



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.

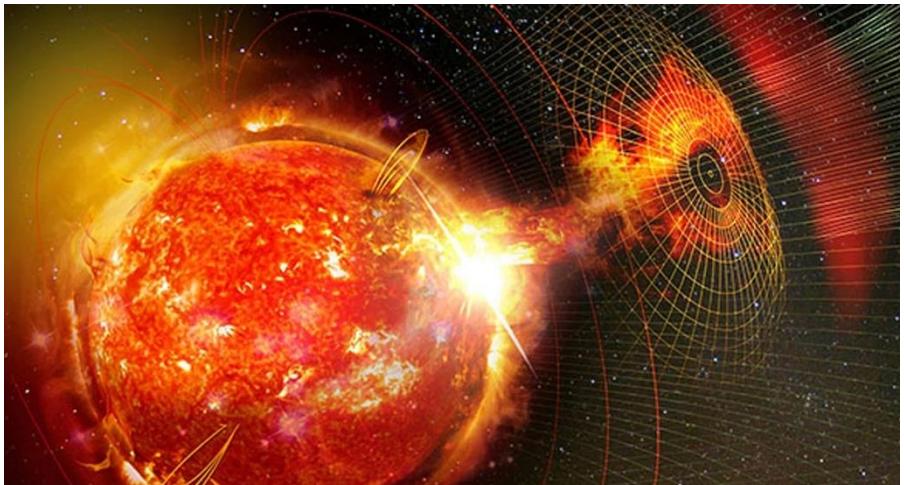
Course Pre/Co-Requisites: None

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

Course delivery method: in-person

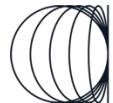
Learning Outcomes:

- 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

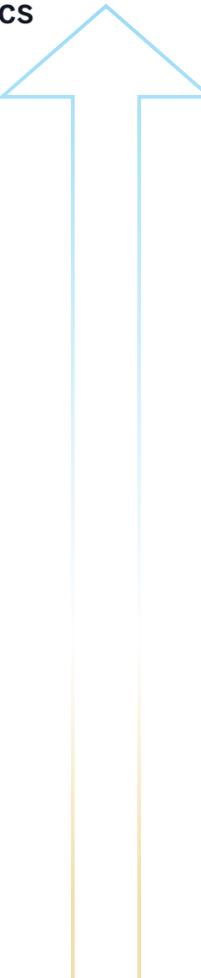


Who am I?





CENTER FOR RELIABLE
& TRUSTED ELECTRONICS
INDIANA UNIVERSITY



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

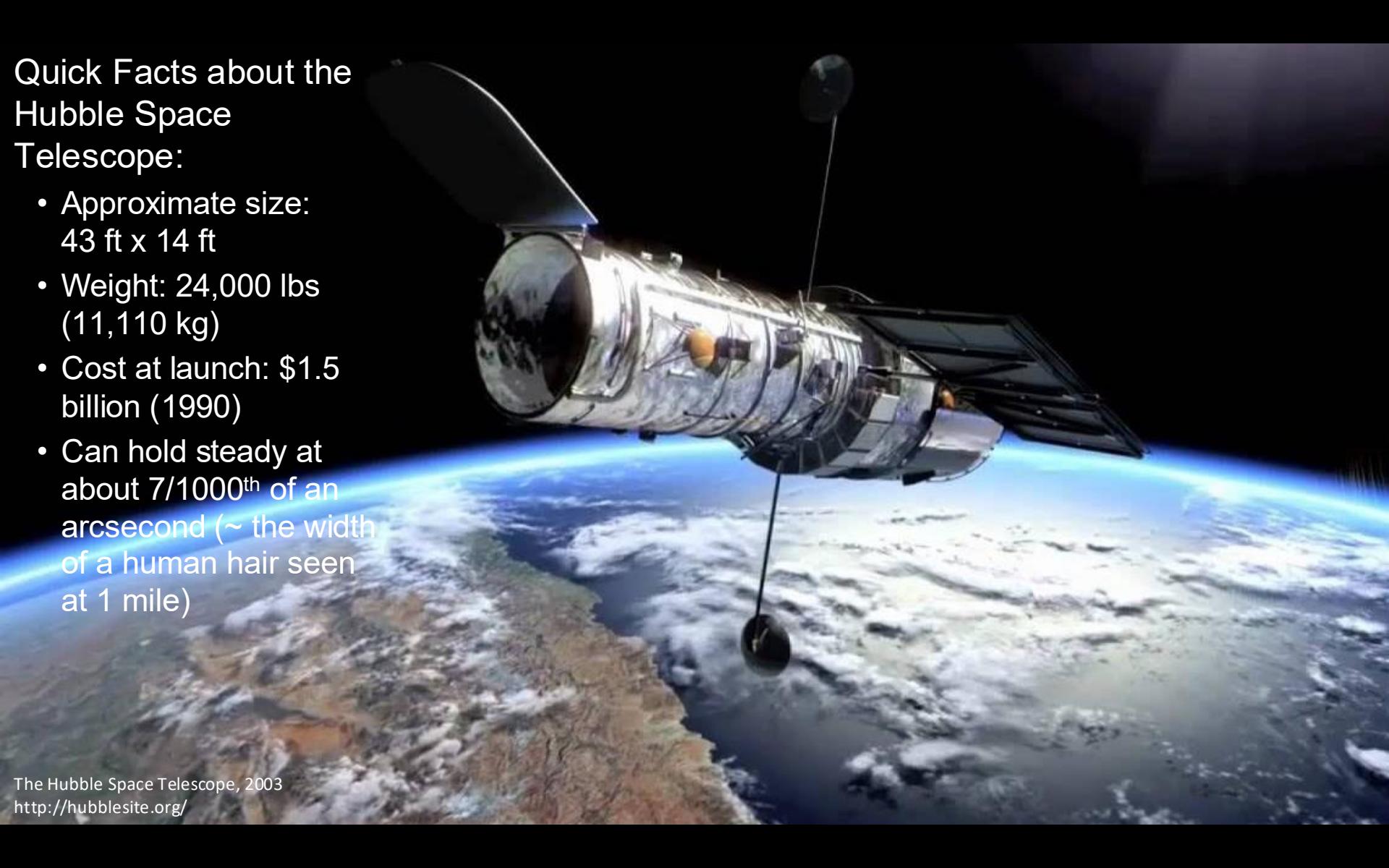


<https://www.history.navy.mil/content/history/museums/nmusn/explore/photography/humanitarian/20th-century/1980-1989/1986-space-shuttle-challenger.html>



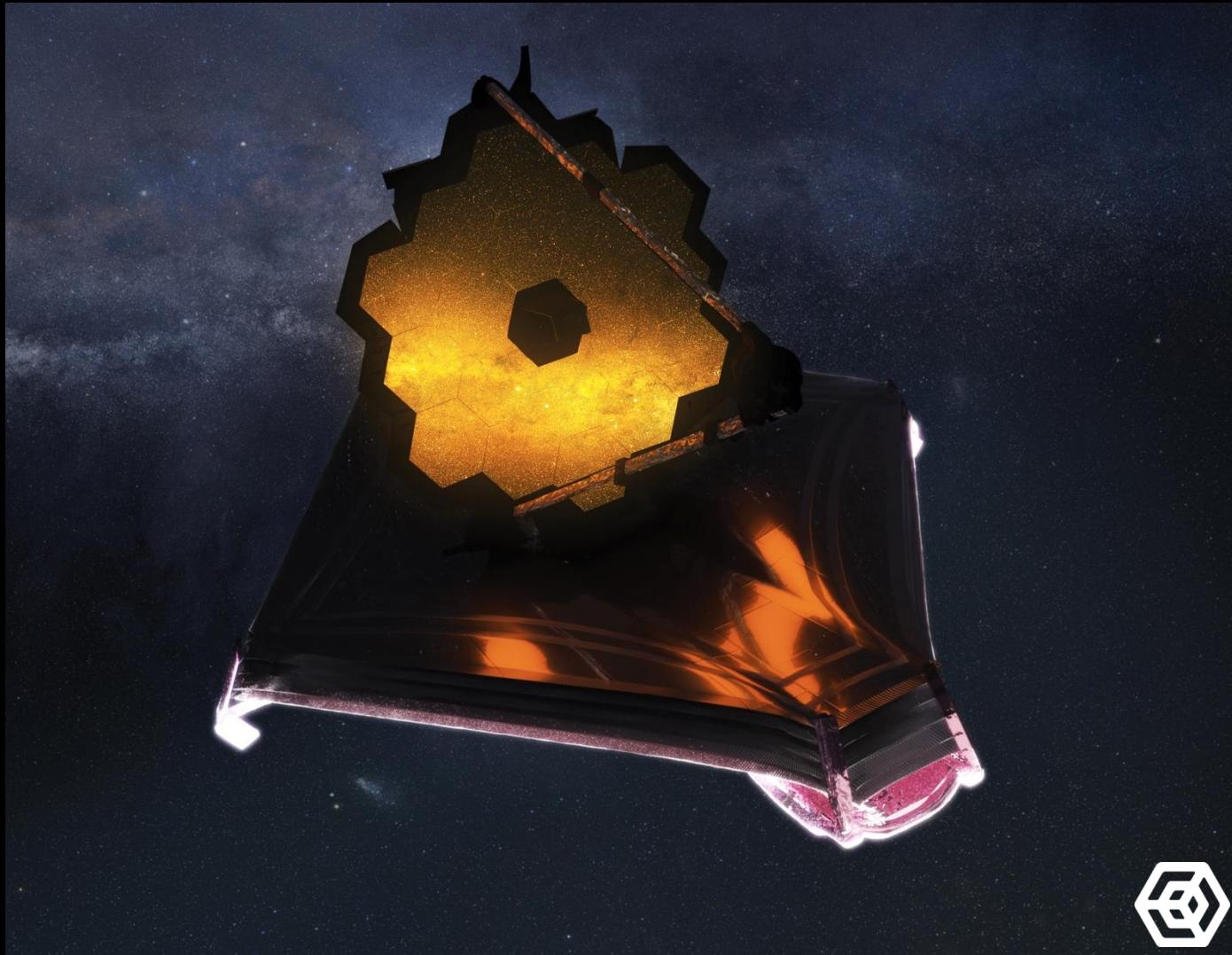
Quick Facts about the Hubble Space Telescope:

- 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 $7/1000^{\text{th}}$ of an arcsecond (~ the width of a human hair seen at 1 mile)



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



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.



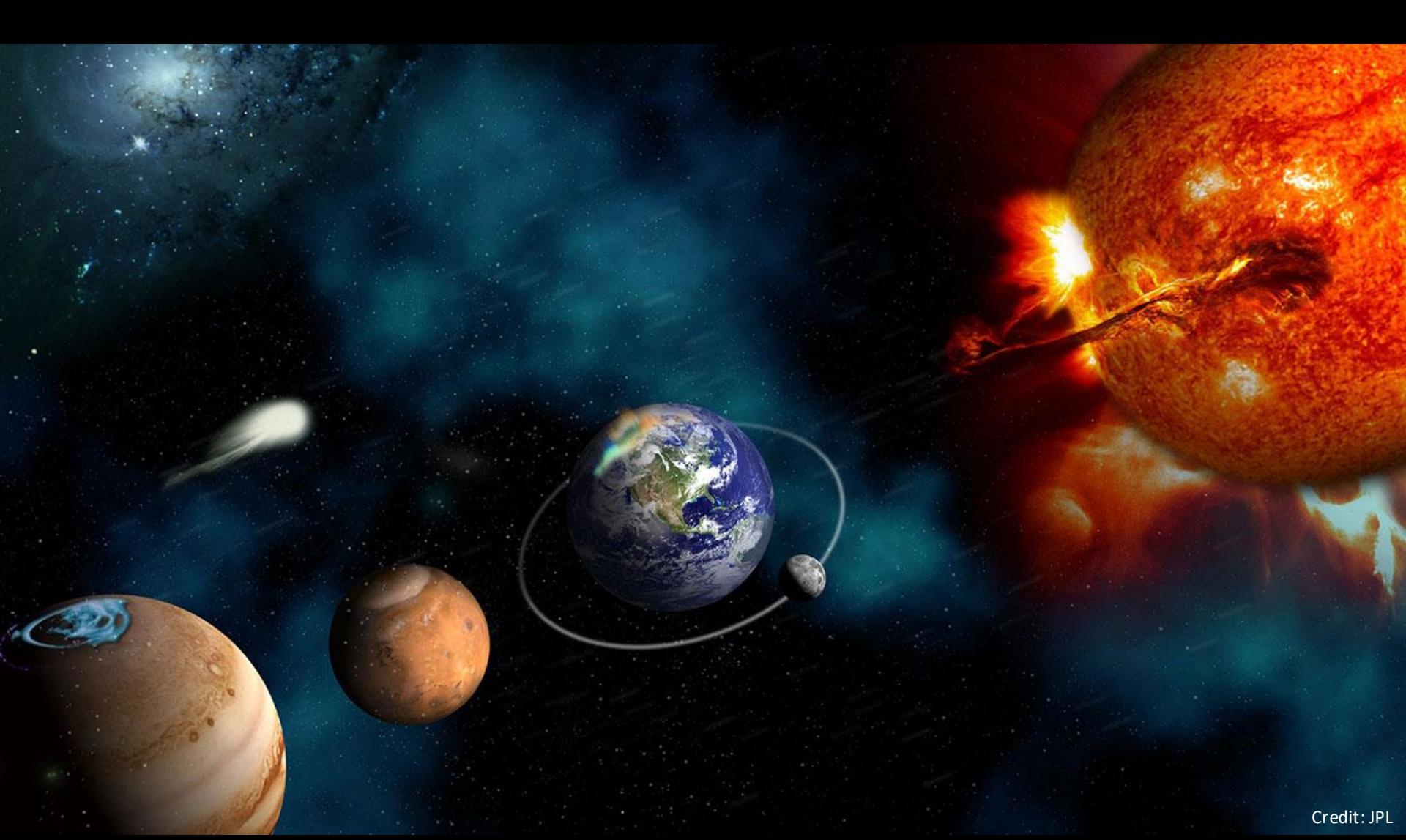
Credit: United States Air Force Senior Airman

Strang[Public domain], via Wikimedia

**An X class flare
resulting in an
aurora over
Bloomington,
IN
May 10, 2024.**



Credit: Trevor Peyton

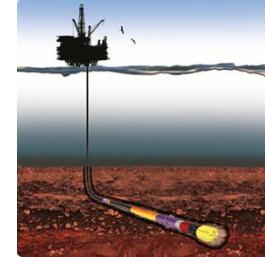
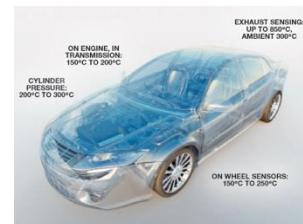
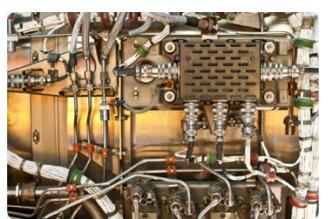


Credit: JPL

Context

- Many applications require electronic devices to operate in extreme environments that can impact operation and reliability

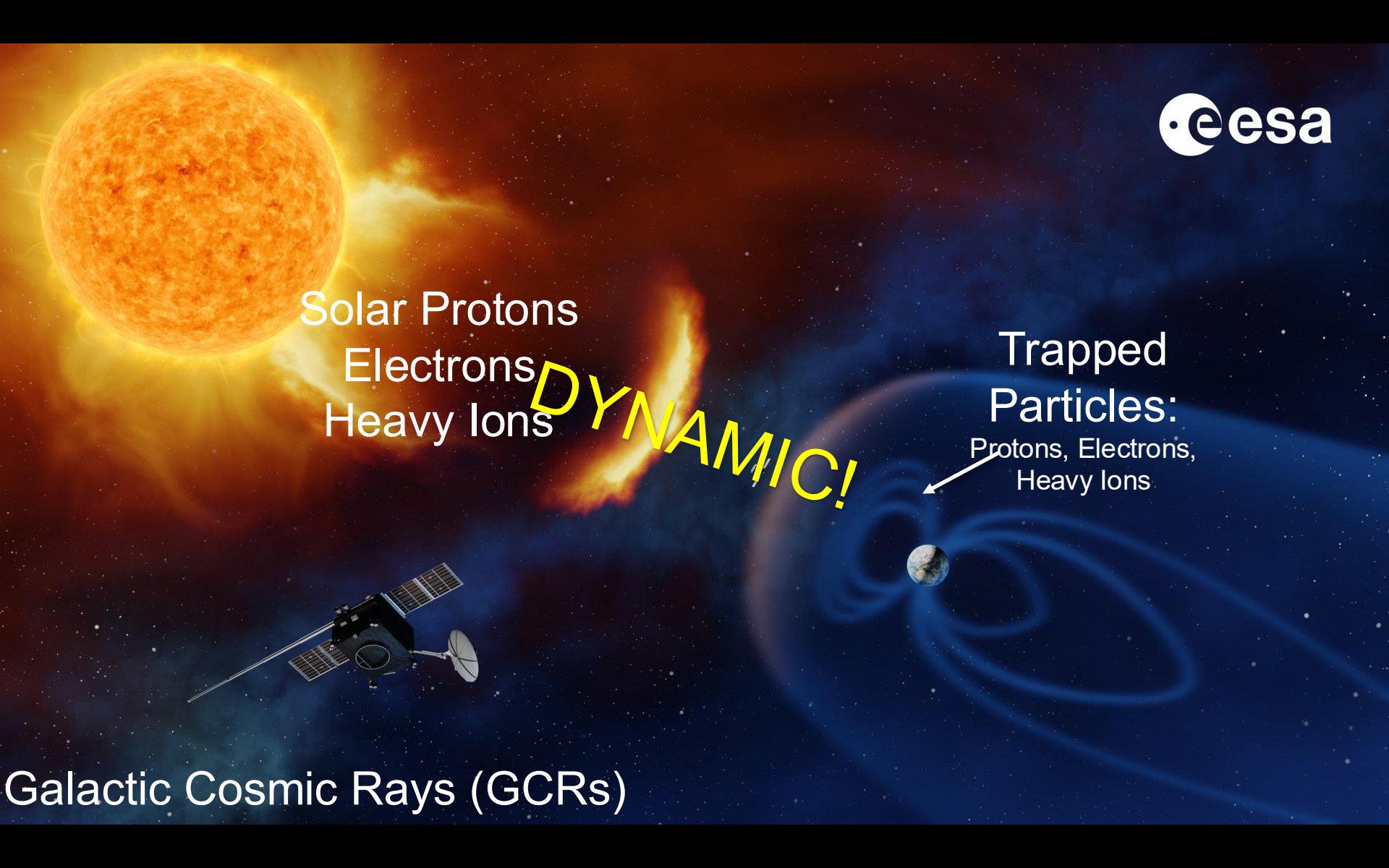
- Vibration/shock
- Temperature
- Pressure
- Radiation



- Natural and man-made radiation environments

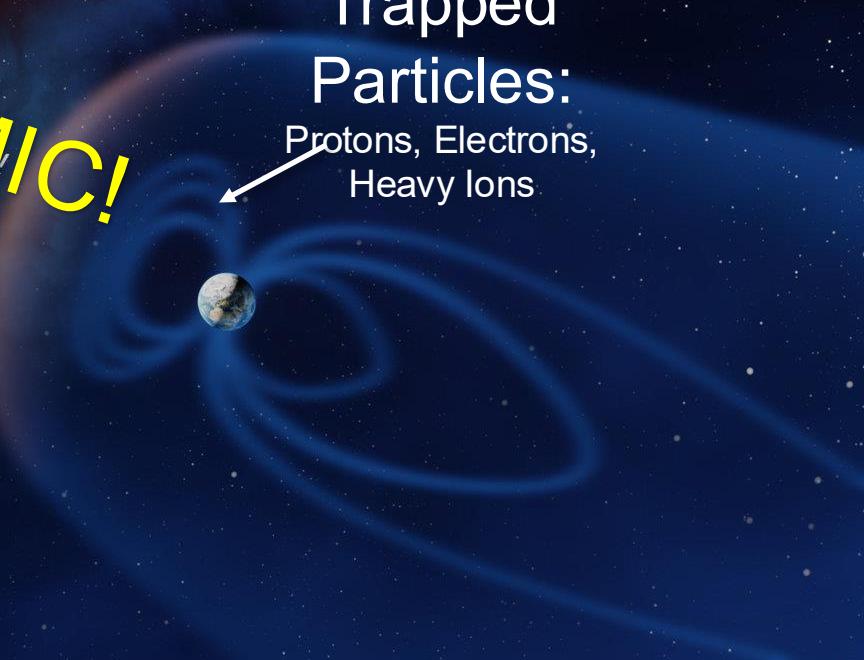
- Space
- Nuclear Power
- Weapons
- Medical
- Terrestrial



A large, bright yellow-orange sun dominates the left side of the image, with several orange and yellow solar flares erupting from its surface. The background transitions from a fiery orange glow near the sun to a deep blue space filled with small white stars.

Solar Protons
Electrons
Heavy Ions

DYNAMIC!

An illustration showing the Earth at the center, surrounded by its magnetic field lines, which appear as blue curved lines. An arrow points from the text "Trapped Particles:" towards the Earth and the magnetic field. The text "Trapped Particles:" is in white, and below it, "Protons, Electrons, Heavy Ions" is also written in white.

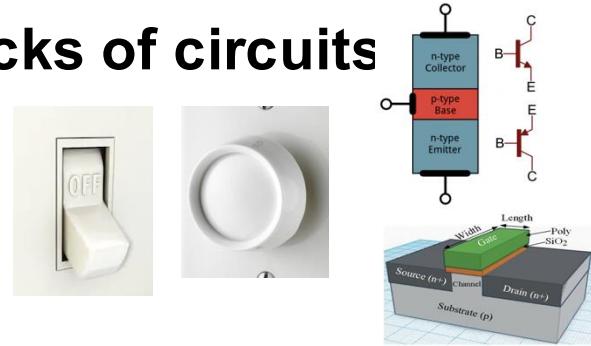
Galactic Cosmic Rays (GCRs)

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)

ELEMENTS OF A SMARTPHONE

ELEMENTS COLOUR KEY: ● ALKALI METAL ● ALKALINE EARTH METAL ● TRANSITION METAL ● GROUP 13 ● GROUP 14 ● GROUP 15 ● GROUP 16 ● HALOGEN ● LANTHANIDE

SCREEN



Inium tin oxide is a mixture of indium oxide and tin oxide, used in a transparent film in the screen that conducts electricity. This allows the screen to function as a touch screen.

The glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al_2O_3) and silica (SiO_4). This glass also contains potassium ions, which help to strengthen it.

A variety of Rare Earth Element compounds are used in small quantities to produce the colours in the smartphone's screen. Some compounds are also used to reduce UV light penetration into the phone.

BATTERY



The majority of phones use lithium ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Some batteries use other metals, such as manganese, in place of cobalt. The battery's casing is made of aluminium.

ELECTRONICS



Copper is used for wiring in the phone, whilst copper, gold and silver are the major metals from which microelectrical components are fashioned. Tantalum is the major component of micro-capacitors.

Nickel is used in the microphone as well as for other electrical connections. Alloys including the elements praseodymium, gadolinium and neodymium are used in the magnets in the speaker and microphone. Neodymium, terbium and dysprosium are used in the vibration unit.

Pure silicon is used to manufacture the chip in the phone. It is oxidised to produce non-conducting regions, then other elements are added in order to allow the chip to conduct electricity.

Tin & lead are used to solder electronics in the phone. Newer lead-free solders use a mix of tin, copper and silver.



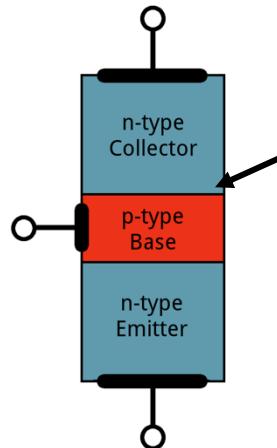
CASING



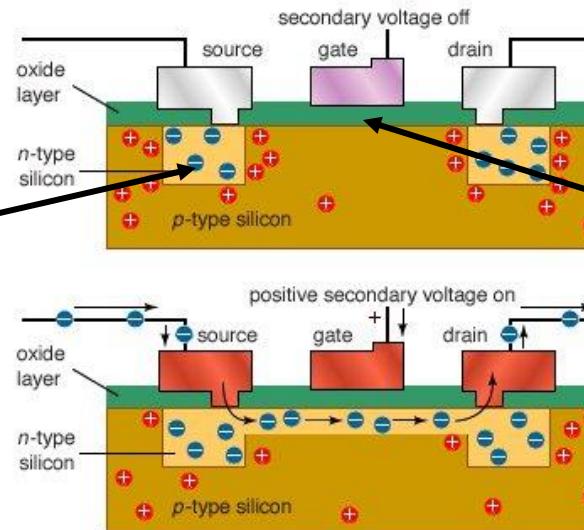
Magnesium compounds are alloyed to make some phone cases, whilst many are made of plastics. Plastics will also include flame retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.

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

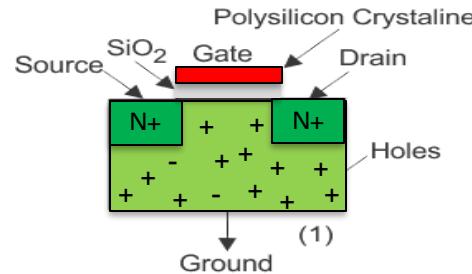


MOSFETs use a
capacitor to “gate”
the conduction via a
field effect

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**

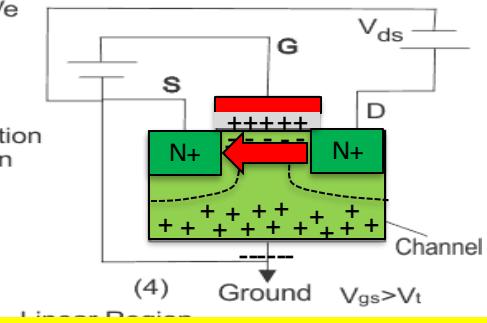
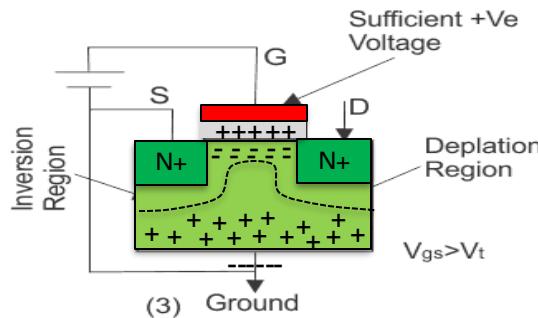
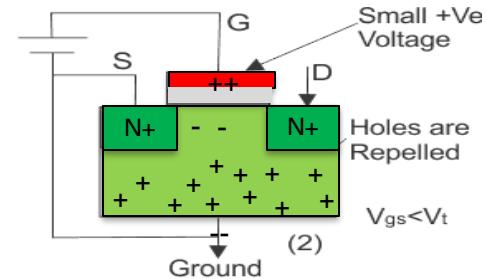
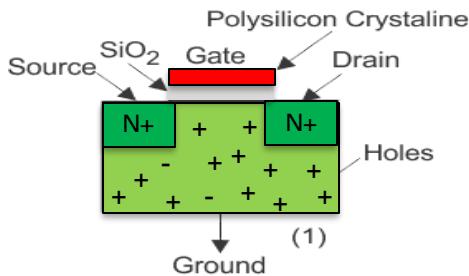


- Field Effect Transistor (FET):

- **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)

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



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/>

The screenshot shows the official website for Scalable Asymmetric Lifecycle Engagement (SCALE). At the top, the Purdue University logo is displayed next to the text "Scalable Asymmetric Lifecycle Engagement (SCALE)". Below the header, there is a navigation bar with links for "ABOUT", "TECHNICAL AREAS", "STUDENTS", "PARTNERS", and "PLACEMENT". The main content area features several sections: "SCALE" (describing it as the preeminent U.S. program for semiconductor workforce development in the defense sector), "Technical Areas" (showing two people working on electronic equipment), "Partners" (showing a map of the world with network connections), and "News" (mentioning a student internship). Each section has a "MORE" button at the bottom right.

PURDUE UNIVERSITY | Scalable Asymmetric Lifecycle Engagement (SCALE)

ABOUT ▾ TECHNICAL AREAS STUDENTS ▾ PARTNERS PLACEMENT

SCALE

SCALE is the preeminent U.S. program for semiconductor workforce development in the defense sector.

Funded by the Department of Defense, SCALE is led by Purdue University and managed by NSWC Crane on behalf of OUSD R&E. SCALE facilitates a different approach to training highly-skilled U.S. microelectronics engineers, hardware designers, and manufacturing experts, ensuring U.S. leadership in this important area.

[ABOUT SCALE](#)

[STUDENT BENEFITS](#)

[STUDENT PLACEMENT](#)

Technical Areas

Partners

Apply Now

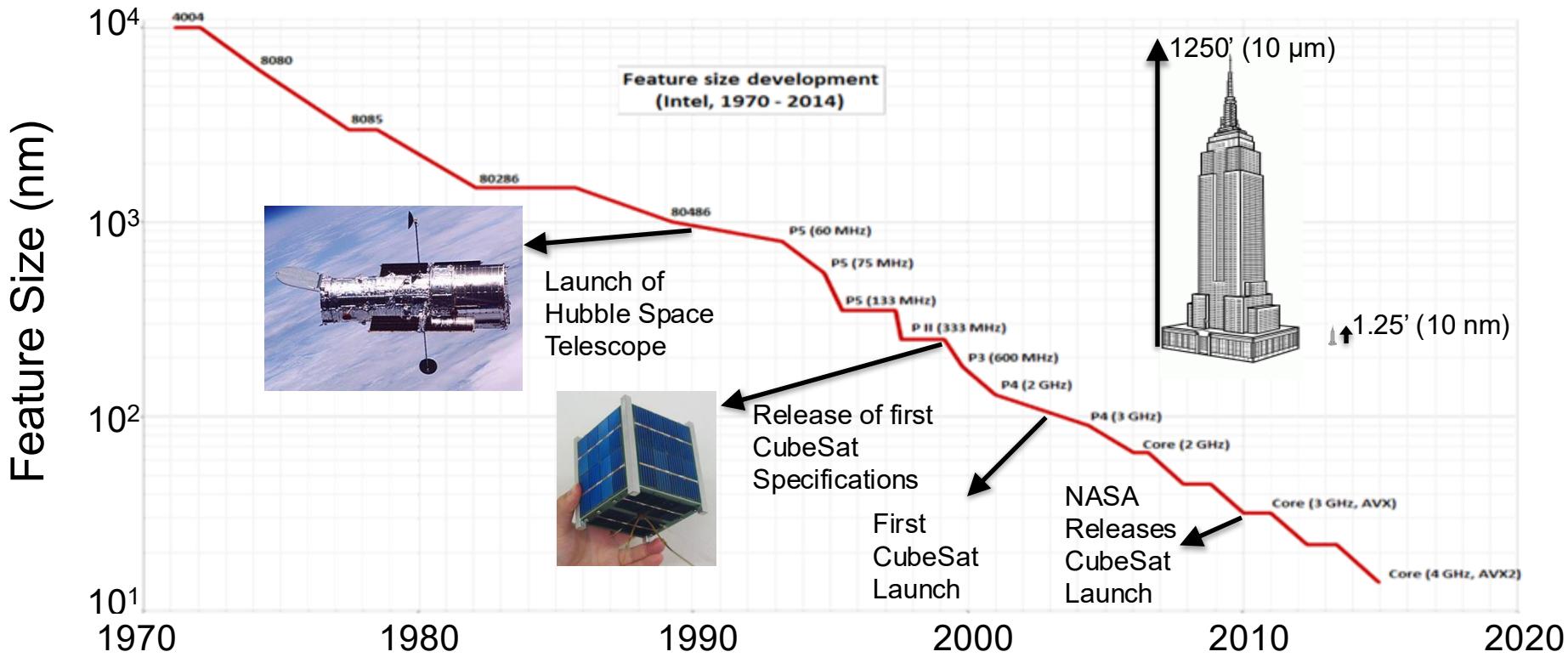
Now accepting student applications

News

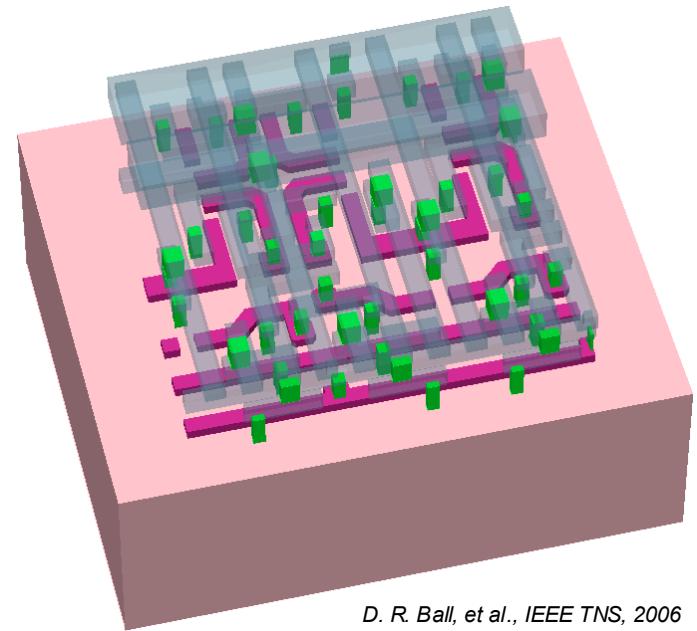
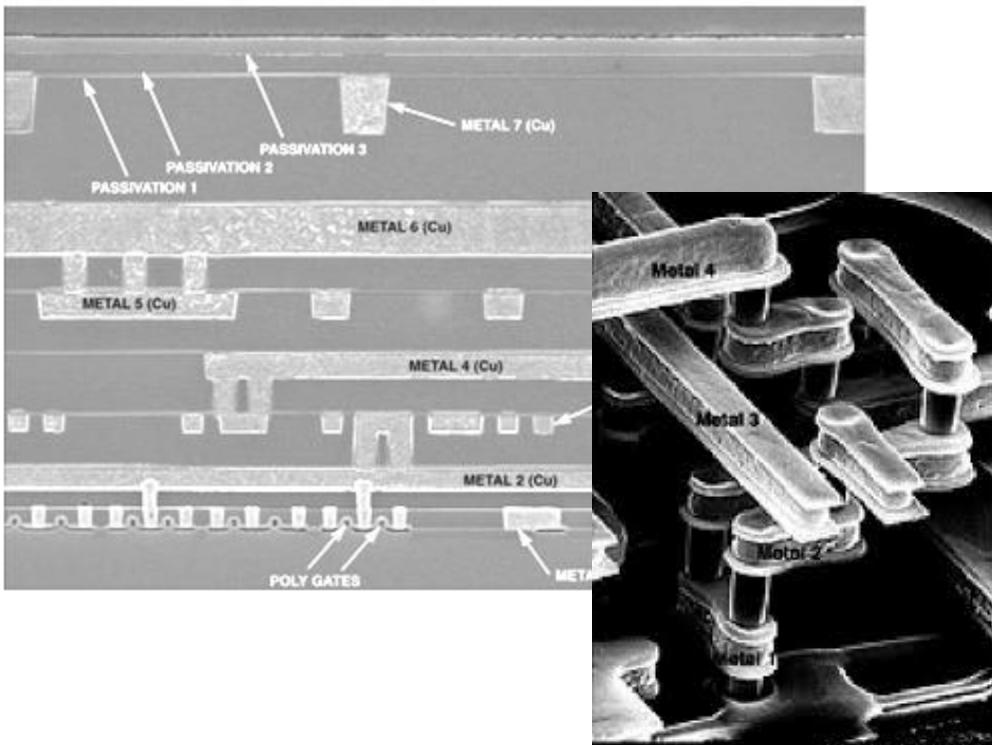
SCALE's 'something to be proud of' internship boosts sophomore's confidence, future career

[MORE NEWS](#)

Feature Size Development (Intel)

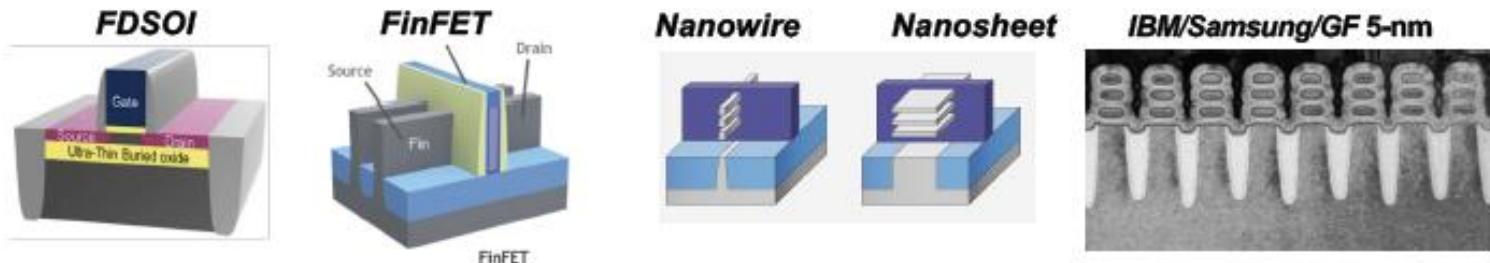


Modern Integrated Circuits (ICs)?



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

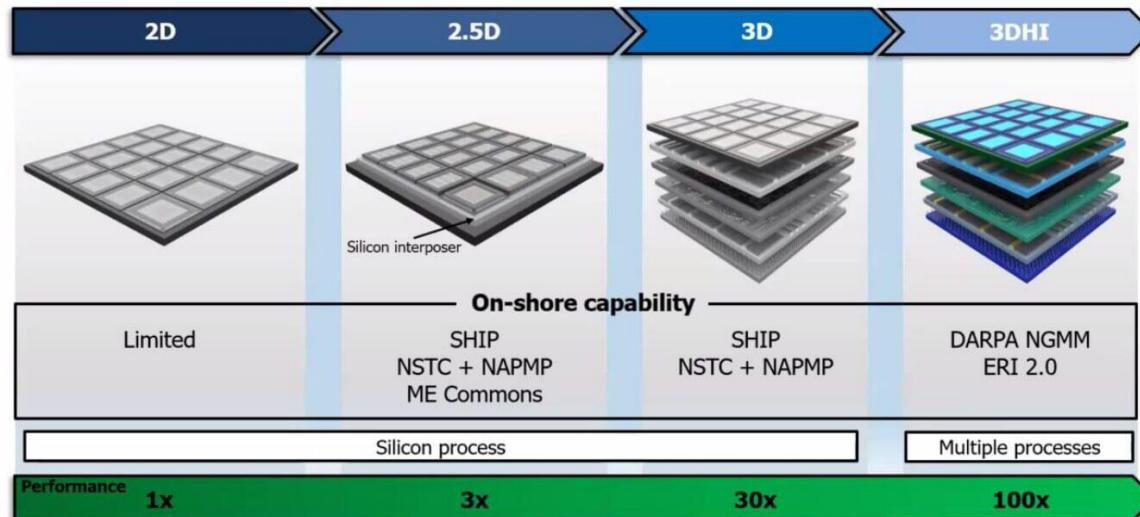
Modern Integrated Circuits

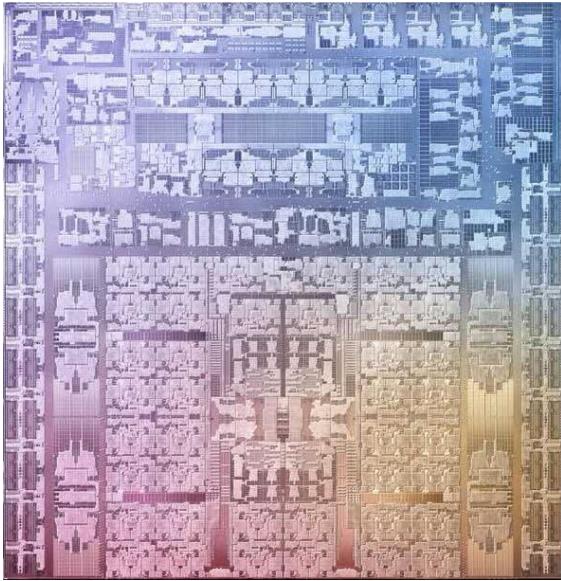


Better electrostatics allows reducing L while controlling SCE

Esqueda, JPL Workshop, 2019

**SCE: Short-Channel Effects*





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

Technology is Evolving Rapidly, So Must Education and Workforce

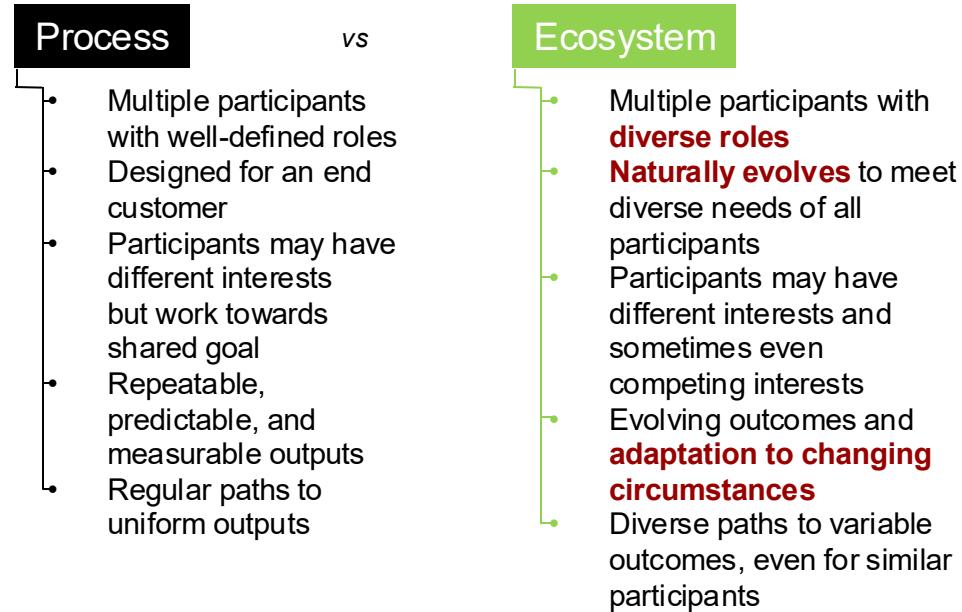
By 2030 ...

300,000

Shortage of engineers

90,000

Shortage of skilled workers



Source: <https://www.mckinsey.com/industries/semiconductors/our-insights/how-semiconductor-makers-can-turn-a-talent-challenge-into-a-competitive-advantage>

Source: deloitte.com/insights

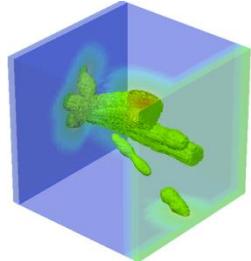
Radiation Effect Types

- 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)

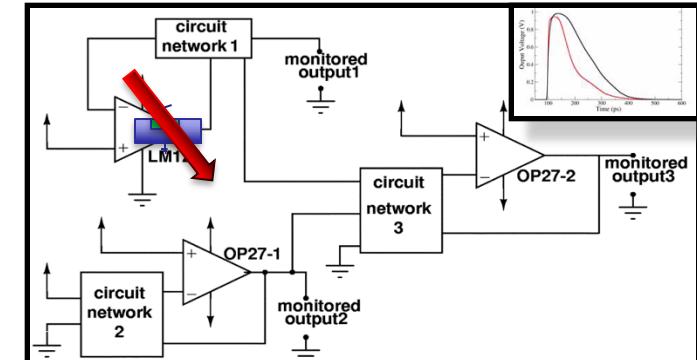
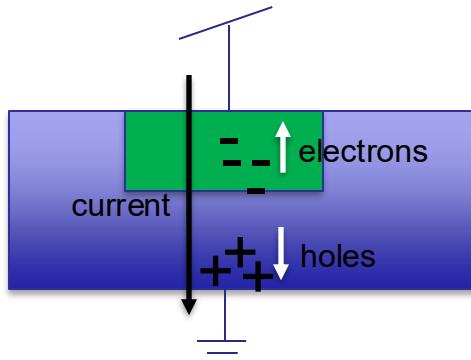
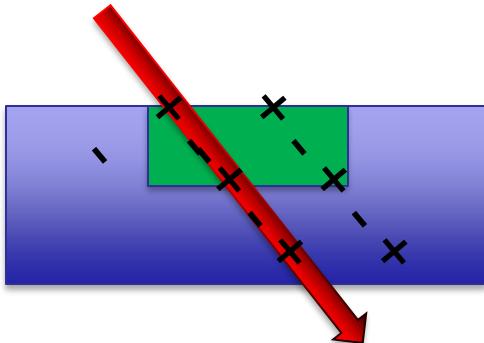
The primary terrestrial and a significant space radiation effect

- **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 an 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)**

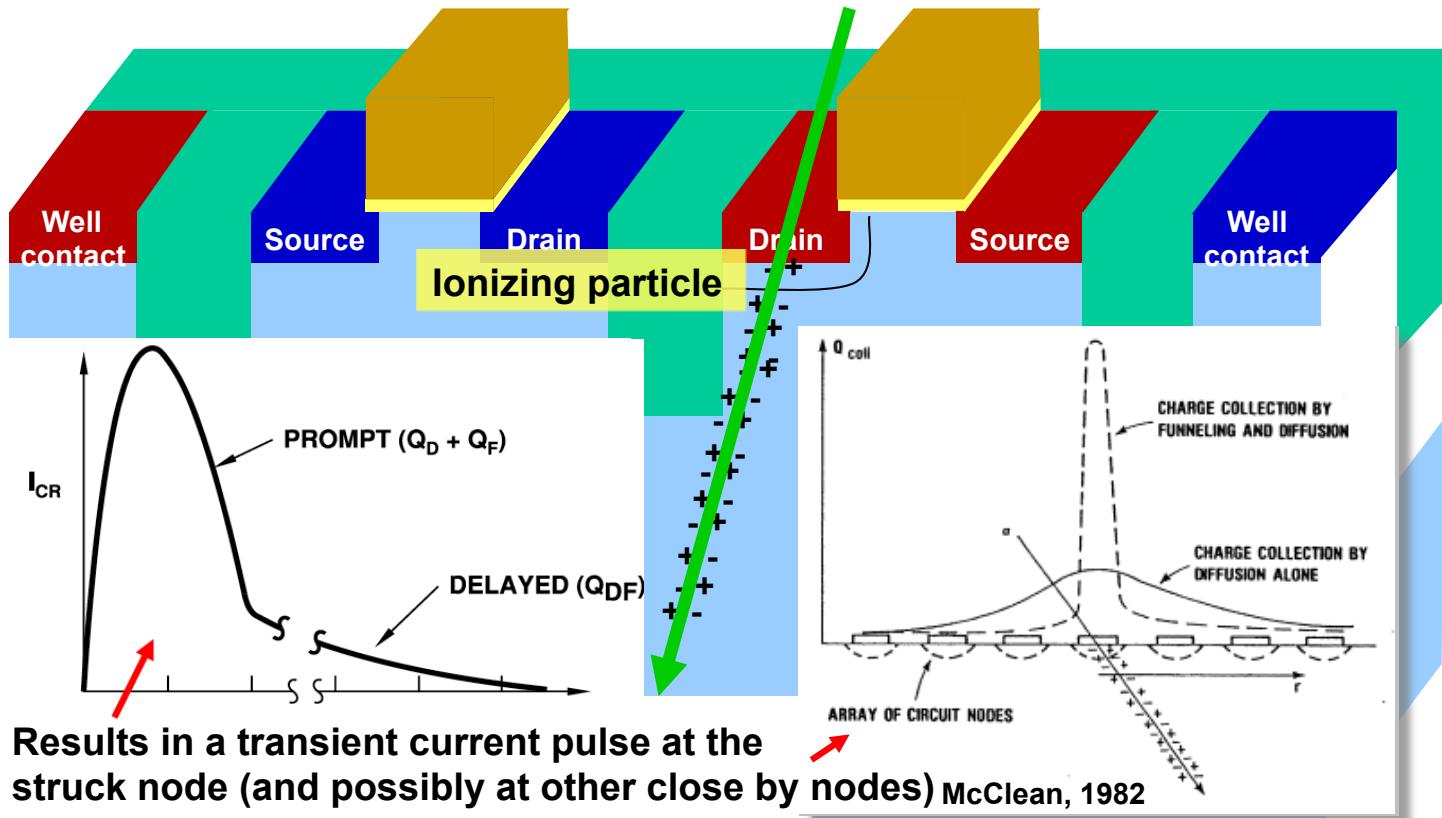


Single-Event Effects in Microelectronics

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



Single-Event Charge Collection



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

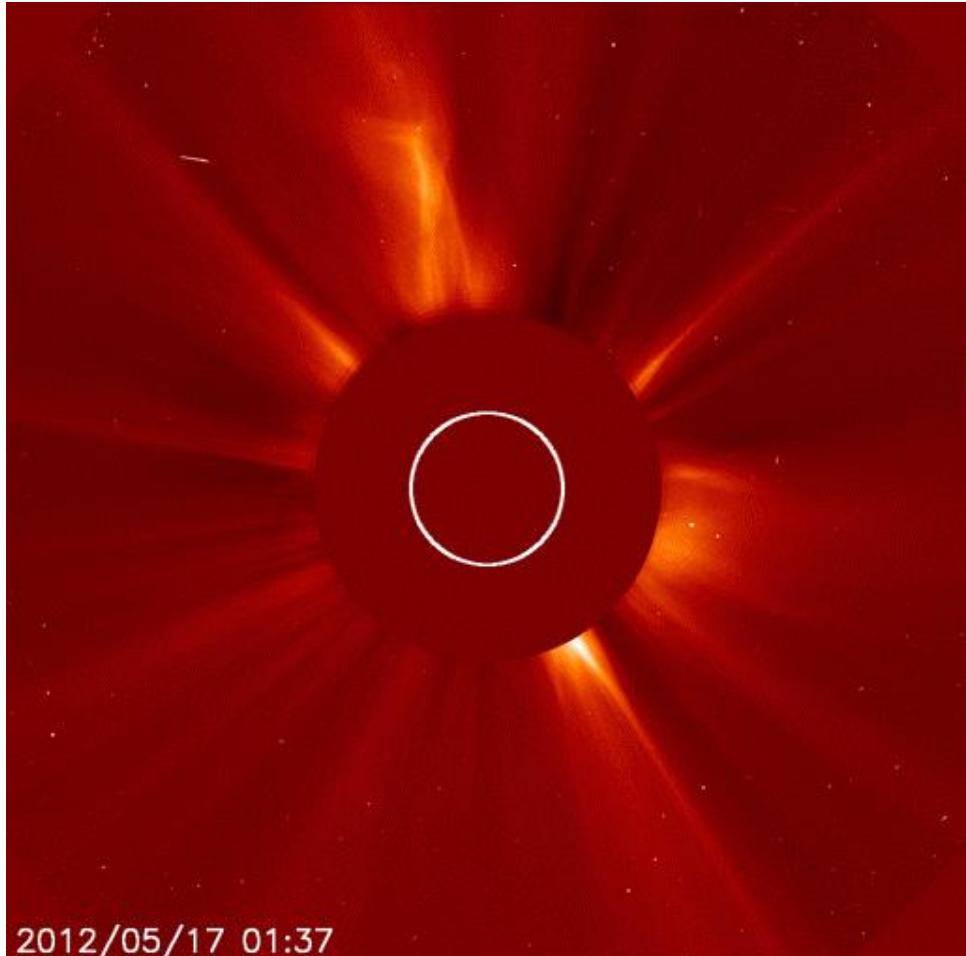
Coronal Mass Ejection

NASA on May 16-17th, 2012:

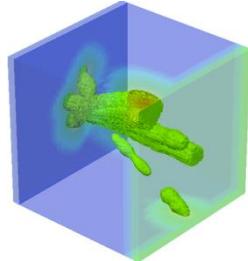
A coronal mass ejection (CME) was associated with a M-class solar flare occurring on May 16th. The burst traveled over 930 mps and impacted a variety of spacecraft. The flare also resulted in a moderate radio blackout.

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

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



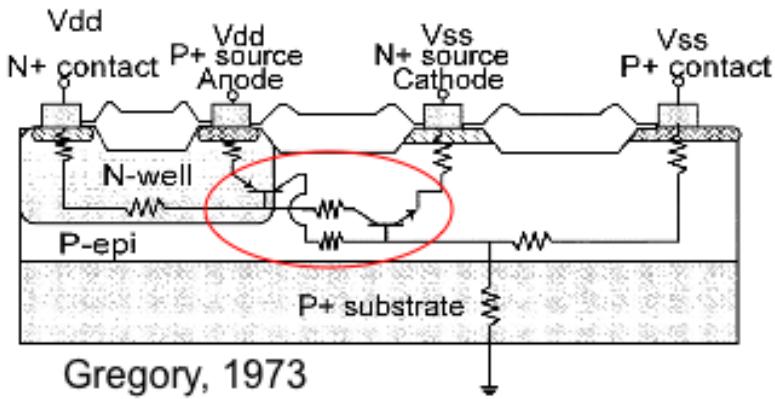
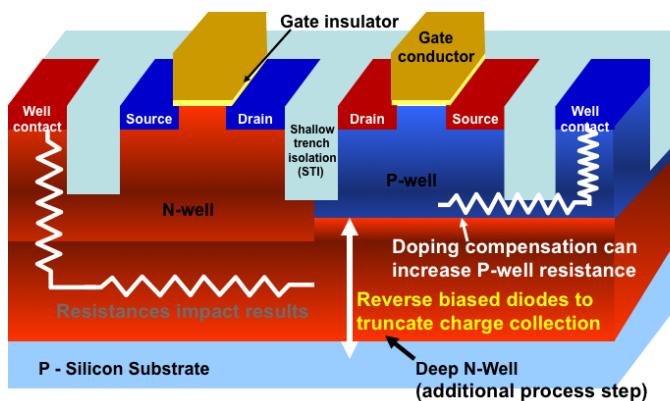
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Single-Event Effects in Microelectronics

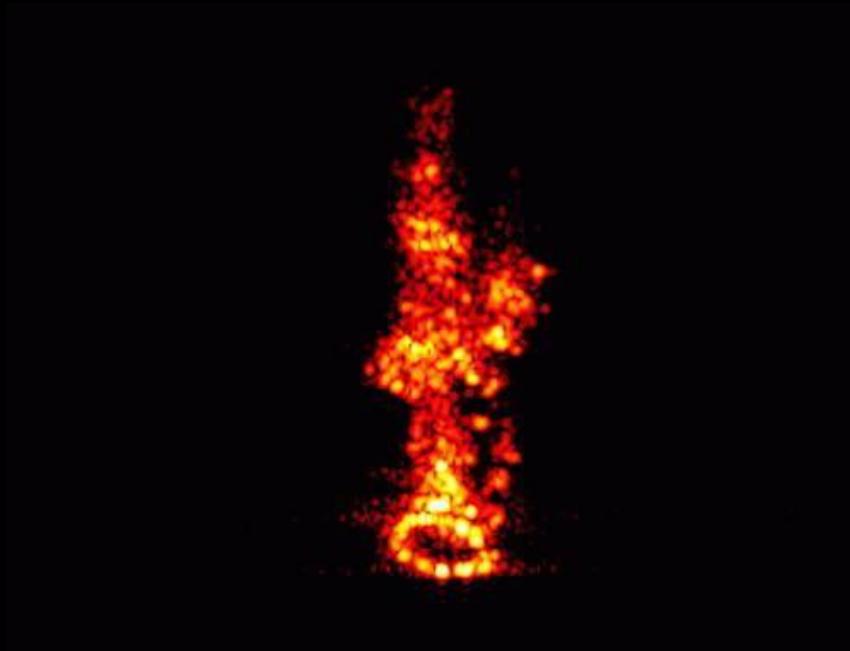
- Caused by the interaction of a single energetic particle
- SEE are determined by:
 - Charge generation
 - Charge collection
 - Circuit response
- Types:
 - Non-destructive:*
 - **Single-event upsets (soft errors)**
 - **Single-event transients**
 - Single-event functional interrupt
 - Multiple-bit upsets
 - Destructive:*
 - **Single-event latchup**
 - Single-event burnout
 - Single-event gate rupture
 - Single-event snap-back

Single-Event Latchup (SEL)



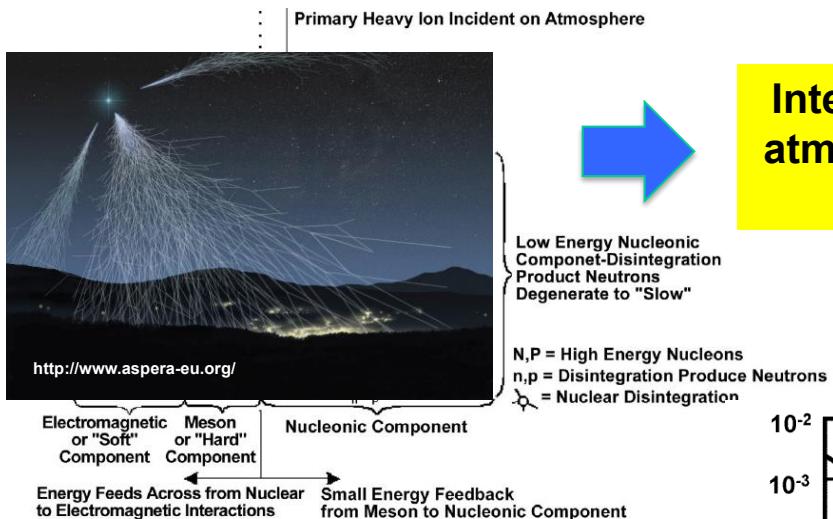
Single event can trigger sub-surface bipolar structures in positive feedback loop in bulk CMOS = Single Event Latchup

Phobos-Grunt Failure



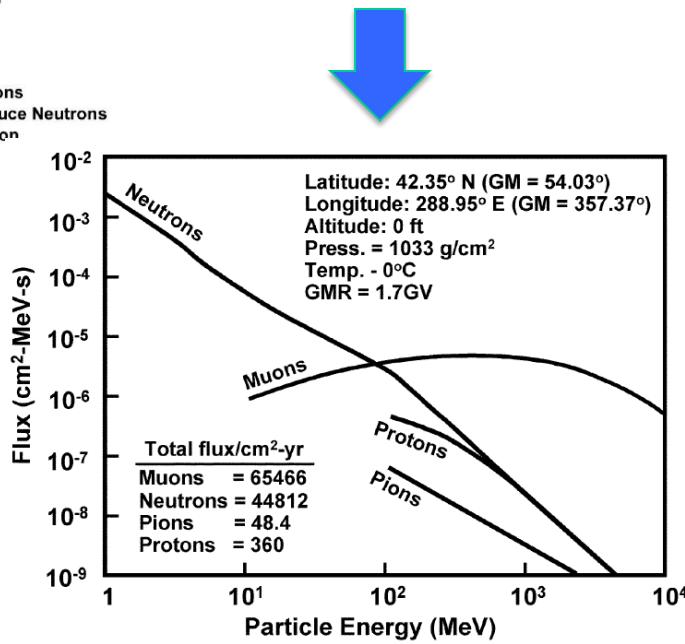
Phobos-Grunt re-entry after mission failure
SEL?

SEE – Terrestrial Radiation



Interaction of radiation with the atmosphere results in terrestrial radiation environment

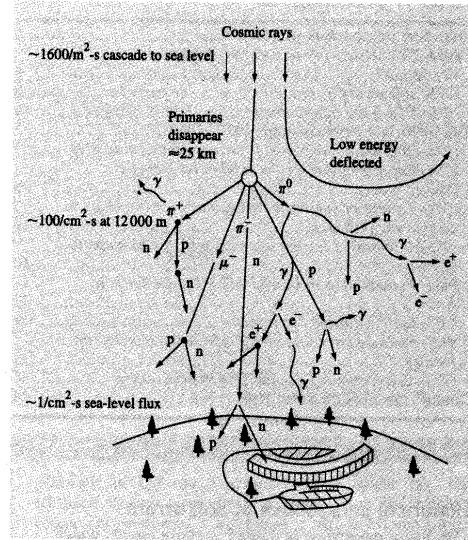
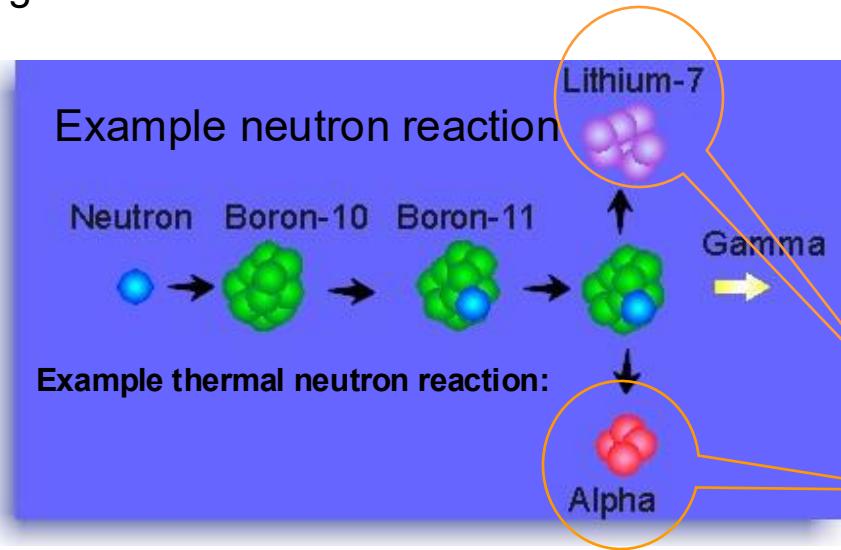
Interact with materials used in microelectronic leading to damage or ionization; processes may include secondary reaction products



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; 2.4 μm ; 1.5ps; 36fC

1.5 MeV; 5.2 μm ; 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	Material	Alpha radiation flux (a/khr cm ²)
Solders	Processed wafers	0.9
Alumina substrates	Cu metal (thick)	1.9
BEOL metallizations	Al metal (thick)	1.4
Fillers in plastics, encapsulants, underfills, mold compounds and solder masks	Mold compound	24 to < 2
Flux	Underfill	2 to 0.9
Lead frame alloys	Pb solders	7200 to < 2
Materials (Au, Cu, Ag etc) used for wire bonding and lid plating	LC II Pb (HEM)	50 to 3
Particulates from PBGA trimming / handling operations	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

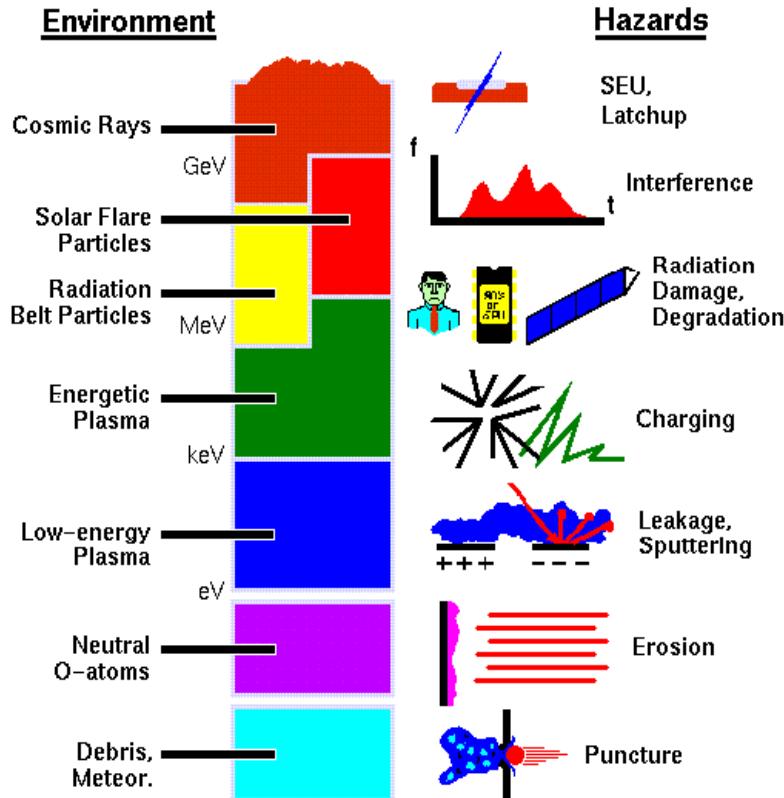
The main sources of energetic particles of concern to spacecraft designers

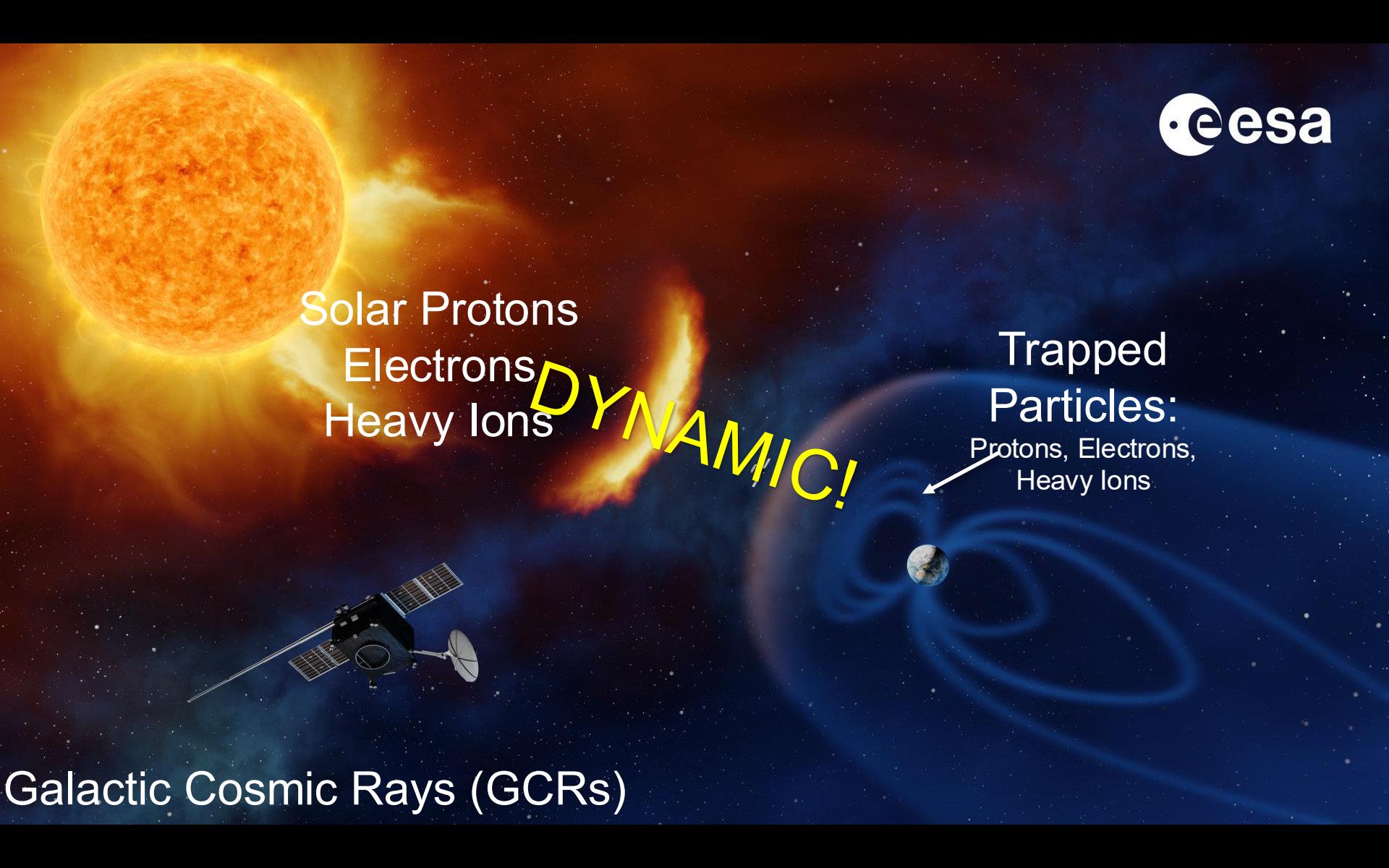
1) cosmic ray protons & heavy ions

2) protons and heavy ions from solar flares

3) protons & electrons trapped in the Van Allen belts

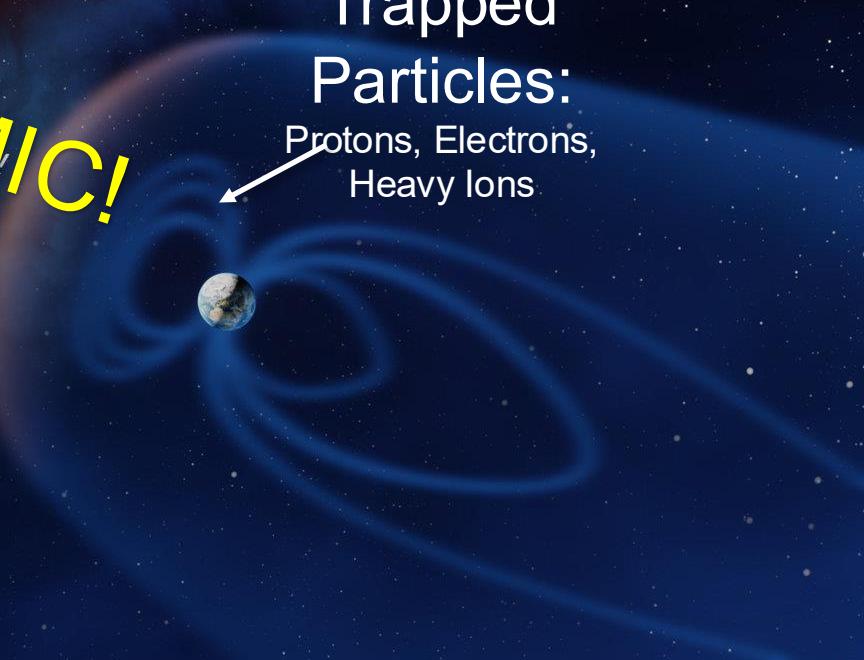
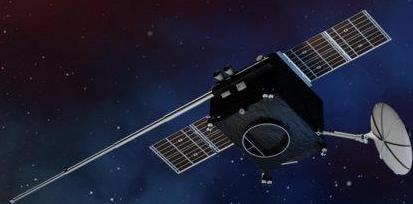
4) heavy ions trapped in the magnetosphere



A large, bright yellow-orange sun dominates the left side of the image, with several orange and yellow solar flares erupting from its surface. The background transitions from a fiery orange glow near the sun to a deep blue space filled with small white stars.

Solar Protons
Electrons
Heavy Ions

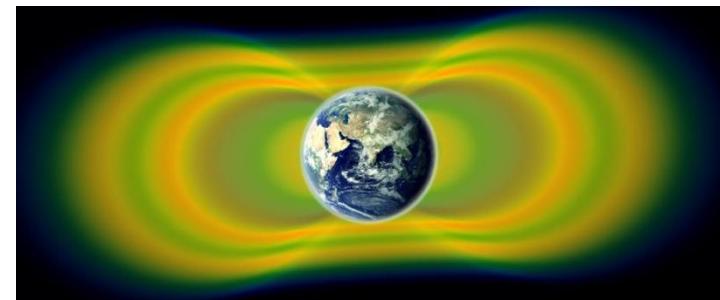
DYNAMIC!

An illustration showing the Earth at the center, surrounded by its magnetic field lines, which appear as blue curved lines. An arrow points from the text "Trapped Particles:" towards the Earth and the magnetic field. The text "Trapped Particles:" is in white, and below it, "Protons, Electrons, Heavy Ions" is also written in white.

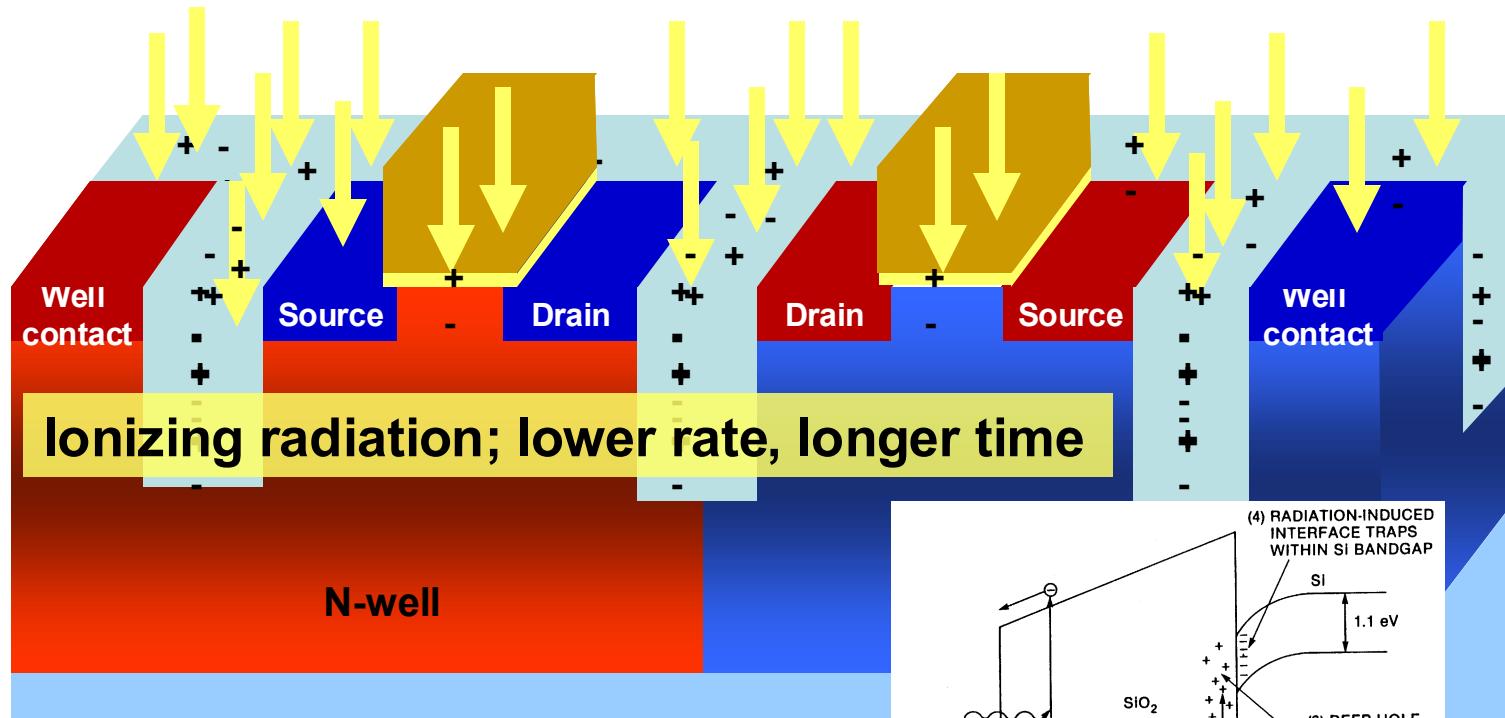
Galactic Cosmic Rays (GCRs)

Single-Event Environments

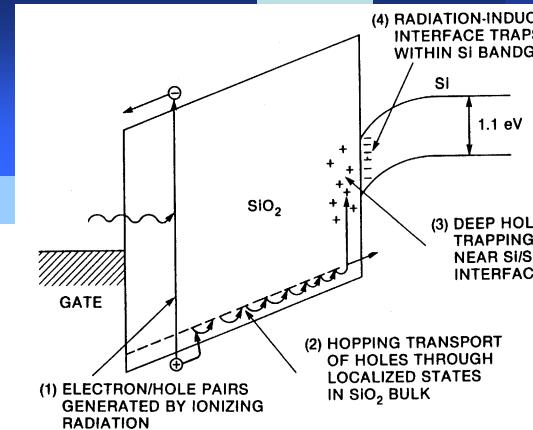
- Heavy, highly-energetic ions from deep space (galactic cosmic rays)
- Energetic protons (trapped in the van Allen radiation belts)
- Neutron products (terrestrial pests)
- Alpha particles (from contaminants and processing materials)
- Muons



Total Ionizing Dose (TID)

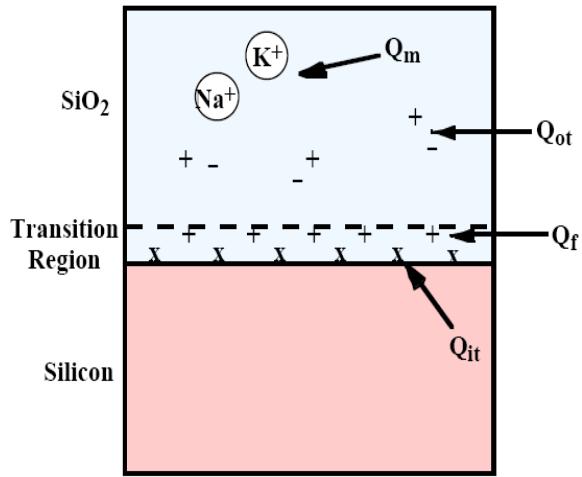


Electron-hole pairs created in insulators:
Higher electron mobility, lower electron
trapping = net positive trapped charge and
interface traps in insulators



McClean, 1987

Electrical Impact of TID



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

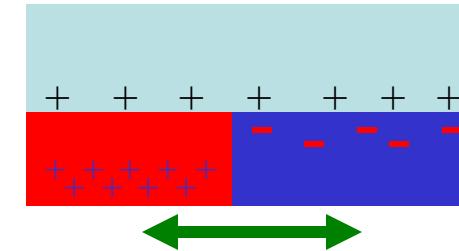
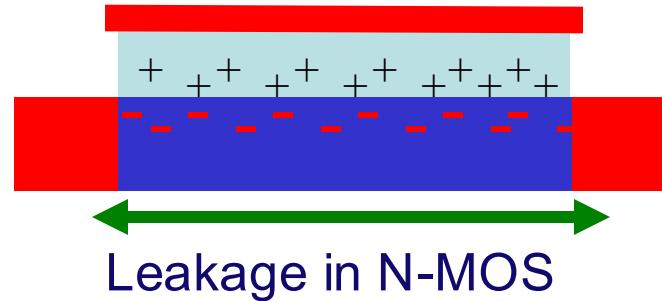
Q_f - fixed oxide charge

Q_{it} - interface trapped charge

Q_m - mobile oxide charge

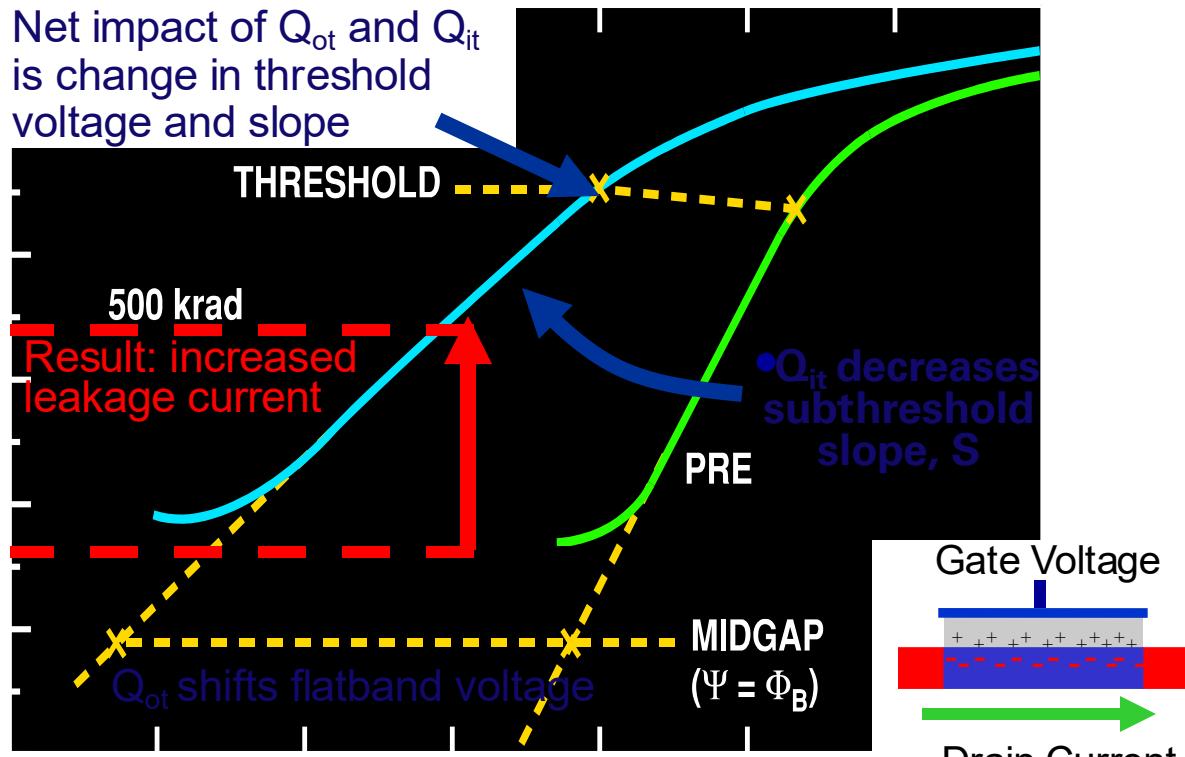
Q_{ot} - oxide trapped charge

[20] Plummer, 2000



Junction Leakage in BJTs

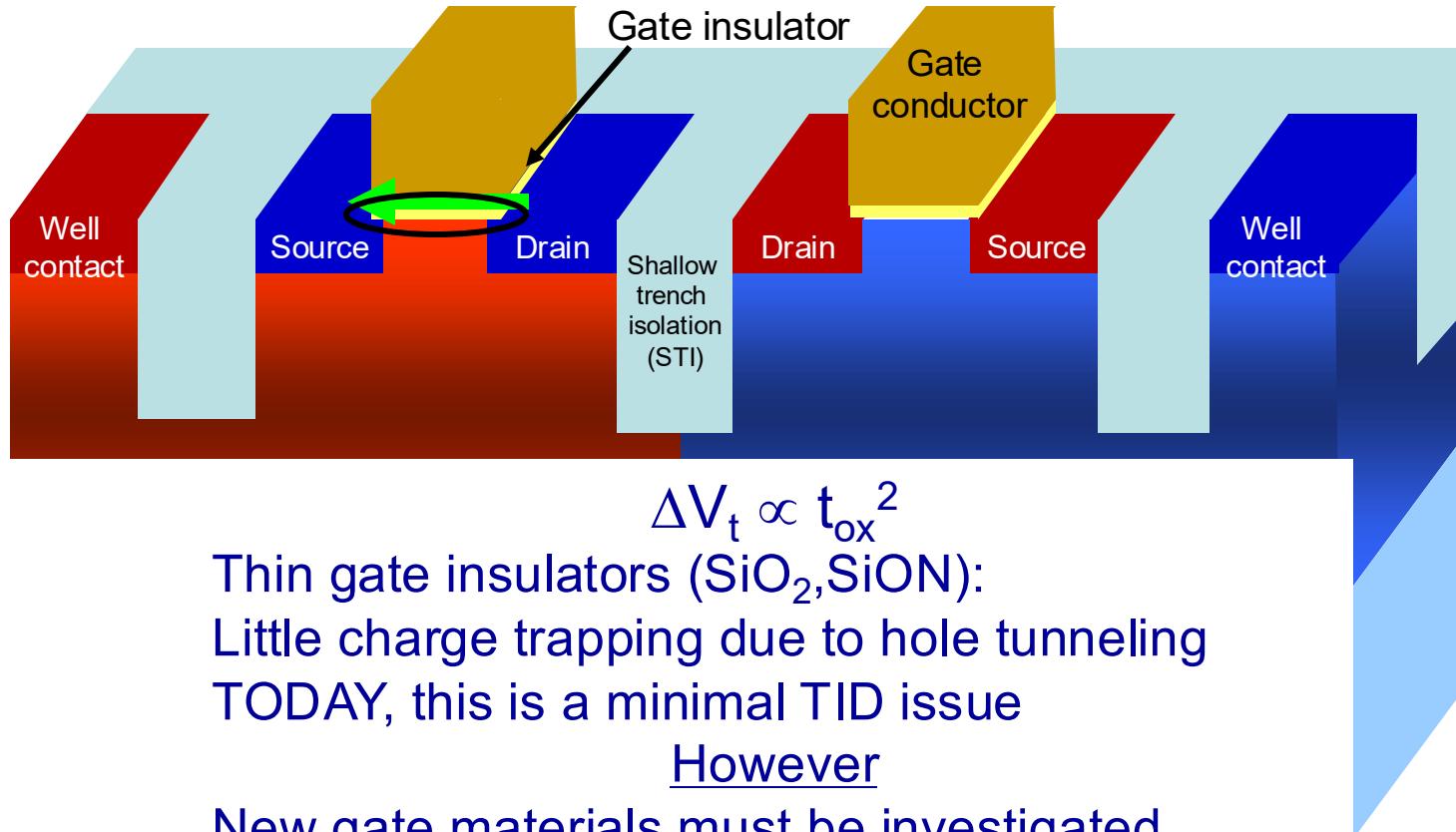
Electrical Impact of TID on MOS



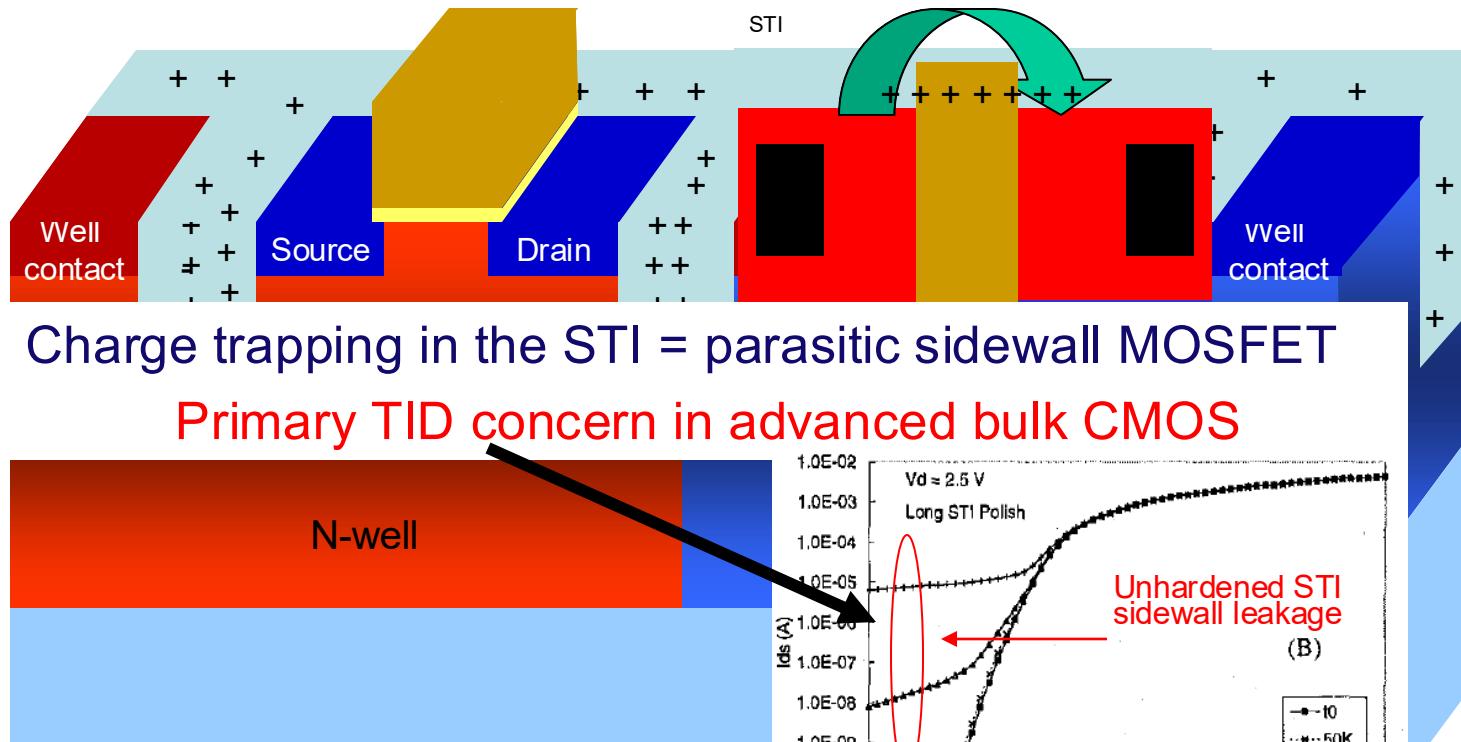
Increased Leakage, Decreased transconductance
(slower, more power consumption)

Schwank, 1994

TID in Gate Insulators

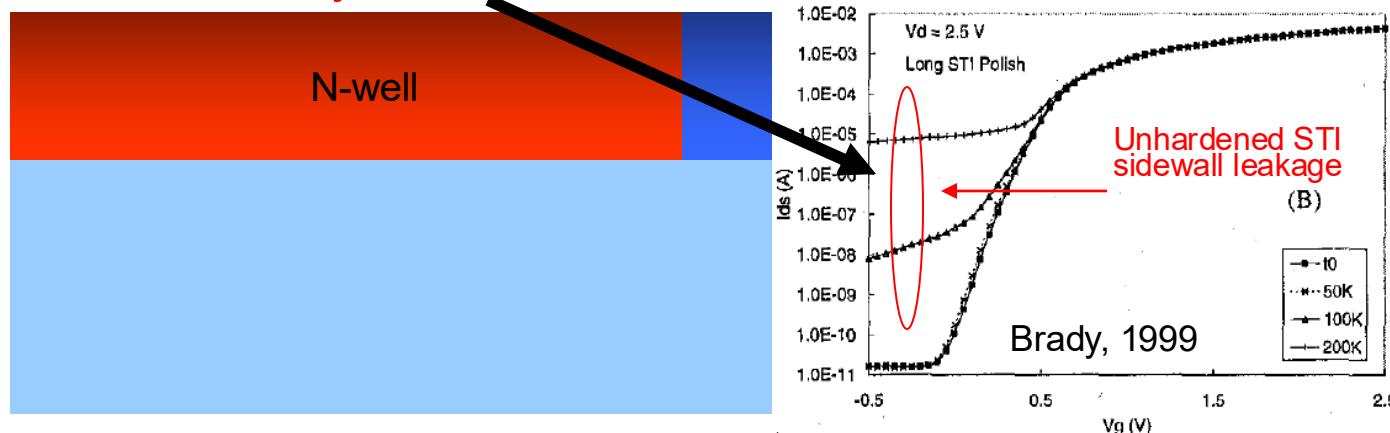


TID in STI Oxides: Intra-Device

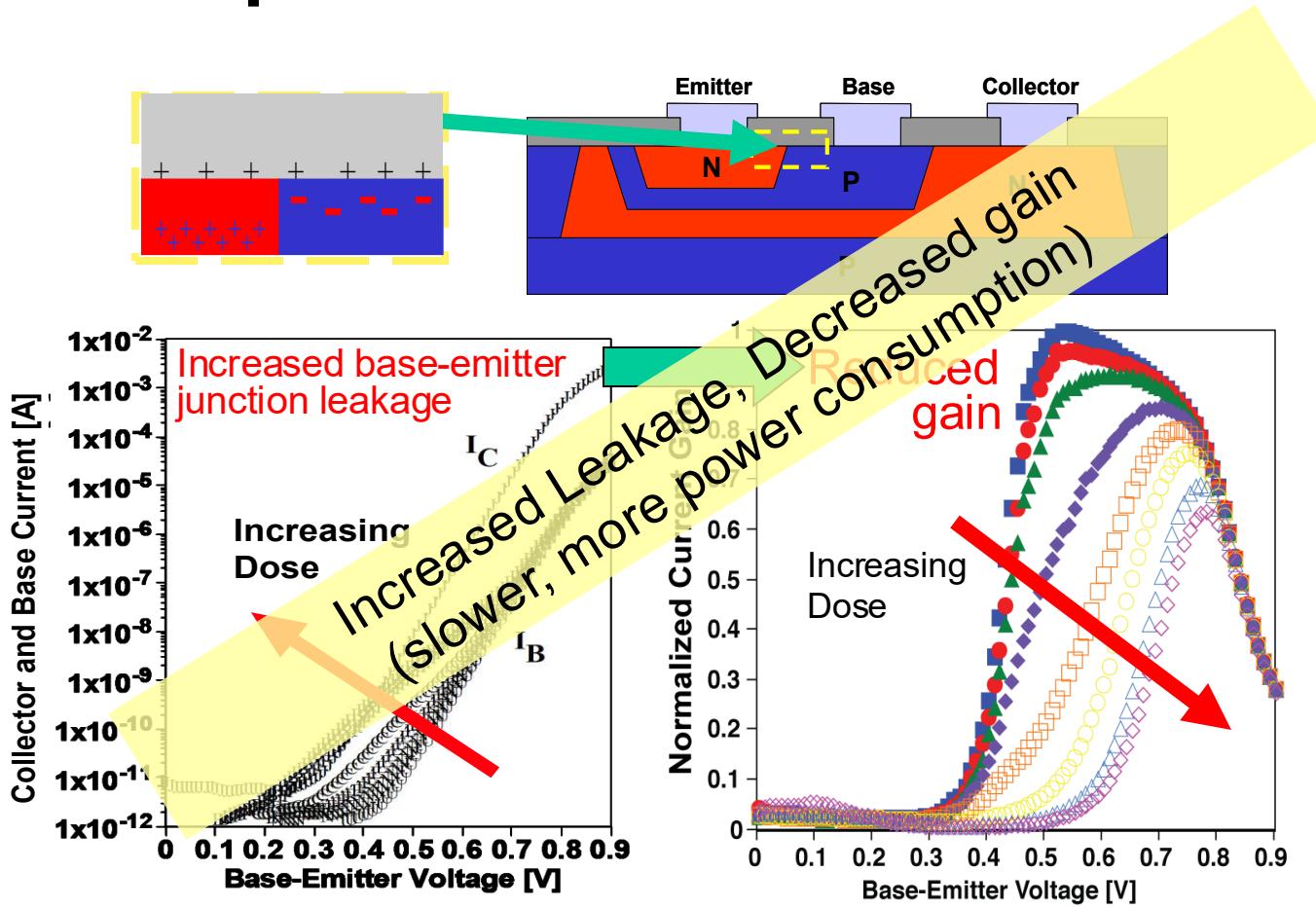


Charge trapping in the STI = parasitic sidewall MOSFET

Primary TID concern in advanced bulk CMOS

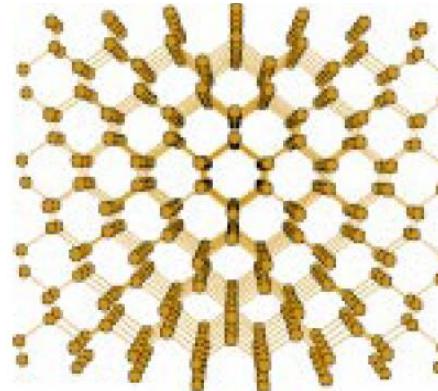


Electrical Impact of TID on BJT

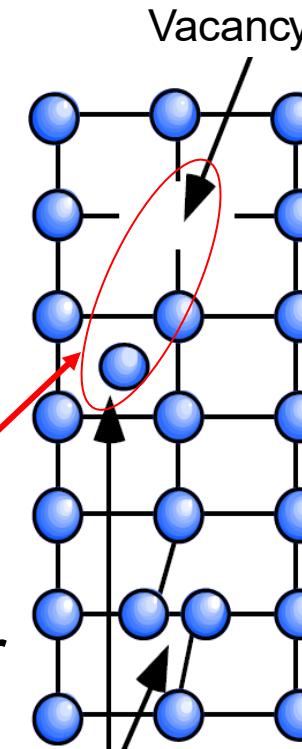


[22] Schrimpf, 2004

Displacement Damage (eps. Neutrons)



- 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



Plummer, 2000

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

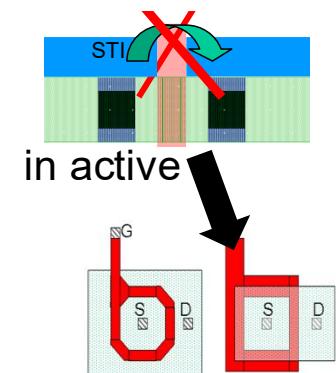
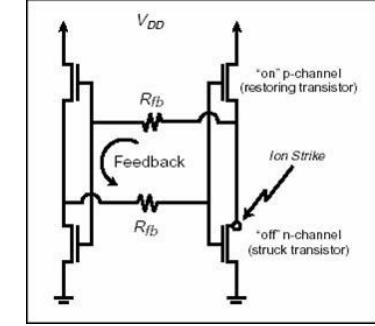
- **System-level management**
 - EDAC, redundancy, voting
 - Circumvention (shut down and restart)
 - Shielding
- **Hardened by design (HBD)**

- 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)**

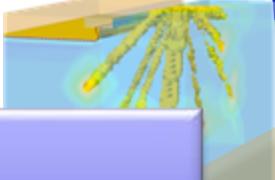


- Modified materials (balance e-h trapping in minority carrier lifetime reduction material regions)
- Doping profiles
- Device structures (FinFETs)
- Substrate engineering (Ex: epi, doping, SOI)



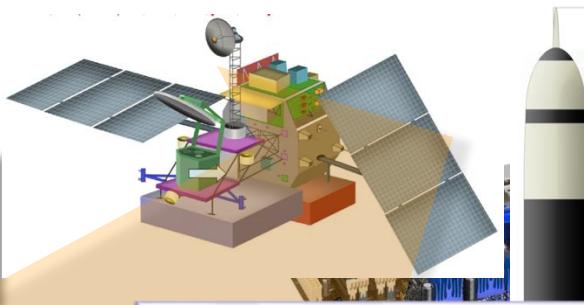
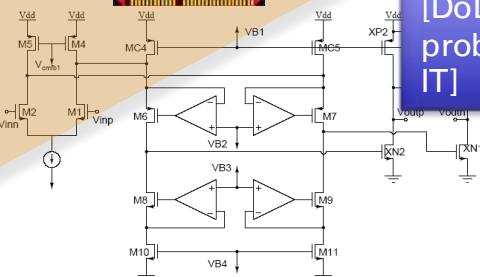
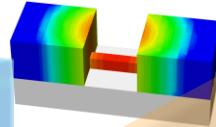
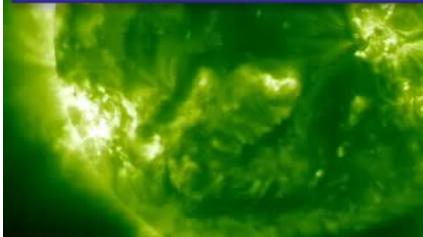
Mechanisms to Missions

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



Hostile Environment

[DoD missions, deep space, commercial/DoD orbit, surface]



Mission-critical systems

[DoD strategic/tactical, probes, sat IT]



Some useful information

- **SEE** 1 rad(material) = 100 erg/g energy per unit mass
- **SET** 1 Gy(material) = 1 J/kg [SI unit = Gray, abbrev. Gy]
- **SER** 1 Gy(material) = 100 rad(material) [usually Si or SiO₂]
- **FIT** LET = linear energy transfer = energy per unit mass per unit area transferred from particle to material
- **MBU** Cross-section = area of device that is sensitive to SEE
- **SEB**
- **SEGR**
- **LET**
- **TID**
- **NIEL**

Material	Mean E_p (eV)	Density (g/cm ³)	Pair density, generated per rad, g_0 (pairs/cm ³)
GaAs	~4.8	5.32	~7x10 ¹³
Silicon	3.6	2.328	4x10 ¹³
Silicon Dioxide	17	2.2	8.1x10 ¹²