Radiation Failures in Intel 14nm Microprocessors

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Agenda

• Introduction & Motivation
• Soft & Hard Failures in FinFET processors
• Catastrophic Failures in 14nm node – Failure Analysis
  – Electrical Testing
  – Magnetic Microscopy
  – Photoemission Microscopy (PEM)
  – Laser Scanning Microscopy (LSM)
• Conclusions
Rad effects in microprocessors

- Microprocessors are too complex to be used for fundamental studies – too many blocks and circuits, too many processes
- Proprietary architecture
- Need to be investigated in their natural working environment

In this study:
- 14 nm Intel “Broadwell” 5th generation core series 5005U-i3 and 5200U-i5
- Mounted on Dell Inspiron laptops, MSI Cubi and Gigabyte Brix barebones
- Tested with Windows 8 and CentOS7 at idle

Rad studies are important as microprocessors are being flown in space …
Introduction

• Intel 14 nm
  – New – 2012 (transistor in 2002)
  – Fabricated in bulk FinFET process (Tri-Gate)
  – Excellent performance vs power specifications
  – Spacecraft candidate electronics

• Previously published Intel Tri-Gate radiation effects data promising
  – TID: functional up to 4Mrad [Szabo 2015]
  – Soft error rate: 1.4x to 23x reduction compared to 32nm planar [Seifert 2014, 2015]

• Can you use FinFETs in space radiation environments?
  – Are there critical issues or showstoppers?
  – Limited FY16 FinFET commercial devices available
    • Intel microprocessors, proprietary cell phone ASICs
Observations prior to this study

Primary Event Types observed during heavy ion testing at Texas A&M Cyclotron

- Normal Operation
- Ion Strike
- Soft Failures
- Machine Check Errors
  - 14 & 22nm
  - Auto-Reboot w/ Elevated Current
  - Power Off w/ Manual Restart Required
  - Auto-Reboot w/ Normal Current
- System Crashes
  - 14 & 22nm
  - 22nm only
  - Current Increases
  - Normal Operation w/ Elevated Current
- Hard Failures
  - 14nm only
  - Temporarily Nonfunctional
  - Our focus
Hard Failures” in 14nm FinFET devices

- System crash observed followed by inability to boot system for 30 min to hours
- Observed at 45° angles of incidence
- Occurs less often than system crashes. Very limited statistics – only 4 events
- System crash observed followed by *permanent inability* to boot. A single event observed

Understanding hard failure root cause is critical to future FinFET use in radiation environments
A (special) case of “hard failure”

Power supply to the CPU (Dell laptop mother board)

**Red** – On all the time
**Black** – Start with the ON switch

- 2.7 V
- 1.7 V
- 1.05 V
- 5.2 V
- 3.4 V
- 1.36 V

Buck diagram:

- Healthy board: 1.7 V
- Failed board: Only 0.6V!
Heavy Ion Event Types (expanded)

The observed ratio of the soft-, hard- and catastrophic failures under heavy ion irradiation is estimated to be 380:7:2.

14 & 22nm
- Machine Check Errors
- System Crashes
  - Current Increases
  - Normal Operation w/ Elevated Current
  - Auto-Reboot w/ Elevated Current
  - Power Off w/ Manual Restart Required
  - Auto-Reboot w/ Normal Current

22nm only
- Hard Failures
- Catastrophic Failures
  - Temporarily Nonfunctional
  - Permanently Nonfunctional

Ar ions, 520 MeV
14nm Intel Microprocessor Package

BGA package, 2 die, PCH = Platform Controller Hub

32 nm planar PCH die

14 nm FinFET CPU die

TAMU beam line view
Direct short (0.2 Ω) on processor 1.05 V power pin to GND

- Neocera magnetic microscope (SQUID and GMR probes) used to identify current path on 1.05 V to GND after catastrophic failure
- Externally applied AC current of 50 mA at 5.3 kHz
- 25 to 50 μm clearance from the top surface and 15 to 50 μm lateral steps
- Two catastrophically failed boards – identical results!

No signs of a short path …
Magnetic microscope: PCH die

Magnetic field mapping

Current density mapping

Two boards – identical results!
DCG IR laser scanning microscopy

- IR photoemission (PEM) indicates high current (and high activity) areas
- Two lasers available for laser scanning (LSM):
  - 1064 nm – producing e/h pairs, similar to heavy ions
  - 1340 nm – just heat
- Rastering across the entire die or selected areas. We can control laser power and scan rate

- Can we simulate radiation failures (soft, hard and catastrophic) using LSM technique? (cheaper than $1000/hour heavy ion beam)
- The laser beam is easy to focus to a micron size spot. Can we pinpoint the sensitive area for failures?
- LSM irradiates one spot at a time
The CPU die

- 1064 nm laser causes soft failures on the CPU die at powers of 2 – 5 mW (×1 objective, scan rate 217 µs/pixel)

- The bottom 1/3 of the die is much more sensitive that the upper 2/3

- 1340 nm laser at up to 80 mW power did not cause ANY upset at multiple scans
Photoemission from the PCH die

Short path (catastrophically failed package)

IR photoemission from a healthy package

×1 Objective

×20 Objective
1064 nm laser on the PCH die

- The most sensitive area (9 \( \mu m \times 140 \mu m \)) on the PCH die occasionally causes hard failures for about 10 min at laser power of about 5 mW!
- 1340 nm laser @ up to 80 mW does not cause ANY upsets
Conclusions

• Heavy-ion-induced hard- and catastrophic failures do not appear to be related to the Intel 14nm Tri-Gate FinFET process. They originate from a small (9 µm × 140 µm) area on the 32nm planar PCH die (not the CPU) as initially speculated

• The hard failures seem to be due to a SEE but the exact physical mechanism has yet to be identified. Some possibilities include latch-ups, charge/ion trapping or implantation, ion channels, or a combination of those (in biased conditions!)

• The mechanism of the catastrophic failures seems related to the presence of electric power (1.05V core voltage)

• 1064 nm laser mimics ionization radiation and induces soft- and hard failures as a direct result of electron-hole pair production, not heat
  – Cost and convenience
  – Laser can be focused within a micrometer size area to selectively study small components.
  – Necessity for thinning and polishing and other considerations

• 14nm FinFET processes continue to look promising for space radiation environments
Recent tests (May, 2016) at TAMU

Ar ions, by A. Williams & C. Szabo:
- Two hard failures on the PCH die
- No hard failure on the CPU die

Possible future paths:
- Landscape info from Intel (?)
- Elementary mechanisms (but how?!?)
- Power consumption vs radiation dose