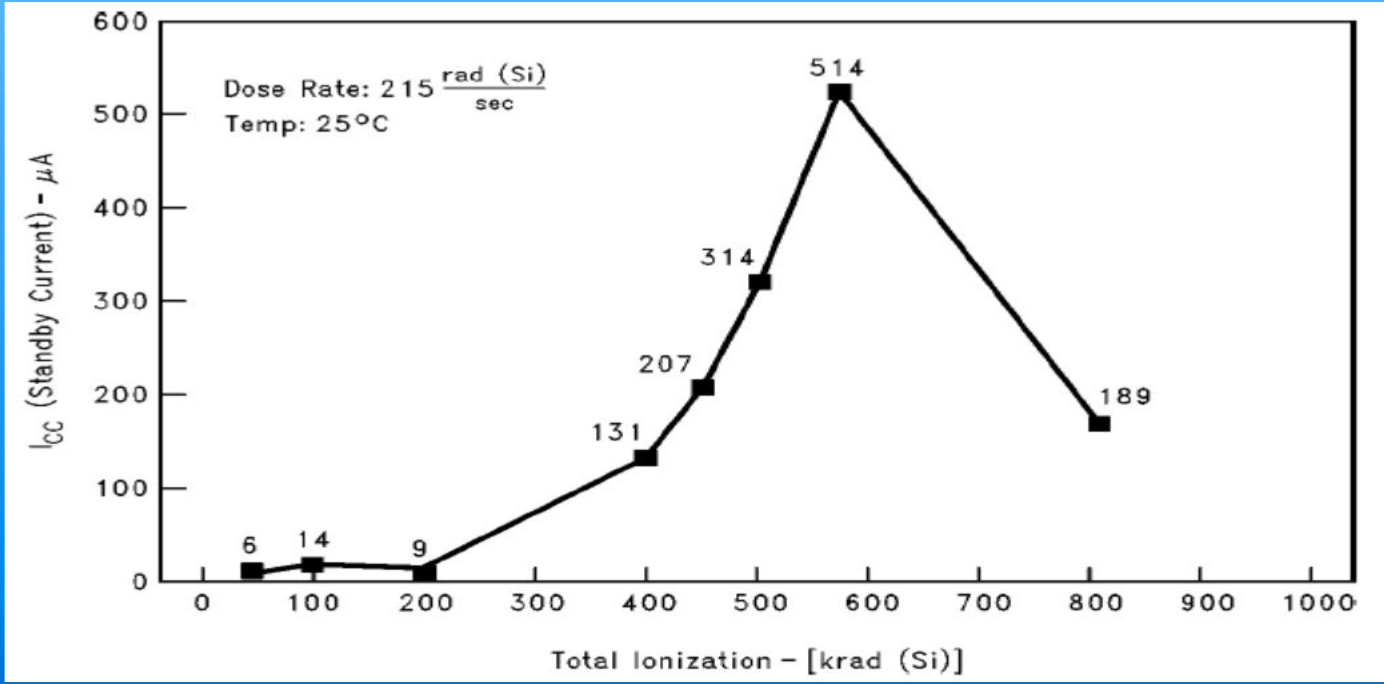
Radiation Design Considerations in CMOS
By TI (1994)

- SEU current (TI Copyright, 2011)



Radiation Design Considerations in CMOS
By TI (1994)

- Icc (standby current) vs. TID



Radiation Resistant Computers

TABLE I

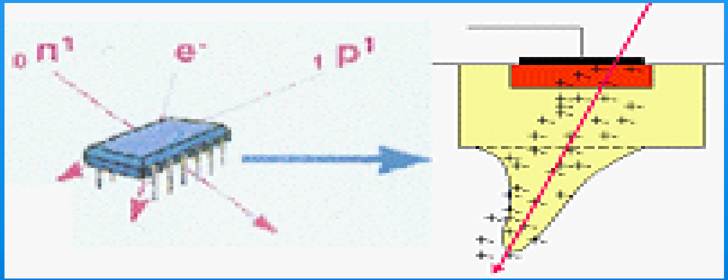
SOI TECHNOLOGY ADVANTAGES BASED ON 0.25 μm SRAM TECHNOLOGY

Category	*SEMATCH Estimation*	*Revenue Gain vs. Bulk CMOS*	*Latest Industry Benchmark*
Process steps	20% less process steps	Simpler well, isolation 6% revenue gain	Between 10–20% simpler
Mask counts	3 less masking steps	Simpler well, isolation	Between 1–3 fewer masks
Circuit density	1.3. improvement	Tighter isolation, latch up rules Additional 45% revenue gain	30% better
Performance	30% faster	Lower capacitance Additional 25% ASP* due to higher performance	Technology generation dependence

*ASP = Average Selling Price

Heavy ions induced micro-dose is a serious concern in
- UTB SOI and
- SOI FinFET

IR discharge current may cause
- Automobile chip failure
- Supercomputer chip error
  - 10,000 chips are used, 10-20 faults/week



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Impact of ESD and Ionizing Radiation

- ESD has been studied on planar technologies of
  - UTB (ultra thin body) SOI
  - SOI FinFET, and
  - Bulk FinFET
- Heavy ions induced micro-dose is a serious concern in
  - UTB SOI and
  - SOI FinFET
- IR discharge current may cause
  - Automobile chip failure
  - Supercomputer chip error
    - 10,000 chips are used, 10-20 faults/week

TID and SEE wrt R and MFP

- Analyzed CDM/ESD
- TID and SET/SEE
  - Dimension of gate oxide
  - SEE by $I_{d,sat}$, g_m
- Calculated (for p, e , a) S, LET, R, MFP
  - SP | LET can be ambiguous
  - Range | MPF is more direct
  - Particle energy at track end is absorbed…
- More studies are needed
  - CDM of ESD
  - SEU & SET of SEE

Recent Applications on DRAM

- **Radiation Effects on DRAM/DDRx [5/28/15]**
  - SEU/ECC NASA, SEE-immunity, std for DARM using 25nm 100 krad
- **Increasing awareness of the need for SEE-immunity in**
  - both aircraft and ground-level systems
- **The XR (eXtra Robust) ECC DRAMs are available in**
  - DDR1, DDR2, DDR3 technologies.
  - tests have passed on: 60/100/350krad, and continued (5/14/15)
- For use in aircraft and high rel ground applications you should test in a spallation neutron source and in a thermal neutron beam. Sometimes this can be done together by using cadmium shielding and taking differences.
  - See IEC-TS62396 for details.

Increased Challenges in Shrinking Chips

By John McHale (May 17, 2011)

- Military and Aerospace Electronics
- Aerospace and Defense
  - Technology Focus
  - Radiation and small components
  - Performance demands
  - Performance vs. rad-hard

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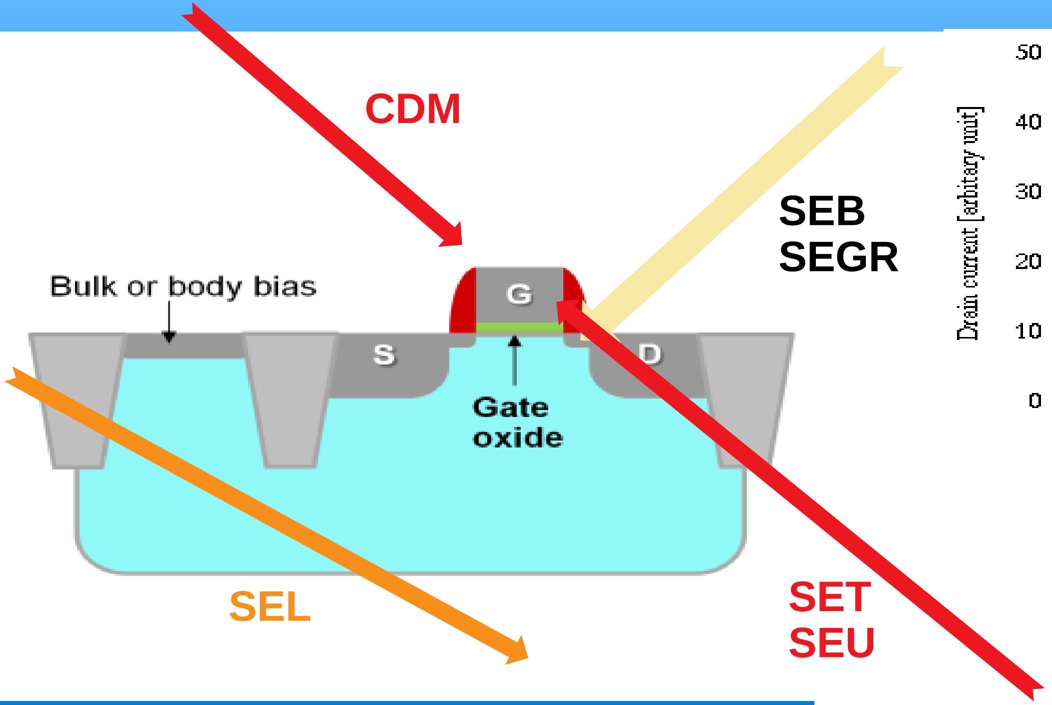
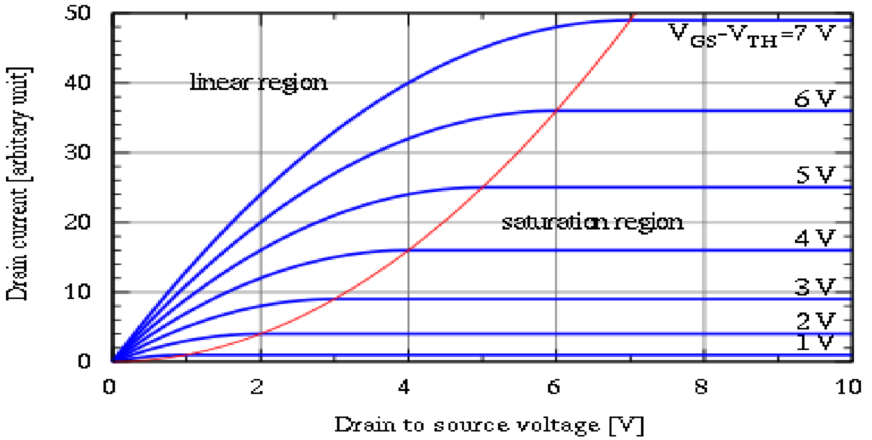
ESD and SEE on Bulk CMOS, FD-SOI, FinFET





SP/LET and D/D-rate of Ionizing Radiation

- SP (Stopping Power, MeV·cm^2/mg)

$$S = k_1 \frac{Zz^2}{M_a \beta^2}\left[\ln \frac{2\mu\beta^2\Delta}{I^2(1-\beta^2)} - \frac{(1-\beta^2)\Delta}{2\mu} - \beta^2 - 2\frac{C}{Z} - \delta\right]$$

$$L = S_{tot} \cdot \rho \qquad (keV / \mu m)$$

- LET (Linear Energy Transfer, SP·ρ → LET)

$$D = \frac{\Delta E_D}{\Delta m} \qquad (1Gy = 100rad = 1J / kg)$$

- Dose (or absorbed Dose)

$$\dot{D} = \frac{dD}{dt} = \frac{d}{dt}\left(\frac{\Delta E_D}{\Delta m}\right) \qquad (1Gy / \sec = 100rad / \sec)$$

Neutrons on SEE

- Increased needs of DFx/Reliability in SoC
- Neutron flux *vs.* altitude (1-100x): applications
  - DC/BD/Supercomputing, ADAS, Aerotronics
- Neutron energy *w.r.t.* interaction types
  - Combined SEE/SEU in materials
- Fluence and SER (SEU) in I/O, RAM
  - Advanced process

Appendix for Neutron Calculation

Diffraction Cross-section, Range, Mean Free Path, Fluence

- Neutron diffraction (elastic scattering), the *Bragg's law*,

$$n\lambda = 2d\sin\theta$$

- The total cross section (*microscopic*), $\sigma_T = \sigma_S + \sigma_A$
- The *Ramsauer Model*, $\sigma_T(E) = 2\pi[(R + \lambda_r(E)]^2(1 - \alpha\cos\beta)$
- The *macroscopic* cross-section Σ_{comp}

$$\Sigma_{comp} = \sigma_i N_i\,, \qquad N_i = \rho N_a n_i / M$$

- The mean free path λ, $\lambda = 1/\Sigma$
- The temperature impact of neutrons, $\sigma_T = \sigma_0 (T_0 / T)^{1/2}$
- The flux I_2 can be calculated at altitude A_2

$$I_2 = I_1 \exp[(A_1 - A_2)/L_n]$$

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