The Importance of Nuclear Reactions in Determining SEE Testing Methodology

Ronald Lacoe
The Aerospace Corporation

Microelectronics Reliability and Qualification Workshop
December 11, 2012
Introduction

• Testing methodologies need to be developed to enable the eventual qualification of technologies for future insertion into space missions
• Understanding physical mechanisms potentially leads to more effective test methodologies
  • Example: Effect of Nuclear Reactions on SEE error rates
• Nuclear reactions can produce additional cross section near and below the LET threshold
  • Can be important for components with higher LET thresholds
  • Likely not important for HBD components with low LET threshold
    • For these types of components, need to measure upset cross section associated with direct ionization from protons
  • Radial track effects can be important, but for now may not impact HBD components
• We are still learning about the role of nuclear reactions in SEEs and there is likely much we do not yet understand
Developing Testing Methodology

Understanding physical mechanisms potentially leads to more effective test methodologies
Recent Example of Increased SEU Cross Section for High Energy Ions

Nuclear reactions produce additional cross-section near or below the low energy LET threshold
Additional Cross Section Can Lead to Large Increases in Error Rate

SRAM NASA MESSENGER

Additional nuclear cross section increases error rate by ~ 100x

Pre-Flight Prediction (Direct Ionization Only)

Reed TNS 2007
GCR Space Environment

Heavy ion energies in space are much higher than found at most ground testing facilities.
Energy/Nucleon Must Exceed Coulomb Barrier to Enable Nuclear Reactions

\[ CB(\text{MeV}) = 1.03 \left( \frac{1 + M_1}{M_2} \right) \left( \frac{Z_1 Z_2}{M_1^{1/3} + M_2^{1/3}} \right) \]

- \( Z \) = Atomic Number
- \( M \) = Atomic Mass

Reed TNS 2006
Large Fraction of Heavy Ions Can Produce Nuclear Interactions

Particles that can produce nuclear reactions dominate for lower LETs
Monte Carlo Energy Deposition Simulation (MRED) at Vanderbilt

- Monte Carlo simulation derives a statistical profile of energy deposition within the sensitive volume from:
  - Direct Ionization (LET)
  - Nuclear Reaction Products
- Based on Geant 4 Libraries
- Inputs overlayers and sensitive volume
- Can derive Cross Section vs. LET Curves → Error Rates

Warren TNS 2005
Typical MRED Result – Histogram of Charge Deposited Within the Sensitive Volume

\[ Q(pC) = 1.1 \times 10^{-5} \cdot L(\mu m) \cdot \text{LET}(MeV - cm^2 / gm) \]

High \( Q_{\text{dep}} \) tail is associated with nuclear reactions which produce secondaries with higher LETs than the primary.

\[ N_{\text{Direct Ion}} \sim 10^4 - 10^6 \, N_{\text{Nucl}} \]
Use Counts vs. Deposited Charge to Generate Integrated Cross Section vs. Critical Charge

\[ \sigma(Q_{\text{Crit}}) = \frac{1}{\Phi} \sum_{i=1}^{\infty} N_i \]

Warren TNS 2005
Redo for Several Ions Species of Varying LET

- If know $Q_{\text{crit}}$, can generate $\sigma$ vs. LET curve
- If have cross section data, vary $Q_{\text{crit}}$ to determine best fit to experimental data to $\rightarrow Q_{\text{crit}}$

Can generate $\sigma$ vs. LET curve and use to determine error rates
Nuclear reactions are only important for higher \( Q_{\text{crit}} \)/\( \text{LET}_{\text{th}} \) circuits.
HBD Components

- HBD components typically use latches/memories with low $Q_{\text{crit}} / \text{LET}_{\text{TH}}$
  - SEU mitigation is achieved through spatial and temporal redundancy
    - TMR
    - DICE
    - EDAC
  - For heavy ions with LET > 1, above LET$_{\text{TH}}$ and the total number of upsets is dominated by primary ionization

For most HBD devices, nuclear reactions do not contribute to SEU rate
Lack of High Energy Effects for 45-nm & 65-nm SRAMs

Experimental validation of lack of nuclear effects for low LET_{th} HBD devices
Recent Anomalous Results

The graph illustrates cross-section data for different energies and elements. The highest energy ion has the lowest cross section at LET = 1.8.

V. Ferlet-Carvois, RADEC 2011 & TBP TNS 2012

- **25 MeV/a Ne**
- **9.3 MeV/a N**
- **500 MeV/a Ni**

Highest energy ion has lowest cross section at LET = 1.8
Recent Anomalous Results

- High energy particle produces secondaries with large spread in $Z$
  - High energy primaries produce high energy secondaries $\rightarrow$ low LET $\rightarrow$ small number of upset?

There is still much we do not understand on the impact of using high energy particles for SEE testing

V. Ferlet-Carvois, RADEC 2011 & TBP TNS 2012
Track Radius Effects

- Extended track radius tends to result in a loss of charge collected in the sensitive volume
  - Underestimates error rate as compared to the lower energy ion
- For HBD technology, where employ spatial redundancy, want to avoid the charge from a single ion upsetting redundant circuitry
  - Design logic so critical node pairs more than 1 \( \mu \text{m} \) apart
- Possibly an issue for grazing angle upsets
- High energy particles can traverse long distances which can be useful for selected applications

From the point of view of non-nuclear charge collection, high energy particle SEU testing is not the conservative testing approach
HBD Components Can Be Sensitive to Direct Ionization Upsets from Low Energy Protons

HBD components (<= 90nm) have a peak in the cross section for low energy protons associated with direct ionization
Summary

- Testing methodologies need to be developed to enable the eventual qualification of technologies for future insertion into space missions
- Understanding physical mechanisms potentially leads to more effective test methodologies
- The space GCR environment is dominated by energetic ions that can produce nuclear reactions ⇒ need to consider the role of nuclear reactions on SEE
- A basic mechanisms analysis leads to generalizations on the need for high-energy SEE testing
  - Nuclear reactions are only potentially important for higher $Q_{\text{crit}}/\text{LET}_{\text{th}}$ circuits
  - For most HBD devices with low $Q_{\text{crit}}/\text{LET}_{\text{th}}$, nuclear reactions do not significantly contribute to the SEU rate
Summary

• The highest energy per nucleon particle for a given LET does not always produce the largest SEE cross section ⇒ default high energy testing is not necessarily the conservative approach

• Devices with low $Q_{\text{crit}}/\text{LET}_{\text{th}}$ need to be tested for direct proton ionization effects

• Increased track radii for energetic particles in space tends to reduce the charge collected at a critical node ⇒ not necessarily a conservative testing approach

• We are still learning about the role of nuclear reactions in SEEs and there is likely much we do not yet understand
Back-Up Slides
Example: Effect of Nuclear Interactions on SEUs

Q(pC) = \frac{L \cdot \frac{LET \cdot \rho}{E_{eh}}}{q} = 1.1 \times 10^{-5} \cdot L(\mu m) \cdot LET(MeV - cm^2 / gm)

D. Mavis, *Microelectronic Reliability Qualification Workshop*, Manhattan Beach, CA 2002

P.E. Dodd, 1999 IEEE NSREC Short Course, Norfork, VA 1999
When SEU current $I_{\text{SEU}}$ exceeds restoring current from cross-coupled inverter such that the node voltage drops below $V_D/2$ for too long, an upset occurs.

Proton LET vs. Energy
GEO Proton Environment
Figure of Merit

22.5 MeV/pC ↔ 0.044 pc/MeV = 44 fC/MeV