Evaluating Constraints on Heavy-Ion SEE Susceptibility Imposed by Proton SEE Testing and Other Mixed Environments

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Acronyms and Symbols

CL=Confidence Level
DSEE=Destructive Single-Event Effects
GCR=Galactic Cosmic Ray
HI=Heavy Ion
LET=Linear Energy Transfer
LET₀=Onset LET
LETₚₑₐₜ=Equivalent Linear Energy Transfer=energy deposited in SV, divided by product of SV depth and SV density.
pdf=probability density function
ρ="rho"=density of Si (2.33 g/cm³)
s, W=Shape and width parameters for the Weibull distribution/form
SEB=Single-Event Burnout
SEE=Single-Event Effect
SEGR=Single-Event Gate Rupture
SEL=Single-Event Latchup
SOTA=State Of The Art
SDRAM=Synchronous Dynamic Random Access Memory
SRAM=Static Random Access Memory
SPE=Solar Particle Event
SV=Sensitive Volume
σ="sigma"=Cross section
σₛₐₜ=Saturation Cross Section
TID=Total Ionizing Dose
Xstr=transistor
Z=Atomic number of a nucleus or atom=# of protons in nucleus

To be presented by Raymond Ladbury at the 2016 Electrical and Electronics Engineers (IEEE) Nuclear and Space Radiation Effects Conference (NSREC), Portland, Oregon, July 11-15, 2016
Can Heavy-Ion Rates Be Bounded with Protons?

- Heavy Ion (HI) Testing:
  - Is Expensive
  - Is Time-Consuming
  - Requires extensive modification of test parts
  - Increasingly difficult to schedule
  - Some parts may be nearly impossible to test w/ normal accelerator ions.
  - Very hard to test boards/boxes.

- Proton testing
  - Causes SEE via recoil ions
    - $3 \leq Z \leq 15$
  - Produces ions reaching sensitive volumes even in difficult parts
  - Allows board/box-level testing
    - Promises significant savings in cost and schedule

- Can Heavy-Ion SEE rates be bounded with proton data?

Some Challenges w/ protons
- Protons inefficient at producing ions
  - $\sim 1/2.9E5$ 200-MeV protons produces a recoil ion; all contribute dose
- We don’t know Z, energy, angle or LET of an ion that causes a given SEE
- Proton recoils low energy/short range
  - Last year, showed this was very important for assessing destructive SEE susceptibilities
  - Cannot compare recoil to GCR or SPE ions
  - Introduce $\rho d = \text{Si density}$, $d = \text{depth of SEE SV}$
  - If LET $\sim$ constant in SV, $\text{LET}_{\text{EQ}} \sim$ Effective LET

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Coverage of SEE Tests

1E10 200 MeV protons/cm²

∀ Z, Angle, Energy

Expect 1.45

1E7 heavy ions/cm²

∀ Z, Angle, Energy

1E12 200 MeV protons/cm²

∀ Z, Angle, Energy

- Coverage of SEE test—how well it probes potentially vulnerable areas on test item
  - Units: μm² per ion or transistors (xstr) per ion.
- IR photomicrograph of 60×70 μm² area of ELPIDA EDS5108 512 Mbit SDRAM
  - Expect 1.45 recoil ions for 10¹⁰ 200-Mev p/cm²
- Intel I7 processor ~ 1 ion per 8000 xstr
  - Intel 8080 8-bit processor had 6000 transistors
- These are average values
  - 10% of parts could have missed areas >78800 μm²
But, Not All Ions Are Created Equal

- Low-LET ions must hit much smaller cross section to cause SEE
- Ion fluence drops with LET in almost any environment
  - Broader $\sigma$ vs. LET (larger Weibull Width, $W$) $\rightarrow$ lower rate
  - Larger shape parameter $s \rightarrow$ lower rate
- Proton recoil fluences
  - Very few proton recoil ions w/ LET $>10$ MeVcm$^2$/mg
  - Short range of proton recoils $\rightarrow$ fluence vs. LET$_{EQ}$ drops even faster for deep SV
SEE Rate Bounds for Shallow SV

- Constraints from proton testing too weak to determine $\sigma$ vs. LET, but event count can tell us which models are inconsistent with the proton data
- Assume device SV made up of $N_{SV}$ representative 1-micron cube SVs
  - LET varies little across this sensitive volume, so $LET_{EQ}$ ~effective LET

$$N_E = \int_{LET_0}^{LET_{Max}} N_{SV} \times F(LET_{EQ}) \times \sigma(LET_{EQ}, LET_0, w, s) \, dLET_{EQ}$$

- Estimate # errors expected for a single 1-micron-cube SV for 175 representative models
  - $W=\{5, 10, 15, 20, 25\}$, $s=\{0.5, 1, 1.5, 2, 2.5\}$, $LET_0=\{0.5, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5 \, MeVcm^2/mg\}$
  - Solve for $N_{SV}$ using upper bound on Poisson Mean for $N_E$ (e.g. 2.31 for 90% CL if 0 events seen)
  - Result: Model performs worst at both high $LET_0$ (where ions are scarce) and low $LET_0$, where increase in GCR fluence is more rapid than increase in fluence of recoil + cascade ions.
  - Note: CRÈME-MC emulator—uses stored CRÈME-MC results for proton recoils and CRÈME-96 rates for each candidate $\sigma$ vs. LET model—can be generalized for any SV
Deep SV Are More Challenging

- Chord-length pdf changes as $\sigma$ rises
  - Use Nested SV to approximate $\sigma$ vs. LET model
  - Use Fluence($\text{LET}_{\text{EQ}}$) for SV depth
  - Estimate $N_E$ and solve for $N_{SV}$

- For 10-$\mu$m cube SV
  - If device $\sigma$ bound $>10^{-2}$ cm$^2$, method fails
  - For $10^{10}$ 200-MeV p/cm$^2$ 122 failures/175 models
  - For $3\times10^{11}$ 200-MeV p/cm$^2$, 40.6% of models fail
  - Protons can bound rate if fluence high, $\text{LET}_0$ is low and $\sigma$ vs. $\text{LET}_{\text{EQ}}$ rises rapidly enough
  - Requires added information or assumptions

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Energy and Fluence Dependence

Table I: Parameters w/ >50% Successful Bound

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LET&lt;sub&gt;0&lt;/sub&gt; (MeV cm&lt;sup&gt;-2&lt;/sup&gt;/mg)</th>
<th>s</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence (cm&lt;sup&gt;-2&lt;/sup&gt;)</td>
<td>200 MeV, 10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>&lt;2</td>
<td>&lt;1</td>
</tr>
<tr>
<td></td>
<td>200 MeV, 3×10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>&lt;5</td>
<td>&lt;1.7</td>
</tr>
<tr>
<td></td>
<td>400 MeV, 10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>&lt;3.5</td>
<td>&lt;1.2</td>
</tr>
<tr>
<td></td>
<td>400 MeV, 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>&lt;6.5</td>
<td>&lt;2.2</td>
</tr>
</tbody>
</table>

~10% of σ vs. LET<sub>EQ</sub> models fail

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Why Bounding Fails

Method fails to bound heavy-ion susceptibility if ion fluence falls faster than cross section rises vs. $\text{LET}_{\text{EQ}}$ (high LET0, W or s).

- Deep SV push fluence distribution left—increasing likelihood of method failure

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Board/Box-Level Testing

- Board/box-level testing irradiates many parts w/ diverse technologies
  - Saves money, but different SV depths mean parts see different Fluence vs. LET\(_{EQ}\) dist.
  - Proton test may vary in effectiveness for every device on board
  - Need to know as much as possible about technology of each device to make sense of proton data
Summary and Conclusions

• Proton SEE data does constrain heavy-ion SEE performance
  – Constraints may be weak due to important differences between recoils and GCR

• Coverage key to whether test reveals SEE susceptibilities
  – Ions per unit area or per transistor is a first approximation, but not all ions equally capable of causing SEEs
  – Rate bounds that consider potential $\sigma$ vs. LET form are more informative

• Shallow SV: LET~ constant through SV—bounding straightforward
  – Consider $\sigma$ vs. LET models for which proton recoils may be effective
    • LET$_0 \leq 6.5$ MeVcm$^2$/mg, width$\leq 25$, shape$\leq 2.5$—other models will perform worse.
  – Estimate rate for single SV—How many SVs possible for test to yield null result?
  – Bounding rate likely $\leq 0.001$/day—worst bounds at both low and high LET$_0$

• For deep SV, ions range limited—use nested SV approach
  – Many plausible models fail to yield meaningful bound
  – Increased fluence and energy help, but only for SV depth $\leq 10$ $\mu$m

• The problem is inherent to proton testing
  – Charge deposited by proton recoils in deep SV limited by range, not LET
  – Fluence vs. LET$_{EQ}$ compressed toward lower LET$_{EQ}$, where $\sigma$

• Applies to SEL—even worse for SEB/SEGR (coverage worse)

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Possible Future Directions

- Proton SEE data only weakly constrain HI SEE susceptibility
  - Must supplement data with other information to increase effectiveness
    - E.g., constrain LET0, w, s, $\sigma_{sat}$ w/ process and/or similarity data
    - Well suited to Bayesian treatment—as this makes subjective assumptions explicit

- Current analysis predicated on DSEE physics of failure
  - Need to understand SV geometry for DSEE better
  - Are there mitigating factors that would lead to tighter WC bounds on HI rates?
    - Cannot be ruled out, but no indication at present

- Develop methods to make sense of board/box-level tests
  - Fluctuations lead to worse coverage for some chips than others
    - Improves less than linearly with increased fluence
  - Different SV depths lead to exposure to different equivalent environments
    - Significantly complicates extrapolation of board-level proton tests to HI environment
  - For these reasons, board/box-level bounding rates must increase at least linearly with board/box complexity (e.g. # of parts)

- Despite problems, proton testing may be the only option for many complicated highly integrated components

- One certainty: interpreting results will not be simple