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

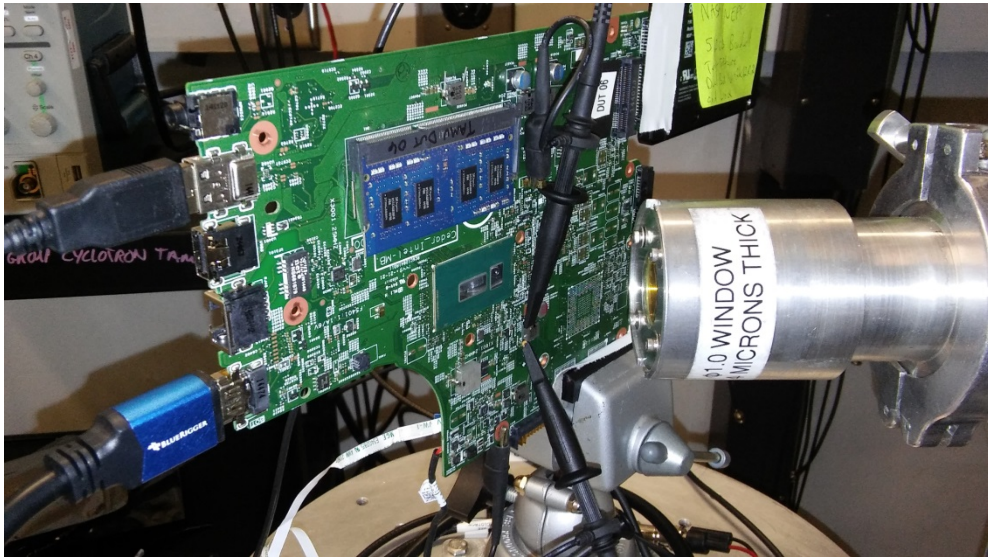
- Microprocessors are too complex to be used for fundamental studies – too many blocks and circuits, too many processes
- Proprietary architecture
- Need to be investigated in their natural working environment

In this study:

– 14 nm Intel "Broadwell" 5th generation core series 5005U-i3 and 5200U-i5

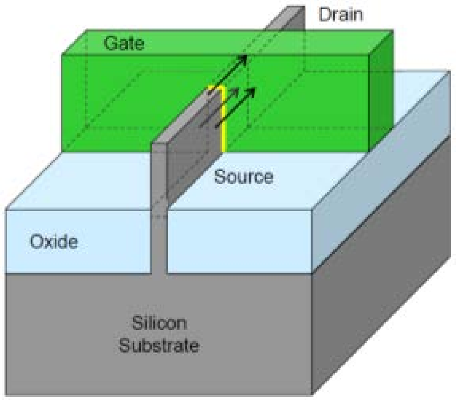
– Mounted on Dell Inspiron laptops, MSI Cubi and Gigabyte Brix barebones

– Tested with Windows 8 and CentOS7 at idle



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

Introduction



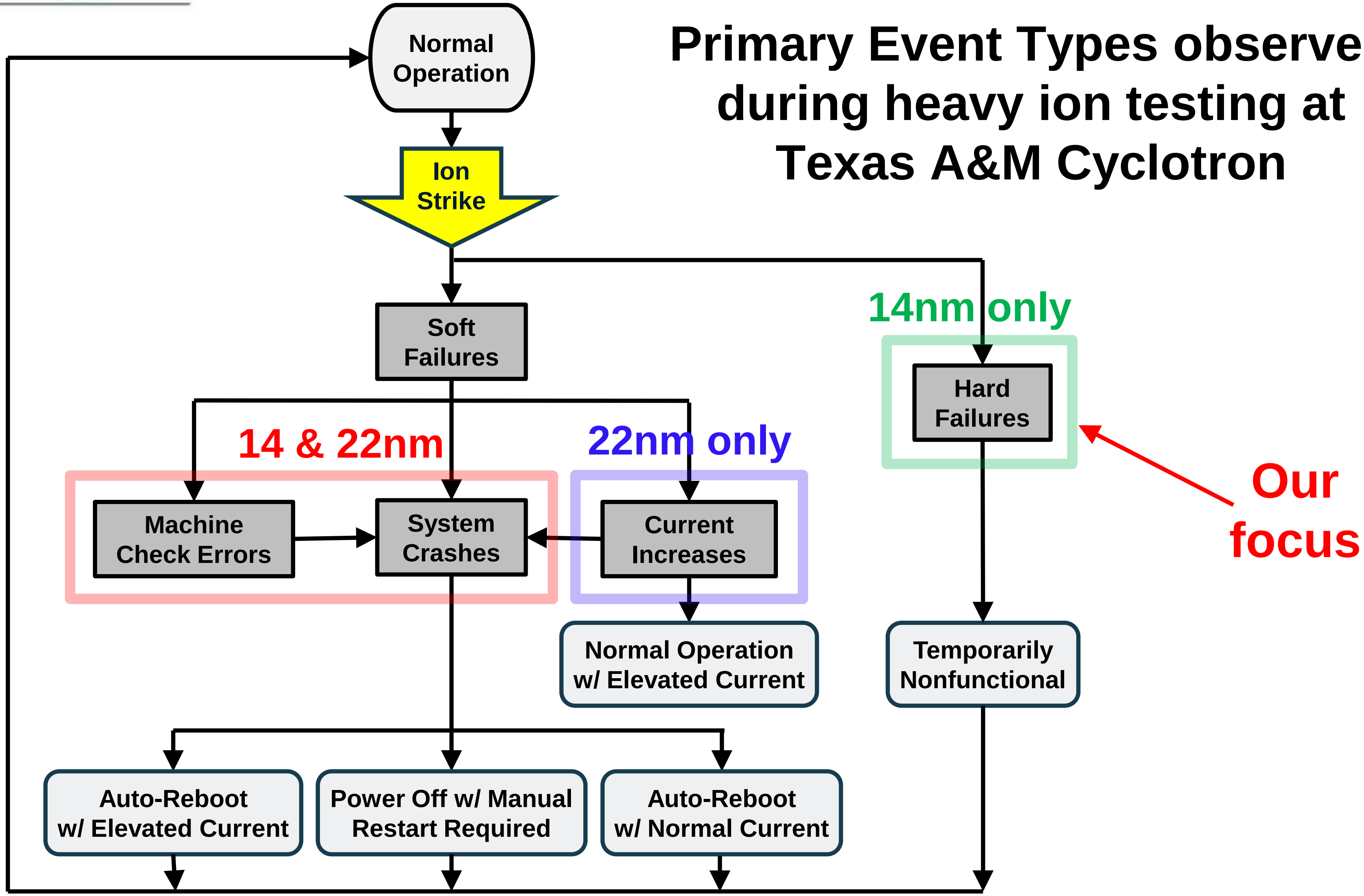
- Intel 14 nm
  - New – 2012 (transistor in 2002)
  - Fabricated in bulk FinFET process (Tri-Gate)
  - Excellent performance vs power specifications
  - Spacecraft candidate electronics

- 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

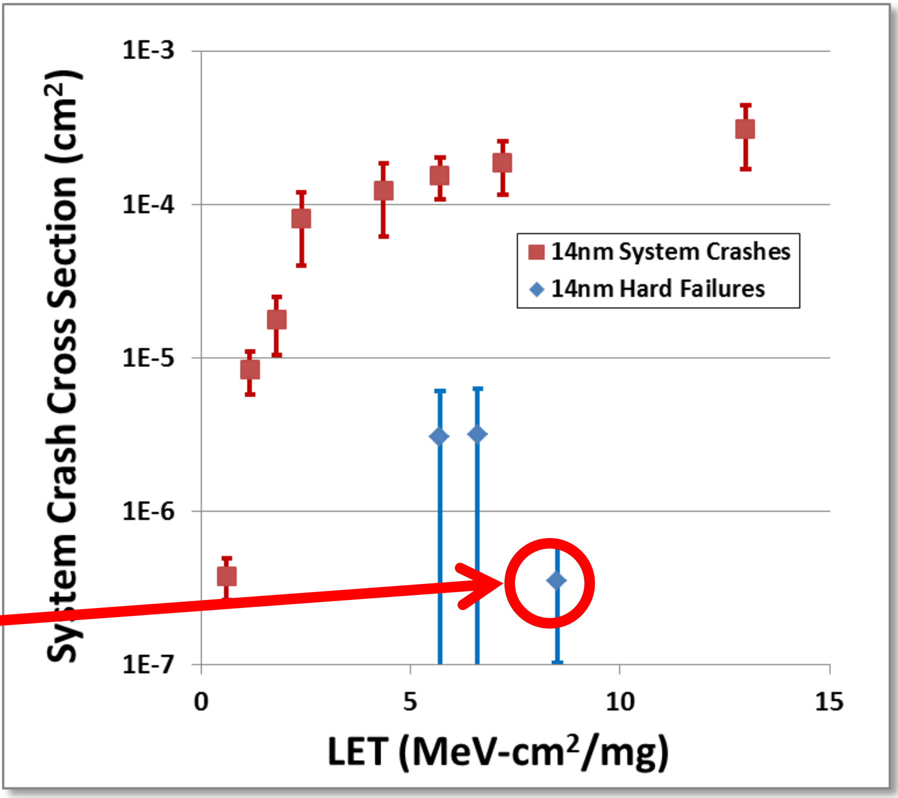
Observations *prior* to this study

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



Hard Failures" in 14nm FinFET devices

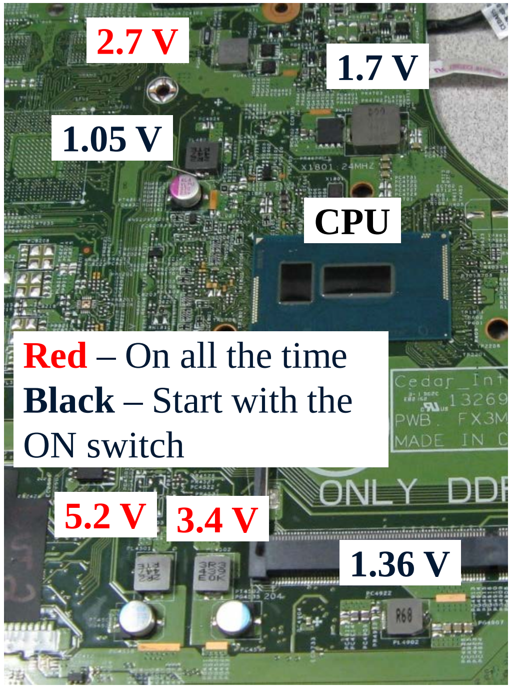
- System crash observed followed by inability to boot system for 30 min to hours
- Observed at 45° angles of incidence
- Occurs less often than system crashes. Very limited statistics – only 4 events
- **System crash observed followed by *permanent inability* to boot. A single event observed**



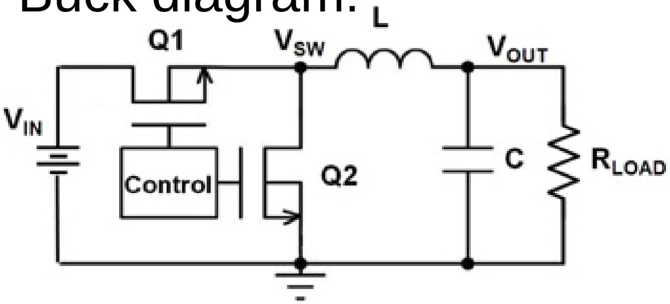
Understanding hard failure root cause is critical to future FinFET use in radiation environments

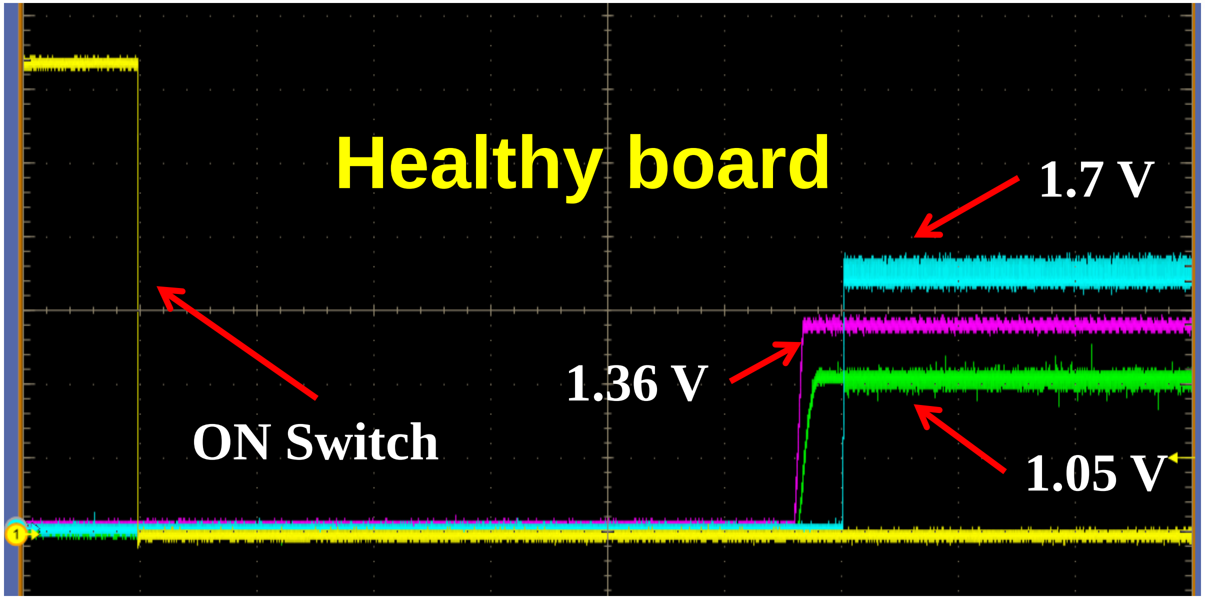
A (special) case of "hard failure"

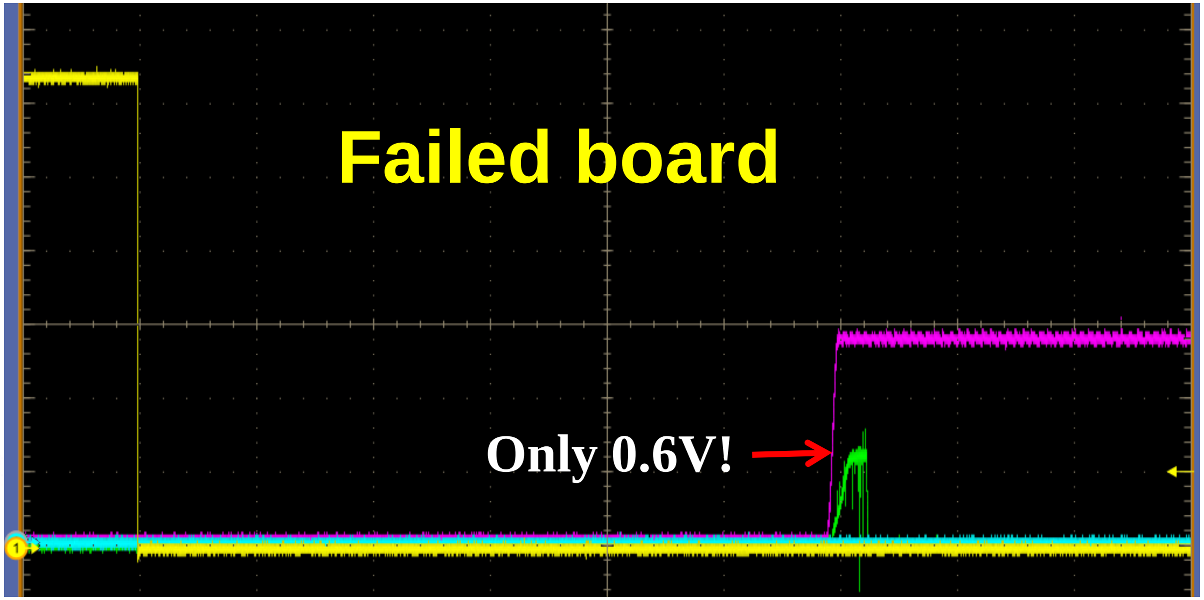
Power supply to the CPU (Dell laptop mother board)



Buck diagram:



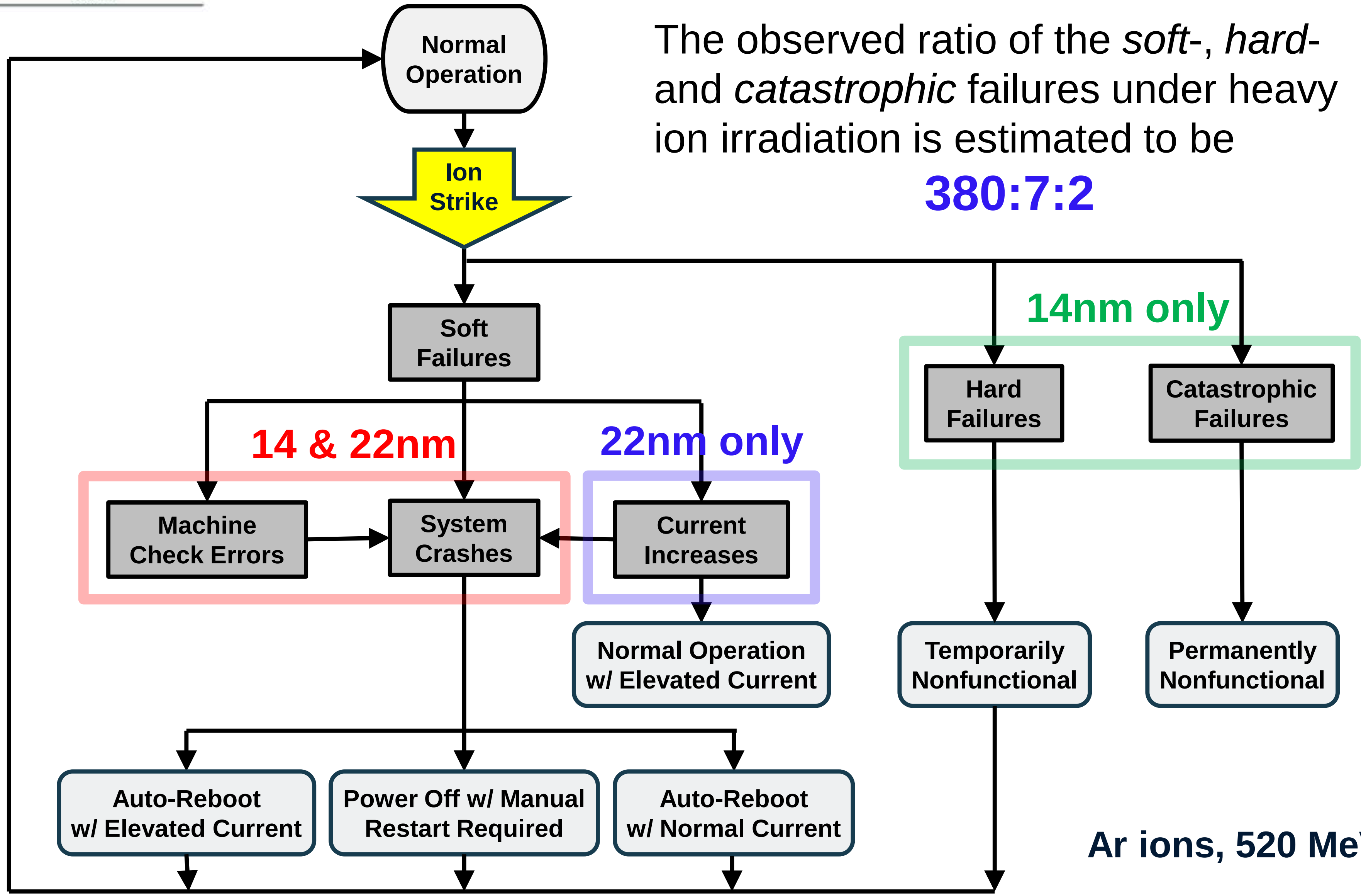




Heavy Ion Event Types (expanded)

The observed ratio of the *soft*-, *hard*- and *catastrophic* failures under heavy ion irradiation is estimated to be

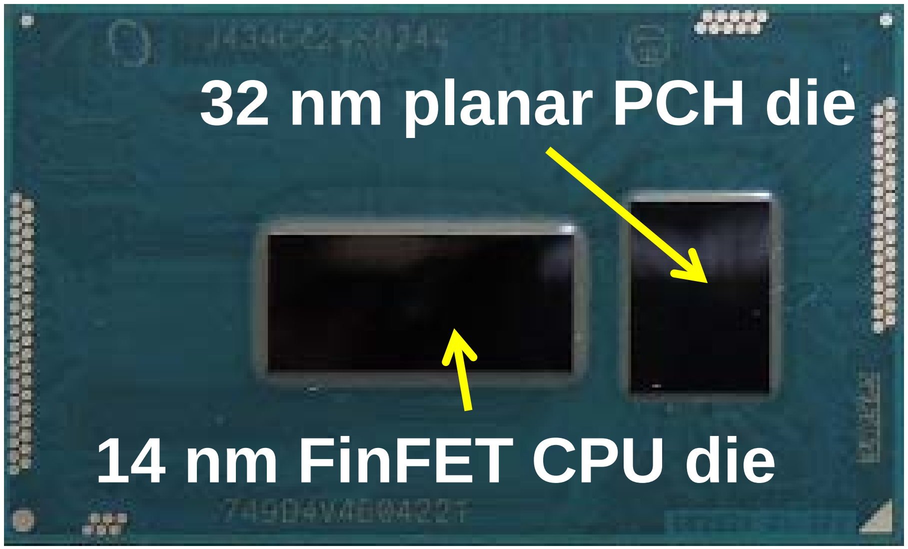
380:7:2



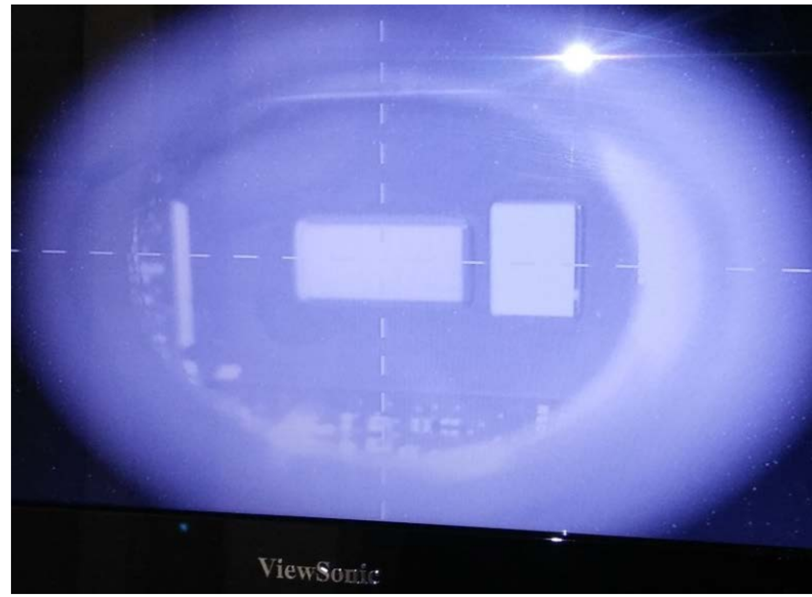
Ar ions, 520 MeV)

14nm Intel Microprocessor Package

BGA package, 2 die,
PCH = Platform Controller Hub



TAMU beam line view



Tracing the short: CPU die

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!

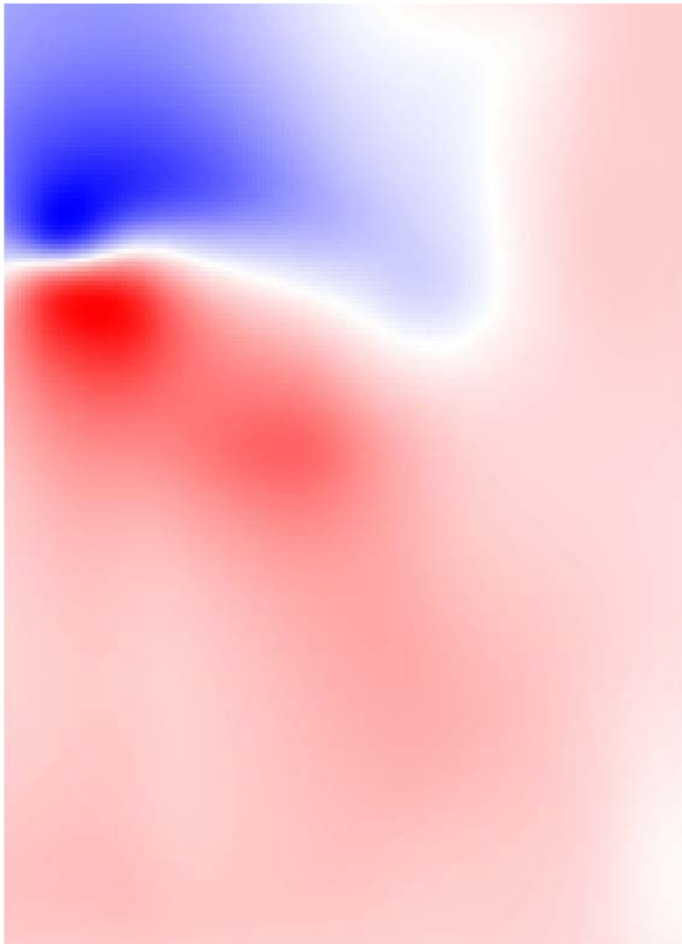
No signs of a short path …

Magnetic field mapping

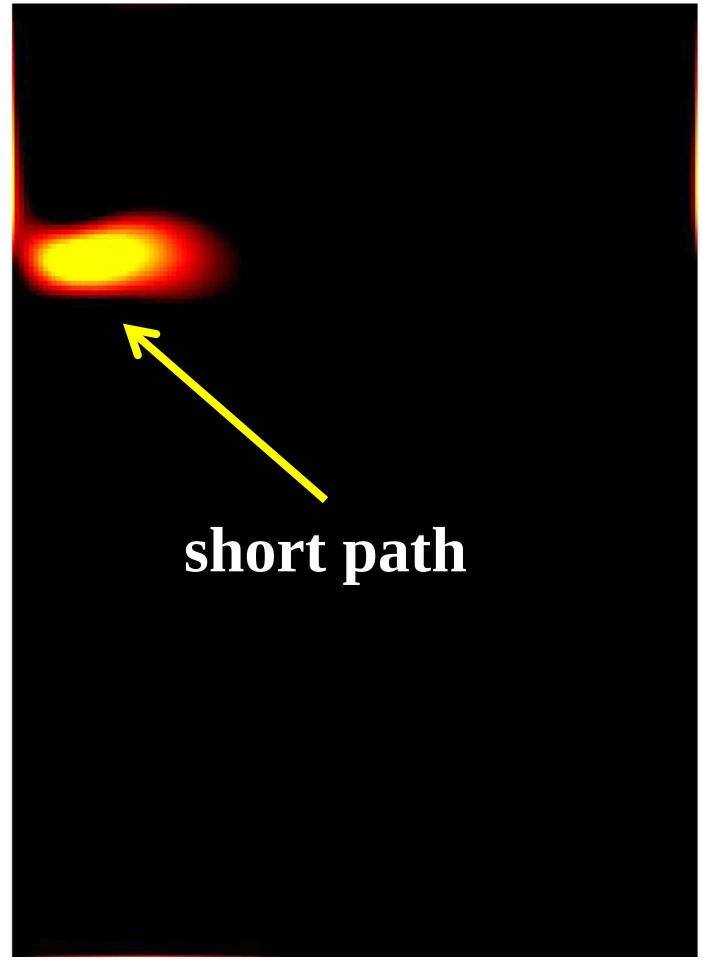
Current density mapping

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

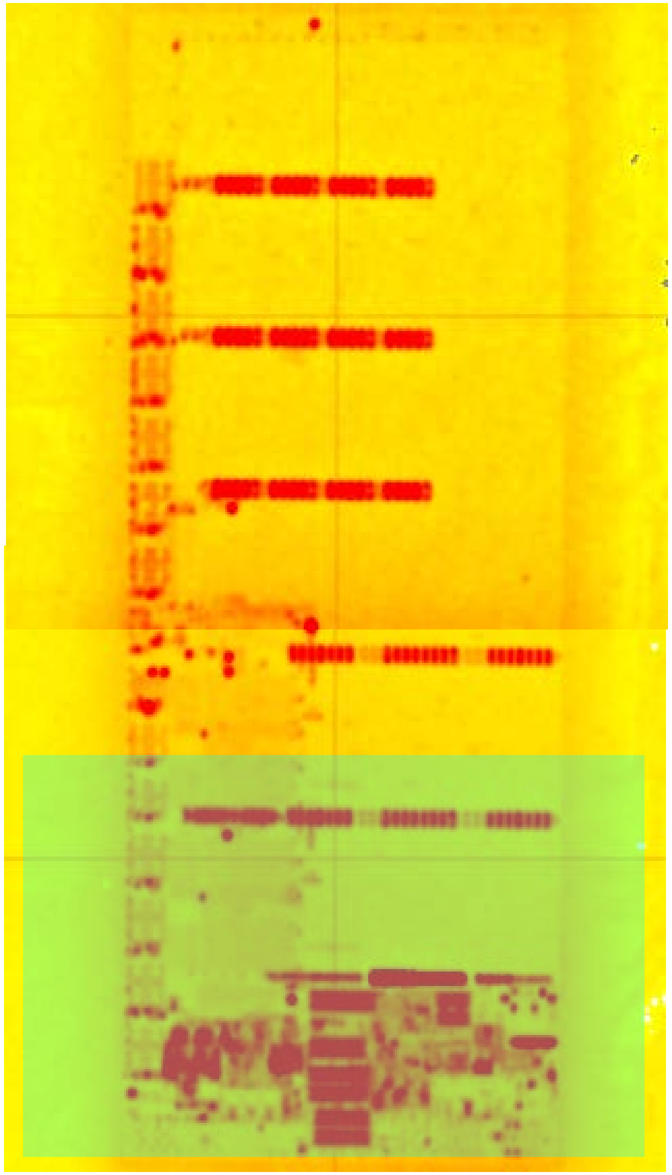
- **Can we simulate radiation failures (soft, hard and catastrophic) using LSM technique? (cheaper than $1000/hour heavy ion beam)**
- **The laser beam is easy to focus to a micron size spot. Can we pinpoint the sensitive area for failures?**
- **LSM irradiates one spot at a time**

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)

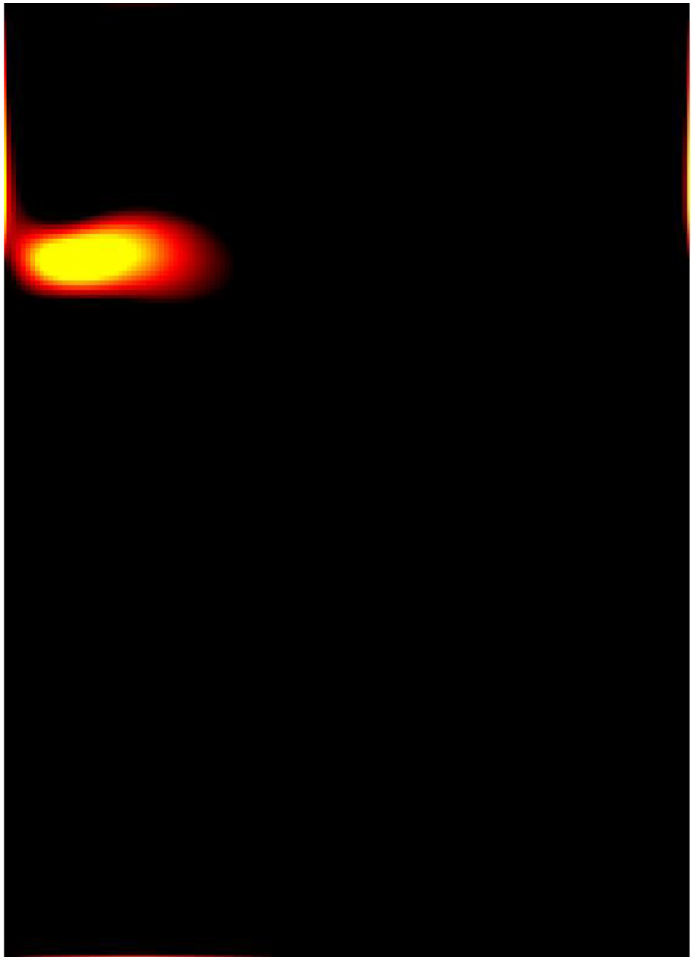
- The bottom 1/3 of the die is much more sensitive that the upper 2/3

- 1340 nm laser at up to 80 mW power did not cause ANY upset at multiple scans



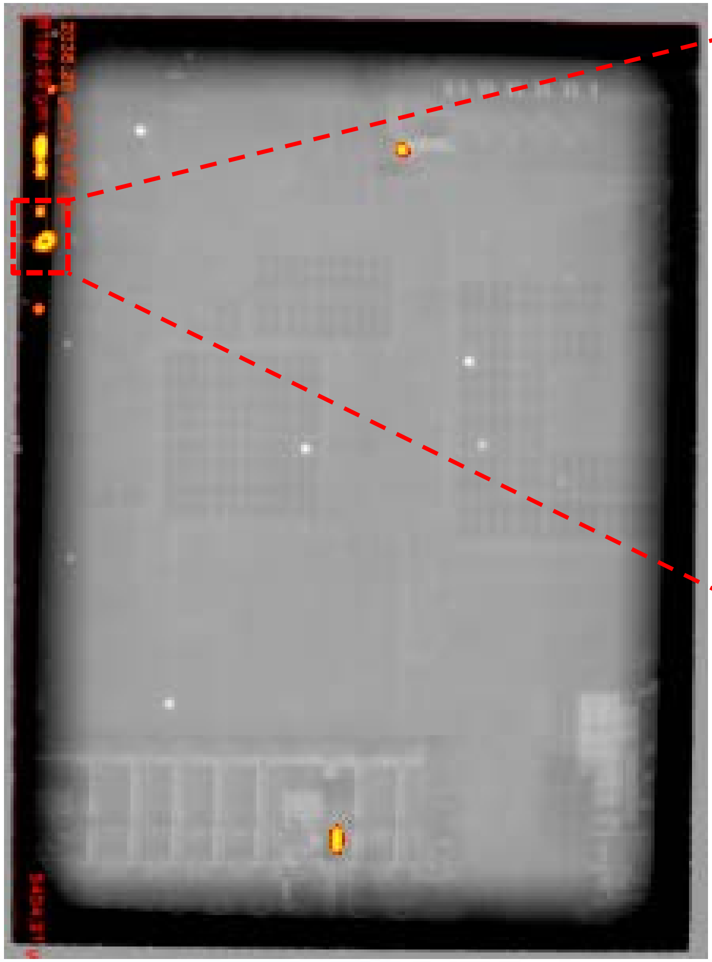
Photoemission from the PCH die

Short path (catastrophically failed package)

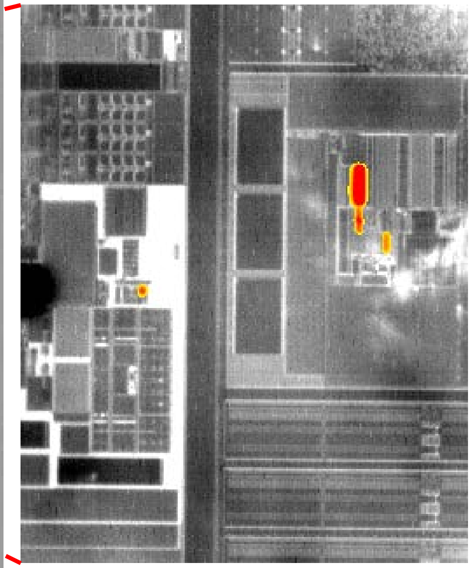


IR photoemission from a healthy package

×1 Objective

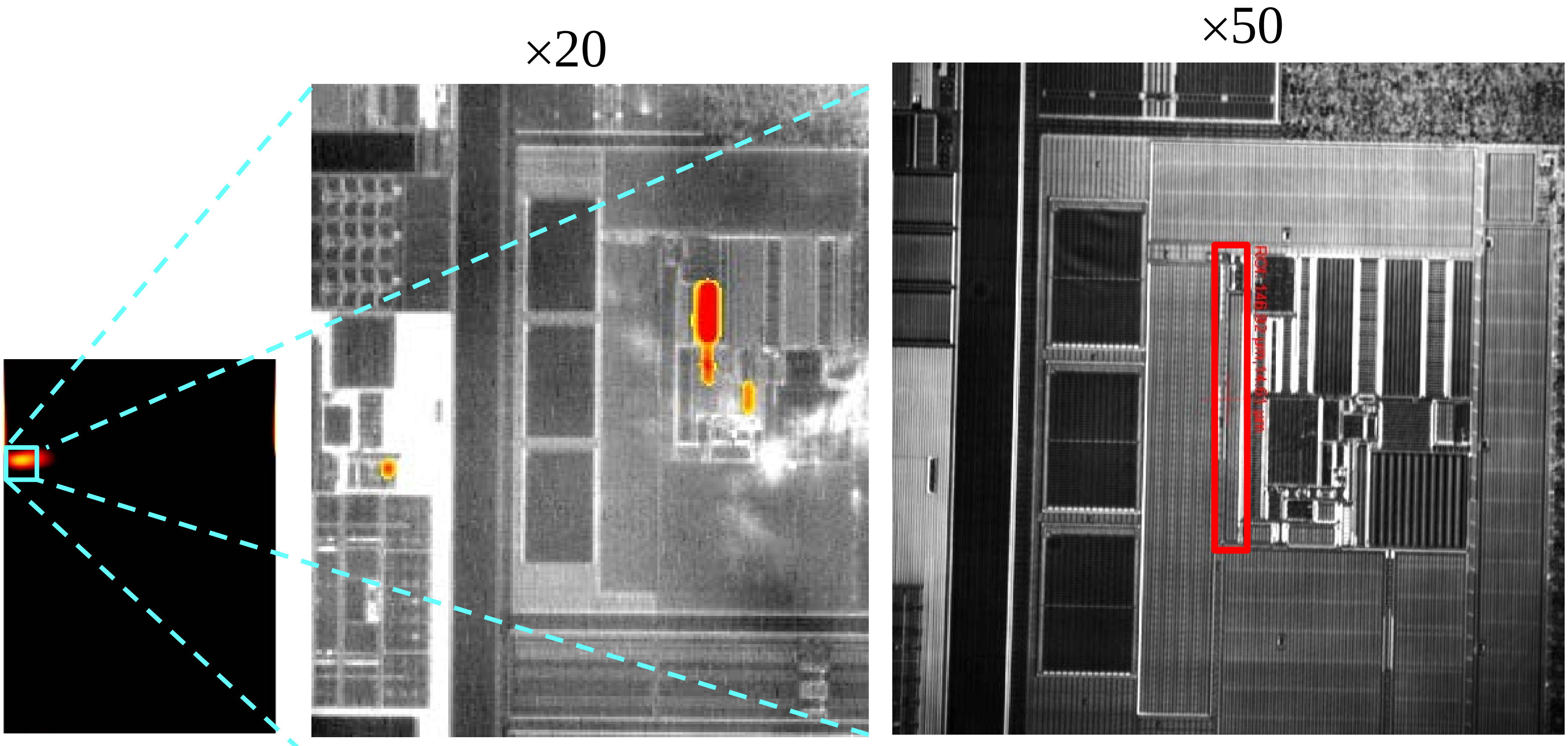


×20 Objective



1064 nm laser on the PCH die

- The most sensitive area (9 μm × 140 μm) 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



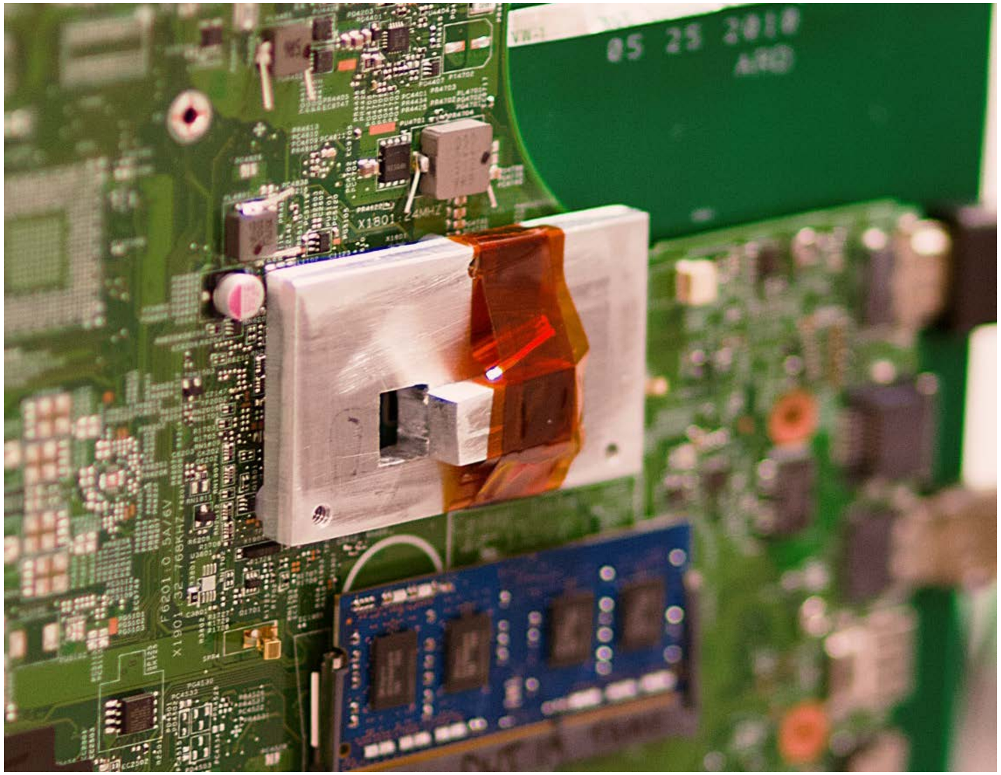
Conclusions

- **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 $\times$ 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