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  
LET$_0=$Onset LET  
LET$_{EQ}=$Equivalent Linear Energy Transfer=$\text{energy deposited in SV, divided by product of SV depth and SV density.}$  
pdf=probability density function  
$\rho=\text{rho'=density of Si (2.33 g/cm}^3)$  
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  
$\sigma=\text{sigma'=Cross section}$  
$\sigma_{\text{sat}}=\text{Saturated Cross Section}$  
TID=Total Ionizing Dose  
Xstr=transistor  
Z=Atomic number of a nucleus or atom=# of protons in nucleus
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 with 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
  - ~$1/2.9E5$ 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 $LET_{EQ} = \frac{E_{Dep}}{(\rho \times d)}$, $\rho$=Si density, $d$=depth of SEE SV
  - If LET ~ constant in SV, $LET_{EQ}$ ~ Effective LET

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
Coverage of SEE Tests

- Coverage of SEE test—how well it probes potentially vulnerable areas on test item
  - Units: \( \mu m^2 \) per ion or transistors (xstr) per ion.
- IR photomicrograph of 60\( \times \)70 \( \mu m^2 \) area of ELPIDA EDS5108 512 Mbit SDRAM
  - Expect 1.45 recoil ions for \( 10^{10} \) 200-Mev p/cm\(^2\)
- 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 \( \mu m^2 \)

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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

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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 $LET_{EQ} \sim$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
  - $W=\{5, 10, 15, 20, 25\}$, $s=\{0.5, 1, 1.5, 2, 2.5\}$, $LET_0=\{0.5, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5 \text{ MeVcm}^2/\text{mg}\}$
  - 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($LET_{EQ}$) for SV depth
  - Estimate $N_E$ and solve for $N_{SV}$

- For 10-µm cube SV
  - If device $\sigma$ bound $>$\text{10}^{-2}$ cm$^2$, method fails
  - For $10^{10}$ 200-MeV p/cm$^2$ 122 failures/175 models
  - For $3 \times 10^{11}$ 200-MeV p/cm$^2$, 40.6% of models fail
  - Protons can bound rate if fluence high, $LET_0$ is low and $\sigma$ vs. $LET_{EQ}$ rises rapidly enough
  - Requires added information or assumptions
Energy and Fluence Dependence

~10% of $\sigma$ vs. LET$_{EQ}$ models fail

**Table I: Parameters w/ >50% Successful Bound**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LET$_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence (cm$^{-2}$)</td>
<td>($\text{MeVcm}^2$/mg)</td>
</tr>
<tr>
<td>200 MeV, $10^{10}$</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>200 MeV, $3\times10^{11}$</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>400 MeV, $10^{10}$</td>
<td>&lt; 3.5</td>
</tr>
<tr>
<td>400 MeV, $10^{11}$</td>
<td>&lt; 6.5</td>
</tr>
</tbody>
</table>
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 \( \text{LET}_0 \), W or s).
  - Deep SV push fluence distribution left—increasing likelihood of method failure
Board/Box-Level Testing

- Board/box-level testing irradiates many parts with diverse technologies
  - Saves money, but different SV depths mean parts see different Fluence vs. \( \text{LET}_{\text{EQ}} \) 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$_0$≤6.5 MeV/cm$^2$/mg, width≤25, shape≤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 ≤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 ≤10 µm

• 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)
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, σ_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