01 - Introduction to Radiation Effects in Microelectronics: What are radiation effects, where are radiation effects, terminology

ENGR-E 399/599
Microelectronics Radiation Effects and Reliability

Context

- **399:** https://iu.instructure.com/courses/2331833
- **599:** https://iu.instructure.com/courses/2331880

- https://github.com/tdloveless/me-radfx

Syllabus for ENGR-E 399: Topics in Intelligent Systems Engineering, Radiation Effects and Reliability of Microelectronics
Section: 13106

Course Description:
This course introduces the space radiation environment and its effects on microelectronics. The basic mechanisms of cumulative and transient radiation effects in state-of-the-art semiconductor devices are discussed, with special focus on the challenges of modeling, simulation, and measurement. Further, the implications of technology scaling are considered. Students will be exposed to industry-standard tools and techniques for estimating the reliability of microelectronics in extreme space environments.

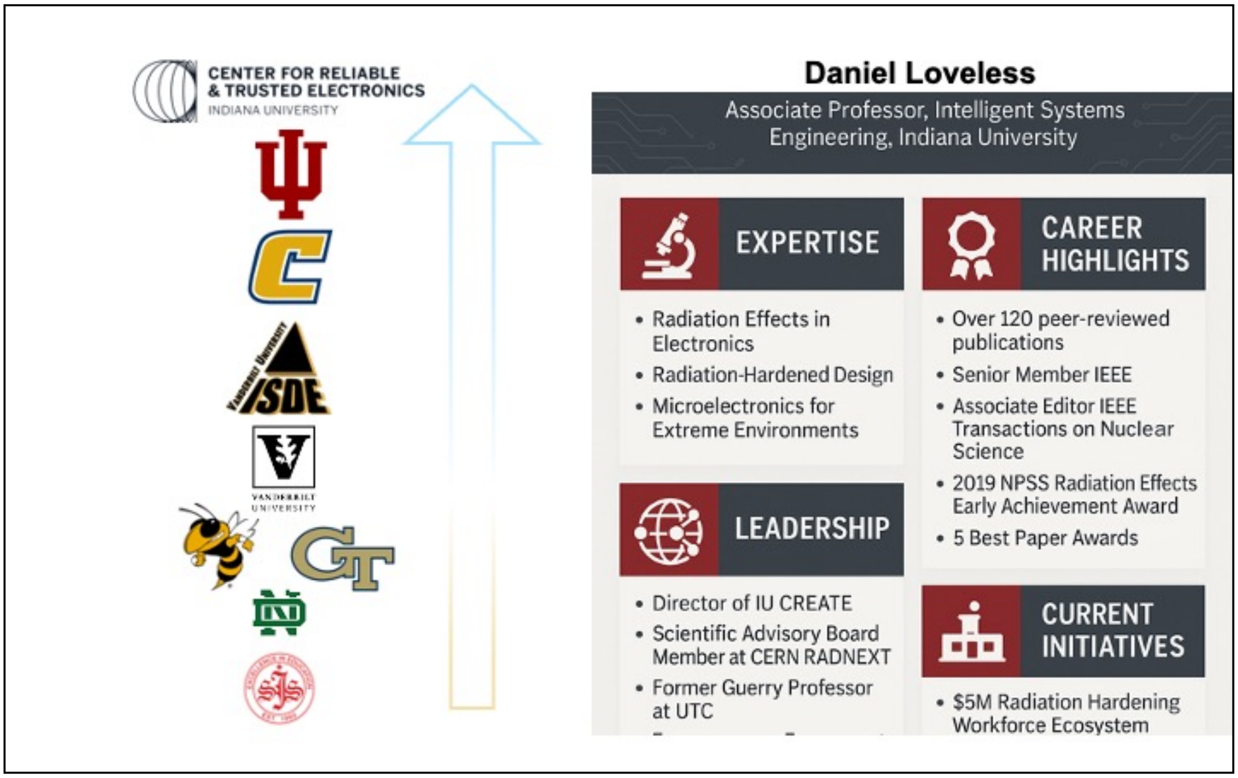
Course Pre/Co-Requisites: None

Meeting Dates: Tuesday / Thursday, 12:45 pm-2:00 pm   Luddy Hall (IF) Room 4063

Course delivery method: in-person

Learning Outcomes:
- Identify, formulate, and solve engineering problems related to the use of microelectronics in space environments
- Demonstrate an ability to communicate effectively
- Recognize the need for, and an ability to engage in life-long learning
- Demonstrate the use of techniques, skills, and modern tools for analyzing microelectronics radiation effects and reliability degradation

Who am I?

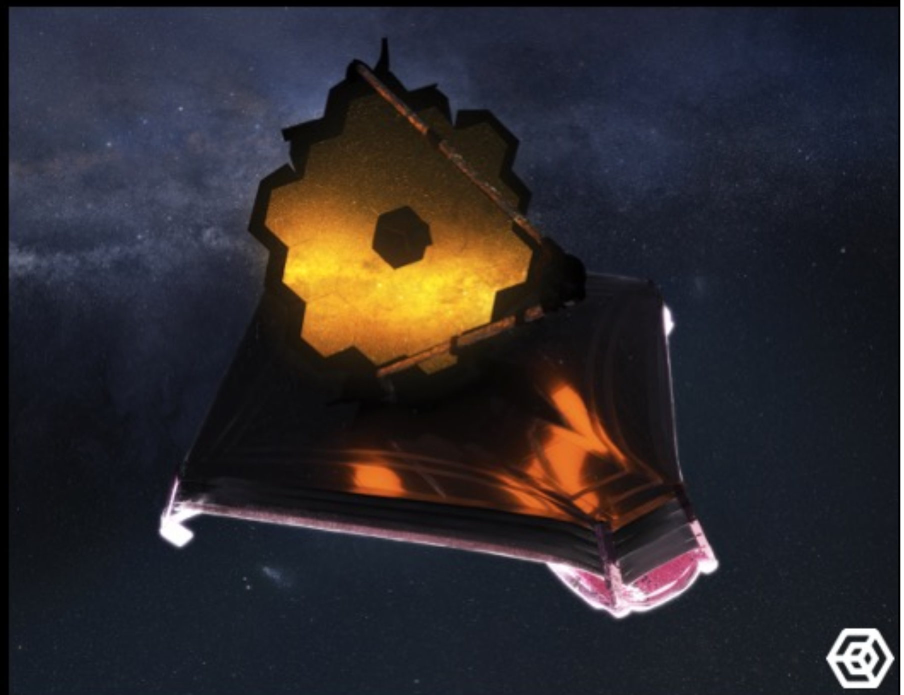

CENTER FOR RELIABLE
& TRUSTED ELECTRONICS
INDIANA UNIVERSITY
VANDERBILT UNIVERSITY
ISDE
Daniel Loveless
Associate Professor, Intelligent Systems Engineering, Indiana University
EXPERTISE
• Radiation Effects in Electronics
• Radiation-Hardened Design
• Microelectronics for Extreme Environments
CAREER HIGHLIGHTS
• Over 120 peer-reviewed publications
• Senior Member IEEE
• Associate Editor IEEE Transactions on Nuclear Science
• 2019 NPSS Radiation Effects Early Achievement Award
• 5 Best Paper Awards
LEADERSHIP
• Director of IU CREATE
• Scientific Advisory Board Member at CERN RADNEXT
• Former Guerry Professor at UTC
CURRENT INITIATIVES
• $5M Radiation Hardening Workforce Ecosystem

https://www.history.navy.mil/content/history/museums/nmusn/explore/photography/humanitarian/20th-century/1980-1989/1986-space-shuttle-challenger.html

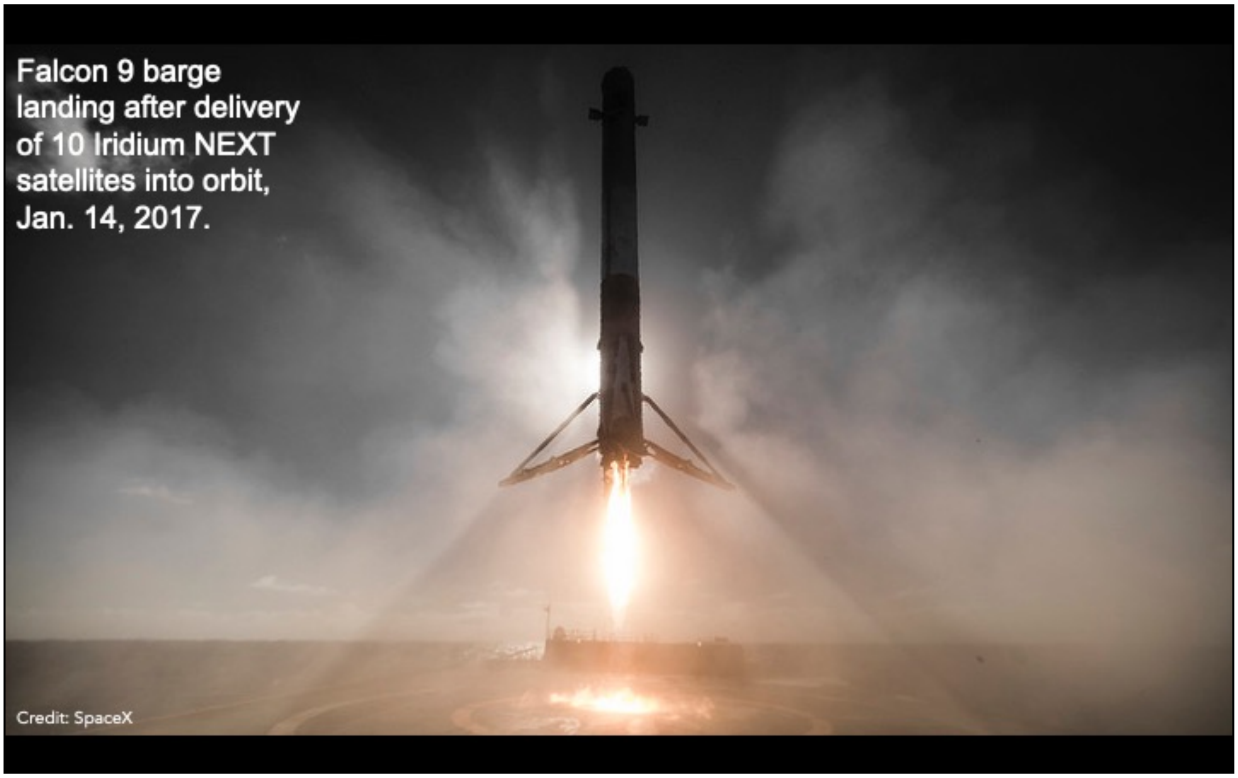

Quick Facts about the Hubble Space Telescope:
• Approximate size: 43 ft x 14 ft
• Weight: 24,000 lbs (11,110 kg)
• Cost at launch: $1.5 billion (1990)
• Can hold steady at about 7/1000th of an arcsecond (~ the width of a human hair seen at 1 mile)
The Hubble Space Telescope, 2003
http://hubblesite.org/

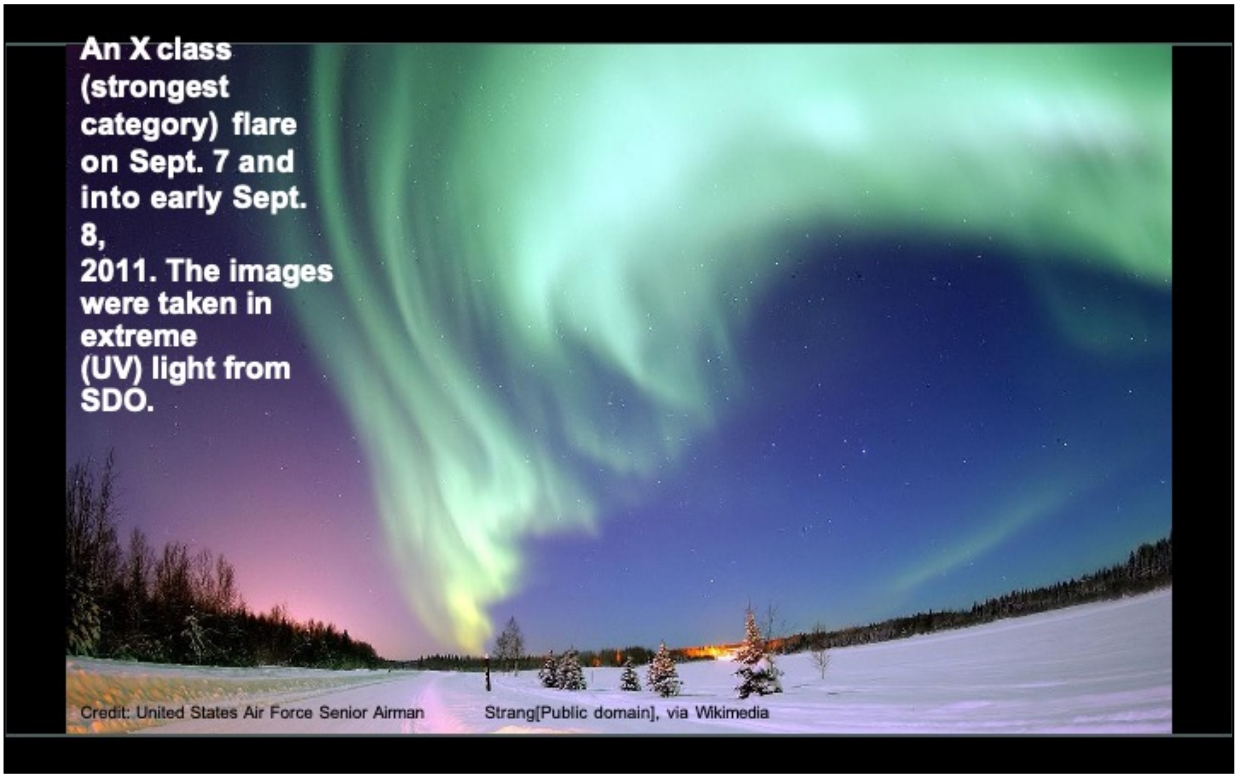
Fun Facts about the Webb Telescope:

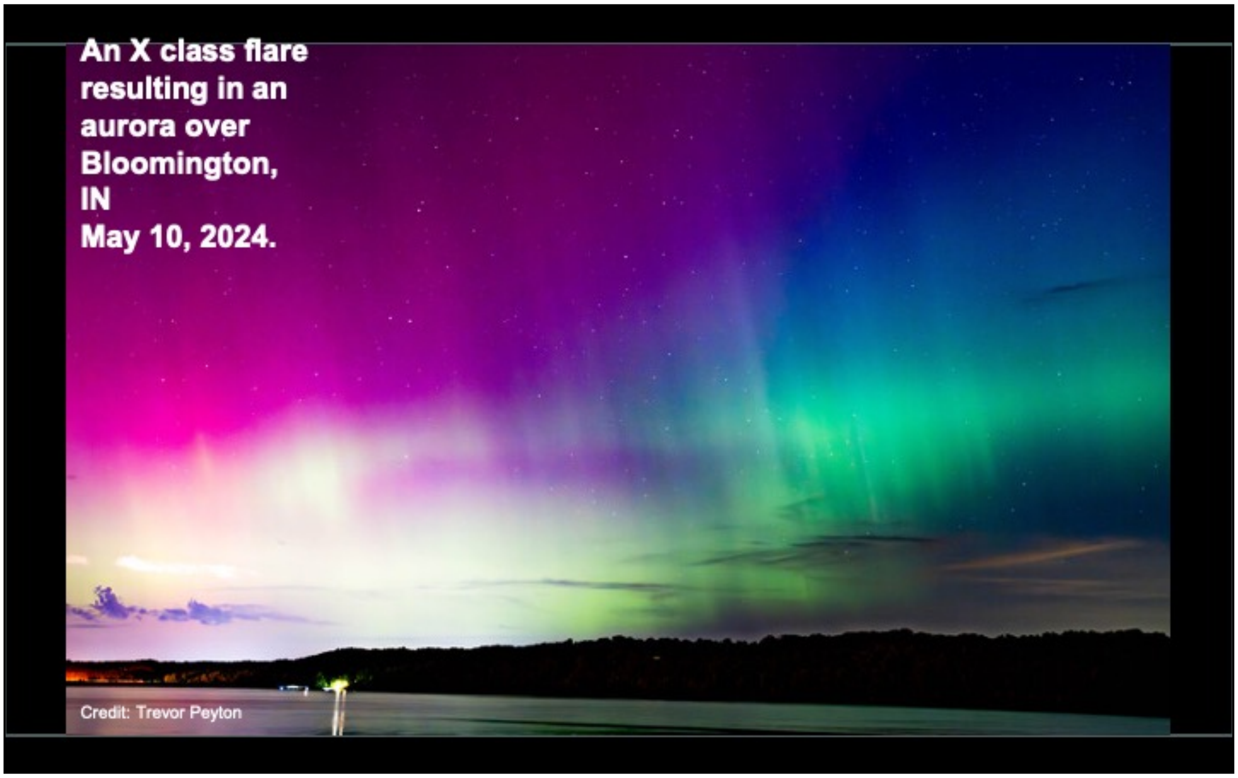
- Approximate size: 66 ft x 46 ft
- Cost at launch: $10 billion (2021)
- Can detect the heat signature of a bumblebee at a distance from the Earth to the Moon

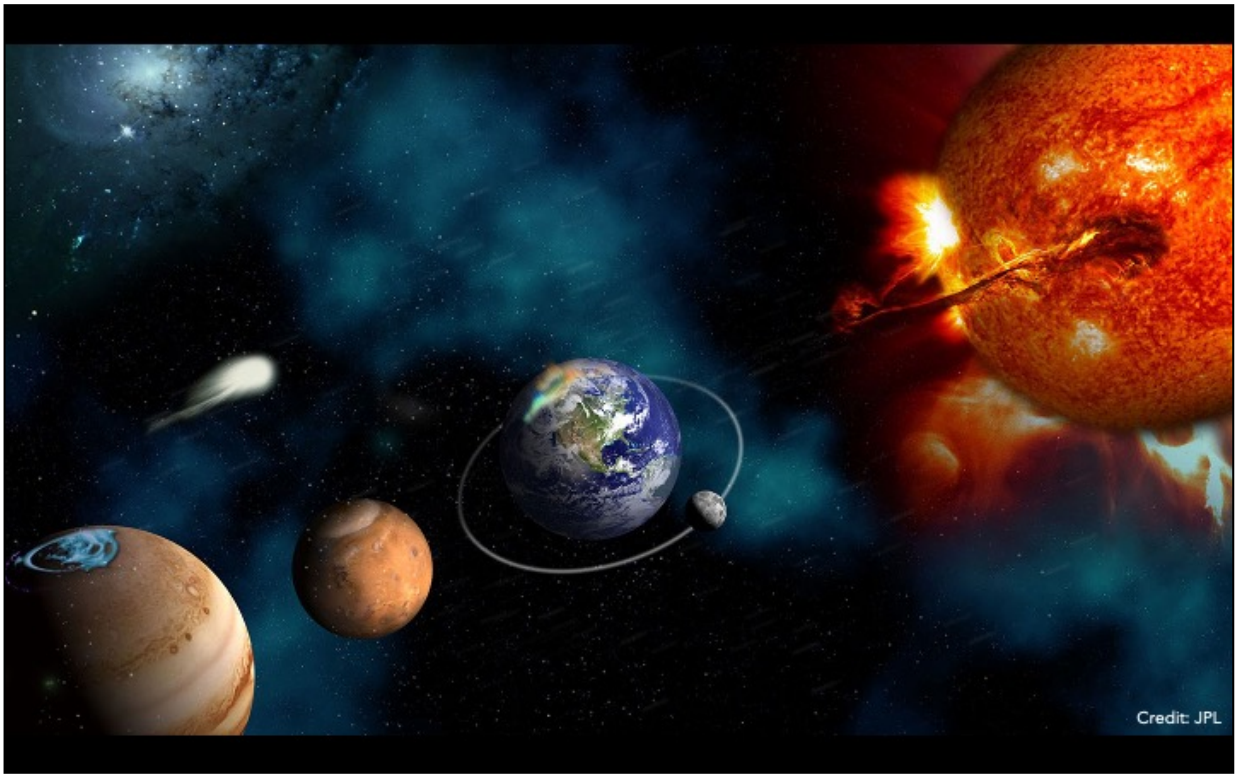


Webb Space Telescope, 2022
https://webb.nasa.gov/


Falcon 9 barge
landing after delivery
of 10 Iridium NEXT
satellites into orbit,
Jan. 14, 2017.
Credit: SpaceX


An X class
(strongest
category) flare
on Sept. 7 and
into early Sept.
8,
2011. The images
were taken in
extreme
(UV) light from
SDO.
Credit: United States Air Force Senior Airman Strang[Public domain], via Wikimedia

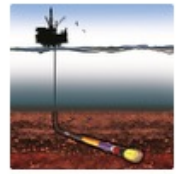

An X class flare
resulting in an
aurora over
Bloomington,
IN
May 10, 2024.
Credit: Trevor Peyton


Credit: JPL

Context

- **Many applications require electronic devices to operate in extreme environments that can impact operation and reliability**
  - Vibration/shock
  - Temperature
  - Pressure
  - Radiation



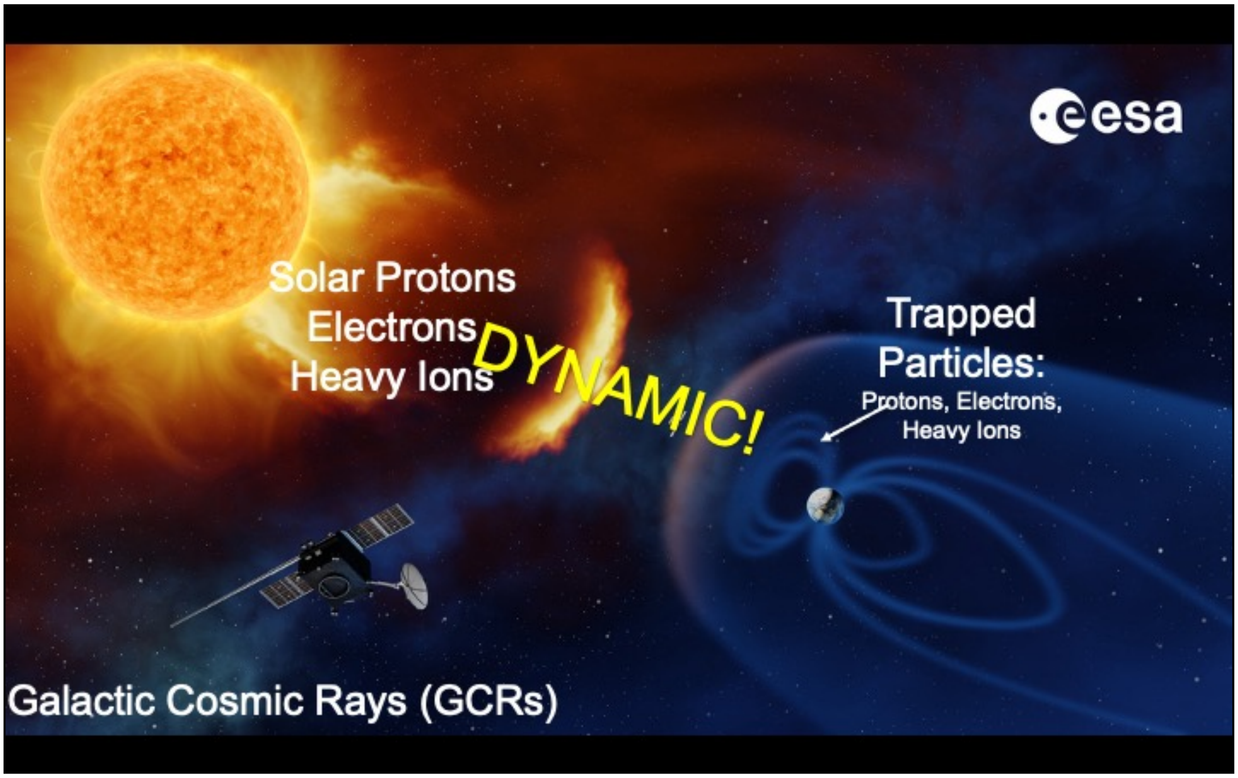


- **Natural and mand-made radiation environments**
  - Space
  - Nuclear Power
  - Weapons
  - Medical
  - Terrestrial







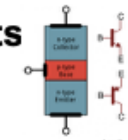


esa
Solar Protons
Electrons
Heavy Ions
DYNAMIC!
Trapped
Particles:
Protons, Electrons,
Heavy Ions
Galactic Cosmic Rays (GCRs)

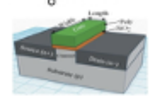
General Characteristics: Radiation Effects in Electronics

- Radiation (photons or particles) transfers energy to materials used in electronics devices
- Mechanisms and manifestations of the energy transfer depend on the material (esp. semiconductor or insulator), characteristics of the radiation, and device type
- Processes can be ionizing (linear energy transfer, LET) or non-ionizing (non-ionizing energy loss, NIEL)
- Interactions may be localized or systematic depending on the radiation type
- Effects may be transient or persistent, and may be recoverable or destructive

Radiation Effects in Electronics - Impact

- Transistors are the basic building blocks of circuits
  - Act like a switch in digital circuits
  - Act like a rheostat in analog circuits

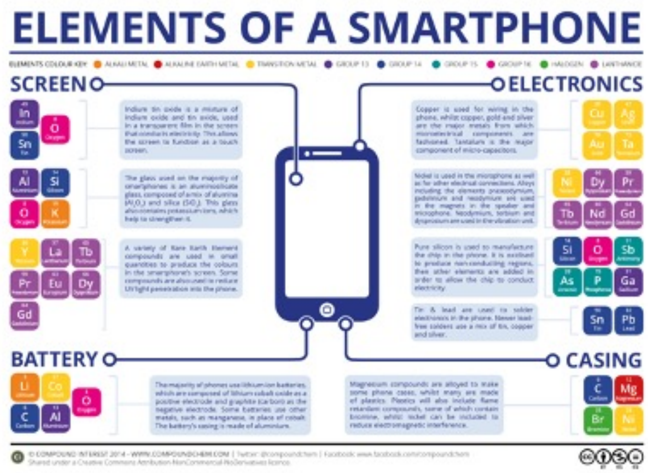


- Radiation can cause one or more of these “switches” to turn on for short times (~ pico to micro seconds), cause the switches to “leak” electricity (increased leakage current), or change the turn-on voltages
- This can result in digital errors (state changes), device burnout, increased standby power consumptions, slower operation, loss of proper functionality

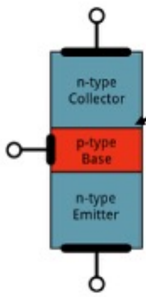
Electronic Devices – Material Types

- **Electronic circuits are generally composed of three types of materials:**
  - **Semiconductors**
  - **Insulators**
  - **Conductors (metals)**

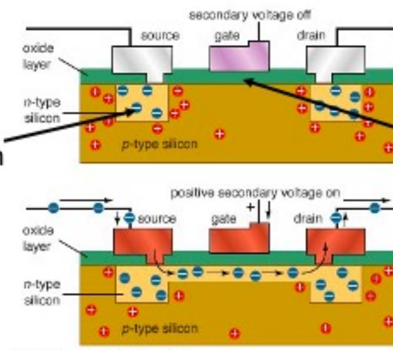


Transistor Basics

- **Transistors are generally comprised of semiconductor p-n junctions and capacitors, contacted by metal conductors, all built on top of a substrate for mechanical support**
- **The most common types are bipolar junction and metal-oxide-semiconductor field-effect transistors (BJTs, MOSFETs) although there are many others**



Both BJTs and MOSFETs contain p-n junctions



© 2004 Encyclopaedia Britannica, Inc.

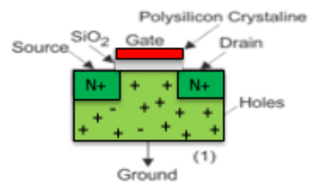
MOSFETs use a capacitor to “gate” the conduction via a field effect

https://cdn.sparkfun.com/assets/learn_tutorials/1/9/3/transistor-construction.png

https://www.britannica.com/technology/transistor

Background: The Transistor

- Bipolar Junction Transistor (BJT):
  - Invented in 1947 (Bell Labs)
  - Relies on conduction by holes **and** electrons
  - Most common transistor in the 60s and 70s
- Field Effect Transistor (FET):
  - Conceptualized in the 20s and thoroughly explained by Bell Labs in 1948
  - Relies on conduction by **either** holes **or** electrons
  - Metal Oxide Semiconductor FET (MOSFET) invented in late 1950s (currently the most common transistor)



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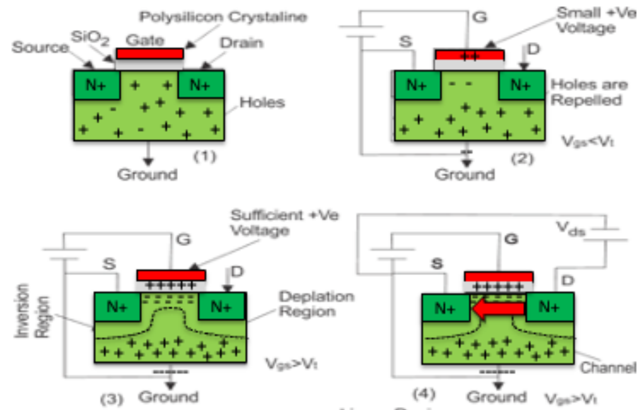
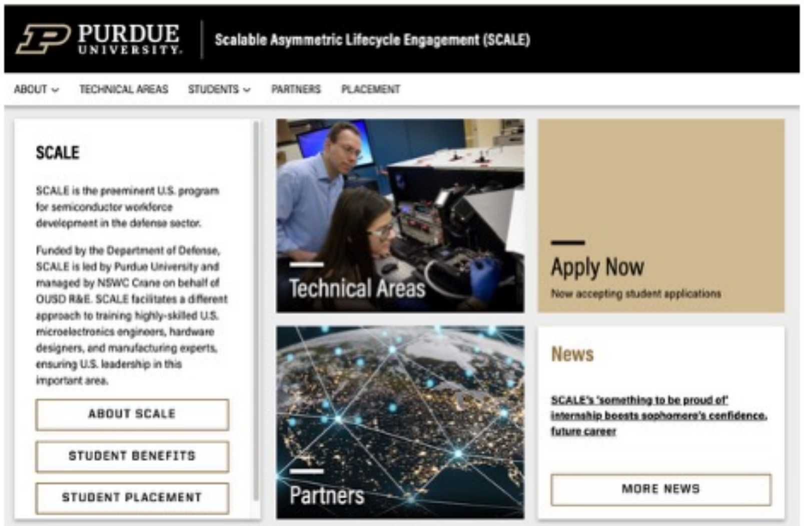


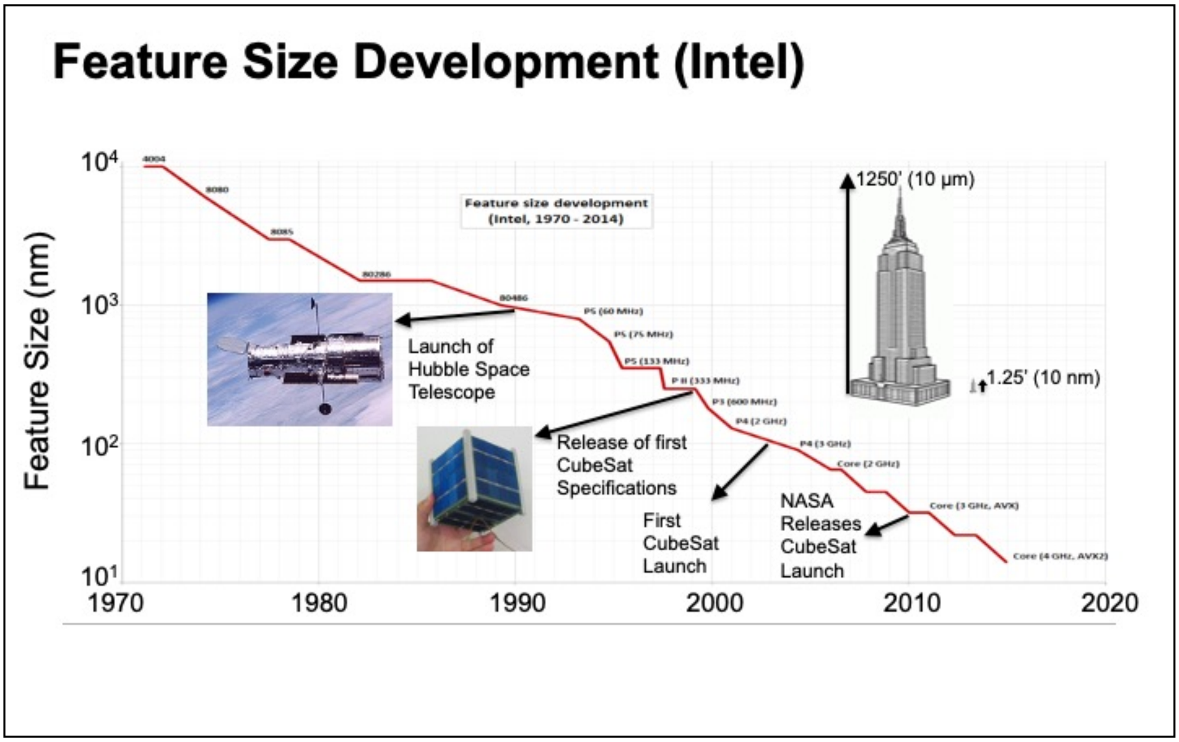
STOP: Take a moment and create an account on nanoHUB.org

Some useful tools and visuals:
https://www.circuitsgallery.com/mosfet-working/
nanoHUB (MOSfet, MOSFET Simulation, ABACUS)

SCALE

https://www.scale4me.org/

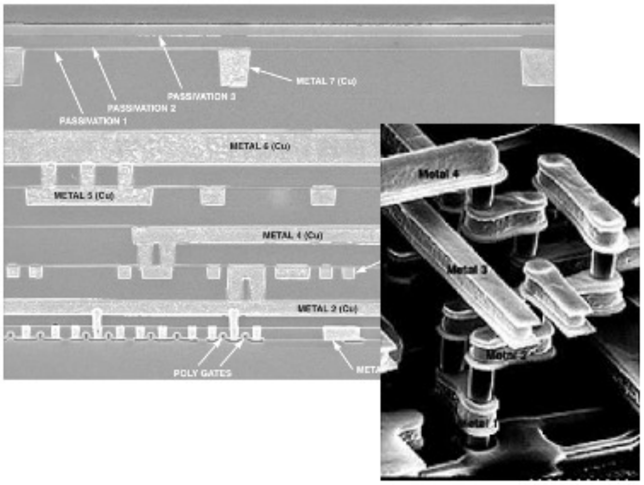


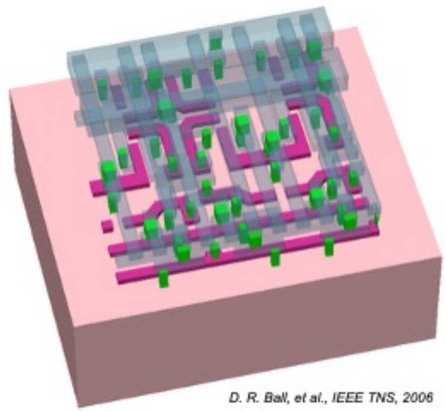


Reliability is an issue for not only space based systems

Soft errors are a key challenge for commercial systems

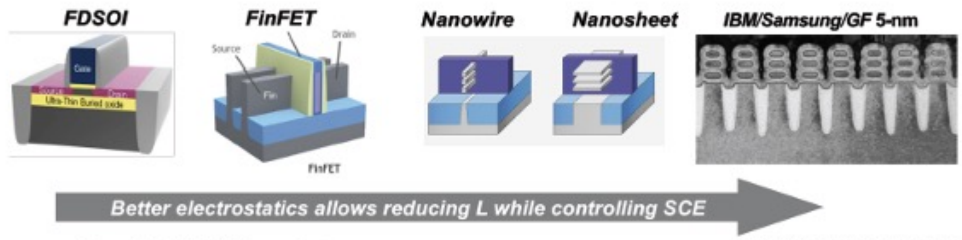
Modern Integrated Circuits (ICs)?





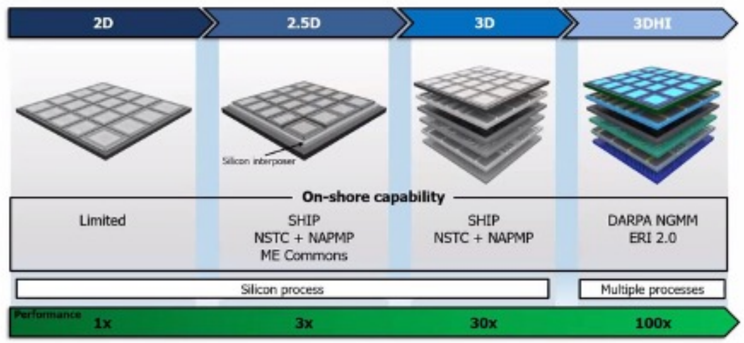
D. R. Ball, et al., IEEE TNS, 2006

Modern Integrated Circuits

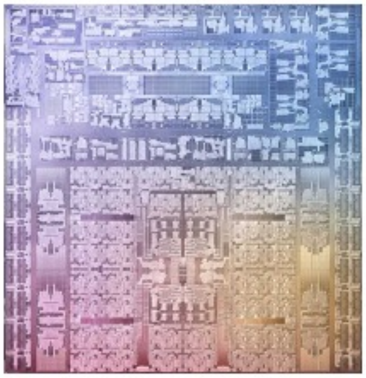


Esqueda, JPL Workshop, 2019

**SCE: Short-Channel Effects*



Manufacturing capabilities are stacking up. (Source: DARPA)

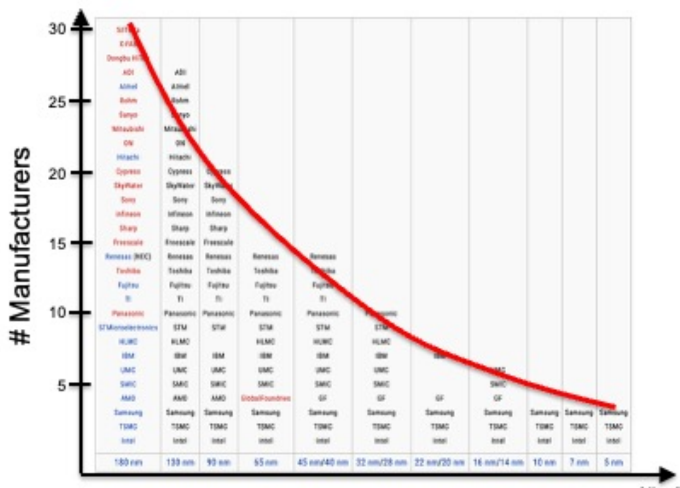


Apple M3-MAX
92 Billion
Transistors

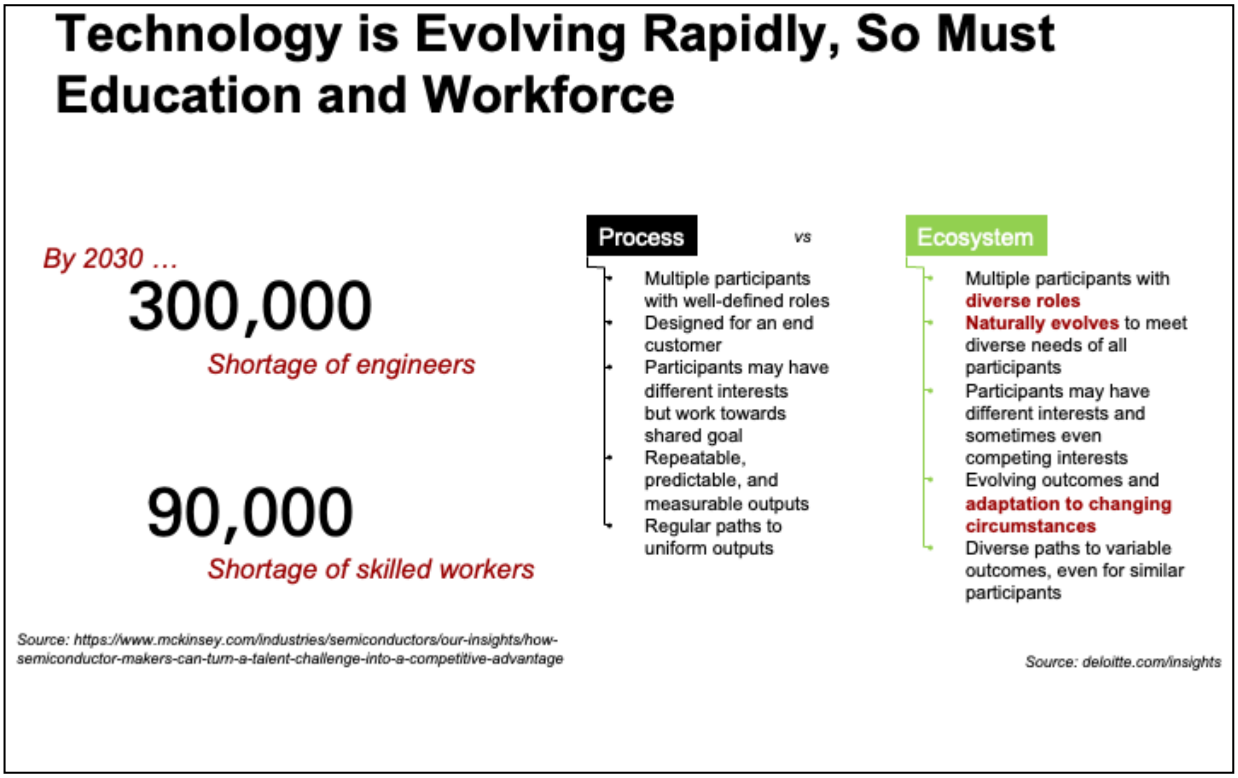
Cerebras Wafer Scale Engine Gen. 2
2.6 Trillion Transistors

The design of integrated circuits is driven by simulation analysis and is dramatically increasing in cost and complexity

Manufacturing Facilities *at the Cutting Edge* are Diminishing



Source:
https://en.wikichip.org/wiki/technology_node



The U.S. semiconductor industry alone could face a shortage of

- about 300,000 engineers
- 90,000 skilled workers
- by 2030[2].

This is critical to our Nation's future as an international leader. Not everyone is destined to go to college to become semiconductor engineer or an engineer.

The need for skilled trades is also huge. Not to mention the need for business, marketing, and creative degrees to propel the US semiconductor industry forward.

[2] https://www.mckinsey.com/industries/semiconductors/our-insights/how-semiconductor-makers-can-turn-a-talent-challenge-into-a-competitive-advantage

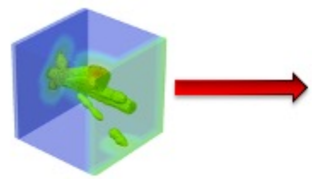
Radiation Effect Types

- **Transient-radiation effect - generally refers to the impact of charge generation and resulting transient currents in the active semiconductor portion of electronic devices**
  - Single-event effects (SEE)
  - Transient-dose effects (prompt dose, gamma-dot)
- **Total-ionizing dose (TID) - generally refers to the impact of charge generation, and resulting distributions of excess charge within the insulating portions of electronic devices**
- **Displacement damage dose – deposited energy does physical damage, specifically displacement damage, in the insulators and/or active regions**
- **Electro Magnetic Pulse (EMP) - EM energy may couple into systems via antenna effect**

Single-Event Effects (SEE)

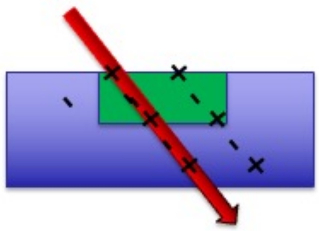
The primary terrestrial and a significant space radiation effect

- **Directly change the state of one or more memory cells or latches**
  - Single-event upset (SEU) or soft error
  - Frequency referred to as Soft-Error Rate (SER) or Failure in Time (FIT) rate
- **Single events induce transients (SETs) that can propagate to a latch and become and error**
- **SETs can disrupt analog and RF operation**
- **Single events can induce high current start (latchup = SEL) and resulting in burnout (single-event burnout, SEB)**
- **Single events can cause hard errors such as gate rupture (generally not concern in very thin insulators in terrestrial environments)**

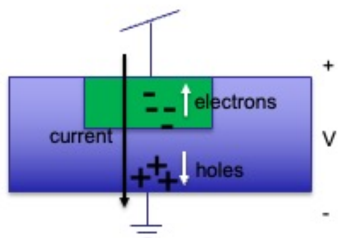


Single-Event Effects in Microelectronics

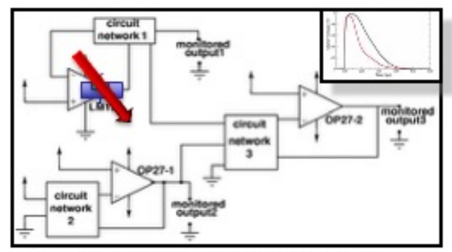
- Caused by the interaction of a single energetic particle
- SEE are determined by:
  - Charge generation
  - Charge collection
  - Circuit response



Charge generation (fs)

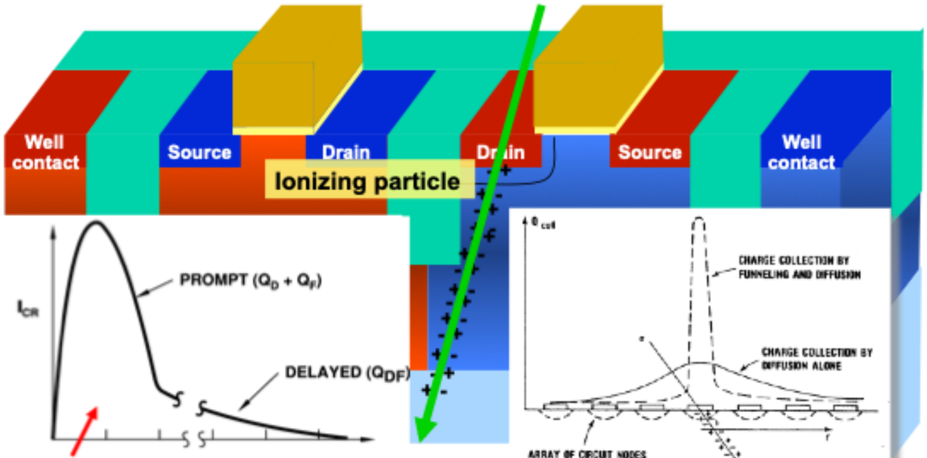


Charge collection (ps-ns)



Circuit Response (ps – ms)

Single-Event Charge Collection



Results in a transient current pulse at the struck node (and possibly at other close by nodes)

McClean, 1982

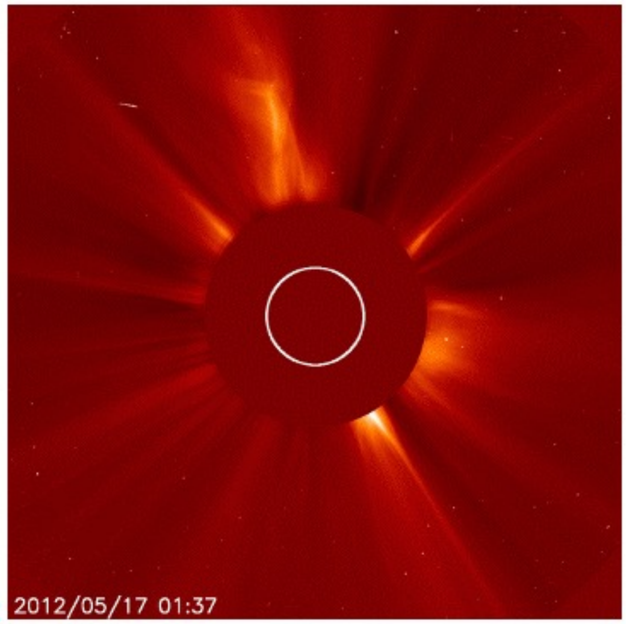
Multi-node effects are major consideration in < 90 nm bulk CMOS

Coronal Mass Ejection

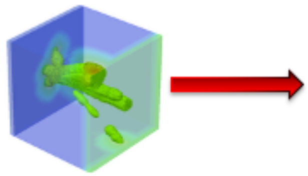
NASA on May 16-17th, 2012:

A coronal mass ejection (CME) was associated with a M-class solar flare occurring on May 16th. The burst traveled over 930 mps and impacted a variety of spacecraft. The flare also resulted in a moderate radio blackout.

http://www.nasa.gov/mission_pages/sunearth/news/News050912-Mflares.html



http://www.spaceweather.com/archive.php?view=1&day=18&month=05&year=2012



Single-Event Effects in Microelectronics

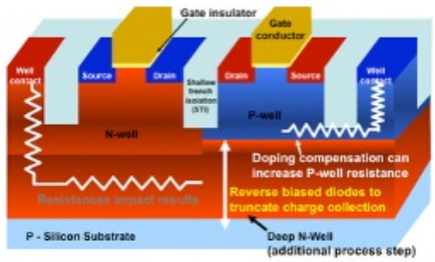
- Caused by the interaction of a single energetic particle
- SEE are determined by:
  - Charge generation
  - Charge collection
  - Circuit response

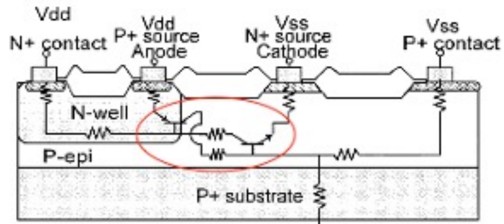
- Types:

  Non-destructive:
  - **Single-event upsets (soft errors)**
  - **Single-event transients**
  - Single-event functional interrupt
  - Multiple-bit upsets

  Destructive:
  - **Single-event latchup**
  - Single-event burnout
  - Single-event gate rupture
  - Single-event snap-back

Single-Event Latchup (SEL)





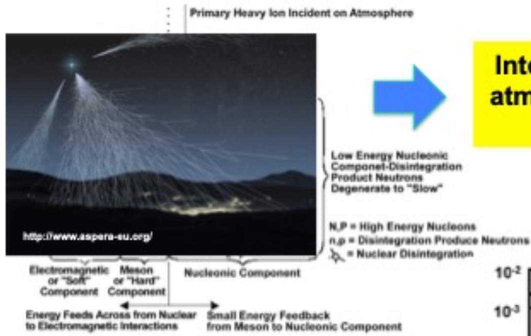
Gregory, 1973

Single event can trigger sub-surface bipolar structures in positive feedback loop in bulk CMOS = Single Event Latchup

Phobos-Grunt Failure

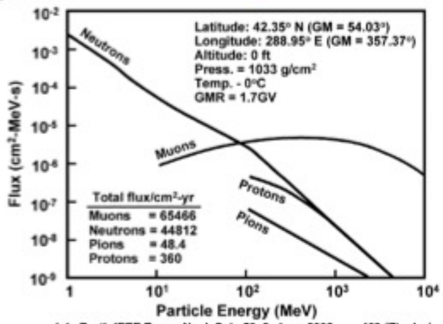
Phobos-Grunt re-entry after mission failure
SEL?

SEE – Terrestrial Radiation



Interaction of radiation with the atmosphere results in terrestrial radiation environment

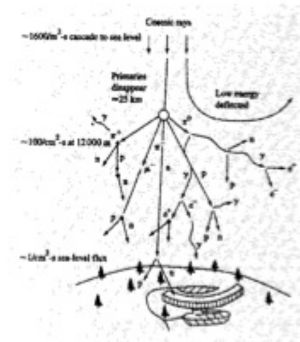
Interact with materials used in microelectronic leading to damage or ionization; processes may include secondary reaction products

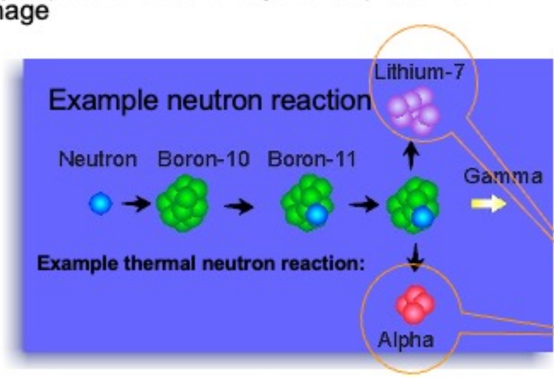


J. L. Barth IEEE Trans. Nucl. Sci., 50, 3, June 2003, pp. 469 (Ziegler/IBM).

SEE – Terrestrial Neutrons

1. Neutrons are created by cosmic ion interactions with oxygen and nitrogen in the upper atmosphere
2. Interact with material (**esp. ^{10}B**) in the electronic devices
3. Reaction products (including protons, alphas, ions) deposit excess charge or displacement damage





Energy; Range;
Time of Flight; Total Charge

0.8 MeV; 2.4µm; 1.5ps; 36fC

1.5 MeV; 5.2µm; 2.4ps; 67fC

SEE - Alpha Particles (He++) and Packaging

- **Packaging contaminants leading to SEE problems in the early 80's: U-238, Y-235, Th232 , Energies: 4 - 9 MeV**
- **Ionizing alpha particles also come from packaging materials**
- **Pb solder is the biggest contributor**
- **Flip chip and 3D stacking increase Pb proximity to devices**
- **Low alpha Pb costs ~ 5-400X more per pound**

Sources
Solders
Alumina substrates
BEOL metallizations
Fillers in plastics, encapsulants, underfills, mold compounds and solder masks
Flux
Lead frame alloys
Materials (Au, Cu, Ag etc) used for wire bonding and lid plating
Particulates from PBGA trimming / handling operations

S. Kumar et al., Rev. Adv. Mater. Sci 34 (2013) 185-202

Material	Alpha radiation flux (a/khr cm^2)
Processed wafers	0.9
Cu metal (thick)	1.9
Al metal (thick)	1.4
Mold compound	24 to < 2
Underfill	2 to 0.9
Pb solders	7200 to < 2
LC II Pb (HEM)	50 to 3
LC I Pb (HEM)	1000 to 130
Alloy 42 (Hitachi)	8
Au-plated alloy 42 (HEM)	4
Sn (HEM)	>1000 to <1
AlSiC (Lanxide)	215
LC6 Al (HEM)	8

Space Radiation Environment

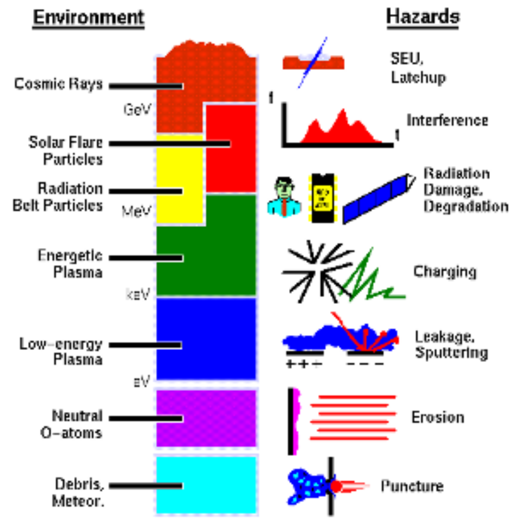
The main sources of energetic particles of concern to spacecraft designers

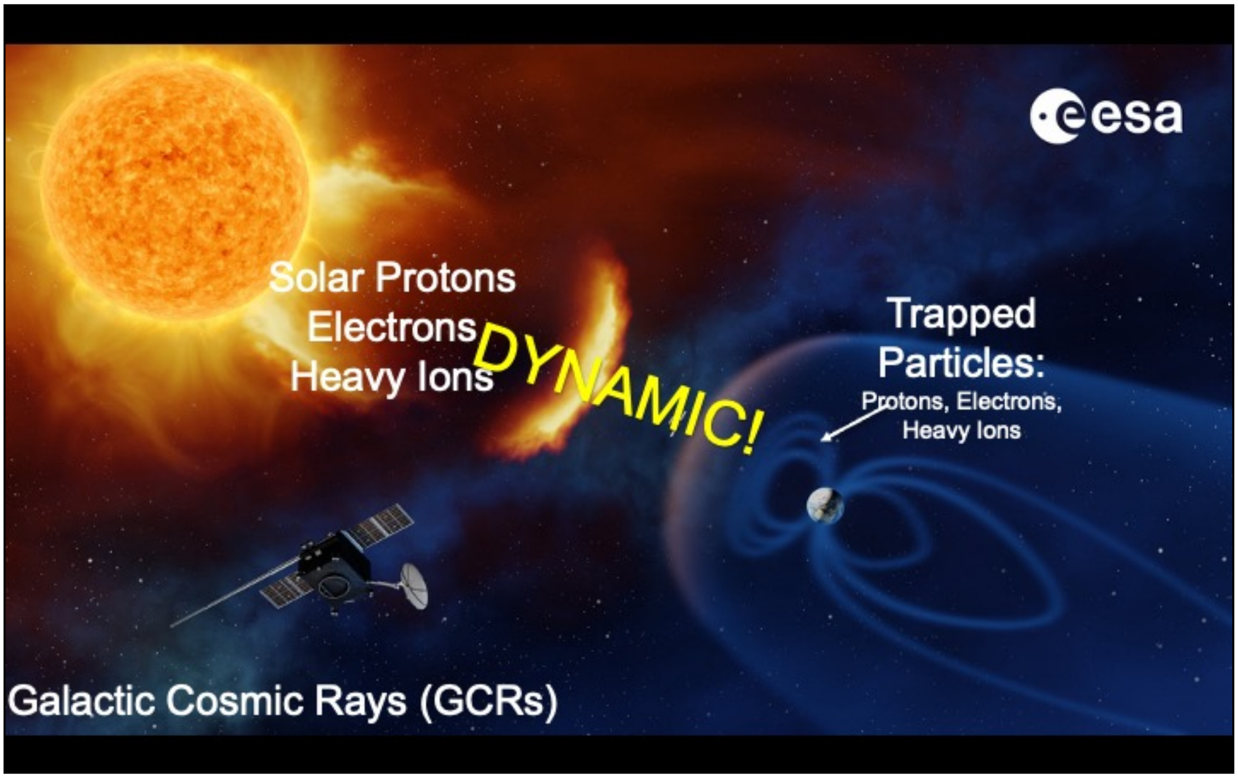
1) cosmic ray protons & heavy ions

2) protons and heavy ions from solar flares

3) protons & electrons trapped in the Van Allen belts

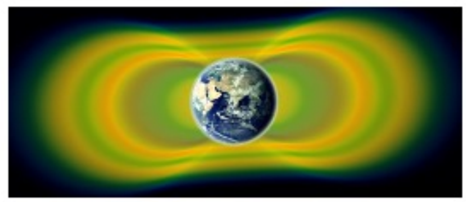
4) heavy ions trapped in the magnetosphere



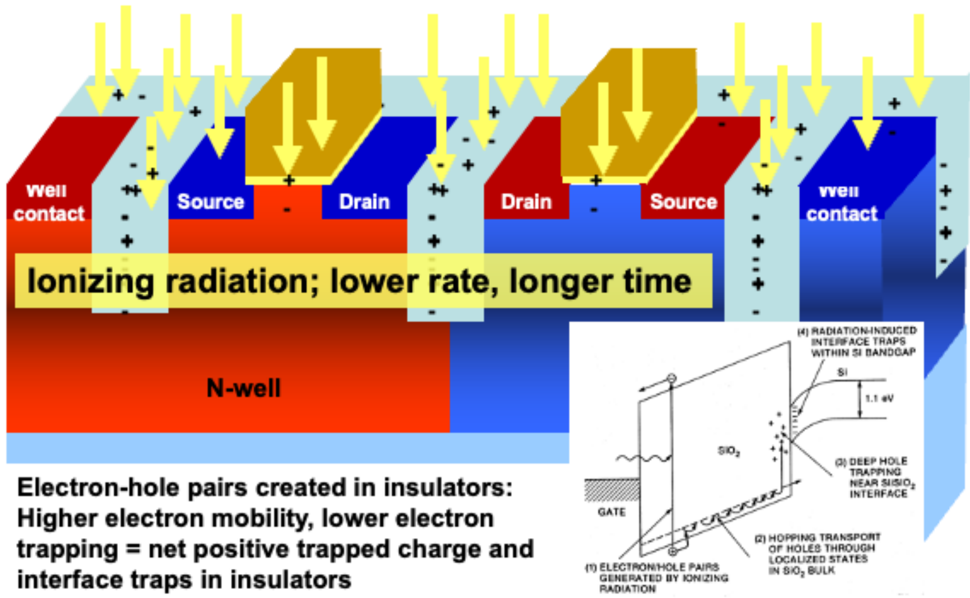

Solar Protons
Electrons
Heavy Ions
DYNAMIC!
Trapped
Particles:
Protons, Electrons,
Heavy Ions
Galactic Cosmic Rays (GCRs)

Single-Event Environments

- Heavy, highly-energetic ions from deep space (galactic cosmic rays)
- Energetic protons (trapped in the van Allen radiation belts)
- Neutron products (terrestrial pests)
- Alpha particles(from contaminants and processing materials)
- Muons



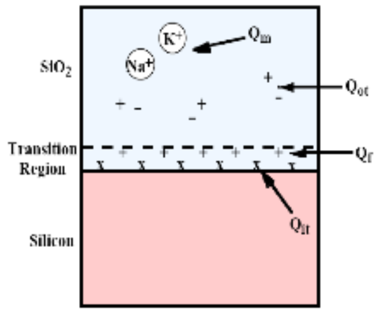
Total Ionizing Dose (TID)



Electron-hole pairs created in insulators: Higher electron mobility, lower electron trapping = net positive trapped charge and interface traps in insulators

McClean, 1987

Electrical Impact of TID



Four charges are associated with insulators and insulator/semiconductor interfaces.

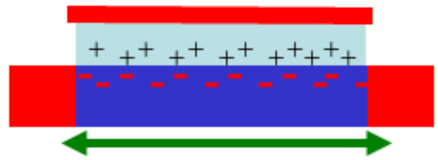
Q_f - fixed oxide charge

Q_{it} - interface trapped charge

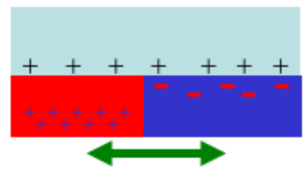
Q_m - mobile oxide charge

Q_{ot} - oxide trapped charge

[20] Plummer, 2000

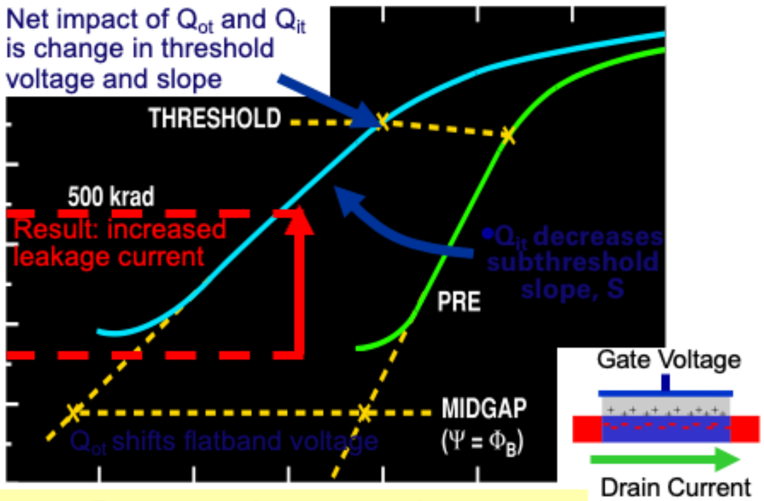


Leakage in N-MOS



Junction Leakage in BJTs

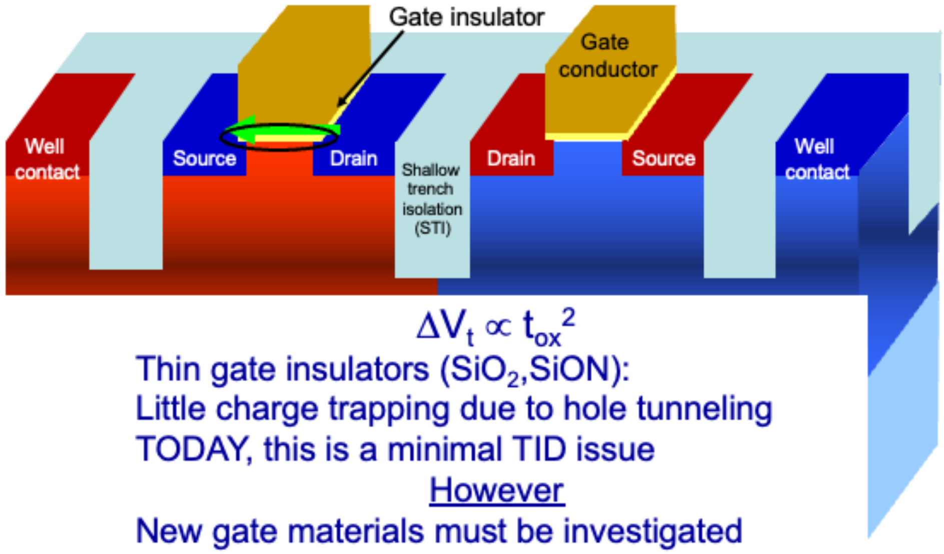
Electrical Impact of TID on MOS



Increased Leakage, Decreased transconductance
(slower, more power consumption)

Schwank, 1994

TID in Gate Insulators



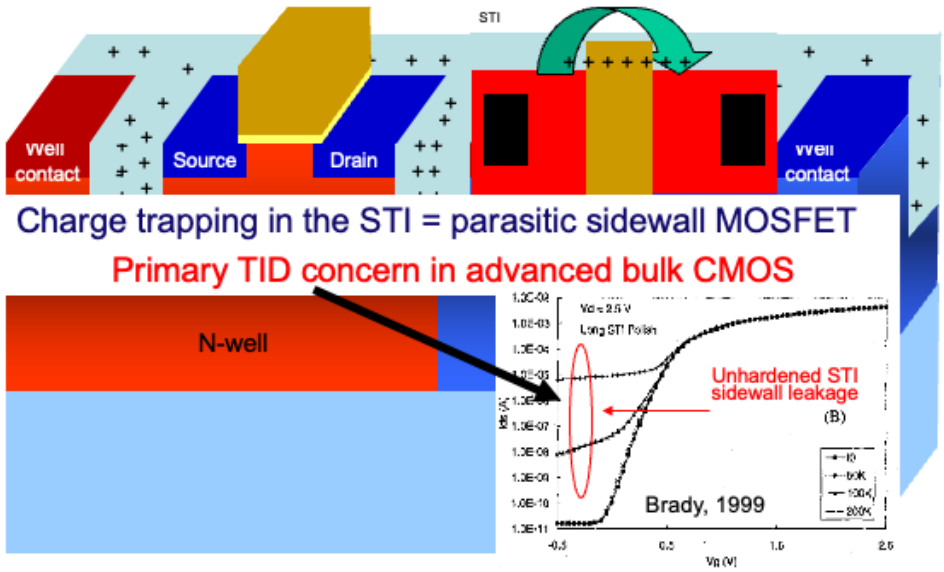
$\Delta V_t \propto t_{ox}^2$

Thin gate insulators (SiO_2,SiON):
Little charge trapping due to hole tunneling
TODAY, this is a minimal TID issue

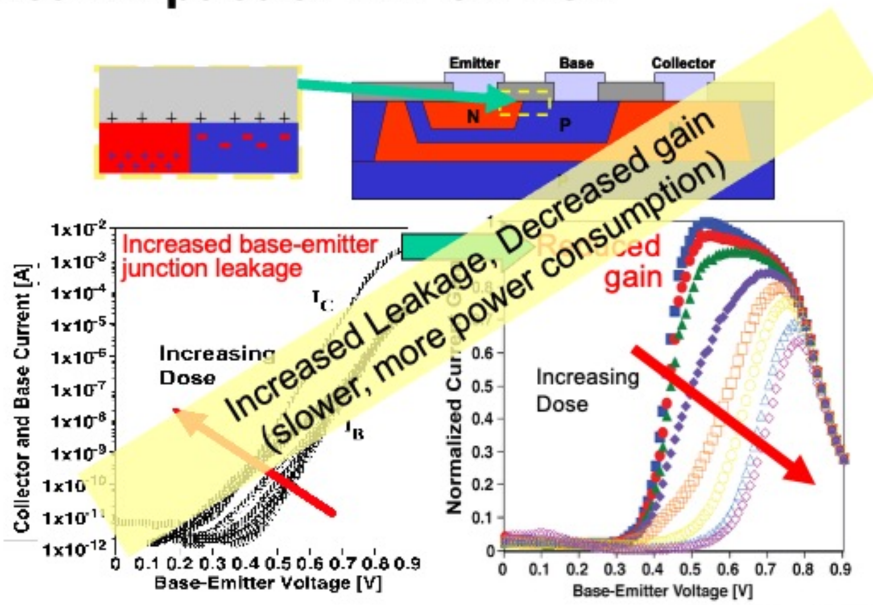
<u>However</u>

New gate materials must be investigated

TID in STI Oxides: Intra-Device

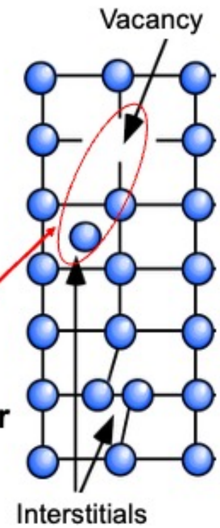


Electrical Impact of TID on BJT



[22] Schrimpf, 2004

Displacement Damage (eps. Neutrons)



Plummer, 2000

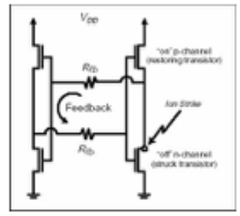
- **Physical displacement of silicon atoms from crystal sites**
- **Results in crystal defects: Frenkel pairs (Interstitial + Vacancy point defects), cluster defects (groups of point defects)**
- **Primarily an issue for bipolar devices, imagers, and solar cells**

Cumulative Dose Environments

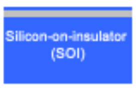
- **Space environment or certain ground base sources such as the LHC or nuclear power generation**
- **Ionizing X-rays, Gamma Rays, or high energy particles**
- **Effects due to integrated dose over time**
- **Impact can depend on dose rate**

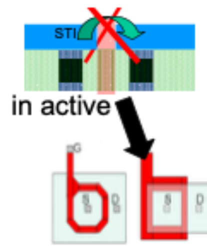



Mitigation



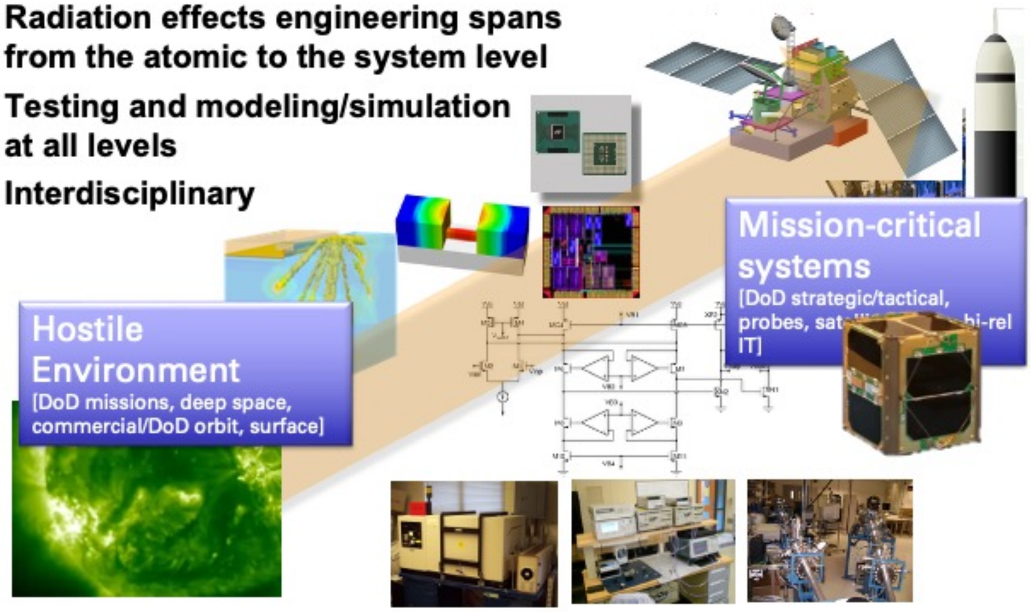
- **System-level management**
  - EDAC, redundancy, voting
  - Circumvention (shut down and restart)
  - Shielding
- **Hardened by design (HBD)**
  - Device layout (ex: annular, edgeless – prohibitive sub 65 nm)
  - Device placement (spacing, interleaving)
  - Guard bands/rings, body contacts, substrate & well contacts
  - Local circuit topology (passive or active temporal filtering, DICE latch, spatial or temporal redundancy)
- **Hardened by process (HBP)**
  - Modified materials (balance e-h trapping in minority carrier lifetime reduction material regions)
  - Doping profiles
  - Device structures (FinFETs)
  - Substrate engineering (Ex: epi, doping, SOI)





Mechanisms to Missions

- Radiation effects engineering spans from the atomic to the system level
- Testing and modeling/simulation at all levels
- Interdisciplinary



Some useful information

- **SEE**
- **SET**
- **SER**
- **FIT**
- **MBU**
- **SEB**
- **SEGR**
- **LET**
- **TID**
- **NIEL**

1 rad(material) = 100 erg/g energy per unit mass
1 Gy(material) = 1 J/kg [SI unit = Gray, abbrev. Gy]
1 Gy(material) = 100 rad(material) [usually Si or SiO_2]

LET = linear energy transfer = energy per unit mass per unit area transferred from particle to material

Cross-section = area of device that is sensitive to SEE

Material	Mean E_p (eV)	Density (g/cm^3)	Pair density, generated per rad, g_0 ($pairs/cm^3$)
GaAs	~4.8	5.32	$\sim 7 \times 10^{13}$
Silicon	3.6	2.328	4×10^{13}
Silicon Dioxide	17	2.2	8.1×10^{12}