Proton Testing: Opportunities, Pitfalls and Puzzles

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# Key to Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>∀</td>
<td>Logical symbol meaning “For all”</td>
<td>LET</td>
<td>Linear energy transfer</td>
</tr>
<tr>
<td>δ</td>
<td>Delta</td>
<td>p</td>
<td>Proton</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>Q</td>
<td>Charge</td>
</tr>
<tr>
<td>σ</td>
<td>Cross section</td>
<td>SDRAM</td>
<td>Synchronous DRAM</td>
</tr>
<tr>
<td>3DS</td>
<td>Three-dimensional stacked</td>
<td>SEB</td>
<td>Single-event burnout</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>SEE</td>
<td>Single-event effect</td>
</tr>
<tr>
<td>DRAM</td>
<td>Dynamic random-access memory</td>
<td>SEGR</td>
<td>Single-event gate rupture</td>
</tr>
<tr>
<td>DSEE</td>
<td>Destructive single-event effect</td>
<td>SEL</td>
<td>Single-event latchup</td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
<td>SV</td>
<td>Sensitive volume</td>
</tr>
<tr>
<td>GCR</td>
<td>Galactic cosmic ray</td>
<td>VDS</td>
<td>Drain-source voltage</td>
</tr>
<tr>
<td>GPU</td>
<td>Graphics processing unit</td>
<td>WC</td>
<td>Worst case</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated circuit</td>
<td>xstr</td>
<td>Transistor</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/output</td>
<td>Z</td>
<td>Ion atomic number</td>
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Can Protons Bound Heavy-Ion SEE Risk and Why Would We Want Them To?

- State-of-the-art ICs and packages often highly integrated
- Significant overburden blocks ions from device SV
- Extensive and risky modification often needed to ensure charge generated in SV

- Accelerator ion ranges 10s-100s of µm of Al
- GCR ions penetrate 10s of cm Al
- High-energy protons attractive
  - Penetrate >10 cm of overburden
  - Generate light ions in SV
  - Fluxes persist over most of proton range—so box-level testing feasible
Outline

• Generation of Recoil and Cascade Ions by Protons
• Recoil, Accelerator and GCR Heavy-Ion Environments
  • Ion Energies and Destructive SEE
  • Test Coverage
  • When are These Differences Important?
• Timely Issues
  • What About Proton-Induced Fission
  • Does Scaling Help or Hurt?
• Conclusions: Challenges, Caveats and Recommendations

Recoil Ion Characteristics for 200-MeV Protons

Ion Species

- <<1% have $Z < 6$
- <18% have $5 < Z < 10$
- ~78% have $10 \leq Z \leq 13$
  - ~63% Na, Mg and Al
- 4.5% Si, <0.05% P
- Most common ion is Mg (~30%)
- Only one proton out of 289100 produces a recoil ion
- Evaporation
  - Including He ~doubles total ion count (LET up to 1.5 MeVcm$^2$/mg and range~10 µm)

Energies and Ranges

- $Z<6$—energies largely above Bragg Peak, but fluxes negligible
- $5 < Z < 10$—>80% have energy >Bragg Peak
  - Flux down 10x for $E>11$ MeV
- $10 \leq Z \leq 13$—<1% have energy >Bragg Peak
  - Flux down >10x for $E > 6$ MeV
  - Ranges < 4 µm for >90% in this range
- Si and P fluxes negligible for practical purposes

Other Characteristics

- Angular distribution fairly flat out to 90° to incoming proton
- Standard wisdom: p generate LETs up to ~15 MeVcm$^2$/mg in Si, but
  - Almost no P ions generated
  - For Si, max LET is 14.5 MeVcm$^2$/mg, but <5% of recoil ions are Si, and they are all below Bragg Peak
  - For Ne-Al, energy below Bragg Peak
  - For hardness assurance purposes, risky to assume LET>10-12 MeVcm$^2$/mg even for shallow SV
- For ion that causes SEE, $Z$, energy, angle are all unknown

Proton Challenge I: Recoil Ranges and DSEE

- SEE susceptibility increases not with LET, but with charge, \( Q = C \times \rho \times \int_0^d \text{LET}(x) \, dx \)
  - Q generated by proton recoil ions may be limited by their energy/range rather than LET, especially for SEE with deep SV

- For DSEE, SV depths often >> range of recoil ions
  - For SEL, charge collected well into substrate, ~10s of \( \mu \text{m} \)
  - For SEB, cross section diminished if ion range <~30 \( \mu \text{m} \)
  - For SEGR, charge collected down to bottom of epi layer, 10-100 \( \mu \text{m} \) depending on rated VDS

- Define \( \text{LET}_{\text{EQ}} \) in terms of energy deposited in SV \( E_{\text{Dep}} \), SV depth \( d \) and Si density \( \rho_{\text{Si}} \):
  - \( \text{LET}_{\text{EQ}} = \frac{E_{\text{Dep}}}{(\rho_{\text{Si}} \times d)} \)
  - \( \text{LET}_{\text{EQ}} \) facilitates translating proton results to mission performance
  - If SV depth unknown, assume representative WC for the SEE mode of interest

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\[ \text{LET}_{\text{EQ}} \propto E_{\text{Dep}} \times d \times \rho_{\text{Si}} \]

Role of Proton Energy

For Recoil Ions w/ $3 \leq Z \leq 9$

- For high proton energies (>200 MeV), increase in inelastic $\sigma$ results in large increase in ions w/ $Z<10$, but with lower average energy

For Recoil Ions w/ $10 \leq Z \leq 15$

- For high proton energies (>200 MeV), $\sigma$ for $Z \geq 10$ drops slightly but ion energy increases; however, detection probability improved only if SV depth $<~10 \mu m$. 

Relative Coverage of Proton and Heavy-Ion SEE Tests

- Infrared micrograph of a portion of a 512 Mb SDRAM ~60×70 µm²
- Shows both memory cells and control logic (~2005); Red spots simulated random recoil ion hits w/ 1µm² area

20% of areas this size get 0 hits for $10^{10}$ cm⁻²

- Coverage: You can’t discover an SEE mode unless you hit the feature responsible for it
- Simplest measures: ions/cm²; transistors/ion...
- 200-MeV protons, ~1/289100 protons generates recoil ion, but every one adds to dose
  - $10^{12}$ protons/cm²: 3.46E6 recoil ions/cm², 58.6 krad(Si)
  - $10^7$ 15 MeV/u Ar ions: 1.2 krad(Si)

Coverage from $1E7$ ions/cm²

Coverage II: Scaling Increases the Stakes

Does this fairly represent proton-recoil coverage?

Elpida 512 Mbit SDRAM (EDS5108) w/ 130 nm CMOS has \(\sim 0.31\) xstr per \(\mu m^2\) (2005)

- What about repeated similar structures?
  - They help, but you’d need >289 repetitions to come close to heavy-ion coverage

- Are the red squares fair ion track representations?
  - Ion track size difficult to define, but probably <<1 \(\mu m^2\)
  - But transistor size~3.2 \(\mu m^2\), so probably OK for this case

Does CMOS scaling affect this conclusion?

Samsung K4B2G0846 DDR3 SDRAM w/ 35 nm CMOS has \(\sim 4.6\) xstr per \(\mu m^2\) (2012). Only gross feature sizes visible @\(~1\ \mu m\) resolution

- Below \(~65\) nm feature size, >1 transistor per \(\mu m^2\)
- Track structure important, but what defines a track?
- Depends on radial charge distribution (depends on \(Z, E\))
- Also depends on device sensitivity—how much charge needed to cause SEE.

Feature Size and Complexity: Just Geometry?

• Naïve expectation gives transistor density increasing \( \sim (\text{Feature Size})^{-2} \).
  • Roughly true for microprocessors and GPU since 1971 (10 \( \mu \text{m} \) feature size)
  • Similar trends hold for DRAMs and Flash

• Area on chip equates to xstr count
  • 2891 \( \mu\text{m}^2 \) per ion corresponds to
    • 130 nm: \( \sim 900 \) transistors
    • 65 nm: 3300 xstr— \( \sim \)Intel 8008
    • 45 nm: 7800 xstr— \( \sim 1.2 \times \) Intel 8085
    • 22 nm: 23000 xstr— \( \sim 0.8 \) Intel 8088

• Imagine testing any of these w/ single ion
  • Average value—37% of such areas get no ion hits at all

• Complexities of areas left untested scale inversely w/ proton/ion flux

Combining Data for Similar Features: Intel I7 Quad Core (45 nm-2008)

- Green square in left-most core represents 315 $\mu$m square (~275000 transistors) or one Intel 80386
- Expand region ~23x to show individual ion hits (green dots) from $10^{10}$ 200-MeV protons/cm$^2$
- Each green dot ~6 $\mu$m on a side—and ion hit is somewhere in there.
- Left 4 squares on bottom could be repeated trials or same area in 4 different quads
- Right-most square combines hits for all 4 quads

Ion Track Structure: It’s All About The Deltas

28 GeV Fe ion (500 MeV/u)  
280 MeV Fe ion (5 MeV/u)

Track radius depends on how much we care if some energy escapes. High-energy ions generate energetic, long-range δ electrons. See Murat et al., TNS 2008, p. 3046.
Does Scaling Help or Hurt Efforts to Constrain Heavy-Ion SEE w/ Protons?

**Well, it could help...**

- Onset LET decreases w/ feature size
  - More ions to detect susceptibility
- $\sigma$ vs. LET rises rapidly w/ increasing LET
  - Higher $\sigma$ facilitates detection if present
- Supply voltages are decreasing, so maybe SEL susceptibility will decrease as well...?
  - Conflicting evidence—seems to be true for SDRAMs, but processors, FPGAs, SRAMs still prone to SEL
- TID tolerance of deep submicron CMOS increasing
  - May allow testing to higher proton fluence without risk of device failure or alteration of SEE performance via TID/SEE synergistic effects

**On the Other Hand...**

- Proportion of protons generating recoil ions constant—still 1 per 289100 200-MeV protons
  - Device complexity (# transistors/$\mu$m$^2$) continues to increase
  - State space continues to get more complex as devices add functionality.
- Lower critical charge coupled with multiple transistors per $\mu$m$^2$ means track structure effects more important
  - GCR, SPE and accelerator ion tracks 50-1000x broader than proton recoil tracks
  - Hardening of commercial chips against neutrons (e.g. using DICE Latch) may not work in space
    - Proton testing might not reveal this.
Proton-Induced Fission: Can We Use Its Powers For Good?

- **Mechanism:** Proton beam knocks Au nucleus out of Au layer
- **Excited Au nucleus oscillates then fissions into two nuclei (30<Z<50)**
- **Fission fragment strikes capacitor, depositing enough charge to rupture capacitor oxide (<100 nm)**
- **Failure more likely if ion incident normally to device surface**
- **Almost all energy of fission ions comes from fission rather than from incident proton**
- **Ions have short range.**
Well, There’s Good News and Bad News

- Cross section per Au nucleon~35 mbarn, or 3.5E-26 cm² @ 200 MeV
- 1 cm² of 1-µm thick Au foil has ~5.9E18 Au nuclei
- Daughter products have 30<LET<40 MeVcm²/mg
- $10^{10}$ 200-MeV p/cm²→2100 Au fissions per µm Au
  - Even 3 µm Au→6300 fissions. Even if >1 ion per fission, coverage likely >3x worse than for p + Si recoil ions

Although high LET, daughter products are short range (<17 µm), well below Bragg Peak, and produced outside of die.
Nuclei Must Traverse Overlayers to Reach SV

- Each additional $\mu$m of Au produces more ions but also degrades ions already produced.
- WC fission product range in Au is $\sim$6.5 $\mu$m
- Overburden on top of SV degrades LET spectrum
- May include passivation, oxides, metal, etc.
- Range in Si <17 $\mu$m

The same factors that keep this threat from killing us on orbit limit its usefulness for SEE testing w/ Protons

Could p on Au Fission Testing Work? If so, how?

**Challenges and Limitations**

- Fission fragment flux limited
  - Even with 3 \( \mu \)m Au and \( 10^{12} \) 200-MeV p/cm\(^2\), get <\( 10^5 \) ions/cm\(^2\), \( \sim \)1 ion/1000 \( \mu \)m\(^2\)
  - Ions produced in 3 \( \mu \)m Au have \( \sim \)flat distribution from 20-35 MeVcm\(^2\)/mg

- Fission products originate outside of Si
  - Must traverse Au layer and overlayer above SV
  - Degrades LET spectrum and may reduce flux if >\( \sim \)10 \( \mu \)m Si equivalent overburden

- Cannot know which ion causes a given SEE
  - Z, Energy, angle all uncertain
  - Yields limited understanding of SEE mechanisms
  - Estimating bounding rate very difficult

**Making It Work...Sort Of**

1. Measure thickness of overburden (passivation, metallization, etc.)
2. Perform Test in Vacuum if possible and/or place foil on top of die
3. Obtain Au or Pb foils 2-3 \( \mu \)m thick
4. Perform TID testing in advance to determine limiting proton fluence
   a) Higher-energy proton beam lowers dose/fission
5. Perform test to high fluence w/o foil, then with
6. If SEE mode seen with, but not without foil:
   a) 10 MeVcm\(^2\)/mg<LET\(_0\)<20-35 MeVcm\(^2\)/mg -or-
   b) You got lucky in the run with the foil
7. At least, you now know about the new SEE mode
8. Multiple runs increase confidence in results
Board-Level Testing Just Makes Things More Complicated

- Ability to test at board level one of the biggest draws for protons
- Board-level testing means giving up even more information
  - Test detects far fewer SEE modes
    - Some not detected due to accelerated nature of test
    - Some masked temporally or logically — may be different during different operation stages
- Part-to-part variability difficult to evaluate w/o testing many boards
  - Don’t even think about differences in synergistic interactions
- It’s not just protons—board-level testing w/ heavy ions poses similar issues (e.g. overburden affects ion LET)

- $\text{LET}_{\text{EQ}}$ means same proton fluence will mean different things for different SEE modes—even in same device
- Proton test cannot be optimized to detect each SEE mode
  - Test is the same whether for SET or SEGR
Relative Advantages of Heavy-Ion and Proton Testing

**Heavy-Ion Testing**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limitations</th>
</tr>
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<tbody>
<tr>
<td>More likely to reveal Destructive SEE (DSEE) modes</td>
<td>Limited ion range may preclude testing some parts/require others be repackaged/modified</td>
</tr>
<tr>
<td>Lower TID per ion allows higher fluence/better coverage for test</td>
<td>Testing at board level difficult; at box level, impossible</td>
</tr>
<tr>
<td>Known ion Z, energy, LET and angle better elucidate SEE mode mechanism/physics of failure</td>
<td>Heavy-ion testing costly; high-energy facilities even more so</td>
</tr>
<tr>
<td>Greater fidelity to Space Ion Environment</td>
<td>Heavy-ion facilities overbooked, difficult to schedule beam time</td>
</tr>
<tr>
<td>Can select ion characteristics to tailor test to physics of failure of SEE mode of interest</td>
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</table>

**Proton Testing**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limitations</th>
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<tbody>
<tr>
<td>Long proton range ensures ions reach depth of SEE sensitive volume</td>
<td>Likely to underestimate DSEE risk if it reveals susceptibility at all.</td>
</tr>
<tr>
<td>Can test highly integrated, complex parts/boards/systems without modification</td>
<td>High TID* limits recoil ion fluence. At board/system level, weakest part limits test fluence</td>
</tr>
<tr>
<td>Can save money if testing done at system level</td>
<td>Test result interpretation can be complicated, especially for system-level tests</td>
</tr>
<tr>
<td></td>
<td>Inability to control characteristics of recoil ions means less understanding of SEE mechanisms</td>
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<tr>
<td></td>
<td>Cannot tailor test to specific SEE modes of concern</td>
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*TID=Total Ionizing Dose—cumulative energy lost by all ionizing particles that goes into generating charge in material

Conclusions

- Testing with proton recoils means giving up information
  - Inability to control recoil ion Z, E, angle limits understanding of SEE mechanisms and dependencies
  - Limited reliability for revealing destructive SEE modes and other modes with deep SV
  - Coverage limited by TID susceptibility of part(s). Adequate coverage depends on:
    - Density and complexity of parts and degree of repetition in circuitry within part (e.g. multiple cores, lots of memory, etc.)
    - Whether variability of SEE response across the part is of interest
    - Onset LET for SEE and rapidity with which $\sigma$ vs. LET rises (affects # of particles that can cause an effect)

- May be useful to look at complexity of device as # transistors/ion or rough equivalent IC

<table>
<thead>
<tr>
<th>Proton Fluence (200 MeV)</th>
<th>Ion Fluence</th>
<th>Ion Density ($\mu$m$^2$/ion)</th>
<th>90 nm CMOS (xstr per ion)</th>
<th>45 nm CMOS (xstr per ion)</th>
<th>22 nm CMOS (xstr per ion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{10}$ cm$^{-2}$</td>
<td>34590 cm$^{-2}$</td>
<td>2891</td>
<td>2009 (~Intel 4004)</td>
<td>8035 (&gt;Intel 8086)</td>
<td>32142 (&gt;Intel 8088)</td>
</tr>
<tr>
<td>$10^{11}$ cm$^{-2}$</td>
<td>345900 cm$^{-2}$</td>
<td>289.1</td>
<td>201</td>
<td>804</td>
<td>8035</td>
</tr>
<tr>
<td>$10^{12}$ cm$^{-2}$</td>
<td>345900 cm$^{-2}$</td>
<td>28.91</td>
<td>29</td>
<td>80</td>
<td>320</td>
</tr>
<tr>
<td>2.89x10$^{12}$ cm$^{-2}$</td>
<td>1x10$^7$ cm$^{-2}$</td>
<td>10</td>
<td>7</td>
<td>28</td>
<td>112</td>
</tr>
</tbody>
</table>

Conclusions II

• Effect of scaling is complicated, with conflicting trends
  • Positive: Scaling generally improves TID hardness, allowing testing to higher fluence
  • Positive: Lower voltages suggest lower SEL susceptibility, lowering importance of ion range
  • Positive: Generally lower onset LET and more rapid rise of $\sigma$ vs. LET $\rightarrow$ more fluence to detect SEE modes
  • Negative: Concept of LET breaks down; energy deposition for <45 nm qualitatively different between high-energy and low-energy ions
    • Protons may not detect susceptibilities to MBU and DSEE, underestimate susceptibility of hardened technology
  • Negative: Increased density means coverage worsens $\sim$inverse square of feature size

• Same factors limiting proton-induced fission impact on orbit limits its hardness assurance impact
  • Fission products short range (<17 $\mu$m in Si, <6.5 $\mu$m in Au) and on low-energy side of Bragg Peak
  • Fission occurs outside of die, necessitating transport across Au layer and device overburden
  • Coverage for fission products even poorer than for recoil ions
  • BUT, may reveal some susceptibilities missed by conventional proton testing

• Board-level testing
• Protons not a panacea for hard/expensive-to-test parts. Sometimes, it’s the best last resort we have