Low-Energy Proton Testing Methodology


¹: Radiation Effects and Analysis Group, NASA/GSFC, Code 561.4, Greenbelt, MD 20771
²: NASA Consultant, Brookneal, VA 24528
³: IBM TJ Watson Research Center, Yorktown Heights, NY 10598
⁴: Sandia National Laboratories, Albuquerque, NM 87175
⁵: MEI Technologies (NASA/GSFC), Code 561.4, Greenbelt, MD 20771
⁶: IBM System and Technology Group, Essex Junction, VT 05452
⁷: Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN 37235

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under Contract DE-AC04 94AL85000.
Overview

- Sub-100 nm technologies show SEU sensitivity to low-energy protons

- Testing challenges associated with low-energy proton beams

- Outline of current best practices

- Is it low-energy protons or high-energy light ions?

- Summary
Moving to Low-Energy Protons

- Proton testing is an integral part of accelerated ground testing and single-event effects evaluation
  - Will continue to use high-energy (> 60 MeV) proton beams
  - New interest in low-energy (< 5 MeV) proton beams


Low-Energy Testing Challenges

- Low proton energy leads to several important topics
  - Where’s the Bragg peak?
  - Tune the beam or degrade it
  - Topside testing (wire-bonded DUT) or backside (C4)
    • Focus mostly on backside testing; is the die thinned?
  - Straggling, which affects both range and energy
Proton Stopping Power in Silicon

Variability of stopping power at the Bragg peak

- $dE/dx$ of interest occurs around Bragg peak
- Systematic complication from both an experimental AND simulation perspective


Ion = Hydrogen (1)
Target = Silicon (14)

Ion Energy (keV/amu)
Stopping Experiment/Theory Hydrogen Stopping (eV-cm²/10¹⁶)

Data Set=18 (200pts)
Mean Error= 6.6 ± 0.4

http://www.srim.org/
Proton Transport and Calorimetry

<table>
<thead>
<tr>
<th>Energy</th>
<th>20.4 MeV</th>
<th>12.5 MeV</th>
<th>6.5 MeV</th>
<th>100 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range$_{Si}$</td>
<td>2.5 mm</td>
<td>1.1 mm</td>
<td>340 μm</td>
<td>0.87 μm</td>
</tr>
<tr>
<td>$dE/dx_{Si}$ (MeV·cm$^2$/mg)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.5</td>
</tr>
</tbody>
</table>

---

- Lower energy tune → easier to get more particles of the same energy***
- Precision of beam energy tune can be critical (range at 100 keV!!)

Proton Transport and Calorimetry

<table>
<thead>
<tr>
<th>Energy</th>
<th>20.4 MeV</th>
<th>12.5 MeV</th>
<th>6.5 MeV</th>
<th>100 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range_{Si}</td>
<td>2.5 mm</td>
<td>1.1 mm</td>
<td>340 µm</td>
<td>0.87 µm</td>
</tr>
<tr>
<td>dE/dx_{Si} (MeV·cm^2/mg)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- Lower energy tune → easier to get more particles of the same energy***
- Precision of beam energy tune can be critical (range at 100 keV!!)

MRED Calculations

Proton Transport and Calorimetry

<table>
<thead>
<tr>
<th>Energy</th>
<th>20.4 MeV</th>
<th>12.5 MeV</th>
<th>6.5 MeV</th>
<th>100 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range(\text{Si})</td>
<td>2.5 mm</td>
<td>1.1 mm</td>
<td>340 (\mu)m</td>
<td>0.87 (\mu)m</td>
</tr>
<tr>
<td>(dE/dx_\text{Si}) (MeV·cm(^2)/mg)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- Lower energy tune \(\rightarrow\) easier to get more particles of the same energy***
- Precision of beam energy tune can be critical (range at 100 keV!!)

MRED Calculations

To be presented by Jonathan A. Pellish at the 18th Annual Single-Event Effects Symposium (SEE Symposium)
Backside Testing – Unthinned DUT

- Xilinx FPGA, Virtex-IV, LX25
- Proton testing conducted at UC Davis Crocker Nuclear Lab
Backside Testing – Unthinned DUT

- Xilinx FPGA, Virtex-IV, LX25
- Proton testing conducted at UC Davis Crocker Nuclear Lab

Various Degrader Stacks Used
67.5 and 20.4 MeV Tunes Used

DPA Cross Section of DUT

To be presented by Jonathan A. Pellish at the 18th Annual Single-Event Effects Symposium (SEE Symposium)
Backside Testing – Thinned DUT

- 36 Mbit IBM Magnum 45 nm SOI SRAM
- Proton testing conducted at UC Davis Crocker Nuclear Laboratory

Various Degrader Stacks Used
67.5 and 20.4 MeV H⁺, and 12.5 MeV H⁺ Tunes Used

Particle energies @ DUT are preliminary

D. F. Heidel et al., SEE Symposium, April 2009.
Backside Testing – Thinned DUT

- 36 Mbit IBM Magnum 45 nm SOI SRAM
- Proton testing conducted at UC Davis Crocker Nuclear Laboratory

Ideal case would be to have a DUT with no substrate – could just use primary beam (no degraders)

Various Degrader Stacks Used

- 67.5 MeV H⁺, and 12.5 MeV H⁺

Tunes Used

Single-bit Errors

Double-bit Errors

Proton Energy at SOI Plane (MeV)

Cross Section (cm² / Mbit)

Particle energies @ DUT are preliminary

Pattern: Blanket "1"

D. F. Heidel et al., SEE Symposium, April 2009.

To be presented by Jonathan A. Pellish at the 18th Annual Single-Event Effects Symposium (SEE Symposium)

Best-Practices for Low-Energy Proton Testing

• Record as much detail as possible regarding materials upstream from the sensitive DUT regions
  – Kapton/aramica windows, degrader foils, air gap, substrate or BEOL thickness, PCBs, package lids, etc.

• Tune the primary beam energy as much as is feasible to achieve lower particle energy
  – Don’t forget straggle (range AND energy)

• Remember that there is nearly unavoidable systematic error in proton energy @ DUT plane

• Utilize available radiation transport tools to make a best estimate of the particle energy and possible flux attenuation at the sensitive region

To be presented by Jonathan A. Pellish at the 18th Annual Single-Event Effects Symposium (SEE Symposium)
Utility of Low LET Particles

- Below 90 nm, difficult to investigate single sensitive features
  - Multi-cell and multi-bit upsets – cannot distinguish features
  - Common example is an SRAM cell

Question to be answered: do low-energy protons and equivalent-LET heavy ions produce the same cross section?

Sensitive regions within are even smaller

To be presented by Jonathan A. Pellish at the 18th Annual Single-Event Effects Symposium (SEE Symposium)
High-Energy Light Ions

TAMU 15 MeV/u tune – He and N also available at 25 and 40 MeV/u

To be presented by Jonathan A. Pellish at the 18th Annual Single-Event Effects Symposium (SEE Symposium)
High-Energy Light Ions

- LBNL BASE facility 4.5, 10, 16, and 30 MeV/u cocktails.
- Note inclusion of $^{11}$B at 10 MeV/u and $^{14}$N at 16 and 30 MeV/u
  - $^3$He available at 16 MeV/u, though not listed
  - $^3$He possible at 30 MeV/u, though untested and would require development time

http://cyclotron.lbl.gov/subpage2.html

Summary

• Use of low-energy protons and high-energy light ions is becoming necessary to investigate current-generation SEU thresholds

• Systematic errors can dominate measurements made with low-energy protons
  – Range and energy straggling contribute to systematic error
    • Not just counting statistics anymore
  – Low-energy proton testing is not a step-and-repeat process

• Low-energy protons and high-energy light ions can be used to measure SEU cross section of single sensitive features – important for simulation