Radiation Challenges for Electronics in the Vision for Space Exploration*

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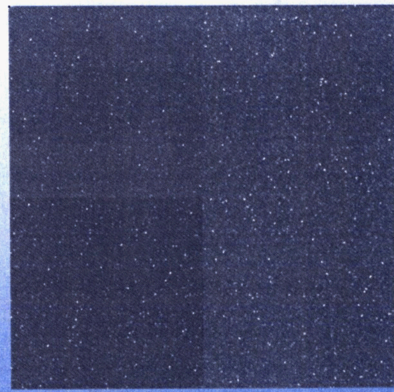
** Radiation effects are the prime consideration in this talk. Reliability must ALSO be considered.*

Outline

- Background – Radiation Effects on Electronics
- Uniqueness of Exploration Systems Missions
  - Types of missions
  - Comparison to traditional missions
- Electronic Parts and Exploration
- Radiation Effects and the Scaling of Electronics
- Simple Trade Study: The Cost of Radiation Effects Testing
- Final Comments

Radiation Effects and Spacecraft

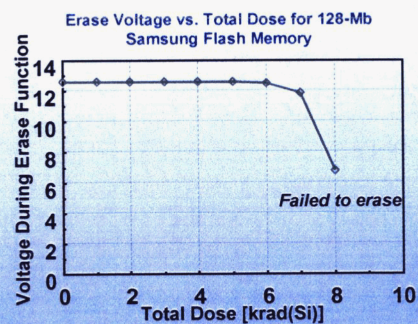
- **Critical areas for design in the natural space radiation environment**
  - Long-term effects causing parametric and /or functional failures
    - Total ionizing dose (TID)
    - Displacement damage
  - Transient or single particle effects (Single event effects or SEE)
    - Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy



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

Total Ionizing Dose (TID)

- **Cumulative long term *ionizing* damage due to protons & electrons**
  - keV to MeV range
- **Electronic Effects**
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures
- **Unit of interest is krads(material)**
- **Can *partially* mitigate with shielding**
  - Reduces low energy protons and electrons

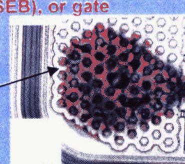


Displacement Damage (DD)

- Cumulative long term *non-ionizing* damage due to protons, electrons, and neutrons
  - keV to MeV range
- Electronic Effects
  - Production of defects which results in device degradation
  - May be similar to TID effects
  - Optocouplers, solar cells, charge coupled devices (CCDs), linear bipolar devices
    - Lesser issue for digital CMOS
- Unit of interest is particle fluence for each energy mapped to test energy
  - Non-ionizing energy loss (NIEL) is one means of discussing
- Can *partially* mitigate with shielding
  - Reduces low energy protons and electrons

Single Event Effects (SEEs)

- An SEE is caused by a *single charged particle* as it passes through a semiconductor material
  - Heavy ions (cosmic rays and solar)
    - Direct ionization
  - Protons(trapped and solar)/neutrons (secondary or nuclear) for sensitive devices
    - Nuclear reactions for electronics
    - Optical systems, etc are sensitive to direct ionization
- Unit of interest: linear energy transfer (LET). The amount of energy deposited/lost as a particle passes through a material.
- Effects on electronics
  - If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen
    - Soft errors such as upsets (SEUs) or transients (SETs), or
    - Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)
- Severity of effect is dependent on
  - type of effect
  - system criticality



Destructive event in a COTS 120V DC-DC Converter

Uniqueness of Exploration Systems Missions

- The Vision for Space Exploration creates a new paradigm for NASA missions
  - Transport (Crew Exploration Vehicle – CEV), and
  - Lunar and Mars Exploration and Human Presence
- If one considers the additional hazards faced by these concepts versus more traditional NASA missions, multiple challenges surface for reliable utilization of electronic parts.
  - The true challenge is to provide a risk as low as reasonably achievable (ALARA – a traditional biological radiation exposure term), while still providing cost effective solutions.
- The following chart tabulates the exploration environmental challenges for electronic parts relative to traditional NASA missions.

Summary of Environment Hazards for Electronic Parts in NASA Missions

	Plasma (charging)	Trapped Protons	Trapped Electrons	Solar Particles	Cosmic Rays	Human Presence	Long Lifetime (>10 years)	Nuclear Exposure	Repeated Launch	Extreme Temperature	Planetary Contaminates (Dust, etc)
GEO	Yes	No	Severe	Yes	Yes	No	Yes	No	No	No	No
LEO (low-incl)	No	Yes	Moderate	No	No	No	Not usual	No	No	No	No
LEO Polar	No	Yes	Moderate	Yes	Yes	No	Not usual	No	No	No	No
Shuttle	No	Yes	Moderate	No	No	Yes	Yes	No	Yes	Rocket Motors	No
ISS	No	Yes	Moderate	Yes - partial	Minimal	Yes	Yes	No	No	No	No
Interplanetary	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	Yes	Yes	No	Yes	Maybe	No	Yes	Maybe
Exploration - CEV	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Yes	Yes	No	Yes	Rocket Motors	No
Exploration – Lunar, Mars	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Yes	Yes	Maybe	No	Yes	Yes

Yellow indicates significant Exploration hazards

Discussion of the Hazard for Electronic Parts and Exploration

- As can be observed from the previous chart, Exploration Systems faces a unique electronic parts challenge not only for radiation exposure, but for reliability challenges as well.
  - Harsher environment than recent human presence missions (ISS, Shuttle)
  - Potentially, the combined hazard of traditional earth science (LEO) and space science (interplanetary) missions
- Cost effectiveness may drive use of innovative commercial electronics usage to meet performance constraints
  - Is this unique to Exploration? No, but with the hazard faced, one must be careful to plan for radiation and electronic parts reliability

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Types of Electronic Parts for Exploration

- One may view electronic parts for Exploration as meeting needs in three categories
  - Standard electronics
    - E.g., capacitors
      - Basic components
  - Standard building blocks
    - E.g., Field Programmable Gate Arrays (FPGAs)
      - Widespread usage in most systems
  - Custom devices not available as "off-the-shelf"
    - E.g., nuclear power or EVA
      - Needed for a specific application
- Note: Commercial-of-the-shelf (COTS) assemblies (e.g., commercial electronic cards or instruments) also may be considered
  - Screening is more complicated than with ISS in this approach due to more extreme environment faced
- In any case, coordination of the parts needs and parts management can be daunting for such a program
  - Infrastructure required to provide a cost-effective basis for electronic parts for Exploration

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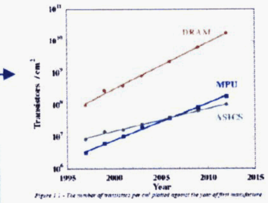
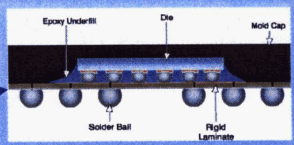
A Critical Juncture for Space Usage –
Commercial Changes in the Electronics World

- Over the past decade plus, much has changed in the semiconductor world. Among the rapid changes are:
  - Scaling of technology
    - Increased gate/cell density per unit area (as well as power and thermal densities)
    - Changes in power supply and logic voltages (<1V)
      - Reduced electrical margins within a single IC
    - Increased device complexity, # of gates, and hidden features
    - Speeds to >> GHz (CMOS, SiGe, InP…)
  - Changes in materials
    - Use of antifuse structures, phase-change materials, alternative K dielectrics, Cu interconnects (previous – Al), insulating substrates, ultra-thin oxides, etc…
  - Increased input/output (I/O) in packaging
    - Use of flip-chip, area array packages, etc
  - Increased importance of application specific usage to reliability/radiation performance





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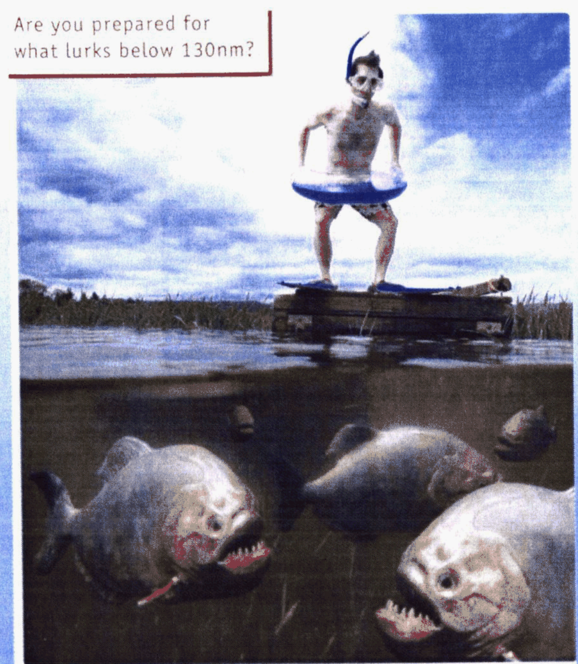

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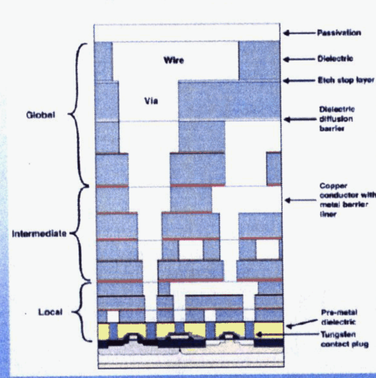
Implications for Electronics in Space

- **With all these changes in the semiconductor world, what are the implications for usage in space? Implications for test, usage, qualification and more**
  - **Speed, power, thermal, packaging, geometry, materials, and fault/failure isolation are just a few for emerging challenges for radiation test and modeling.**
    - **Reliability challenges are equally as great**
  - **The following chart (courtesy of Vanderbilt University) looks at some of the recent examples of test data that imply shortfalls in existing radiation performance models.**
    - **Technology assumptions in tools such as CREME96 are no longer valid**



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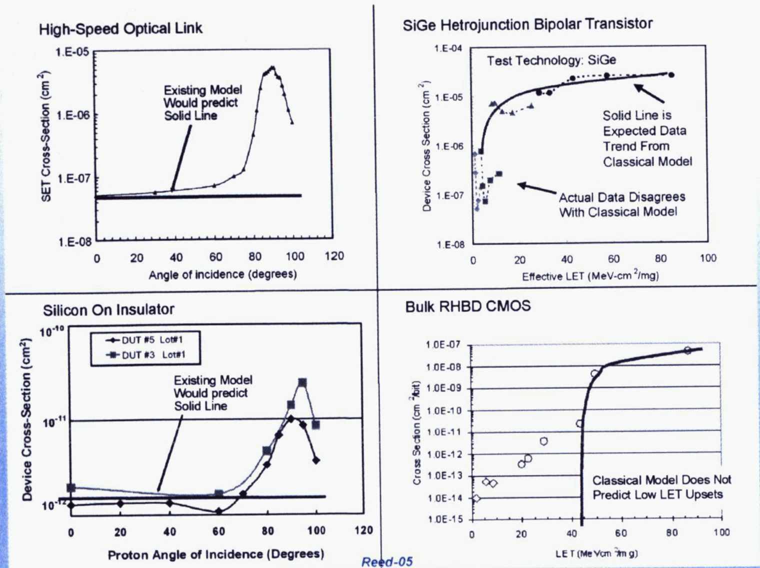
Sample Modeling Shortfalls



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Sample Cost Drivers for Radiation Testing from 1996 to 2006 - Example

- Device under test (DUTs): Commercial Memories
  - Used in solid state recorder (SSR) applications
- 1996
  - SRAM memory
    - 4 mbits per device
    - <50 MHz bus speed
    - Ceramic packaged DIP or LCC or QFP
- 2006
  - DUT: DDR2 SDRAM
    - 1 Gbit per device
    - >500 MHz bus speed
    - Plastic FBGA or TSOP
    - Hidden registers and modes
    - Built-in microcontroller

- Issues
  - Size of memory
    - Drives complexity on tester side for amount of storage, real time processing, and length of test runs
  - Speed
    - *Difficult to test at high-speeds reliably*
      - Need low-noise and high-speed test fixture
    - Classic bit flips (memory cell) extended to include transient propagation (used to be too slow a device to respond)
    - Thermal and mechanical issues (testing in air/vacuum)
  - Packaging
    - *Modern devices present problems for reliable test board fixture, die access (heavy ion tests) requiring expensive facility usage or device repackaging/thinning*
    - *Difficulty in high-temp testing (worst-case)*
  - Hidden registers and modes
    - Functional interrupts driving "anomalous data"
      - Not just errors to memory cells!
  - Microcontroller
    - Not just a memory

Sample Cost for SEE Testing: *1996 vs 2006 a 3X Cost Delta*

1996 SEE Test of a 4M SRAM				
Description	Man-weeks or units	Cost in $	Total	Note
Heavy Ion at BNL SEUTF				
Test plan	0.20	$4,000.00	$800.00	Includes eng, rad, other to define what needs to go into test set with project.
Device procurements	10.00	$50.00	$500.00	
Misc parts	1.00	$250.00	$250.00	Sockets, connectors, etc...
Device delidding	0.05	$3,500.00	$175.00	
Test board design - electrical and layout	0.40	$4,000.00	$1,600.00	
Board fab and population	1.00	$3,500.00	$3,500.00	In-house board build
Board/tester debug	0.50	$4,000.00	$2,000.00	
Rad expert (test oversight and plan)	0.40	$5,000.00	$2,000.00	
Heavy ion test performance - contractor	2.00	$1,500.00	$3,000.00	
BNL Beam	6.00	$700.00	$4,200.00	Simple data: bit flips, latchup
Data analysis	1.00	$3,500.00	$3,500.00	
Test report (eng, rad expert, rad lead)	0.50	$4,000.00	$2,000.00	
		Total:		$23,525.00

2006 SEE Test of SDRAM				
Description	Man-weeks or units	Cost in $	Total	Note
Heavy Ion at TAMU				
Test plan	1.00	$4,000.00	$4,000.00	Includes eng, rad, other to define what needs to go into test set with project.
Device procurements	10.00	$75.00	$750.00	
Misc parts	1.00	$1,000.00	$1,000.00	Higher speed drives cost
Device thinning and package processing	10.00	$350.00	$3,500.00	Assumes FBGA package; If *this does not work, more* expensive test facility like NSCL needed: >$100K delta
Daughterboard Board design - electrical	0.40	$4,000.00	$1,600.00	
Daughterboard Board design - PCB	0.50	$3,500.00	$1,750.00	
Test Boards	10.00	$500.00	$5,000.00	
Board population	0.40	$3,500.00	$1,400.00	
Board/tester debug	0.50	$4,000.00	$2,000.00	
Tester VHDL development	3.00	$4,000.00	$12,000.00	
Technician	1.00	$3,500.00	$3,500.00	
Rad expert (test oversight and plan)	0.60	$5,000.00	$3,000.00	
Heavy ion test performance - contractor	2.00	$2,000.00	$4,000.00	
TAMU	16.00	$750.00	$12,000.00	2X time required: more data, more error types, more complex results
Data analysis	3.00	$3,500.00	$10,500.00	
Test report (eng, rad expert, rad lead)	1.00	$4,000.00	$4,000.00	
			Total in	$70,000.00

Cost to "Radiation Qualify" – Trade Study for Exploration

- Expectation is to use lots of devices NOT specifically designed for the radiation environment
  - Qualification/testing of commercial devices and boards likely required
    - Expect >1000 device types requiring lot-specific tests
- Biggest driver: SEE (heavy ion)
  - ISS used protons (different hazard faced)
  - Exploration needs heavy ions
    - Use of expensive test facilities or risky device/package manipulations required
- Estimated cost delta from ISS to Exploration
  - Assumes fewer devices need testing (each more complex) and no nuclear testing

Program	Number of components for testing	Average "qual" cost	Total	Note
ISS	500	10000	$5,000,000.00	Proton only tests
Exploration	300	60000	$18,000,000.00	TID and Heavy Ion SEE required; NSCL required for some devices/boards
			Cost Delta	$13,000,000.00

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Bottom Line

- This presentation has been a brief snapshot discussing electronics and Exploration-related challenges.
  - Radiation effects have been the prime target, however, electronic parts reliability issues must also be considered.
    - Modern electronics are designed with a 3-5 year lifetime typical.
      - "Upscreening" does not improve reliability, merely determine inherent levels.
  - Testing costs are driven by device complexity
    - Increases tester complexity, beam requirements, and facility choices
  - Commercial devices may improve performance, but are no cost panacea
  - Big need is for a more cost-effective access to high energy heavy ion facilities (NSCL and NSRL)
    - NSCL is ~$2500/hr with a 24-hour minimum
- Cost for test equipment is not discussed, but capable testers can run >>$1M for full testing
  - Niche technology (wireless, for example) would also require infrastructure test equipment

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