Proton Induced Recoil Trajectories and The Angular Dependence of Single-Event Upset Cross-Section Measurements

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Background

• Proton induced recoil trajectories are historically considered to be a 2\textsuperscript{nd} order effect in most microelectronic devices
  – Most proton-induced Single Event Upset (SEU) testing is carried out with the proton beam normal to the die surface
• In 1994 and 1995 Reed, et al. presented proton-induced SEU simulation results that predicted an angular dependence if:
  – The sensitive volume had at least one dimension sufficiently thin compared to the others, and
  – Critical charge was sufficiently large
• Very limited data available that shows an angular effect
  – Proton data presented by Gardic et al, at RADECS in 1995 showed angular effect data on a Silicon-On-Insulator (vendor unnamed) and a Matra (HM65656) Bulk CMOS memory devices
  – In 1997, we presented proton data at NSREC on the bulk device from Matra (HM65656). Our data did not show an angular effect.
Outline

• Proton-induced SEUs over proton beam angle-of-incidence
  – Experimentally determine if an angular effect exists
  – Investigate the relationship between proton energy, critical charge and the angular effect.

• Proton interaction effects on recoil trajectories and charge deposition in thin structures
  – Review and discuss the basic p+Silicon interaction mechanisms and determine how each induces an angular effect

• Modeling the Effects of Proton Beam Angle-of-Incidence
  – Compare experimental results to new simulation on test devices that are based on actual device geometries

• Conclusions
Devices Tested and Test Organizations

- **Peregrine Semiconductor 3.5 GHz Prescaler**
  - 0.5 \( \mu \)m Ultra Thin Silicon (UTSi.™) Silicon-On-Sapphire (SOS) Process
  - Gate Length = 0.5 \( \mu \)m and Width = 1.5 \( \mu \)m to 10 \( \mu \)m
  - Thickness of Silicon under gate = 0.098 \( \mu \)m
  - Testing performed by NASA Goddard Space Flight Center
  - Testing performed at University of California at Davis and Indiana University

- **Honeywell 512K x 8 Static RAM**
  - 0.35 \( \mu \)m RICMOS™ V Silicon-On-Insulator (SOI) Process
  - Gate Length = 0.35 \( \mu \)m and Width = 1 \( \mu \)m
  - Thickness of Silicon under gate = 0.21 \( \mu \)m
  - Testing performed by Honeywell SSEC
  - Testing performed at Indiana University
63 MeV Proton Bit Error Events
Peregrine Prescaler

Proton Angle of Incidence (Degrees)

Device Cross-Section (cm$^2$)

- DUT #5 Lot#1
- DUT #3 Lot#1
158 MeV Proton-Induced Upsets in Honeywell 4M SRAM
Very Different Circuits Show an Angular Effect

- Experimental data shows sensitivity of SOI and SOS technologies to proton beam angle-of-incidence
- Two very different circuits and test conditions
  - The Honeywell device is a SRAM tested in static mode
  - Peregrine device is a high speed prescaler with inputs set at 3.5 GHz
  - Angular effect is not a circuit phenomena
- Both technologies have sensitive volumes with large aspect ratios (max length / min length)
  - Peregrine is up to 100
  - Honeywell is up to 5

- What is the basic mechanism that causes the angular effect?
Proton-Induced Direct Ionization

• Direct ionization: primary proton interacts with electrons of the Silicon atom to liberate charge
• Can direction ionization cause the effect for the Peregrine prescaler?
  – Heavy ion threshold LET is $\sim 2.5 \text{ MeV} \cdot \text{cm}^2/\text{mg}$
  – To upset the prescaler, 63 MeV proton must have a path through a sensitive volume that is $> 30 \text{ m}$
  – Maximum path length is $\sim 10 \text{ m}$
• Honeywell SRAM?
  – 158 MeV proton must have a path through a sensitive volume that is $> 150 \text{ m}$
  – Maximum path length is $\sim 1 \text{ m}$
• Direction ionization cannot induce an upset in these devices at the test energies used for this study
Inelastic Scattering with Target Nucleus

Modeling the interaction

- GEANT is a Monte Carlo modeling tool that can simulate spallation reactions
- Use GEANT to Model recoil angle

62 MeV Protons

Recoil Angle (Degrees)

LET (MeV cm²/mg)

0 5 10 15
0 60 120 180
Assume billiard ball collision physics to model interaction

- Recoil Angle (Degrees)
- Recoil Energy (MeV)
- Integral Nuclear Elastic Cross-Section (mb)

63 MeV Protons

July 15-19, 2002
Presented by Robert Reed, NASA/GSFC at 2002 The Nuclear and Space Radiation Effects Conference, Phoenix, AZ
Comparing Nuclear Interactions

Which one dominates?

- Nuclear Inelastic cross section is >350 mb
- Inelastic cross section is more that a factor of 4 greater than elastic
- Forward directed recoils are dominated by inelastic
- Inelastic’s dominate Energies > 63 MeV

Not a general result

- Elastic cross section peak at 30 MeV
- Elastics may become important at 30 MeV
Data Trends are Consistent with Spallation Reaction

- Path length increases as incident proton angle increases
- More energy is deposited in sensitive volume at grazing angles
- This is consistent with the data on SOI and SOS devices
Modeling Energy Deposition from Spallation Reactions

- Clemson University Proton Interactions in Devices (CUPID)
- Monte Carlo simulation codes for spallation reaction
- Predicts the integral cross section for depositing energy in a sensitive volume (SV)
- Input parameters include
  - Proton energy
  - Proton incident angle
  - SV dimensions
  - Surrounding volume dimensions

[Graph showing cross-section vs. energy deposited for different incident angles and proton energies]
Experimental Data and Modeling Results for Peregrine SOS Technology - Energy Dependence

**Measured Data**

- DUT #3 - 63 MeV
- DUT #3 - 200 MeV

**Simulations**

SV=2.5?m x 1.5 x 0.098?m

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Experimental Data and Modeling Results for Peregrine SOS Technology - Energy Dependence

- **Magnitude of angular effect depends on incident proton energy**
  - Spallation products from 200 MeV p+Si inelastic collisions are more isotropic for LETs < 6
- Simulations agree with well with measured data near 0 and 90 degrees
- Contribution from elements other than Silicon can explain the disagreement between 30 and 60
  - GEANT simulations
Experimental Data for Peregrine SOS Technology - Critical Charge Dependence

Device #3 has a 50% higher threshold LET
Conclusions

- New proton SEU data demonstrate enhanced sensitivity in SOI technologies, including SOS
  - Classical testing approach would under predict on-orbit SEU rate
  - This effect is not limited to SOI technologies. Any device with an aspect ratio >3 and a critical charge >20 fC is suspect
- Spallation reaction is the dominate mechanism for the devices tested, elastics may be important at 30 MeV
- Experimental data showed angular effect can depend on proton energy and critical charge
- New simulations result show “good” agreement with experiments over energy and critical charge
- Our findings impact both test planning and rate prediction approaches, and present methods may underestimate observed upset rates by > 5x