# Radiation Effects of Commercial Resistive Random Access Memories

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    - **Defense Threat Reduction Agency (DTRA)**
    - **National Reconnaissance Office (NRO)**

- **Adesto and Panasonic for providing technical support**

# Acronyms

- 1T1R – 1 transistor 1 resistor
- BEOL – Back-end-of-line
- CBRAM – Conductive-bridge random access memory
- CMOS – Complimentary metal-oxide-semiconductor
- EEPROM – Electrically erasable programmable read only memory
- LCDT – Low cost digital tester
- LBNL – Lawrence Berkeley National Laboratory
- LET – Linear energy transfer
- RAM – Random access memory
- ROM – Read-only memory

- ReRAM – Reduction-oxidation random access memory
- RRAM – Resistive Random Access Memory
- SEE – Single-event effect
- SEFI – Single-event functional interrupt
- SEU – Single-event upset
- SOIC – Small Outline Integrated Circuit
- TAMU – Texas A&M University

# Motivation

- Limited availability of radiation tolerant flash memories

- Radiation performance of state-of-the-art flash is generally good but include some weaknesses

- Flash already reaching scaling limits

- Resistive random access memory (RRAM) has shown very good tolerance to radiation*

- Published radiation test results only from test chips

- A first look at the SEE performance of two commercial production-level RRAMs

* M. J. Marinella, S. M. Dalton, P. R. Mickel, P. E. Dodd, M. R. Shaneyfelt, E. Bielejec, G. Vizkelethy, and P. G. Kotula, "Initial assessment of the effects of radiation on the electrical characteristics of TaO$_x$ memristive memories," *IEEE Trans. Nucl. Sci.*, vol. 59, pp. 2987 – 2994, Dec. 2012
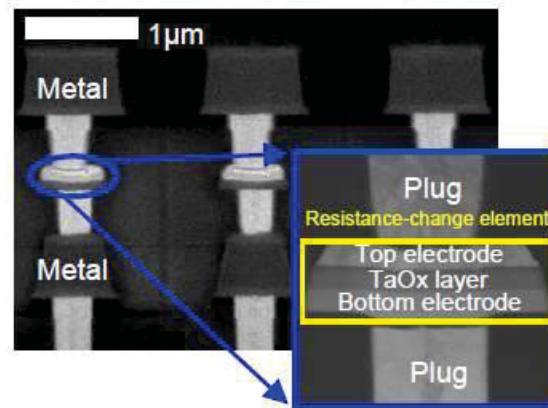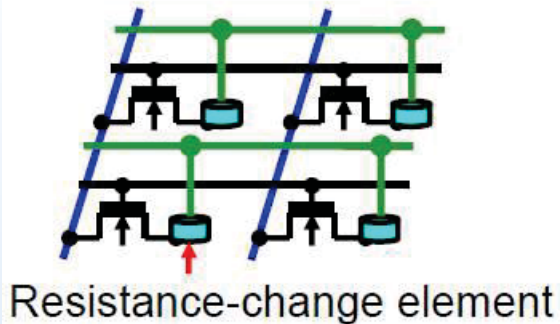
H. J. Barnaby, S. Malley, M. Land, S. Charnicki, A. Kathuria, B. Wilkens, E. DeIonno, and W. Tong, "Impact of alpha particles on the electrical characteristics of TiO$_2$ memristors," *IEEE Trans. Nucl. Sci.*, vol. 58, pp. 2838–2844, Dec. 2011.

J. S. Bi, Z. S. Han, E. X. Zhang, M. W. McCurdy, R. A. Reed, R. D. Schrimpf, D. M. Fleetwood, M. L. Alles, R. A. Weller, D. Linten, M. Jurczak, and A. Fantini, "The Impact of X-Ray and Proton Irradiation on HfO2/Hf-Based Bipolar Resistive Memories," *IEEE Trans. Nucl. Sci.*, vol. 60, pp. 4540 – 4546, Dec. 2013.

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# Panasonic Embedded ReRAM

## 1T1R-ReRAM Memory Cell



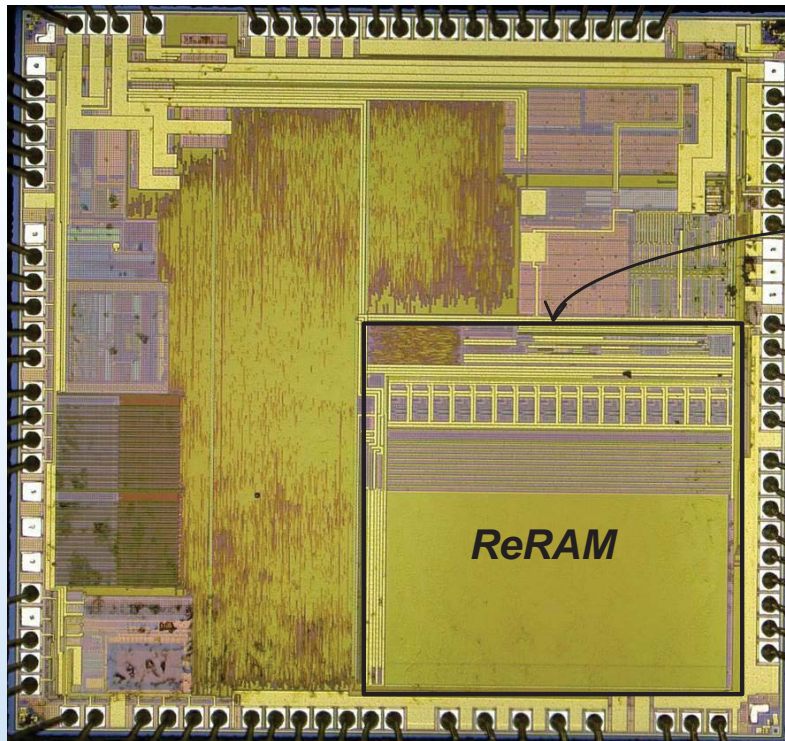Resistance-change element

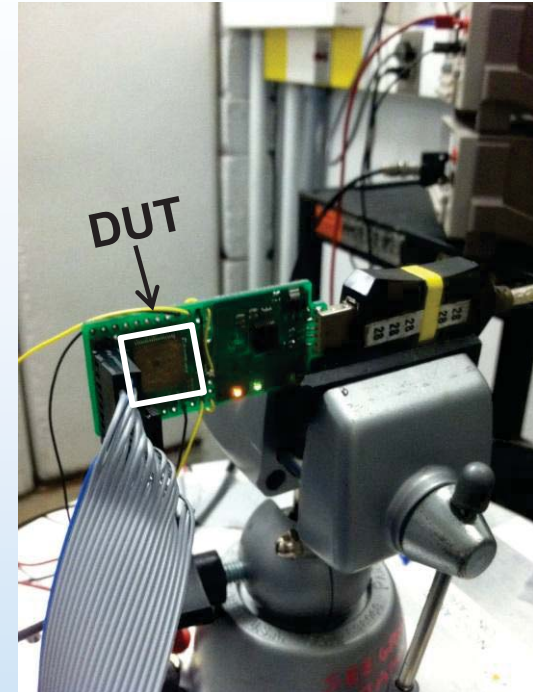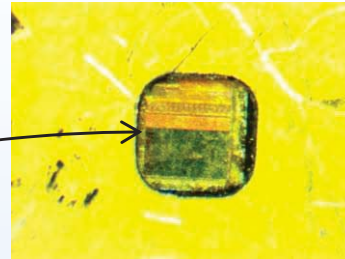| Function | Description |
|---|---|
| Memory Size | 64 KB |
| Program Endurance | Program area (62 KB): $\geq 10^3$ <br> Data area (2 KB): $\geq 10^5$ |
| Programming Voltage | 1.8 to 3.6 V |
| Reading Voltage | 1.1 to 3.6 V |
| Data Retention | 10 years |

http://www.semicon.panasonic.co.jp/en/products/microcomputers/mn101l

- **Panasonic MN101L**
  - 16 bit microcontroller with embedded ReRAM
  - Industry's first mass production-level ReRAM

- **1T1R array architecture, with CMOS transistor as access transistor to each ReRAM stack**

- **TaO$_x$ as switching layer**

- **Minimum device width ~ 0.5 µm**

- **Fabricated back-end-of-line in a 180 nm CMOS process**

ReRAM – Reduction-Oxidation Random Access Memory
1T1R – 1 transistor 1 resistor

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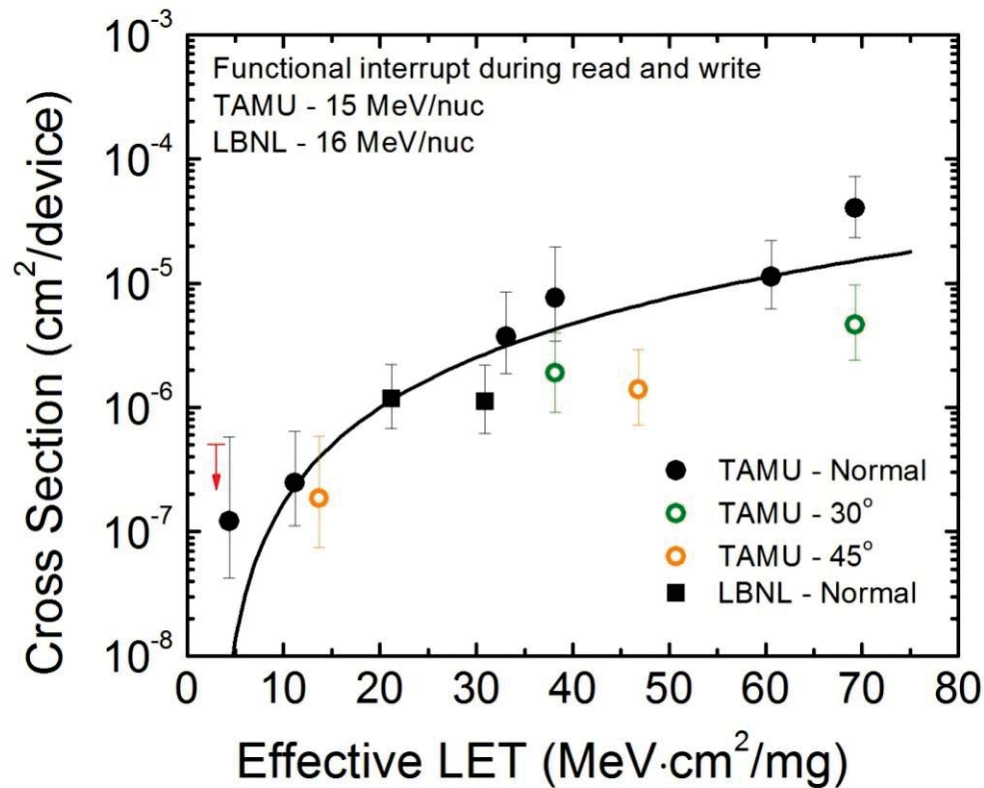
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# Heavy Ion Testing



*Microphotograph courtesy of JPL*

- **Kovar lid collimator (254 μm) exposed ReRAM array and peripheral control circuits**
- **Used Panasonic's evaluation card as test vehicle**
- **ROM operating conditions: $V_{cc}$ = 3.3 V, Frequency = 8 MHz or DC**
- **Test modes: static, dynamic read, read/compare/write, and write**
- **Data patterns: 00, FF, 55, and AA**
- **15 MeV/amu heavy ions in air at Texas A&M University**
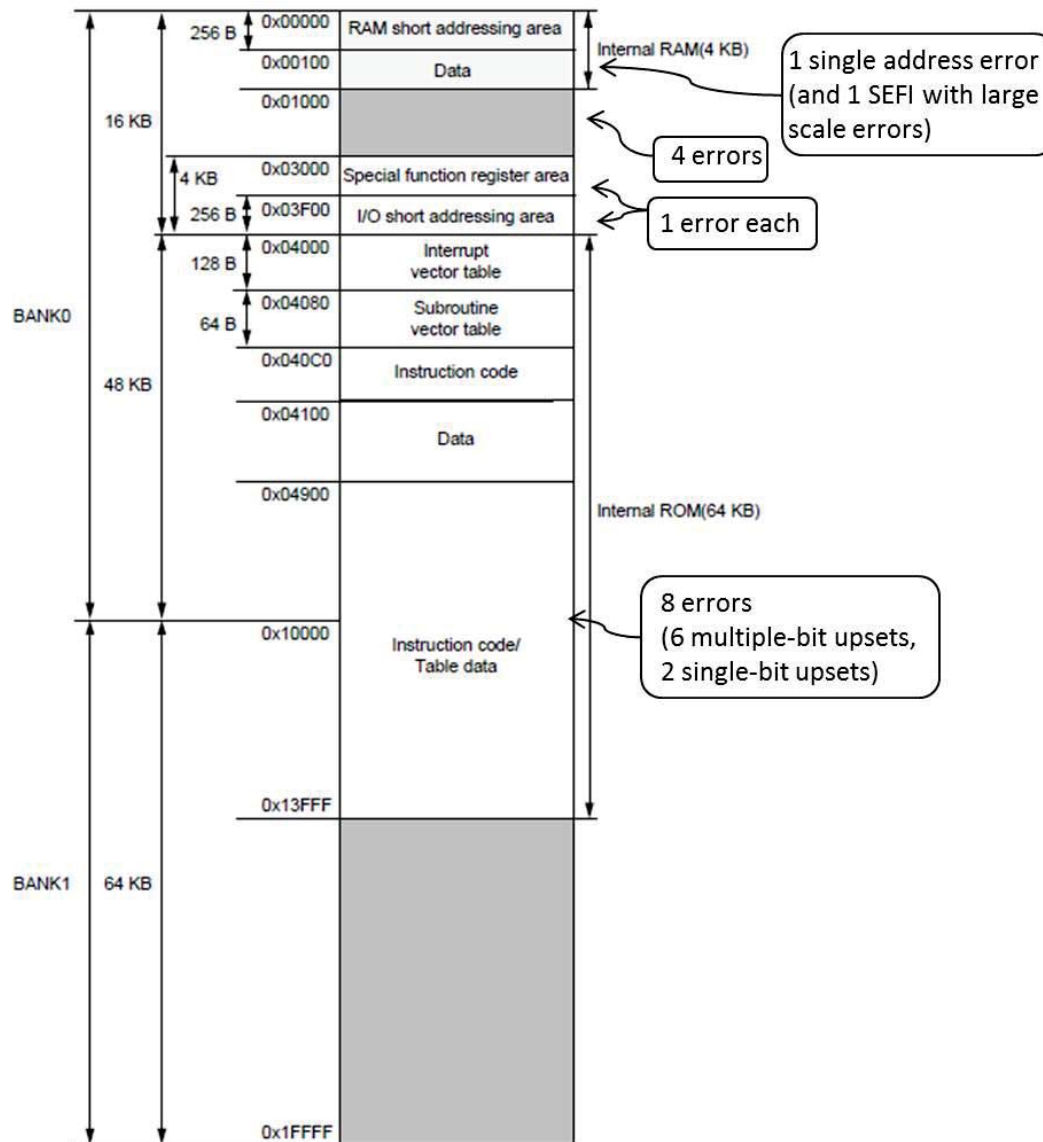- **16 MeV/amu heavy ions in vacuum at Lawrence Berkeley National Laboratory**

ROM – Read-Only Memory

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# Heavy Ion Test Results



Functional interrupt during read and write
TAMU - 15 MeV/nuc
LBNL - 16 MeV/nuc

Legend:
- TAMU - Normal (●)
- TAMU - 30° (○ green)
- TAMU - 45° (○ orange)
- LBNL - Normal (■)

X-axis: Effective LET (MeV·cm²/mg)
Y-axis: Cross Section (cm²/device)

- **No SEU from static test**
  - 1 functional error following Xe irradiation, during read-back, recovered by a reset
- **Dynamic read and write produced mostly SEFIs**
  - 1 locked mode event
- **Similar SEFI cross sections for read and write test mode**
- **Angular irradiation**
  - Beam shadowing from the collimator likely contributed to reduced cross section

SEU – Single-Event Upset
SEFI – Single-Event Functional Interrupt

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# SEE Characteristics



256 B 0x00000 RAM short addressing area
0x00100 Data
Internal RAM(4 KB)
16 KB 0x01000
1 single address error (and 1 SEFI with large scale errors)
4 errors
4 KB 0x03000 Special function register area
256 B 0x03F00 I/O short addressing area
1 error each
0x04000 Interrupt vector table
128 B
0x04080 Subroutine vector table
64 B
0x040C0 Instruction code
0x04100 Data
48 KB
0x04900
Internal ROM(64 KB)
BANK0
8 errors (6 multiple-bit upsets, 2 single-bit upsets)
0x10000 Instruction code/ Table data
0x13FFF
BANK1 64 KB
0x1FFFF

http://www.semicon.panasonic.co.jp/en/products/microcomputers/mn101l

- **Functional interrupts**
  - **Microcontroller stops reading/writing**
  - **Flash vulnerable to large scale page and block errors**
- **Bit upsets**
  - **Include single-bit and multiple-bit upsets**
  - **Error address locations distributed throughout the microcontroller memory bank**
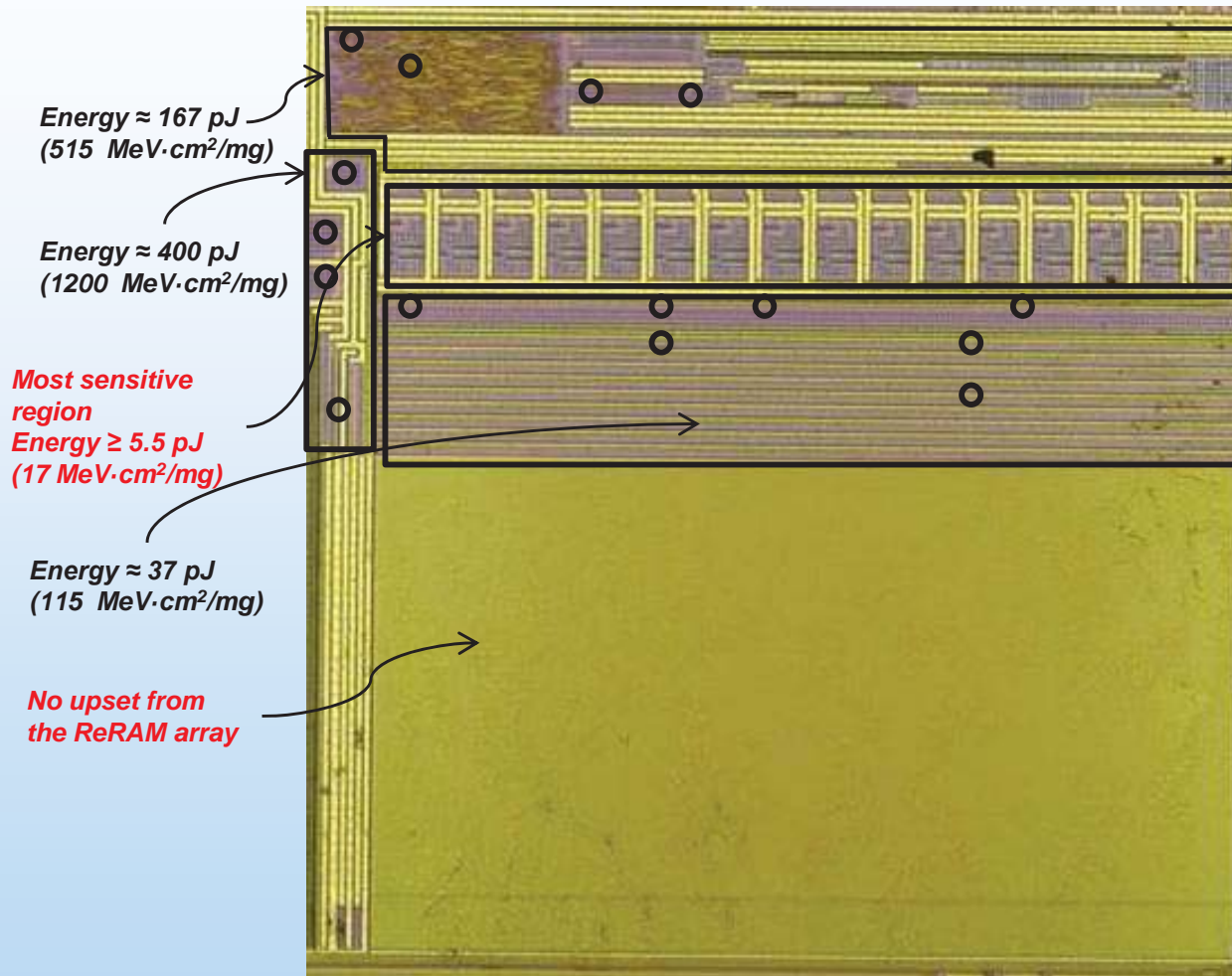  - **8 SEUs in the ROM**

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# Pulsed-Laser Testing

- **Pulsed-laser testing was carried out at the Naval Research Laboratory**

- **Laser characteristics**
  - **Wavelength = 590 nm**
  - **1/e penetration range = 2 μm in silicon**
  - **Beam diameter = 1.7 μm for 20× lens, 0.9 μm for 100× lens**

- **We probed the ReRAM array and surrounding peripheral circuits with a 20× lens to identify the sensitive regions**

- **Sensitive areas were further investigated with a 100× lens, and the energy was fine-tuned to determine the upset energy threshold**

- **Equivalent LET values are based on empirical data from previous studies on other device types**
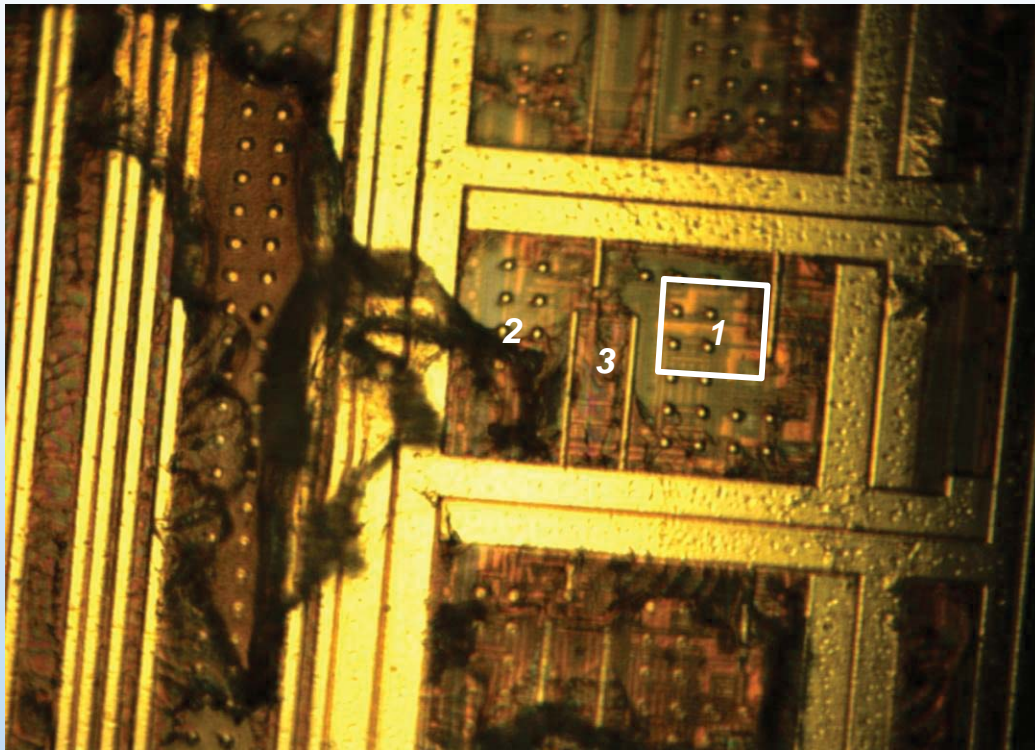
LET – Linear Energy Transfer

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# Sensitive Locations



Energy ≈ 167 pJ
(515 MeV·cm²/mg)

Energy ≈ 400 pJ
(1200 MeV·cm²/mg)

*Most sensitive region*
Energy ≥ 5.5 pJ
(17 MeV·cm²/mg)

Energy ≈ 37 pJ
(115 MeV·cm²/mg)

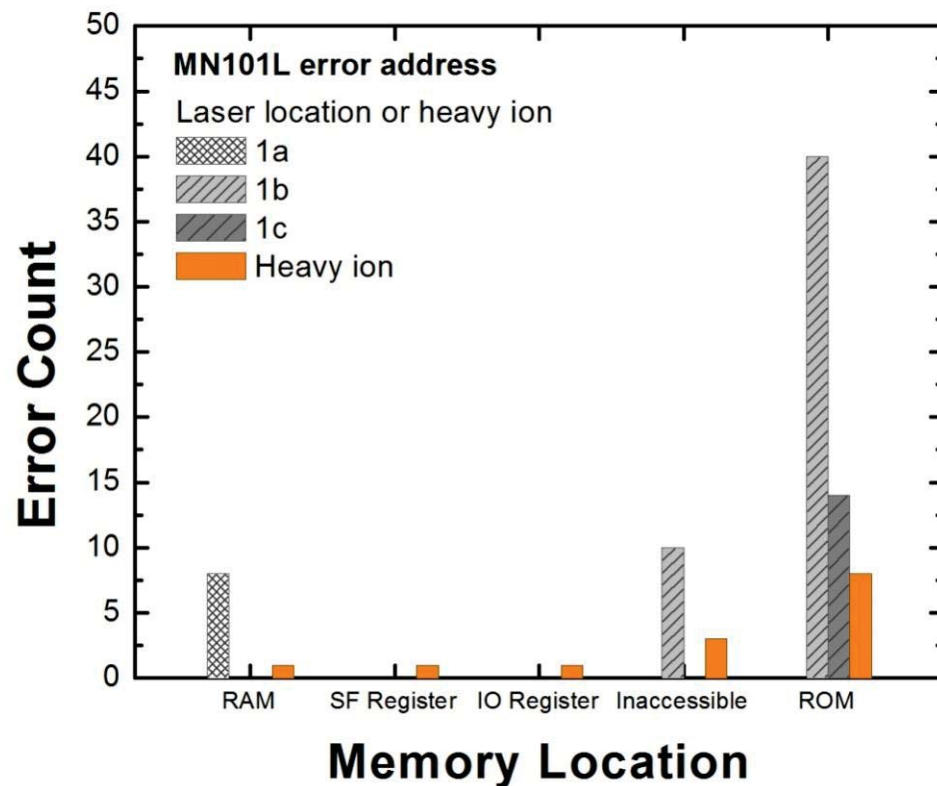*No upset from the ReRAM array*

- **Bit upsets**
  - **Did not originate from the ReRAM array**
  - **Location sensitive to SEUs also susceptible to SEFIs**

- **Functional interrupt**
  - **Stops reading/writing**
  - **Continuously reading out errors from the ROM**
  - **Stuck reading at end of Bank0 (FFFF)**
  - **Continuously reading errors from other address locations beside the ROM**

# Upset Sensitivity in the Most Sensitive Location



- **Determine upset energy threshold at the most sensitive location using 100× lens**

- **Location 1:**
  - Read mode: 5.5 pJ (17 MeV·cm$^2$/mg)
  - Write mode: 8.6 pJ (26.5 MeV·cm$^2$/mg)

- **Location 2:**
  - Read mode: 71 pJ (220 MeV·cm$^2$/mg)

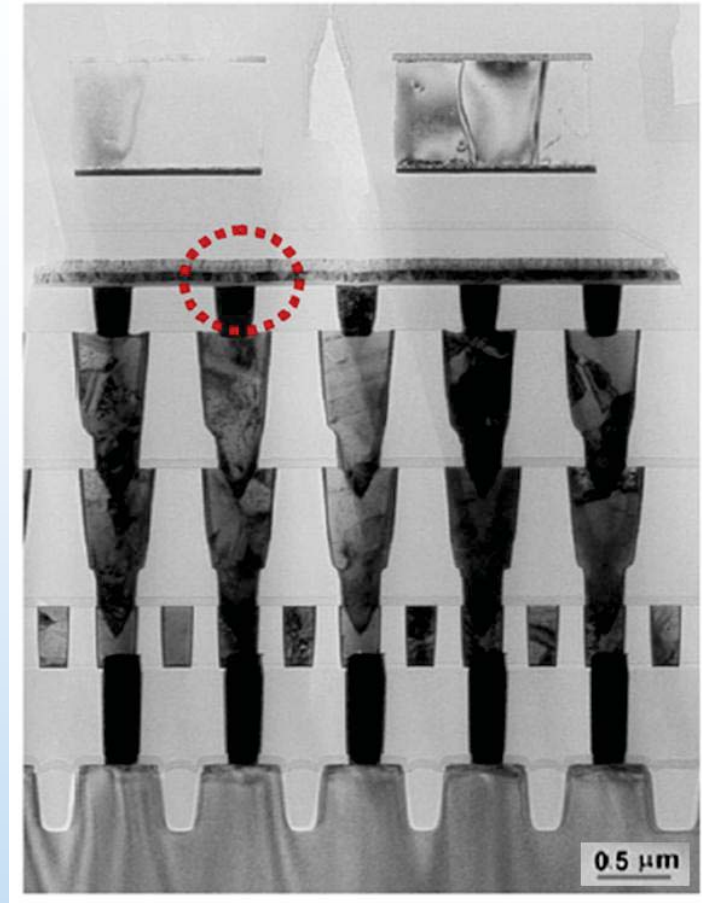- **Location 3:**
  - Read mode: 105 pJ (320 MeV·cm$^2$/mg)

# SEE Characteristics



MN101L error address

Laser location or heavy ion
- 1a
- 1b
- 1c
- Heavy ion

(Chart: Error Count vs. Memory Location: RAM, SF Register, IO Register, Inaccessible, ROM)

SF Register – Special function register
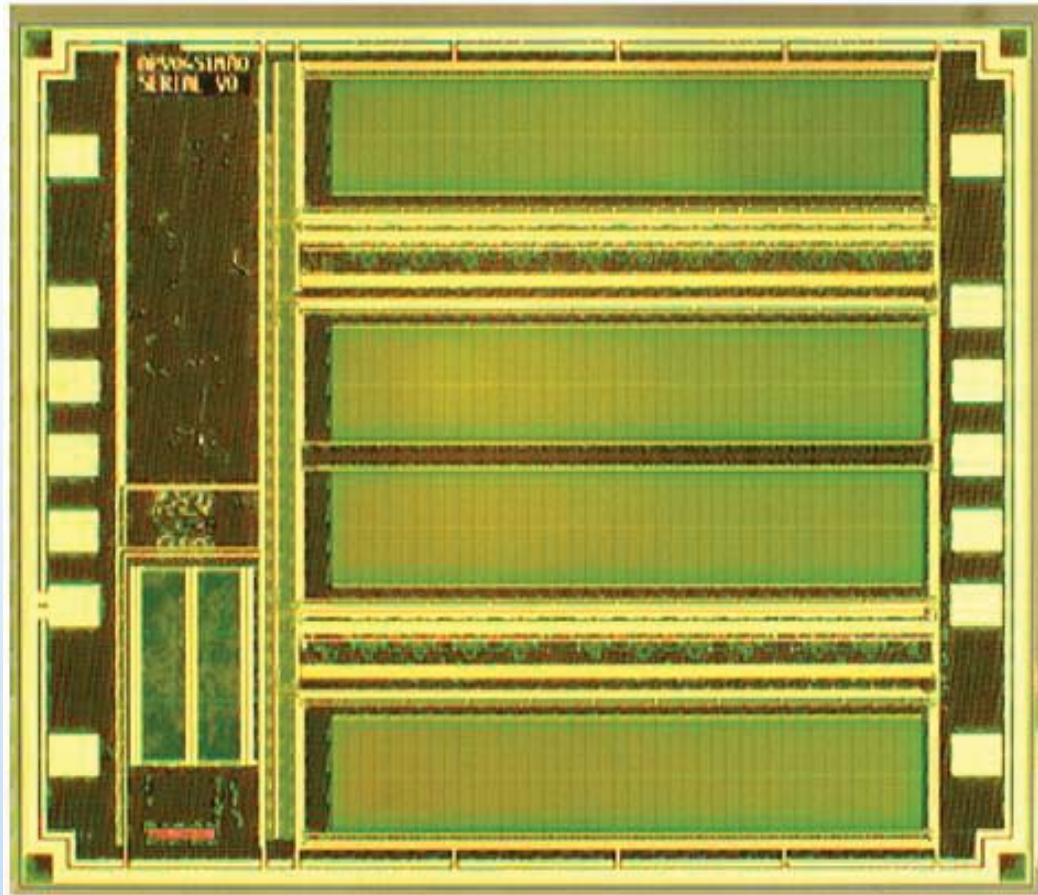IO Register – Input/Output register

- **Compare SEE characteristics with heavy ion results**
- **Memory address of errors from laser test are similar to those from heavy ion test**
- **SEFI modes from laser and heavy ion test are also similar**
  - **Although limited information was gained from SEFIs that caused immediate cease of operation**
- **Sensitive region consists of sense amplifier circuit**
  - **SEU in the sensing circuit of flash devices lead to SEFI\***

\* D. Nguyen and L. Scheick, "SEE and TID of emerging non-volatile memories," in Proc. IEEE Radiation Effects Data Workshop, 2002, pp. 62–66.
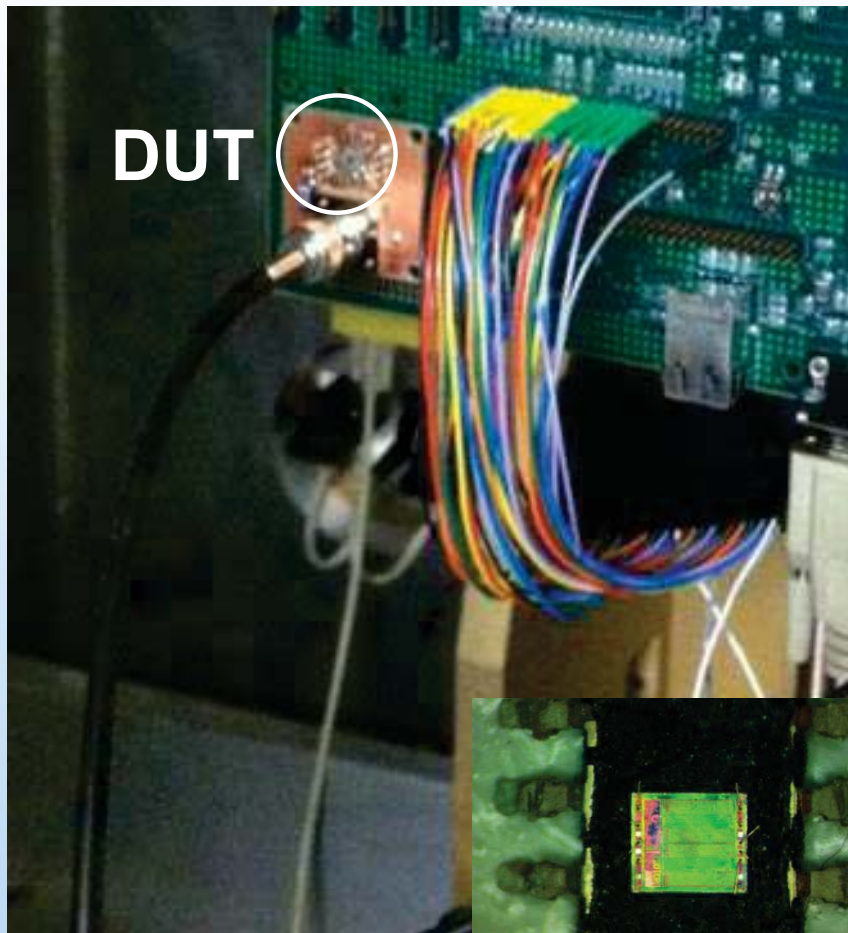
# Adesto CBRAM





- **128 kb EEPROM from Adesto**
- **Ag/GeS2/W conductive bridge memory (CBRAM)**
- **1T1R structure**
- **Back-end-of-line 130 nm CMOS**

EEPROM – Electrically Erasable Programmable Read-Only Memory

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# Adesto CBRAM



DUT

- **Heavy ion test carried out at LBNL in vacuum**
- **8-pin SOIC packages were chemically etched to expose die**
- **16 MeV/nuc cocktail**
- **Test conditions:**
  - **NASA's LCDT tester**
  - **Vcc = 3.3 V**
  - **Frequency = 1 kHz or DC**
  - **Mode: static random read, static sequential read, continuous random read, write all/random read, write all/sequential read**
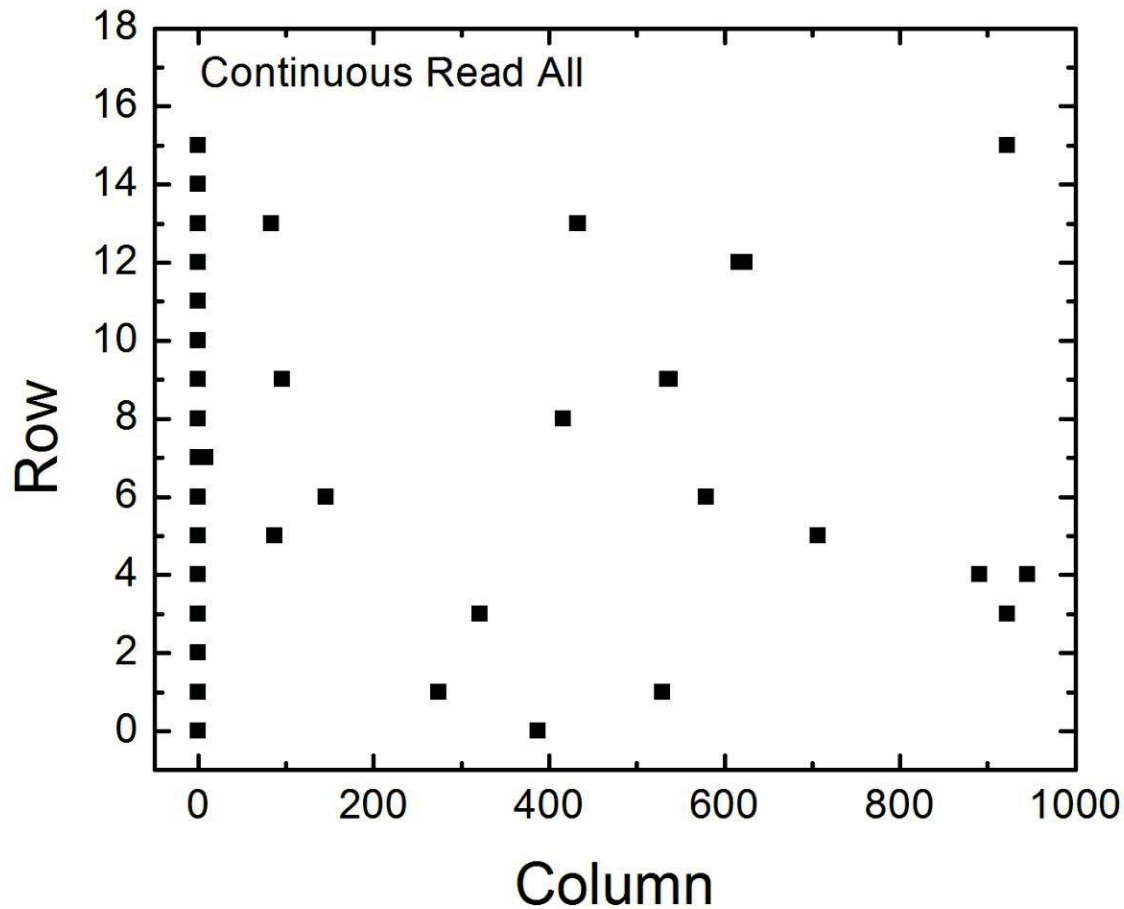  - **Patterns: 00, FF, AA, and counter**

LBNL – Lawrence Berkeley National Laboratory
SOIC – Small Outline Integrated Circuit
LCDT – Low Cost Digital Tester

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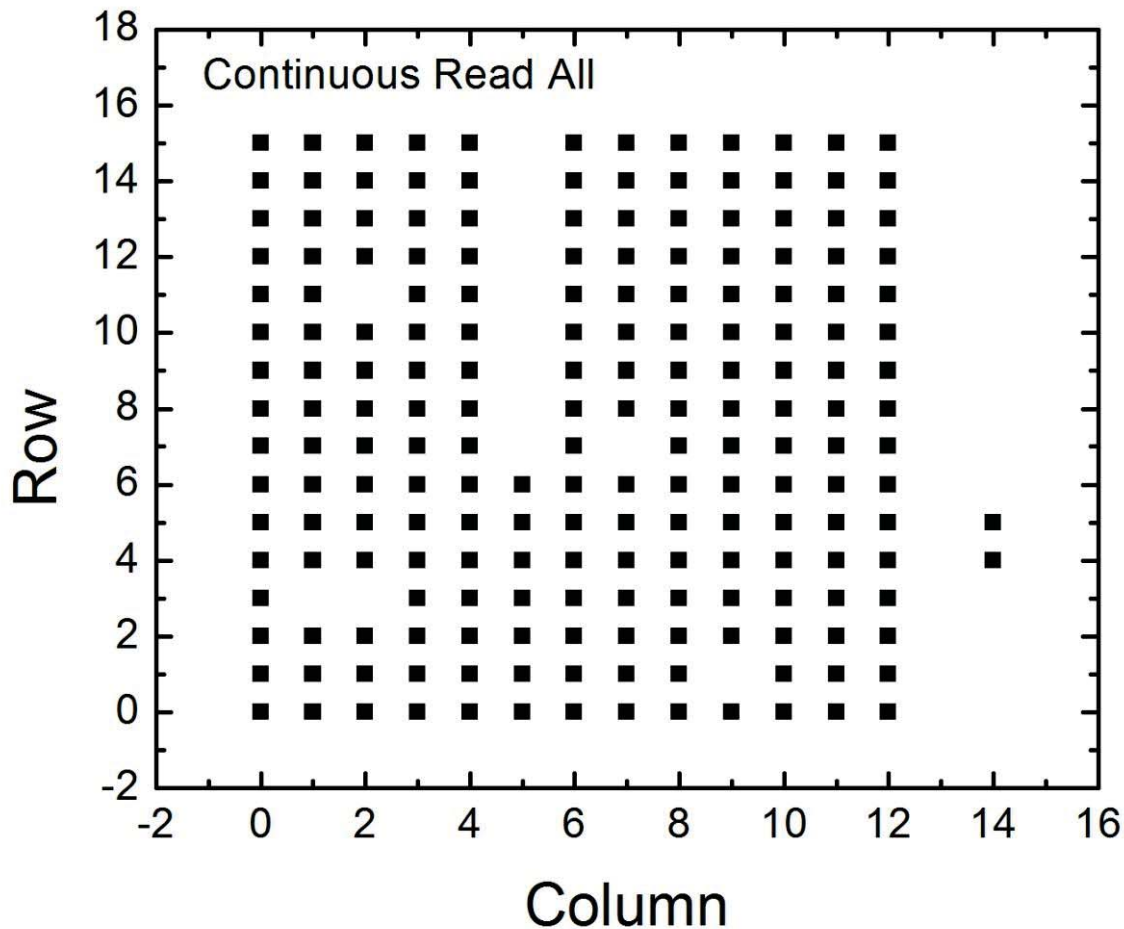
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# SEE Characteristics

- **Static "On" and dynamic test modes produced mostly SEFIs**

- **Most (if not all) bit upsets due to acknowledgement fails, indicative of control circuit errors and not array errors**

- **SEFI modes**
  - Stuck address, accumulating acknowledgement failures
    - Occurred during read and write/read test modes
    - Reset usually required
  - Read errors in continuous addresses
    - Column, page, or entire memory read out 00FF
    - Errors may clear by itself, or reset required

- **No Apparent pattern sensitivity for FF, 00, AA, and Counter**
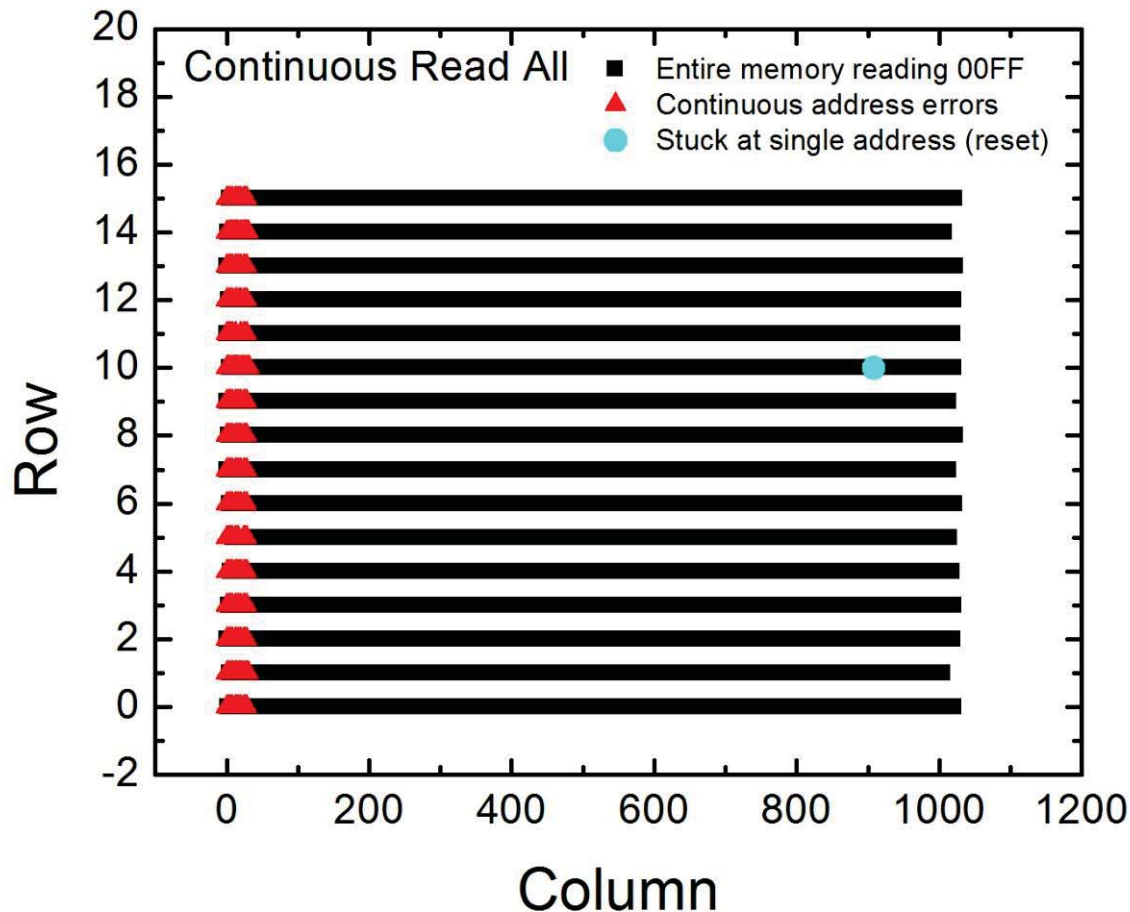
# SEE Characteristics



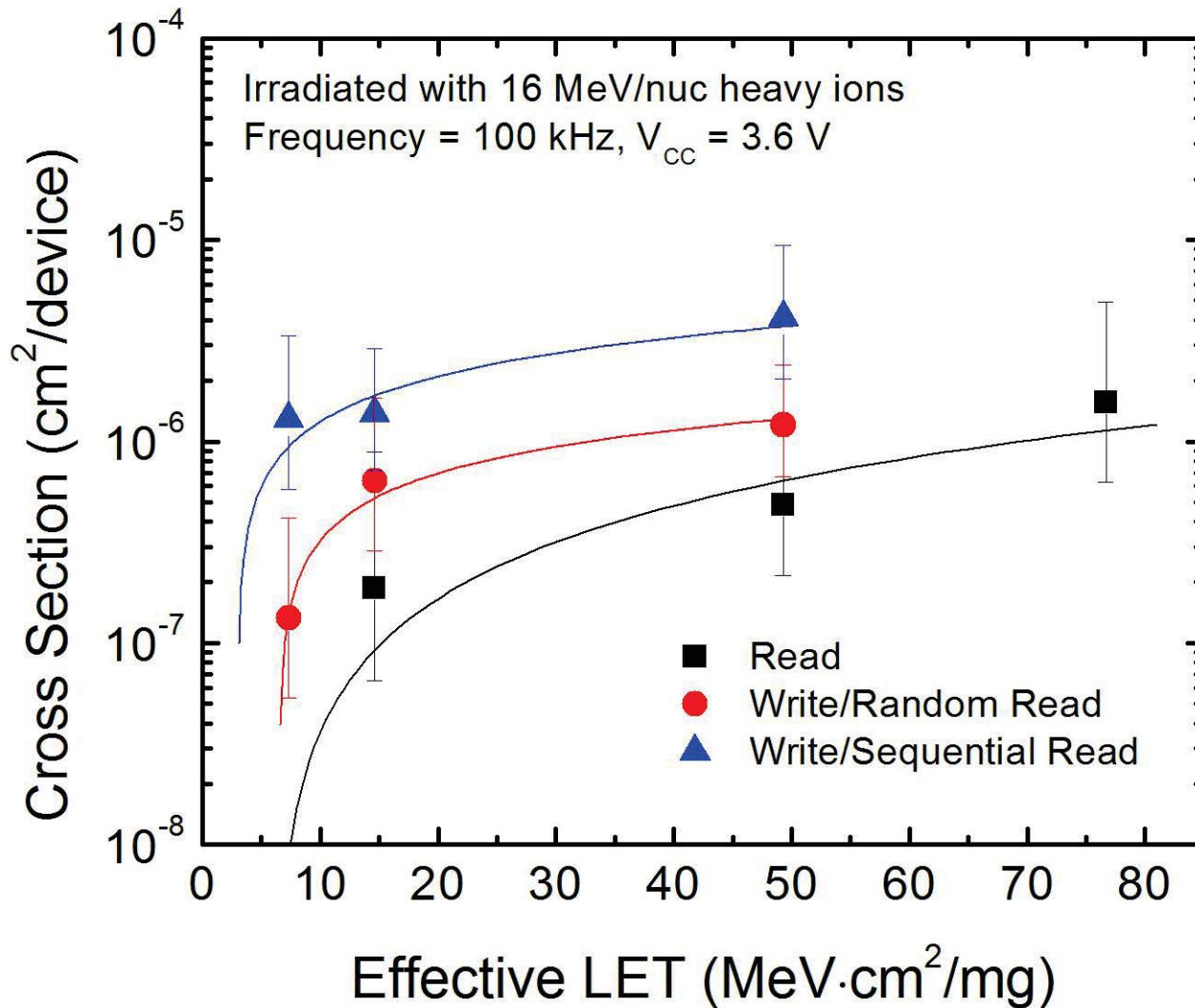- **Column errors (0000 to 000F) during read; memory still functional**

# SEE Characteristics



- **Column errors (0000 to 00CF) during read; memory still functional**

# SEE Characteristics



- **Entire memory reading 00FF during read**
- **Column errors (0000 to 00CF) during read**
- **Stuck at single address; reset required**

# SEE Characteristics

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# Conclusion

- **RRAM array immune to heavy ions with LET as high as 75 MeV·cm$^2$/mg**

    – **SEU in CMOS access transistor not enough to cause bit flip**

- **SEFI is the dominant error mode**

    – **Panasonic MN101L embedded ReRAM's SEFIs originate from sense amplifier circuits**

    – **Adesto CBRAM showed column/page errors, mass read errors from entire memory, and stuck address errors**

- **Lack of charge pump reduces sensitivity to erase or program failure**

    – **Eliminates block erase failures (issue for flash)**