



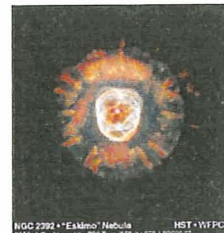
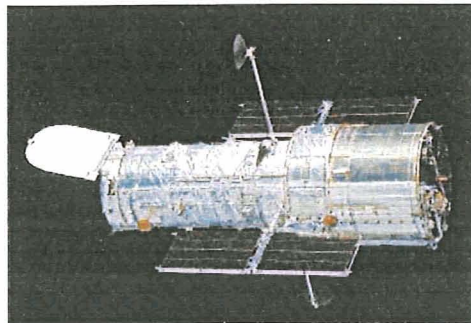
Space Electronics

A challenging world for designers

Christian Poivey
Kenneth A. LaBel
NASA-GSFC

DCIS04 – Space Radiation Effects presented by Christian Poivey, Bordeaux, France, November 26, 2004

Designing Electronics for Space



- Low power
- High reliability
- Harsh environment
 - Thermal
 - Mechanical
 - Electro-magnetic
 - Radiation



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Outline

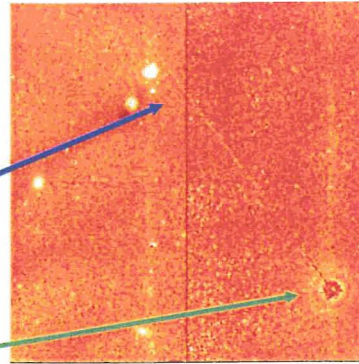
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- Direct Ionization

Interaction with Nucleus

- Indirect Ionization
- Nucleus is Displaced

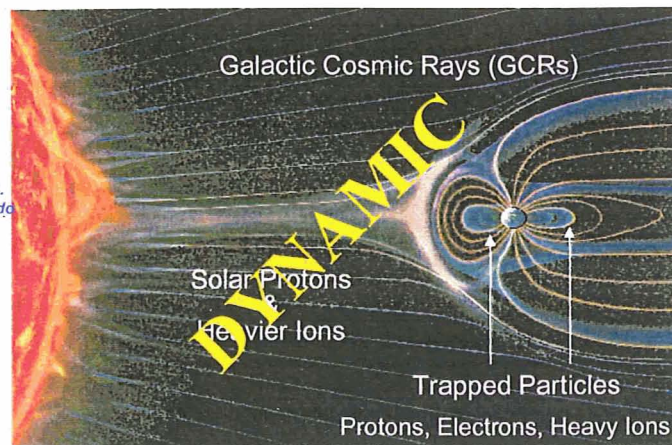


<http://www.stsci.edu/hst/nmos/performance/anomalies/bigcr.html>

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Space Radiation Environment



Nikkei Science, Inc.
of Japan, by K. Endo

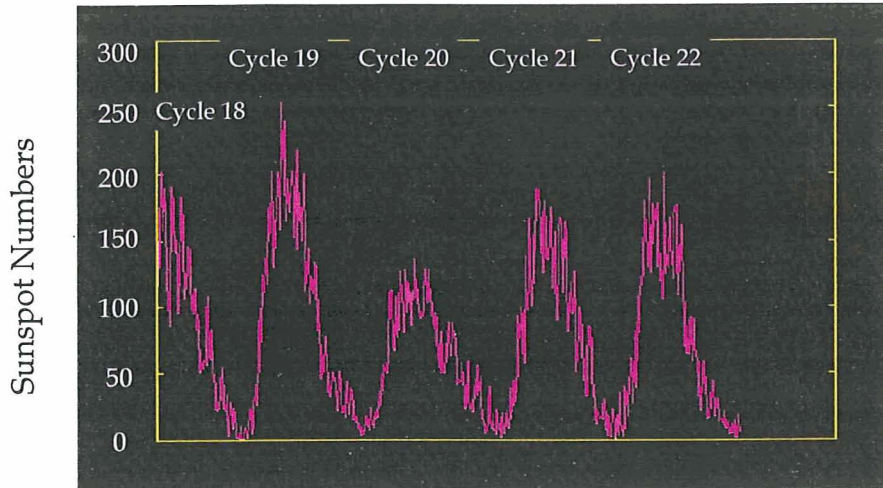
*Deep-space missions may also see: neutrons from background
or radioisotope thermal generators (RTGs)
Atmosphere and terrestrial may see GCR and secondaries*

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Sunspot Cycle: An Indicator of the Solar Cycle

after Lund Observatory



Length Varies from 9 - 13 Years
7 Years Solar Maximum, 4 Years Solar Minimum

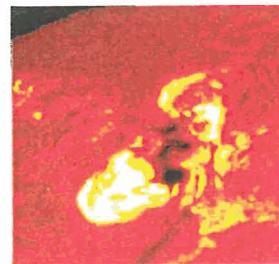
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Solar Particle Events

- **Cyclical (Solar Max, Solar Min)**
 - 11-year **AVERAGE** (9 to 13)
 - Solar Max is more active time period
- **Two types of events**
 - Gradual (**Coronal Mass Ejections** - CMEs)
 - Proton rich
 - Impulsive (**Solar Flares**)
 - Heavy ion rich
- **Abundances Dependent on Radial Distance from Sun**
- **Particles are Partially Ionized**
 - Greater Ability to Penetrate Magnetosphere than GCRs

Holloman AFB/SOON

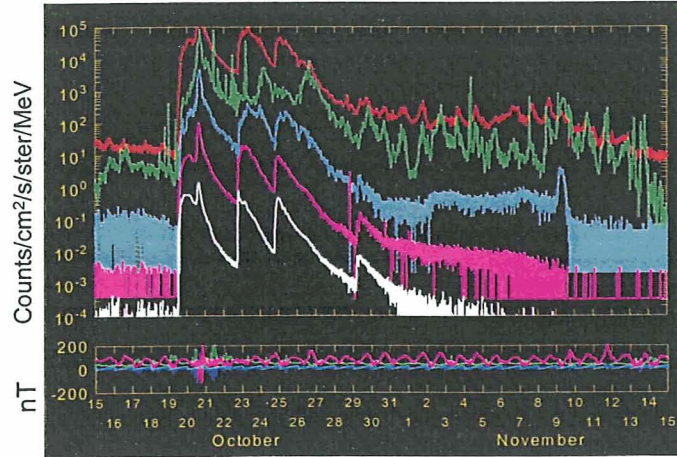


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Solar Proton Event - October 1989

Proton Fluxes - 99% Worst Case Event



GOES Space Environment Monitor

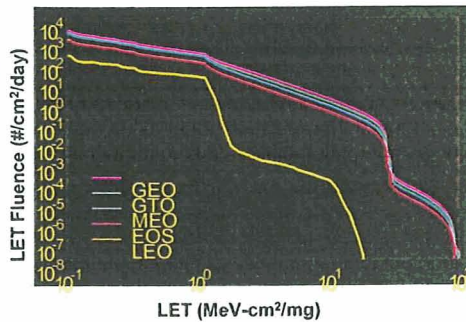
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Free-Space Particles: Galactic Cosmic Rays (GCRs) or Heavy Ions

- **Definition**
 - A GCR ion is a charged particle (H, He, Fe, etc)
 - Typically found in free space (galactic cosmic rays or GCRs)
 - Energies range from MeV to GeVs for particles of concern for SEE
 - Origin is unknown
 - Important attribute for impact on electronics is how much energy is deposited by this particle as it passes through a semiconductor material. This is known as **Linear Energy Transfer** or LET (dE/dX).

CREME 96, Solar Minimum, 100 mils (2.54 mm) Al

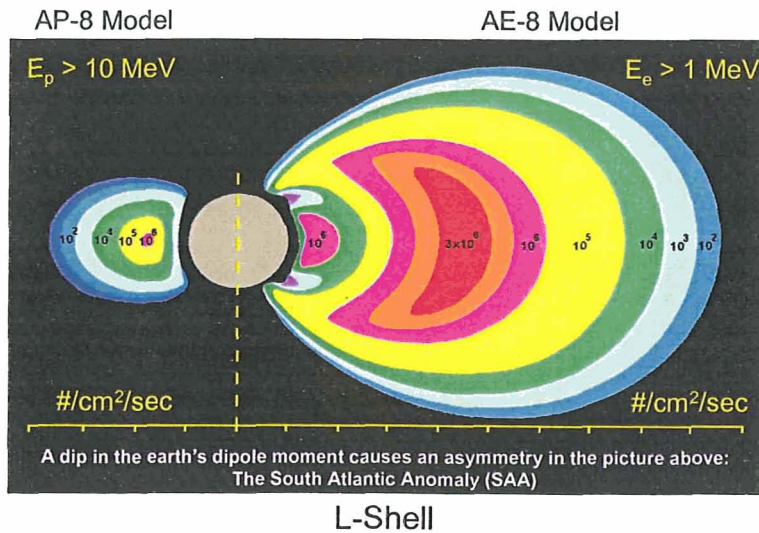


Time
Commercial Technology Sensitivity

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Trapped Particles in the Earth's Magnetic Field: Proton & Electron Intensities

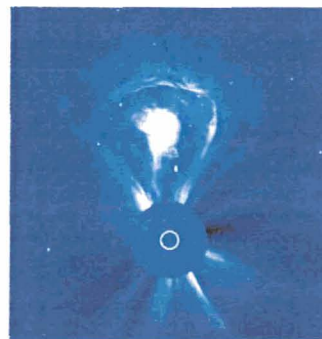


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Solar Cycle Effects: Modulator and Source

- **Solar Maximum**
 - Trapped Proton Levels Lower, Electrons Higher
 - GCR Levels *Lower*
 - Neutron Levels in the Atmosphere Are Lower
 - Solar Events More Frequent & Greater Intensity
 - Magnetic Storms More Frequent -- > Can Increase Particle Levels in Belts
- **Solar Minimum**
 - Trapped Protons Higher, Electrons Lower
 - GCR Levels *Higher*
 - Neutron Levels in the Atmosphere Are Higher
 - Solar Events Are Rare



*Light bulb shaped CME
courtesy of SOHO/LASCO C3 Instrument*

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Outline

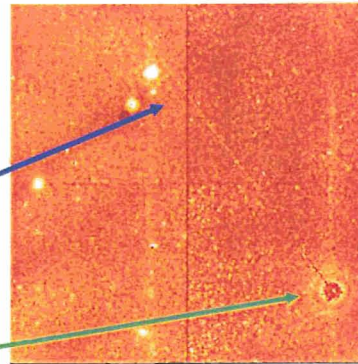
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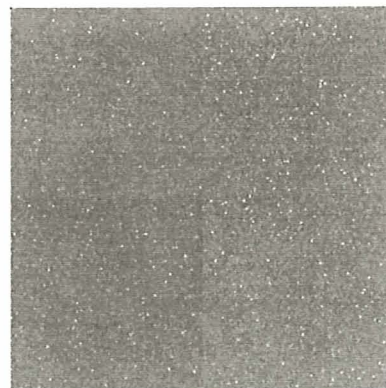
<http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html>

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Radiation Effects and Spacecraft

- High energy particles loose energy when they cross electronic parts materials and cause radiation effects
 - Long-term effects
 - Total ionizing dose (TID)
 - Displacement damage
 - Transient or single particle effects (Single event effects or SEE)
 - Soft or hard errors



An Active Pixel Sensor (APS) imager under irradiation with heavy ions at Texas A&M University Cyclotron

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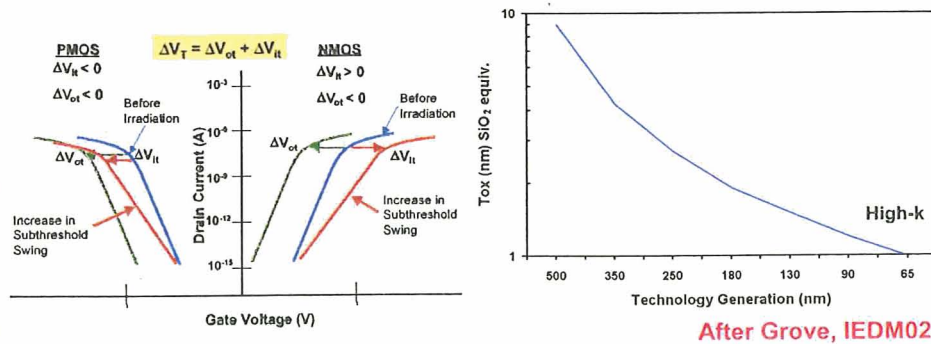
Total Ionizing Dose (TID)

- Cumulative long term *ionizing* damage due to protons & electrons
 - Incident particles transfer energy to material through electron hole creation. Holes are trapped within devices' oxides or the interfaces oxide/silicon.
- Effects
 - Increase of Leakage Currents
 - Degradation of logical input levels and noise margin
 - Degradation of fan out
 - Degradation of propagation delays
 - Functional Failures
- Unit of radiation: dose in Gray or rad
 - 1 Gray = 100 rad = 0.01 J/Kg

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TID-induced threshold voltage shifts effects in CMOS devices



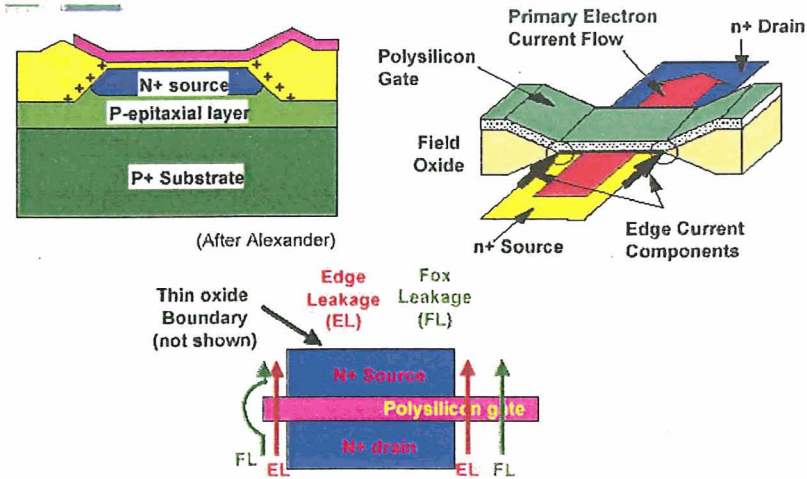
$$\Delta V_T \propto t_{ox}^2 \text{ (After Mc Garrity)}$$

When $t_{ox} < 5$ nm, significant hole tunneling out of the gate oxide occurs, resulting in negligible number of remaining holes: $\Delta V_{ot} \sim \Delta V_{it} \sim 0$

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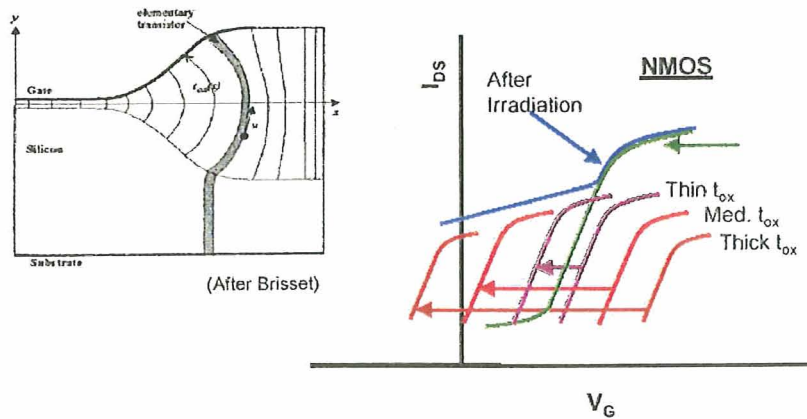
TID-induced intra device edge leakage



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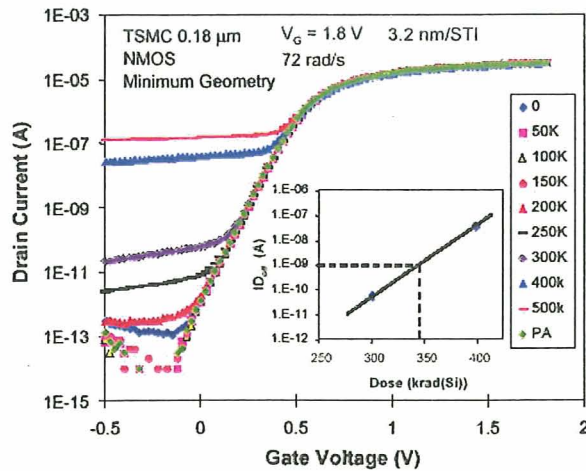
Edge Leakage – Basic Mechanism



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Example of Edge Leakage for 0.36/0.18 μm NMOS Transistor



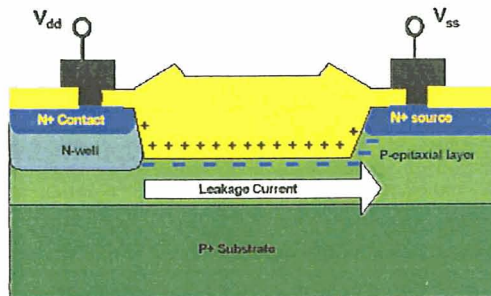
After Lacoé, EWRHE 2004

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Inter device isolation-oxide leakage

- Inversion of field oxide results in leakage path between N+ contact (V_{dd}) in the N-well and N+ source (GND)
- Field oxide leakage paths can also span N+ source/drain regions between adjacent N- channel transistors



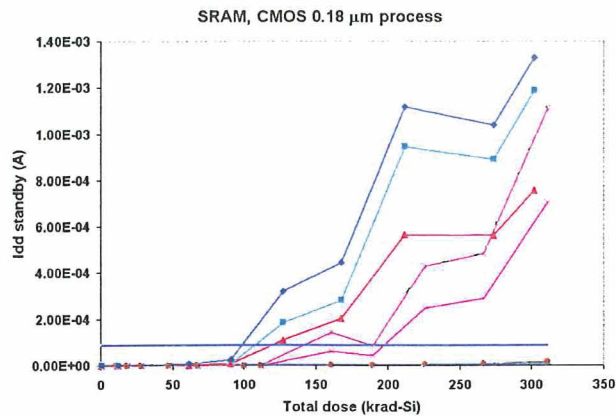
Field oxide leakage path

(After Alexander)

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Example of TID degradation for 0.18 μm CMOS SRAM



- No significant degradation up to 90 krad-Si
- Sufficient for most space applications, typical dose levels:
 - Geostationary Orbit, 10 years: 50 krad-Si
 - Low Earth Orbit, 5 years: 20 krad-Si

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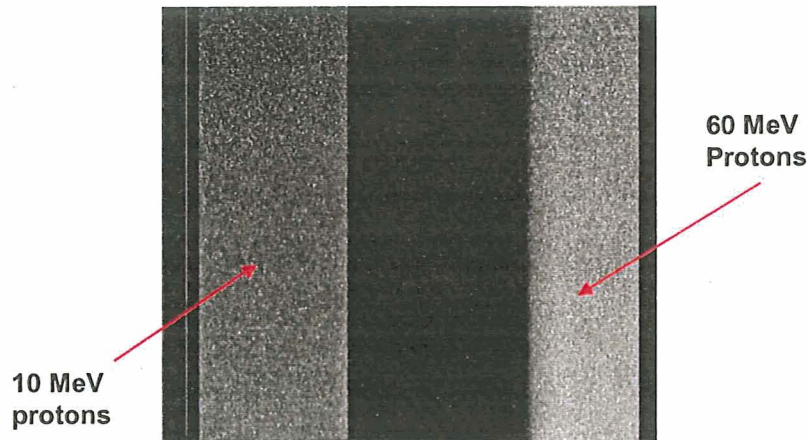
Displacement Damage (DD)

- Cumulative long term *non-ionizing* damage due to protons, electrons, and neutrons
 - Incident particles transfer energy by elastic or inelastic collisions with atoms of the devices material (Silicon). Structural defects are created on the crystallographic structure.
- Effects
 - Minority carrier lifetime in the semiconductor is decreased
 - Increase leakage currents
 - Decrease gain of bipolar transistors
 - Important for opto-electronics and linear bipolar devices, not significant for CMOS devices.
- Unit of radiation:
 - equivalent fluence for a selected electron or proton energy in particles/cm²

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DD damage example, CCD

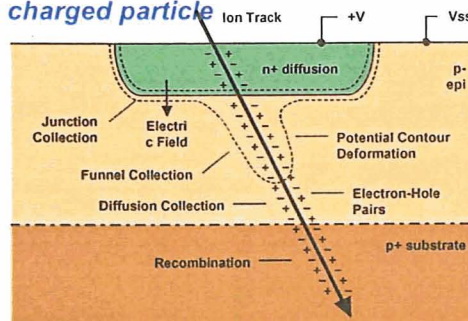


(After Hopkins RADECS 03 short course)

Single Event Effects (SEEs)

- **Ionizing effect caused by a single charged particle**

- Heavy ions
 - Direct ionization
 - Creation of a very dense plasma of electrons hole pairs
 - The pairs that do not recombine are separated by the junction electric field, and a current spike is generated.
- Protons for sensitive devices
 - Nuclear reactions for standard devices

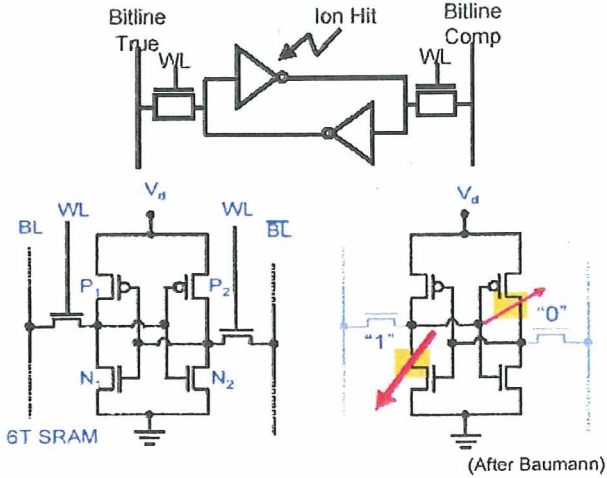


- **Unit of radiation:**

- LET (Linear Energy Transfer) in MeVcm^2/mg
- If the LET of the particle (or reaction) is greater than the amount of energy or **critical charge** required, an effect may be seen

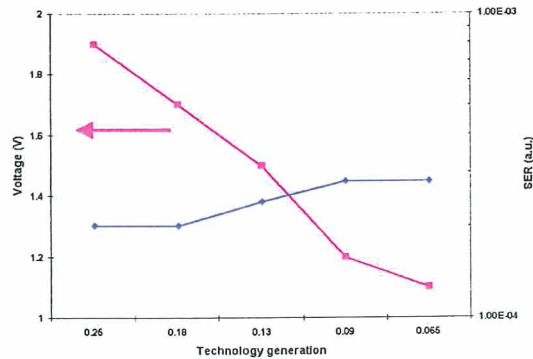
Single Event Upset (SEU)

When SEU current I_{SEU} exceeds restoring current from cross-coupled inverter such that the node voltage drops below $V_D/2$ for too long, an upset occurs



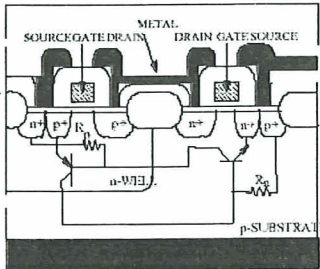
SEU trend on SRAM

- At fixed voltage SER decreased by 13% per generation.
- At the nominal voltage for each generation (14% scaling per generation), the SER sensitivity has increased by about 8% per generation.

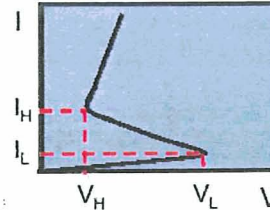
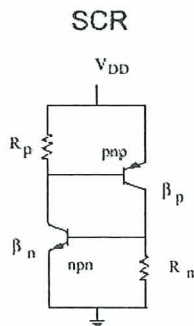


After Hazucha, IEDM 03

Single Event Latchup (SEL) in CMOS circuits



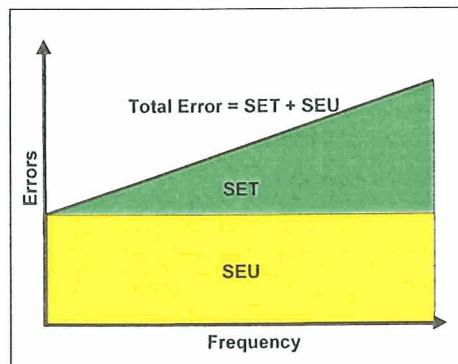
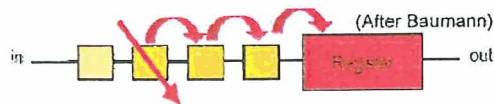
Latchup can cause circuit lockup and/or catastrophic device failure



- If an energetic particle produces $I > I_L$, $\beta_n \beta_p > 1$ and $V_{DD} > V_H$, then latchup will occur
- As technology scales, soon $V_{DD} < V_H$ and latchup is no longer a problem
- Epi reduces $R_n \Rightarrow$ increase latchup threshold

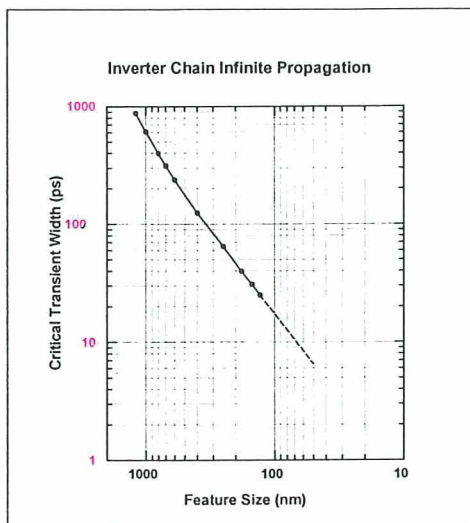
Single Event Transient (SET)

- Voltage transients can propagate through combinatorial logic
 - Indistinguishable from normal signals
 - Incorrectly latched if arrive at clock edge
- Errors rates now depend on clock frequency
- Total error rate is the sum of the SEU + SET contributions



Transient propagation in CMOS

- If transient pulse width is greater than critical width, the pulse will propagate indefinitely through combinatorial logic.
- For pulses shorter than the critical transient width, the transient will be attenuated.
- Critical width decreases with feature size
 - Estimate of heavy ion transient pulse width is 100-200 ps
 - SETs important for CMOS at or below 0.25 μm technology node

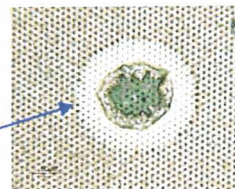


After Mavis, EWRH 04

Other Single Event Effects

Multiple Event Upset (MEU)	Several bits corrupted by a single particle	Memories
Single Event Functional Interrupt (SEFI)	Loss of normal operation	Complex devices with built-in state machine/control sections
Single Event Burnout (SEB)	High current condition	BJT, N channel power MOSFETs
Single Hard Error (SHE)	Stuck bit	Memories
Single Event Gate Rupture (SEGR)	Rupture of gate dielectric	Power MOSFETs, flash PROM,...
Other events	SESB, HCA,....	

Destructive event in a MOSFET used in a DC-DC Converter



Outline

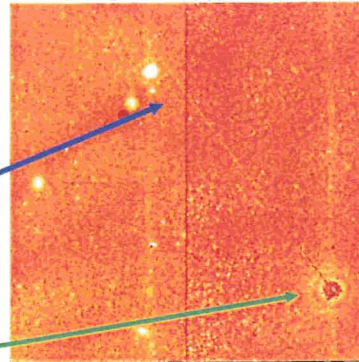
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<http://www.stsci.edu/hst/nimos/performance/anomalies/bigcr.html>

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Radiation Effects on Electronics and the Space Environment

- Three portions of the natural space environment contribute to the radiation hazard
 - **Solar particles**
 - Protons and heavier ions
 - SEE, TID, DD
 - **Free-space particles**
 - GCR
 - For earth-orbiting craft, the earth's magnetic field provides some protection for GCR
 - SEE
 - **Trapped particles (in the belts)**
 - Protons and electrons including the South Atlantic Anomaly (SAA)
 - SEE (Protons)
 - DD, TID (Protons, Electrons)

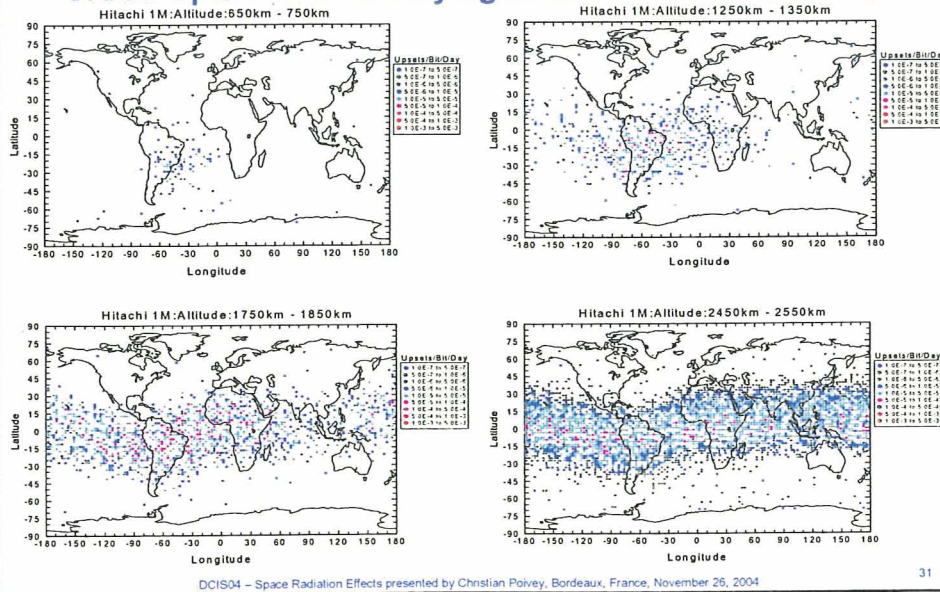


The sun acts as a modulator and source in the space environment

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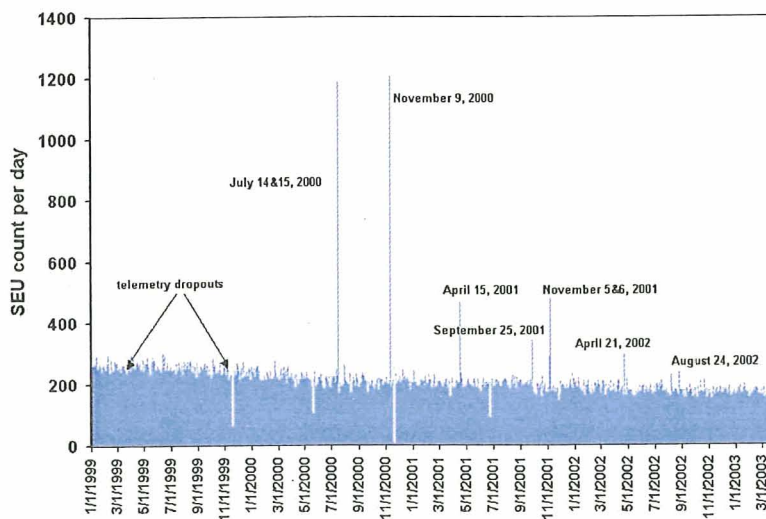
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SAA and Trapped Protons: Effects of the Asymmetry in the Proton Belts on SRAM Upset Rate at Varying Altitudes on CRUX/APEX



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Background environment and solar events SRAM upset rate versus time on Orbview-2 SSRs

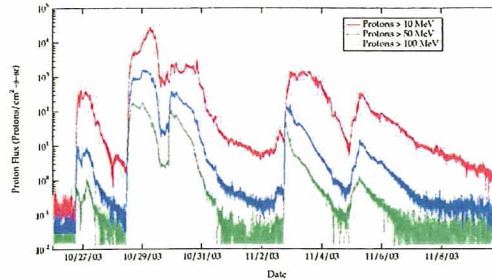


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Recent Solar Events – A Few Notes and Implications

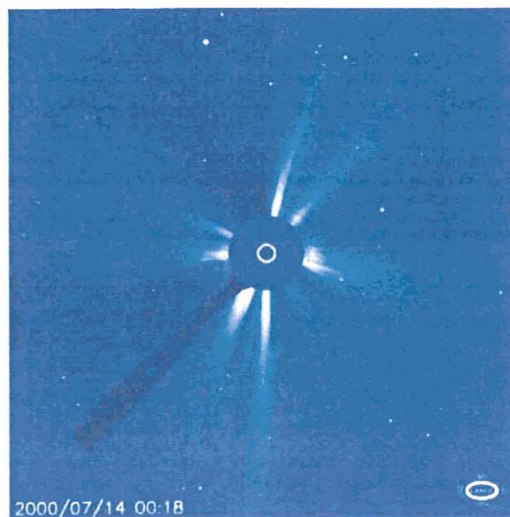
- In Oct-Nov of this year, a series of X-class (X-45!) solar events took place
 - High particle fluxes were noted
 - Many spacecraft performed safing maneuvers
 - Many systems experienced higher than normal (but correctable) data error rates
 - Several spacecraft had anomalies causing spacecraft safing
 - Increased noise seen in many instruments
 - Drag and heating issues noted
 - Instrument FAILURES occurred
 - Two known spacecraft FAILURES occurred
- Power grid systems affected, communication systems affected...



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SOHO LASCO C2 of the Solar Event

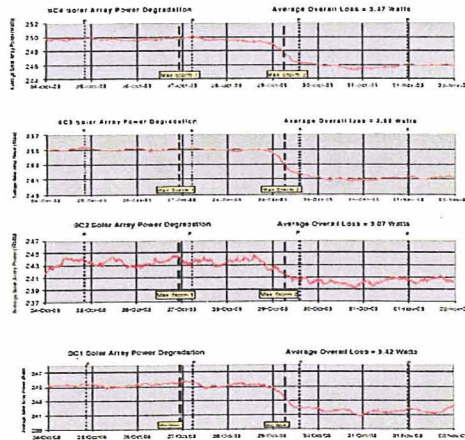


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Solar Event Effect - Solar Array Degradation on CLUSTER Spacecraft

ANNEX 1: Evolution of the Solar Array Power from 24-Oct to 02-Nov 2003 when two solar radiation storms occurred (the time of their maximum is indicated in the plot "..."). The degradation of the panels was about 1.4% and the average power loss is shown for each spacecraft. The perturbed passes are marked as "....." and labeled with "P".



Many other spacecraft to noted degradation as well.

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Science Spacecraft Anomalies During Recent Solar Events

Type of Event	Spacecraft/ Instrument	Notes
Spontaneous Processor Resets	RHESSI	3 events; all recoverable
	CLUSTER	Seen on some of 4 spacecraft; recoverable
	ChipSAT	S/C tumbled and required ground command to correct
High Bit Error Rates	GOES 9,10	
Magnetic Torquers Disabled	GOES 9, 10, 12	
Star Tracker Errors	MER	Excessive event counts
	MAP	Star Tracker Reset occurred
Read Errors	Stardust	Entered safe mode; recovered
Failure?	Midori-2	
Memory Errors	GENESIS	19 errors on 10/29
	Many	Increase in correctable error rates on solid-state recorders noted in many spacecraft

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Science Instrument Anomalies During Recent Solar Events

Type of Event	Spacecraft/ Instrument	Notes
Instrument Failure	GOES-8 XRS	Under investigation as to cause
	Mars Odyssey/Marie	Under investigation as to cause; power consumption increase noted; S/C also had a safeshold event – memory errors
	NOAA-17/AMSU-A1	Lost scanner; under investigation
Excessive Count Rates	ACE, WIND	Plasma observations lost
	GALEX UV Detectors	Excess charge – turned off high voltages; Also Upset noted in Instrument
	ACE	Solar Proton Detector saturated
Upset	Integral	Entered Safe mode
	POLAR/TIDE	Instrument reset spontaneously
Hot Pixels	SIRTF/IRAC	Increase in hot pixels on IR arrays; Proton heating also noted
Safe Mode	Many	Many instruments were placed in Safe mode prior to or during the solar events for protection

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Selected Other Consequences

- **Orbits affected on several spacecraft**
- **Power system failure**
 - Malmö, Sweden
- **High Current in power transmission lines**
 - Wisconsin and New York
- **Communication noise increase**
- **FAA issued a radiation dose alert for planes flying over 25,000 ft**

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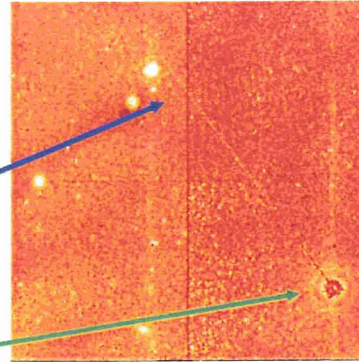
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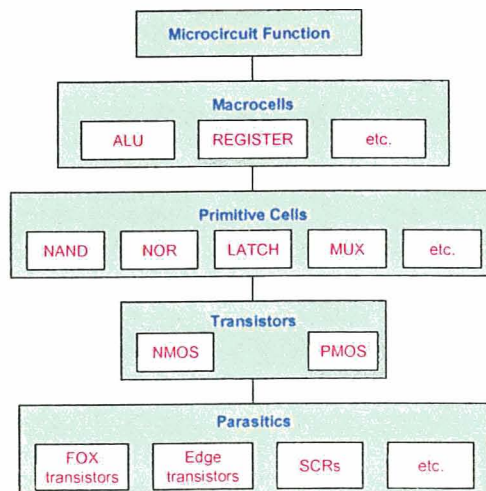
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<http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html>

Hardening by design to radiation effects

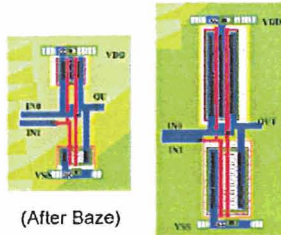


Layout:
Guard band/Guard ring
Spacing
Body ties

Alexander, NSREC 96 short course

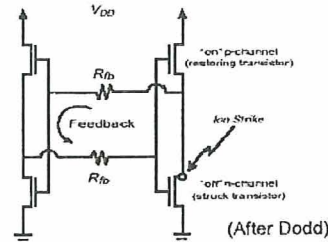
SEU hardening at primitive cell level

Increased Drive Current



- Increase Drive current I_D ($\uparrow W$) increasing restoring current
- No speed penalty
- Area penalty $\propto I_D$

Resistive Coupling

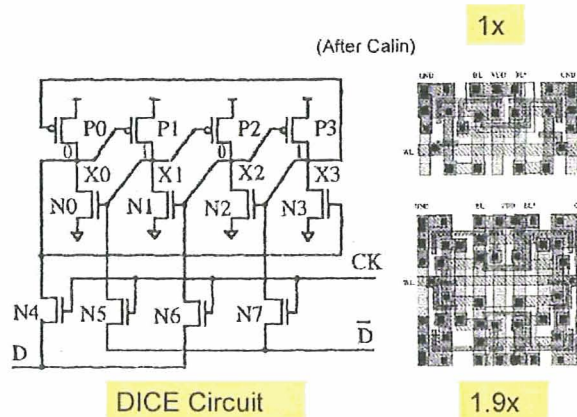


- Decrease response time by increasing RC with feedback resistors
- Resistors are not an option at many commercial foundries
- Speed penalty
- Small area penalty

SEU hardening at macrocell level

- Design enhancements: deal with SEU occurring in primitive cells
 - Hardened data latches: DICE, HIT,...

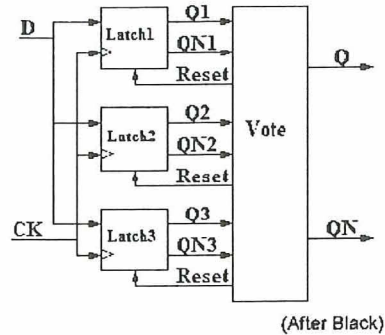
- Uses a 4-node redundant structure
 - Stores data as 1010 or 0101
- Relies on dual node feedback control
 - Two nodes must be struck simultaneously to generate an upset
- Decrease in effective sensitive area



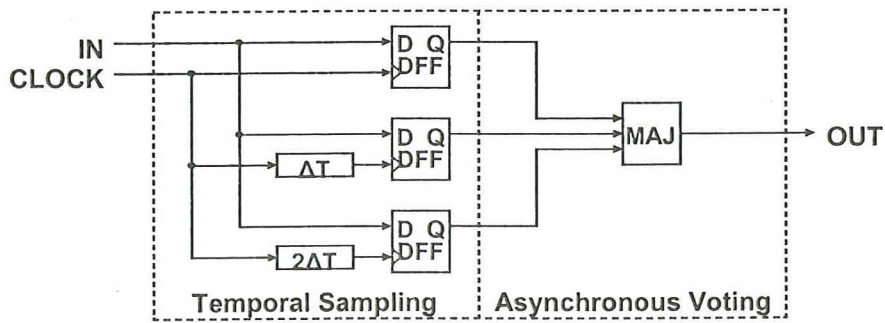
SEU hardening at macrocell level

- Design enhancements: deal with SEU occurring in primitive cells
 - redundancies

- Triple Module Redundancy (TMR)
 - Triple logic + vote
- Reduce effective sensitivity
 - 2 latches must be struck simultaneously to get an error
- Does not increase tolerance of individual latches
- ~ 3x-4x power/area

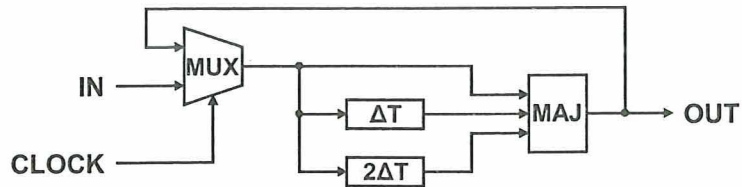


SEU/SET hardening at macrocell level



- By delaying clocks, transient can only be captured at 1 latch
 - Voted out
- Can delay data instead of clocks
- Sensitive to transients on clock line
- Area penalty ~ 3x - 4x
- Speed penalty: $1/f_{\text{eff}} = 1/f_0 + 2 \Delta T$
- Many variations on this concept

SEU/SET hardening at macrocell level



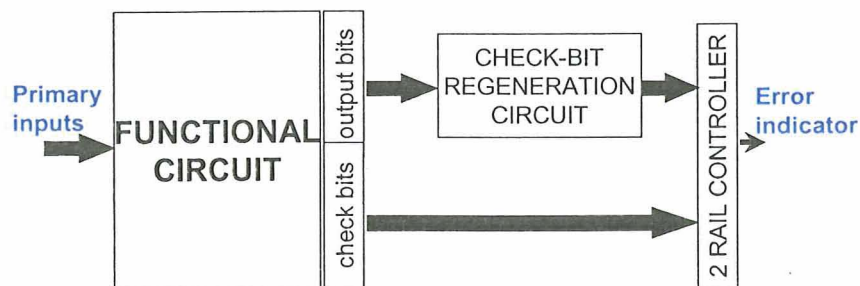
- Achieves equivalent of triple spatial redundancy by using same circuitry at three different times
- With appropriate ΔT , can be immune to upset from multiple node strikes
- Immune to transients on: data, clock, asynchronous control, and synchronous lines

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Hardening at the function level

- Design enhancement to deal with errors occurring in macrocells
 - Redundancies and voting or lockstep
 - EDAC/Self checking



- Watchdog timer

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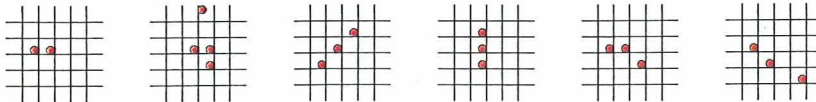
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EDAC example: Hamming code

- Parity evaluation of different bit combinations allows for m bit correct, n bit detection
- Can be used to correct/detect memory output
- Can be used to scrub memories
 - Time between scrubs determines max error latency

Data Bits	Check Bits	Total bits
1	3	4
2 to 4	4	6 to 8
5 to 11	5	10 to 16
12 to 26	6	18 to 32
27 to 32	7	34 to 39

Single Bit-Error Correct, Double Bit-Error Detect



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Outline

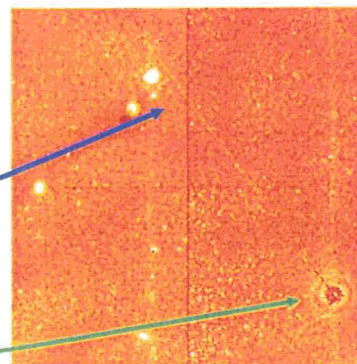
- The Space Radiation Environment
- The Effects on Electronics
- The Environment in Action
- Hardening Approaches to Commercial CMOS electronics
 - CMOS devices vulnerabilities
 - Hardening approaches
- **Conclusion**

Atomic Interactions

- Direct Ionization

Interaction with Nucleus

- Indirect Ionization
- Nucleus is Displaced



<http://www.stsci.edu/hst/nmos/performance/anomalies/bigcr.html>

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Conclusion

- **The radiation environment makes the design of electronics for space very challenging**
- **High total dose hardness levels can be achieved with state of the art technologies**
- **A variety of design techniques exist for mitigating SEE**
 - **Area, power, speed penalties depend on chosen mitigation approach**
- **New effects occur for each new technology generation**