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Perpendicular MTJ stack development for STT MRAM on Endura PVD platform

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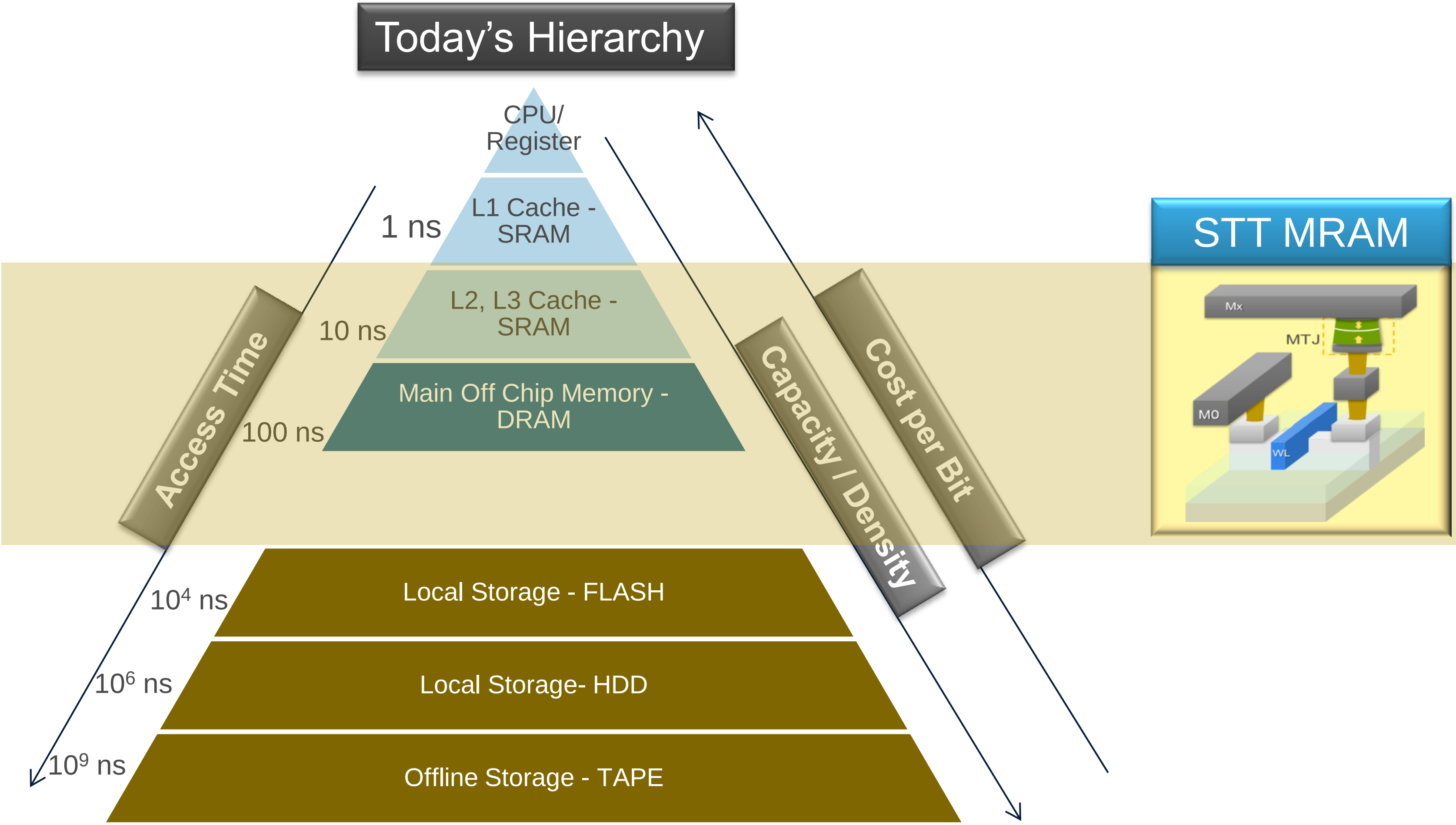
**All data in presentation is internal Applied generated data*

OUTLINE

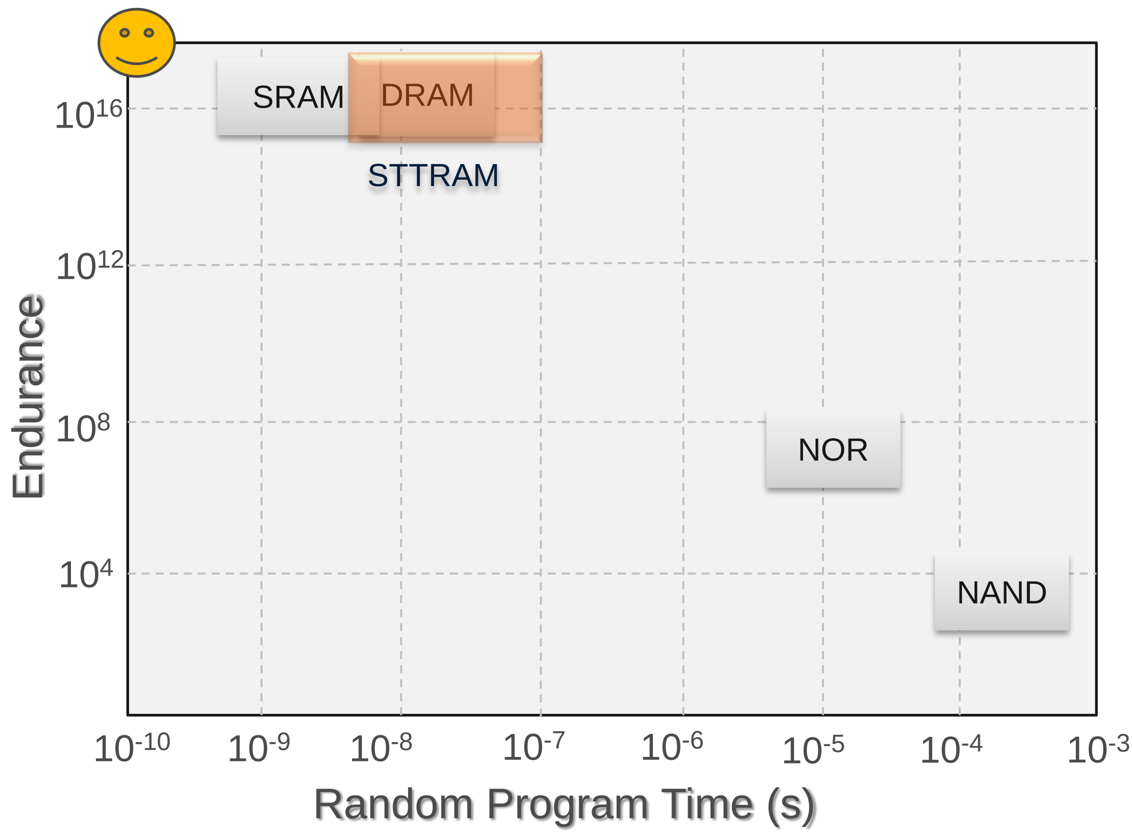
- STT MRAM Background
- Perpendicular Magnetic Tunnel Junction Basics
- Perpendicular Magnetic Tunnel Junction Using Endura PVD

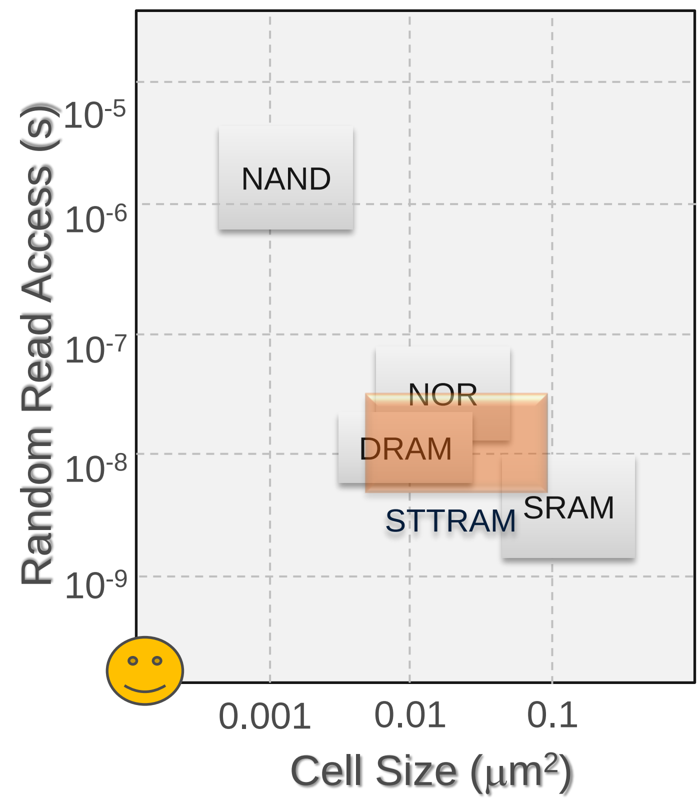
Key Drivers for STT MRAM



Scaling challenges of current RAM
Latency gap between Storage and RAM

Memory Performance Comparison



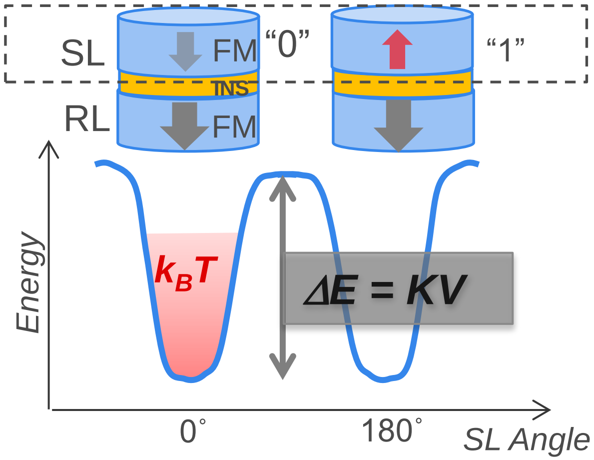


- STT RAM attributes: Endurance, Fast Access & Non-Volatility

STTRAM BIT OPERATION

Storing Data

Magnetic direction of storage layer



K, Anisotropy is material property and,
V is the volume of storage layer

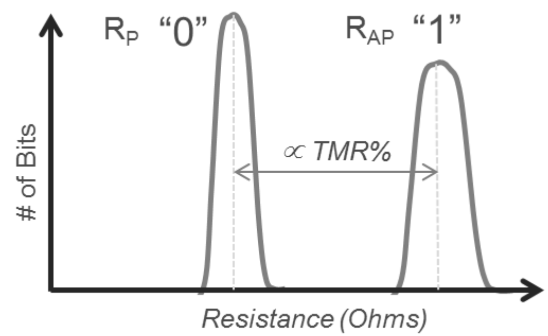
N-B thermally activated flip probability:

$$F\ (t) = 1 - \exp\left[-N\frac{t}{\tau_o} exp\left(-\frac{\Delta E}{k_B T}\right)\right]$$

Δ (= $\Delta E / k_B T$) is a measure of length of data retention.

Reading Data

Reading is done by sensing the resistance (high or low)



Tunneling Magneto-resistance (TMR):

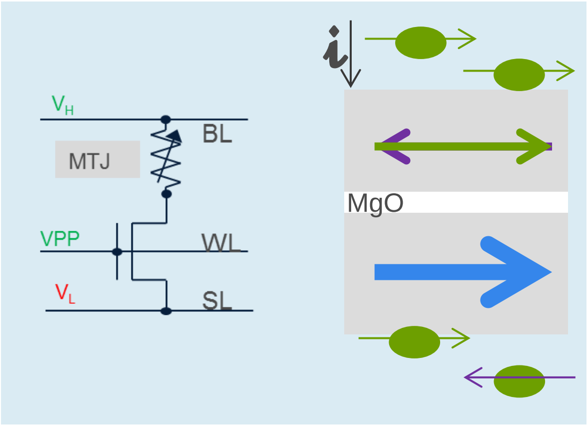
$$\text{TMR\%} = \frac{R_{AP} - R_P}{R_P} \times 100$$

High TMR% and low σ (R) for fast read

Writing Data

Writing is done using Spin Transfer Torque (STT) switching

(MRAM, a precursor used magnetic field writing – not scalable)



Switching current:

damping const.

$$I_c \propto \frac{\alpha}{\eta}(\Delta)$$

spin polarization

Low I_c at high Δ is one of the tradeoffs in design

Switching Current (Writing) vs. Data Retention

Switching Current (I_{co})

moment of SL

damping const.

Volume of SL

$$I_{co} \propto \frac{\alpha\ M\ V}{\eta}\left(H_{eff}\right)$$

spin polarization

effective field

Data Retention / Thermal Stability (Δ)

Anisotropy

(~ effective field for pMTJ)

$$\Delta = \frac{V H_k M_s}{2\ k_B T}$$

❑ **Low I_{co} at high Δ is key challenge for Magnetic Tunnel Junction (MTJ) stack development (along with high TMR, large pinning and thermal stability of stacks)**

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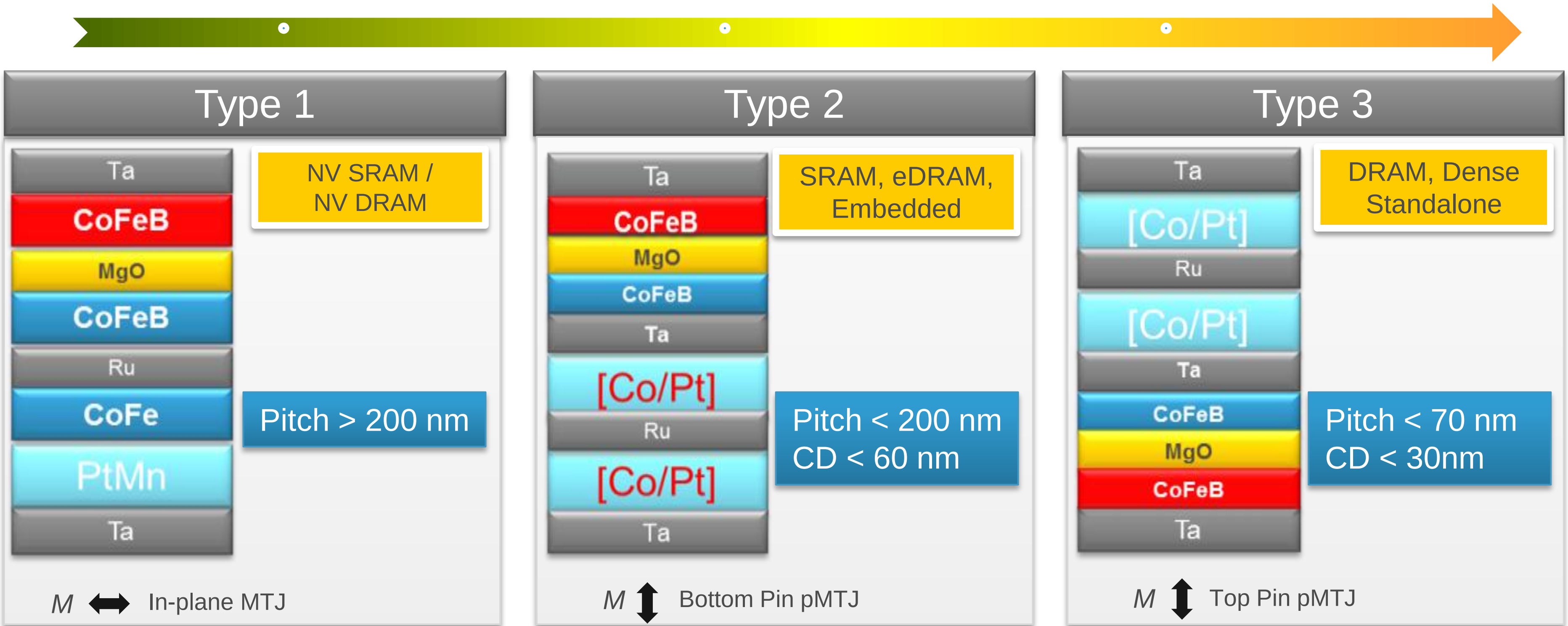
STT RAM Technology Options



- ❑ Perpendicular MTJ preferred for scalability
- ❑ Many new thin films (few Å) and, interfaces to control

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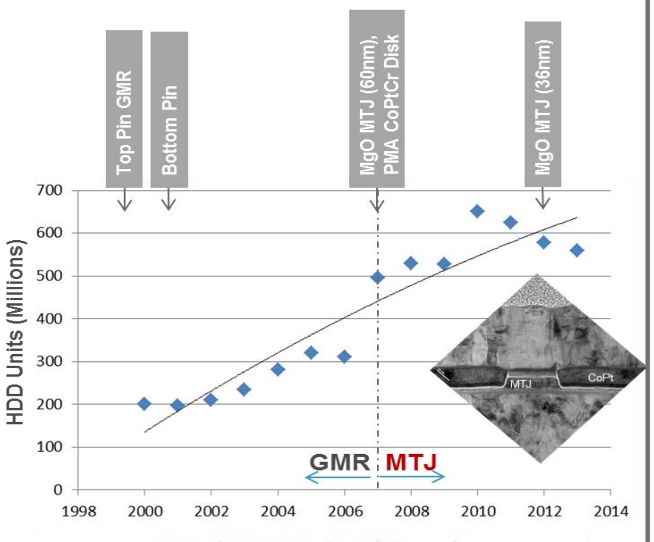
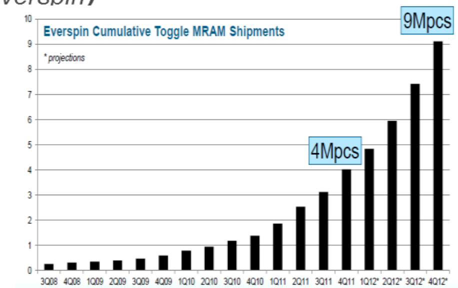
Key Enabler: Magnetic Tunnel Junctions (MTJ)

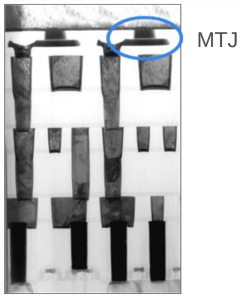
HDD: First Adopter of MgO MTJ
(WDC, HGST, Seagate, TDK)



Gartner/Tomklin

MRAM:
(Everspin)





RIE based approach for MTJ Patterning

STT MRAM

Sampling:
Everspin
TDK/Headway

Developing:
Toshiba/Hynix
Samsung
Global Foundries
Micron
Intel
.
.
.
.

IN PRODUCTION **Pilot/R&D**

- ❑ In-plane MTJ manufacturability demonstrated in HDD/MRAM (in products since 2007)
- ❑ Current Industry focus is on Perpendicular MTJ to enable high density arrays

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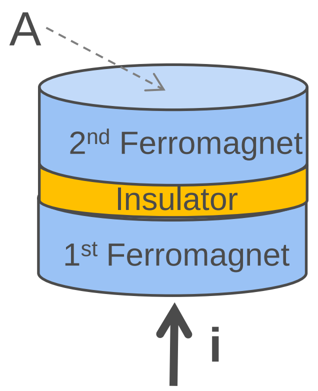
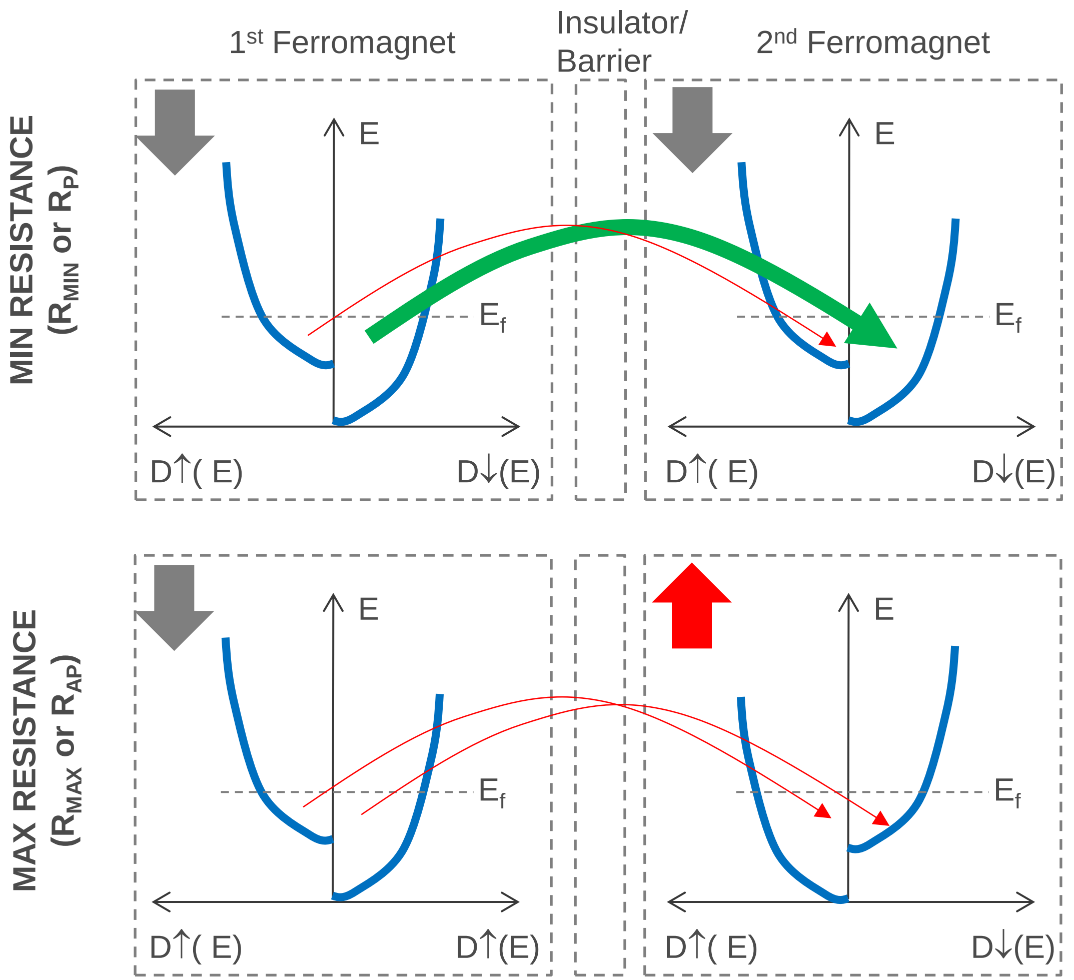
Magnetic Tunneling Junction (MTJ)



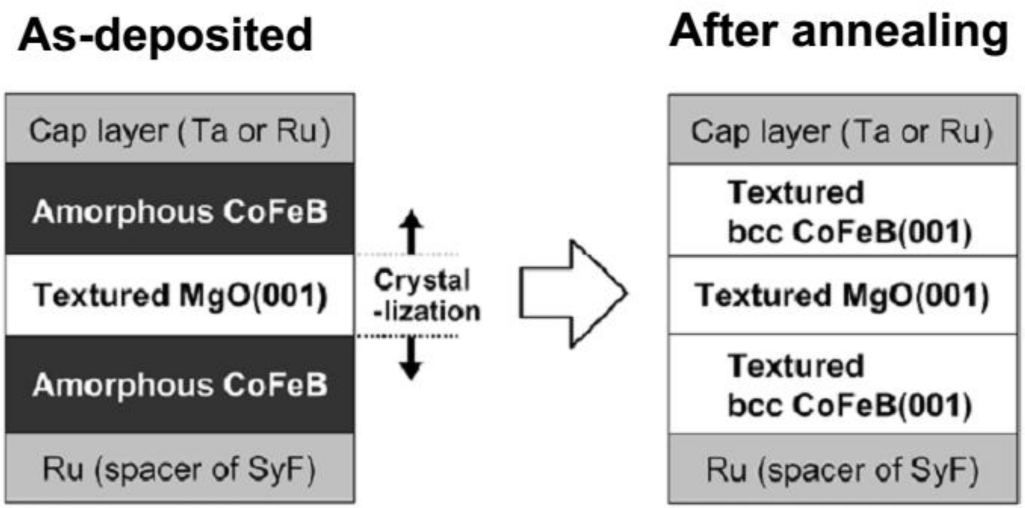
$$RA(\Omega.\mu m^2) = R_P \times A$$

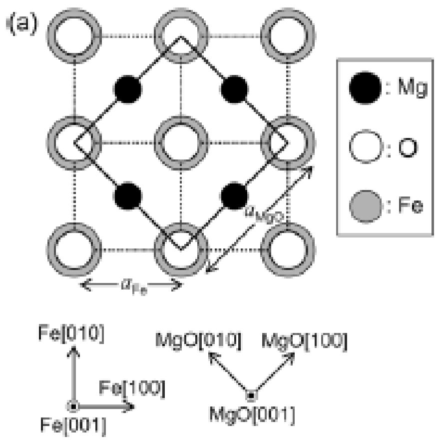
$$TMR\% = \frac{R_{AP} - R_P}{R_P} \times 100$$



- ❑ 2 spin independent channel conduction – amorphous barrier
- ❑ Spin filtering for tunneling through MgO crystalline barrier

Growth and Annealing of MgO MTJ





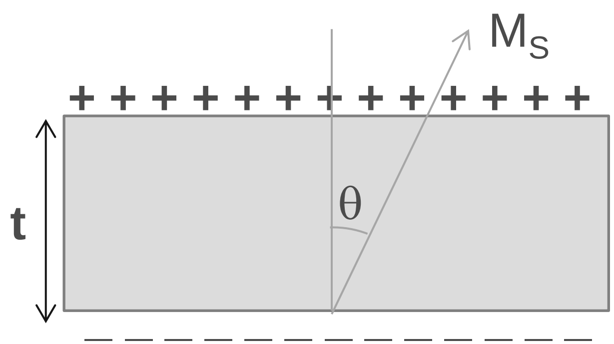
S.Yuasa et al, J. Phys. D: Appl. Phys. ***40*** *(2007) R337–R354*

- ❑ Annealing at 300˚ to 450˚C to obtain high TMR%

Anisotropy in Magnetic Films

Anisotropy: Preferred direction/axis of magnetization. Many sources…only 2 shown here

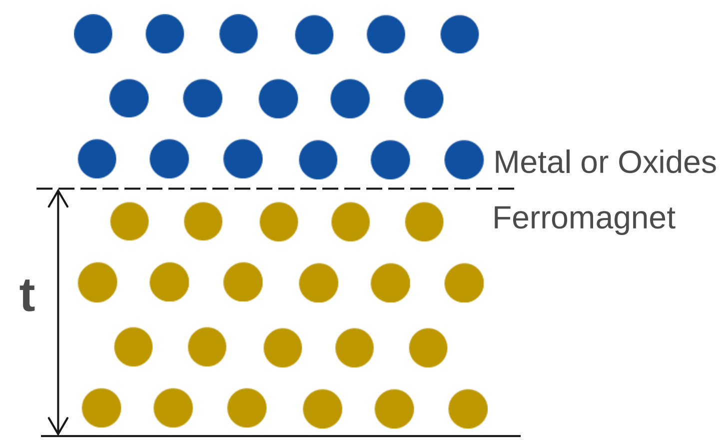
- ❑ Shape Anisotropy (in-plane)
  - ❑ Demagnetizing field (H_D)



$$H_D = 4\pi M_S \cos\theta$$

film prefer in-plane magnetization, to reduce demagnetization field/energy

- ❑ Interfacial Anisotropy (⊥ to plane)
  - ❑ Symmetry breaking
  - ❑ Strain
  - ❑ Electron hybridization



$$K = K_V + K_S / t$$

Effective Anisotropy — bulk — interface

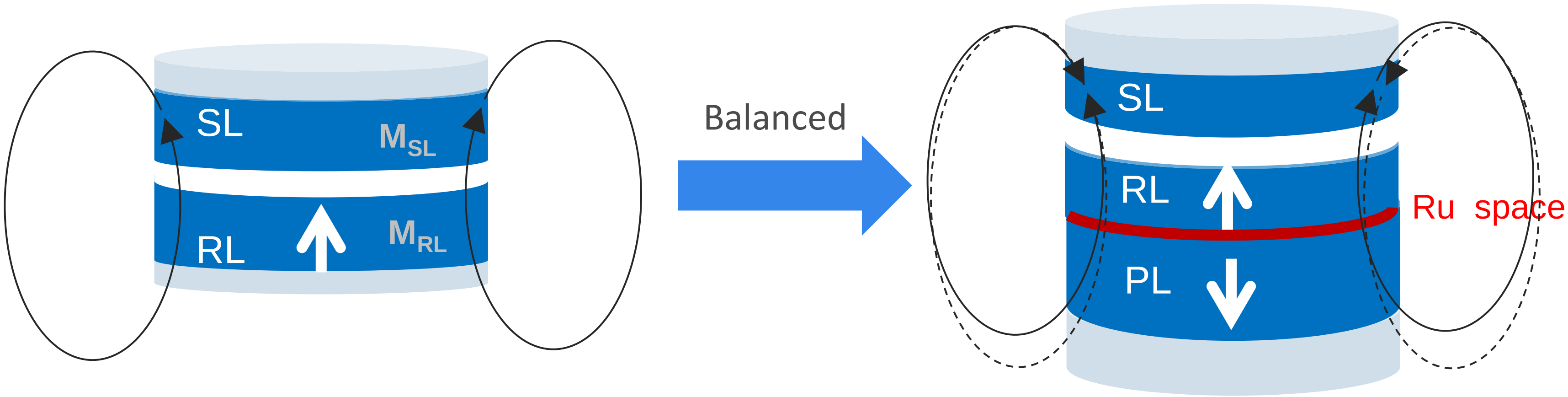
$$H_K = 2K / M_S$$

For a film to have **perpendicular (⊥) magnetization**, need to satisfy:

$$\mathbf{H_K - H_D > 0}$$

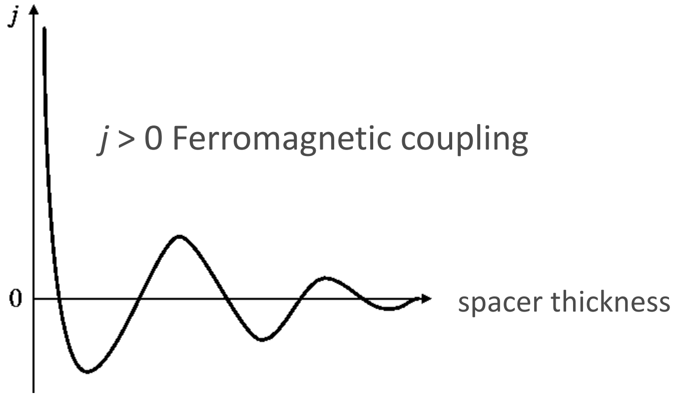
Stray Field Balance in MTJ: SAF

SAF: Synthetic Anti-Ferromagnet



RKKY Oscillatory Coupling in non-magnetic spacer layer (Ru, Ir, Cr,…)

Eg., CoFe\Ru\CoFe(FCC)

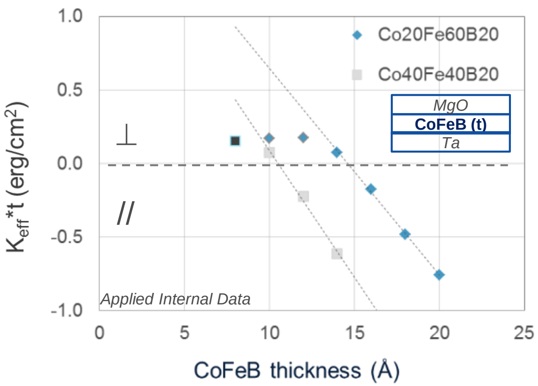


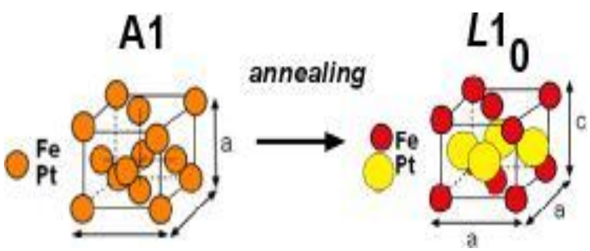
- ❑ Reduces stray field on storage layer.
- ❑ Increases pin layer stability

STT MRAM: pMTJ Stack Engineering Summary

PMA

Interface & Bulk PMA

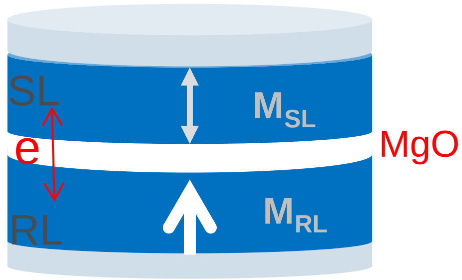




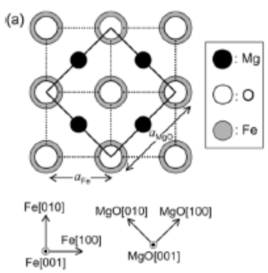
Thickness and thermal budget control

Basic MTJ

Spin Dependent Coherent tunneling

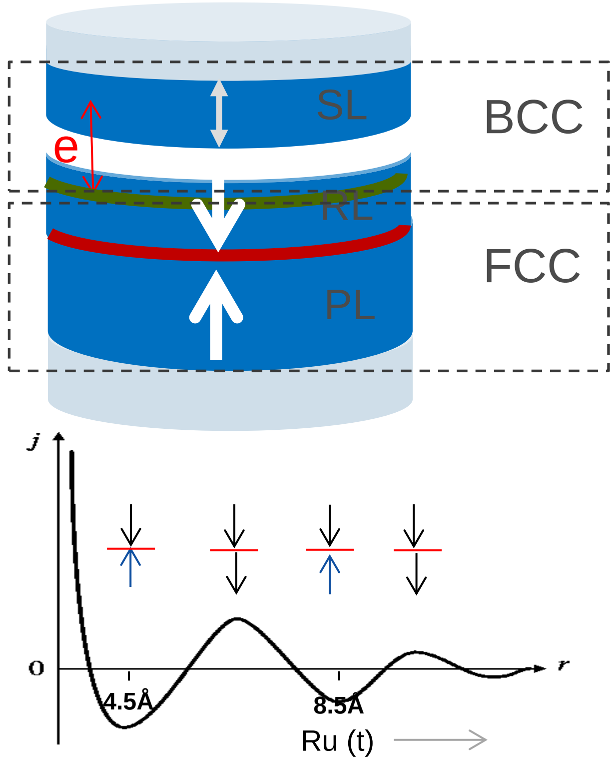


Atomic level matching across interface



SyAF /SAF Pin MTJ

RKKY coupling



RKKY coupling as function of Ru thickness

- ❑ Sub Å control of film thickness and interface roughness
- ❑ MgO growth condition for crystal texture/quality (low impurity, OH) and anneal
- ❑ Crystalline texture for magnetic materials

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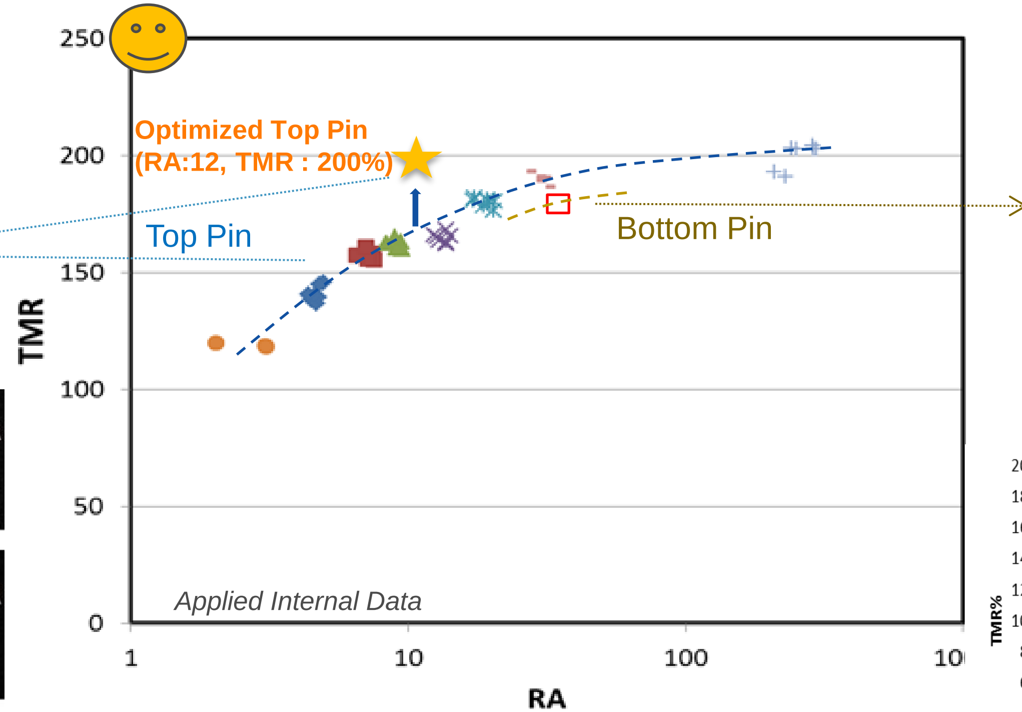
Perpendicular MTJ Stack Deposition

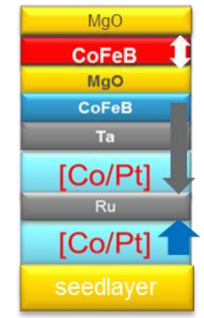
Endura PVD Platform

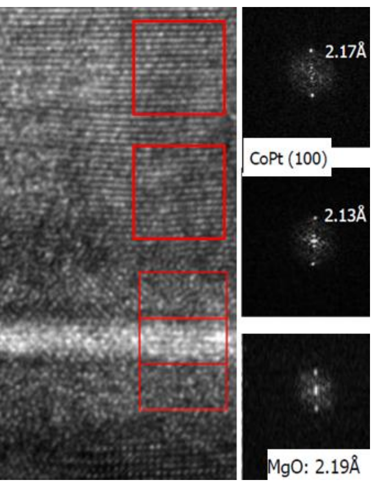
Perpendicular MTJ Stack Blanket Film Performance:
Transport/Tunneling (CIPT)

Top Pin

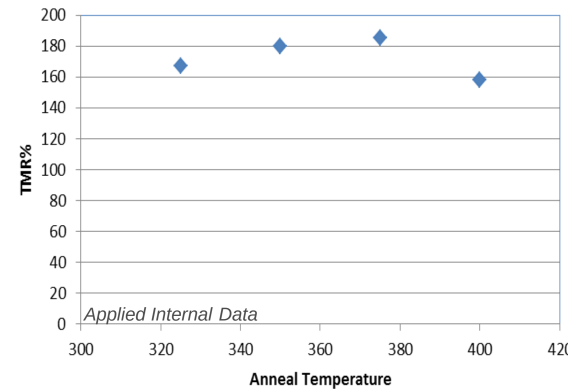


Bottom Pin



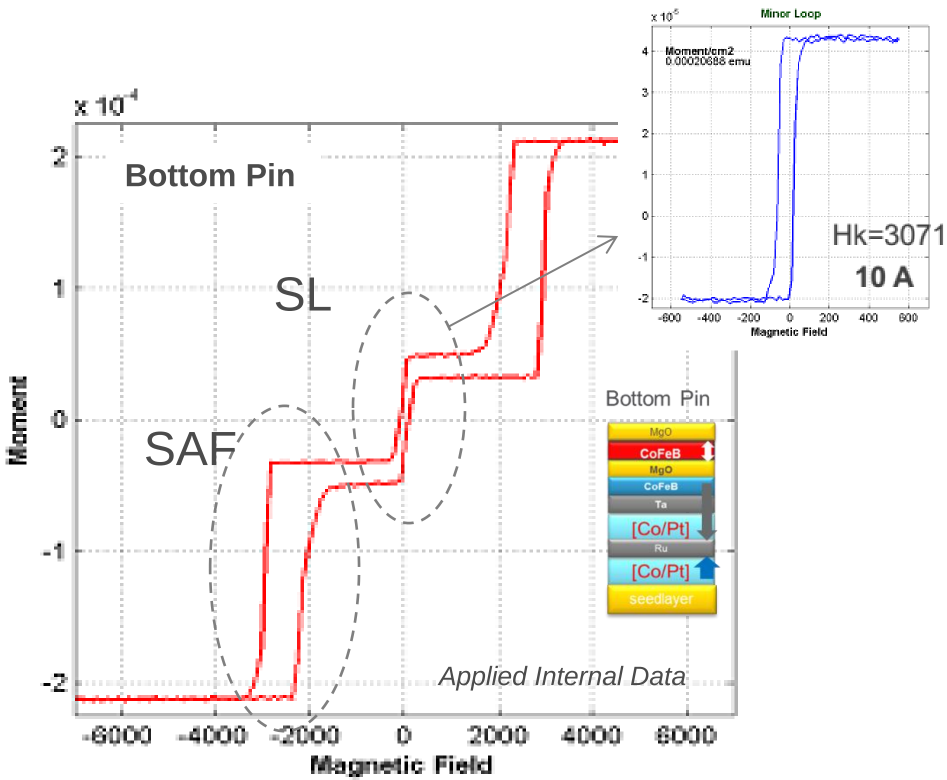


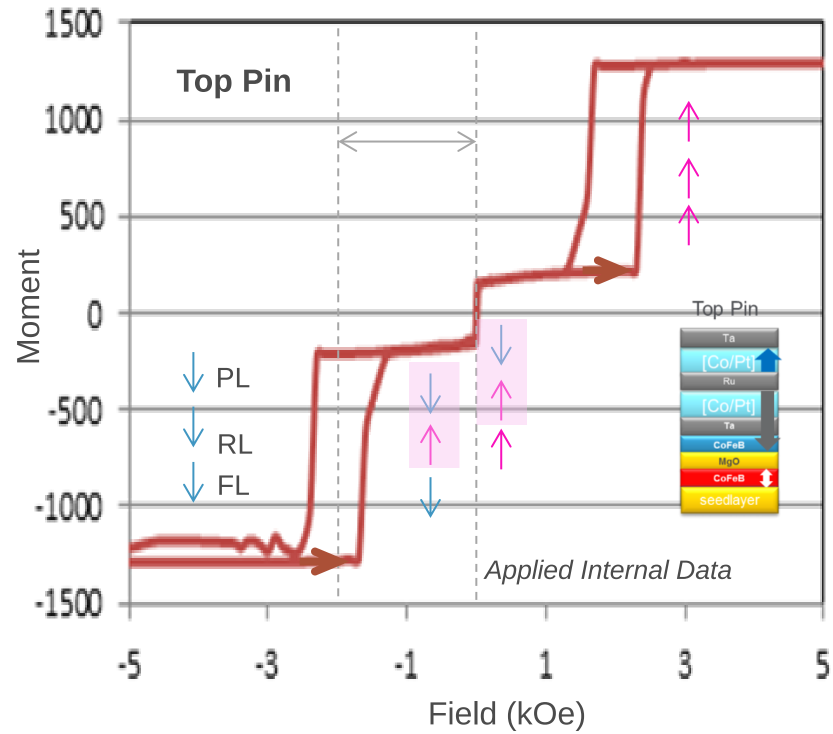
Thermal Stability of Bottom Pin



High TMR and BEOL Thermal Budget Compatibility for MTJ Stack Dep

Perpendicular MTJ Stack Blanket Film Performance, Magnetics (VSM)

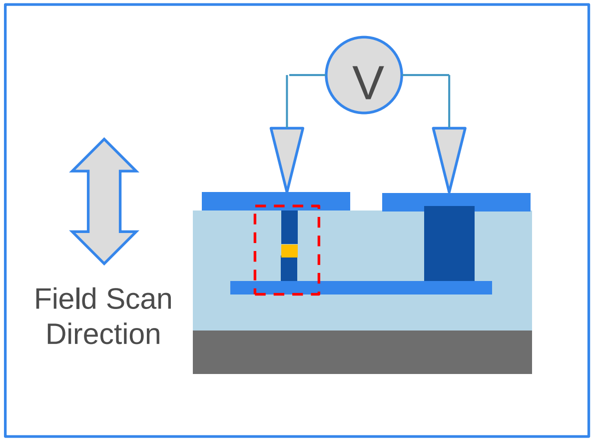


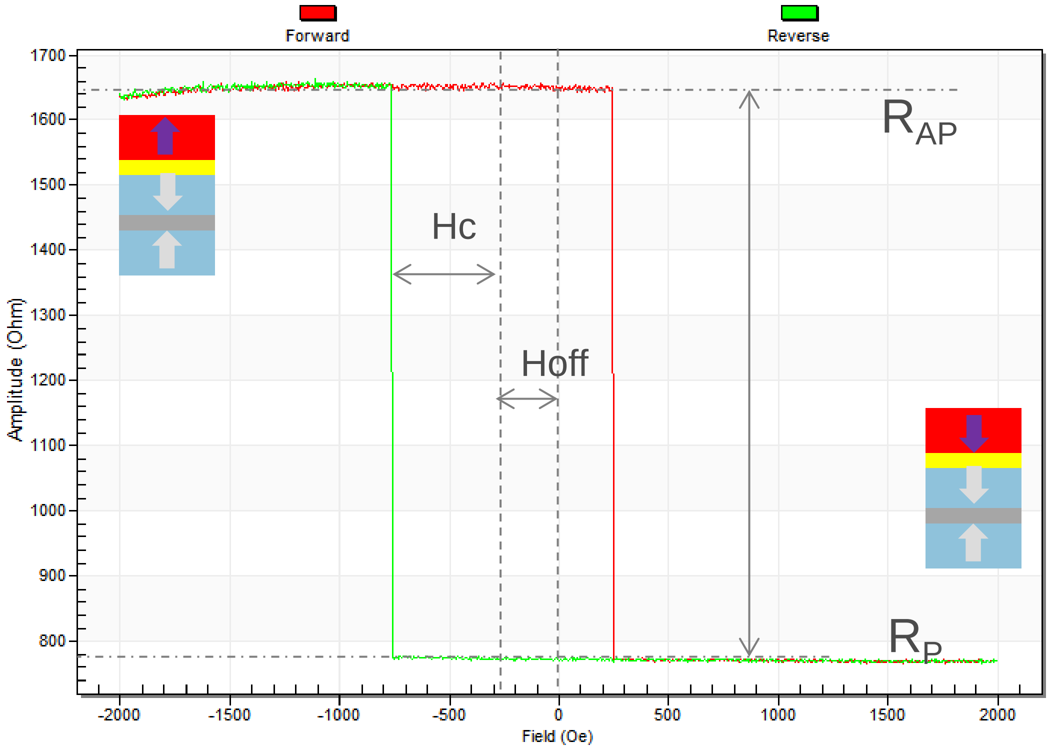


- ❑ Large pinning strength for SAF and square loop for Free Layer

Patterned pMTJ Performance Metrics

1) Quasi Static Test (measure MTJ resistance as field is scanned),
2) Pulse current measurements





High TMR for fast read

Low H_{off} for reliability

Low R_P sigma for yield

High H_c (∝ Hk) for data retention

$$TMR = \frac{R_{AP} - R_P}{R_P} \times 100\%$$

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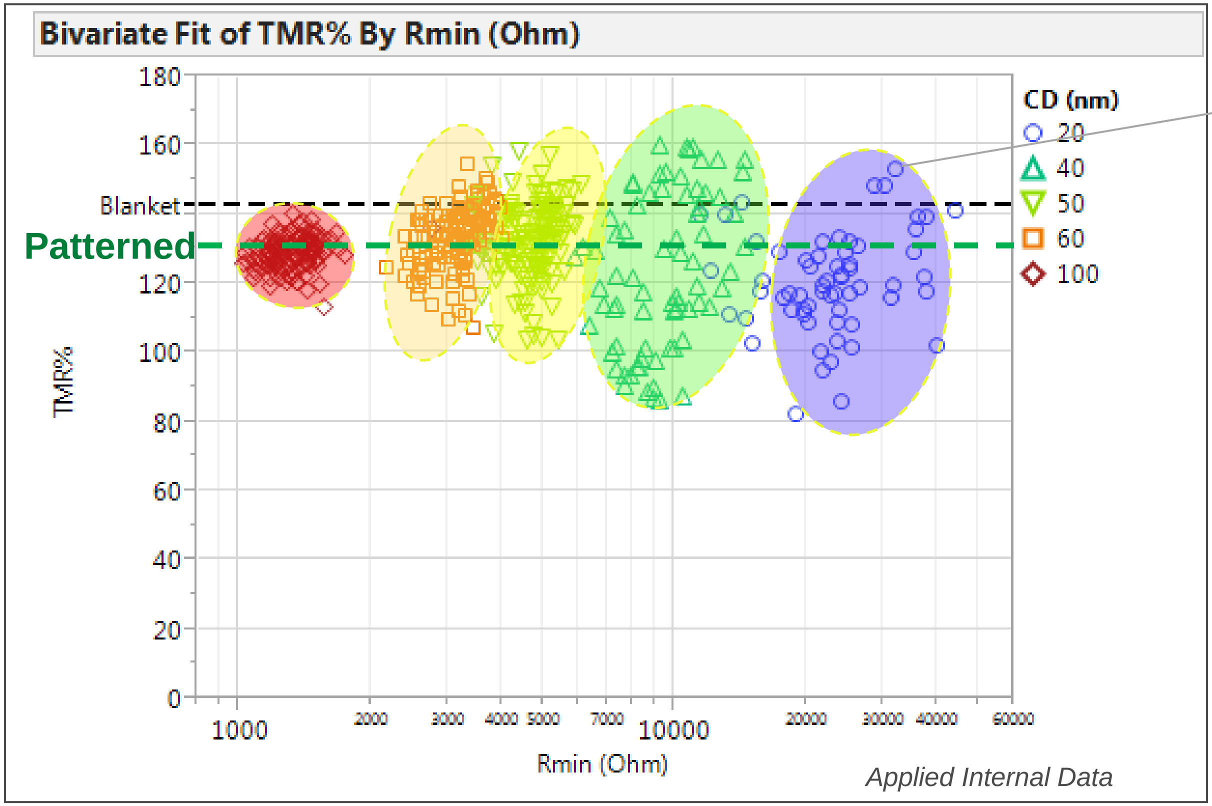
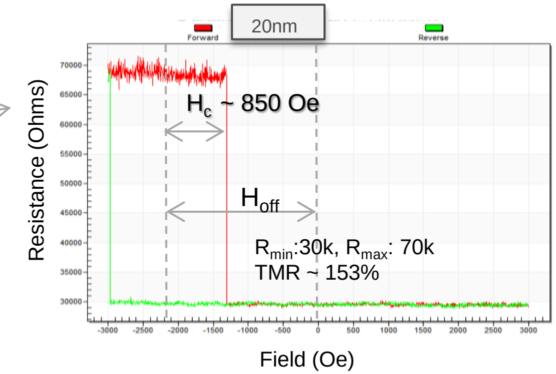
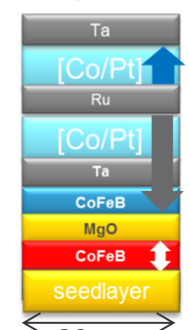
MTJ Size Dependence (Patterned): Top Pin





Top Pin



20nm
(smallest CD)

- ❑ High TMR and H_C can be achieved by MTJ stack optimization and etch process tuning.
- ❑ 20nm bits with highest TMR of ~ 153% and Hc ~ 850 Oe.

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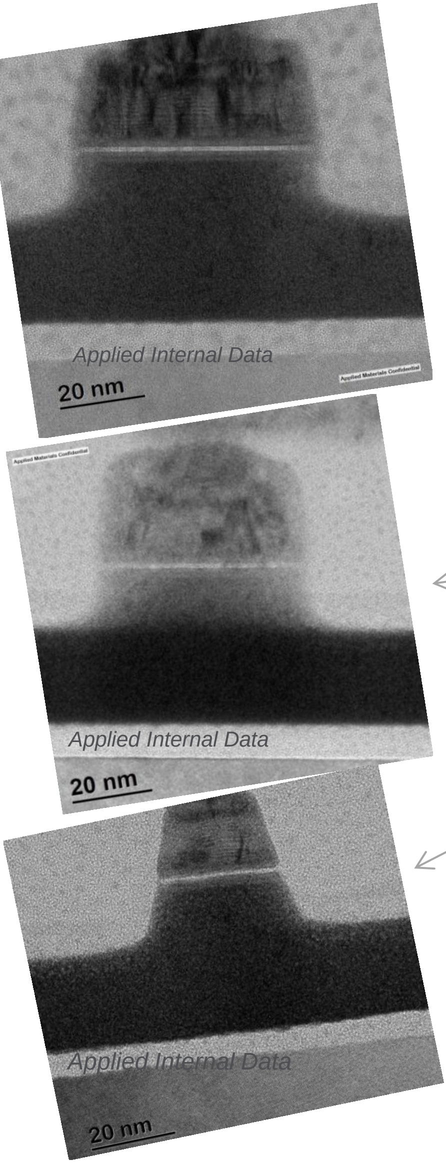
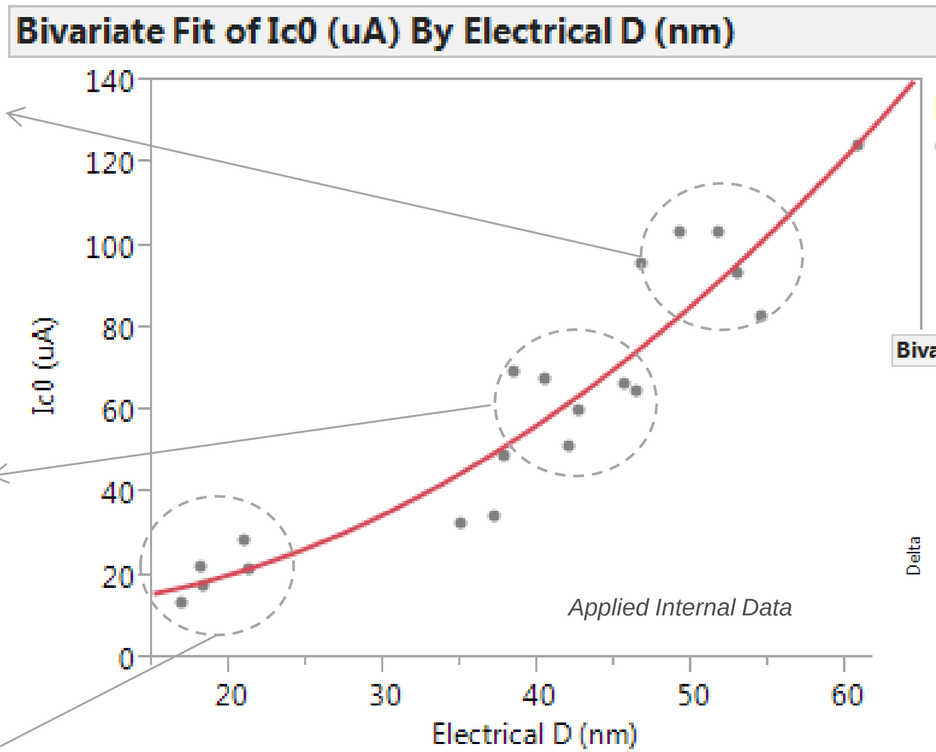
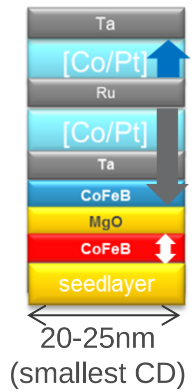
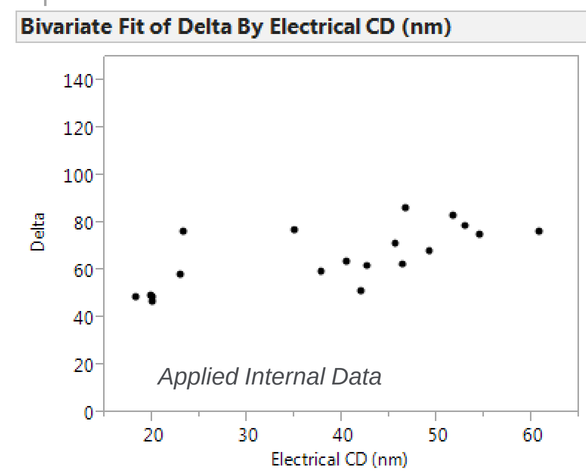
Switching Current (Ic) & Scalability





Top Pin





- ❑ Low switching current (~ 20uA) obtained by pMTJ stack optimization
- ❑ Δ (data retention) ~ 50 for ~ 20nm.

Summary

- STT MRAM offers good endurance, speed and non-volatility. Hence being considered for embedded, cache and stand alone memory.
- One key challenge for making high density STT MRAM is developing materials with low switching current (I_{co}) at high thermal stability (Δ), with high TMR% & pinning.
- Using Endura PVD system, perpendicular MTJ stacks with performance suitable for dense arrays were demonstrated.
  - Blanket film performance: TMR ~ 200% at RA ~ 12. Pinning > 2kOe.
  - 20nm patterned MTJ: I_{co} of ~ 20uA, Δ > 50, patterned TMR of ~ 153%

Thanks for your attention!

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