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ECE695: Reliability Physics of Nano-Transistors
Lecture 37: Effect of Radiation Induced Charge
-- Soft Errors

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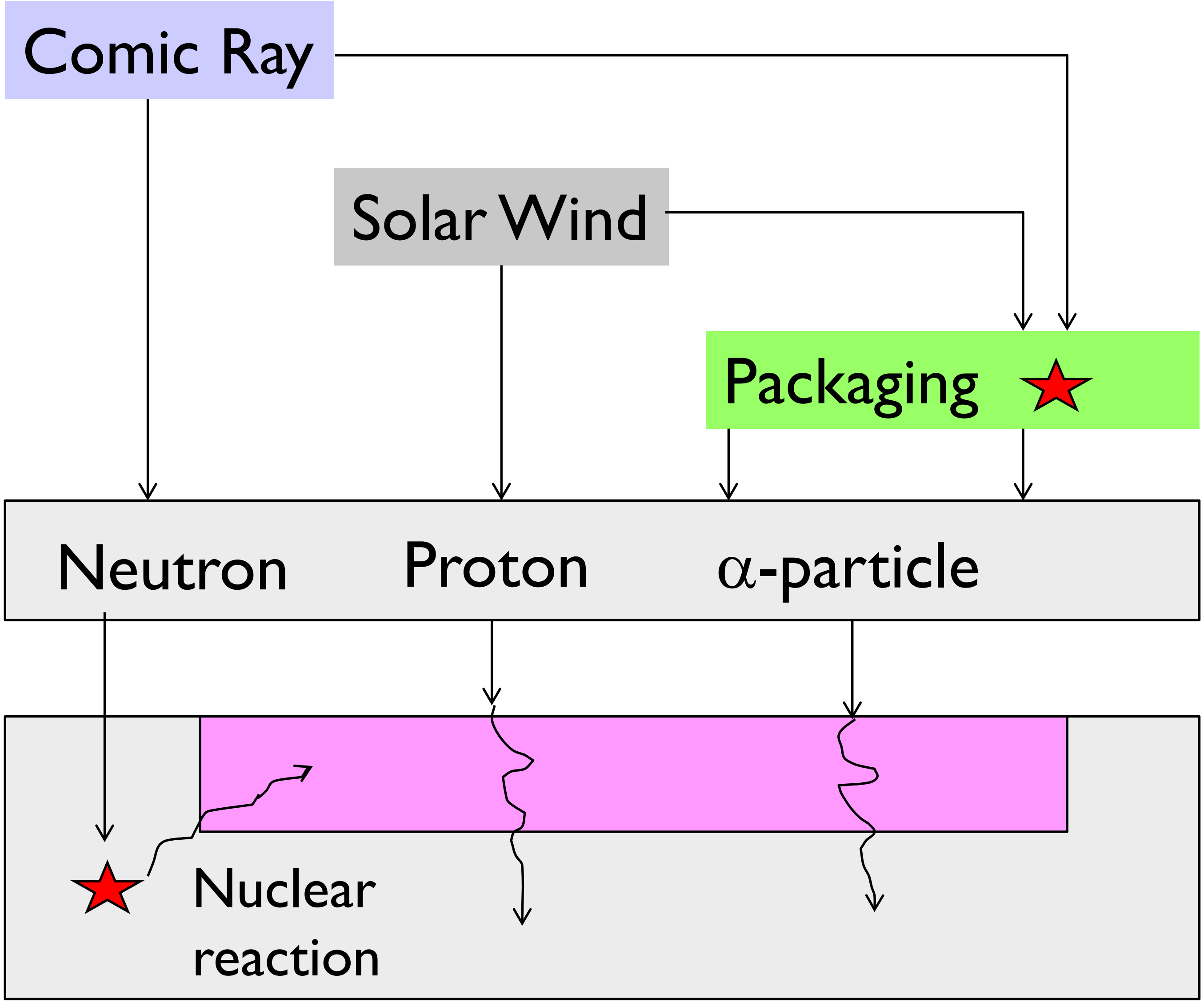
Outline

1. Sources of radiation
2. Basics of charge generation and perturbation of potential
3. Charges and junctions
4. Conclusions

Outline



Comic Ray

Solar Wind

Packaging ★

Neutron

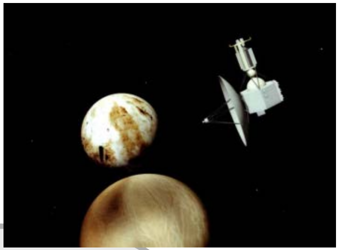
Proton

α-particle

Nuclear reaction

Sources of Radiation

Cosmic Ray



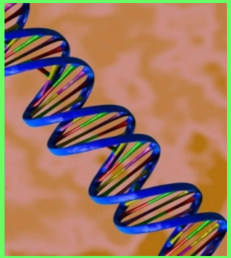
- 4/17 Satellite yrs
- Telestar 1 < 1yr

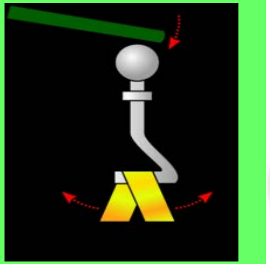
- 1 fail/flight
- Exponential with altitude

Solar Wind

Earth Sources

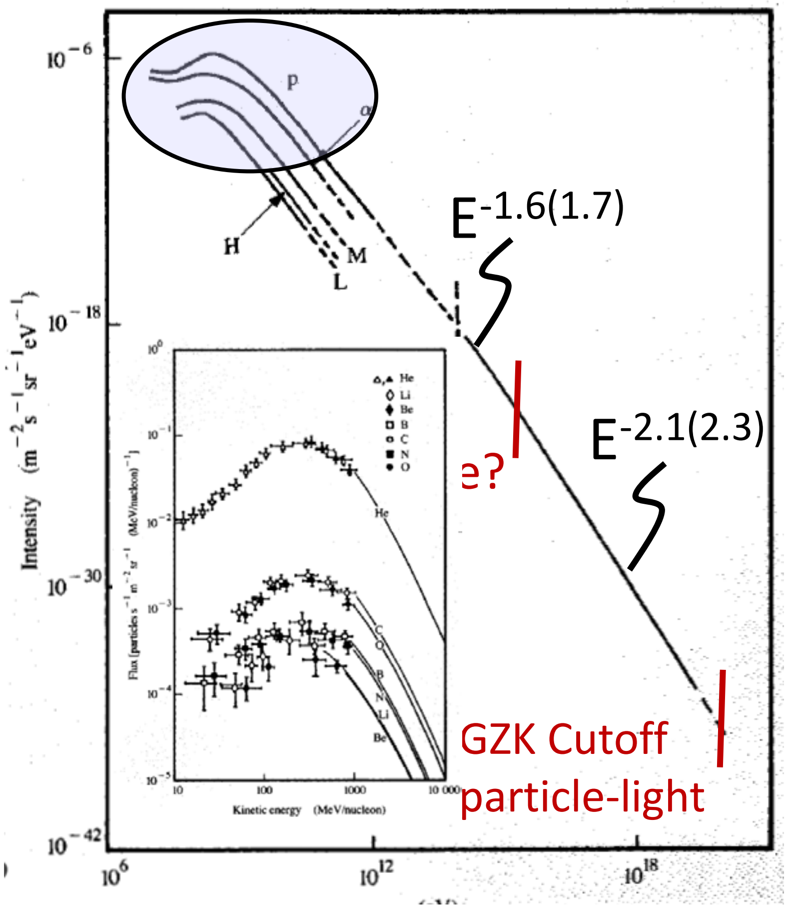
- mutation
- foil electrometer





Source 1: Cosmic Ray (above atmosphere)

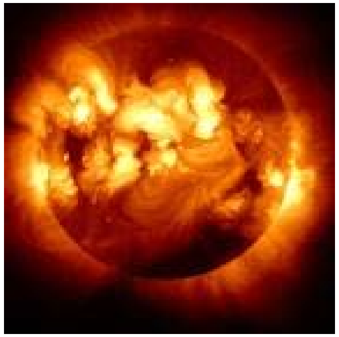
- 92% proton, 6% alpha (or, 70% proton, 30% neutron)
- 2% pion, muon, positron, Li, B, e, B, Pb, Fe(1% to earth, physics testbed)
- 1/cm^2 integrated above 1GeV, inconsequential

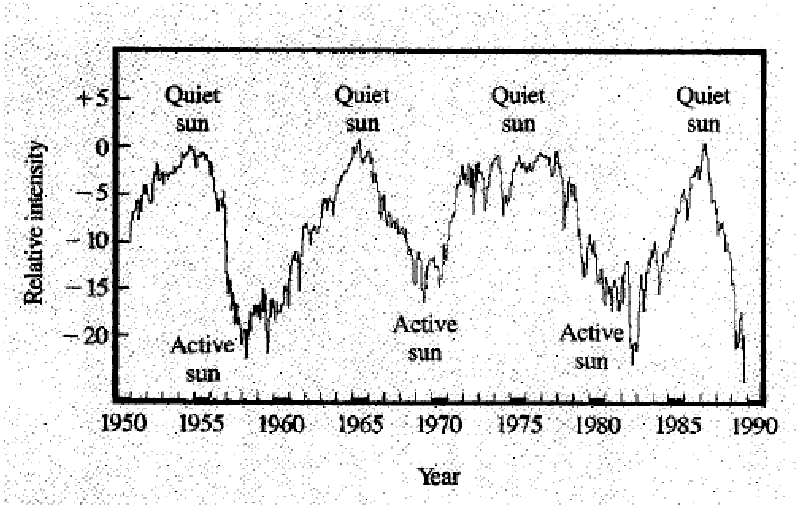


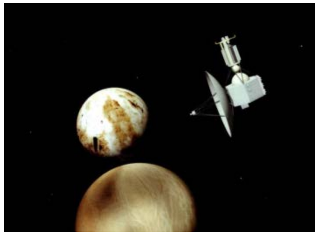
Isotropic:

- $\rho \times d = 4.2$ g/cm^2
- ρ (space; C,N,O) ~1.7×10^{-26} g/cm^3
- Distance = c × time
- Scattering time ~ 300 million-years (equivalent from Lab Expt).
- Isotropy indicates vast distances!

Sources 2: Solar Wind



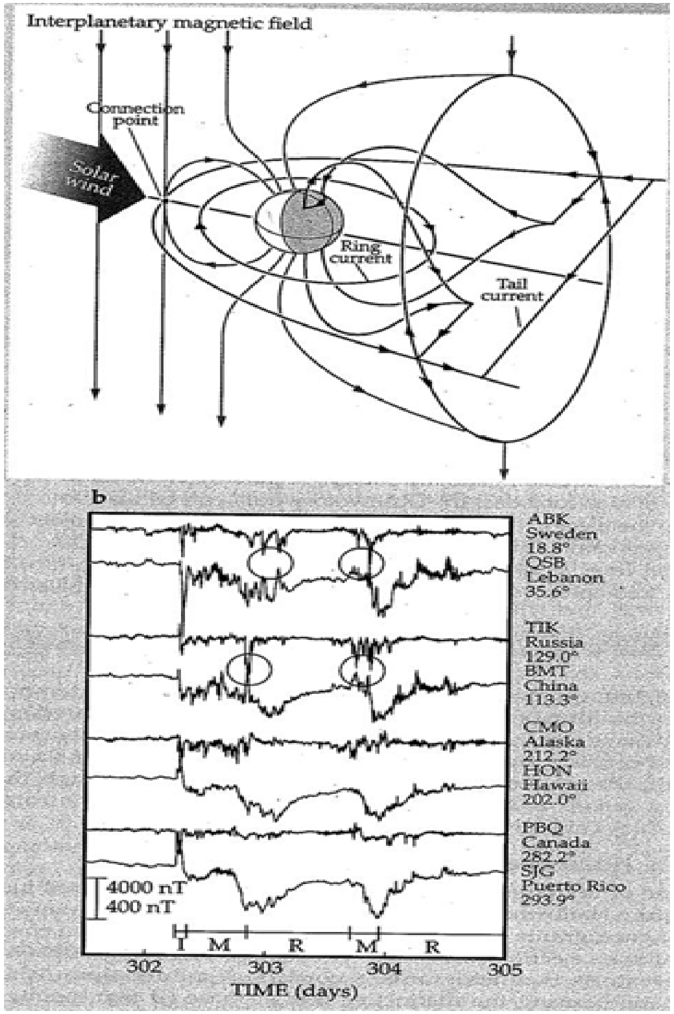




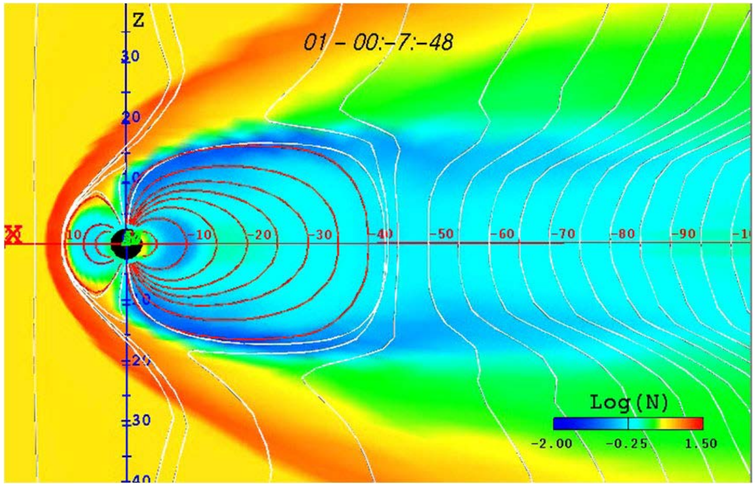
- 90B one MTon bombs; powers oceans, photosynthesis, atmosphere, etc.
- 2000 – 1 millions/cm^2-sec < 1GeV (anisotropic)
- 1859: burned telegraph wire, forest fire;
- 1989: Blackout in North-Eastern America; 11k/19k Satellites lost contact
- 1365 W/cm^2 at surface, 450 reaches earth, 300 reaches surface. Particles reach earth in 4 days

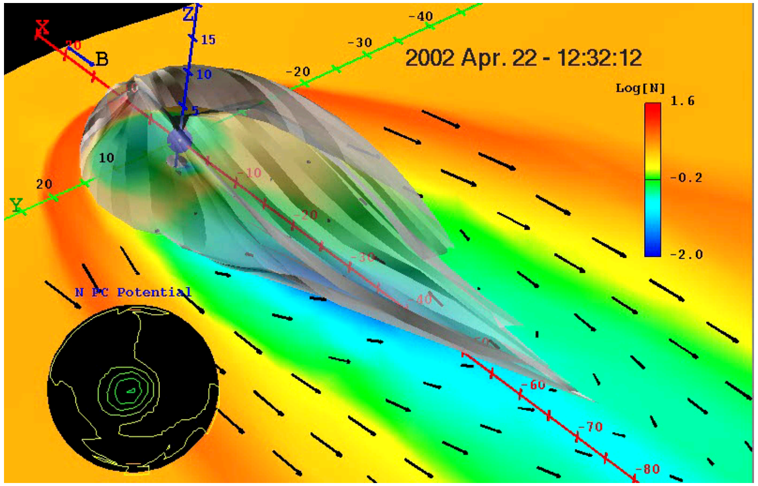
Asymmetry of Solar Wind

Measurement



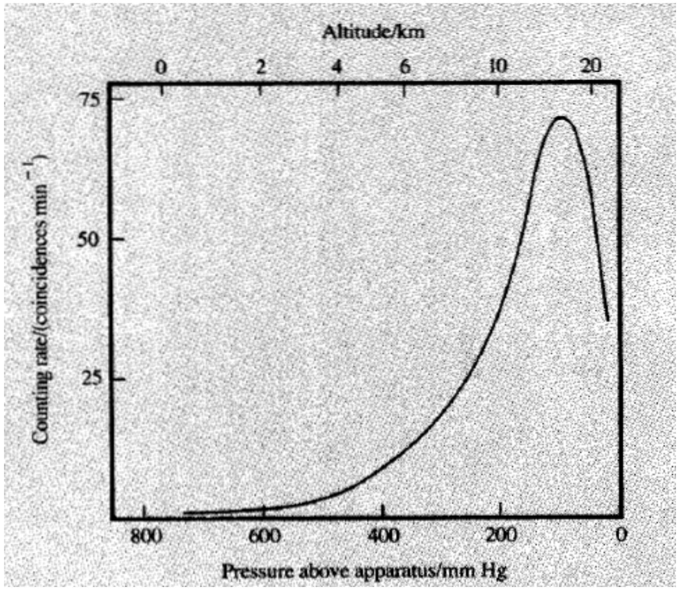
Simulation

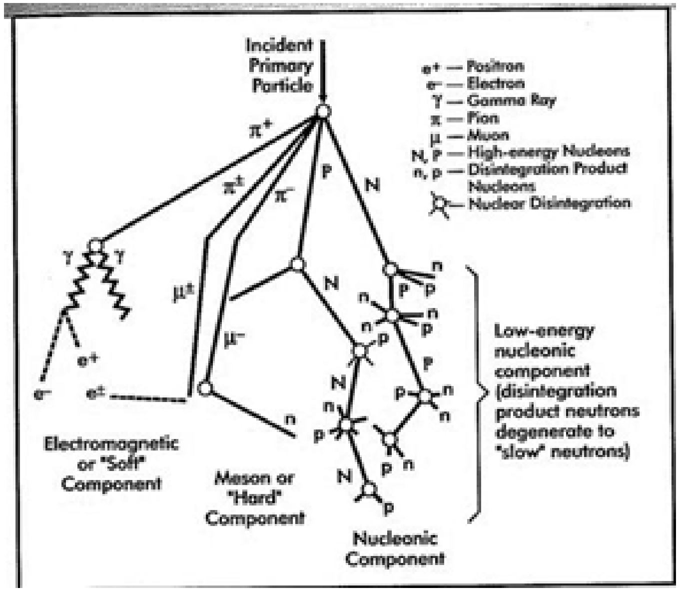


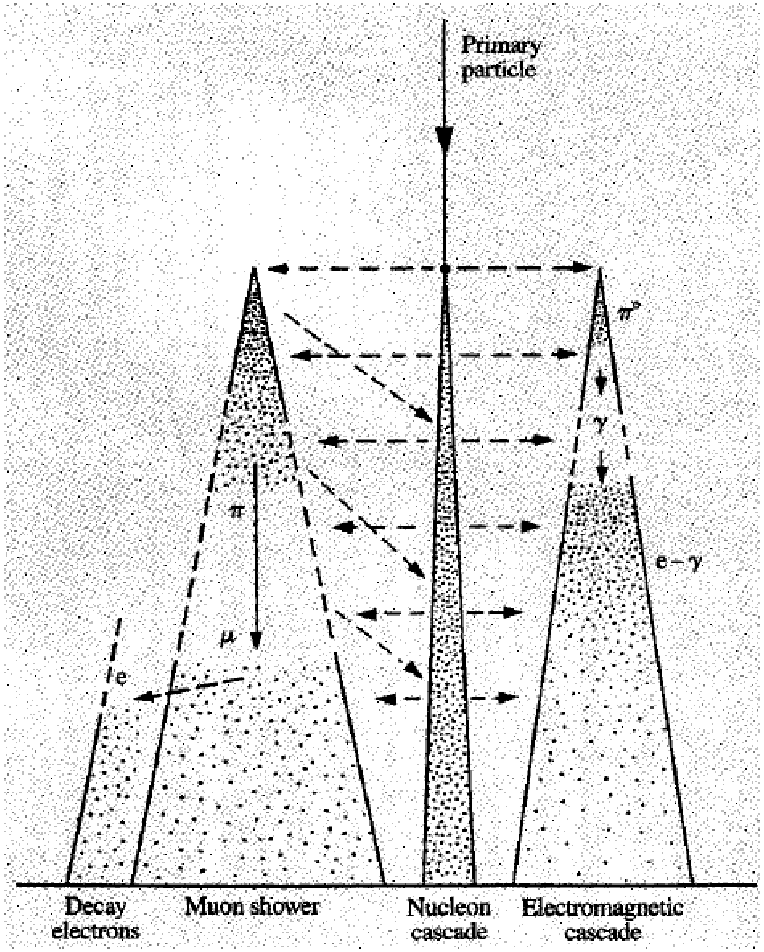


http://spp.astro.umd.edu/Rb_eduation/index.htm

Altitude Dependent Radiation Flux



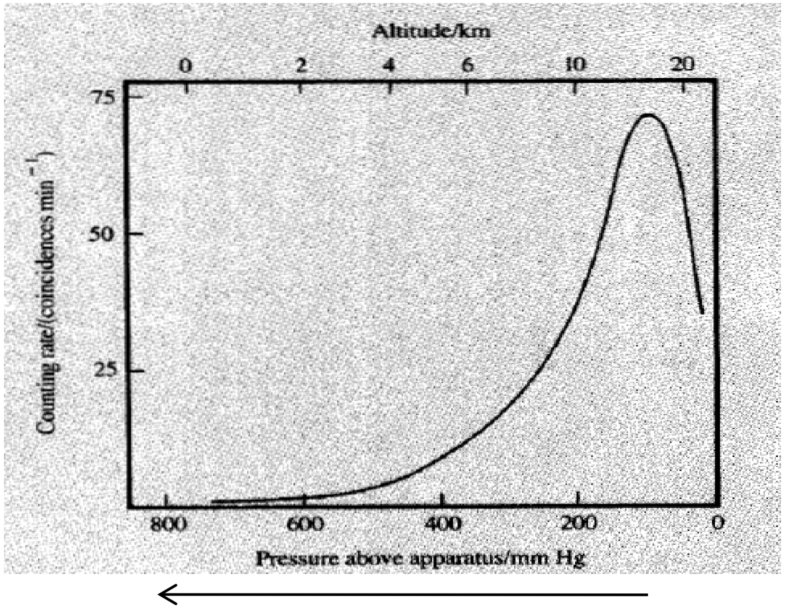




Original – Hess Nobel Prize

Full curve – Pfotzer curve

Altitude Dependent Radiation Flux



Empirical Model:

$$I_2 = I_1 \exp\left(\frac{A_1(@H_1 - A_2 @H_2}{L} \right)$$

$$A = 1033 - (0.03648H) + (4.26\times10^{-7} H^2)\ \text{g/cm}^2$$

$$L_e = 100\ \text{g/cm}^2, L_p = 110\ \text{g/cm}^2$$

$$L_n = 148\ \text{g/cm}^2, L_\mu = 520\ \text{g/cm}^2$$

Brian solid slab model:

Atomic weight 14.48
Atomic number 7.22
Ionization 92. 8 eV – reminiscent of Nitrogen

Bethe formula for energy loss:
dE/dx ~ ln(E)/E (see Lec. 38)

Example1: $Denver, H = 5280$ ft

$A_1(H = 0) = 1033$

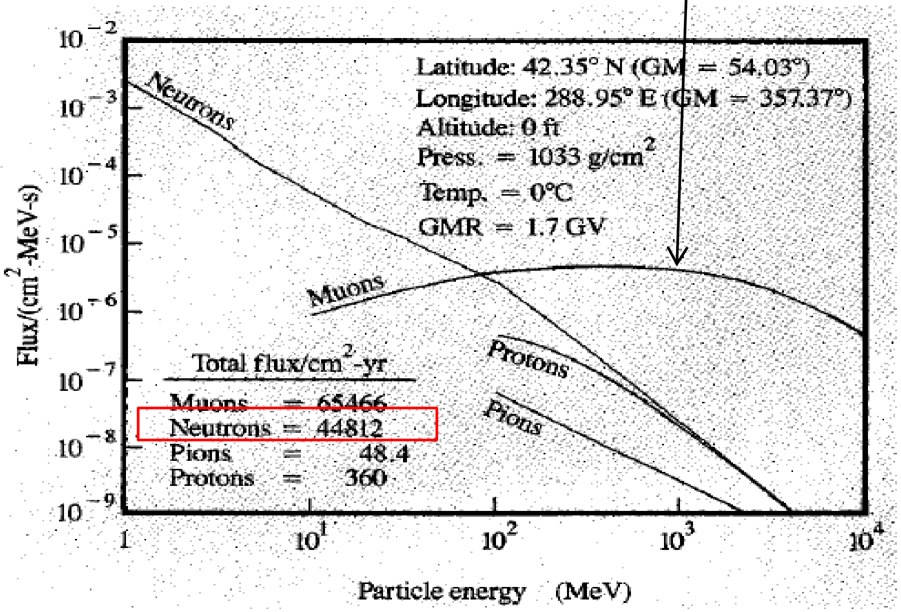
$A_2(H = 5280) = 862$

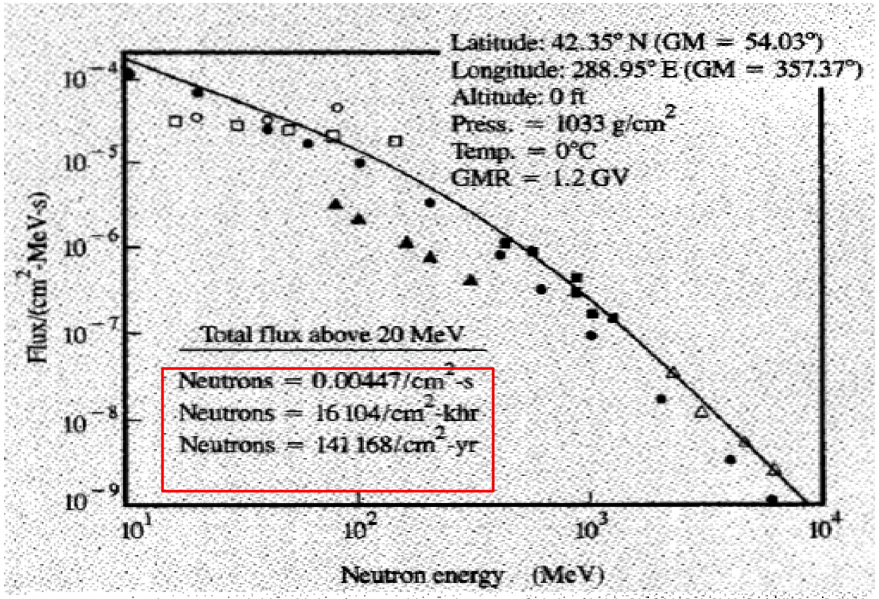
$I\,@5280\,ft = \exp(1033 - 862)/148) = 3.4$

Example2: At 1.5km (Airlines): 100x increase

Radiation Intensity at the Earth Level

Number is high, but cannot break anything (LET, dE/dx small)





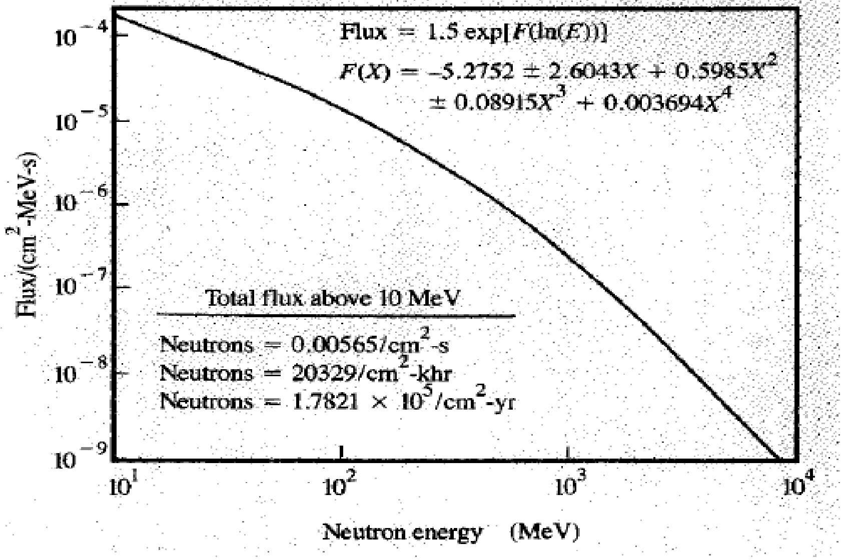
Empirical Model (Energy Distribution)

$$I_2 = I_1 \exp\left(\frac{A_1 - A_2}{L}\right) \times 1.5 \exp F(x) \quad x \equiv \ln E$$

$$F(x) \equiv -5.28 \pm 2.6x + 0.6x^2 \pm 0.09x^3 + 0.00369x^4$$

$$I_n(> 20\ \text{MeV}) = 0.5\text{-}1.5\text{x}10^5\ \text{cm}^{-2}\text{yr}^{-1}$$

$$I_\mu >> I_n \quad \text{but} \ \left(dE/dx\right)_\mu > \left(dE/dx\right)_n$$

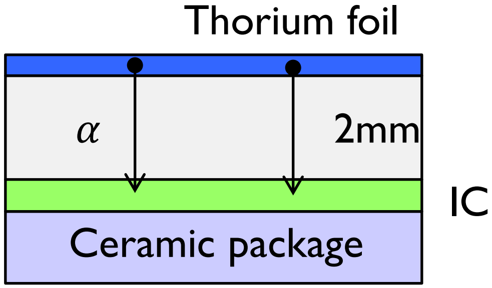


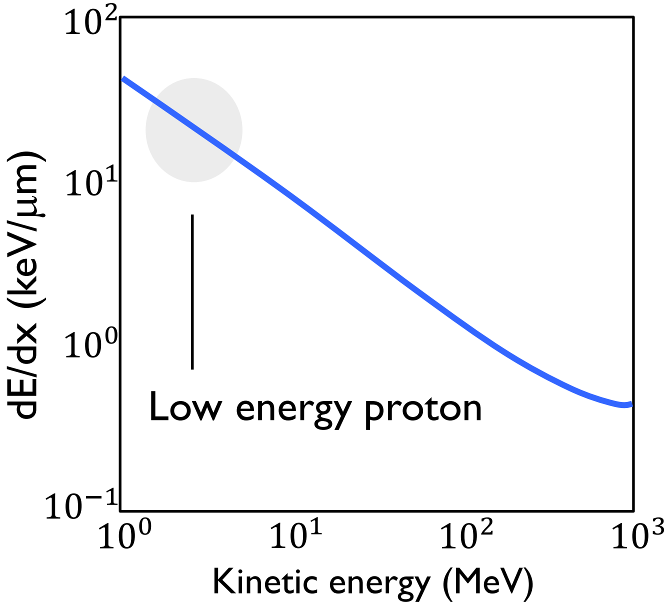
Sources of Radiation 3: Packaging

Earth Sources

Thermal Neutron in BPSG

Proton on Li – Thermal Neutron

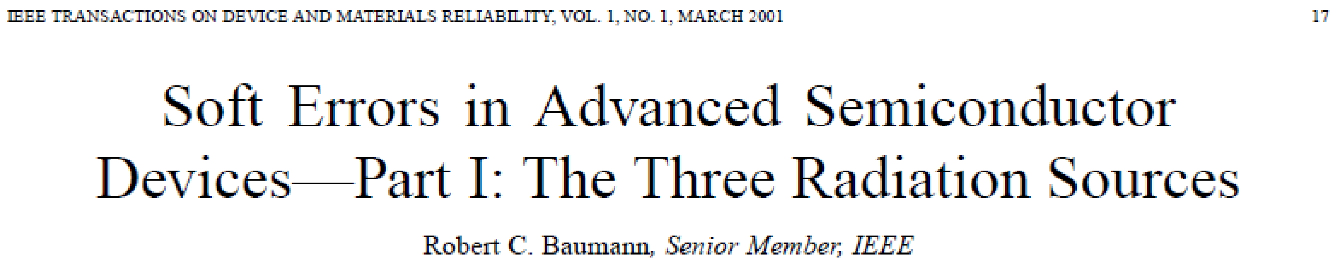




Alpha particle fluxes (#/cm^2-hr)	
Processed Wafers	0.0009
Cu Metal (thick)	0.0019
Al Metal (thick)	0.0014
Mold compound	0.024-0.002
Underfill	0.002-0.0009
Pb-solders	7.2-0.002
Ceramic package	0.0011

Slow particles from IC are devastating, previously did not survive

Sources of Radiation: Packaging



IEEE TRANSACTIONS ON DEVICE AND MATERIALS RELIABILITY, VOL. 1, NO. 1, MARCH 2001 17

Soft Errors in Advanced Semiconductor Devices—Part I: The Three Radiation Sources

Robert C. Baumann, *Senior Member, IEEE*

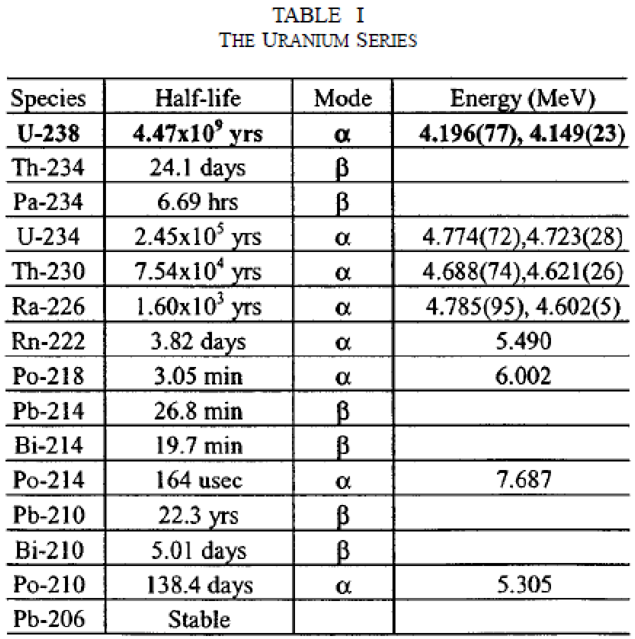


TABLE I
THE URANIUM SERIES

Species	Half-life	Mode	Energy (MeV)
U-238	**$4.47\text{x}10^9$ yrs**	**α**	**4.196(77), 4.149(23)**
Th-234	24.1 days	β	
Pa-234	6.69 hrs	β	
U-234	$2.45\text{x}10^5$ yrs	α	4.774(72),4.723(28)
Th-230	$7.54\text{x}10^4$ yrs	α	4.688(74),4.621(26)
Ra-226	$1.60\text{x}10^3$ yrs	α	4.785(95), 4.602(5)
Rn-222	3.82 days	α	5.490
Po-218	3.05 min	α	6.002
Pb-214	26.8 min	β	
Bi-214	19.7 min	β	
Po-214	164 usec	α	7.687
Pb-210	22.3 yrs	β	
Bi-210	5.01 days	β	
Po-210	138.4 days	α	5.305
Pb-206	Stable		

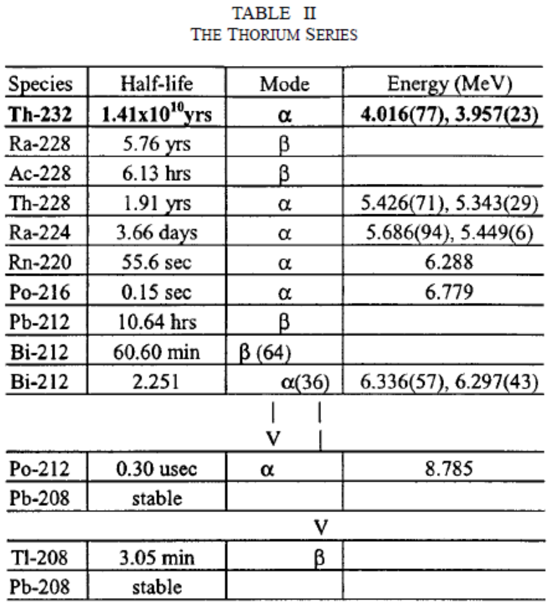
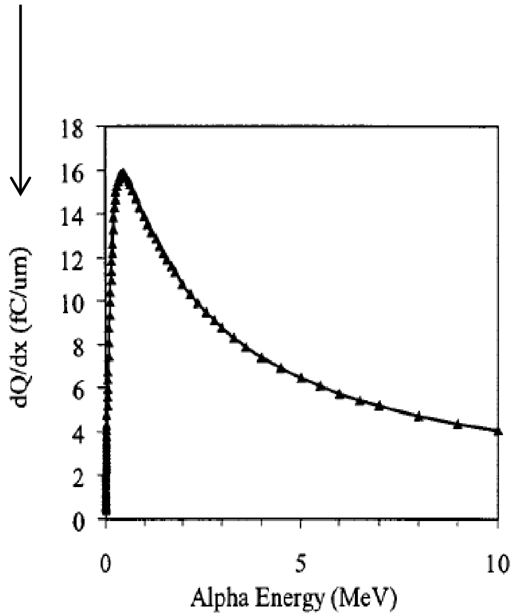


TABLE II
THE THORIUM SERIES

Species	Half-life	Mode	Energy (MeV)
Th-232	**$1.41\text{x}10^{10}$yrs**	**α**	**4.016(77), 3.957(23)**
Ra-228	5.76 yrs	β	
Ac-228	6.13 hrs	β	
Th-228	1.91 yrs	α	5.426(71), 5.343(29)
Ra-224	3.66 days	α	5.686(94), 5.449(6)
Rn-220	55.6 sec	α	6.288
Po-216	0.15 sec	α	6.779
Pb-212	10.64 hrs	β	
Bi-212	60.60 min	β (64)	
Bi-212	2.251	α(36)	6.336(57), 6.297(43)
		| |	
		V |	
Po-212	0.30 usec	α	8.785
Pb-208	stable		
		V	
Tl-208	3.05 min	β	
Pb-208	stable		

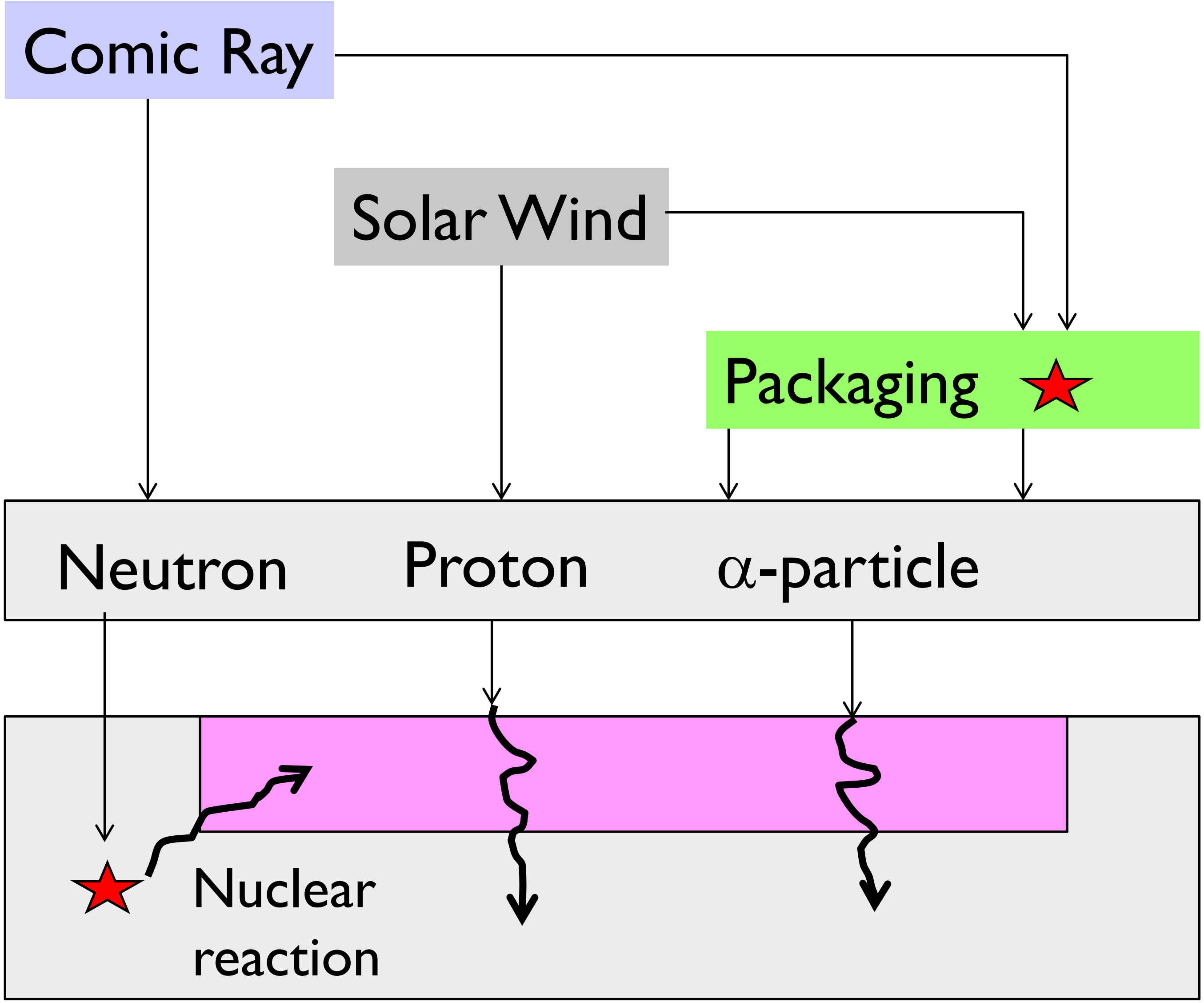
Charge generated



Outline

1. Sources of radiation
2. Charge generation and potential fluctuation
3. Junctions and critical charges
4. Conclusions

Outline



Comic Ray

Solar Wind

Packaging ★

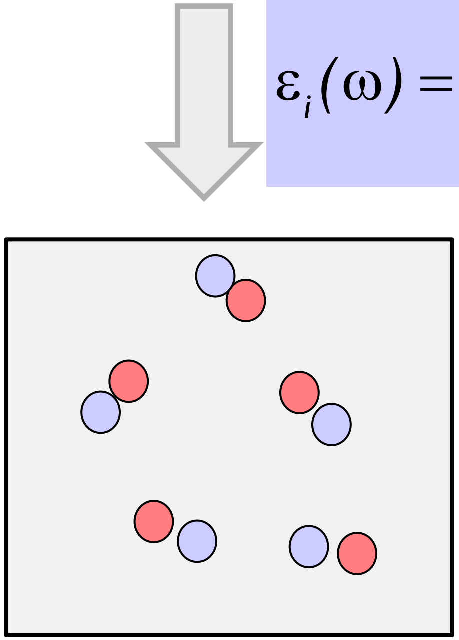
Neutron

Proton

α-particle

Nuclear reaction

Generation of Electron-Hole Pairs

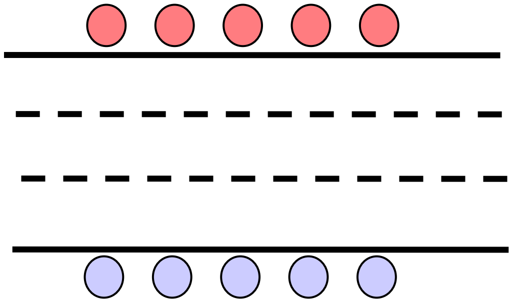


$$\varepsilon_i(\omega) = \frac{q^2 P_0^2 \sqrt{\mu(\hbar\omega - E_g)}}{\pi m_0^2 \omega^2 \hbar^3} \qquad P_0^2 = \frac{m_0 E_g}{2}\left(\frac{m_0}{m_c} - 1\right)\frac{3E_g + 3\Delta}{3E_g + 2\Delta}$$

$$n_{ph} = \frac{I_0(e^{-\alpha x} - 1)}{c'} = n = p$$

$$\alpha_{dir} = \frac{q^2 (2\mu)^{3/2} \sqrt{(\hbar\omega - E_g)}}{nch^2 m_e}$$

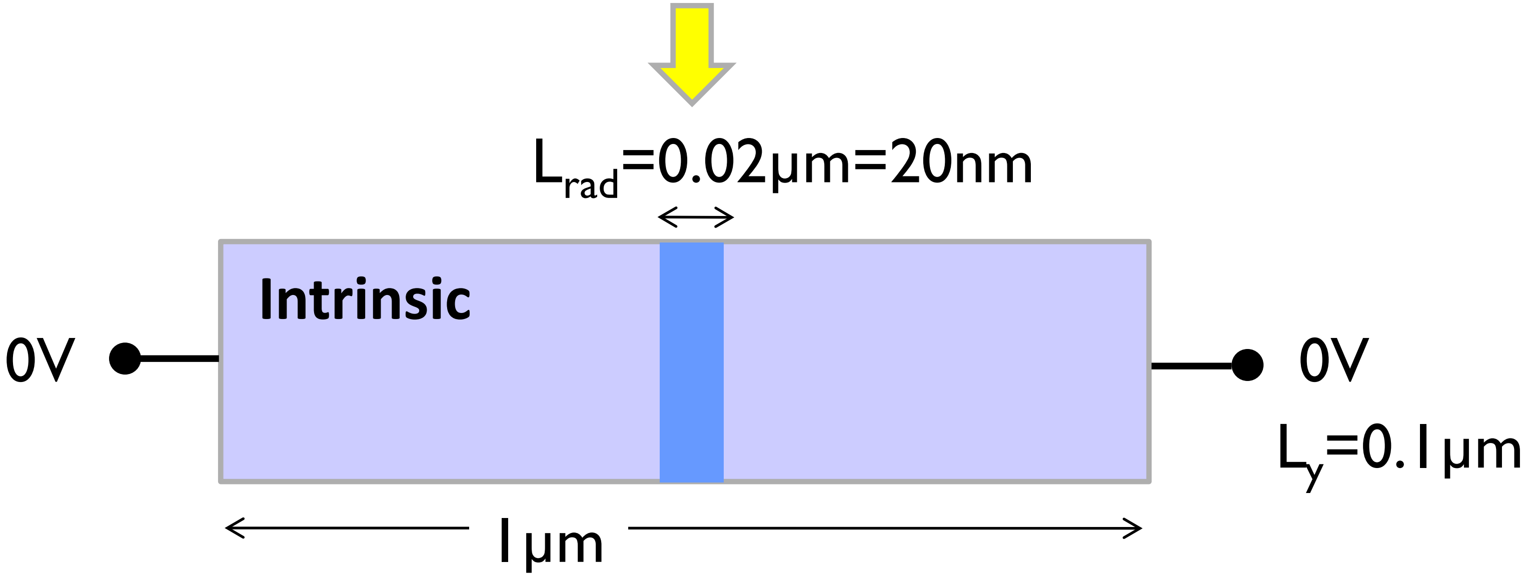
$$= 2 \times 10^4 \sqrt{(\hbar\omega - E_g)}\ cm^{-1}$$



$$\alpha_{indir} = \frac{4}{3}\frac{q^2 \mu^{5/2} (\hbar\omega - E_g)^{3/2}}{nch^2 m_e m_h h\nu}$$

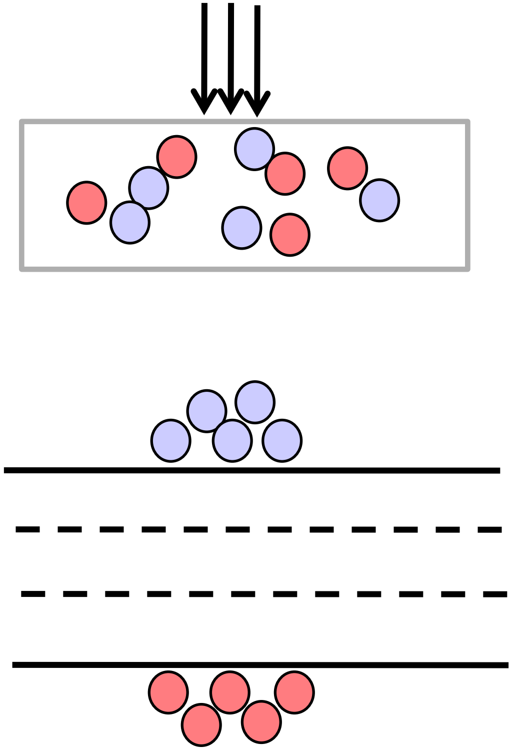
$$= 1.3 \times 10^4 \frac{(\hbar\omega - E_g)^{3/2}}{h\nu}\ cm^{-1}$$

Intrinsic structure: particle strike

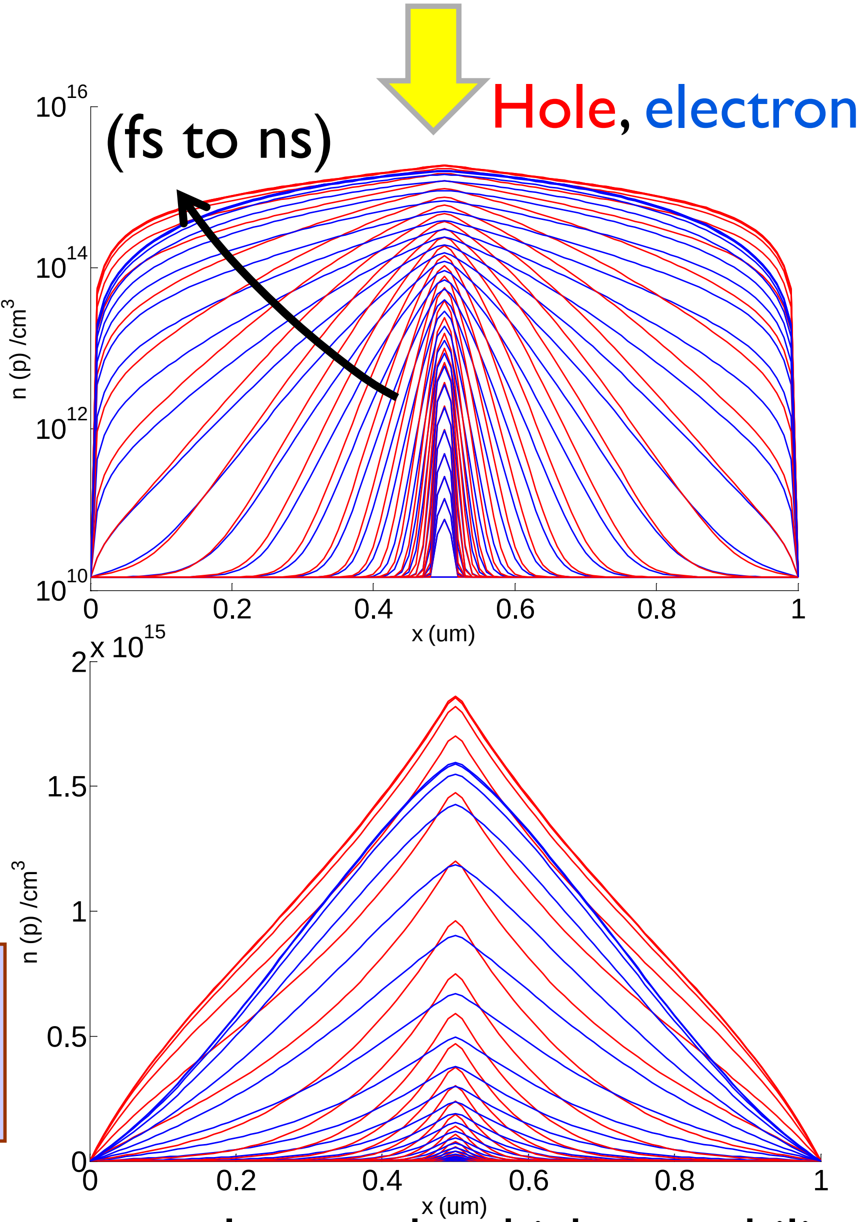


Assume that the incident flux is 1.6 fC/micron=10^{15}/sec/micron,
Or 10^{27} photon /cm^3/sec is the incident density
Flux= 10^{27}x0.1x10^{-4} =10^{22} photon /cm^2/sec
= 6.4 nC/cm^2/sec (same number of e-h pair)
n_i=10^{10} /cm^{3,} no recombination

Localized photo generated e-h pairs



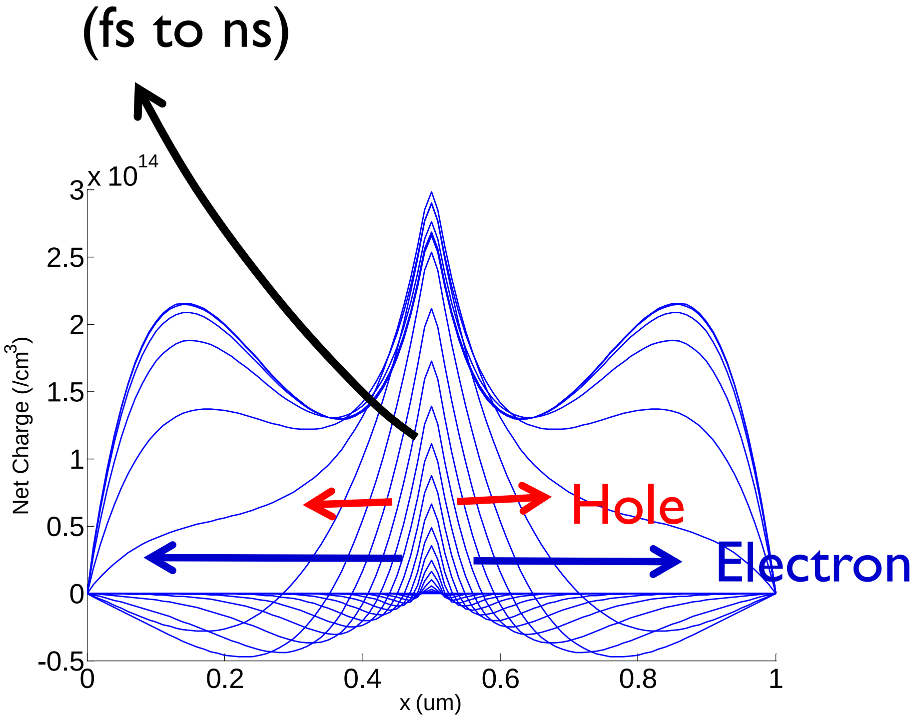
$$-\frac{d^2V}{dx^2}=\frac{dE}{dx}=\frac{q}{\varepsilon}\left(p-n+N_D-N_A\right)$$

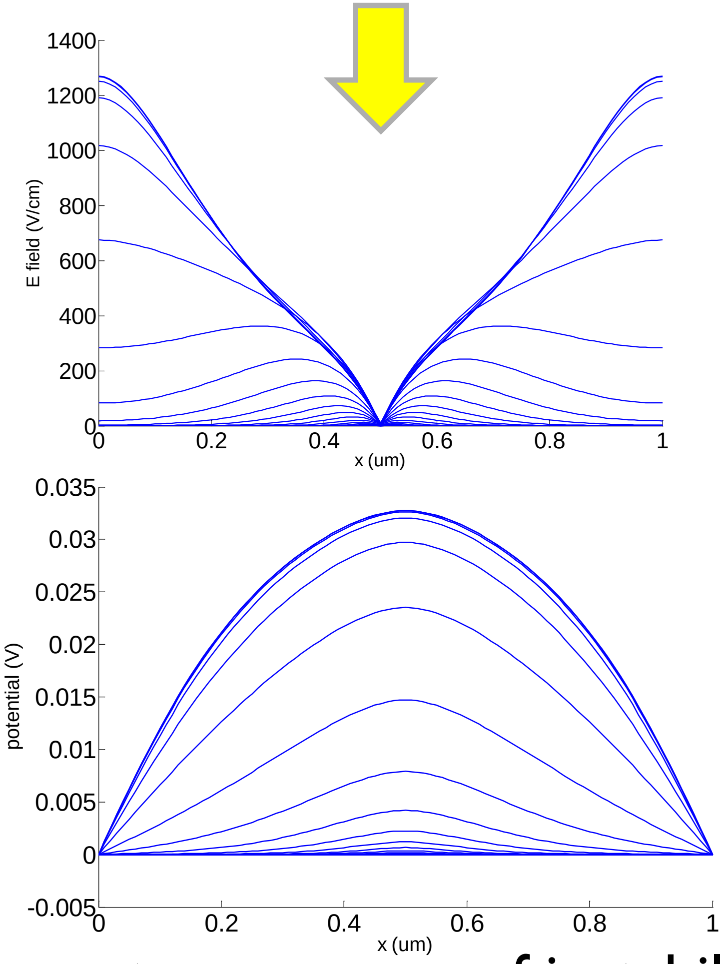


At steady state, more holes than electron, as electron has higher mobility

Importance of Electrostatics

$$-\frac{d^2V}{dx^2} = \frac{dE}{dx} = \frac{q}{\varepsilon}\left(p - n + N_D - N_A\right)$$





Dynamic charge separation in an importance source of instability …

Outline

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2. Charge generation and potential fluctuation
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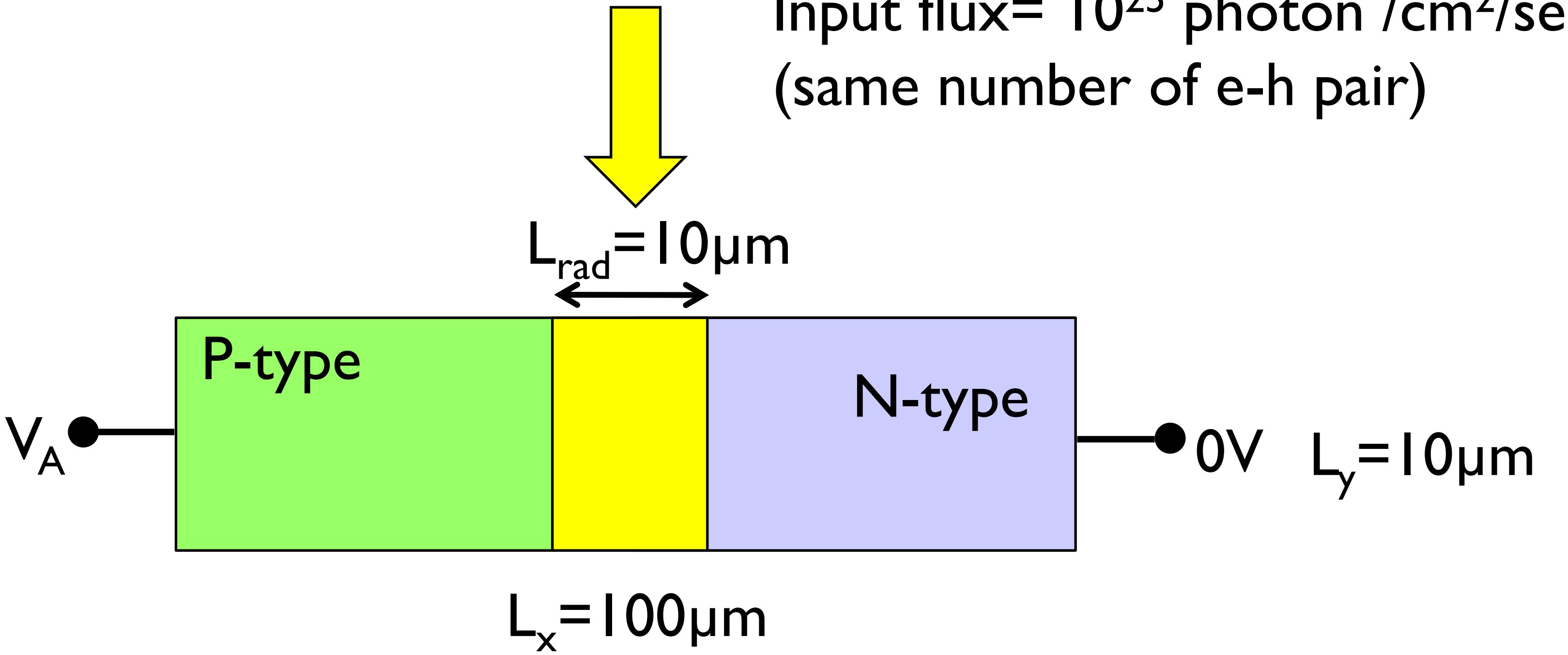
For p-n junction: even with very low lifetime

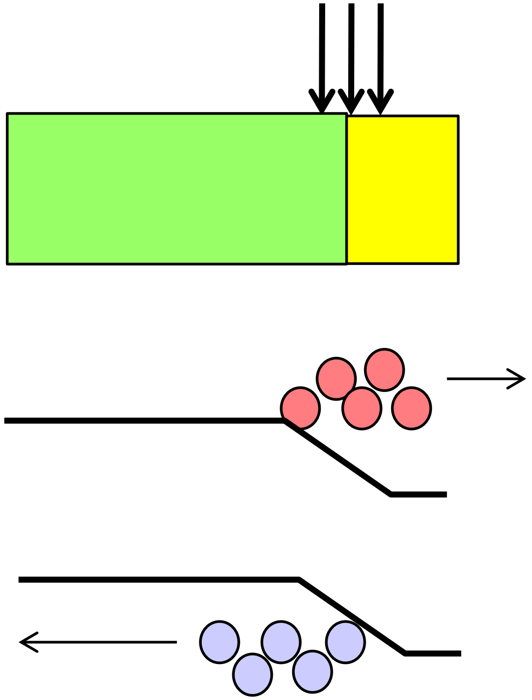
$G=10^{28}$ photon /cm^3/sec
Input flux= 10^{25} photon /cm^2/sec
(same number of e-h pair)

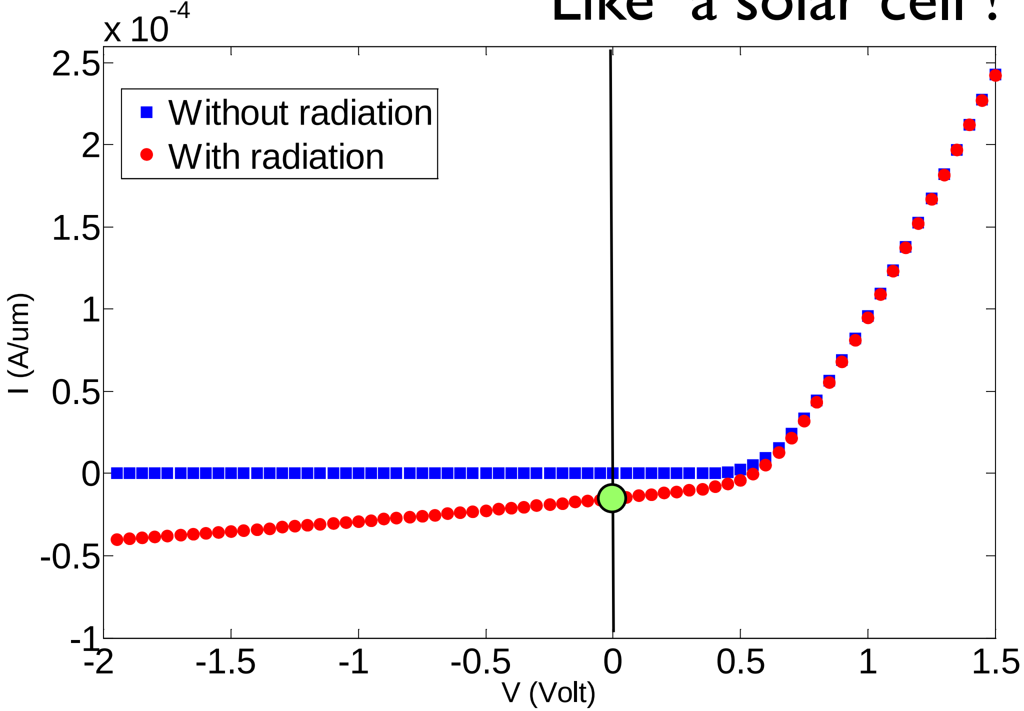


$N_A=N_D= 10^{18}$ /cm^3

Minority carrier lifetime, $\tau=10^{-12}$ sec
=> L_D (estimated) = $\sqrt{(6.5\text{cm}^2/\text{sec} * 10^{-12}\text{ sec})}$ ~0.025 μm

Photo generated e-h pairs at Junctions

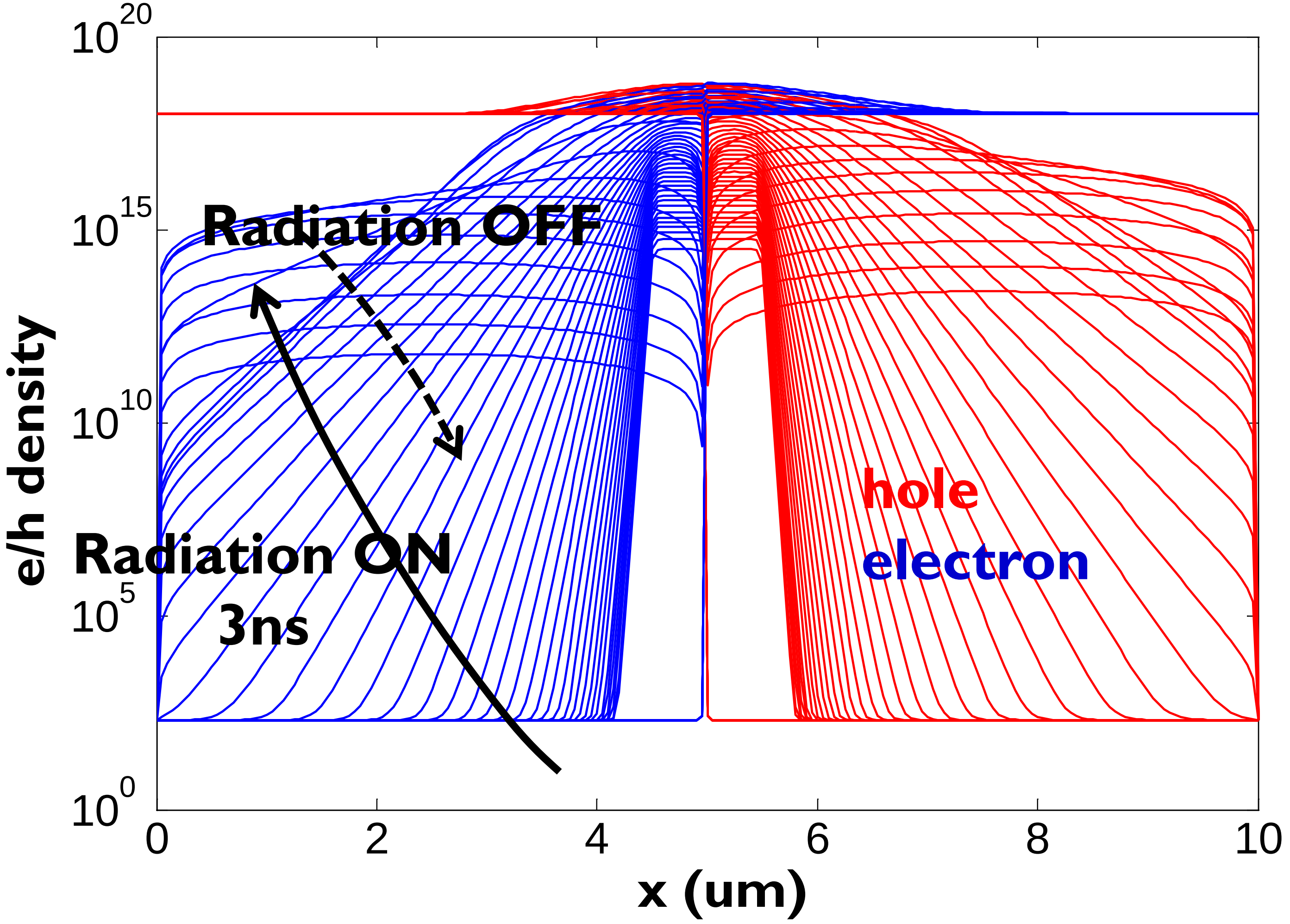




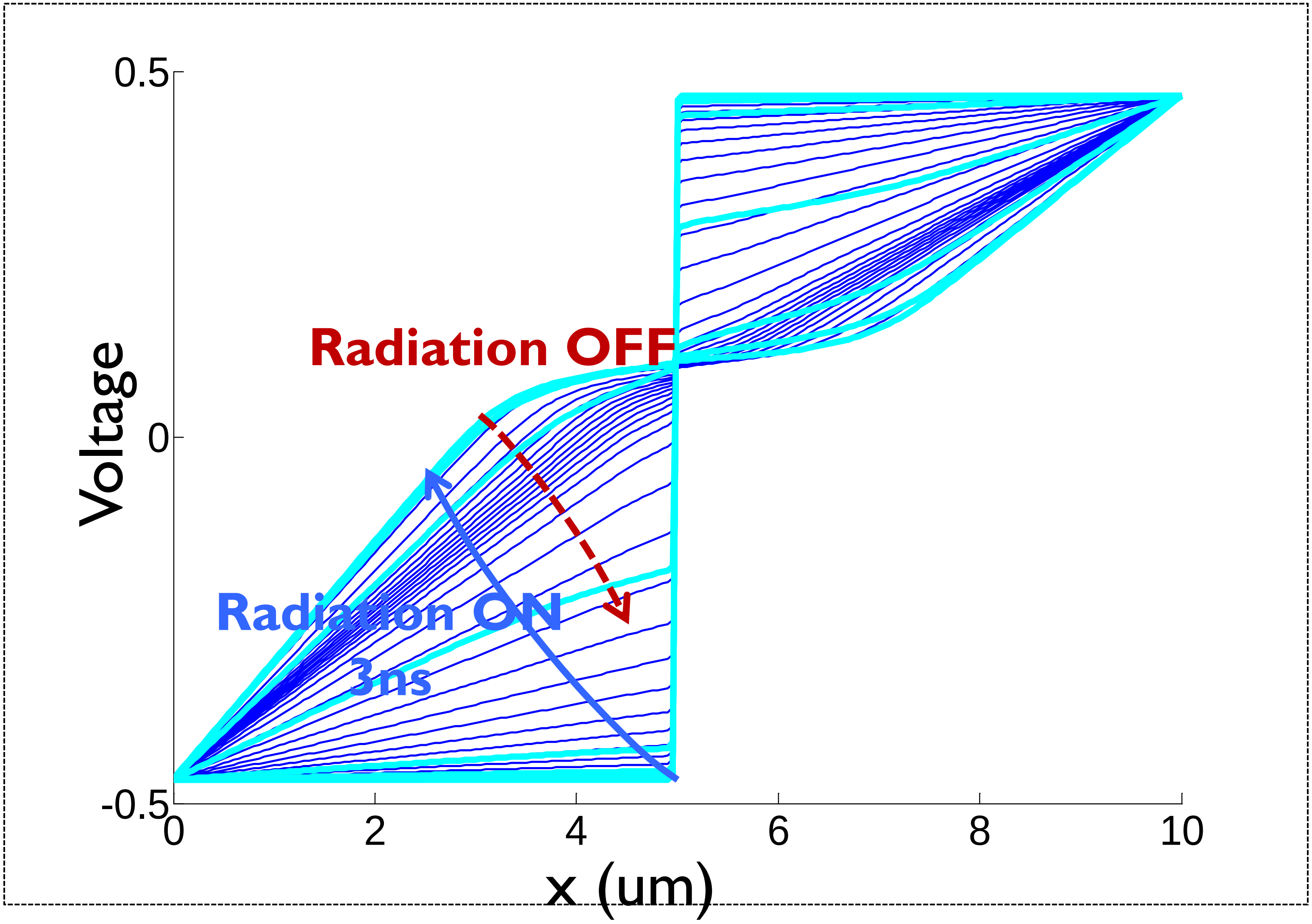
Like a solar cell !

$$-\frac{d^2V}{dx^2} = \frac{dE}{dx} = \frac{q}{\varepsilon}\left(p - n + N_D - N_A\right)$$

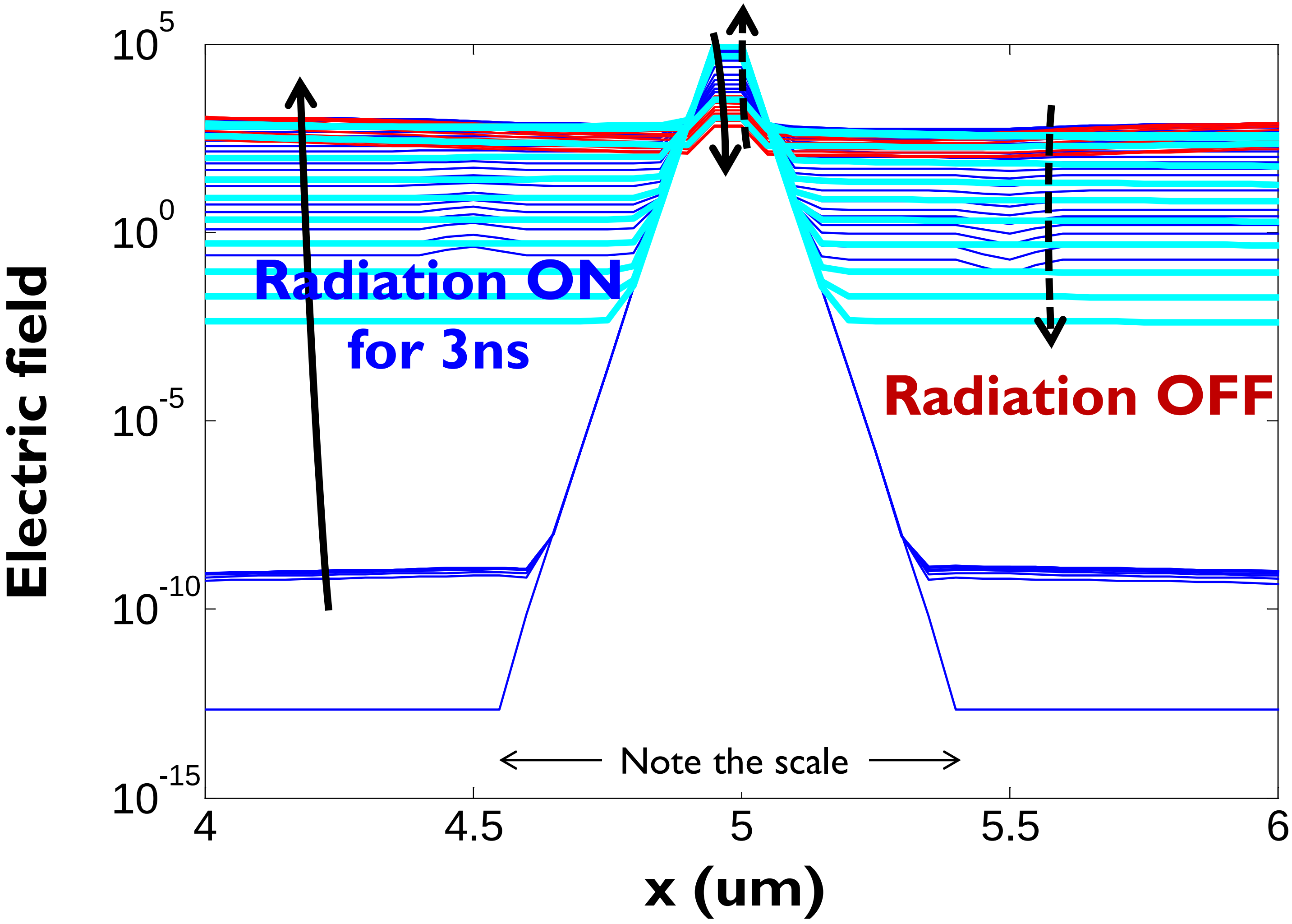
Electron/hole densities



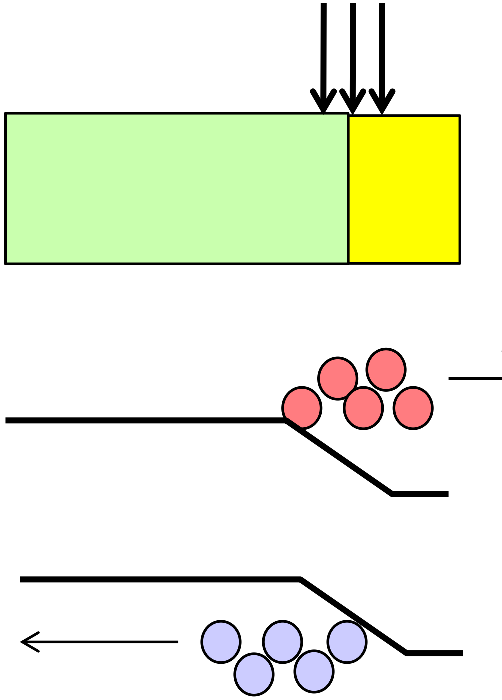
Potential before and after radiation

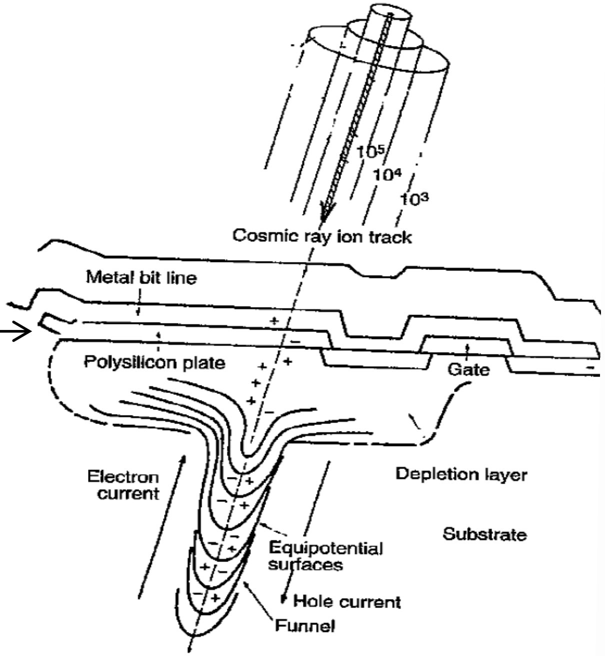


E- field before and after radiation



Critical Charge: Qcrit





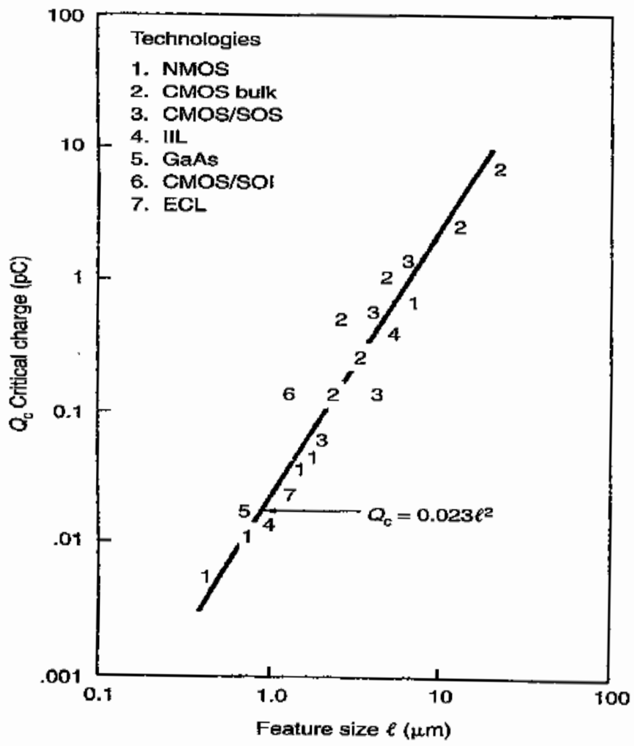


Fig. 7-15 Critical charge for SEU (Q_C) vs feature size in different devices. From E. L. Peterson and P. Marshall, *J. Rad. Eff. Res. and Eng.* (Jan 1989).

$$-\frac{d^2V}{dx^2}=\frac{dE}{dx}=\frac{q}{\varepsilon}\left(p-n+N_D-N_A\right)$$

Critical charge in devices

Circuit design and modeling for soft errors

A. KleinOsowski
E. H. Cannon
P. Oldiges
L. Wissel

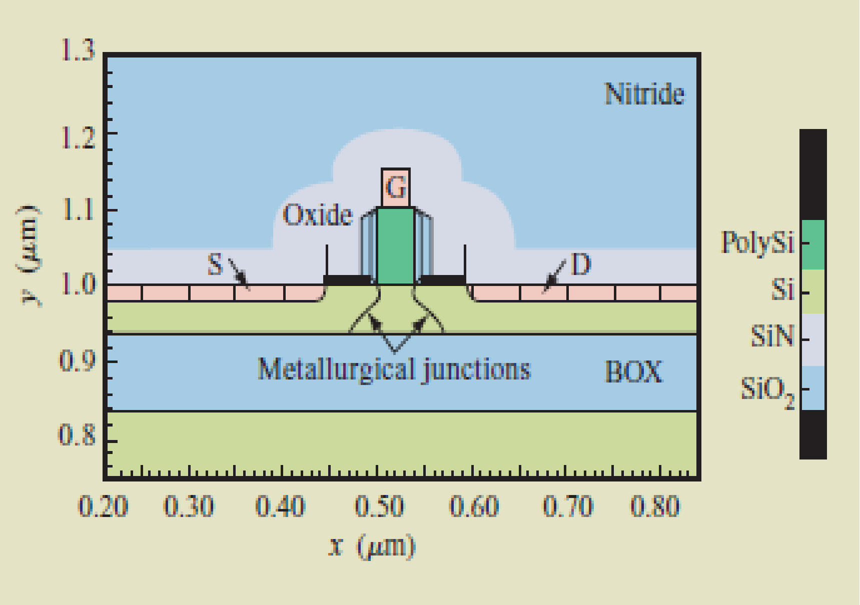


Figure 1

Modeled structure of a 65-nm SOI technology n-FET. (BOX: buried oxide.)

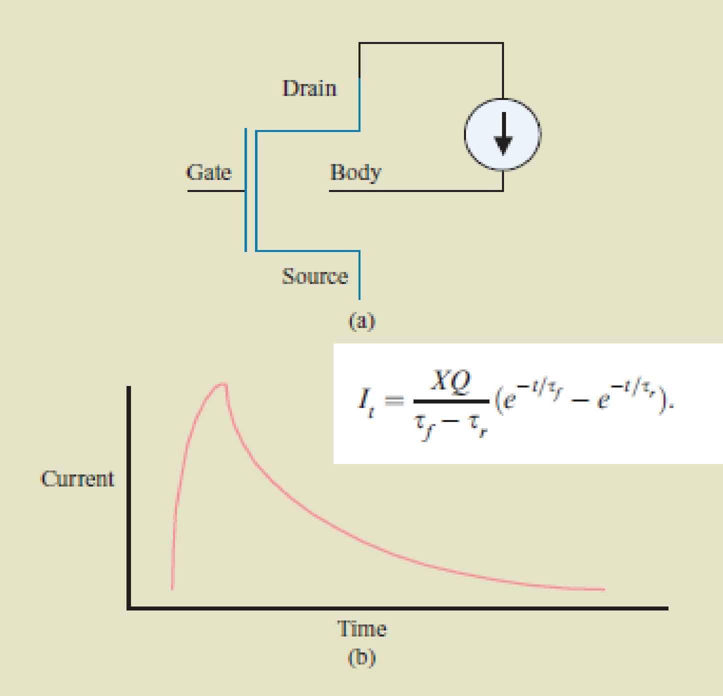


Figure 3

(a) Method for connecting injected current pulse into circuit simulation for SOI Q_{crit} modeling. (b) Current pulse wave shape used for circuit modeling.

Critical Charge in circuits

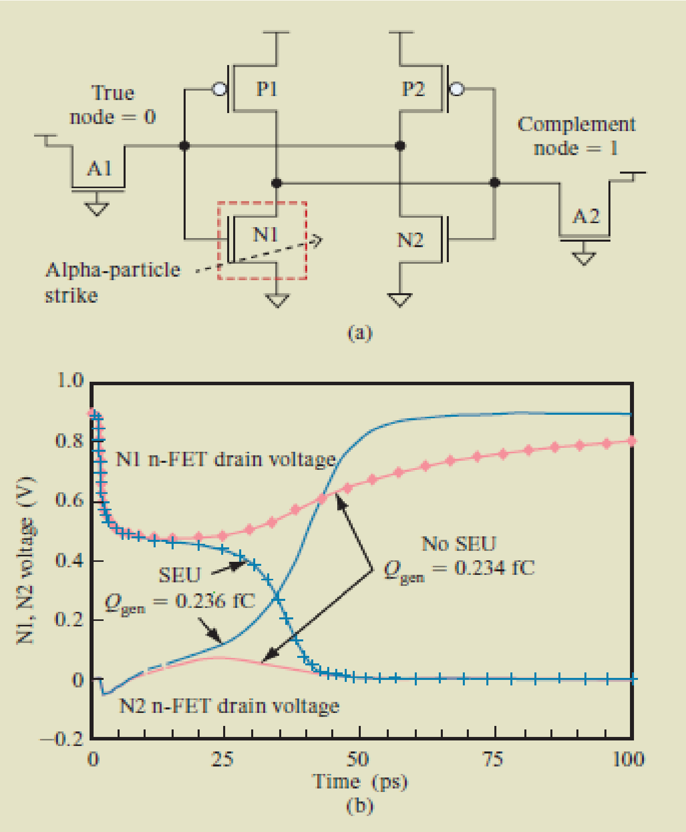


Figure 2

(a) Typical six-transistor SRAM circuit. (b) Evolution of the node voltages for an alpha-particle strike in an off-state n-FET pull-down device (N1) of a 65-nm SOI SRAM cell at V_{dd} = 0.9 V. (SEU: single-event upset.)

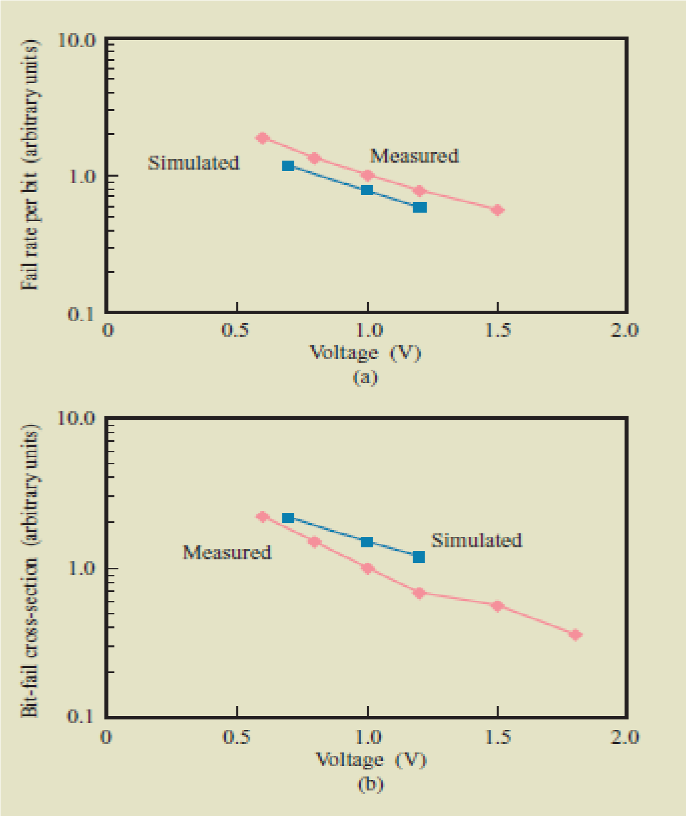


Figure 6

(a) Alpha-particle sensitivity for 90-nm bulk technology SRAM: measurements with a Th-232 foil and Monte Carlo simulations. (b) 150-MeV proton sensitivity for 90-nm bulk technology SRAM: measurements in a proton beam and Monte Carlo simulations. (Reproduced from [8].)

IBM J. RES. & DEV. VOL. 52 NO. 3 MAY 2008

Conclusions

1. Soft error is related to generation of electron-hole pairs that perturbs the electrostatics and temporarily destroys the logic state of the devices.

2. Soft error is reversible: memory can be rewritten; the logic state can be recomputed.

3. The asymmetry of electron hole transport (either due to difference in mobility, doping, or junction) that causes soft errors.

4. Soft errors can be mitigated by clever device design as well as redundant circuit approaches. The solutions are costly – therefore DARPA and NASA uses special radiation hardened components.

5. The story of Icarus and the role radiation damage!

References

R.C. Bauman wrote an wonderful review on packing related soft-errors, see Soft errors in Advanced Semiconductor Devices, TDMR, 1, 1, 2001.

IBM Journal of Research and Development has published two special issues on radiation induced damage. They contain wonderful sources of information.

The following book gives a very good introductory overview of the physics of soft errors" SER – History, Trends, and Challenges, A guide for designing with memory Ics, J. F. Ziegler and H. Puchner, Cypress. 2004.

A number of figures are taken from various sources:

http://www.meyerinst.com/html/oem/in-focus/default.htm (package)
Lfm.mit.edu (nuclear explosion)
http://www.military-heat.com/tag/jet/page/2/ (Fighter jet)
www.wired.com (Sun)

Iracus picture taken from http://wings.avkids.com/Book/Myth/Images/icarus_03.jpg

Review Questions

1. How does Earth's magnetic field deflect charged particles? What is its consequences for geography-specific radiation damage?

2. What is a Pfotzer curve. How is it used?

3. What does the isotropy of radiation say about the origin of galactic radiation sources?

4. A special type of high-energy particle was used to validate Einstein's theory of relativity. Are those particles radiation concern for ICs?

5. Nuclear reaction from *packaging* leads to large number of upsets. Why?

6. Can soft-error occur in a intrinsic CNT? Why or why not?

7. Define "critical charge". Is it a property of a device or a property of the radiation source?