Catastrophic Heavy-Ion Failure of a Commercial ASIC

By

1, 2 Luis E. Selva
1 Gary M. Swift

1 Jet Propulsion Laboratory, California Institute of Technology
2 UCLA School of Medicine, department of Biomedical Physics

Sponsor: NASA Code AE under NASA Microelectronics Space Radiation Effects Program (MSREP)
Outline

I. Background

II. Problem

III. Module Level Test

IV. Analysis

V. Results of radiation test

VI. Conclusions

Central Theme: Gate Rupture at 14V!
Multi-Chip Module mounted on test board

Key:
1. MOSFET
2. ASIC
3. Integrated Circuit

Potting Material protecting passive and magnetic components
I. Background (commercial unit)

Multi-Chip Module (MCM)

Previous test good up to an LET < 100 MeV cm$^2$/mg

Application Specific Integrated Circuit (ASIC) is implemented

By the "Sea of Transistors"

Around periphery

Drivers

Buffer Transistors

ASIC is implemented as top layer of metal
II. Catastrophic Problem Low LET (BNL and Texas A&M)

Single-Event Latchup (SEL)?

Single-Event Gate Rupture (SEGR)?

III. Module Level Test (SEL setup strip chart)

Complexity: System vs. Isolated part

Ideal: Statistics w/o destruction

Identifying the Culprit device

Small beam (Cause and effect)

Result: Commercial ASIC!

Discover: Change of Foundry (Layout same)

Electrical Characteristics: NEW = OLD (Not Rad.!)
IV. Revisiting test results

Not SEGR

Electric Field low (~0.8MV/cm, Power MOSFET ~8MV/cm)

Not SEL

Unable to capture Current Signature

1. Complexity

2. Lack of visibility of ind. Components

3. Disconnecting Enable pin ➔ MCM Functional!
“The Smoking Gun”

Concluded:
1) Not a Latchup (cut = MCM functional)

2) Isolated Transistor → SEGR experiment
V. Investigated SEGR as mode of failure

Test ASIC alone

Use Californium (inc. LET 40 – 45 MeV cm$^2$/mg)

Increase Voltage (SEGR is sensitive to voltage): 30V rated

Protection Diode (needed to prevent forward bias)

Methodology

Static Bias Condition

Voltage Steps (0.25 V)

Number of Ions ($1 \times 10^5$) for 30 minutes
MOSFET drain current during irradiation

Typical SEGR Threshold

$V_{\text{DRAIN}} = 14$ Volts

Luis E. Selva R.

Page 9

04/17/00
VI. Conclusions

- Shown that SEGR is the mode of failure of ASIC

Why not more MOSFET failures?
Is there a Contradiction?

No! “Sea of Transistors” there are SEGRs, albeit small ruptures, perhaps not enough to completely “turn on” Output MOSFET Drivers, but never-the-less gate ruptures!

- Question: Why SEGR at Low Voltage (14V) and Low Electric Field (0.8MV/cm) in a commercial device?
  This is 1 order of magnitude below Pwr MOSFETs.
- Is this an isolated case?
- Or is this the tip of the Iceberg
Monologue

Title Slide
• My name is Luis Selva
• And the title of my paper is “Catastrophic Heavy-Ion Failure of a Commercial ASIC”
• The co-author in this paper is Gary Swift

Slide 2
• The outline for this presentation is as follows;
• We will talk about background and a brief history of the device.
• Then we’ll talk about the Catastrophic problem,
• The Module level test,
• Analysis of test results,
• Then we’ll talk about the radiation test results
• And lastly we’ll draw conclusions
• Purpose: Show SEGR does occur in commercial devices
Slide 3

- This is a picture of the Module.
- The module is mounted on a heat sink.
- The white is Potting material which is protecting passive and magnetic components underneath it.
- Key features of the device are the active components:
  1) MOSFET
  2) Integrated Circuit
  3) ASIC
  4) There are other active components ...
Slide 4

- **Background:** We irradiated a commercial unit
- A Multi-Chip Module (MCM),
- We had previously tested and was good up to LET<100
- Inside of the this MCM unit is an Application Specific Integrated Circuit or ASIC, which is a CMOS Gate Array
- For pedagogical purposes I’ve included this picture
- Around the periphery of the ASIC you’ll find
  - Drivers
  - Buffer Transistors
  - And in the center of the ASIC, is the “Sea of Transistors”
  - Where all transistors are identical
- The ASIC application is implemented by the top metal layer
Slide 5

- **The Catastrophic Problem:**
  We irradiated the MCM at Brookhaven National Laboratory and at Texas A & M.
- We discovered that the unit was failing catastrophically following irradiation with heavy-ions
- We were unable to determine the mode of failure:
  1. Single-Event Latchup (SEL)?
  2. Single-Event Gate Rupture (SEGR)?
- In order to answer this question we had to conduct a **Module Level Test (System)**
- In this experiment we setup a SEL test where we monitored currents via a stripe chart
- The difficulty with this experiment was getting good statistics without destroying the device
Module Level Test (continued)

- Complexity of a Module level Test:
  1) Lack of visibility into cause and effect
  2) Isolation of individual component

- In order to identify the culprit device, we had to reduce the beam size
- We swept the beam across the Multi-Chip Module
- We discovered that it was the Commercial ASIC that was the culprit!
- After this result we approached the manufacturer and inquired if there had been any design changes to the ASIC. They said “no” but added that they had changed foundry!
- In fact, everything on the ASIC was the same including the Layout.
- Electrically, the pre-foundry and post-foundry changes were identical. The only difference was the Radiation Response!
Slide 6

- Based on this discussion we decided to revisit the radiation test results, in order to rule out SEL or SEGR.
- We ruled out SEGR
  1. The electric field was too low \( \sim 0.8 \text{MV/cm} \)
     Typically in power MOSFETs \( E_{\text{crit}} \sim 8 \text{MV/cm} \)
  2. By disconnecting the Enable pin the Module Worked!
- We ruled out SEL
  1. Unable to capture SEL signature in stripe chart
     a. Events too fast to capture (unlikely)
  2. Complexity of Module level test
  3. Lack of visibility into current monitoring of individual electrical components
  4. Disconnecting Enable Pin \( \rightarrow \) module began to work again following heavy-ion irradiation!
Slide 7

"The Smoking Gun"

- The gate of the Output Driver (N-MOSFET) controlled by Buffer
- When MOSFET "on" current flows from source to drain
- Protection diode
  A) If forward bias current flows to $V_{CC}$
  B) If reversed bias current flows to output pin
- Current from output pin goes through a "pull-up" resistor and Enable pin
- 1) Cutting the connection between output pin and the "pull-up" resistor and the MCM unit became operational $\Rightarrow$ not a destructive Latchup
- 2) Disconnecting the Enable pin allowed us the ability to isolate the Output Driver (n-MOSFET) $\Rightarrow$ the opportunity to conduct a SEGR experiment
Slide 8
- We decided to investigate if SEGR was the failure mode
- In order to do this we had to test the ASIC alone
- We used Californium Fission fragments, LET range of 40 to 45 MEV cm$^2$/mg
- We increased the drain voltage on the MOSFET by 0.25V and in some cases by 0.5V increments
- In order to conduct this experiment we had to prevent the protection diode from being forward bias, we could not allow the drain voltage above $V_{CC}$
- In order to circumvent this problem we had to increase $V_{CC}$ along with the drain voltage. The offset was 0.25V.
- Methodology used was the standard SEGR test:
  - The Device was statically bias
  - Voltage increments between irradiation was 0.25V
  - Number of ions used were $1\times10^5$ for 30 minute runs
Slide 9
- This graph shows the result of four radiation experiments.
- On the Ordinate you have Drain current in amperes
- And on the Abscissa you have time of exposure in seconds
- In a typical SEGR experiment, the current threshold for defining Gate Rupture is at $1 \times 10^{-6}$ Amps.
- Note that devices 1, 3, and 4 did not reach the Typical SEGR threshold current. However, these are Gate ruptures, albeit small ruptures.
- Note that for devices 1 and 3 there are two SEGR events
- These additional events were observable because we monitored the Drain current (in Situ) during irradiation
- In most SEGR experiments, SEGR classification is done post irradiation. If $I_{\text{Drain}} \geq 1 \times 10^{-6}$ A then SEGR.
- So, events that occurred in device 1 and 3 would not be classified as SEGR, typically.
In Conclusion

1. We have shown that the Catastrophic problem experienced by the ASIC is a SEGR failure mode.
   a. Why are there not more MOSFETs failing? Is there a contradiction?
   b. No! Because in the “Sea of Transistors” we found SEGR, albeit small ruptures, which allowed ASIC functionality.

2. Question: Why is SEGR taking place at low applied Electric Fields?

3. Is this the tip of an iceberg?

4. Are there other commercial devices that are sensitive heavy-ion irradiation within normal operating conditions?

Thank you
Operational Current During Irradiation

Device 11 Manufacturer X