VOLTAGE-CONTROLLED MAGNETIC TUNNEL JUNCTIONS DEMONSTRATE RESILIENCE TO DISPLACEMENT DAMAGE

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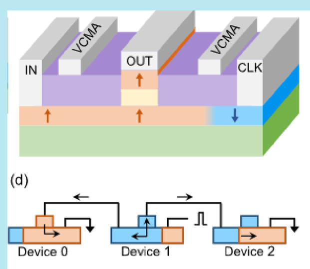
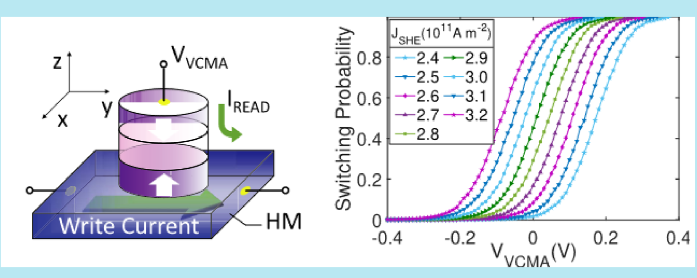
A. Motivation

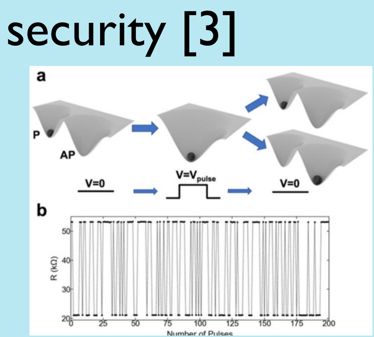
- Magnetic Tunnel Junctions (MTJs) meet multiple key metrics for future radiation tolerant memory and/or logic devices
  - High-speed, scaled/CMOS-integration ready, but difficult to integrate at high bit density due to large write currents
- Voltage-controlled magnetic anisotropy (VCMA) is a fundamentally new mechanism for controlling the On/Off states in MTJ memory or logic
  - Enables lower energy writes and modifiable reading of state
- Applications:
  - Controllable, high-speed VCMA based magnetic logic [1]
  - Neuromorphic applications (controllable neural behavior) [2]
  - True random number generation for hardware security [3]



Source: Zogbi et al, [1]



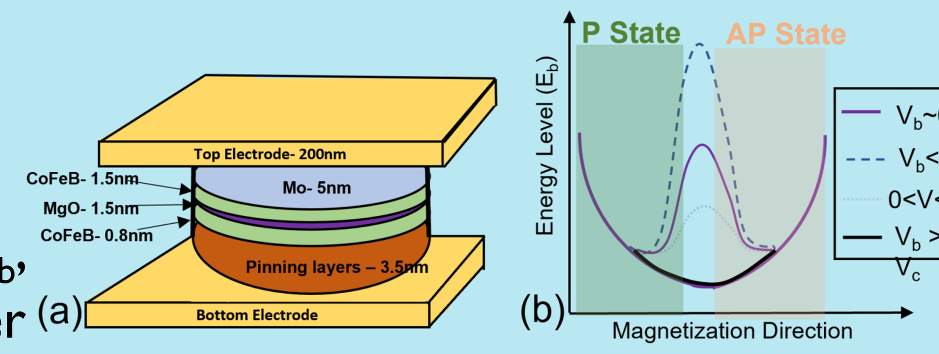
Source: Su et al, [2]



Source: Shao et al, [3]

B. Basic Device Mechanisms

- Devices are similar in stack to modern perpendicular anisotropy MTJs (p-MTJs)
  - Modifications to capping layer induces VCMA effect
- Negative (positive) bias voltage, V_b, increase (decrease) energy barrier
- Key studied behaviors:
  - On/Off ratio or Tunneling Magnetoresistance (TMR) of particular device
  - Coercivity (sensitivity to magnetic fields) of device (H_c)

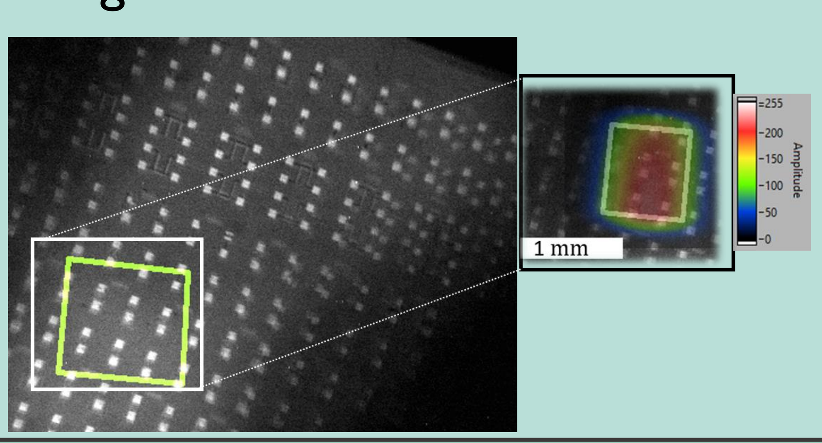


B1. (a): Schematic of studied device. An MTJ trilayer is modified with functional pinning layers for the VCMA effect

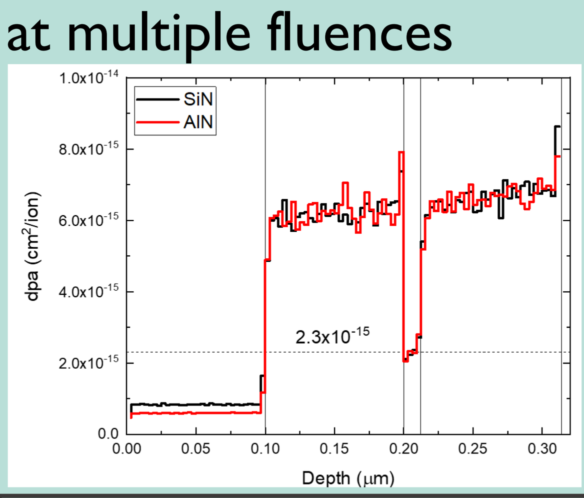
B1.(b): Cartoon of the VCMA effect, adapted from [4]. As shown, application of different bias voltages changes the device's energy barrier

C. Experimental Design & Dataset

- Previous work shows MTJs are resilient to ionizing radiation (non-charge-based), but sensitive to high levels of displacement damage
- 20 MeV Au beam chosen to maximize displacements in active layers based on Stopping Range of Ions in Matter (SRIM) calculations
- Multiple known VCMA-MTJ devices profiled, and micro-beam targeted was used to raster over them at multiple fluences



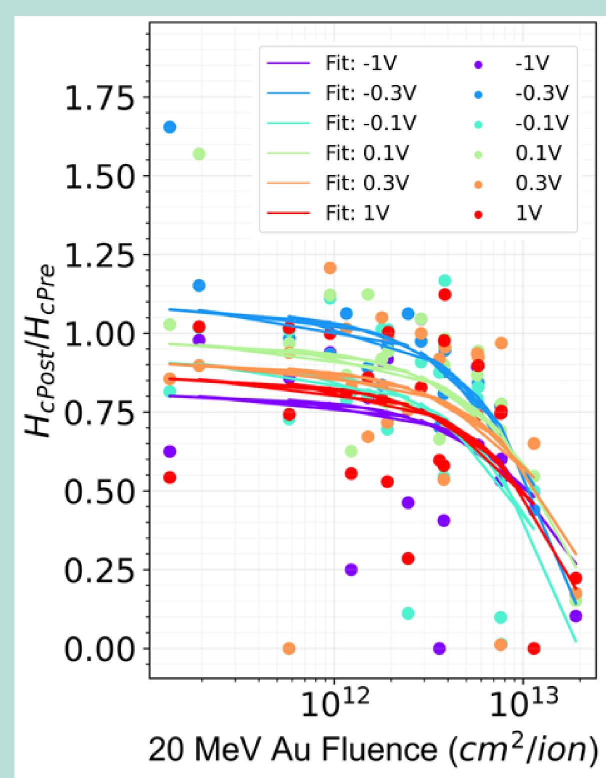
C1. Microscope images taken at Sandia's Ion Beam Laboratory (IBL) depicting calculated beam spot and energy level. This method allows for individual fluences to be applied to devices.



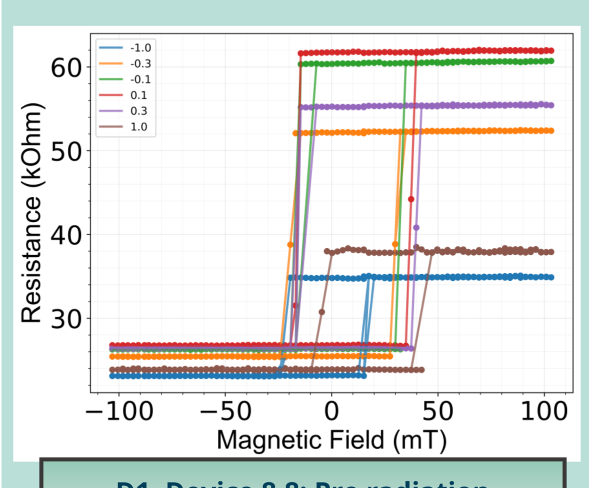
C2. Calibrated SRIM calculations based on thin film stacks . DPA is reduced, but still high, in active area

D. Statistical Response to Displacement Damage in VCMA pMTJ Devices

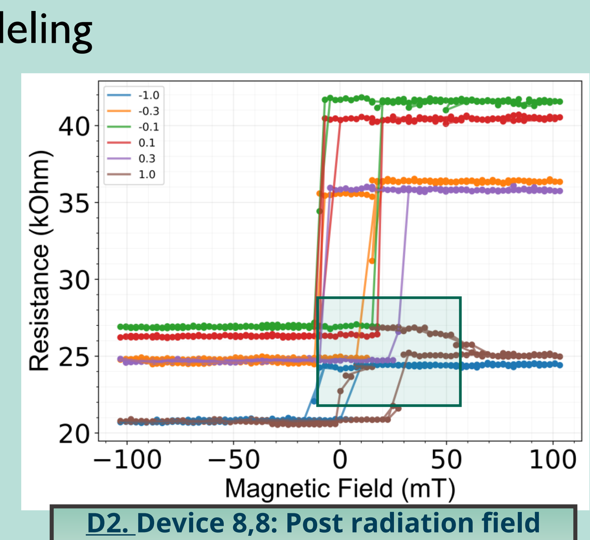
- Typical responses occur in VCMA pMTJs due to structural damage above 1×10^{12} ions/cm^2
  - 1) Coercivity reduced across all V_b
  - 2) TMR reduced across all V_b, but especially larger voltages
  - Overall conductance of device increases
  - Example: D1 (pristine) v D2 (post 1.1×10^{13} ions/cm^2)
- Core contribution of work: broader statistical analysis over a large device dataset
  - 23 devices analyzed; 41 individual beam shots between 1×10^{10} and 5×10^{13} ions/cm^2
  - Population statistics for TMR are all highly statistical significant
  - Population statistics for 5 out of 6 V_b levels are statistically significant; more failures
    - H_c demonstrates large # of incomplete loops at high fluence (D2 inset)
  - Fits modeling response to displacement damage can be used for logic or memory resilience modeling



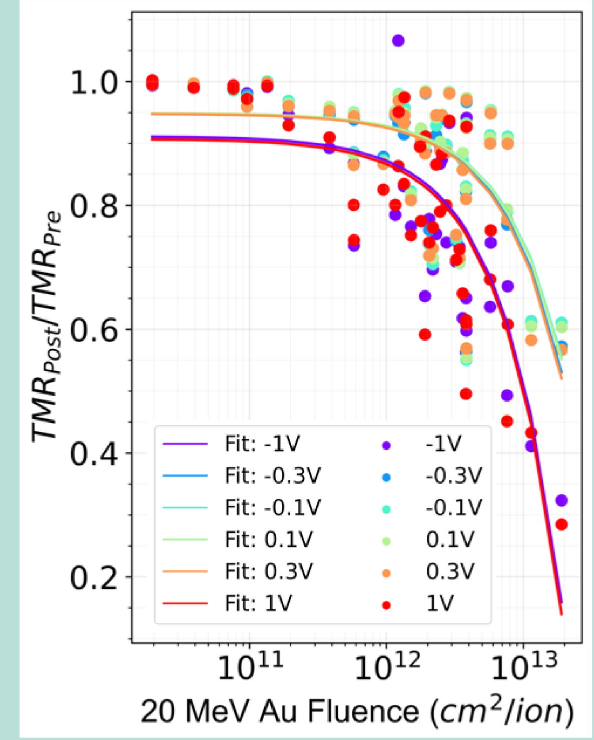
D3. Statistical analysis of coercivity response across 11 devices at 23 different fluence levels



D1. Device 8,8: Pre radiation Standard field loops



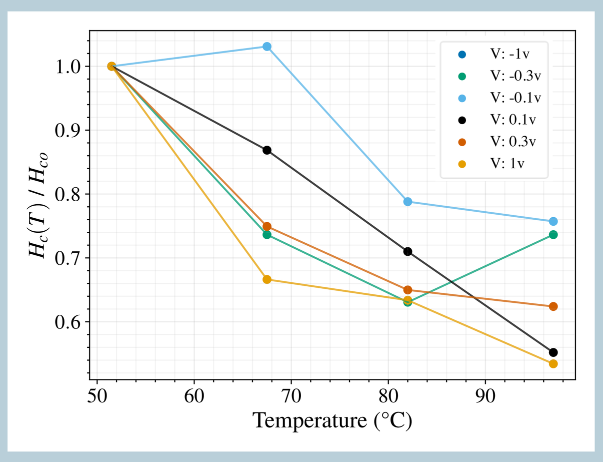
D2. Device 8,8: Post radiation field loops showing typical changes (failed loop at V_b = 1 in inset)



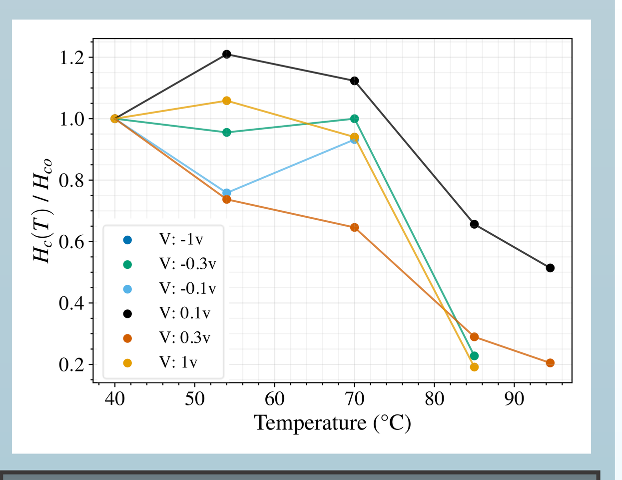
D4. Statistical analysis of TMR response across 23 devices at 41 different fluence levels

E. Resilience to Temperature Effects

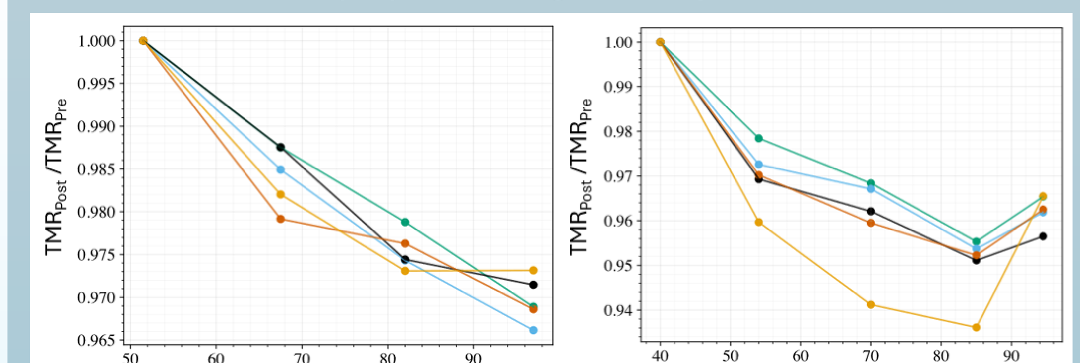
- Temperature is known to reduce coercivity / TMR in MTJs
- We analyzed response of VCMA-pMTJs to temperatures between RT and 100C
  - Typical degradation is ~20-40% in coercivity, (E1-2) and < 5% TMR reduction (E3-4)
- Compounding effect of radiation-induced damage (irreversible) and thermal stress (reversible) was analyzed
  - Evidence of increased temperature sensitivity wasn't found
  - Minor increases in H_c loss shown (E2), but larger sample size needed



E1. Device 7,28: Pre radiation temperature response (Coercivity)



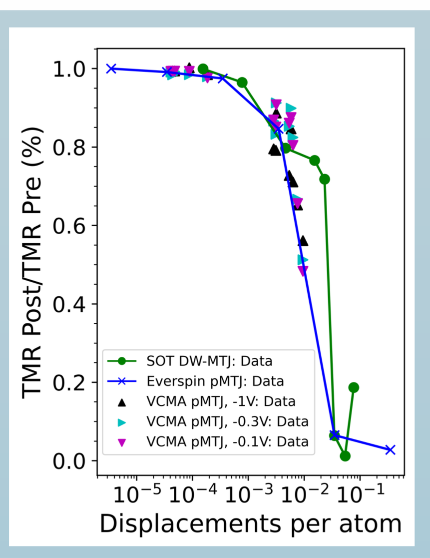
E2. Device 7,28: Post-radiation (5.77×10^{11} ions/cm^2) temperature response (Coercivity)



E3. Device 7,28: Pre (Left) and Post-radiation (5.77×10^{11} ions/cm^2) temperature response in TMR (On/Off ratio)

F. Perspective

- Physical mechanisms
  - VCMA effect is based on magneto-crystalline anisotropy (MCA), and specifically, electron depletion in *d*-orbitals along MgO/CoFeB interfaces [5]
  - Displacement damage reduces VCMA effect at surprisingly large fluences, implying that built in electrical field at interfaces is resilient
- Comparison to other MTJs
  - Degradation of VCMA-pMTJs is similar to other known pMTJs . No reason to forgo new capabilities!



F1. Comparison of sensitivity across multiple pMTJ species

References: [1] N. Zogbi et al, IEEE JXDC, 2023, [2] Su et al, IEEE TED 2023, [3] Shao et al, Nanotechnology 2023, [4] Kang et al, IEEE Transactions on Nanotechnology 2017, [5] Zhang et al, https://arxiv.org/pdf/1612.02724

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