The Role of Singly-Charged Particles in Microelectronics Reliability

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November 17, 2011

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Outline

- Singly-Charged Particles
- Natural Radiation Environments
- Energy Loss Mechanisms
- Accelerated Testing
- Technology Scaling
- Predictions of Error Rates
- Recommendations
- Conclusions
Singly-Charged Particles

- Historically, alpha particles (Q=2e) and heavy ions (Q>2e) cause errors in microelectronics primarily through *electronic stopping*, energetic protons and neutrons through *nuclear stopping*

- Experimental data indicate protons are capable of causing errors due to ionization

- Stopping protons and muons are predicted to be significant contributors to error rates in sub 65 nm processes

### COMMON SINGLY-CHARGED (Q=±e) PARTICLES

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Mass (MeV/c²)</th>
<th>Mean Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>p⁺ / p⁻</td>
<td>938</td>
<td>--</td>
</tr>
<tr>
<td>pion</td>
<td>π⁺ / π⁻</td>
<td>140</td>
<td>26 x 10⁻⁹</td>
</tr>
<tr>
<td>muon</td>
<td>μ⁻ / μ⁺</td>
<td>106</td>
<td>2.2 x 10⁻⁶</td>
</tr>
<tr>
<td>electron</td>
<td>e⁻ / e⁺</td>
<td>0.511</td>
<td>--</td>
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Background

- Wallmark and Marcus (IRE '62) predicted limits to scaling
- Ziegler predicted muon ionization would eventually dominate chip error rates
- Bendel (TNS '83) asserted “a part sensitive to the ionization in a proton track would be grossly unfit for spacecraft use”

Ziegler, Sci. 1979

Rodbell, TNS. 2007
Space Environments

GEO

GEO (Worst Day)

Van Allen belts

ISS
Terrestrial Environments

- GCR particles responsible for cosmic ray showers
  - Neutrons, protons, pions, muons, ...
- Flux spectra best modeled by Monte Carlo applications (EXPACS)
Single Event Upsets

- SEU occur as the result of ionizing particles
- In older technologies, protons only able to cause upsets through nuclear interactions
- Reliability decreasing as gate capacitance, restoring currents decrease
Motivation

- NASA Goddard proton data show 3-4 orders magnitude increase at low-energy
- Saturated cross section consistent with probability of nuclear reaction
- Low-energy cross sections on order of physical feature dimensions
- Features indicate proton direct ionization

TI 65nm Bulk CMOS SRAM
Energy Loss Mechanisms

- Stopping power strongly dependent on particle charge and velocity
- Bragg peak identical for singly-charged particles \(~0.5\ \text{MeV-cm}^2/\text{mg}\)
- Circuits sensitive to proton direct ionization likely sensitive to other singly-charged particles
- Threshold LETs decreasing in modern circuits
  - Further decreases will include greater range of particles and energy
Devices Under Test

- Bulk CMOS 6-transistor SRAMs
  - Texas Instruments 65 and 45 nm
  - Marvell Semiconductor 55 and 40 nm
- Tests conducted at Berkeley, Texas A&M, and TRIUMF
- Experiments performed in air, close to beam window
- Parts bonded as chip-on-board or were de-lidded
LBNL Proton Testing

- LBNL used to confirm apparent direct ionization effect
- Goddard facility uses Van de Graaff
- Low-energy test used custom 6 MeV H₂ beam
- Results rule out dosimetry issues
Heavy ion test results demonstrate sensitivity to small quantities of charge. Low-LET data require high-energy tests at TAMU. Low-energy protons comparable with 0.5 MeV-cm²/mg heavy ions.
Single Event Upset Model

- Single bit cross sections correspond to physical device areas
- Low-LET heavy ion cross sections used to define sensitive area
  - Single, well-known stopping power
- MRED code predicts low-energy proton response

\[
\alpha_1 = 1.0 \\
\alpha_2 = 0.82 \\
\alpha_3 = 0.30 \\
\alpha_4 = 0.05 \\
Q_{crit} = 1.3 \text{ fC}
\]
Proton Mechanisms

1.4 MeV p

Direct Ionization

Metal Lines
Sensitive Volumes
Substrate

4.6 MeV p

Coulomb Scatter

32.5 MeV p

Spallation

\( p \)
\( e^- \)
\( \gamma \)
\( Al \)
Muon Testing

- Proton sensitivity suggests muon sensitivity
- TRIUMF M20 beam produces 30 MeV/c surface muons ($\mu^+$)
- Surface barrier detector characterized beam
- Geant4 muon transport agrees with calorimetry
Muon Results

1.0 V

- Upsets / $10^9$ muons
- $\sigma \sim 10^{-13}$ cm$^2$/bit

21 MeV/c

- Upsets / $10^9$ muons
- Supply Voltage (V)
- $\sigma \sim 10^{-12}$ cm$^2$/bit

21.6 MeV/c

- Upsets / $10^9$ muons
- Technology Node (nm)
Scaling Trends

- Device sensitivity steadily decreasing
- Predictions of charge threshold based on ITRS and SPICE
- IBM published 65 nm SOI SRAM critical charge 0.21 – 0.27 fC

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<th>Technology (nm)</th>
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<td>0.13</td>
<td>0.088</td>
<td>0.056</td>
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<tr>
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Contribution of Protons in ISS

- Applying ISS environment to sensitive volume model reveals error rate as function of species and critical charge
- Direct ionization is becoming the dominant upset mechanism for protons
Contribution of Protons in GEO

- Applying GEO environment shows iron and other common ions drive the error rate
- Proton flux too low to be an issue (in quiescent conditions)
Contribution of Worst Day Protons

- Worst Day shows large contributions to error rate from both protons and alpha particles
- Need to assess impact on reliability
Predictive SEU Models

- Protons already relevant at 65 nm
- Muon SEU increasing below 65 nm
- What are the effects of scaling, process technologies?

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• Critical charge bounds define valid range in error rates
• Proton ionization contribution substantial, but relatively constant with scaling
NYC Sea Level Muons

- Range of error rates relatively unchanging with scaling
- Prediction ranges from insignificant to > 10,000 FIT
- Steep rise indicates small differences between cells may make substantial differences in reliability
Effect of Process Technology

- 22nm process SEU models assumed to differ by charge collection depth
  - Bulk 500nm, bulk FinFET 240nm, SOI 10nm
  - SOI may have lower threshold thereby increasing maximum error rate
Recommendations

- Lack of threshold in degraded proton beam?
  - No
  - Yes

  - No additional predictions required
    - No
    - Yes

  - Electrostatic proton accelerator shows increased cross section?
    - No
    - Yes

    - Ion beam tests indicate \( \text{LET}_{th} \ll 1 \text{ MeV-cm}^2/\text{mg} \)?
      - No
      - Yes

      - Proton prediction required
        - No
        - Yes
          - Terrestrial application?
            - No
            - Yes
              - Muon prediction required

Conclusions

• Neutrons and high-energy protons only rarely interact with nuclei, low-energy protons and muons are able to cause upsets through ionization

• Accelerated tests can demonstrate sensitivity
  • Few high-energy facilities in the world produce muon beams
  • If a part has been shown to be insensitive to proton direct ionization, there is a high confidence that it is also immune to muon direct ionization

• Simulations show that singly-charged particle direct ionization is a concern for reliability
  • Small changes in design (eg. Collection depth, cell area, low power) may cause large changes in error rates