Low-Energy Proton Single Event Upsets in SRAMs

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

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

Stopping protons are predicted to be significant contributors to error rates in sub 65 nm processes.
Electronic Stopping

- Stopping power strongly dependent on particle charge and velocity
- Bragg peak identical for singly-charged particles ~0.5 MeV-cm²/mg
- Threshold LETs decreasing in modern circuits
  - Further decreases will include greater range of particles and energy
Proton SEU Cross Sections

- 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

Texas Instruments 65nm Bulk CMOS SRAM

[Graph showing SEU cross section versus proton energy]
Space Environments

GEO

GEO (Worst Day)

Van Allen belts

ISS
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
GSFC Van de Graaff tests indicate elevated SEU cross section
LBNL used to confirm direct ionization effect
Low-energy test used custom 6 MeV H$_2$ beam
Results rule out dosimetry issues
Width of beam energy will affect rate predictions
Heavy Ion Test Results

- Heavy ion data 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

\[ Q_{\text{crit}} = 1.3 \text{ fC} \]

**Calibration**

**Prediction**

\[ \hat{\alpha}_1 = 1.0 \]
\[ \alpha_1 = 1.0 \]

\[ \hat{\alpha}_2 = 0.82 \]
\[ \alpha_2 = 0.52 \]

\[ \hat{\alpha}_3 = 0.30 \]
\[ \alpha_3 = 0.25 \]

\[ \hat{\alpha}_4 = 0.05 \]
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Proton Mechanisms

- Metal Lines
- Sensitive Volumes
- Substrate

1.4 MeV p
- Direct Ionization

4.6 MeV p
- Coulomb Scatter

32.5 MeV p
- Spallation
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
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
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

### Technology (nm) and Vdd (V)

<table>
<thead>
<tr>
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### Capacitance (fC) and Spice Threshold (fC)

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Petersen, NSREC 97
Predictive SEU Models

- Protons already relevant at 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
Recommendations

Lack of threshold in degraded proton beam?

- No
- Yes

- No

Electrostatic proton accelerator shows increased cross section?

- No
- Yes

- No

Ion beam tests indicate $\text{LET}_{\text{th}} \ll 1 \text{ MeV-cm}^2/\text{mg}$?

- No
- Yes

- Yes

Advanced proton prediction required

- No
- Yes
Proton SEU Characterization

- Continuing relationship with Texas Instruments and NASA NEPP will investigate proton sensitivity of 28 and 20 nm bulk CMOS SRAMs
- Additional data for the evaluation of proton test methods, facilities, and SEU models will be collected
- Investigations will examine changes in SEU thresholds, trend with CMOS process technology – will low-energy tests be required for all future SRAMs?
Vanderbilt Pelletron

- Completion of beamline allows for low-energy single event tests on microelectronics in-vacuum
  - 4 MeV protons
  - 6 MeV alphas
  - 10 MeV oxygen
CubeSat Program

Our goal is to develop, fabricate, simulate, and operate a low cost on-orbit system to improve our understanding of the impact of space radiation environments on satellite components and systems.

Sponsors:
- NASA EPSCoR
- DTRA Basic Research Program
- NASA Tennessee Space Grant
- NASA Exploration Space Grant Project

Supporters:
- NASA Electronics Parts and Packaging
- DTRA Radiation-Hardened Microelectronics Program
- Air Force University Nanosat Program
- Texas Instruments
- Jazz Semiconductor

### Payloads

<table>
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<th>Woodland</th>
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<tr>
<td>2U CubeSat</td>
<td>1U CubeSat</td>
</tr>
<tr>
<td>Partner: SLU (Argus – high)</td>
<td>Partner: AMSAT</td>
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### Low-Energy Proton (LEP) Experiment

- Count on-orbit single event upsets in a COTS memory
- Complement on-orbit data with ground-based accelerated tests
- Evaluate proton test and error rate prediction methods
Summary

- Modern static random access memories have demonstrated elevated low-energy proton SEU cross sections sufficient to affect on-orbit error rates
- Established test methods and rate prediction tools do not properly account for this mechanism
- Test campaigns should accommodate for low-energy proton characterization of parts with no clear proton threshold or low-LET (\(< 1 \text{ MeV-cm}^2/\text{mg}\)) threshold
- Radiation transport simulations provide best indication of on-orbit performance