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Heavy-ion-induced displacement damage effects in magnetic tunnel junctions with perpendicular anisotropy

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Spin transfer torque magnetic random access memory (STT-MRAM)

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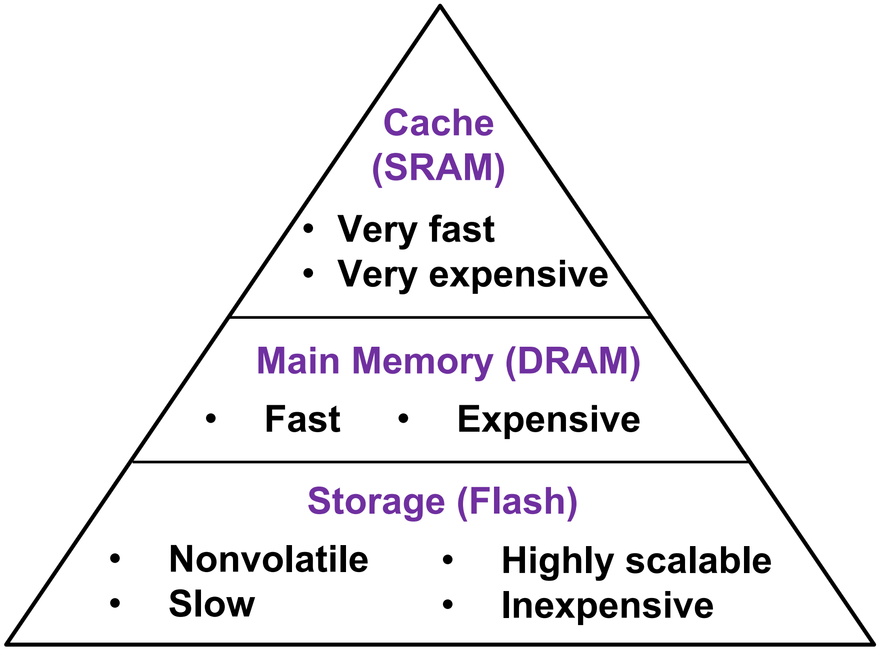
	Conventional memory				
	SRAM	DRAM	3D NAND Flash	eFlash (NOR)	Toggle-MRAM
Non-volatility	No	No	Yes	Yes	Yes
Endurance (cycles)	Unlimited	Unlimited	10^3–10^5	10^4–10^7	Unlimited
Write speed (ns)	<1	1–10	10^5–10^6	10^5	1–10
Memory capacity	Small–Medium	Medium	Large	Small	Small
Reference			[4]	[5]	

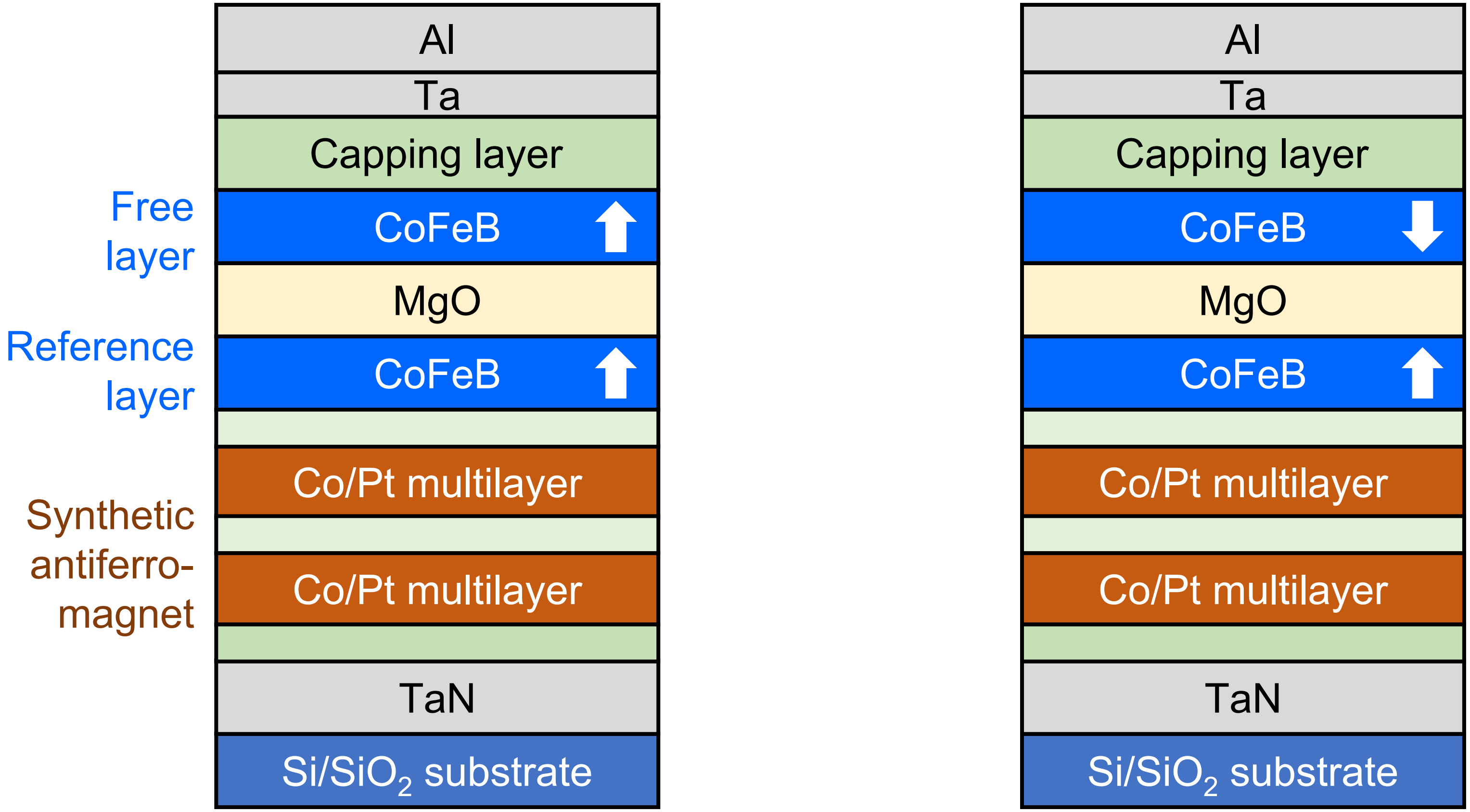
	Emerging memory				
	STT-MRAM	ReRAM	PCM	FeFET	NRAM (CNT)
Non-volatility	Yes	Yes	Yes	Yes	Yes
Endurance (cycles)	10^9–10^{12}	10^5–10^9	10^6–10^9	10^4–10^5	10^{15}
Write speed (ns)	1–100	10–10^5	100–10^4	10	10
Memory capacity	Medium	Medium	Medium	Medium	Medium
Reference	[1]	[1]	[1]	[2]	[3]



+ more radiation-hard than charge-based memories

S. Ikegawa, F. B. Mancoff, J. Janesk, S. Aggarwal, *IEEE Trans. Elec. Dev.* (2020)

Spin transfer torque magnetic random access memory (STT-MRAM)

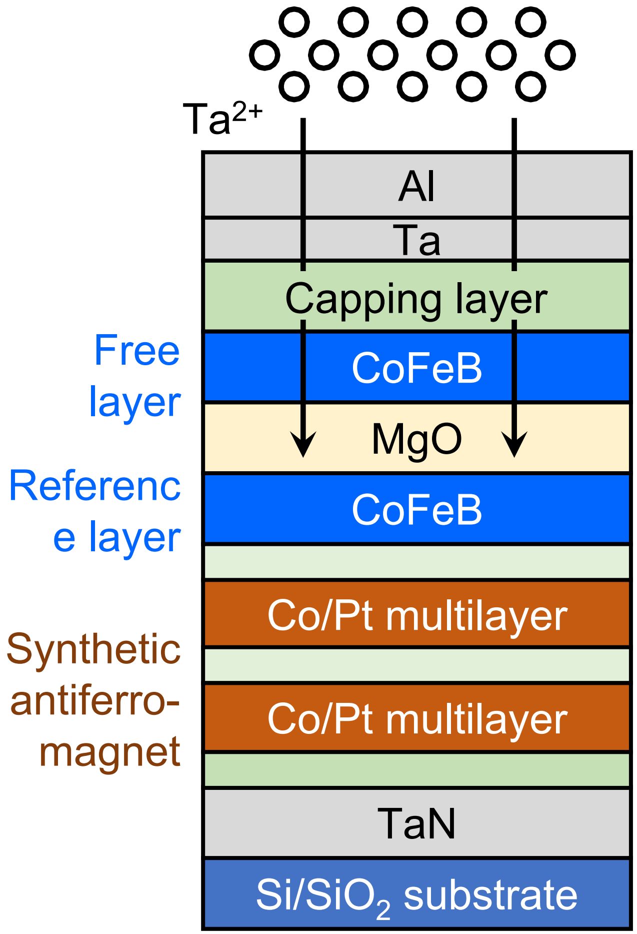


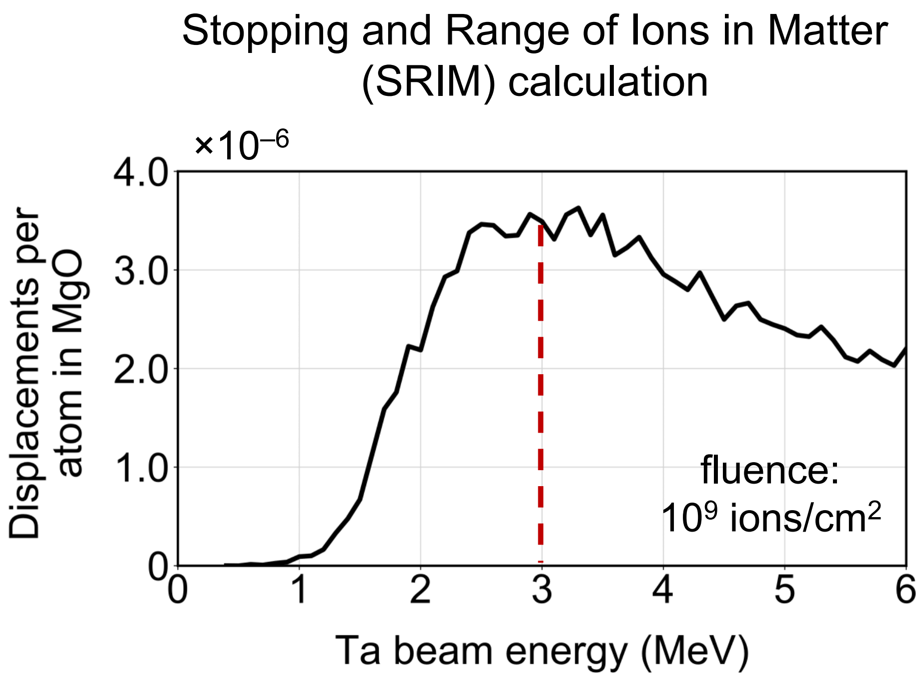
Parallel state:
Low resistance R_P

Anti-parallel state:
Low resistance R_P

MTJ diameter: 80 – 115 nm

Inducing displacement damage via a heavy ion beam





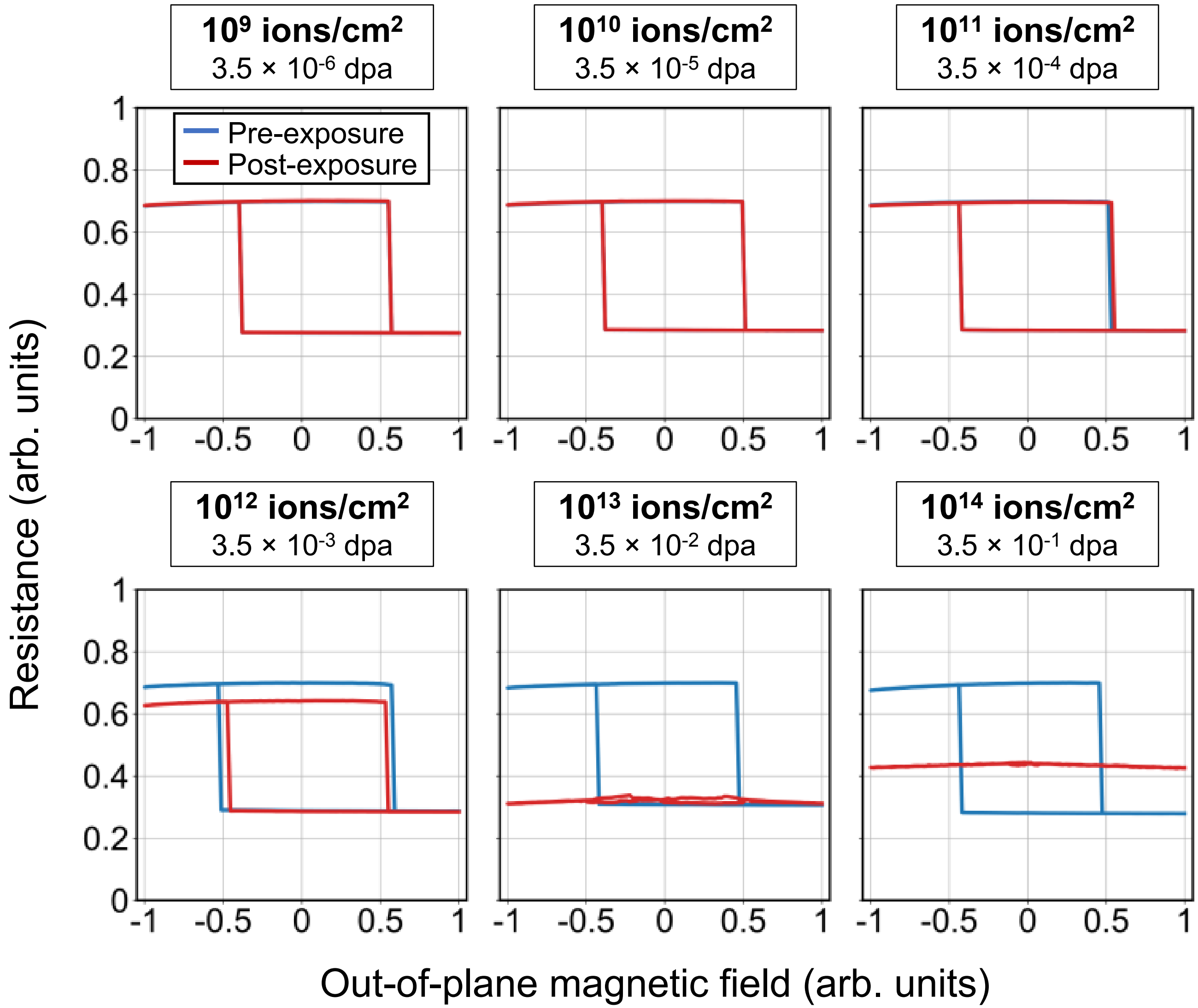
Beam fluence [ions/cm^2]	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}
Displacements per atom (dpa)	3.5×10^{-6}	3.5×10^{-5}	3.5×10^{-4}	3.5×10^{-3}	3.5×10^{-2}	3.5×10^{-1}

Closest prior work:

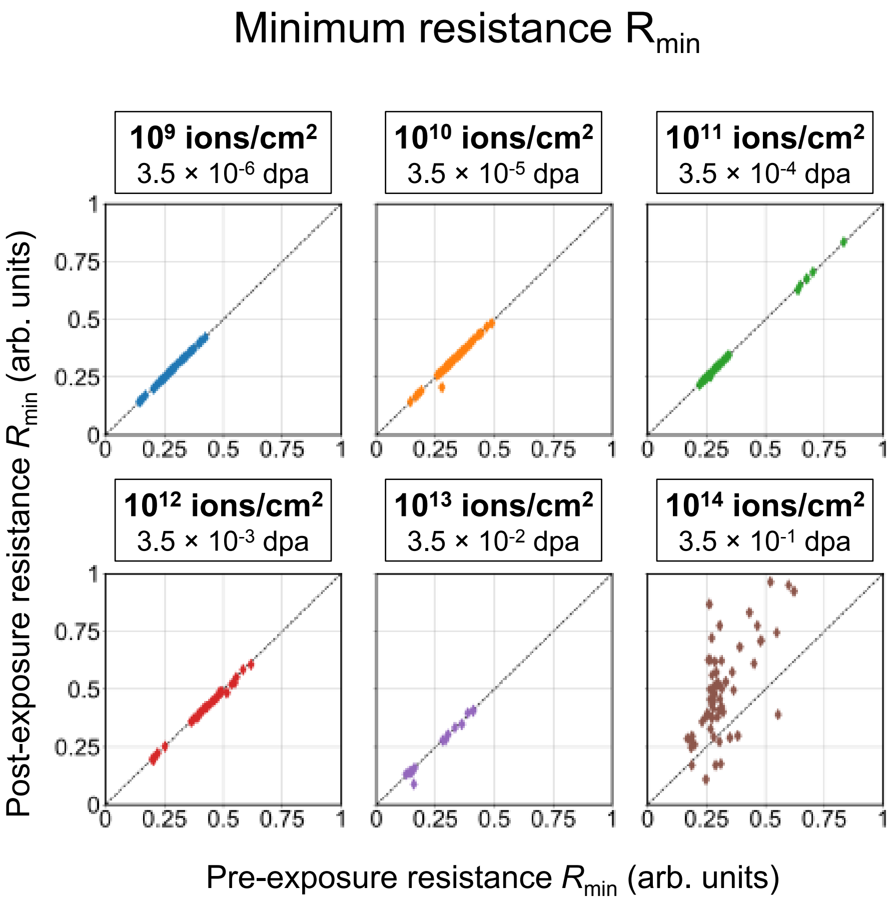
D Kobayashi et al, *Jap. J. Appl. Phys*, 2017: CoFeB/MgO pMTJ, 250-500 MeV various ions, ~10^{11} ions/cm^2

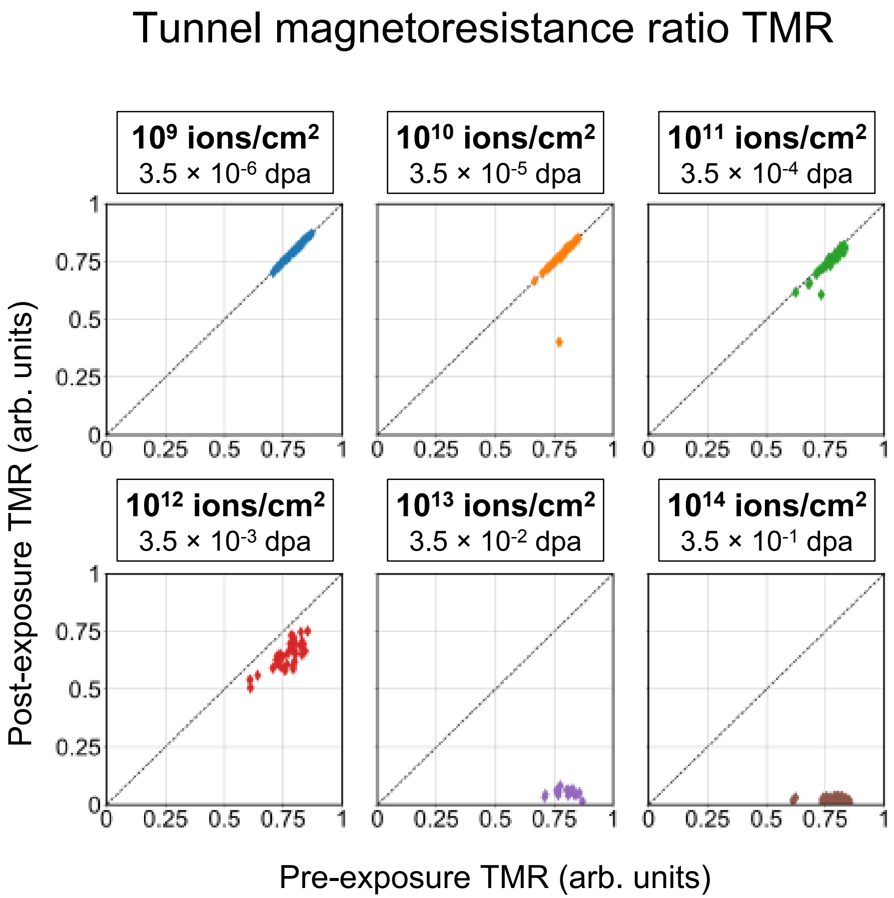
J.-Y. Park et al, *Thin Solid Films*, 2019: CoFeB/MgO pMTJ, 40 keV Cr, 5×10^{13} ions/cm^2

Change in magnetoresistance (single device)



Change in magnetoresistance (ensemble)

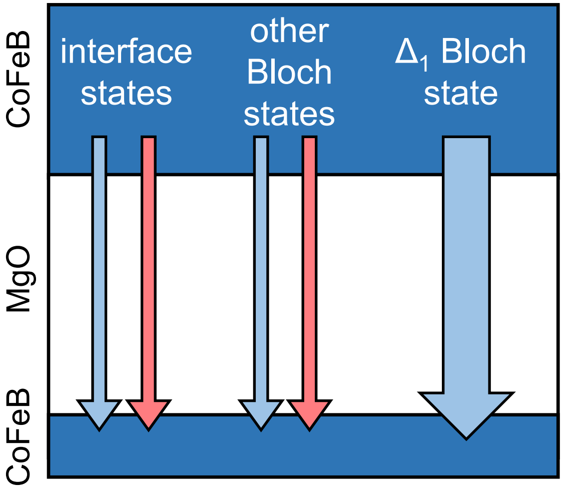




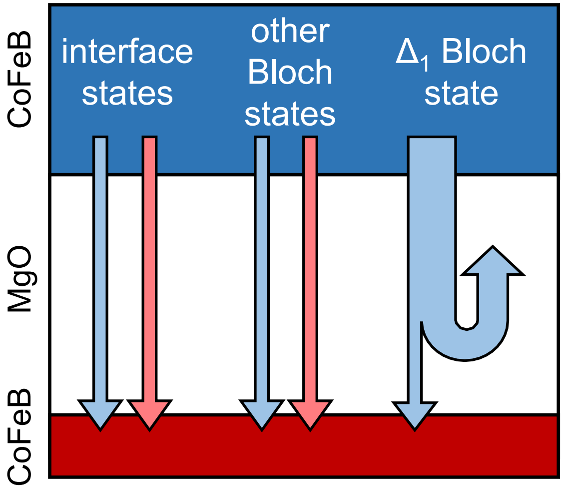
What is happening?

Before damage to interface

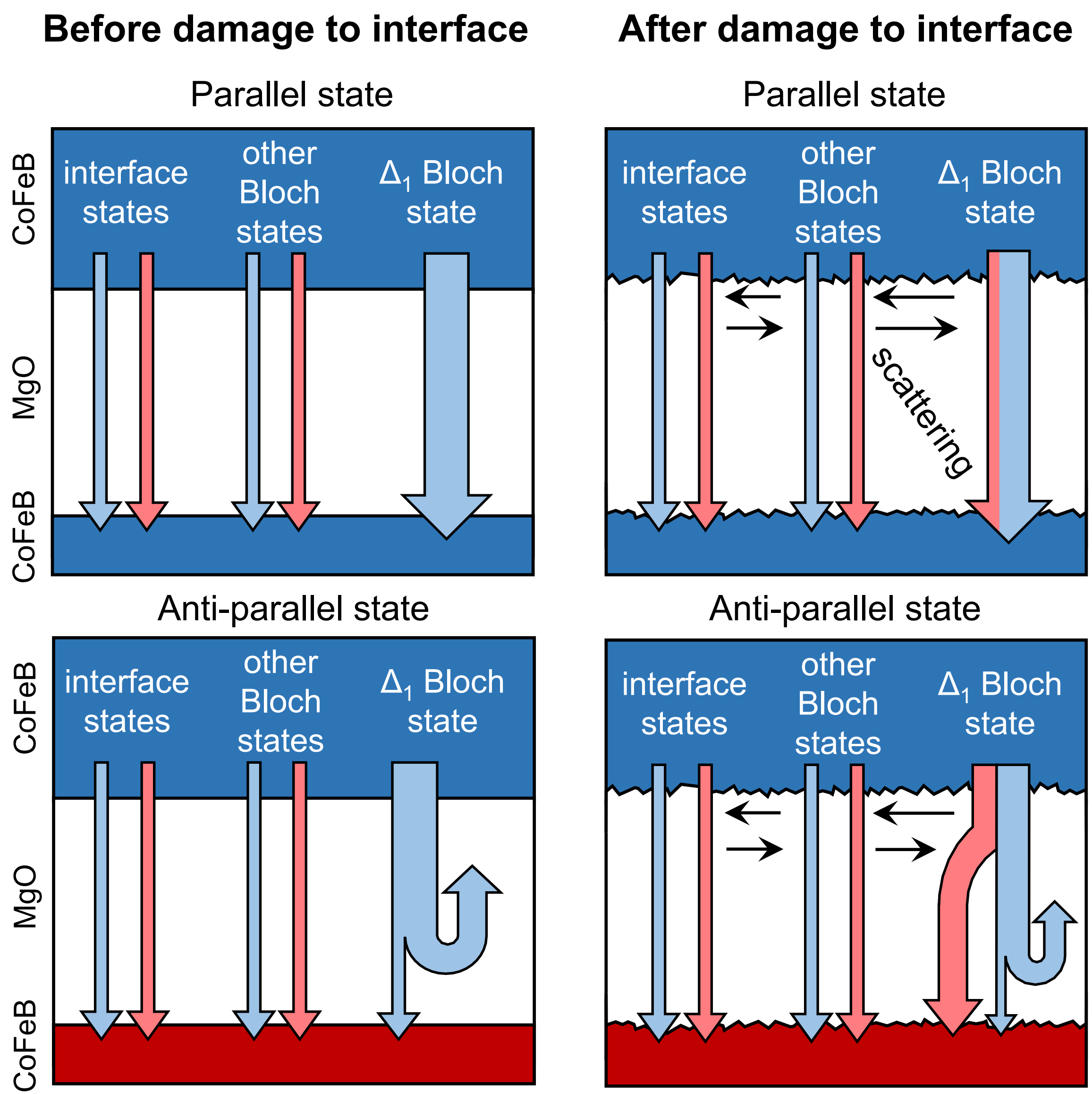
Parallel state

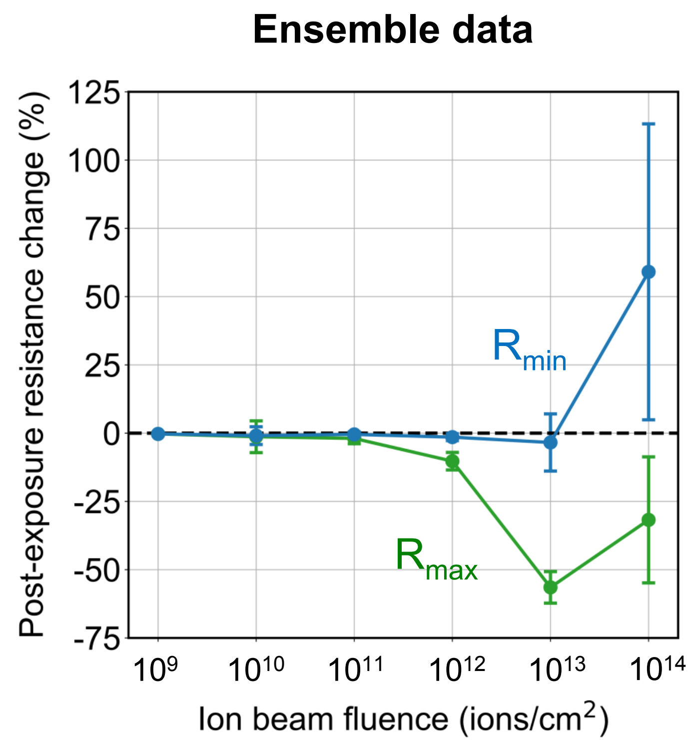


Anti-parallel state



Displacement damage reduces electron spin polarization

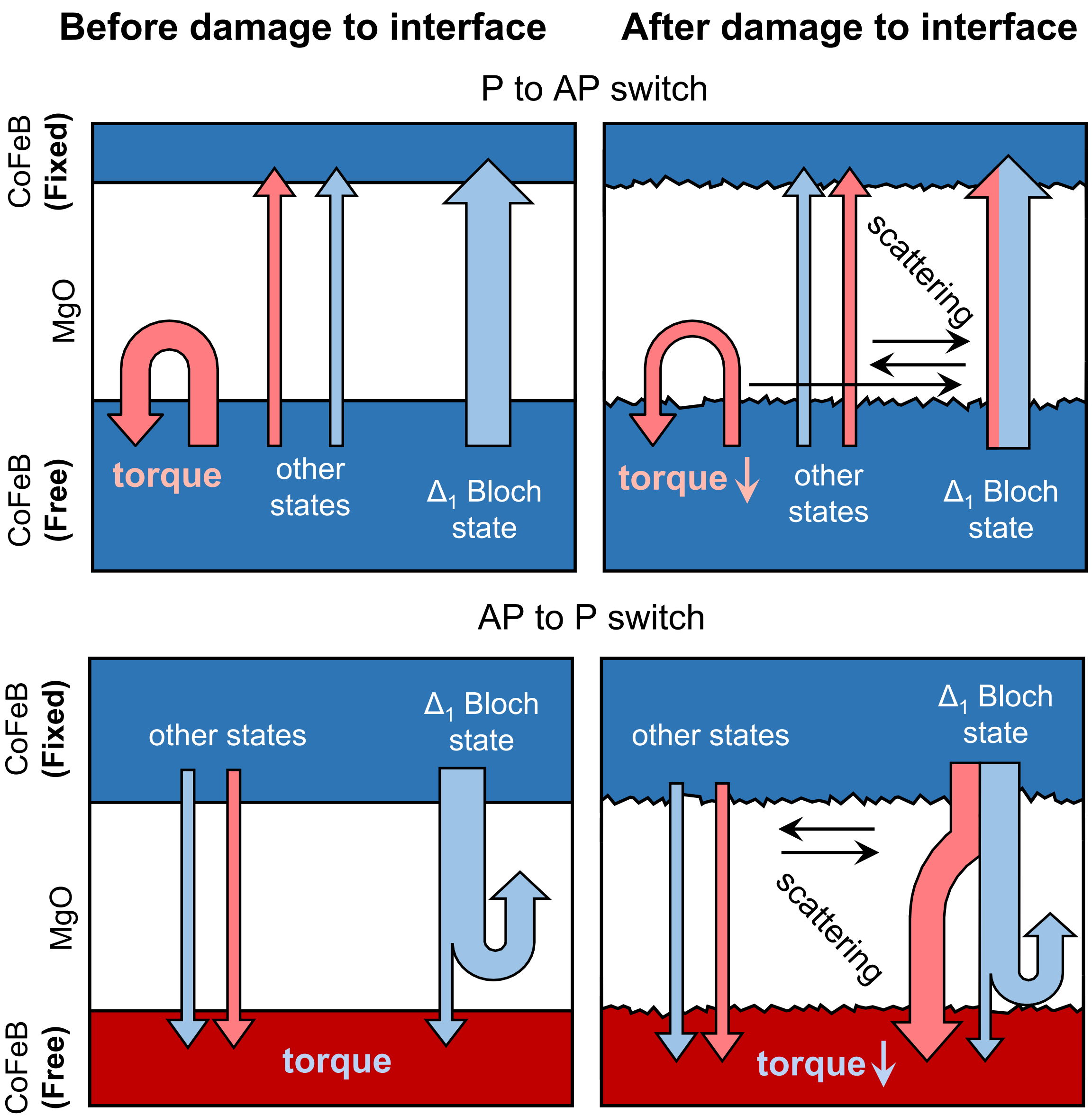


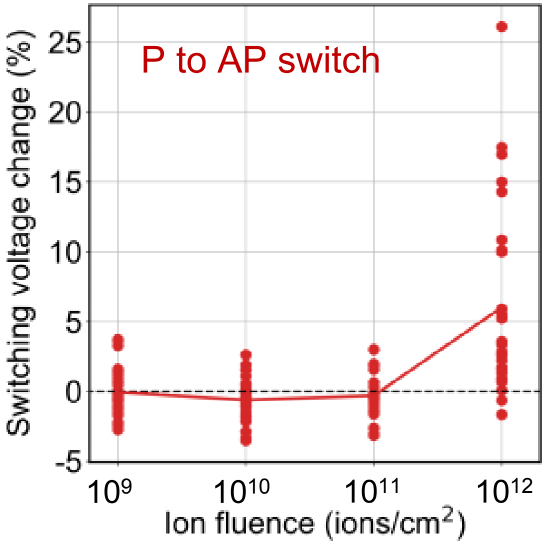


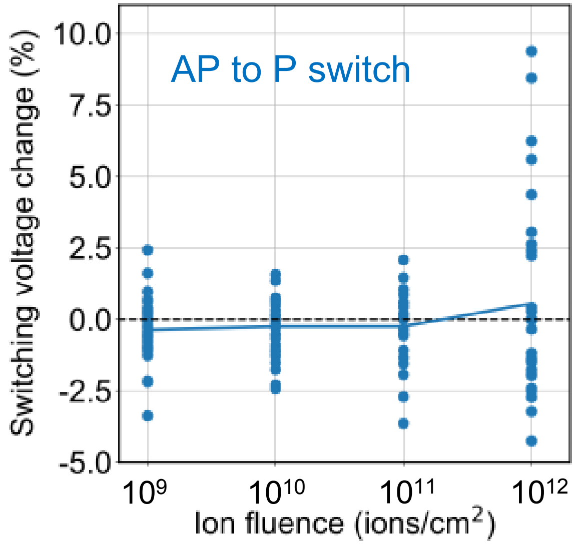
E. Y. Tsymbal et al, *J. Phys: Cond. Matt.* 2003

S. Yuasa and D. D. Djayaprawira, *J. Phys D: Appl. Phys*, 2007

Displacement damage reduces electron spin polarization

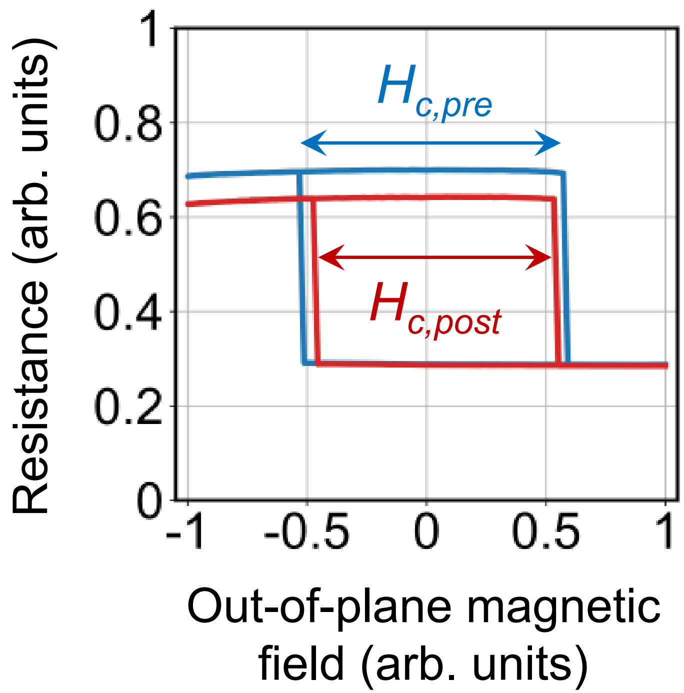


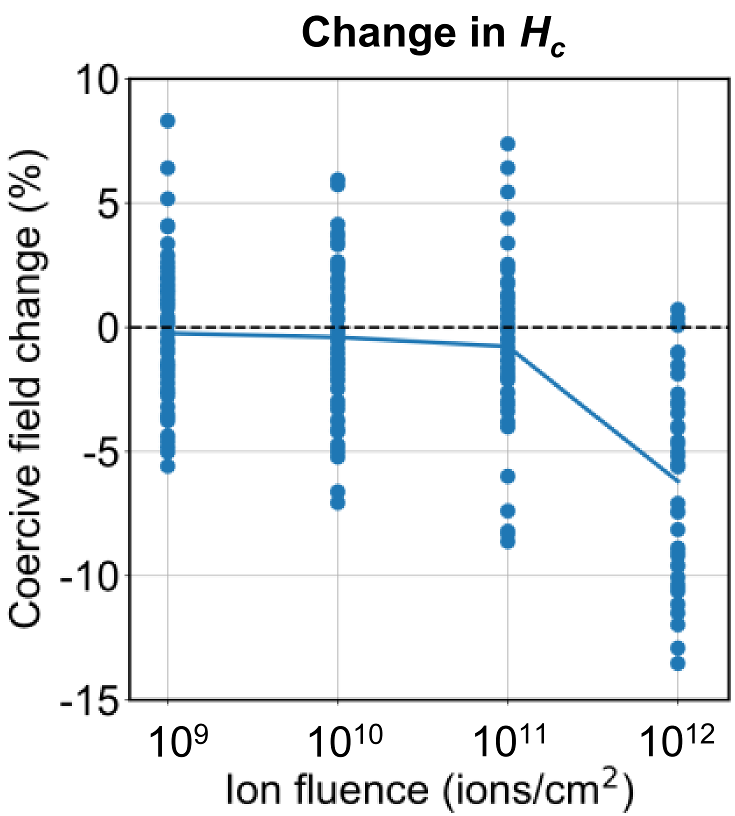




Displacement damage reduces perpendicular magnetic anisotropy

10^{12} ions/cm^2
3.5×10^{-3} dpa





H. X. Yang et al, *Phys Rev B*, 2011
A. Gupta et al, *J. Phys: Cond. Matt*, 1998

Conclusions

- Irradiated CoFeB/MgO pMTJs with very high heavy ion (3 MeV Ta) fluences
  - Up to 10^{11} ions/cm^2: No visible effect
  - 10^{12} ions/cm^2: Magnetoresistance and coercive field decrease
  - Above 10^{13} ions/cm^2: Out-of-plane magnetoresistance lost
- We propose the main effect of displacement damage is to introduce disorder to the CoFeB/MgO interface:
  - Disorder at the interface allows scattering among the tunneling modes, reducing the electron spin polarization
  - Disruption of bonds at the interface causes loss of perpendicular magnetic anisotropy

Thank you!