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Acronyms

- CMOS: complementary metal oxide semiconductor
- CNL: Crocker Nuclear Laboratory
- CSDA: continuous slowing down approximation
- DBU: double-bit upset
- DUT: device under test
- IBM YKT: Yorktown Heights, NY
- ICRU: International Commission on Radiation Units & Measurements
- IEEE: Institute of Electrical and Electronics Engineers
- IUCF: Indiana University Cyclotron Facility
- LBNL: Lawrence Berkeley National Laboratory
- LEP: low-energy proton
- MCU: multi-cell upset (errors not necessarily in the same data word)
  - Different from multi-bit upset (MBU)
- NIST: National Institute of Standards and Technology
  - ASTAR and PSTAR are NIST tools, not acronyms
- NPTC: Northeast Proton Therapy Center
- SBU: single-bit upset
- SEEM: secondary electron emission monitor
- SEU: single-event upset
- SOI: silicon on insulator
- SRAM: static random access memory
- SRIM: Stopping and Range of Ions in Matter (software program)
- TNS: Transactions on Nuclear Science
- TRIUMF: not an acronym – formerly the Tri-University Meson Facility, Vancouver, Canada
- UC Davis: University of California at Davis
Outline

• Introduction
  – Low-energy protons (LEPs)
  – Test facility setup
• Protons vs. alphas
• DUT is 32 nm SOI CMOS 128 Mb SRAM
  – Heavy ion data baseline
  – DUT is in a flip-chip package
• SBU and MCU SRAM data
• Die thickness reverse engineering with SRIM
• Summary
Early Low-Energy Proton Data

- Cross sections are plotted as a function of *incident* proton energy – inversely proportional to degrader thickness.
  - Several implications: changes to the energy distribution shape, flux depletion near end-of-range, etc.
  - Can plot data as a function of degrader thickness.
- How do we know the mean energy and standard deviation?


The Problem with LEPs – Range & dE/dx

- Greatest effect in the shortest distance
- Short range in region of interest implies flux depletion
- Cross sections tend to be uncorrected for flux loss and plotted as a function of known quantities (e.g., degrader thickness)

The Alpha ($^4$He) Alternative

**Hypothesis**: Alpha particles can replace LEPs for direct ionization single-event effects testing.

In the context of LEPs, mentioned as early as 2009 – B. D. Sierawski et al., including J. Pellish.

- **H** starts at 6.5 MeV
- CNL uses ~13 MeV $H_2^+$ to generate LEPs

$^4$He starts at 30 MeV
Assuming Setup In-Air (can do vacuum)

- Beam diameter on 0.25 mil Ta foil is ~5/16 in.
- Defining collimator is 2.75 in with acceptance angle of 0.018 rad.
- Secondary electron emission monitor (SEEM) uses three 0.25 mil Al foils.
- User-selected degraders can be Al or Mylar.
- Exit window is 5 mil Kapton.
- Air gap is user-selected within experimental parameters.

Courtesy of T. Essert and M. Van de Water (UCD/CNL).
30 MeV Alpha SEU Data
0x0000 Pattern

Error bars, if shown, are at the 90% confidence level.
6.5 MeV Proton SEU Data
0x0000 Pattern

Error bars, if shown, are at the 90% confidence level.
On the low-energy side of the Bragg peak, the cross sections are similar, but the type of events are not.

One of the key features is the separation between SBUs and DBUs.
Alpha & Proton DBU Fraction

Shows both 0x0000 and 0xFFFF data patterns.
Physical Failure Maps – Alphas

0x0000 Pattern

- 30 MeV primary
  - No user degrader
  - Actual alpha energy below primary tune
- Only 14 total MCUs
  - All DBUs
  - 4 on left, 10 on right
- For alpha/proton comparison, remember, these plots are absolute event counts.
  - Total fluence and LET dependencies.
Physical Failure Maps – Protons
0x0000 Pattern

- 6.5 MeV primary
  - No user degrader
  - Actual proton energy below primary tune
- 32 total MCUs
  - 13 on left, 19 on right
- Most MCUs are word-line DBUs
  - One 3-bit MCU and one 4-bit MCU – both word line
- For alpha/proton comparison, remember, these plots are absolute event counts.
  - Total fluence and LET dependencies.

In legend – MBU = MCU
Incorporation of SRIM Simulations to Calculate Die Thickness

- Fail mapping can be used to isolate areas of interest for analysis.
- Beam stopping degrader thickness can be used to “back out” silicon die thickness.

Calculated Energy Distribution
Summary

• Low-energy proton testing is challenging.

• At this point, there appears to be no suitable proxy for the observed single-event effects produced by low-energy protons.
  – While alpha particle and proton SBU behavior seems to be proportional to LET, the MCU behavior is not.
    • There are subsequent implications for radiation hardness assurance.
  – May be more room for compromise at CMOS technology nodes > 65 nm.

• Additional analysis techniques presented to aid data reduction efforts.
  – Many technologies are flip-chip (such as our SRAM DUT), and die thickness uncertainty has always been one of the larger sources of systematic error.
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Questions?