Radiation Effects on Electronics

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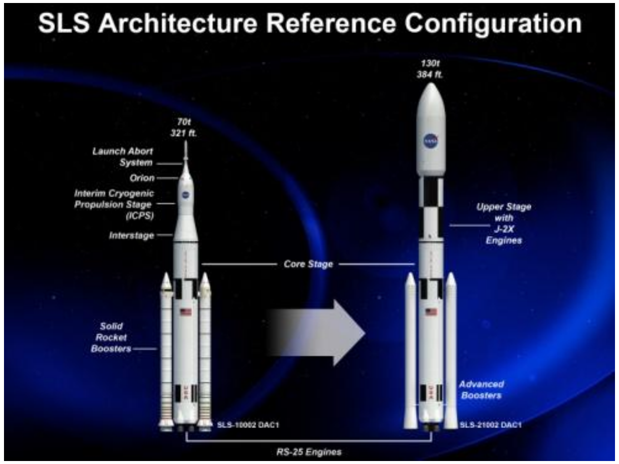
Support the Computing Needs of Space Exploration & Science

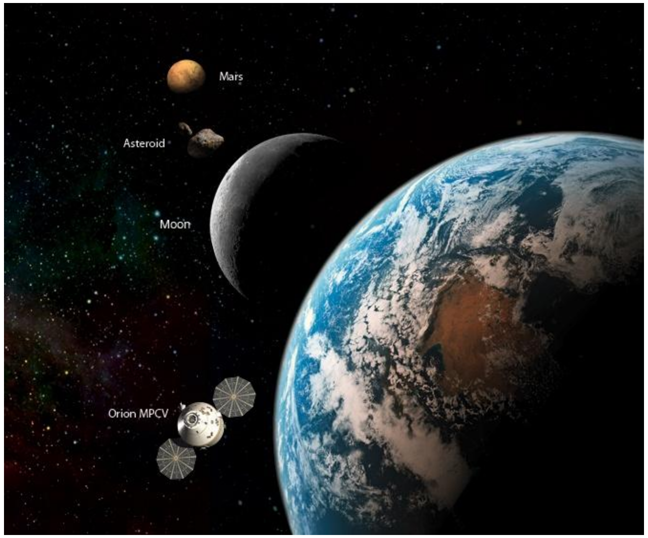
- Computation
- Power Efficiency
- Mass

Space Launch System (SLS)

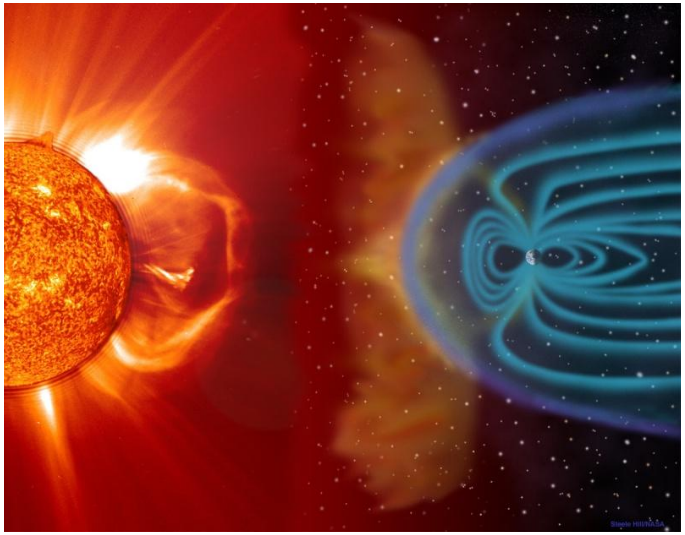


Provide a Radiation Tolerant Platform for Reconfigurable Computing

- Reconfigurable Computing as a means to provide:
  - Increased Computation of Flights Systems
  - Reduced Power of Flight Systems
  - Reduced Mass of Flight Hardware
  - Mission Flexibility through Real-Time Hardware Updates
- Support FPGA-based Reconfigurable Computing through an underlying architecture with inherent radiation tolerance to Single Event Effects



The Future



The Problem

Radiation Effects on Electronics

On Earth Our Computers are Protected

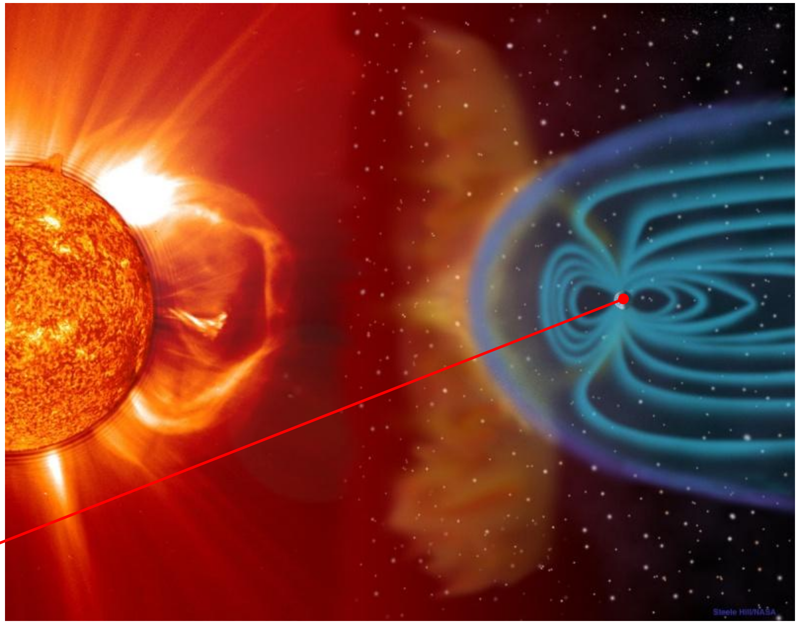
- Our magnetic field deflects the majority of the radiation
- Our atmosphere attenuates the radiation that gets through our magnetic field

Our Satellites Operate In Trapped Radiation in the Van Allen Belts

- High flux of trapped electrons and protons

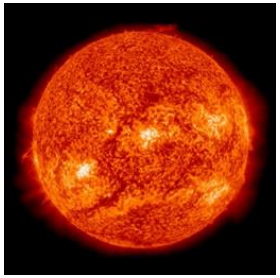
In Deep Space, Nothing is Protected

- Radiation from our sun
- Radiation from other stars
- Particles & electromagnetic



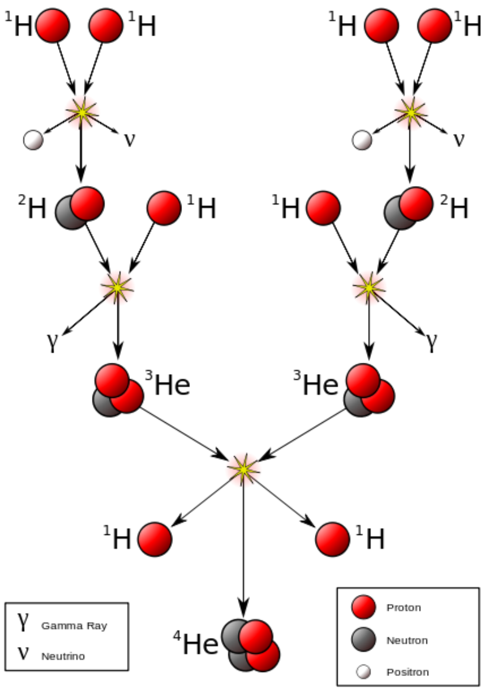
You Are Here

Where Does Space Radiation Come From?



- Nuclear fusion in stars creates light and heavy ions + EM
- Stars consists of an abundant amount of Hydrogen (^{1}H = 1 Proton) at high temperatures held in place by gravity

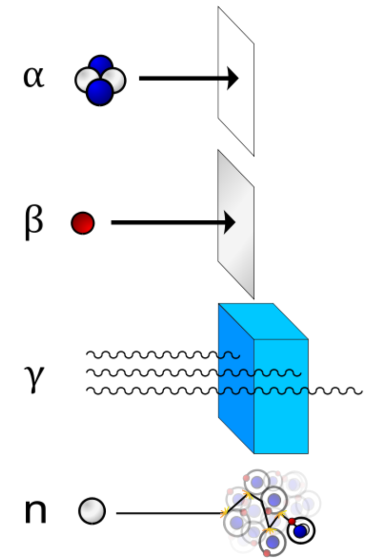
1. The strong nuclear force pulls two Hydrogen (^{1}H) atoms together overcoming the Columns force and fuses them into a new nucleus
   - The new nucleus contains 1 proton + 1 neutron
   - This new nucleus is called *Deuterium (D) or Heavy Hydrogen* (^{2}H)
   - Energy is given off during this reaction in the form of a Positron and a Neutrino
2. The Deuterium (^{2}H) then fuses with Hydrogen (^{1}H) again to form yet another new nucleus
   - This new nucleus contains 2 protons + 1 neutron
   - This nucleus is called *Tritium* or Hydrogen-3 (^{3}H)
   - Energy is given off during this reaction in the form of a Gamma Ray
3. Two Tritium nuclei then fuse to form a Helium nucleus
   - The new Helium nucleus (^{4}H) contains 2 protons + 2 neutrons
   - Energy is given off in the form of Hydrogen (e.g., protons)



Radiation Effects on Electronics

Radiation Categories

1. Ionizing Radiation
   - Sufficient energy to remove electrons from atomic orbit
   - Ex. High energy photons, charged particles
2. Non-Ionizing Radiation
   - Insufficient energy/charge to remove electrons from atomic orbit
   - Ex., microwaves, radio waves

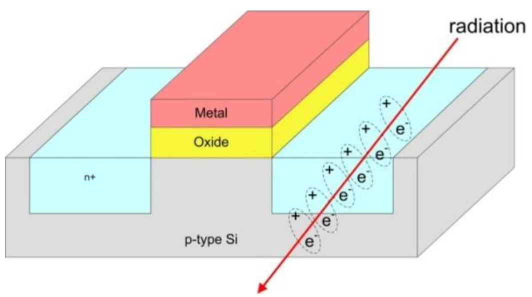


Types of Ionizing Radiation

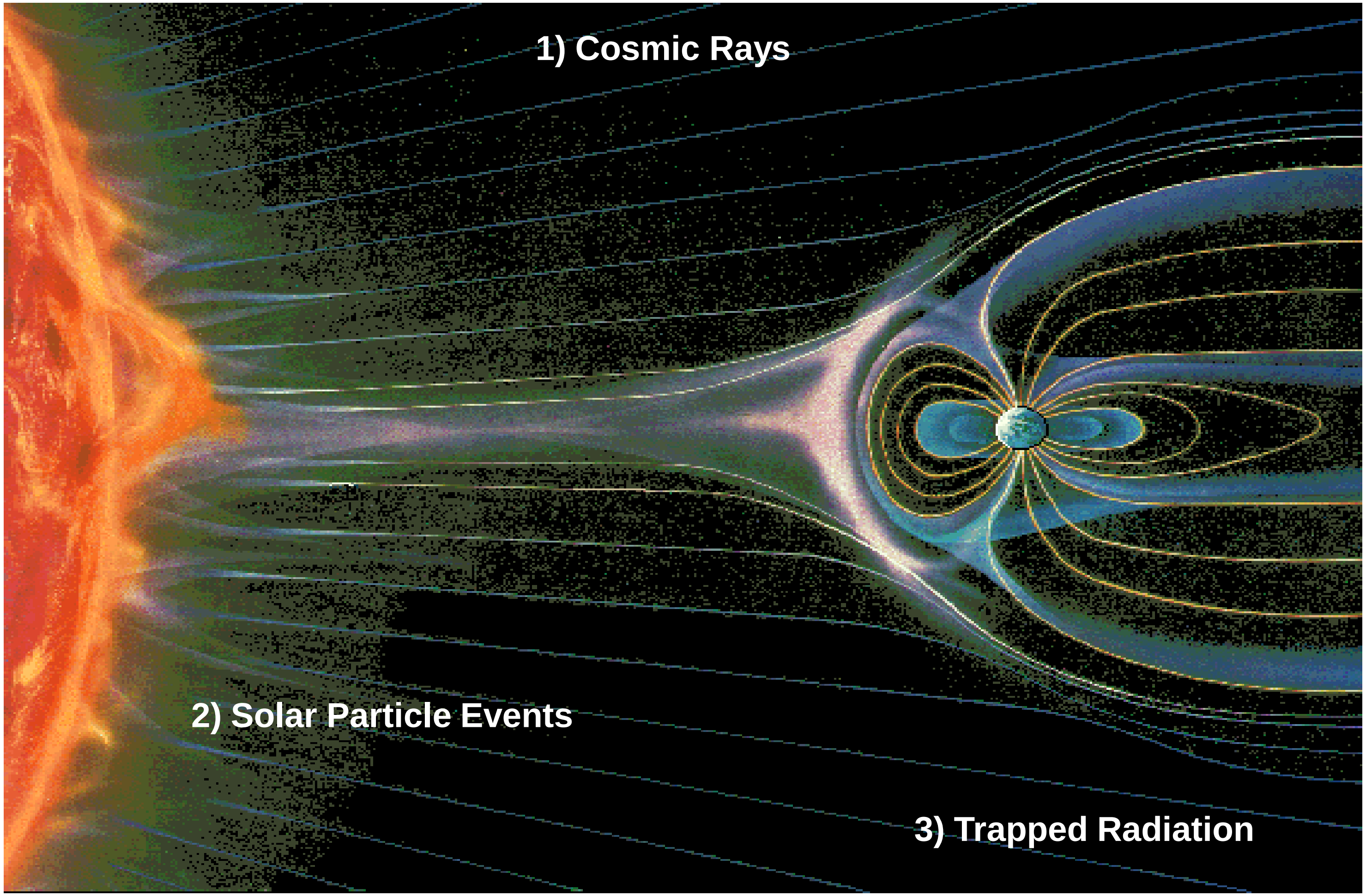
1. Gamma & X-Rays (photons)
   - Sufficient energy in the high end of the UV spectrum
2. Charged Particles
   - Electrons, positrons, protons, alpha, beta, heavy ions
3. Neutrons
   - No electrical charge but ionize indirectly through collisions

What Type are Electronics Sensitive To?

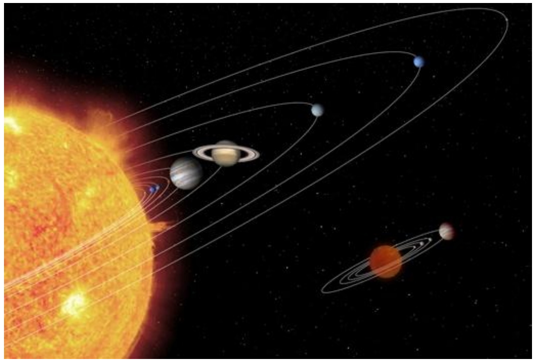
- Ionization which causes electrons to be displaced
- Particles which collide and displace silicon crystal

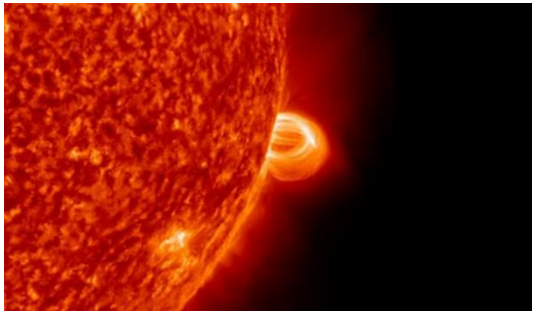


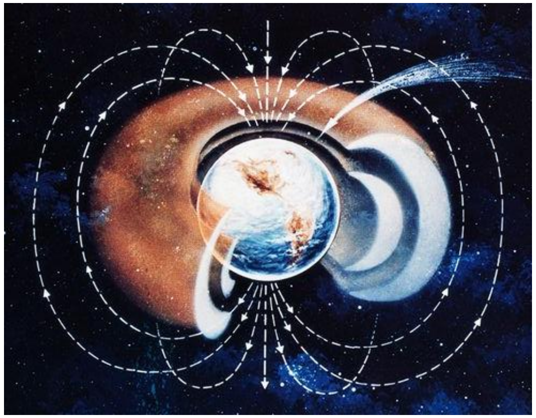
Classes of Ionizing Space Radiation



Classes of Ionizing Space Radiation







1. Cosmic Rays
   - Originating for our sun (Solar Wind) and outside our solar system (Galactic)
   - Mainly Protons and heavier ions
   - Low flux

2. Solar Particle Events
   - Solar flares & Coronal Mass Ejections
   - Electrons, protons, alpha, and heavier ions
   - Event activity tracks solar min/max 11 year cycle

3. Trapped Radiation
   - Earth's Magnetic Field traps charged particles
   - Inner Van Allen Belt holds mainly protons (10-100's of MeV)
   - Outer Van Allen Belt holds mainly electrons (up to ~7 MeV)
   - Heavy ions also get trapped

Which radiation is of most concern to electronics?

Concern

- Protons (^{1}H)
  - Makes up ~85% of galactic radiation
  - Larger Mass than electron (1800x), harder to deflect
- Beta Particles (electrons & positrons)
  - Makes up ~1% of galactic space
  - More penetrating than alphas
- Heavy Ions
  - Makes up <1% of galactic radiation
  - High energy (up to GeV) so shielding is inefficient
- Neutrons
  - Uncharged so difficult to stop

No Concern

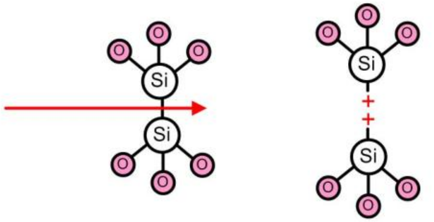
- Alpha Particles (He nuclei)
  - Makes up ~14% of galactic radiation
  - ~ 5MeV energy level & highly ionizing but…
  - Low penetrating power (50mm in air, 23um in silicon)
  - Can be stopped by a sheet of paper
- Gamma
  - Highly penetrating but an EM wave
  - Lightly ionizing

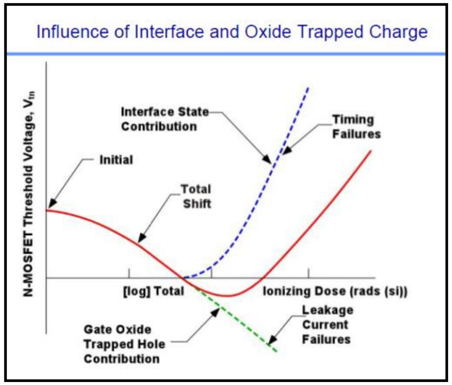
What are the Effects?

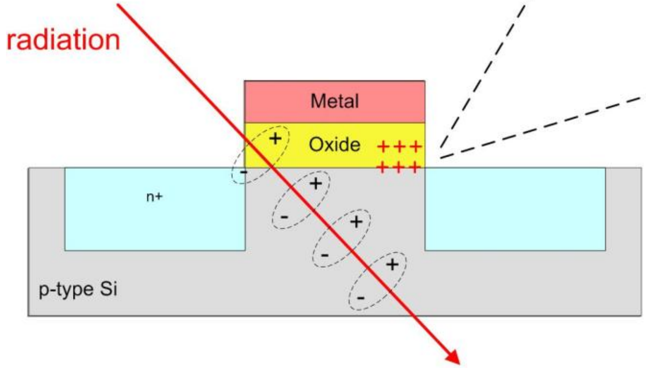
1. Total Ionizing Dose (TID)
    - Cumulative long term damage due to ionization.
    - Primarily due to low energy protons and electrons due to higher, more constant flux, particularly when trapped
    - Problem #1 – Oxide Breakdown
        - » Threshold Shifts
        - » Leakage Current
        - » Timing Changes

Hole Trapping

- EHP formed by ionization
- Electrons recombine quicker due to faster mobility
- Holes get "stuck" due to lower mobility
- Lowers Vt by effectively "thinning" the oxide
- Vt eventually goes negative turning on MOS

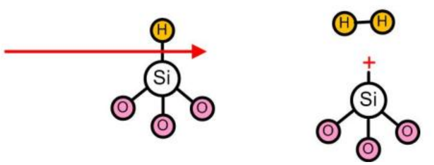






Interface Trapping

- The Si/Si02 interface typically contains Si/H bonds
- This is due to the annealing process in hydrogen
- When this bond is severed, H will bond with itself
- This leaves a dangling Si bond with net positive charge
- This initially lowers Vt and then ultimately raises it.



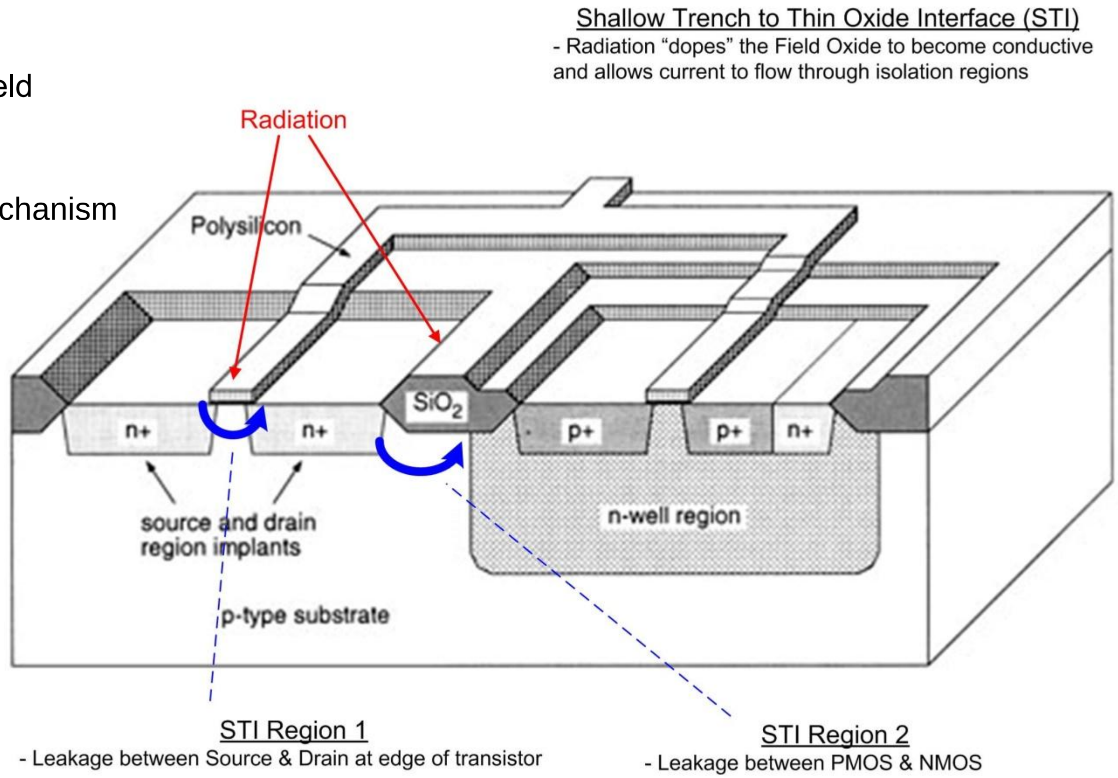
What are the Effects?

1. Total Ionizing Dose (TID) Cont…

   - Problem #2 –Leakage Current

     » Hole trapping slowly "dopes" field oxides to become conductive

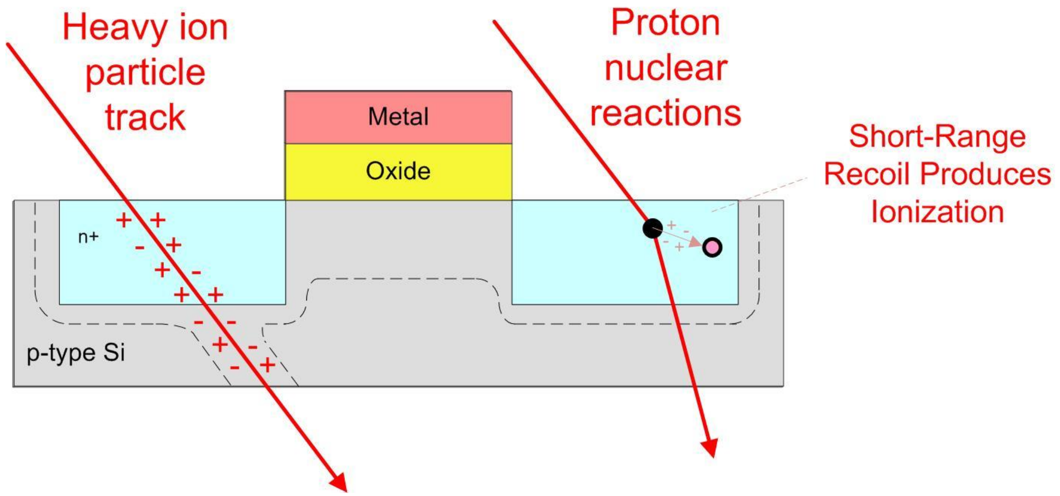
     » This is the dominant failure mechanism for commercial processes



What are the Effects?

2. Single Event Effects (SEE)
   - Electron/hole pairs created by a single particle passing through semiconductor
   - Primarily due to heavy ions and high energy protons
   - Excess charge carriers cause current pulses
   - Creates a variety of destructive and non-destructive damage
   - The ionization *itself* does not cause damage, the damage is secondary due to parasitic circuits

"Critical Charge" = the amount of charge deposited to change the state of a gate

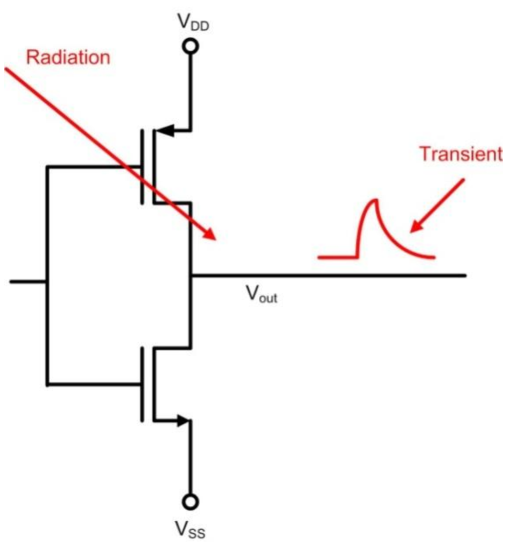


What are the Effects?

2. Single Event Effects (SEE) - **Non-Destructive** (e.g., soft faults)

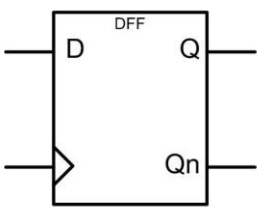
Single Event Transients (SET)

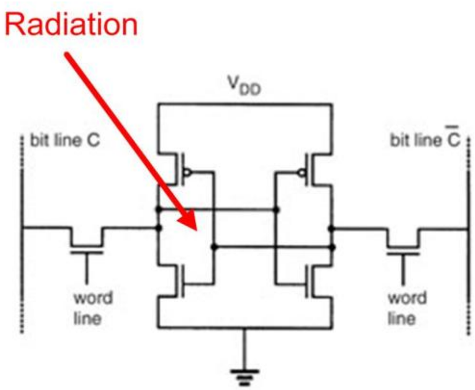
- An induced pulse that can flip a gate
- Temporary glitches in combinational logic



Single Event Upsets (SEU)

- The pulse is captured by a storage device resulting in a state change





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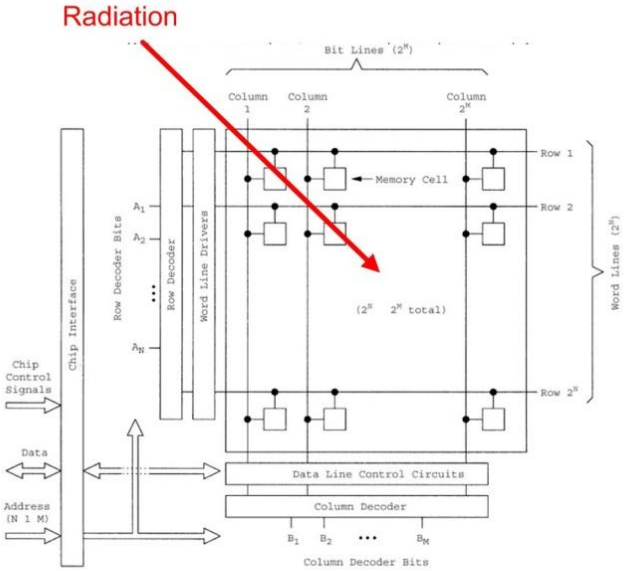
What are the Effects?

2. Single Event Effects (SEE) - **Non-Destructive** (e.g., soft faults)

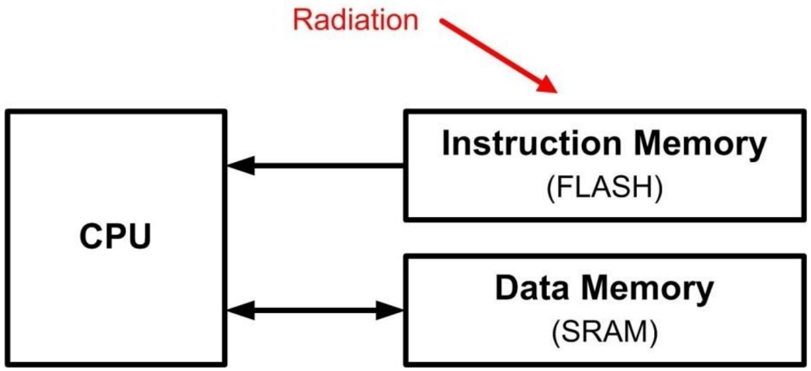
Multiple Bit Upsets (MBU)

- A single particle causes multiple SEUs due to its path being non-orthogonal



Single Event Functional Interrupt (SEFI)

- The system is put into a state that causes function failure
- Typically requires reset, power cycle or reprogramming

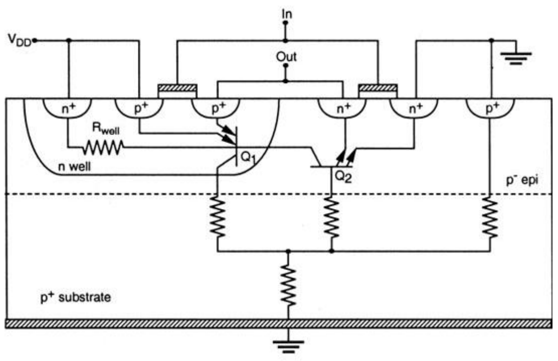


What are the Effects?

2. Single Event Effects (SEE) – **Destructive** (e.g., hard faults)

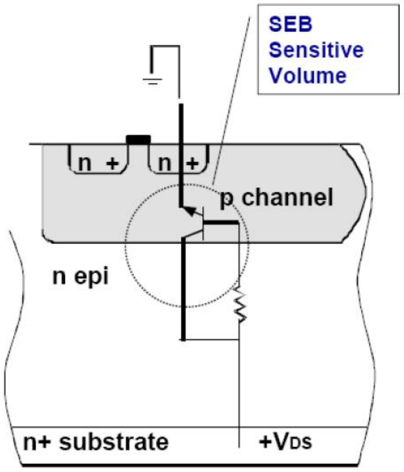
Single Event Latchup (SEL)

- Parasitic NPN/PNP transistors are put into positive feedback condition (PNPN).
- Runaway current damages device
- Due to heavy ions, protons, neutrons.



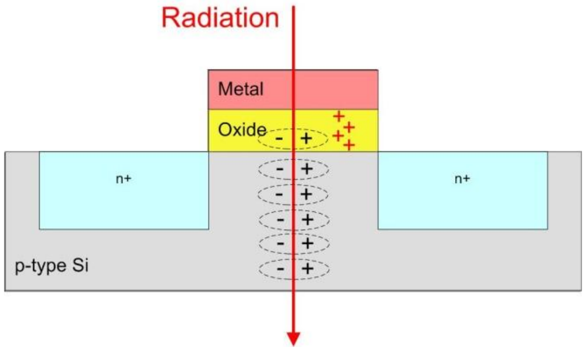
Single Event Burnout (SEB)

- Localized current in body of device turns on parasitic bipolar transistors.
- Runaway current causes heat.
- Due primarily to heavy ions.



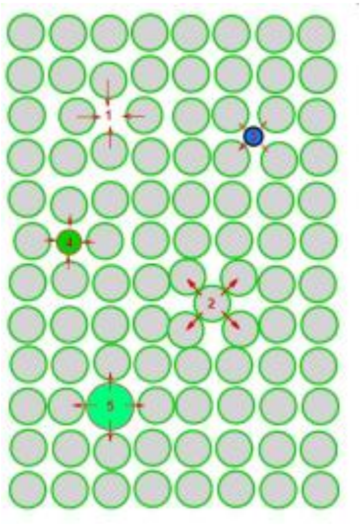
Single Event Gate Rupture (SEGR)

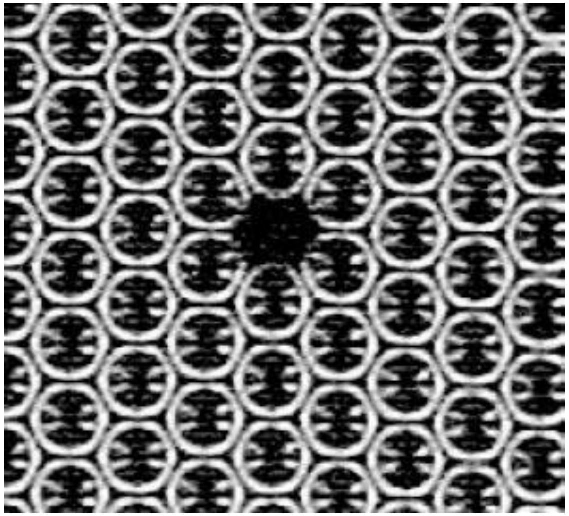
- Permanent short through gate oxide due to hole trapping.
- Thin oxides are especially immune.
- Due to heavy ions.

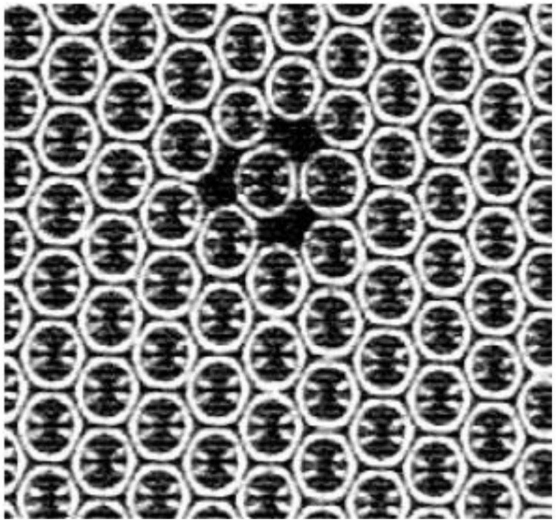


What are the Effects?

3. Displacement Damage
   - Cumulative long term damage to protons, electrons, and neutrons
   - Not an ionizing effect but rather collision damage
   - Minority Carrier Degradation
     - Reduced gain & switching speed
     - Particularly damaging for optoelectronic & linear circuits





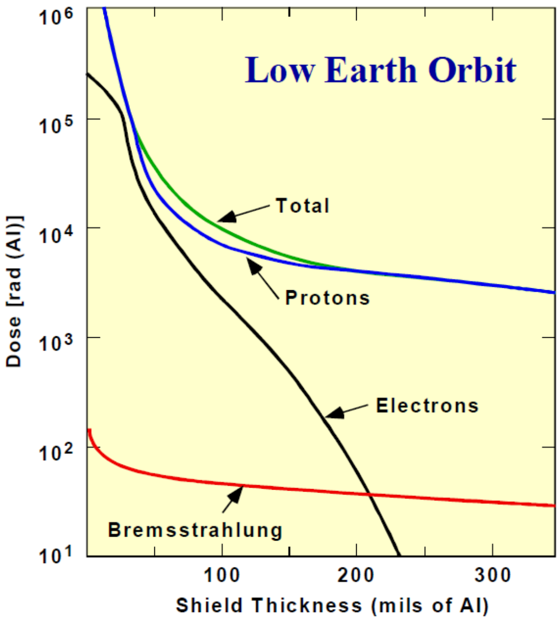


Current Mitigation Techniques

Shielding

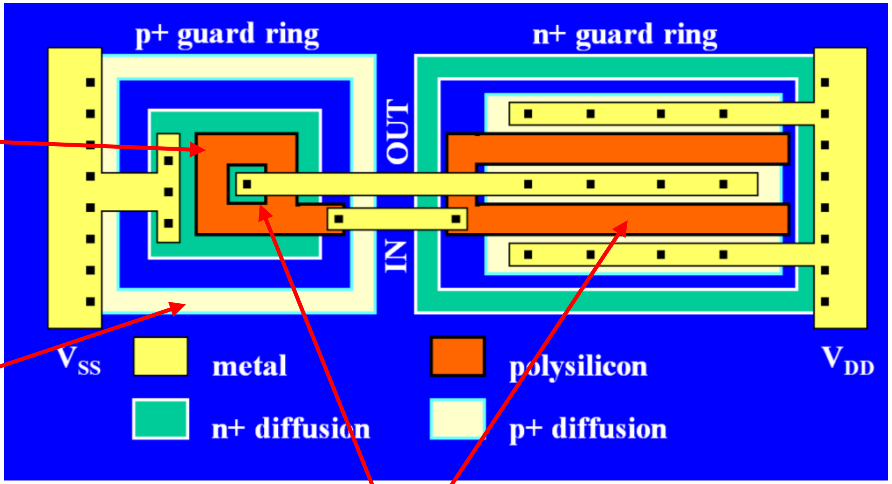
- Shielding helps for protons and electrons <30MeV, but has diminishing returns after 0.25".
- This shielding is typically inherent in the satellite/spacecraft design.

Shield Thickness vs. Dose Rate (LEO)



Radiation Hardened by Design (RHBD)

- Uses commercial fabrication process
- Circuit layout techniques are implemented which help mitigate effects



Enclosed Layout Transistors

- Eliminates edge of drain terminal
- This eliminates any leakage current between source & drain due near edge of gate **(STI Region 1)**

Guard Rings

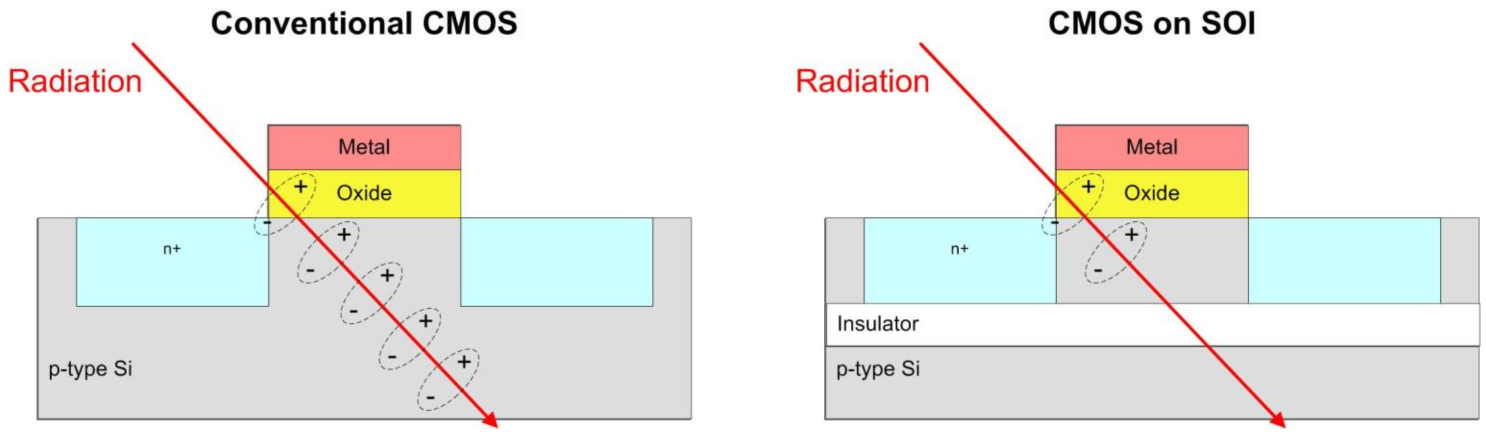
- Reduces leakage between NMOS & PMOS devices due to hole trapping in Field Oxide **(STI Region 2)**
- Separation of device + body contacts
- Adds ~20% increase in area

Thin Gate Oxide

- This oxide reduces probability of hold trapping.
- Process nodes <0.5um typically are immune to Vgs shift in the gate.

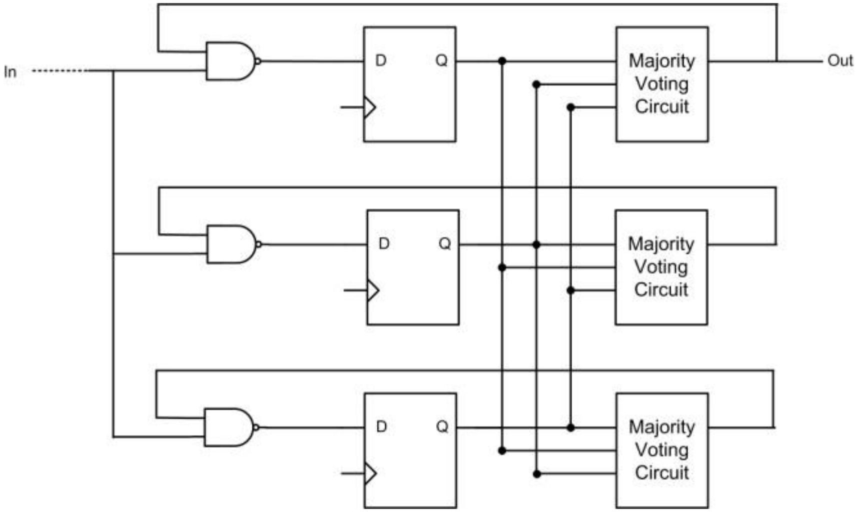
Radiation Hardened by Process (RHBP)

- An insulating layer is used beneath the channels
- This significantly reduces the ion trail length and in turn the electron/hole pairs created
- The bulk can also be doped to be more conductive so as to resist hole trapping



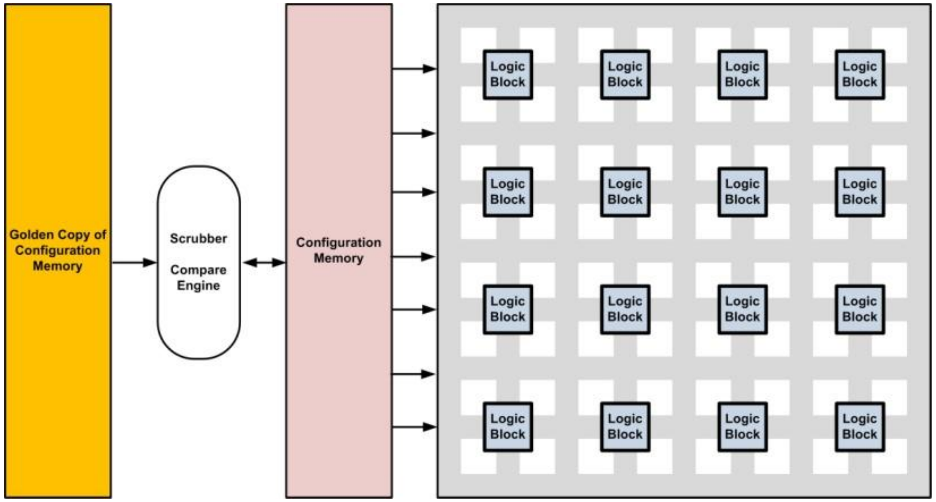
Radiation Tolerance Through Architecture

1. Triple Module Redundancy
   - Triplicate each circuit
   - Use a majority voter to produces output
   - Advantages
     - » Able to address faults in real-time
     - » Simple
   - Disadvantages
     - » Takes >3x the area
     - » Voter needs to be triplicated also to avoid single-point-of-failure
     - » Doesn’t handle Multiple-Bit-Upsets



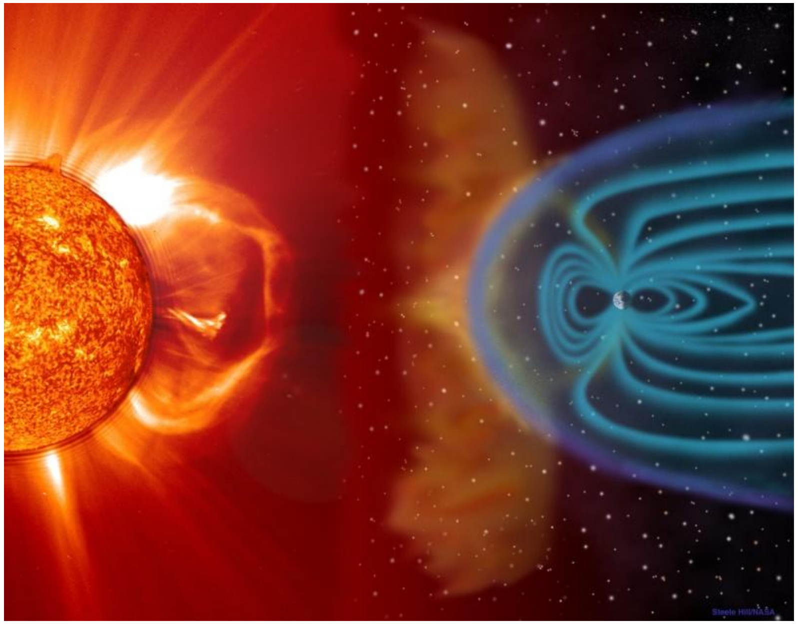
Radiation Tolerance Through Architecture Cont…

2. Scrubbing
   - Compare contents of a memory device to a "Golden Copy"
   - Golden Copy is contained in a radiation immune technology (fuse-based memory, MROM, etc…)
   - Advantages
     - » Simple & Effective
   - Disadvantages
     - » Sequential searching pattern can have latency between fault & repair



Effects Overview

- Primary Concern is Heavy Ions & high energy protons
- All modern computer electronics experience TID and will eventually go out
- Heavy Ions causing SEEs cannot be stopped and an architectural approach is used to handle them.



Questions?