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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.


- $^4$He starts at 30 MeV
- $^1$H starts at 6.5 MeV
- CNL uses ~13 MeV $^2$H$^+$ to generate LEPs
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

64 MeV points offset from low-energy proton data and shown for reference. No degrader foils were used.

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

Showed 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.

In legend – MBU = MCU
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.
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?