National Institute of Standards and Technology
U.S. Department of Commerce

Influence of Total Ionizing Dose (TID) on Magnetic Tunnel Junctions for Rad-Hard Memory

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Jet Propulsion Laboratory — California Institute of Technology

Everspin Technologies®

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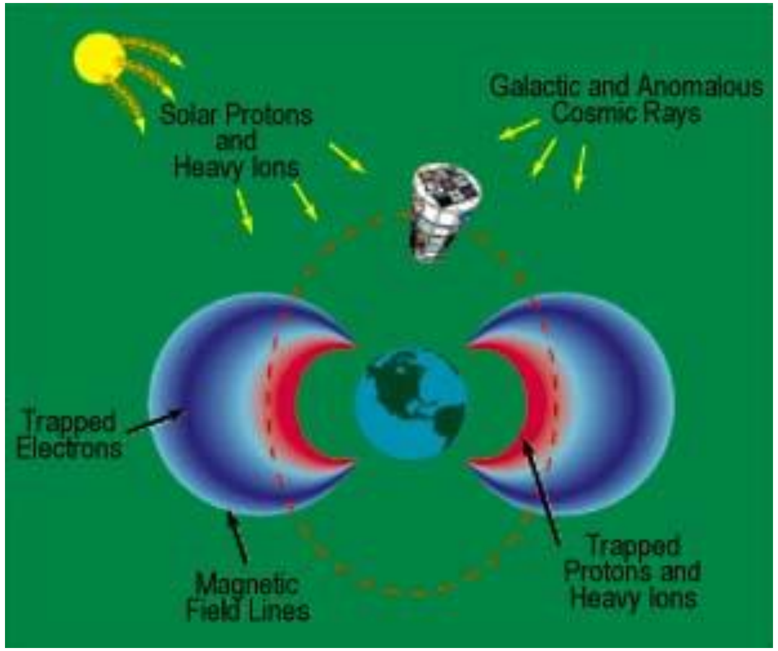
Outline

- Sources and influence of ionizing radiation.
- Mitigation techniques.
- Non-volatile memory for radiation-hard memory
- Current progress of MRAM based rad-hard memory.

Types of Ionizing radiation

Total Ionizing Dose (TID)

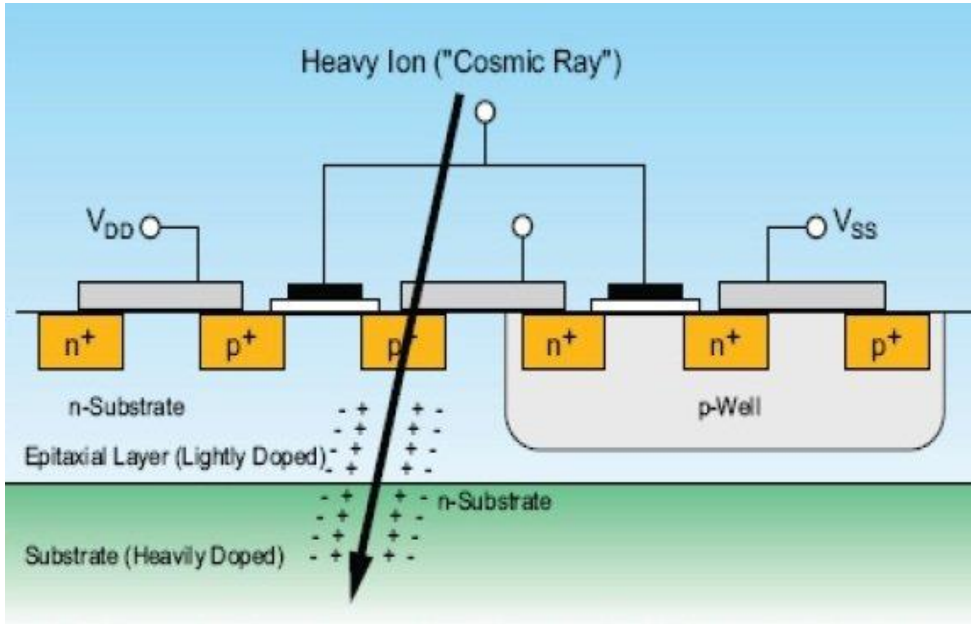
- Cumulative effects of ionizing radiation.
- Will focus on in this presentation.



http://holbert.faculty.asu.edu/eee560/tiondose.html

Single Event Effects (SEE)

- High energy particles (heavy ions, large nucleus, etc.).



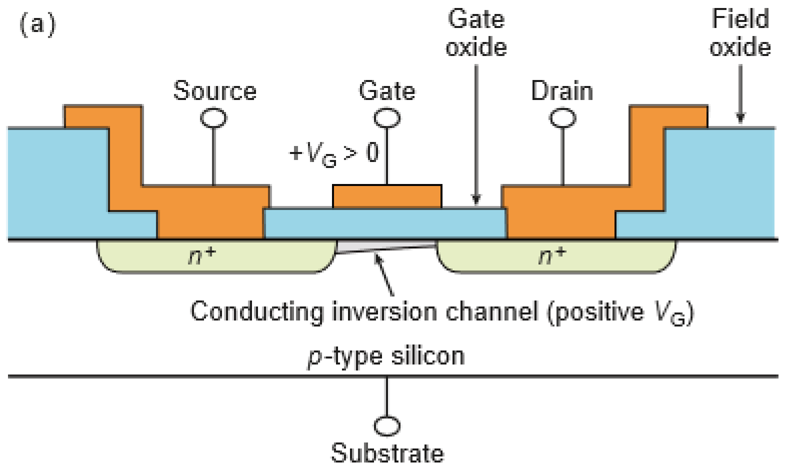
https://www.esa.int/spaceinimages/Images/2012/12/Radiation-driven_Single_Event_Effect

Effects of TID on MOSFETs

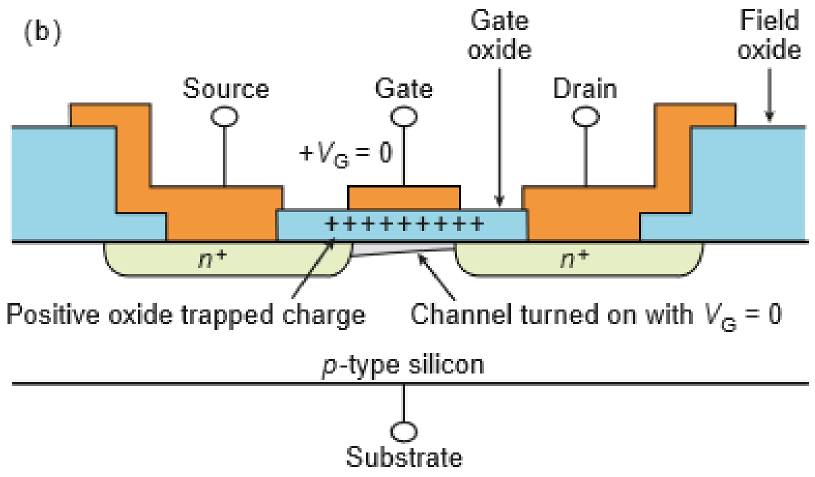
Effects of TID on MOSFETs

- Generates electron-hole pairs inside gate oxide or dangling bonds at oxide/gate interface.
  - ➢ Two effects compete → V_{TH} shifts randomly
- Worst case → Cannot turn off due to high leakage current (I_{LEAK})
  - ➢ I_{LEAK} can increase by 1 order of magnitude.

Before ionizing radiation exposure



After ionizing radiation exposure

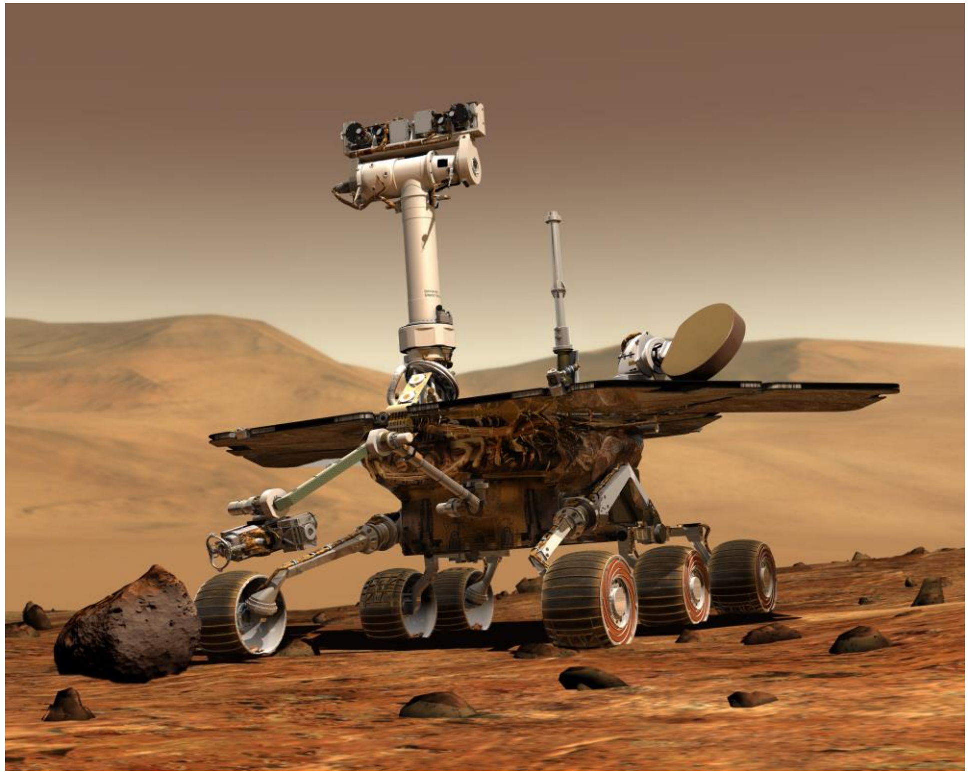


R. H. Maurer et al, *Johns Hopkins APL Technical Digest*, vol. 28, no. 1, pp. 17 – 29, Jan. 2008.

Effects of Ionizing radiation on CMOS

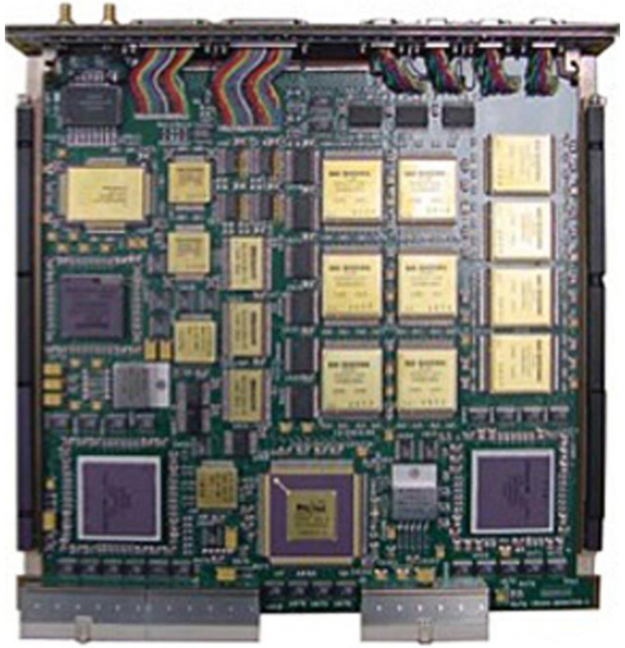
Computers for space exploration require radiation hardened designs

Opportunity Mars Rover (2004 – 2018)



https://en.wikipedia.org/wiki/Opportunity_%28rover%29

RAD6000 computer (BAE Systems)



Comparison to conventional computers.

- <10X slower.
- <8X lower cell density.
- Require rigorous design work and testing.
- $200,000 - $500,000

https://www.cnet.com/science/slow-but-rugged-curiositys-computer-was-built-for-mars/

- In 2011, experienced data loss due to radiation damage.

Mitigation techniques

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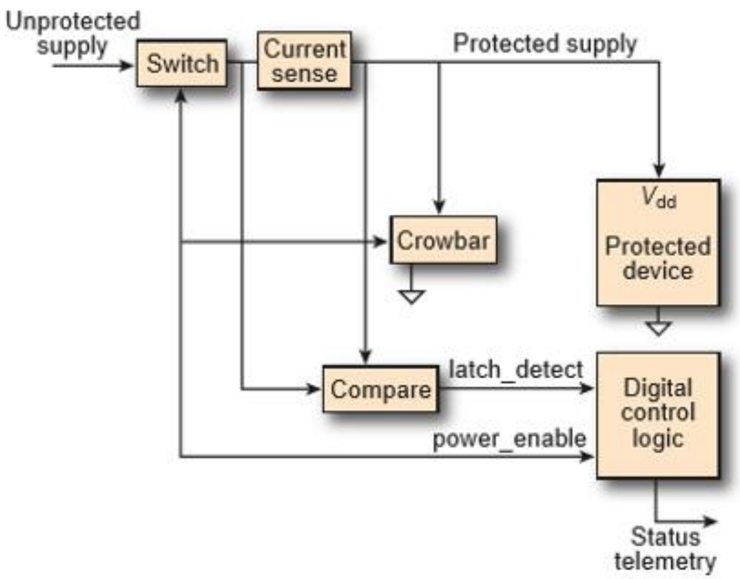
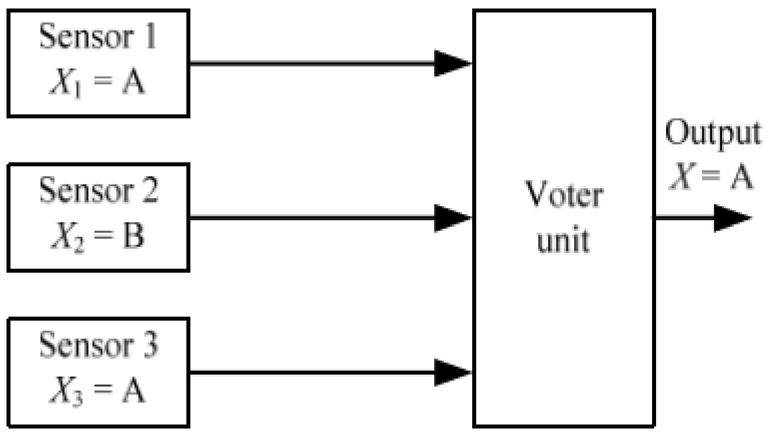
1. Implement latch-up protection circuits (left figure)
2. Use triple voting redundancy (right figure)
3. Physical shielding
   - ➤ These mitigation techniques have significant area and latency costs.



R. H. Maurer et al, *Johns Hopkins APL Technical Digest*, vol. 28, no. 1, pp. 17 – 29, Jan. 2008.



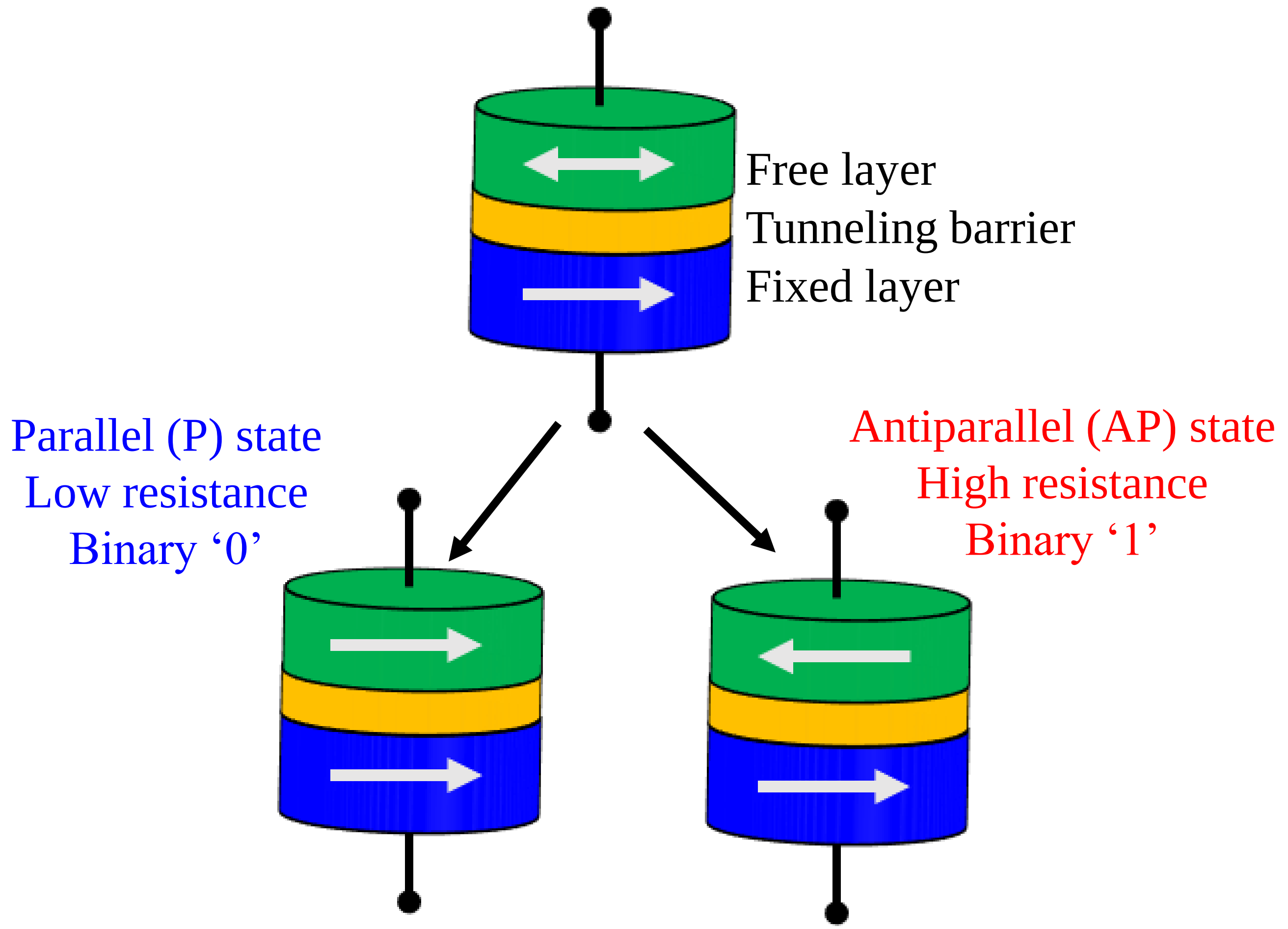
V. Danecek and P. Silhavy, *Int. Conf. Telecommunications and Signal Processing*, Bedafest, Hungary, Oct. 2011. pp. 472 – 477.

➤ **<u>Preferred method</u>: Replace CMOS with a more intrinsically rad-hard solution.**

Magnetic random-access memory (MRAM)

MRAM is a promising alternative to CMOS for rad-hard memory applications.

- **Elementary component of MRAM is the magnetic tunnel junction (MTJ).**



<u>Advantages of MRAM</u>

- High speed (~100ps – 1ns switching times).
- High endurance (~10^{16} switching cycles).
- High tolerance for ionizing radiation.
  - Can tolerate doses 100X larger than CMOS.
  - Already used in aerospace field (ExoMars in 2016).
- Capable of on-board information processing.
  - No need for ground-based processing.

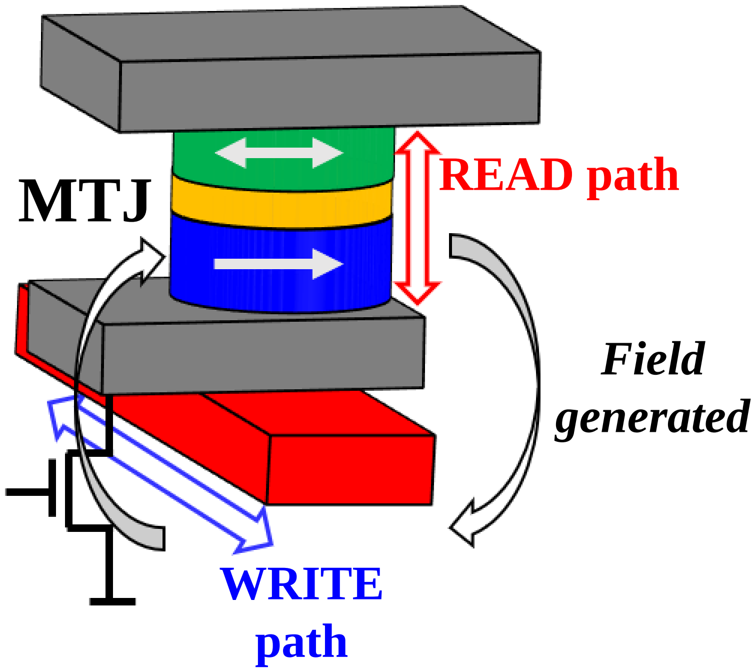
MRAM switching mechanisms

NIST

Toggle MRAM

First commercial product in 2005.

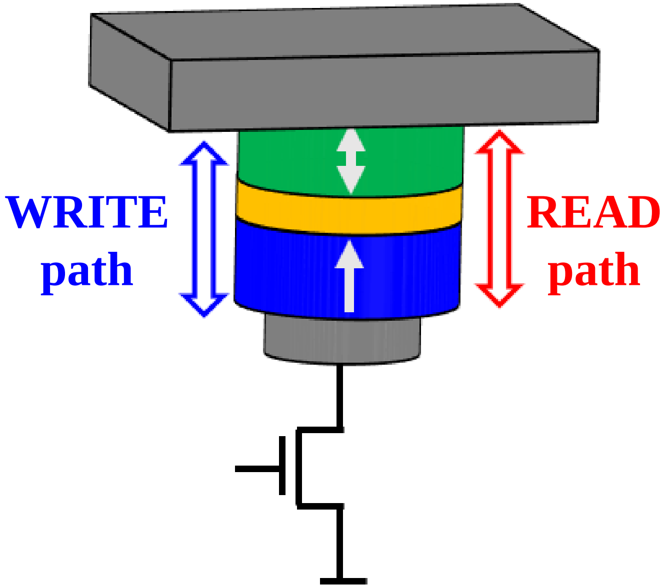
Limited cell density and high power consumption.



STT-MRAM

Commercial products available for rad-hard applications.

- Everspin, Samsung, IBM, Avalanche

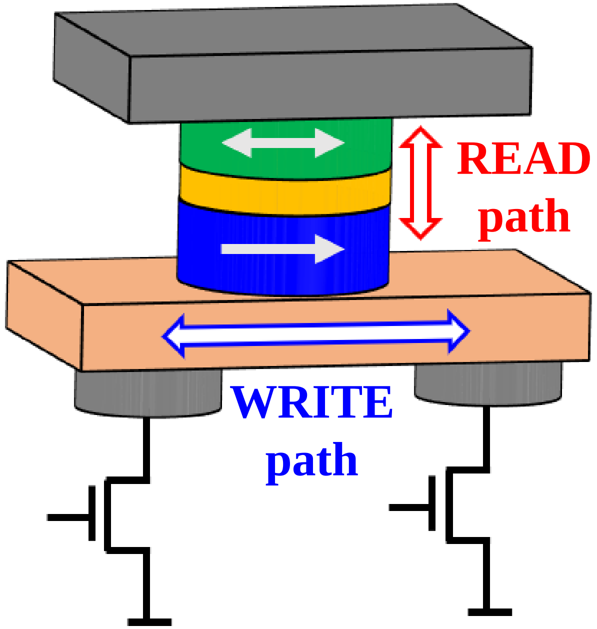


SOT-MRAM

No commercial product available.

Advantages over STT-MRAM

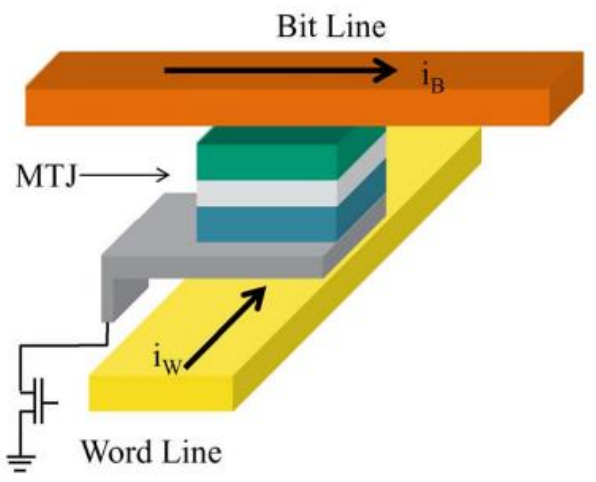
- Faster switching, no barrier breakdown.



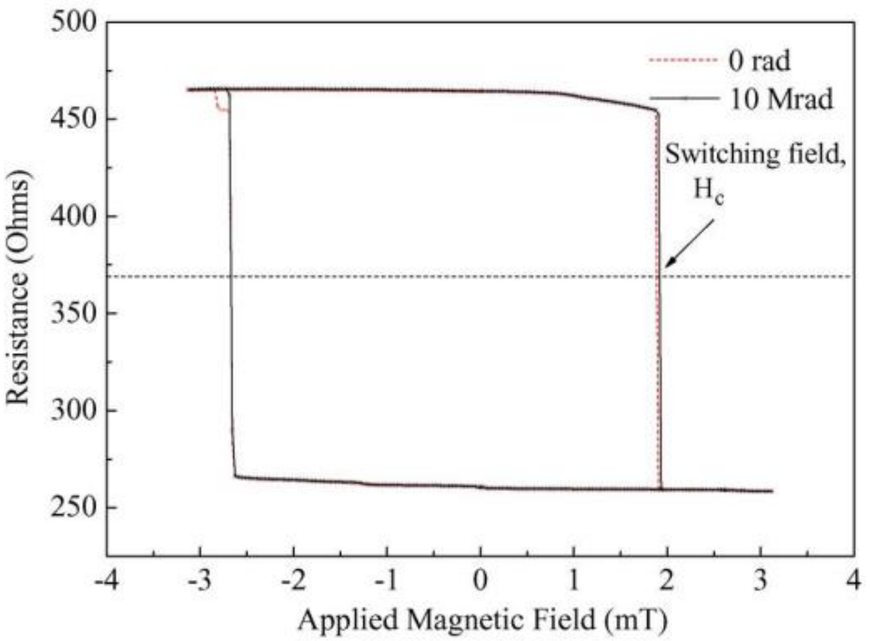
Effects of TID on Toggle MRAM

In 2012, F. Ren et al tested TID resilience of Toggle MRAM.

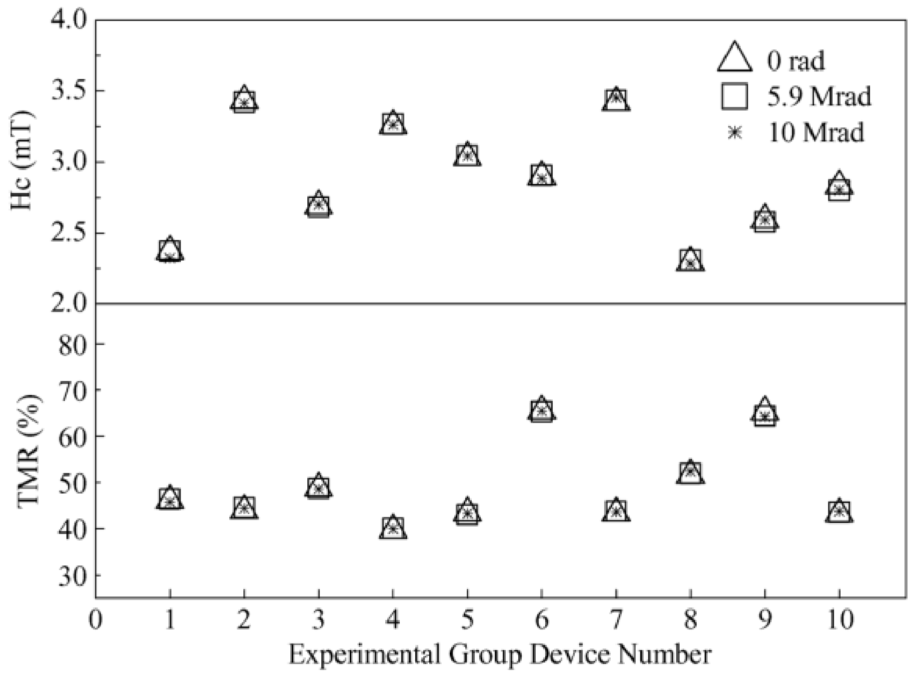
Toggle MRAM Cell



Field switching hysteresis plot



Influence of gamma radiation



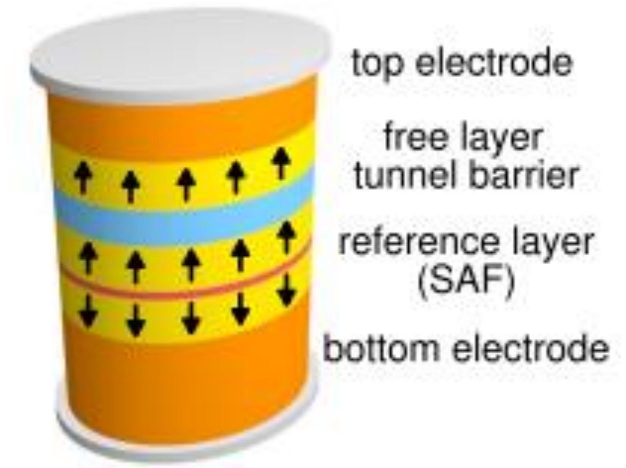
F. Ren *et al*, *IEEE Trans. Nucl. Sci.*, vol. 59, pp. 3034 - 3038 (2012)

- **Gamma radiation had no effect on coercivity (H_C) and TMR, even at doses of 10 Mrad.**
- **CMOS devices fail at doses ~50 krad.**

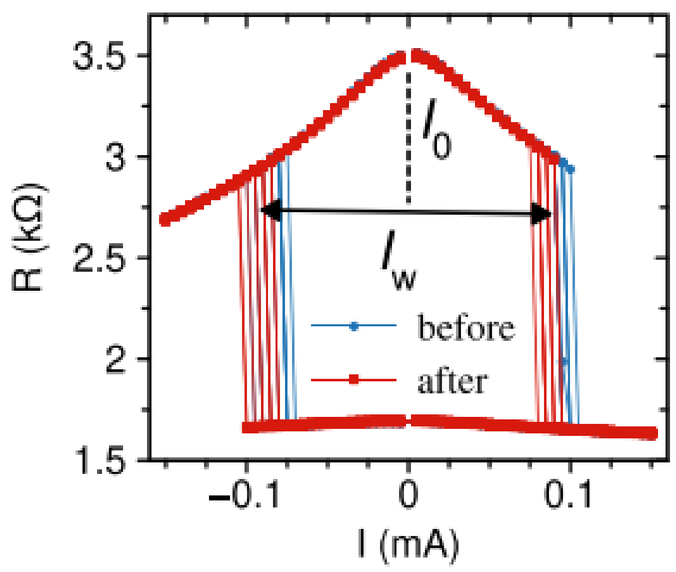
Effects of TID on STT switching

In 2020, E. A. Montoya et al tested the STT switching properties of STT MTJs.

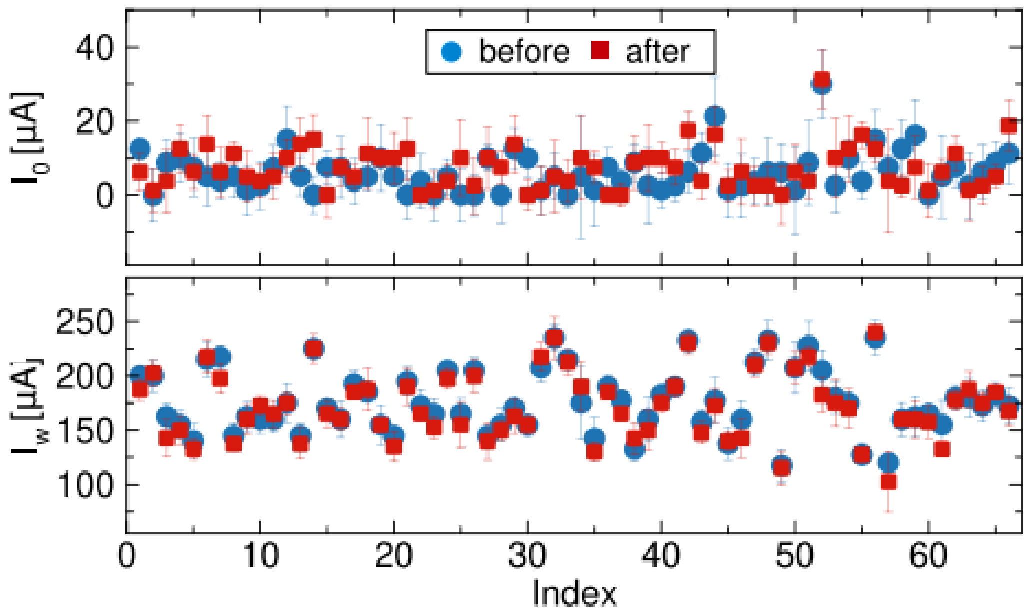
P-MTJ stack



Current switching hysteresis plot



Influence of gamma radiation



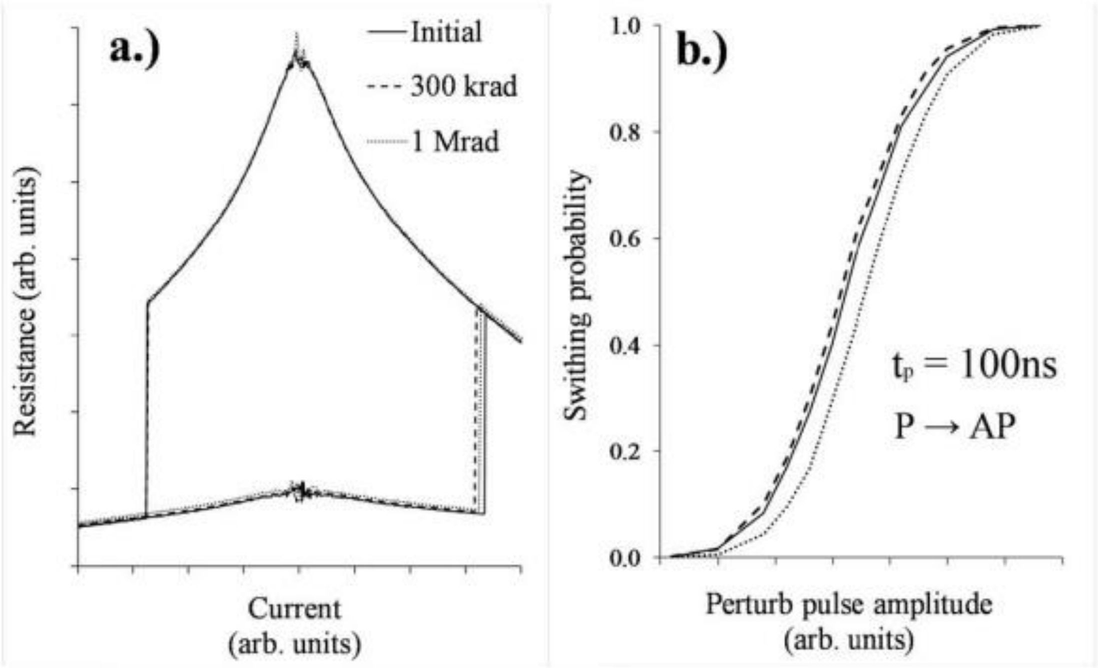
➢ **Showed that gamma radiation (doses up to 15 Mrad) have no influence on the current switching properties of perpendicular MTJs.**

E. A. Montoya *et al*, *Sci. Rep.*, vol. 10, 10220 (2020)

Effects of TID on STT-MRAM

In 2021, we studied effects of TID on switching probability distribution plots.

Switching probability distribution plots



B. R. Zink *et al*, *IEEE Trans. Nucl. Sci.*, vol. 68, pp. 748 – 755 (2021)

Measurements collected

$$\text{Switching probability} = 1 - \exp\left(-\frac{t_P}{\tau}\right)$$

$$\tau = \tau_0 \exp\left(\Delta\left[1 - \frac{V_P}{V_{C0}}\right]\right)$$

$\Delta \rightarrow$ Thermal tability factor

$V_{C0} \rightarrow$ Critical switching voltage

- **Used the switching probability distribution curves to measure changes in thermal stability, critical switching voltage, and write energy.**

Effects of TID on STT-MRAM

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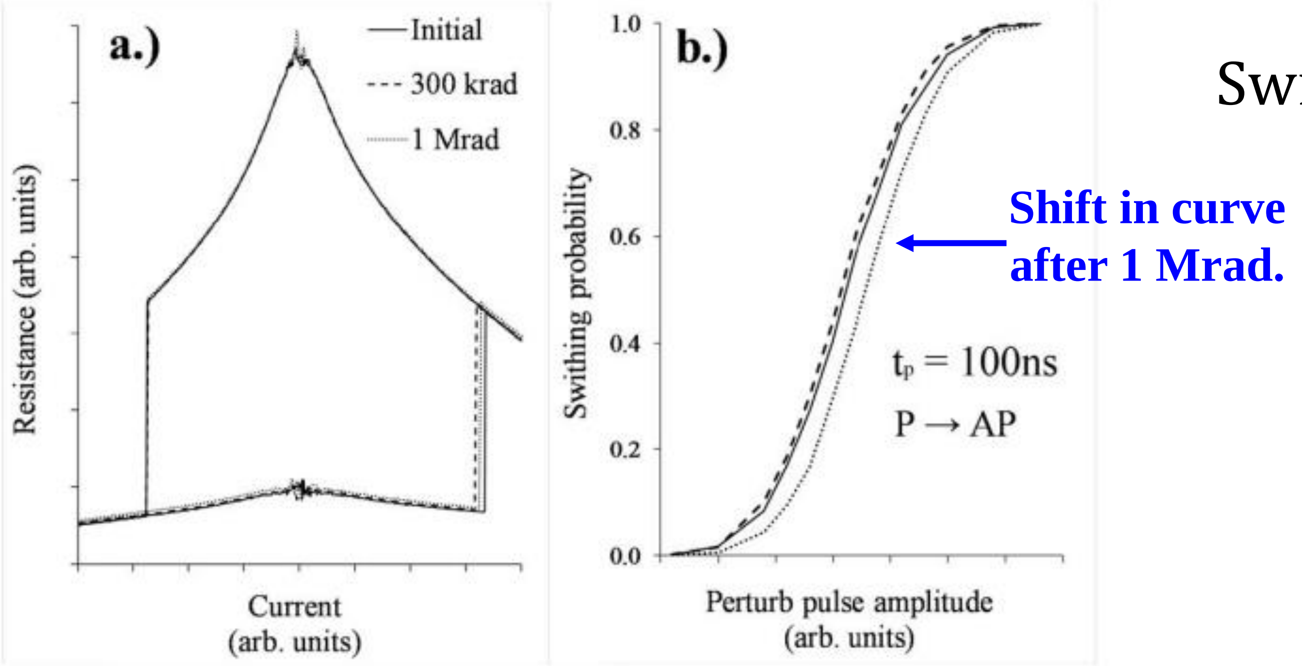
Switching probability distribution plots



B. R. Zink *et al*, *IEEE Trans. Nucl. Sci.*, vol. 68, pp. 748 – 755 (2021)

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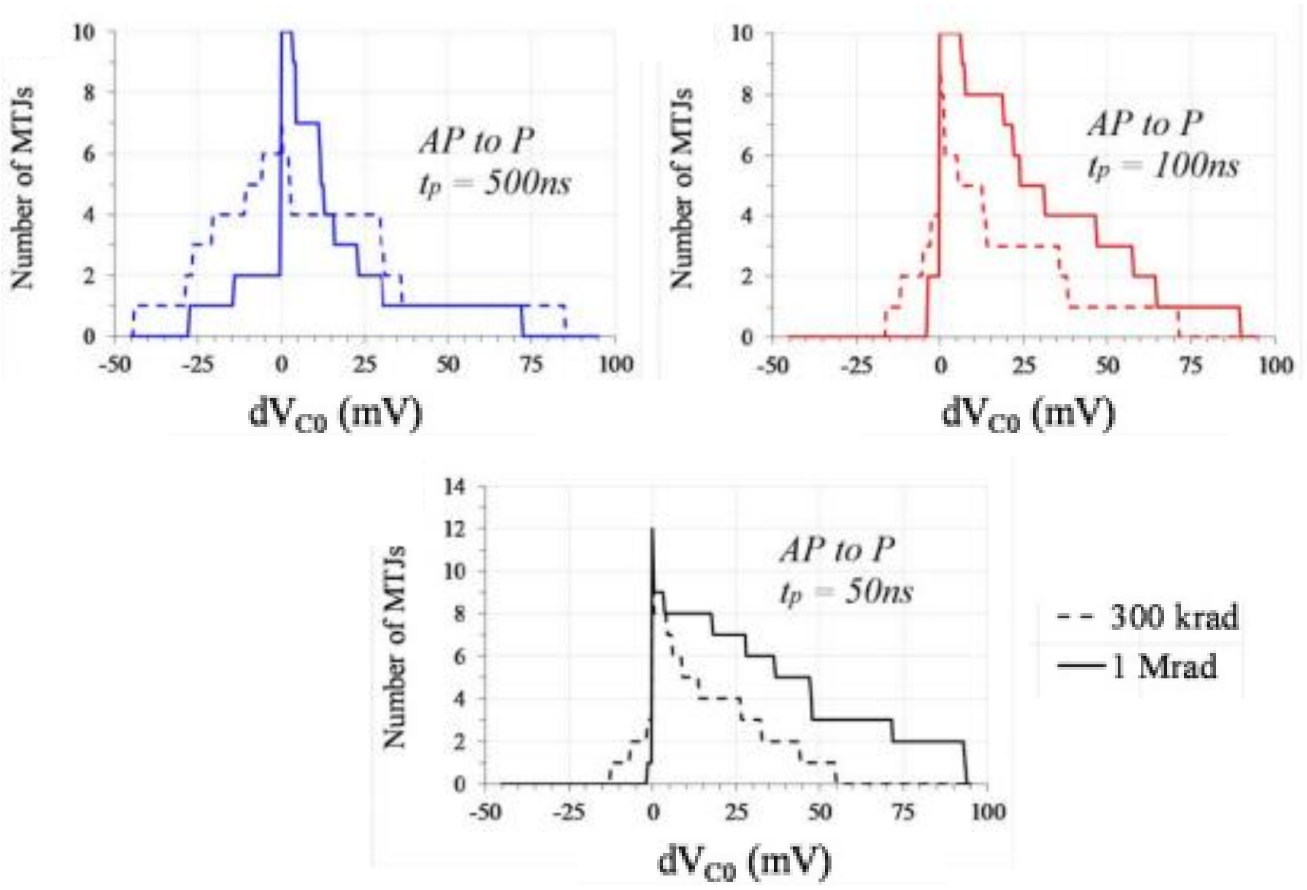
Effects of TID on STT-MRAM

Distribution of changes in switching voltage (V_{C0})



Observations

- Most MTJs tested showed negligible changes.
- Distributions were dependent on pulse width.
- Changes in V_{C0} were more significant with smaller pulse widths.

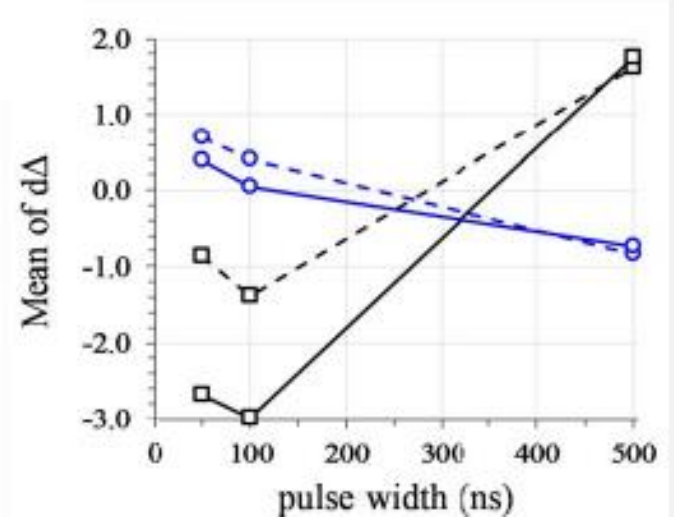
➢ **Center and standard deviation of distributions were obtained for analysis.**

B. R. Zink *et al*, *IEEE Trans. Nucl. Sci.*, vol. 68, pp. 748 – 755 (2021)

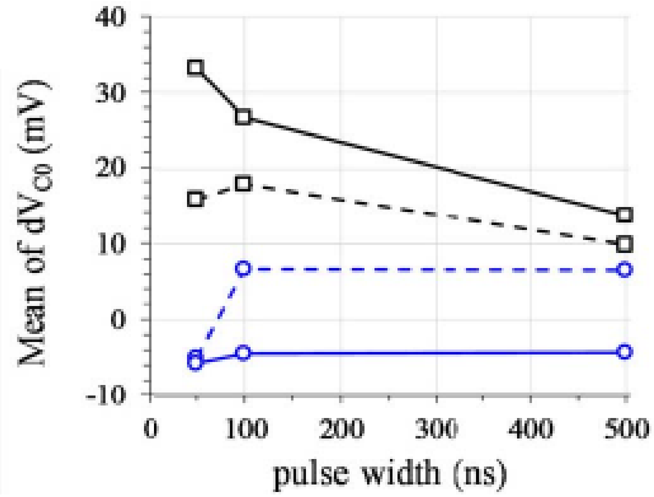
Effects of TID on STT-MRAM

Switching probability distribution plots revealed slight changes in thermal stability and write energy.

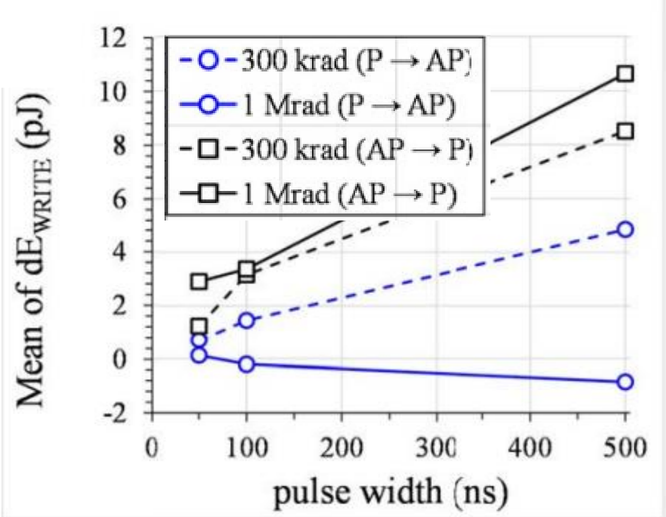
Thermal stability (Δ)



Critical switching voltage (V_{C0})



Write Energy (E_{WRITE})



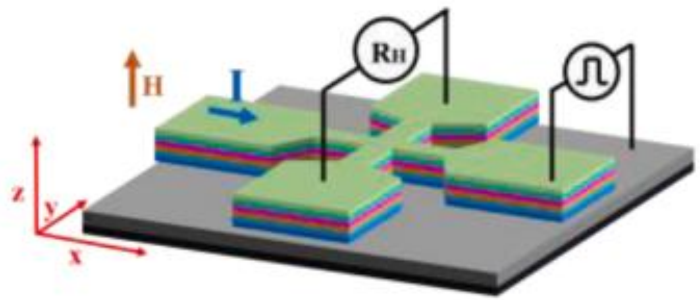
- ➢ **These slight changes varied with pulse width → Change in voltage controlled magnetic anisotropy (VCMA)?**
- ➢ **Note that these slight changes would not be revealed in deterministic switching measurements.**

B. R. Zink *et al*, *IEEE Trans. Nucl. Sci.*, vol. 68, pp. 748 – 755 (2021)

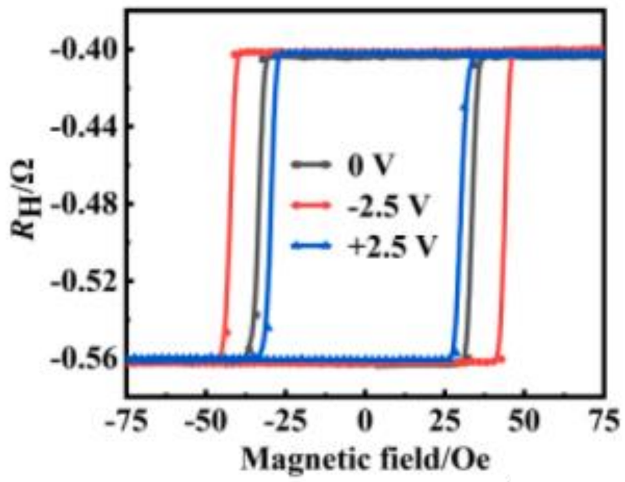
Effects of TID on VCMA-MRAM

In 2023, W. Cao et al tested HfZrO/CoFeB Hall bar devices and studied the influence of gamma irradiation on the VCMA coefficient.

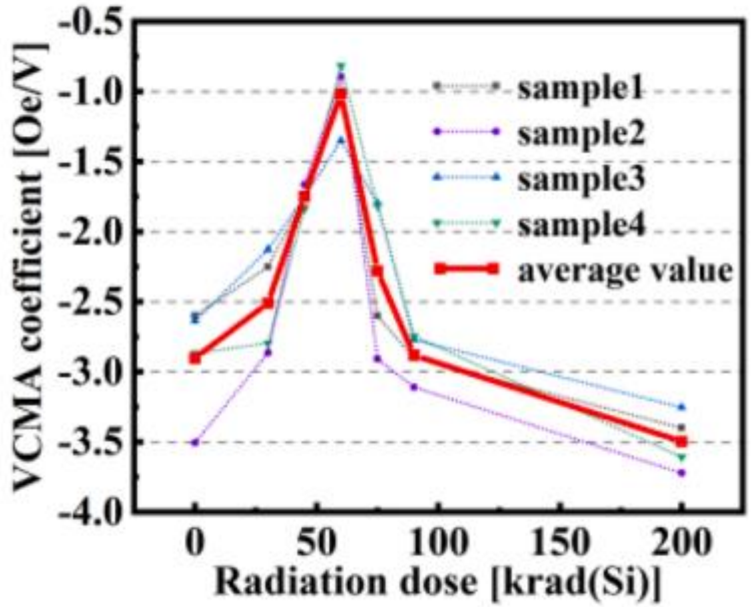
Hall bar device experiment



Field switching properties



Influence on VCMA coefficient



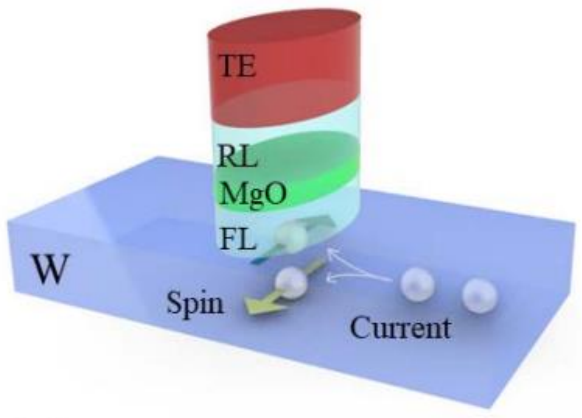
W. Cao *et al*, *J. Magn. Magnetic Mater.*, vol. 575, 170695 (2023)

- **Authors suggested that trapped interface charges could explain influence on VCMA coefficient.**

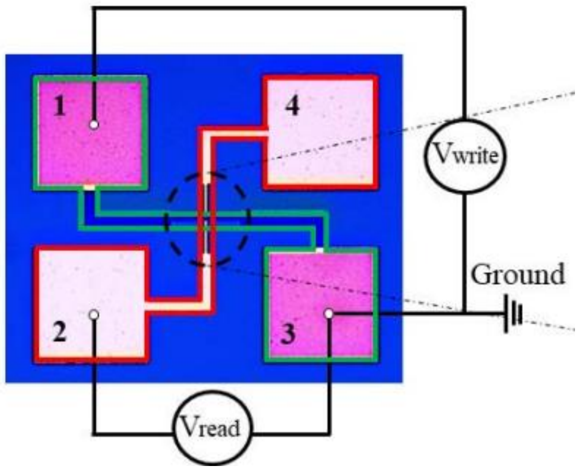
Effects of TID on SOT-MRAM

In 2022, B. Wang et al studied the effect of gamma irradiation and heavy ion displacement on SOT-MTJs.

SOT-MRAM schematic

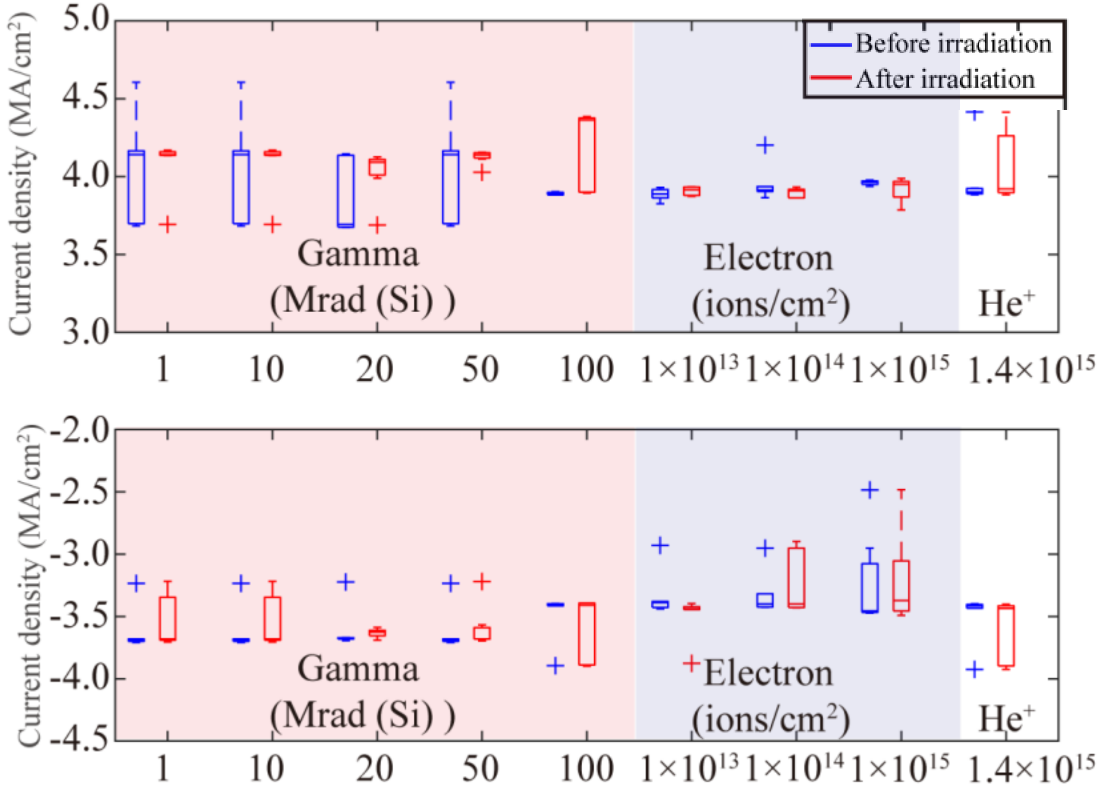


Experiment set-up



B. Wang *et al*, *IEEE Trans. Nucl. Sci.*, vol. 69, pp. 43 – 49 (2022)

Influence of gamma irradiation on switching current



- **First study testing ionizing radiation effects on SOT -MTJs.**
- **Results shows switching current density increases with dose → agrees with our results!**

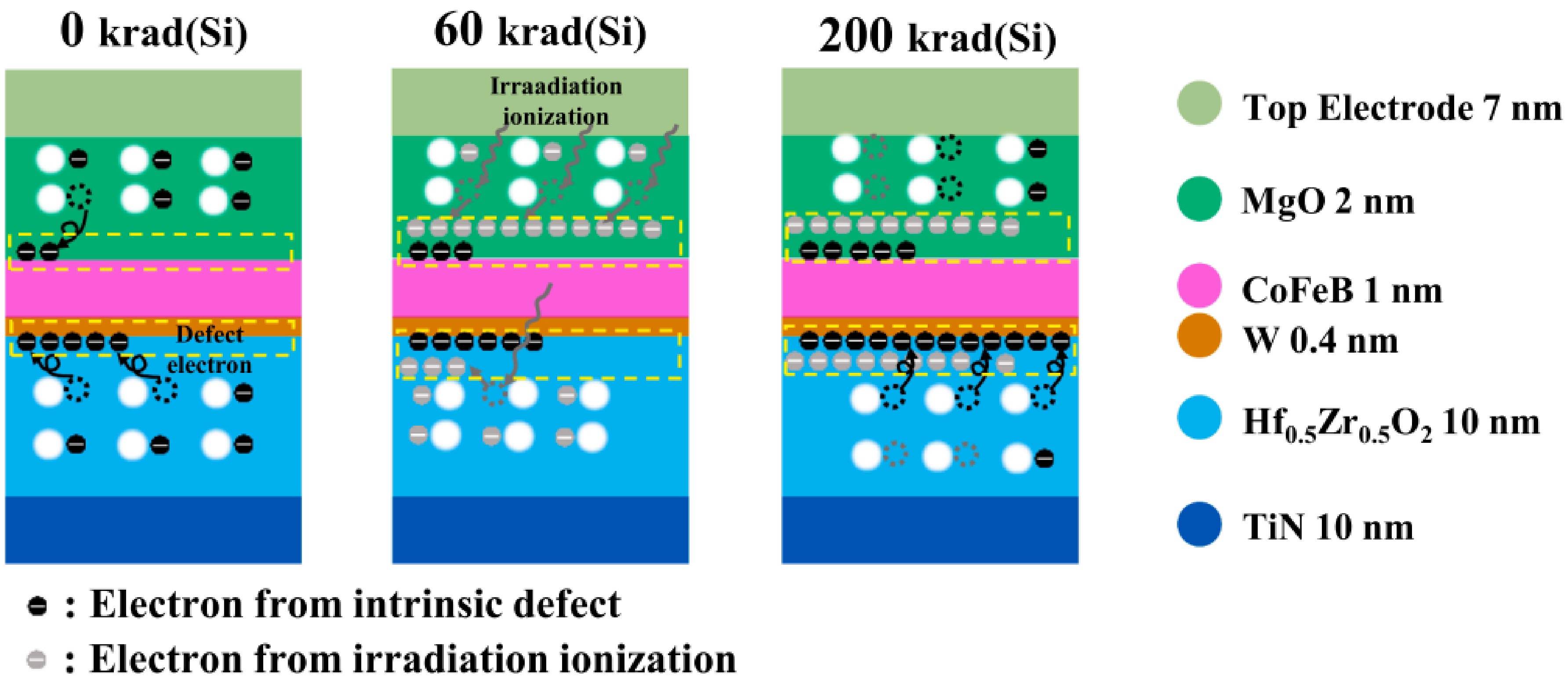
Conclusions

- CMOS based electronics are vulnerable to effects of ionizing radiation.
- MRAM is a promising solution for radiation-hard computing applications.
  - ➢ Be aware of shifts in thermal stability and switching voltages due to altering VCMA effects.
- ***Moving forward:***
  - ***Develop radiation hardened SOT-MRAM.***
  - ***Investigate effect of ionizing radiation on future MRAM switching mechanisms (VCEC, VCMA, etc.)***

B. R. Zink *et al*, *IEEE Trans. Nucl. Sci.*, vol. 68, pp. 748 – 755 (2021)

Effects of TID on VCMA-MRAM

W. Cao et al suggested that trapped interface charges could explain this phenomenon.



- **This mechanism would also explain why we observed a pulse width dependence on the changes in the thermal stability in our 2021 study.**

W. Cao *et al*, *J. Magn. Magnetic Mater.*, vol. 575, 170695 (2023)

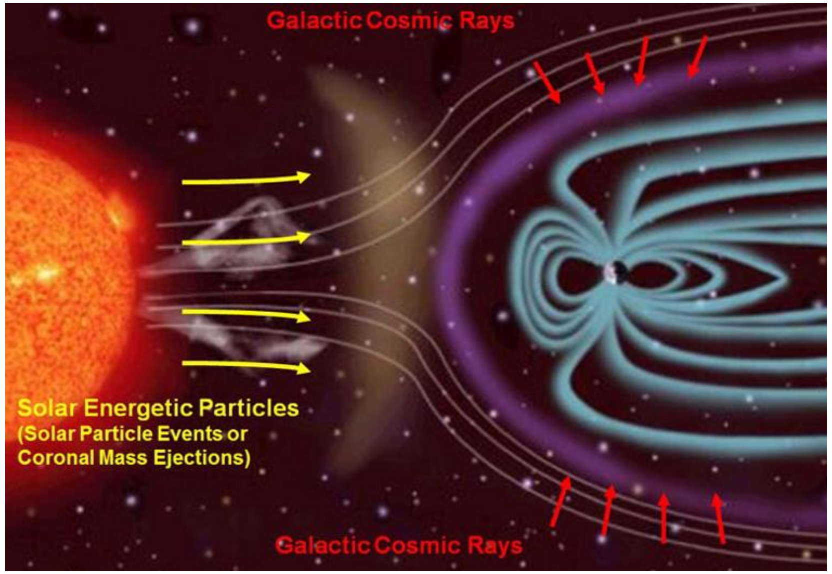
Ionizing radiation overview

Describe sources of radiation

Nuclear explosions (ex. Supernova's)

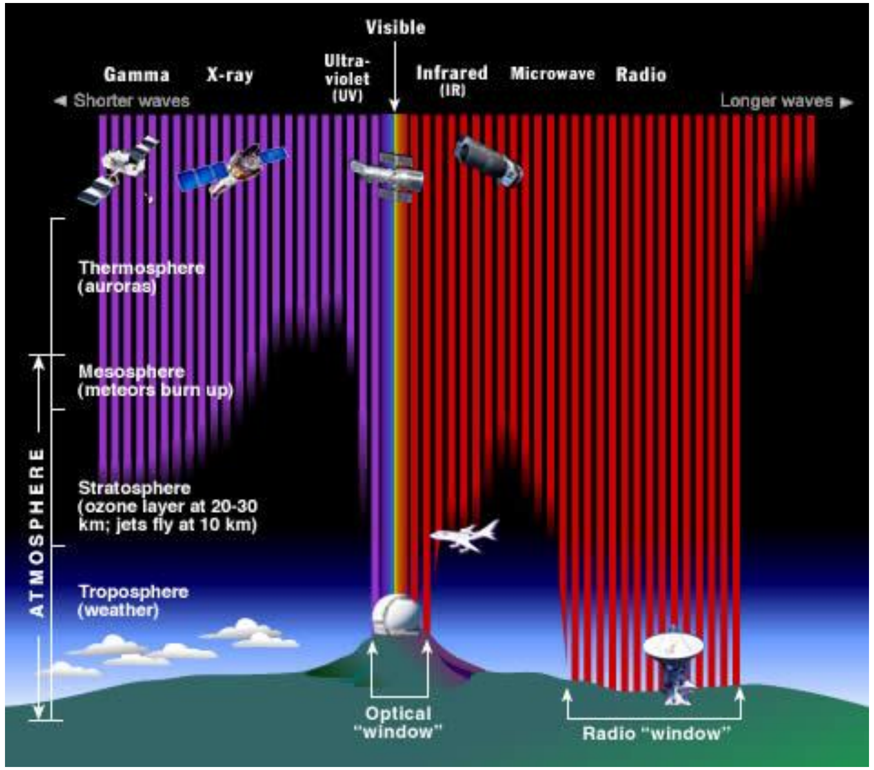

https://spaceplace.nasa.gov/supernova/en/

Solar particle events and cosmic rays



https://www.nasa.gov/mission_pages/msl/multimedia/pia16938.html

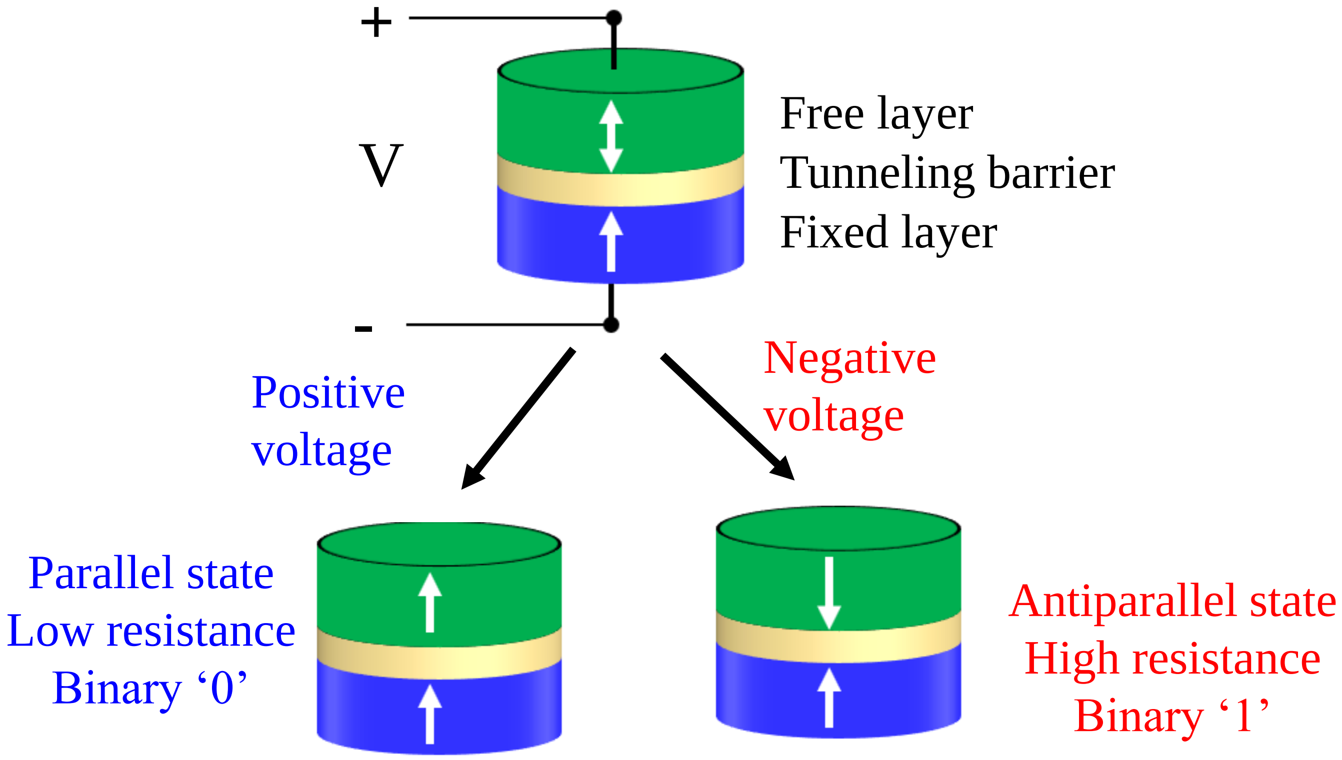
Exposure to more x-rays and γ-rays



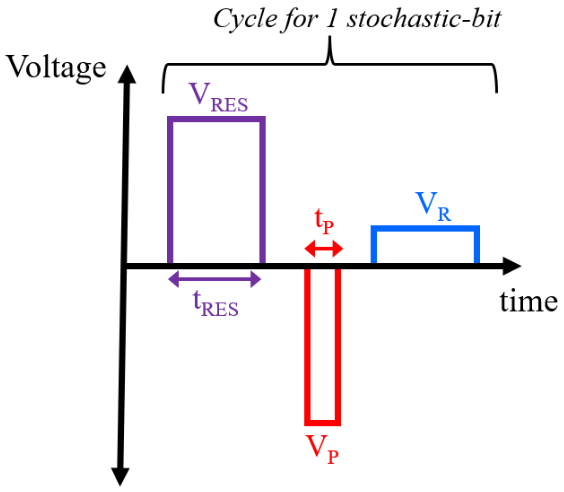
https://www.windows2universe.org/earth/Atmosphere/earth_atmosph_radiation_budget.html

Stochastic bit generation methods – Spintronics

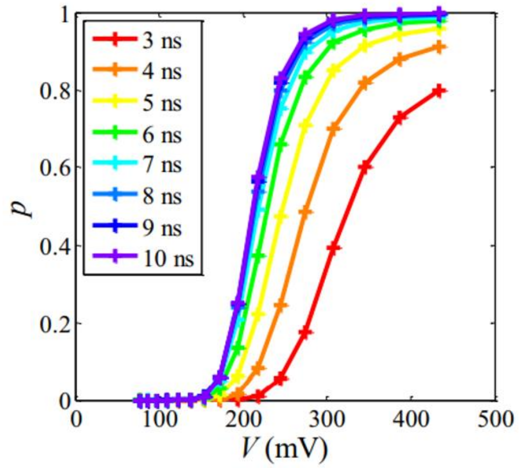
Magnetic tunnel junction (MTJ) structure



Pulse scheduling



P_{SW} distribution

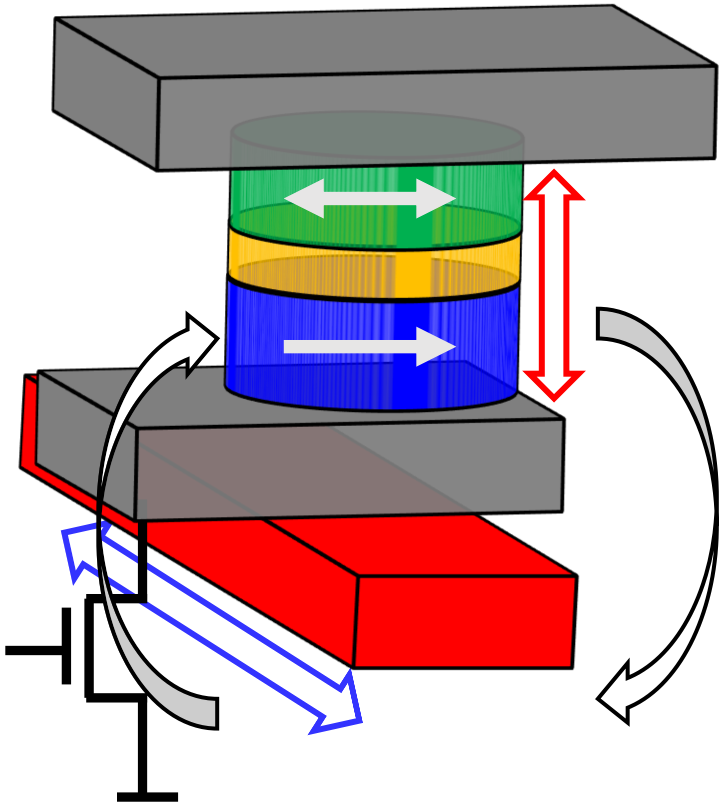


Y. Lv *et al*, *IEEE Int. Electron Devices Meeting*, pp. 36.2.1 – 36.2.4 (2017)

- ➢ **A magnetic tunnel junction (MTJ) is a resistive memory element that stores binary information via the magnetization of the free layer.**
- ➢ **A single MTJ can be also be used a true random number generator.**

MTJs for Rad-hard memory

Describe new results from JPL (2022 paper).



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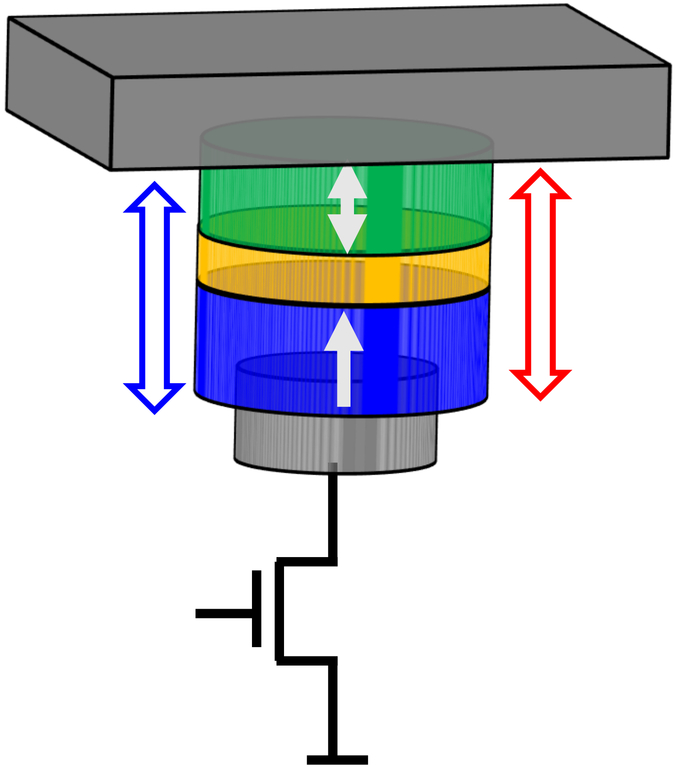

MTJs for Rad-hard memory

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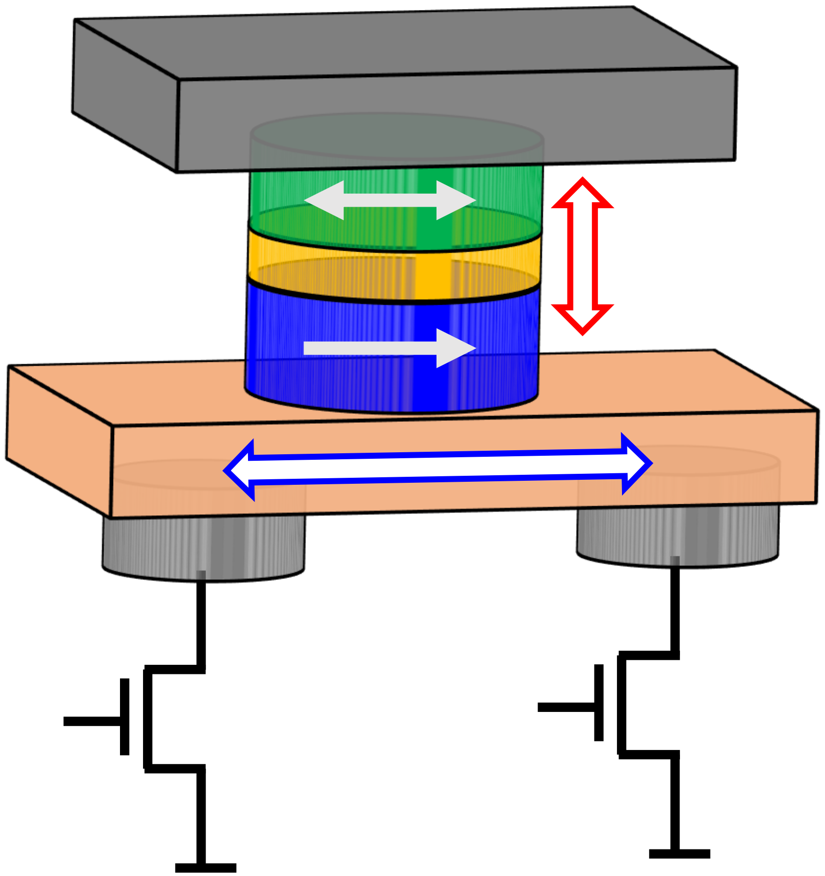

MTJs for Rad-hard memory

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