Particle Test Fluence: What's the Right Number?

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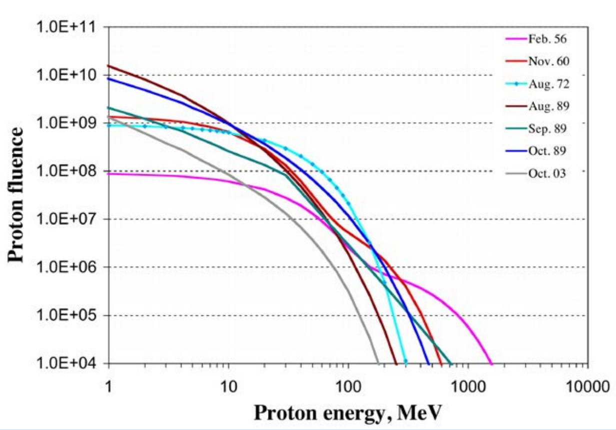
Acronyms

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

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**



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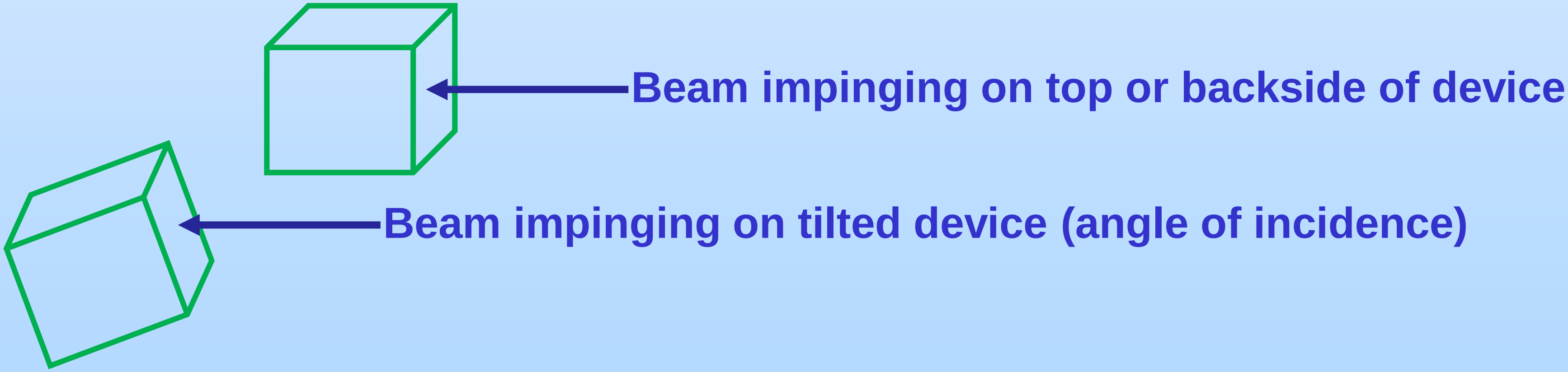
What's All This Fluence Stuff, Anyhow?

- **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(θ), where θ 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)/cm^2 for a given test run**
- **JESD57* (the long time guidance for heavy ion SEE) gives recommendations of:**
  - **A fluence of 1×10^7 particles/cm^2, or**
  - **100 events, or**
  - **Significant event (such as SEFI or SEL).**
- **Proton testing is often stopped at a fluence of 1×10^{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?**

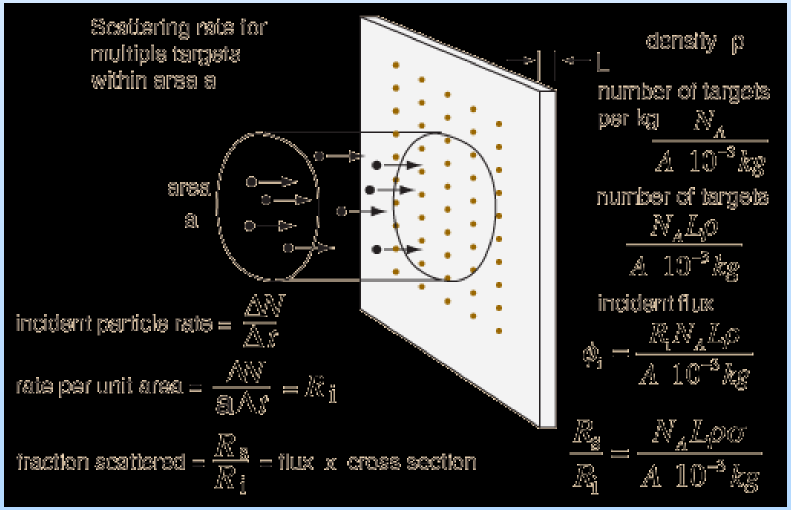
**** JEDEC JESD57: Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation, Revised 1996***

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)…



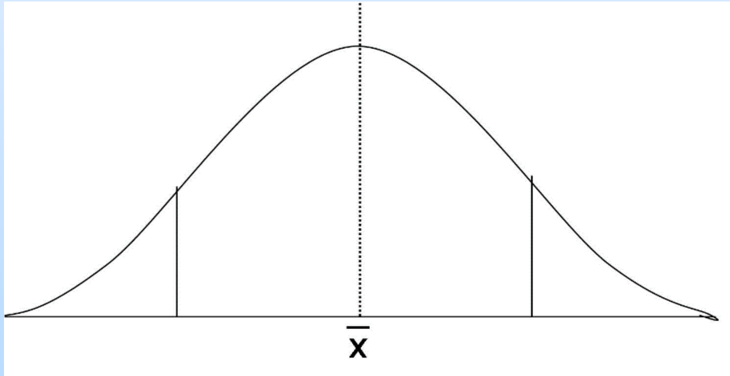
http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/imgnuc/crosec.gif

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?

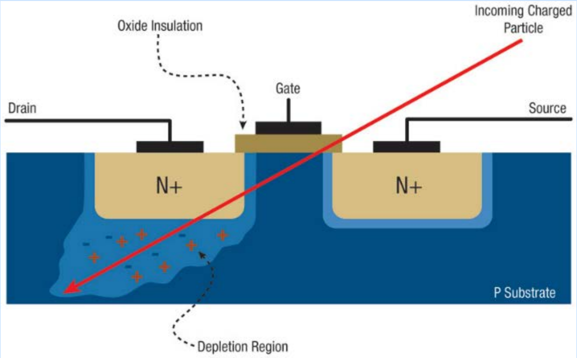
[1] K.A. LaBel, A.H. Johnston, J.L. Barth, R.A. Reed, C.E. Barnes, "Emerging Radiation Hardness Assurance (RHA) Issues: A NASA Approach for Space Flight Programs," IEEE Trans. Nucl. Sci., Vol. 45, No.6, pp. 2727-2736, Dec. 1998.

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?**



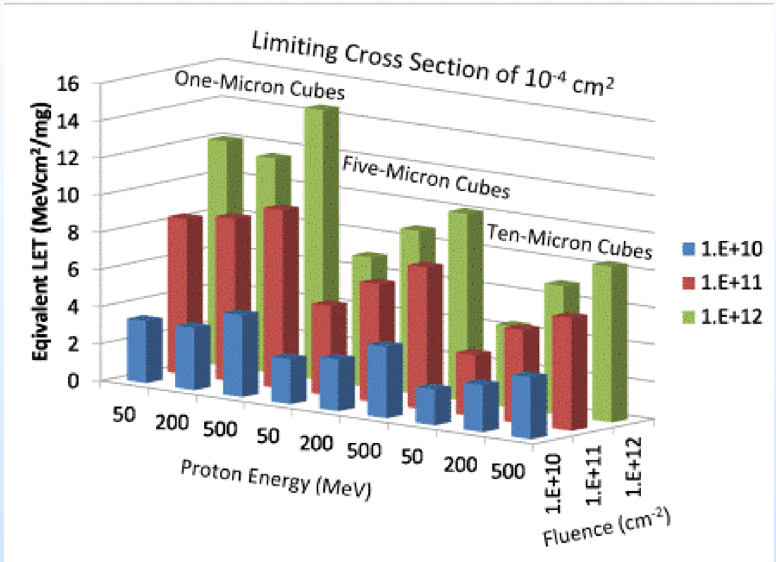
http://www.cotsjournalonline.com/files/images/1896/cots1201_Mic_Fig2_large.jpg

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.***

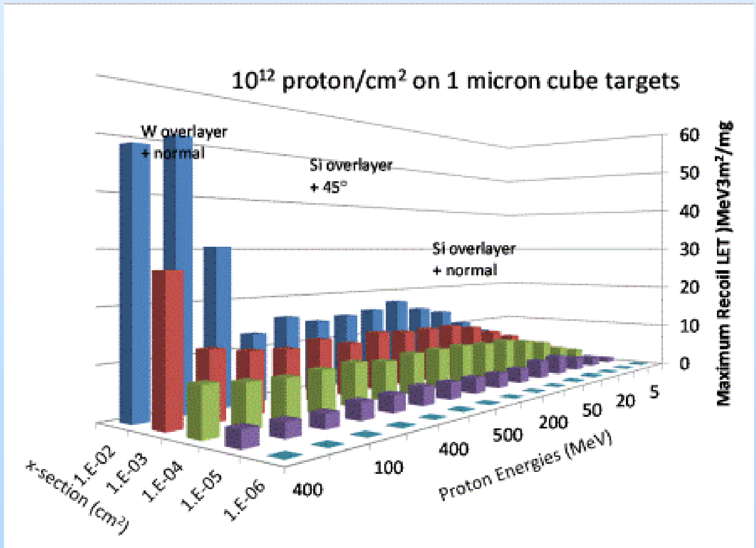
Visual Protons

(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

- **Melanie Berg, ASRC Space & Defense**
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