National Aeronautics and
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Tutorial:
Radiation Effects in Electronic Systems

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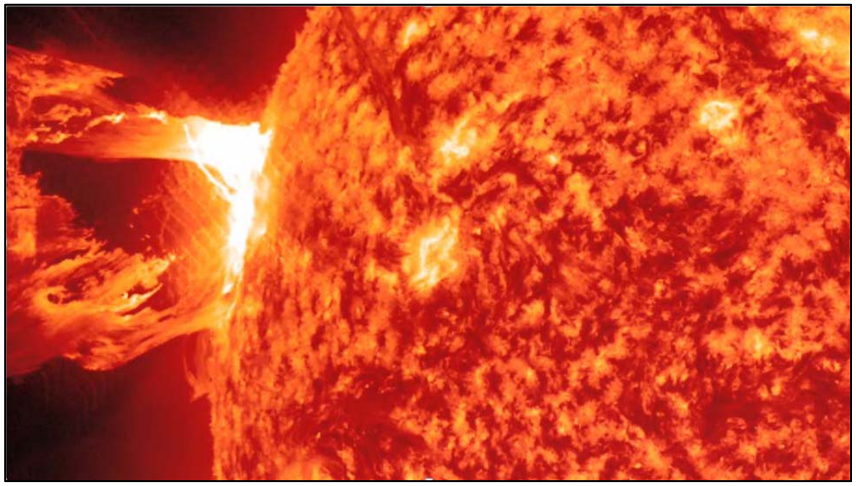
Background image courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

To be presented by Jonathan Pellish at the 2017 Applied Space Environments Conference (ASEC) in Huntsville, AL, USA, May 15-19, 2017.

Outline

- Basis and challenges for radiation effects in electronics
- 3 types of radiation effects in electronics
  - Total ionizing dose (TID)
  - Total non-ionizing dose (TNID), displacement damage dose (DDD)
  - Single-event effect (SEE)
- Relevant examples of effects and some current concerns

Coronal mass ejection shot off the east limb (left side) of the Sun on April 16, 2012



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What makes radiation effects so challenging?

- Field is still evolving as are the technologies we want to use
- A problem of dynamic range
  - Length: 10^{16} m → 10^{-15} m (1 light year, 1 fm)
    - 10^{31}
  - Energy: 10^{19} eV → 1 eV (extreme energy cosmic ray, silicon band gap)
    - 10^{19}
  - Those are just two dimensions; there are many others.
    - Radiation sources, electronic technologies, etc.
- Variability and knowledge of the environment

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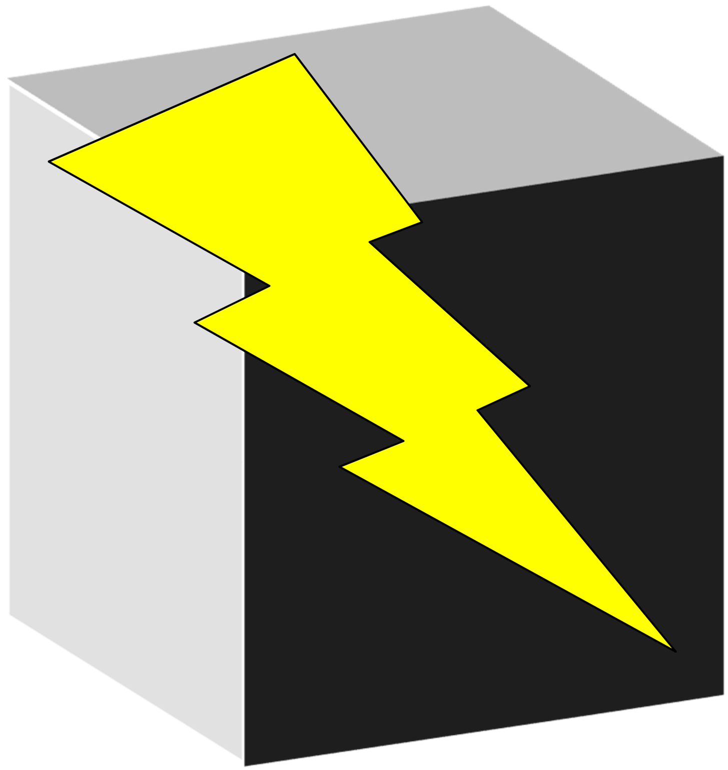
What are radiation effects?



- Energy deposition rate in a “box”
- Source of energy and how it’s absorbed control the observed effects

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What is total ionizing dose?

- Total ionizing dose (TID) is the absorbed dose in a given material resulting from the energy deposition of ionizing radiation.
- Total ionizing dose results in cumulative parametric degradation that can lead to functional failure.
- In space, caused mainly by protons and electrons.

Examples

Metal Oxide Semiconductors Devices	Bipolar Devices
Threshold voltage shifts	Excess base current
Increased off-state leakage	Changes to recombination behavior

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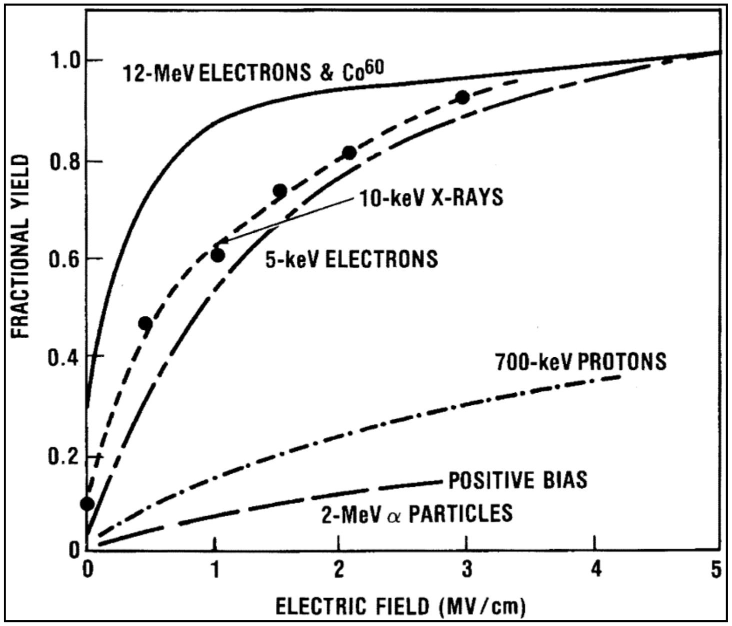
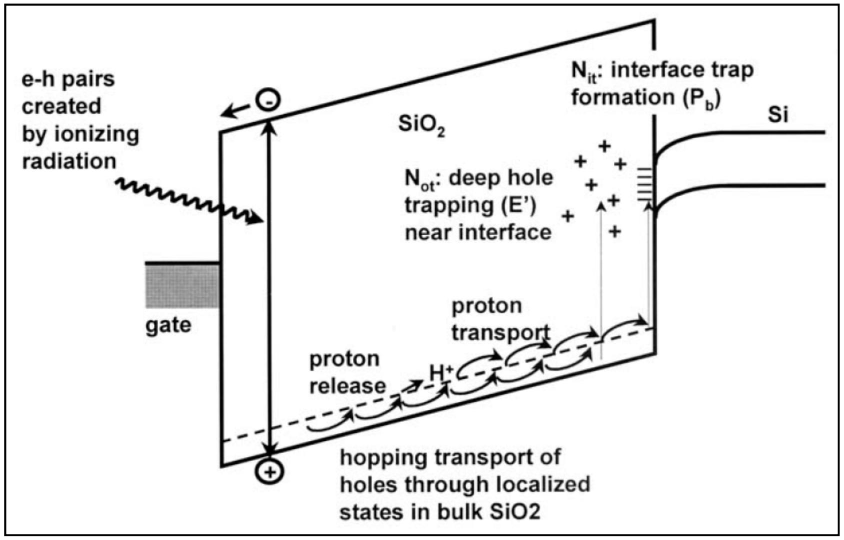
Total ionizing dose

Fractional Hole Yield by Particle Type



T. R. Oldham and J. M. McGarrity, *IEEE TNS*, 1983.
T. R. Oldham and F. B. McLean, *IEEE TNS*, 2003.

Processes Involved in TID Damage



F. B. McLean and T. R. Oldham, Harry Diamond Laboratories Tech. Report, 1987.
T. R. Oldham and F. B. McLean, *IEEE TNS*, 2003.

- Caused by the energy deposition of protons, electrons, energetic heavy ions, and photon-material interactions – *focused on insulators*
- Holes build up in deep traps and interface traps, which are manifest as electrical changes in device performance

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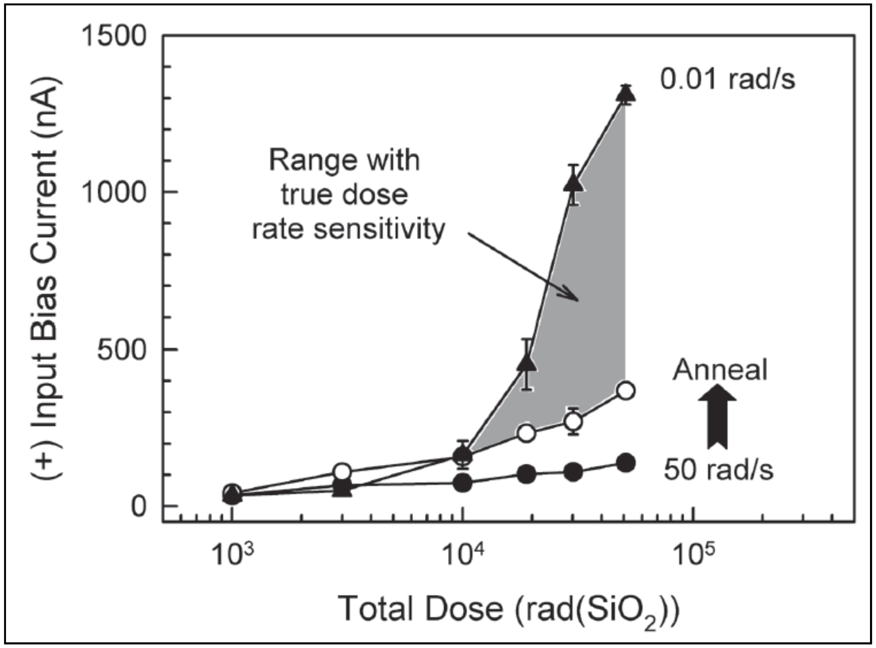
ELDRS effects in bipolar devices

I_{B+} *vs.* Total Dose for LM111 Voltage Comparators



M. R. Shaneyfelt, et al., *IEEE TNS*, 2000.

- First observed in bipolar devices and circuits in the early 1990s
- Amount of total dose degradation at a given total dose is greater at low dose rates than at high dose rates
    - True dose-rate effect as opposed to a time-dependent effect

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What is displacement damage?

- Displacement damage dose (DDD) is the non-ionizing energy loss (NIEL) in a given material resulting from a portion of energy deposition by impinging radiation.
- DDD is cumulative parametric degradation that can lead to functional failure.
- In space, caused mainly by protons and electrons.

DDD Effects
Degraded minority carrier lifetime (e.g., gain reductions, effects in LEDs and optical sensors, etc.)
Changes to mobility and carrier concentrations

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What is NIEL?

- Most always applies to protons and electrons.
- Vast majority of incident kinetic energy lost to ionization, creating TID and single-event effects.
- A small portion of energy lost in non-ionizing processes causes atoms to be removed from their lattice sites and form permanent electrically active defects (i.e., displacement damage) in semiconductor materials.
- NIEL (non-ionizing energy loss) is that part of the energy introduced via both Coulomb (elastic), nuclear elastic, and nuclear inelastic interactions, which produces the initial vacancy-interstitial pairs and phonons (e.g., vibrational energy).

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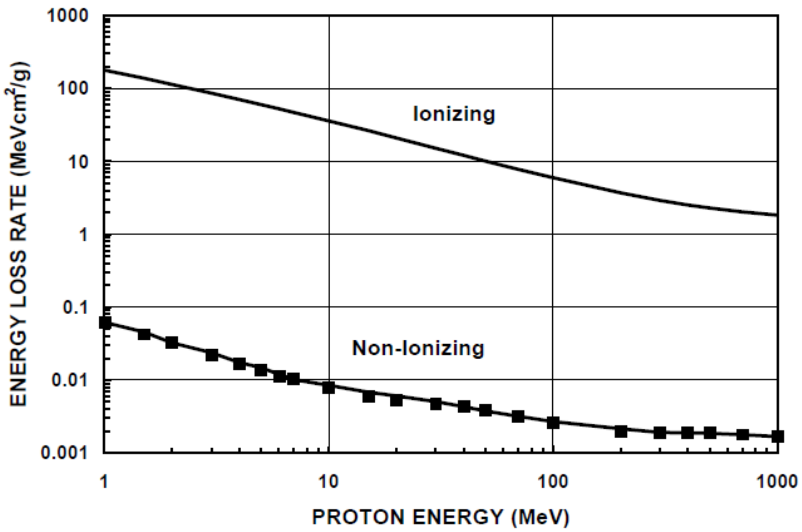
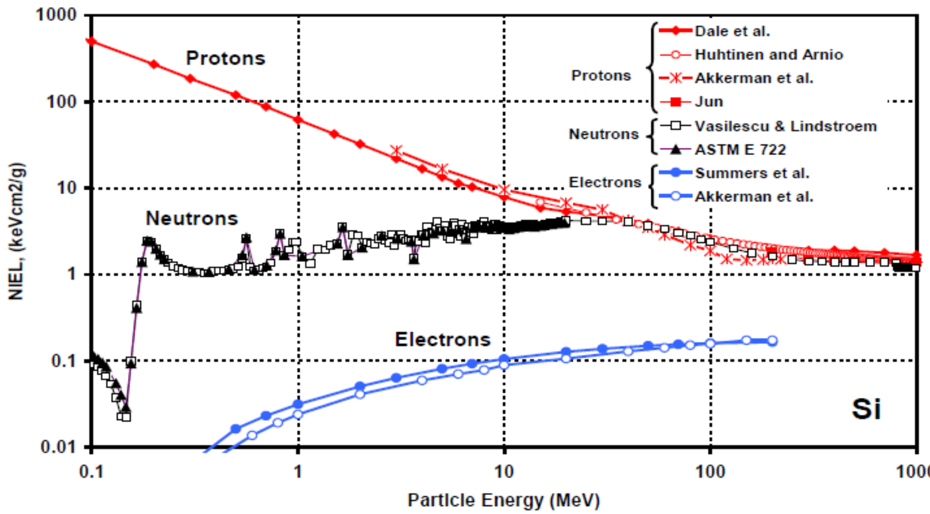
What is NIEL?

Silicon Material System



After C. J. Marshall, 1999 IEEE NSREC Short Course.



After C. Poivey & G. Hopkinson, “Displacement Damage Mechanism and Effects,” Space Radiation and its Effect on EEE Components, EPFL Training Course, 2009.

- Non-ionizing energy causes cumulative damage, much like TID

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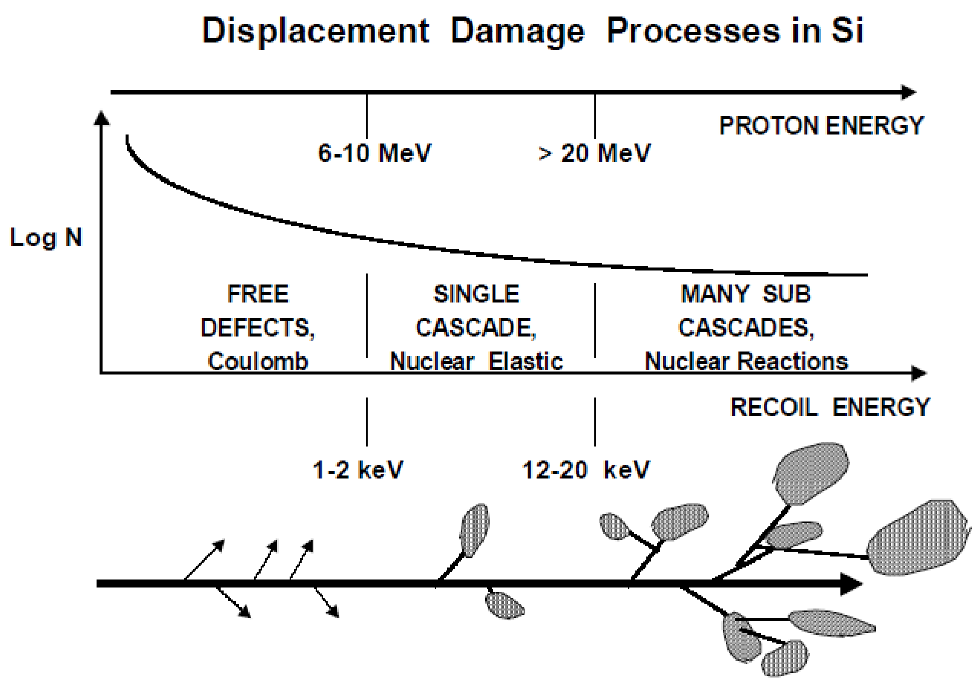
NIEL, visually



After C. J. Marshall, 1999 IEEE NSREC Short Course.

- Pictorial relating the initial defect configuration to the primary knock-on atom (PKA) energy in Si material.
- For recoil energies above a couple of keV, the overall damage structure is relatively unchanged due to the formation of cascades and sub-cascades.

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What are single-event effects?

- A single-event effect (SEE) is a disturbance to the normal operation of a circuit caused by the passage of a single ion (proton or heavy ion) through or near a sensitive node in a circuit.
- SEEs can be either destructive or non-destructive.

Examples

Non-Destructive	Destructive
Single-Event Upset (SEU)	Single-Event Latchup (SEL)
Multiple-Bit Upset (MBU)	Single-Event Burnout (SEB)
Single-Event Transient (SET)	Single-Event Gate Rupture (SEGR)
Single-Event Functional Interrupt (SEFI)	

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France.

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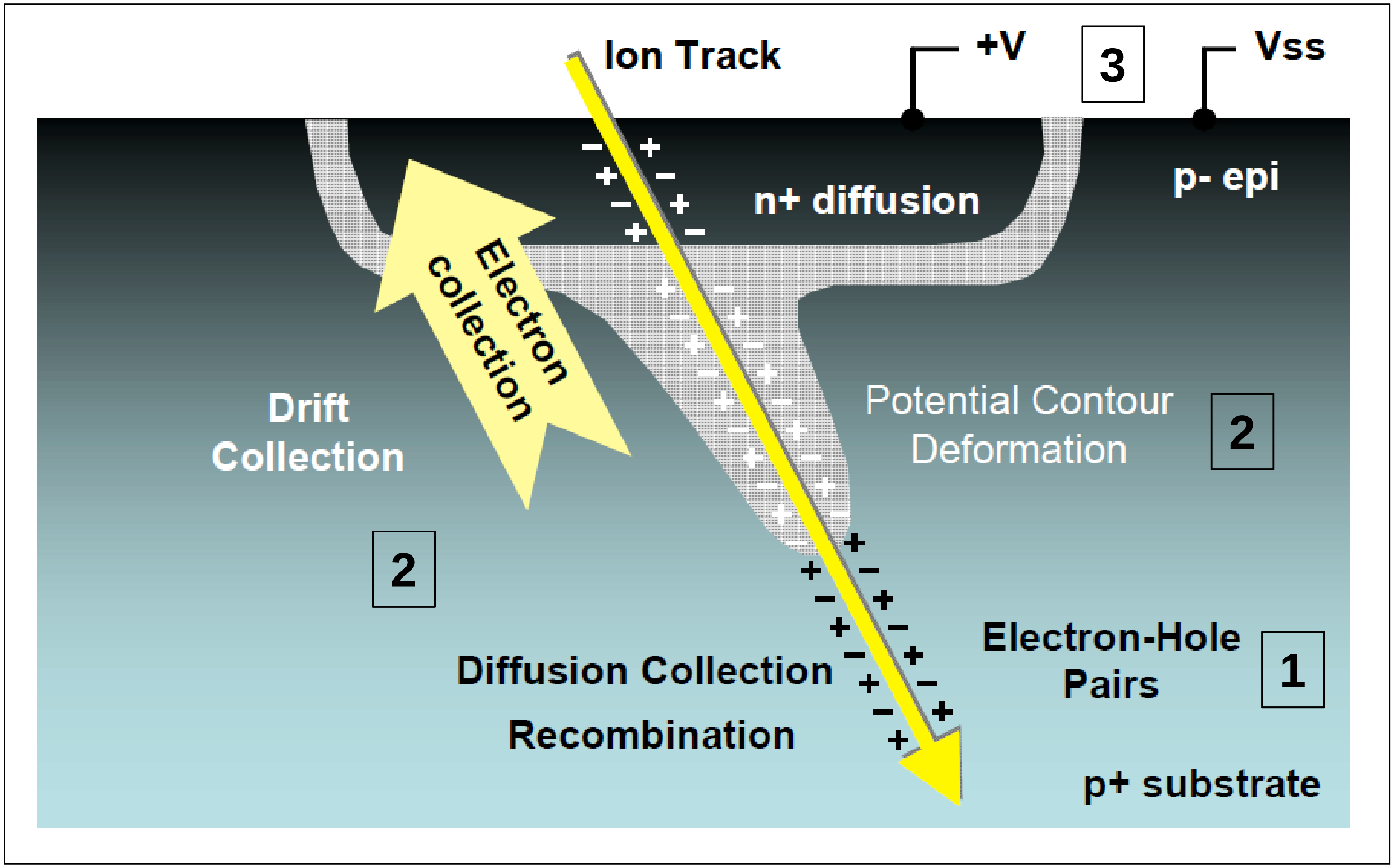
Single-event effects processes



R. Baumann, *IEEE NSREC Short Course*, Seattle, WA, 2005.

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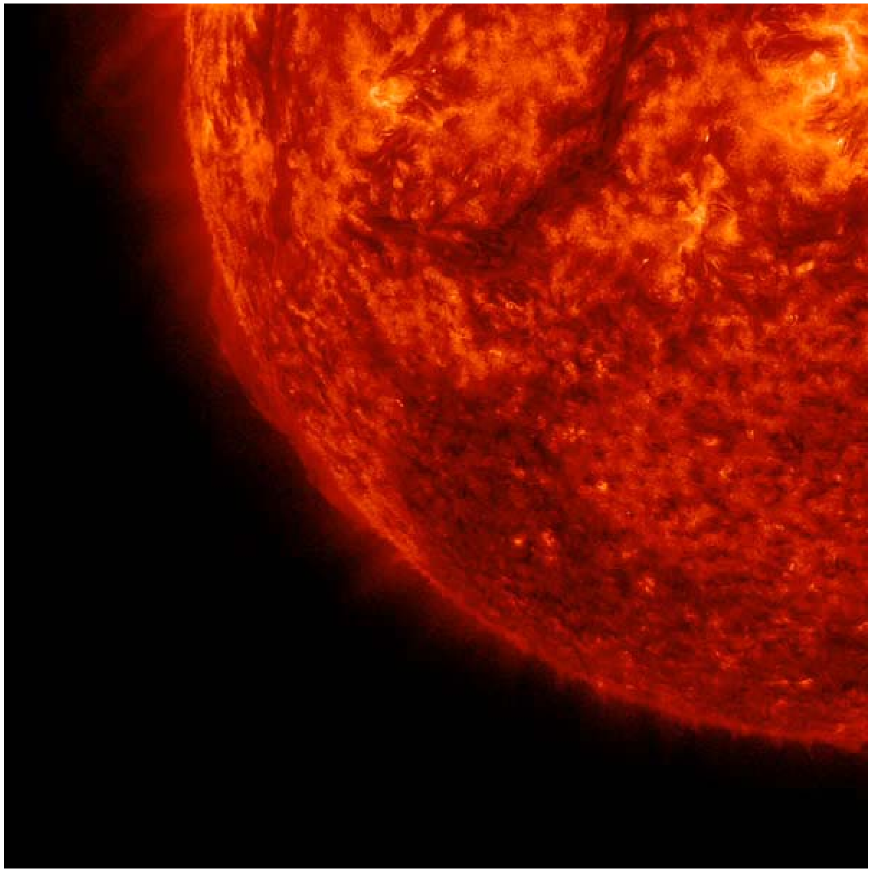
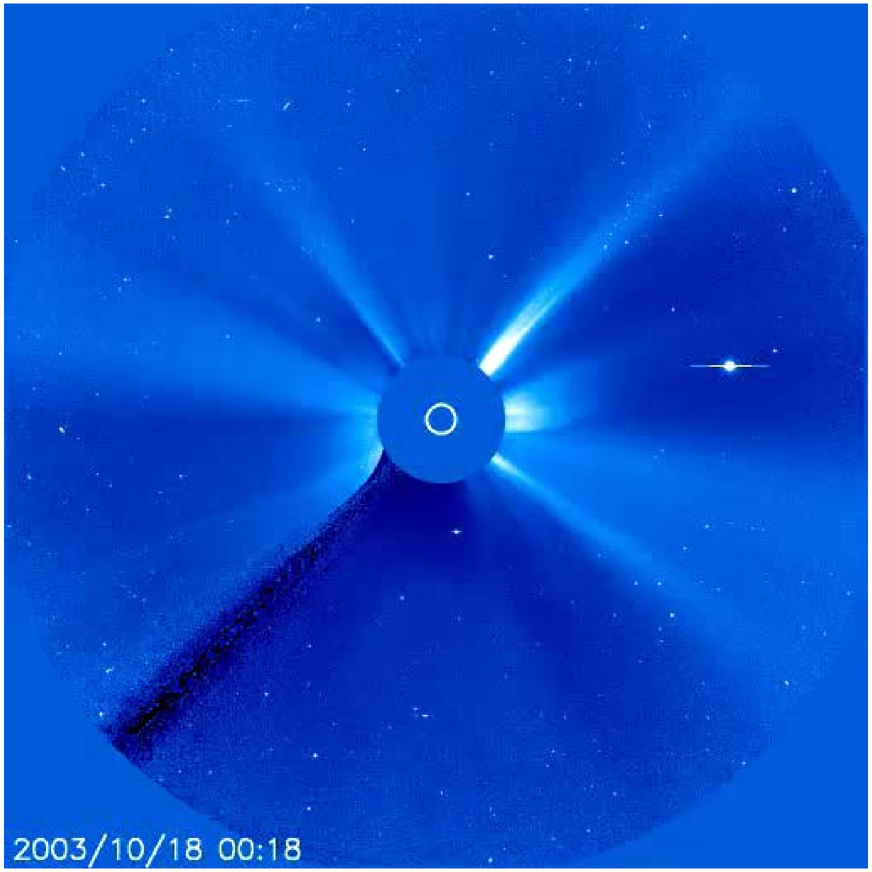
Direct SEE from a CME

Coronal Mass Ejection and Filament (Feb. 24, 2015)



Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

Halloween Storms (Oct. 18 - Nov. 7 2003)



Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA.

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Short history of single-event effects

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France.

- The possibility of single event upsets was first postulated in 1962 by Wallmark and Marcus. ***J.T. Wallmark***, *S.M. Marcus, "Minimum size and maximum packaging density of non-redundant semiconductor devices," Proc. IRE, vol. 50, pp. 286-298, March 1962.*
- The first actual satellite anomalies were reported in 1975. SEUs in flip-flops. ***D. Binder***, *E.C. Smith, A.B. Holman, "Satellite anomalies from galactic cosmic rays," IEEE Trans. on Nuclear Science, vol. 22, no. 6, pp. 2675-2680, Dec. 1975.*
- First observation of SEUs on earth was in 1978. Observed in RAM caused by the alpha particles released by U and Th contaminants within the chip packaging material and solder. Vendors took specific actions to reduce it. ***T. C. May and M. H. Woods***, *"A New Physical Mechanism for Soft Errors in Dynamic Memories", Proceedings 16 Int'l Reliability Physics Symposium, p. 33, April, 1978.*
- First report of SEUs due to cosmic rays on earth in 1979. ***J. F. Ziegler*** *and W. A. Lanford, "Effect of Cosmic Rays on Computer Memories", Science, 206, 776 (1979).*
- First report of destructive SEE (proton induced latch-up) in a memory operating in space in 1992 **L. Adams** *et al.*, *"A Verified Proton Induced Latch-up in Space," IEEE TNS vol. 39, No. 6, pp. 1804 – 1808, Dec. 1992.*

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Proton SEE notes

- Proton LET is very low (<< 1 MeV-cm^2/mg)
  - o Upsets are usually dominated by indirect ionization – nuclear reactions
  - o Reaction products have appreciable LETs, usually less than 15 MeV-cm^2/mg, but short ranges compared to GCRs
  - o Low-energy protons can also cause SEE through direct ionization
- Importance of proton SEE
  - o In proton-dominated environments, can be a large portion of the overall SEE rate – LEO, for instance
  - o Sufficient proton test techniques and data analysis are critically important

N. A. Dodds *et al*., in *IEEE Trans. Nucl. Sci.*, vol. 62, no. 6, pp. 2440-2451, Dec. 2015.

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Where we are going…

THEN	NOW
Magnetic core memory	NAND flash, resistive random access memory (RAM), magnetic RAM, phase-change RAM, programmable metallization cell RAM, and double-data rate (DDR) synchronous dynamic RAM (SDRAM)
Single-bit upsets (SBUs) and single-event transients (SETs)	Multiple-bit upset (MBU), block errors, single-event functional interrupts (SEFIs), frequency-dependence, etc.
Heavy ions and high-energy protons	Heavy ions, high- and low-energy protons, high-energy electrons, ???
Radiation hardness assurance (RHA)	RHA what?

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Where we are going…

THEN **NOW**

Increases in capability introduce additional evaluation challenges

- FinFETs/Tri-gate devices
- Nanowire MOSFETs
- Organic transistors
- Ultra-thin body SOI
- Ge MOSFETs
- III-V MOSFETs
- Carbon nanotube FETs
- GaN, SiC,…

TESTABILITY

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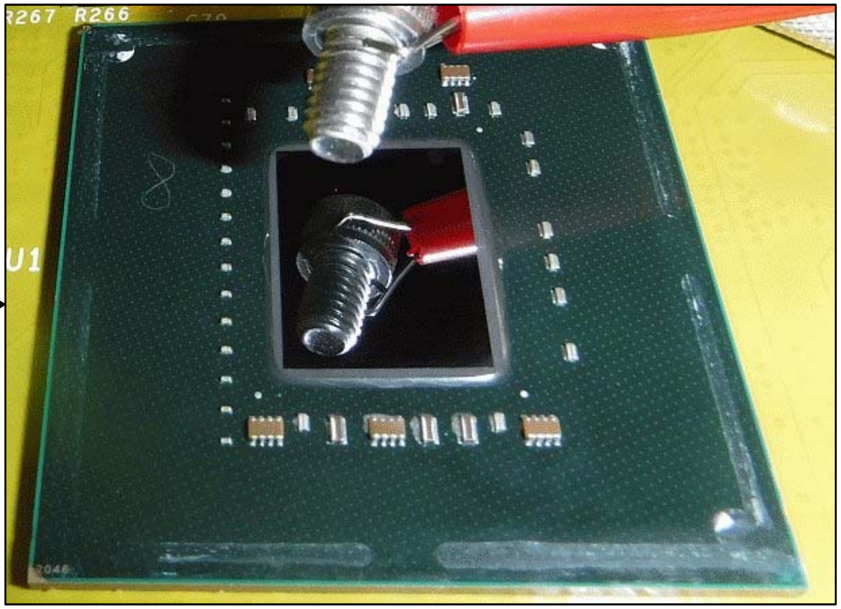
Electronics for Space Use

- Commercial Off the Shelf (COTS)
  - Designed with no attempt to mitigate radiation effects. COTS can refer to commodity devices or to application-specific integrated circuits (ASICs) designed using a commercially available design system.
- Radiation-Tolerant
  - Designed explicitly to account for and mitigate radiation effects by process and/or design



Xilinx Virtex-7 (28 nm CMOS) thinned in preparation for SEE testing

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Summary

- Radiation effects are challenging due to:
    - Space environment knowledge,
    - Number/type of physical processes involved, and
    - Rapid evolution of technology.
- Effects split into cumulative and single-particle varieties
- Radiation effects community is aggressively pursuing advanced technologies (e.g., CMOS ≤ 45 nm, SiGe, etc.), which is increasing the need for evolutions in both test techniques and data analysis

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QUESTIONS?

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Acronyms

Acronym	Definition
AIA	Atmospheric Imaging Assembly
AIEE	American Institute of Electrical Engineers
CME	Coronal Mass Ejection
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial Off the Shelf
DDD	Displacement Damage Dose
ELDRS	Enhanced Low Dose Rate Sensitivity
EVE	Extreme Ultraviolet Variability Experiment
FET	Field Effect Transistor
FPGA	Field Programmable Gate Array
GCR	Galatic Cosmic Ray
GSFC	Goddard Space Flight Center
HMI	Helioseismic and Magnetic Imager
IEEE	Institute of Electrical and Electronics Engineers
IRE	Institute of Radio Engineers
LASCO	Large Angle and Spectrometric Coronagraph
LED	Light-Emitting Diode
LEP	Low-Energy Proton
LET	Linear Energy Transfer
MBU	Multiple-Bit Upset
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NASA	National Aeronautics and Space Administration

Acronym	Definition
NIEL	Non-Ionizing Energy Loss
NSREC	Nuclear and Space Radiation Effects Conference
PKA	Primary Knock-on Atom
RAM	Random Access Memory
RHA	Radiation Hardness Assurance
SAA	South Atlantic Anomaly
SAMPEX	Solar Anomalous Magnetospheric Explorer
SBU	Single-Bit Upset
SDO	Solar Dynamics Observatory
SDRAM	Synchronous Dynamic RAM
SEB	Single-Event Burnout
SEE	Single-Event Effects
SEFI	Single-Event Functional Interrupt
SEGR	Single-Event Gate Rupture
SEL	Single-Event Latchup
SET	Single-Event Transient
SEU	Single-Event Upset
SOHO	Solar & Heliospheric Observatory
SOI	Silicon-on-Insulator
TAMU	Texas A&M University
TID	Total Ionizing Dose
TNID	Total Non-Ionizing Dose

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