Non-Volatile Memory Radiation Update

Ted Wilcox

ted.wilcox@nasa.gov

NASA Goddard Space Flight Center

NASA Electronic Parts and Packaging Program

To be presented by Ted Wilcox at the 2021 NEPP Electronics Technology Workshop (ETW), NASA GSFC, Greenbelt, MD, June 16, 2021.

Acronyms

- BER: Bit Error Rate
- CMOS: Complementary Metal-Oxide Semiconductor
- COTS: Commercial Off The Shelf
- DRAM: Dynamic Random Access Memory
- ECC: Error-Correcting Code
- EDAC: Error Detection and Correction
- EEPROM: Electrically-Erasable Programmable Read-Only Memory
- LET: Linear Energy Transfer
- MLC: Multi-level Cell
- MRAM: Magnetoresistive RAM
- NAND: Not AND (Flash Technology)
- NEPP: NASA Electronics and Packaging Program
- NVM: Non-Volatile Memory
- PMIC: Power Management Integrated Circuit
- QLC: Quad-level Cell
- SBU: Single Bit Upset
- SEE: Single Event Effects
- SEFI: Single Event Functional Interruption
- SEU: Single Event Upset
- SLC: Single-level Cell
- SSD: Solid State Drive
- SSR: Solid State Recorder
- STT-MRAM: Spin-torque Transfer MRAM
- TID: Total Ionizing Dose
- TLC: Triple-level Cell

Outline

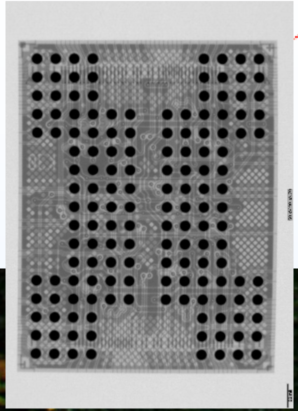
- NEPP's Interest in NVM
- Past NEPP Memory Testing
- 2021 Test Results
- Plans for 2021-2022

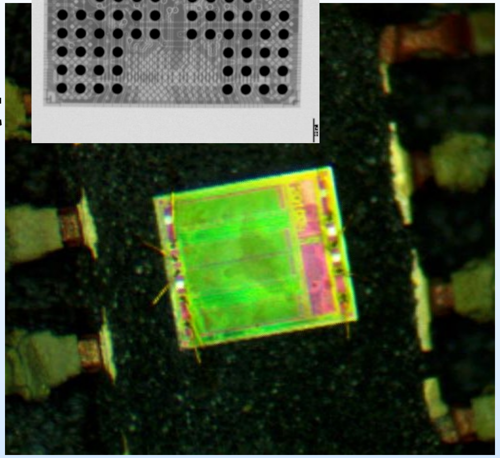
NEPP Non-Volatile Memory Radiation Task

Our interest is not to qualify particular components for flight, but to

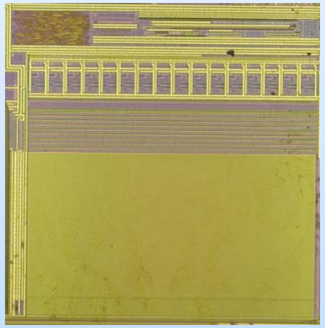
1. **Evaluate broad trends in TID and SEE response in advanced NVM**
   - Understand general differences between technologies to aid in parts selection
   - Characterize trade-offs in radiation performance
   - Identify testing challenges and develop guidelines or recommendations
2. **Explore radiation response with device and module-level testing**
   - Lean towards testing of COTS modules where it makes sense
     - How can we characterize errors? How can we test thoroughly?
   - Device level: Understand complex effects to improve understanding for flight
     - SEFI Modes, MBUs vs Multi-Level Upsets, Destructive SEE, retention/endurance changes, irradiation bias effects, etc.

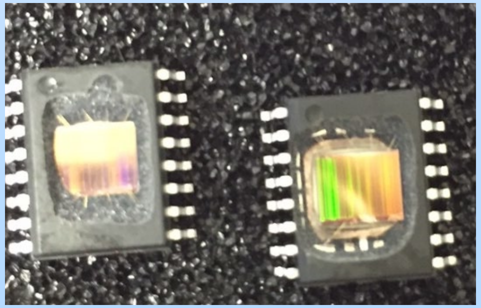
Past NEPP NVM Radiation Tests

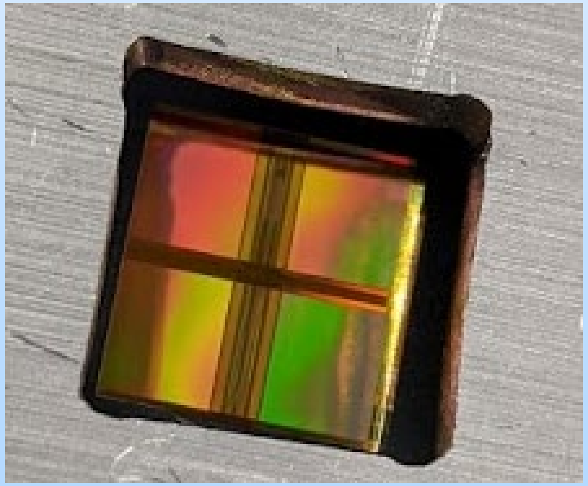




- 3D NAND Flash:
  - 2016-2017: Samsung 32L V-NAND SSD, Hynix 36L NAND parts
  - 2018-2021: In-Depth Characterization: Micron 32L NAND → Flight
  - 2019-2020: Hynix 72L NAND
- 3D Xpoint:
  - 2017 high-energy proton SEE testing
- MRAM:
  - 2017+ Avalanche Technologies STT-MRAM
  - Everspin STT-MRAM (JPL)
- Farther back…
  - 2015: Adesto CBRAM
  - 2017: Fujitsu ReRAM
  - 2014: Panasonic ReRAM





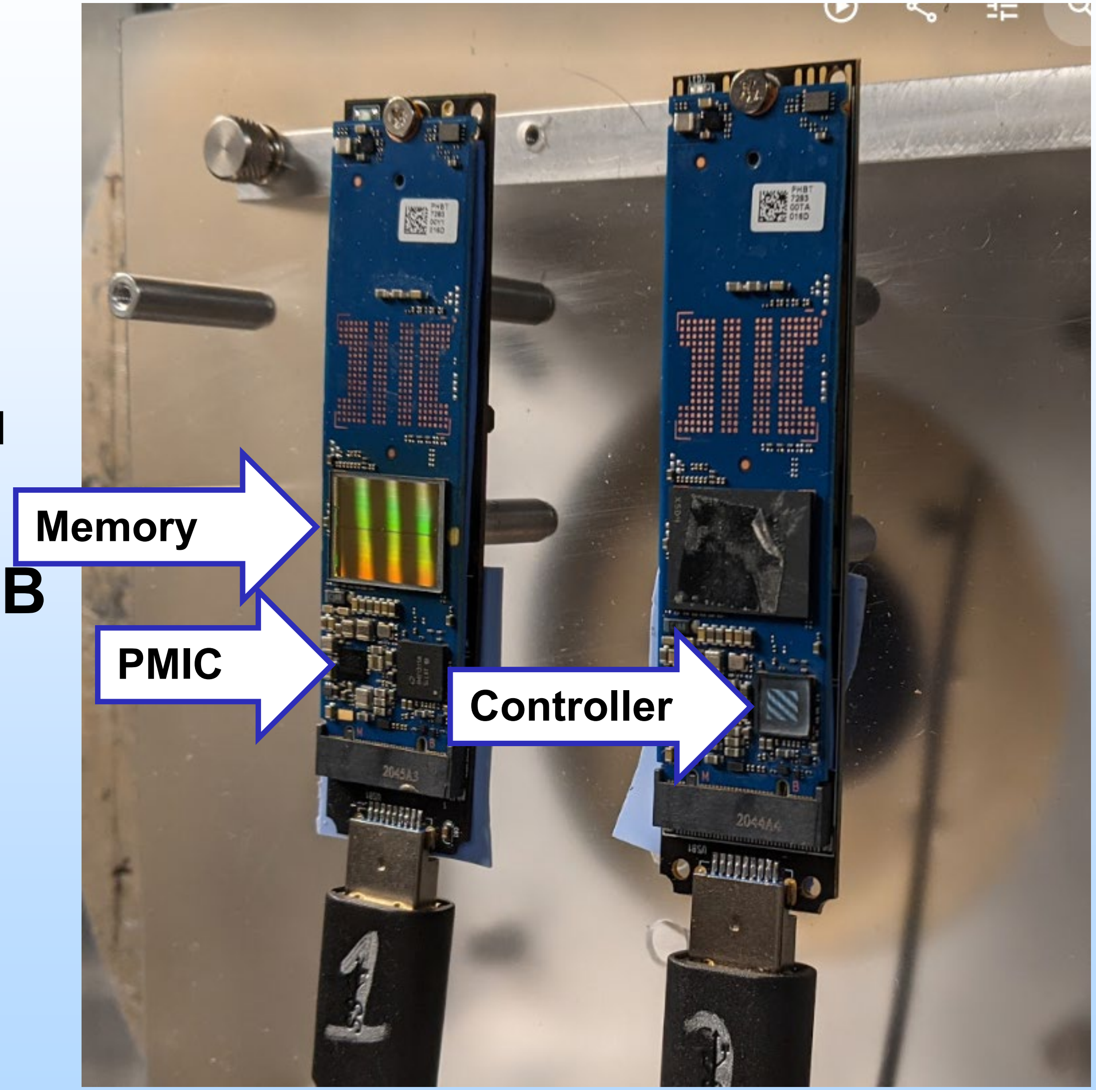


New Testing: Intel Optane

- Intel launched a pair of 16 and 32 GB Optane-branded accelerator cards in 2017 using 3D Xpoint technology developed with Micron
- NEPP performed some preliminary proton testing, which is released as "Proton Irradiation of the 16GB Intel Optane SSD" (Wyrwas, 2017).
- Without low-level access to the memory devices, we did not perform meaningful heavy-ion testing until 2021. Industry interest has only increased but…
- …decapsulation yields of commercial solid-state drives are low, parts perform unpredictably in a vacuum, and data interfaces are tricky

Intel Optane Heavy Ion Testing

- Seven devices prepared
  - Three with Optane exposed
  - Two with controller
  - Two with PMIC
- Testing with LBNL's 16 MeV/amu tune
- Dynamic reading/writing to 2.5 GB via USB 3.0-to-NVME adapter
- No differentiation between types of error (SEFI vs SEL)



Optane Results by Device

- 3D Xpoint Memory Irradiations:
  - 16 MeV/amu N (LET ~1.2 $MeVcm^2/mg$)
    - Device #3 survived four irradiations without unrecoverable failure; average fluence-to-SEFI was $8.33x10^4/cm^2$.
  - 16 MeV/amu Si (LET ~4.6 $MeVcm^2/mg$)
    - Device #1 failed at a fluence of $1.00x10^4/cm^2$ (unrecoverable)
    - Device #3 failed at a fluence of $1.99x10^3/cm^2$ (unrecoverable)
  - 16 MeV/amu Cu (LET ~16.5 $MeVcm^2/mg$)
    - Device #2 failed at a fluence of $6.74x10^3/cm^2$ (unrecoverable)
- In all cases, a “SEFI” represents a sudden lack of read/write functionality from the host OS without automatic recovery.

Optane Results by Device

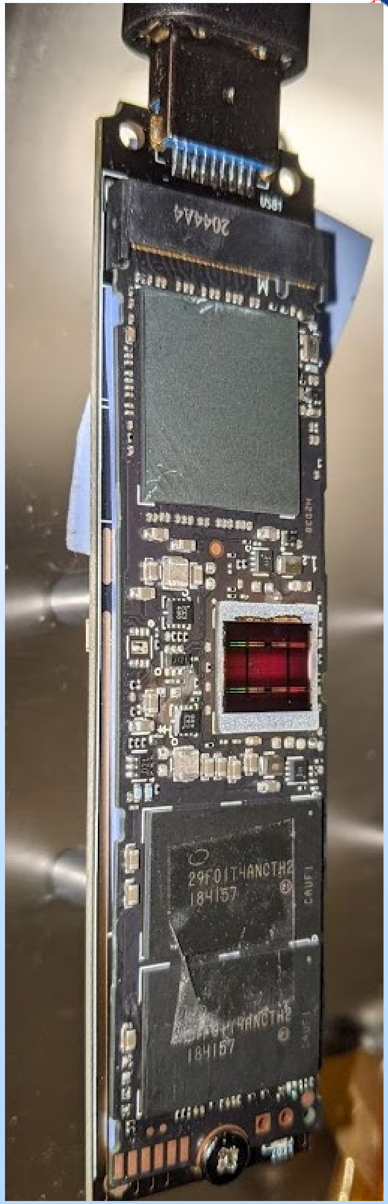
- **Controller Irradiations:**
  - 16 MeV/amu Si (LET ~4.6 $MeVcm^2/mg$)
    - 7 of 10 runs SEFI; average fluence-to-SEFI was $2.81x10^4/cm^2$. 10th run was unrecoverable.
  - 16 MeV/amu N; exact LET TBD (testing a lidded controller)
    - Failed unrecoverably at $6.97x10^5/cm^2$.
- **PMIC Irradiations:**
  - 16 MeV/amu N (LET TBD; flip chip device)
    - Both parts failed unrecoverably at $6.7x10^4/cm^2$ and $1.36x10^5/cm^2$
    - Nearby parts covered with extra shielding due to range of N beam

Optane Future

- Micron discontinued 3D Xpoint development and sold fab
- Outlook remains unsettled for Intel's future with 3D Xpoint
- Radiation results for first-gen parts are not inspiring
  - The non-volatile 3D Xpoint may be rad-hard, but the off-the-shelf modules are extremely sensitive to functional failure
  - On the other hand, a future product line could be lucky in the opposite direction (this is more of a COTS problem than an NVM problem)
- However, non-volatile DDR-like memories have clear appeal to space computing, as does a high-endurance, SEU-immune storage-class memory (sharing space with MRAM)

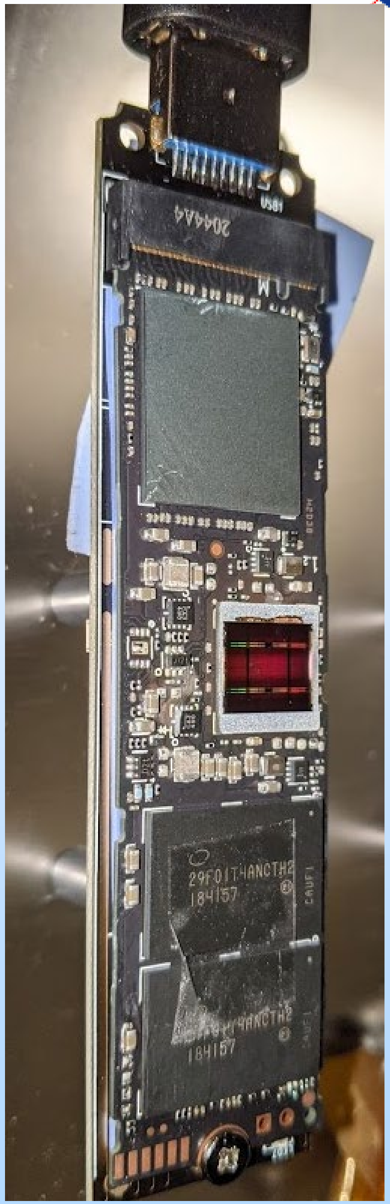
Intel 760P NAND Flash SSD

- Intel's 760P is a mainstream consumer solid state drive (released 2018)
  - Silicon Motion's SM2262 controller
  - 256 Gb 64 layer TLC 3D NAND
  - Winbond DRAM
- Six devices prepared
  - Two with NAND exposed
  - Two with controller (none survived decapsulation)
  - Two with DRAM
- Dynamic reading/writing to 2.5 GB via USB 3.0-to-NVME adapter
- No differentiation between types of error (SEFI vs SEL)



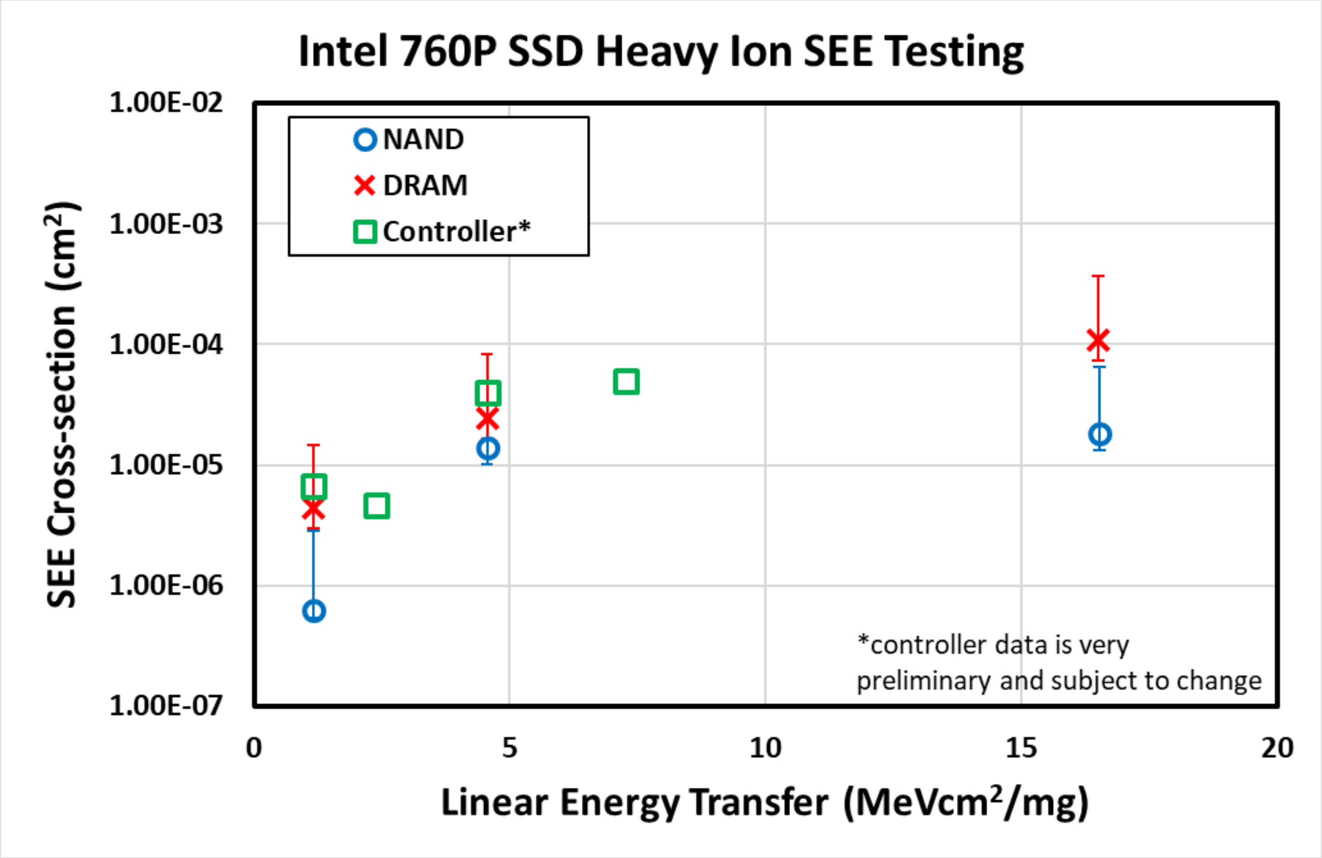
Intel 760P Heavy Ion Results

- Unlike the Optane, Intel 760P SSD never failed unrecoverably.
- NAND cross-section is limited to the exposed die, so module rates would be higher depending on capacity
- DRAM is highly sensitive as expected
- No controllers survived decapsulation; an attempt was made to test the lidded package of another module.
  - LETs will have to be calculated after the fact
  - The DRAM was not covered for all runs, which required some re-testing. It is TBD whether the higher LET runs of the lidded controller are actually real data or contamination from DRAM.



Intel 760P SEE data

- Unprocessed data is provided below as an illustration of magnitude
- The controller points must still be adapted to true surface-incident LET



Takeaways

- **3D NAND Flash Plans**
  - NEPP will continue part-level SEE testing where available, primarily with heavy ions to evaluate low-level radiation response
  - Planning comparison of part-level TID testing between several generations of devices to evaluate trends
- **Solid-state drive module testing (primarily NAND)**
  - Planning to evaluate module performance as baseline data for SmallSat/CubeSat/COTS users, and to compare piece-part heavy ion data to with module-level proton data
- **Explore non-flash technologies where prudent**
  - MRAM, RRAM, 3D Xpoint all have direct applications for spaceflight and state-of-the-art COTS parts exist without hi-rel equivalents.