Particle Test Fluence: What’s the Right Number?

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# Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>DUT</td>
<td>Device Under Test</td>
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<td>F</td>
<td>Fluence</td>
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<tr>
<td>Gbit</td>
<td>Gigabit</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>LET</td>
<td>linear energy transfer ((\text{MeV}\cdot\text{cm}^2/\text{mg}))</td>
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<tr>
<td>MeV</td>
<td>million electronvolts</td>
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<td>NEPP</td>
<td>NASA Electronic Parts and Packaging</td>
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<td>POF</td>
<td>Physics of Failure</td>
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<td>SEE</td>
<td>Single Event Effect</td>
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<td>SEFI</td>
<td>Single Event Functional Interrupt</td>
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<td>SEL</td>
<td>Single-Event Latchup</td>
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<td>SEU</td>
<td>Single Event Upset</td>
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<td>SOC</td>
<td>Systems on a Chip</td>
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<td>TNS</td>
<td>Transactions on Nuclear Science</td>
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Outline

• What’s fluence?
  – Brief history lesson

• The factors that influence fluence levels:
  – Mission environment and particle kinematics,
  – Number of samples being used in flight,
  – Number of transistors/nodes, and
  – Number of dynamic operating states.

• Considerations and implications

• Summary

http://journalofcosmology.com/images/StraumeFigure3a.jpg
What’s All This Fluence Stuff, Anyhow?

• Fluence is:
  – The number of particles impinging on the surface of a device during a single ion beam test run normalized to a square centimeter. Denoted F.

• It is NOT:
  – *Cumulative fluence*: the sum of all individual fluence levels for all beam runs (usually only for a given ion, energy, and angle).
  – *Effective fluence*: beam run fluence normalized by $\cos(\theta)$, where $\theta$ is the angle of incidence.
Motivation

- Assumption: dynamic operations
- Each transistor and operating-state has the same random probability of getting hit.
  - That's the challenge: single event effects (SEE) are random.*
    - In other words, the error signature will be a function of where a particle hits and when a particle hits in a dynamic operating system.
- Testing is an attempt to quantify this random process and provide:
  - Some reasonable coverage of the possible error signatures by getting sufficient particles to provide confidence in coverage of the transistor/state space.
- For a billion-transistor, complex, system on a chip (SOC) device, how do we ensure this?
  - This is the crux of this talk: doing enough testing to have a reasonable level of confidence.

*Okay, it’s really a Markov process – whether the occurrence of an SEU in the future and past are independent.
Tradition: When Do We Stop a Test at the Particle Beam?

- Existing test standards provide guidance on setting a “beam stop” at either a given fluence or specific number of events.
- Fluence is \((\text{number of particles})/\text{cm}^2\) for a given test run
- JESD57* (the long time guidance for heavy ion SEE) gives recommendations of:
  - A fluence of \(1 \times 10^7\) particles/cm\(^2\), or
  - 100 events, or
  - Significant event (such as SEFI or SEL).
- Proton testing is often stopped at a fluence of \(1 \times 10^{10}\) protons/cm\(^2\) (or 100 errors or a significant event).
- Are these numbers taking into account:
  - Physics of failure (POF),
  - Circuit operation, and
  - Sufficient statistics?

The Challenges

• There are four basic considerations for determining fluence levels:
  – Geometry:
    • The number of potentially sensitive nodes or transistors in the device (statistical node coverage).
  – Operation (and propagation):
    • The dynamic operation of the device under test (statistical state and error propagation coverage).
  – Sample size:
    • The number of samples of the device being used in the system (statistical system coverage).
  – POF and (more) statistics:
    • The environment exposure and particle kinematics (i.e., what happens when a particle striking the semiconductor).

• Note, for dynamic operations we are often looking not only at measuring a cross-section, but determining as many possible error signatures as reasonable.
  – A simple example is the range of transients induced in an amplifier.
Gee, I’m a Tree!

- This is the simplest of the challenges to discuss. So consider,
  - If a memory device under test (DUT) has a billion bits (Gbit), how many random particle strikes on the die surface are required to cover a sufficient number of potentially sensitive bits in order to obtain good statistics?
    - 1%?, 10%?, 50%?, 100%?
  - Ask yourself, what is the objective?
    - Mean distribution?
    - Corner cases?
  - Suggest 10% at a minimum, but…
    - Remember there’s timing involved (more to come next)…

http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/imgnuc/crosec.gif
Dynamic Operation Constraints

- **State space issues:** Assume that a particle strikes a specific location (sensitive node). What can happen?
  - An error can occur immediately,
  - An error can occur at a undetermined time (and/or location) later, or
  - Nothing.
- **Why?** Let’s look at that Gbit memory.
  - How long might it take to cycle through the device memory space? Maybe a minute or so? Is it a simple form of propagation?
  - What if I’m writing over the memory space? Is it possible to clear errors by re-write and never detect them?
- **Take, for example** (courtesy Melanie Berg), a 32-bit counter.
  - There are $2^{64}$ states.
  - Operational frequency of 50 MHz (20 nsec per state) – over 300 billion seconds to cover all states.
    - Not happening during a beam run.
    - Key is understanding the error signature space and propagation effects… (ask Melanie about “Test Like You Fly” - not always best).
  - Remember, each state has the same random chance of taking a hit.
    - Consider a truly complex device like a system on a chip.
- **Operating state coverage (statistics), and error signatures.**
(Sample) Size Matters

• Besides the usual discussion of statistical relevance of samples from a single wafer lot, consider what the test results will be applied to.
  – How many samples in the flight application are being used?
    • There’s a big difference between flying two samples of a device and one thousand!
    • Outlier results are important when device is being used extensively. [1]

• It’s also important to grasp the idea of limiting cross-section (i.e., no events observed).

How important is knowing outliers in SEE testing?

Application Environment

• Rule #1: Ground irradiation is a confidence test and not a precise risk definition process.
  – The test is being performed to “bound” a problem. In other words,
    • Test fluence levels are not meant to be the same as what a device will be exposed to, but to provide confidence that the risk will be less than X of occurring.
    • Remember, X can be based on a limiting cross-section when no events have been observed
      – Though not likely true, assume that the next particle that hits the DUT causes an event, so that the limit of the cross-section is ~1/F.
  – It is important to remember that a test fluence of two to ten times a mission predicted fluence only goes so far in reducing risk.
    • Higher levels should be considered (keeping in mind total dose concerns at the DUT level) for better risk reduction.
    • If a mission proton fluence (of energies of interest) is $10^9$, what does a test to $10^{10}$ buy?
More on POF

• Not all particles are created equal:
  – Some deposit energy “on a track” as per image below.
  – Some interact with materials and cause secondary particles to deposit the energy.
    • This is the traditional proton SEU concern (though direct ionization with low energy protons is a consideration for advanced technology nodes).
    • This is a lesser concern for heavy ions though it shouldn’t be ignored.

• So what’s this have to do with fluence levels?

http://www.cotsjournalonline.com/files/images/1896/cots1201_Mic_Fig2_large.jpg
Proton Physics

- Something on the order of 1 in $10^5$ protons that hit a cm$^2$ of a silicon DUT interacts to cause a secondary particle.

- These secondary particles have a distribution of linear energy transfer (LET – hey, how’d I get so far in this talk without mentioning LET?) as well as usually being of short range.
  - These are particle kinematic effects to consider when establishing a proton fluence:
    - Number of interactions,
    - Distribution of secondary ions, and
    - Risk coverage versus mission environment, sample size, etc…
  - Is $10^{12}$ protons/cm$^2$ a realistic choice?

- Be wary of total dose or displacement damage at higher fluence levels: consider more samples of the DUT at lower fluence levels.
Visual Protons
(courtesy R. L. Ladbury and J.-M. Lauenstein, NASA/GSFC)

How good are protons at simulating heavy ions?

Silicon’s not the only culprit in creating problems.
And You Just Wanted a Number…

• Sorry folks, there’s no easy answer when you consider that:
  – F is a function of (geometry, operations, sample size, and POF).

• Suggestions:
  – Remember, it’s a bounded problem and reducing risk is the desired outcome.
    • Risk can’t fully be eliminated, but weeding out a reasonable coverage of error signatures and sensitivity levels is the goal.
  – Understand the dynamics of an accelerated beam test versus what you’ll be exposed to in space:
    • Drives data collection and how to apply it.
  – Melanie Berg’s “learning session” talk on Wednesday provides some thoughts on how you apply gathered data, but there are hidden gems that link with concerns noted here.
Acknowledgements

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