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

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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

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

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SRIM-2008 Values

- Lower energy tune → easier to get more particles of the same energy***
- Precision of beam energy tune can be critical (range at 100 keV!!)
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SRIM-2008 Values

20.4 MeV Protons

Si + Degrader Stack
1×10\textsuperscript{7} particles

Energy Deposited in a 1 μm thick volume

MRED Calculations

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## Proton Transport and Calorimetry

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- **20.4 MeV Protons**
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  - 1×10⁷ particles
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**MRED Calculations**

Backside Testing – Unthinned DUT

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

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Beam

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

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

Single-bit Errors

Double-bit Errors

Particle energies @ DUT are preliminary

Pattern: Blanket “1”

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 and 20.4 MeV H⁺, and 12.5 MeV H⁺ Tunes Used

Various Degrader Stacks Used

67.5 and 20.4 MeV H⁺, and 12.5 MeV H⁺ Tunes Used

- Particle energies @ DUT are preliminary
- Solid symbols → VDD₂ = 0.6 V
- Open Symbols → VDD₂ = 1.2 V

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
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

![Diagram showing 0.5 μm² and 1.0 μm² areas with 45 nm and 65 nm dimensions]

Sensitive regions within are even smaller

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

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By Special request

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