Advanced Magnetic Tunnel Junctions for Computation in and Near Random Access Memory

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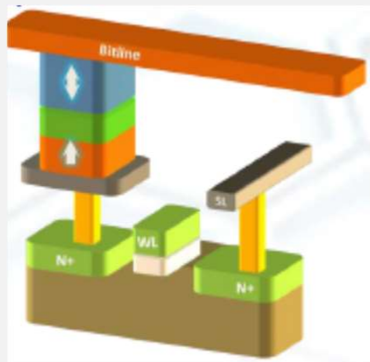
Materials & Integration: Framework for Novel Compute (FRANC)

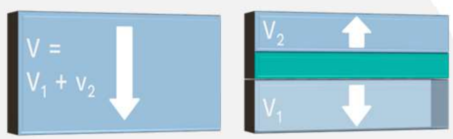
Motivation: The magnetic tunnel junction (MTJ) is the most important building block for advanced memory topologies, including computing in- and near-random access memory (CRAM)

- The perpendicularly magnetized MTJ (p-MTJ) is a two-terminal nanoelectronic device comprising a thin (~ 1 nm) tunneling barrier layer separating a "fixed"-magnetization ferromagnet from a ferromagnet whose magnetization is "free" to switch parallel or antiparallel to the "fixed" layer
  - Tunneling magnetoresistance (TMR) gives a factor of 2 ON/OFF ratio for parallel/antiparallel magnetization configuration
  - Locally switch "free" layer with electric current by the spin transfer torque (STT) effect→ no cross talk = high device density
  - Non-volatile (>10 yrs), rugged for high temperature (automotive) and radiation (aerospace) environments
  - Back-end-of-line compatible with semiconductor processing
- pMTJs are found in commercial products today:
  - Standalone RAM
  - Hardware accelerators
  - Extreme environments, including automotive and aerospace
- To get to the next level, MTJs need a performance leap:
  - 10x faster
  - 50x less energy consumption
  - 4-5x higher tunneling magnetoresistance (TMR) ratio (ON/OFF ratio)
- We will design and fabricate MTJs with composite synthetic antiferromagnetic (SAF) free layer to enable fast switching, low energy switching, high TMR ratio and low writing error:
  - Ultra-high TMR ratio (>400%)
  - Ultra-fast switching (50 ps for 50% switching probability for 60 k_BT MTJ)
  - Ultra-low switching energy (100 aJ)
  - Ultra-small feature size (10 nm)
  - Damping constant for the proposed composite SAF free layers <0.01
- Compared to competing approaches for advanced MTJs, our proposal best meets the demands of CRAM as established by our partners working on the FRANC TA-1 teams.



Technical Approach: Develop two advanced p-MTJ candidates based on composite synthetic antiferromagnetic (SAF) free layers:

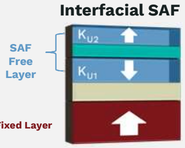
- Basic concept: Composite SAF free layers enable much shorter write delays than conventional single phase layers
- MTJs with both interfacial perpendicular SAF and bulk perpendicular SAF will be demonstrated.
- Advanced materials, stack structures and deposition methods will be explored to produce high-performance MTJs. A novel voltage controlled magnetic anisotropy (VCMA) effect will be investigated, where voltage with both polarities can reduce perpendicular magnetic anisotropy (Even-VCMA).



"Conventional" Free Layer

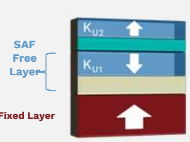
SAF Free Layer

Interfacial SAF



K_{U1} (V) < K_{U1} (0)
K_{U1} (V) < K_{U1} (0)
Damping ~ 0.002
TMR 400%-500%
Switching mechanism: STT + Even-VCMA

Bulk SAF

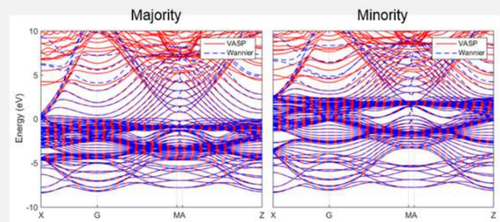


K_U ~ 10^7 erg/cm^3
Damping ~ 0.002
TMR 200%-300%
Switching mechanism: STT

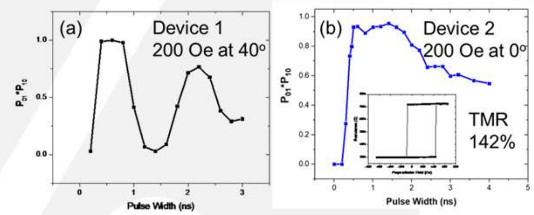
10 nm p-MTJ, Energy-Delay = 100 aJ · 10 ps

Unique advantages of the SAF-pMTJs compared to other approaches

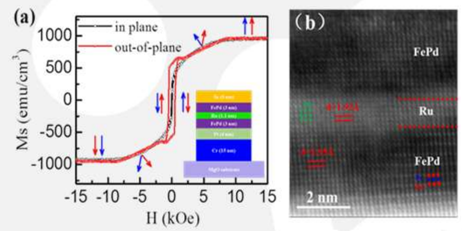
	Other On-going Research				This proposal	
Metrics	SOT	ME-MTJ	Magnonic switching	VCMA	SAF p-MTJ interfacial PMA	SAF p-MTJ Bulk PMA
Large TMR >400% at RT	Maybe	NO	NO	YES	YES	YES
Δ > 60k_BT at 10nm	YES	NO	Maybe	YES	YES	YES
Damping constant (α)	0.02	Maybe	10^{-4}	0.02	0.02	10^{-3}
Ultra-fast (<100ps)	NO	Maybe	YES	Maybe	YES	YES
Ultra-low Energy (100aJ)	NO	Maybe	YES	Maybe	YES	YES
Write Error (10^{-10})	YES	Maybe	Maybe	NO	YES	YES



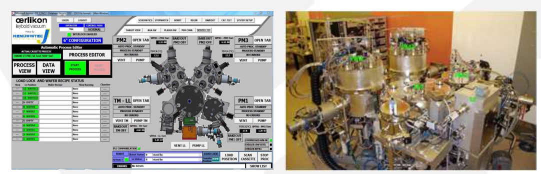
Advanced Modeling of electron band structure in MTJ:
Band structure of the majority and minority spin channels of an MTJ with Fe contacts and 3-layer MgO tunnel barrier in the parallel configuration using a DFT calculation with VASP and after Wannier interpolation.



Low energy switching of MTJ with interfacial PMA:
(a) Voltage controlled magnetic anisotropy (VCMA) switching of p-MTJ at 400ps, with switching energy of 18 fJ.
(b) Switching probability for a similar device, where the applied external field is in-plane. Inset show the TMR curve of the device measured at 10 mV.



FePd SAF structures for MTJ with bulk PMA:
(a) The magnetic hysteresis loops of the FePd(3nm)/ Ru(1.1nm)/FePd(3nm) p-SAF structure measured at room temperature.
(b) A magnified STEM image of FePd/Ru/FePd trilayer, which shows the smooth interface between the FePd and Ru layers. Meanwhile, the lattice spacing of the FePd and Ru layers was calculated from the TEM, labelling in TEM image.
Zhang, et al, Phys. Rev. Appl. 2018



Multi-Chamber sputtering cluster at Minnesota Clean Room
(a) 4 chambers, including 2 chambers for sputtering
(b) Base vacuum: $2*10^{-8}$ Torr
(c) 8 guns, 4 guns in each sputtering chamber.
(d) 6-8" wafer
(e) Automatic sputtering system in the industry level

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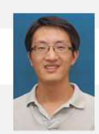
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