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Acronym Definitions

- BNL = Brookhaven National Laboratory
- CAD = Computer-Aided Design
- CMOS = Complementary Metal Oxide Semiconductor
- CNL = Crocker Nuclear Laboratory
- ESP = Emission of Solar Protons
- ICRU = International Commission on Radiation Units & Measurements
- IUCF = Indiana University Cyclotron Facility
- IEEE = Institute of Electrical and Electronics Engineers
- LBNL = Lawrence Berkeley National Laboratory
- LET = Linear Energy Transfer
- NASA/GSFC = NASA Goddard Space Flight Center
- NIST PSTAR (National Institute of Standards and Technology)
- SEU = Single-Event Upset
- SNL = Sandia National Laboratories
- SOI = Silicon-On-Insulator
- SRAM = Static Random Access Memory
- SRIM = Stopping and Range of Ions in Matter
  - http://www.srim.org
- TAMU = Texas A&M University
- TNS = Transactions on Nuclear Science
- TRIUMF = Tri-University Meson Facility
  - Definition no longer used – dropped after University of Alberta joined the TRIUMF consortium (http://www.triumf.ca/)
- UCD = University of California/Davis

Elemental abbreviations used – e.g., N = nitrogen, O = oxygen, etc.
Literature Background

• Observed first low-energy proton, direct ionization SEUs in 2007 through IBM internal effort
  – IBM 65 nm SOI CMOS latches and SRAM

• Confirmed the following year by a NASA/GSFC, IBM, and Sandia National Labs collaboration
  – IBM 65 nm SOI CMOS SRAM

• Expanded research efforts reported in subsequent publications
Low-Energy Proton SEUs

IBM 45 and 65 nm SOI SRAMs

Cross sections increase by one or more orders of magnitude below 2 MeV

Two Goals for Low-Energy Proton Test Guideline Development

• Evaluate new technologies for low-energy proton sensitivity
  – Will it upset or not?
  – What accelerator source do I use?

• Determine effective error rate contribution from space environment
  – What’s the incident environment?
  – How can you calculate an upset rate?
Evaluation of Low-Energy Proton Sensitivity

- Only protons near the Bragg Peak can cause SEUs
  - Protons (and other ions) near end-of-range behave erratically

NIST PSTAR tool (ICRU Report 49, 1993)
Evaluation of Low-Energy Proton Sensitivity

- As proton energy decreases, the uncertainty in the experimental mass stopping power (LET) increases.
- Origin of the suggestion to use high-energy, light heavy ions as a surrogate
  - He, C, N, and O
  - Greater than 16 MeV/amu
  - Higher energy beams could utilize heavier ions

B. D. Sierawski et al., IEEE TNS, 2009.
Components with measurable cross sections below a LET of 1 MeV-cm$^2$/mg are likely sensitive to low-energy protons.
Evaluation of Low-Energy Proton Sensitivity

Lingering questions as to whether or not low-energy proton and high-energy, light heavy ion upset mechanisms are identical.


40 MeV/amu nitrogen @ TAMU
Choosing an Accelerator Source

Van de Graaff

- Small, low-cost
- Energy range for modest machines tends to be less than 10 MeV – most less than 5 MeV
  - BNL and SNL Van de Graaffs are exceptions
- Energy width of tuned beam is excellent (~1 keV)
- Particle range is limited
  - Constrains angled irradiations

Cyclotron (Excludes synchrotrons)

- Large, high-cost
- Energy range up to 500 MeV
  - UCD = 6.5 MeV < x < 63 MeV
    - Excluding degraders
  - IUCF = 30 MeV < x < 200 MeV
  - TRIUMF = 70 MeV < x < 500 MeV
    - Excluding degraders
- Energy width is larger (typically of order 100 keV)
- Particle range is large
  - Less constraints, but more systematic uncertainty
Uncertainty of Degraded Beams

Uncertainty of Degraded Beams

Degrading high-energy beams increases energy and range dispersion
Removes quasi-monoenergetic characteristics

UCD CNL Proton Simulations

B. D. Sierawski et al., IEEE TNS, 2009.
Angular Effects with Protons

Path length (i.e., angle of incidence) and LET affect efficacy of low-energy protons
Cannot capture this important effect with high-energy, light heavy ions

Considerations for Low-Energy Proton Measurements

• Measure and record materials in the beam line upstream from the device-under-test
• Experimentally determine the mean beam energy and beam energy-width at the device-under-test location
  – Angular dispersion knowledge a plus if attainable
• Complete transport calculations using accurate and properly ordered material stacks
  – Analytic methods acceptable, though Monte Carlo often required
• Different levels of systematic error in the form of energy loss straggling can be introduced depending on the type of device-under-test package, silicon thickness, degraders, etc.
• If the die is thinned, variations in proton stopping power can occur in different regions of the device producing non-uniform SEE response
Space Environment

Differential proton spectrum

Incident environment defined in interplanetary space by ESP model (example here)

Some “slice” of the environment will impact sensitive components

Shielding does not eliminate low-energy protons

Accurate determination of local radiation environment requires 3-D CAD analysis


To be presented by J. Pellish at the 2012 Microelectronics Reliability & Qualification Workshop (MRQW), 11-12/Dec/2012 in Los Angeles, CA and published on https://nepp.nasa.gov/
Low-Energy Proton Modeling

- Modeling, informed by accelerated ground data, is essential for on-orbit event rate prediction for low-energy proton effects.
- Simulations must be 3-D and have adequate radiation transport physics to handle necessary electromagnetic interactions.

B. D. Sierawski et al., IEEE TNS, 2009.
Possible Modeling Techniques

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Modeling name acronyms are defined in references below.

- CREME96: https://creme.isde.vanderbilt.edu/ (other references available at URL)
- CRÈME-MC: https://creme.isde.vanderbilt.edu/ (other references available at URL)
Hardness Assurance Strategy

• Measure the upset cross section with long-range, low-LET, light ions (He, C, N, and O) to detect potential low-energy proton sensitivity
  – Determines potential sensitivity to low-energy protons
  – Should have energy greater than 16 MeV/amu, though 16 MeV/amu N and O at LBNL could be considered
  – Could be optional if already planning to test with low-energy protons
  – **Assumes that upset mechanisms are the same/similar**

• Create an event model using low-LET data and technology information
  – Applicable if using Monte Carlo techniques
  – Some intentional ambiguity regarding “technology information”

• Validate the model by comparing it with the measured low-energy proton response
  – Some methods would skip directly to this step

• Use the [calibrated] model to predict the on-orbit error rate
Conclusions

• CMOS nodes at and below 90 nm have been identified as sensitive to low-energy proton direct ionization

• Energy/range variation inherent to particles near end-of-range increase low-energy proton testing systematic errors

• Hardness assurance practices for including low-energy proton sensitivity must address the issue with a combination of relevant data collection and calibrated models
Main References and Additional Reading


- N. Haddad et al., "Heavy ion, high energy and low energy proton SEE sensitivity of 90-nm RHBD SRAMs," presented at the European Conf. on Radiation Effects on Components and Systems, Langenfeld, Austria, 2010.


