Low-Energy Proton Testing Methodology


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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

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

**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>
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<tr>
<td>Range&lt;sub&gt;Si&lt;/sub&gt;</td>
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- Lower energy tune → easier to get more particles of the same energy***
- Precision of beam energy tune can be critical (range at 100 keV!!)

SRIM-2008 Values
Proton Transport and Calorimetry

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20.4 MeV Protons

Si + Degrader Stack

1×10$^7$ particles

Energy Deposited in a 1 $\mu$m thick volume

MRED Calculations

Proton Transport and Calorimetry

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**SRIM-2008 Values**

- 20.4 MeV Protons
  - 100 \mu m Si
  - 100 \mu m Si + 15 mil Ta
  - 100 \mu m Si + 15 mil Ta + 20 mil Al

- 12.5 MeV Protons
  - 100 \mu m Si
  - 100 \mu m Si + 3 mil Ta
  - 100 \mu m Si + 3 mil Ta + 13 mil Al

**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

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Various Degrader Stacks Used
67.5 and 20.4 MeV Tunes Used

DPA Cross Section of DUT

Static test results only

Particle energies @ DUT are preliminary

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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

Single-bit Errors

Double-bit Errors

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

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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** 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.

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
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

<table>
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<tr>
<th>0.5 (\mu\text{m}^2)</th>
<th>Roughly</th>
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<td>45 nm</td>
<td></td>
<td>65 nm</td>
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High-Energy Light Ions

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

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

**By Special request**

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