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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<tr>
<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 (MeV•cm²/mg)</td>
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<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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<tr>
<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.

Beam impinging on top or backside of device
Beam impinging on tilted device (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* processes.
  - 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 (number of particles)/cm² 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/cm², 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/cm² (or 100 errors or a significant event).
- Are these numbers taking into account:
  - Physics of failure (POF),
  - Circuit operation, and
  - Sufficient statistics?

*JEDEC JESD57: Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation, Revised 1996*
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 strikes 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)…
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 an 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?
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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