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make possible

Challenges and Process Solutions for STT MRAM Scaling

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Applied Materials, Inc.

AGENDA

New Memory Application Space

Applied Solutions for MRAM

MRAM Scaling (Process and Device)

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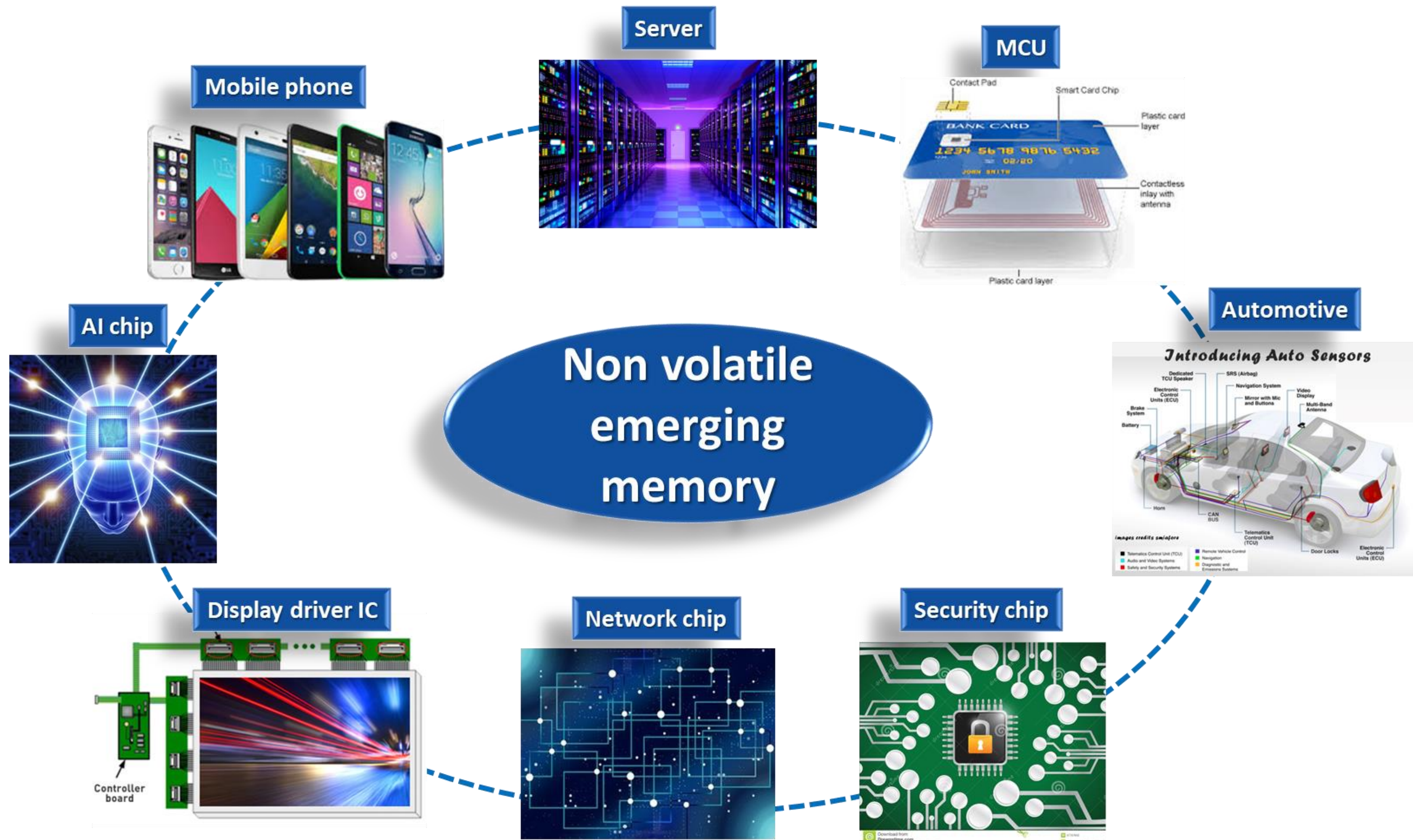
Emerging Memory | Markets



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AI – Big Data Driving a Renaissance of Hardware Development and Investment

	INITIAL DEPLOYMENT	CLOUD		EDGE
Accelerators GPU, TPU, ASICS, FPGAs	Now	✓		Autos
Near Memory DDR, SRAM, HBM, NAND, SCM	Now to 2 years	✓		✓
New Memory MRAM, ReRAM, PCRAM, FeRAM	Now to 5 years	✓	←	✓
In-Memory Compute Analog, ReRAM, PCRAM	2 to 5 years	✓	←	✓
Novel HPC Quantum, Synaptic	5 to 10 years	✓	→	✓

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New Memory Outlook

Product Availability

- MFG / Ready
- Sampling

← Performance

	STT MRAM	HfOx FEFET	NRAM	OXRAM	CBRAM	PCM
MEMORY	LRS / HRS: FL CoFeB, MgO, RL CoFeB, [Co/Pt]y, Ru, [Co/Pt]x, SAF	Low Vt / High Vt: Gate, HfOX, channel	Low R / High R: Electrode (TiN), Electrode	LRS / HRS: Electrode, TaO_x, Ta_2O_5, Electrode	LRS / HRS: Electrode, Cu/Ag reservoir, Electrode	LRS / HRS: GeSbTe, Electrode
Standalone* **(node)**	256Mb/1 Gb (40/22nm, ES/GF)	R&D	*R&D*	4 Mb (180nm, Fujitsu)	*R&D*	128 Gb (20nm, Intel, Micron)
Embedded* **(node)**	< 100 Mb (2xnm SEC, TSMC)	*R&D*	*R&D*	64 kB (180nm, PAN)	0.512 Mb (> 100nm, Adesto)	*128 Mb (28nm, ST)*
Cell Size (F2)	10 – 20	10 - 20	< *4 - 8*	< 4 – 8	< 8 – 16	< *4 - 8*
WFE **Deposition**	**PVD**	**ALD**	**Spin Coat**	**PVD**	**PVD**	**PVD**
WFE **Etch**	**IBE / RIE**	NA	**RIE**	**RIE**	**RIE / IBE**	**RIE**

- PCRAM, STT MRAM and RERAM (OxRAM and CBRAM) enter volume manufacturing phase
- PVD is preferred process to deposit these complex material systems
- RIE is preferred etch process. IBE being introduced for scaled STT MRAM

**Announcements from Everspin, GF, SEC, Panasonic, ST, Adesto, Techinsights*

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Example of Elements to Enable New Memories

Periodic Table of the Elements

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Series															
Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

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PCM, Selector
- M-K. Lee, IEDM 2012
- G.H. Kim, APL 2012
- L. Zhang, IEDM 2014

STT-MRAM
- K. Ando, JAP 2014

FE-FET
- X. Tian, APL 2018
- A. Pal, APL 2017

CBRAM
- Adesto Technologies, IEEE 2013 talk

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New Memory Application Space

Applied Solutions for MRAM

MRAM Scaling (Process and Device)

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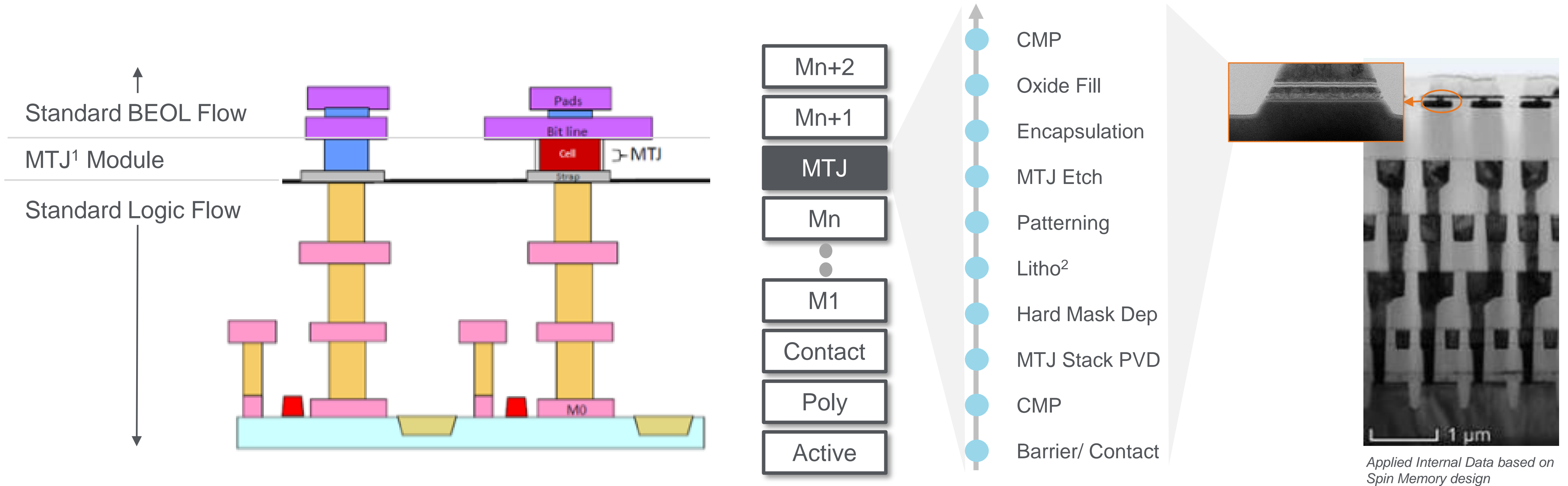
STT MRAM Fabrication | Typical Process Flow



Applied Internal Data based on Spin Memory design

MTJ Module conveniently inserted in logic flow with up to 4 additional masks[2]

[1] *MTJ: Magnetic Tunnel Junction*

[2] *Optional bottom and top contact and mark open mask steps*

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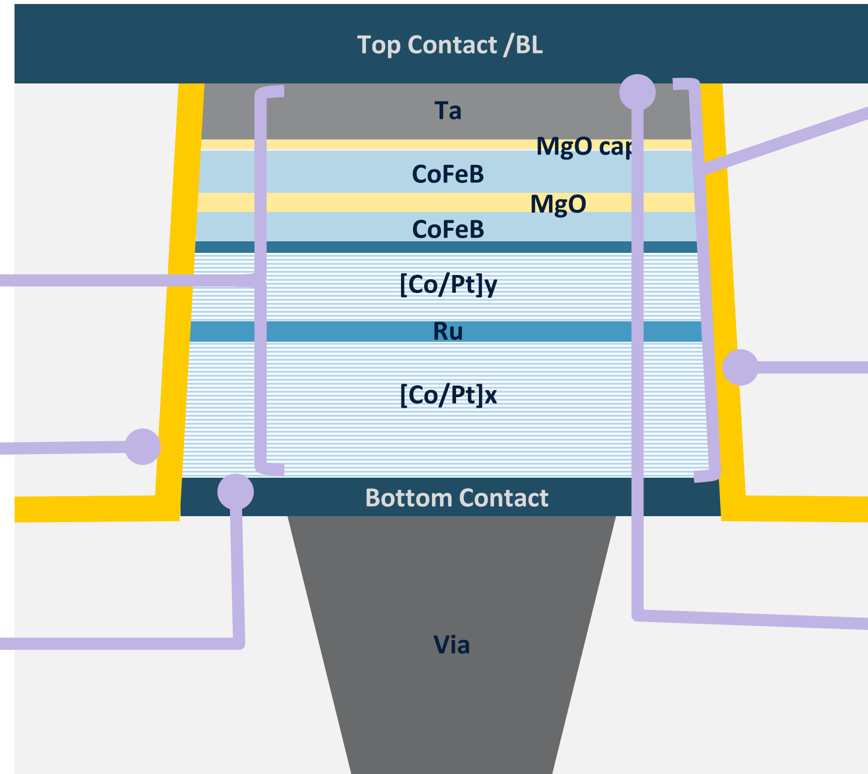
MTJ Module Fabrication | Critical Steps

MTJ PVD:
- Complex stack of 30+ layers
- Precise thicknesses & uniformity
- Sharp interfaces
- Formation / preservation of textures
- MgO stoichiometry & defect control

ILD: Low Temp

Bottom-electrode CMP:
Atomic smooth surface



MTJ Etch:
- No re-dep on sidewall
- Minimize damage
- Non-corrosive
- Straight sidewall

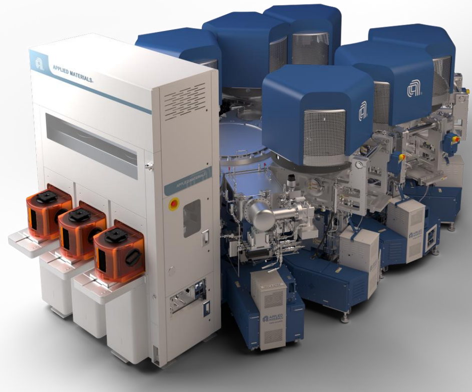
Encapsulation:
- Low Temp
- Hermetic

Oxide CMP:
- High selectivity on oxide
- Damage free

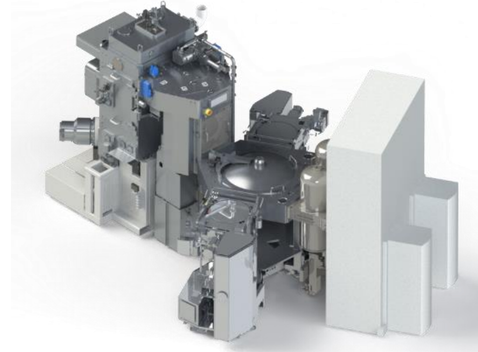
Critical: Controllability of uniformity, stoichiometry, structure, interfaces & damage free patterning
MTJ CD of 20-50nm and dense pitch is desired

MTJ Module Fabrication | Wafer Fab Equipment

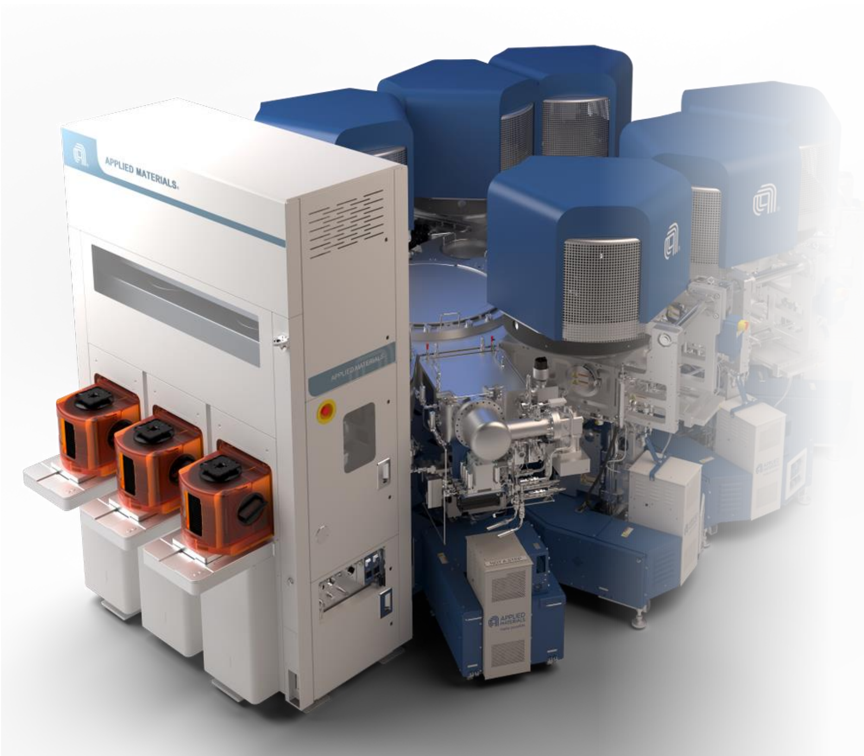
Bottom Electrode CMP	MTJ Stack Dep	MTJ Pillar Patterning	MTJ Etch & Encapsulation	Oxide Fill & CMP
LK Prime™	**Endura™ Clover**	**Centura™ Sym 3**	**Centura™**	**Producer™**



VeritySEM™ (Metrology)



MTJ Stack Dep: Endura® Clover™ MRAM PVD System



- Ultra-high purity environment for pristine film and interface → **UHV platform (low E-9)**
- Complex cell stack → **Multi-cathode Clover PVD chamber**
  - Complex stack: 10+ materials with 30+ layers
  - Ultrathin film in the range of a few angstroms
- High quality tunnel barrier → **Clover PVD RF-MgO chamber**
  - Critical for high on/off signal and endurance
- Special treatments → **Cooling/Anneal chambers**
  - Surface preparation, thermal treatment for optimal performance
- Stability in HVM → **OBM real-time monitoring**

Additional details in talk NEWM-202B-1 on Wednesday

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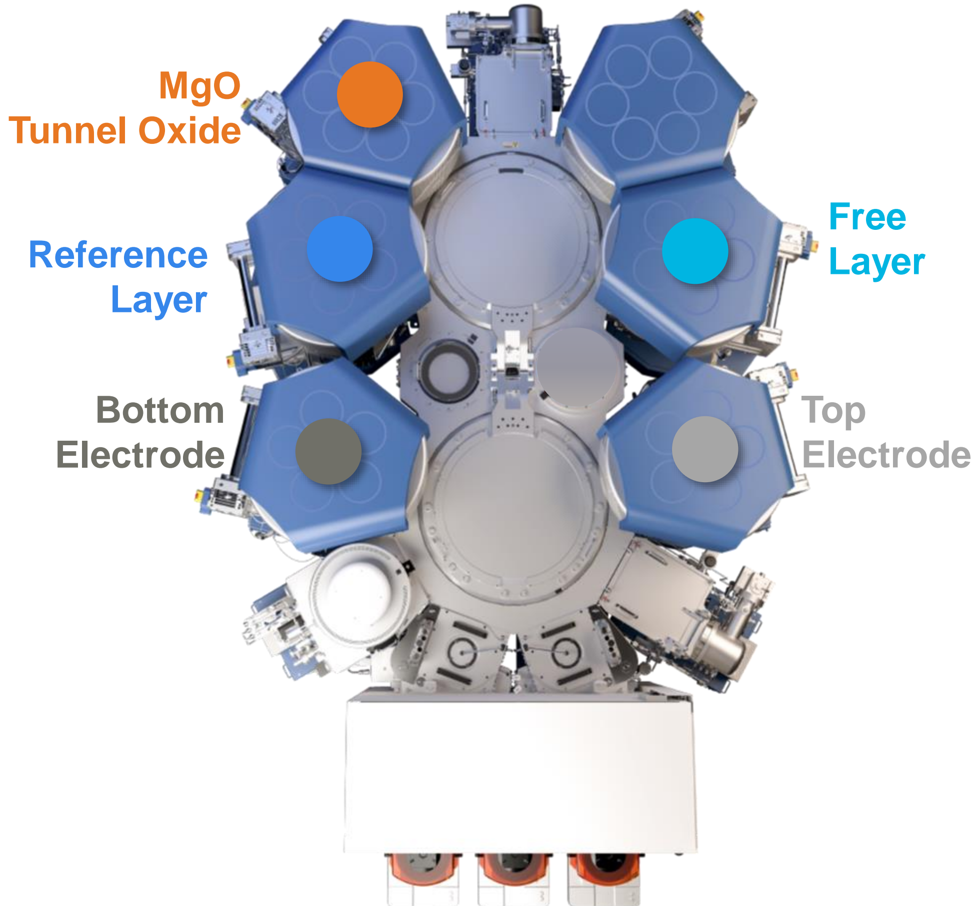
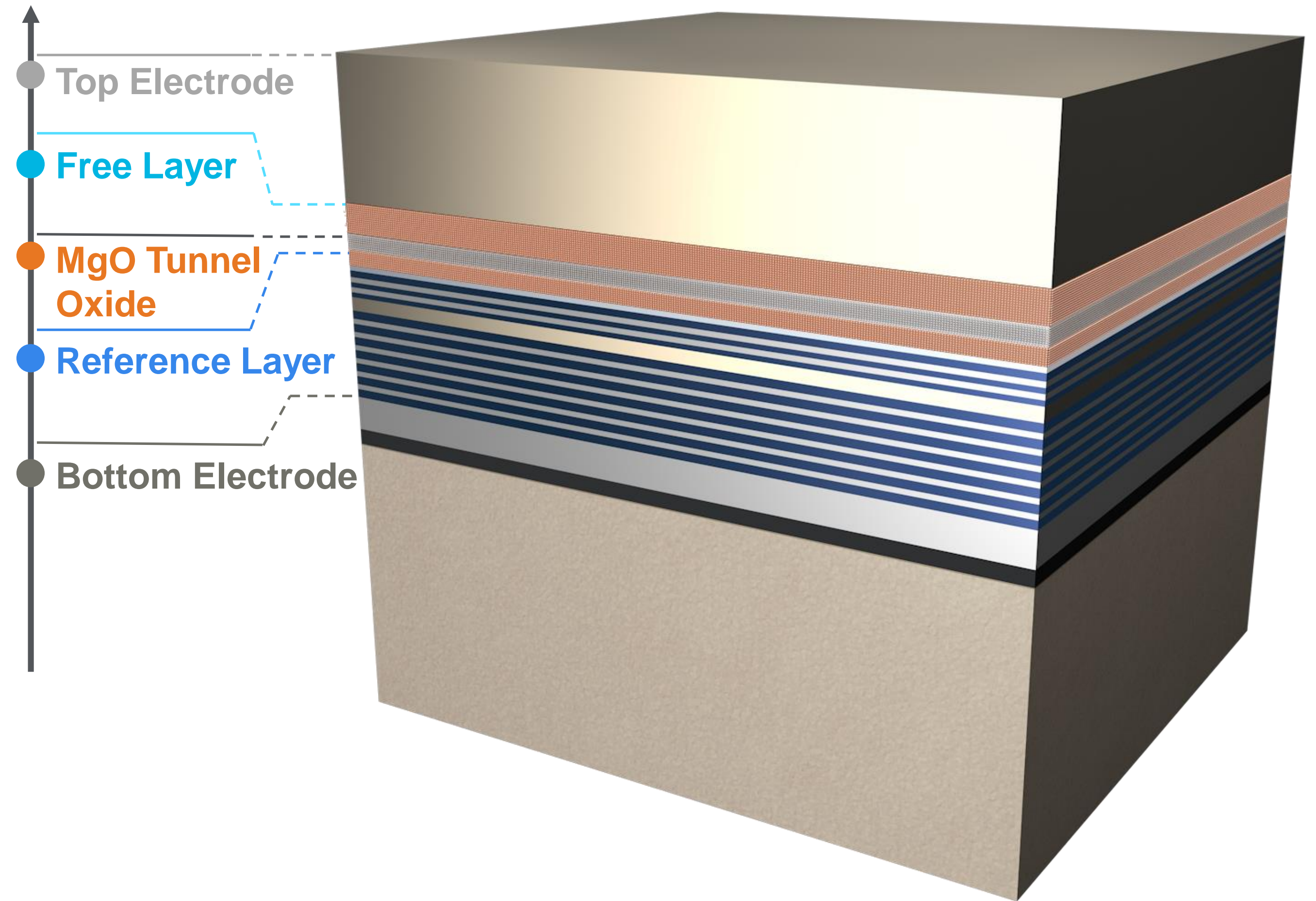
30+ Layers, 10+ Materials in Single Integrated System





Integrated Material Solution with Multi-Cathode Chambers for Complex MRAM Stack

Additional details in talk NEWM-202B-1 on Wednesday

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AGENDA

New Memory Application Space

Applied Solutions for MRAM

MRAM Scaling (Process and Device)

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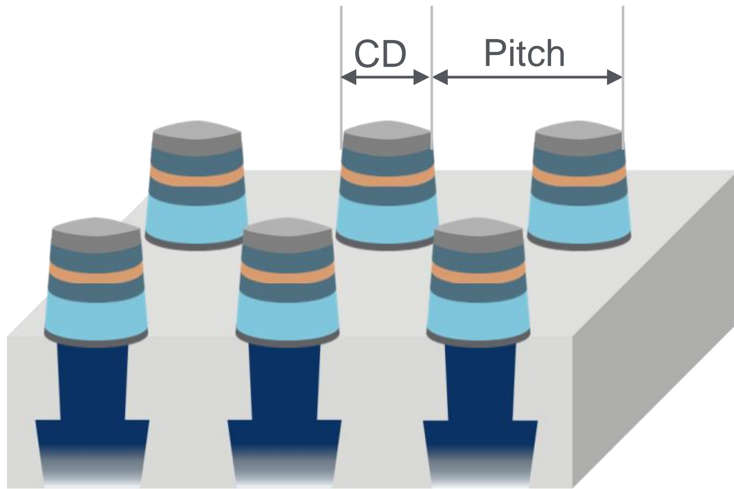
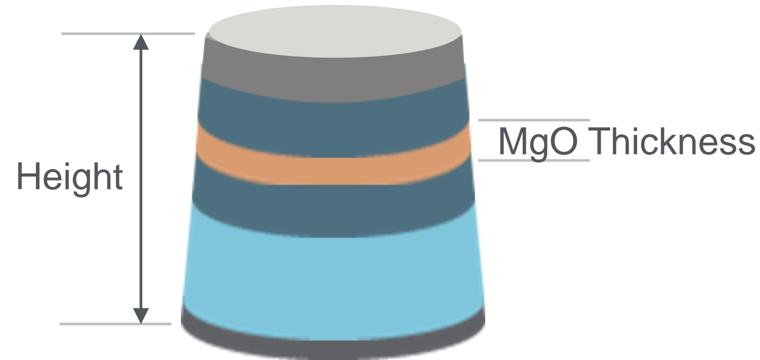
STT MRAM Scaling

Pitch and CD



Reduce pitch/CD to increase bit density (reduce cost / bit)

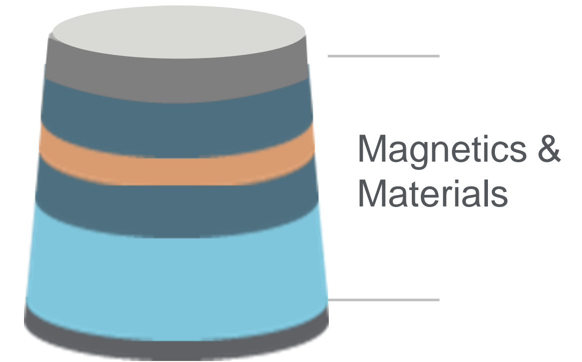
Stack Height / MgO Thickness (RA*)



Reduce height to maintain AR
Reduce MgO thickness to scale V_{DD}

Spin Efficiency

(~ Data Retention ÷ Programming Current)



Material engineering to increase spin efficiency

** RA : Resistance-Area product*

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Pitch Scaling

Key Scaling Challenge: Reducing yield loss (shorts and opens) as cell pitch shrinks

MRAM Etch Trilemma

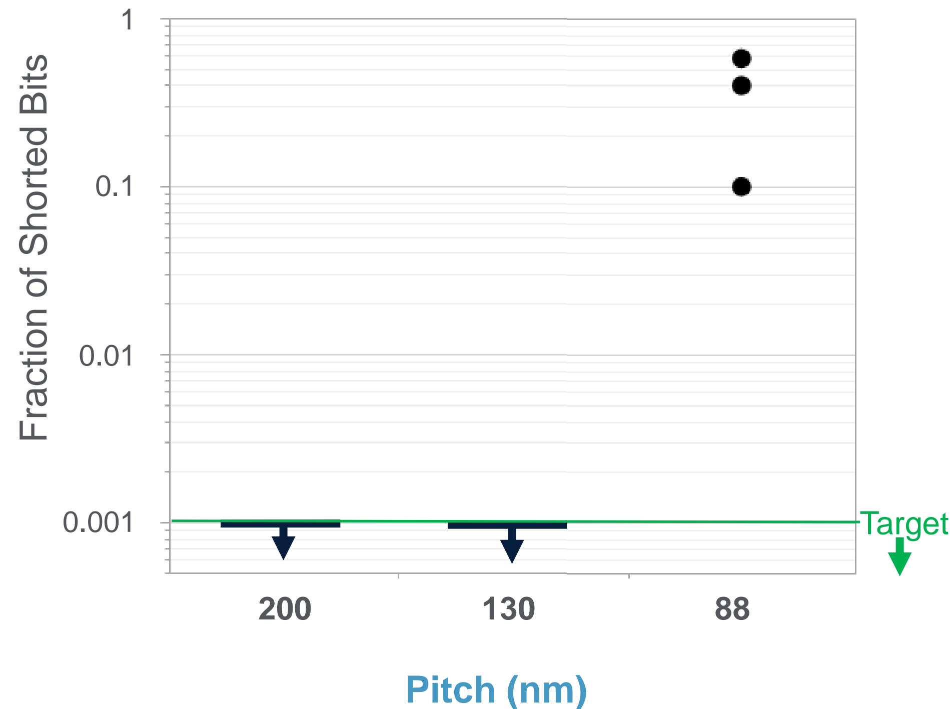
Re-dep on Pillar Side Wall (electrical shorts)

Chemical Damage (magnetics)

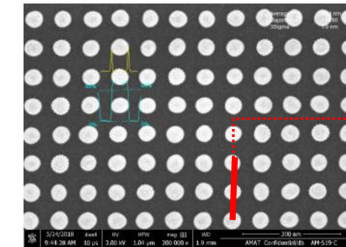
Pillar Profile (including HM)

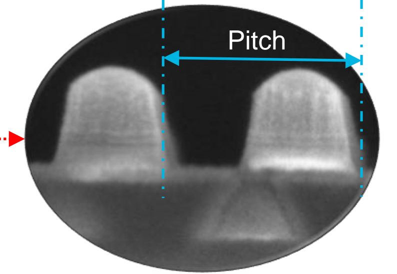
First order effects:
- Profile impacts yield (opens/shorts)
- Re-dep on pillar impacts yield (shorts)
- Chemical damage impacts performance

Shorts Versus Pitch



Etch Profile at 88nm Pitch





Pitch: 88nm;
Cell size: 0.008um^2

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Pitch scaling to next node (pitch ~ 130-150nm) demonstrated. Sub 100nm pitch area of development

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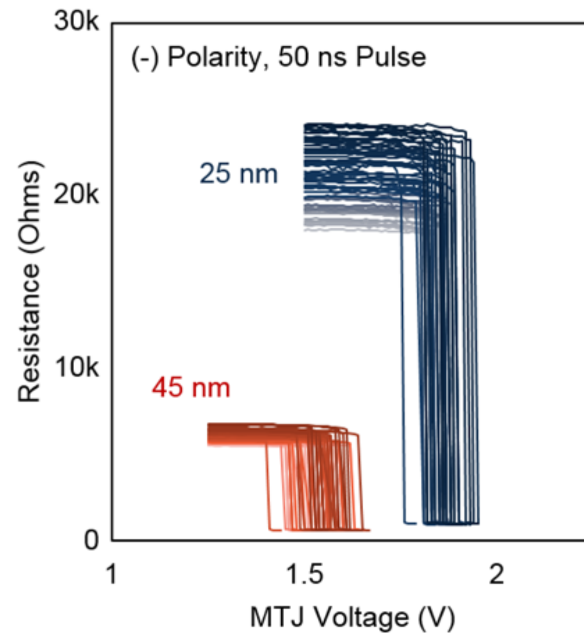
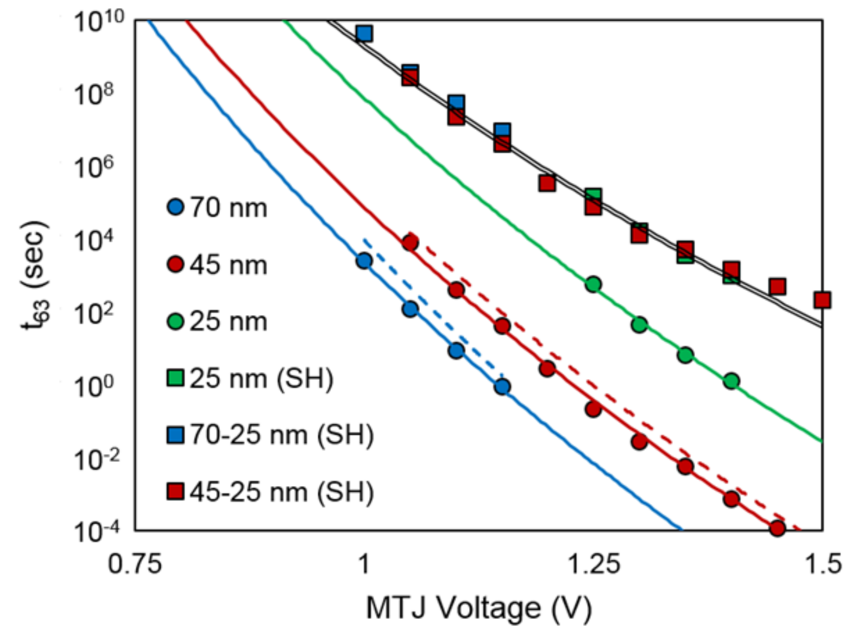
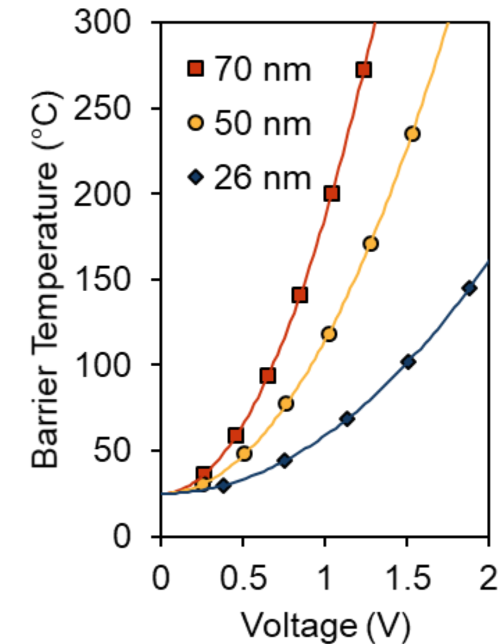
CD Scaling

Key challenge: Maintaining / reducing device resistance to conform to V_{DD}. Benefit: Positive impact on endurance

Breakdown and TDDB dependence on CD







Qualcomm & Applied, (IEDM), Dec. 2016.

MgO tunnel oxide breakdown voltage / t_{63} improves as CD (size) is reduced from thermal effect

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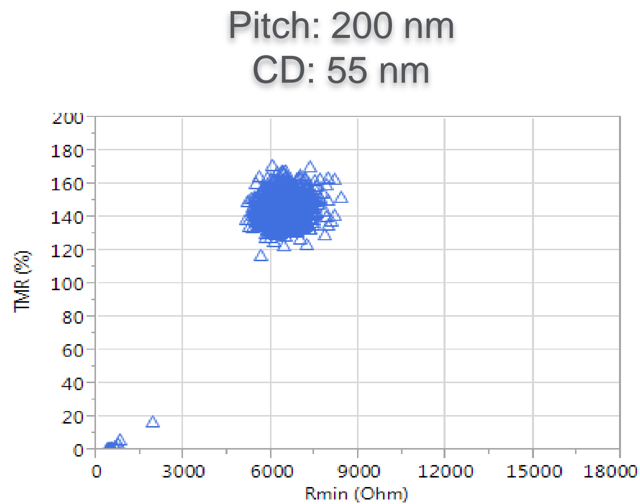
CD Scaling

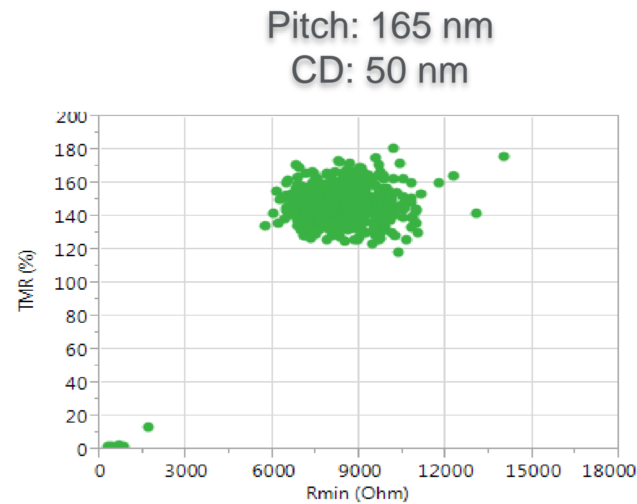
Key challenge: Increased distributions for device resistance (and magnetics)

Resistance Distribution with CD

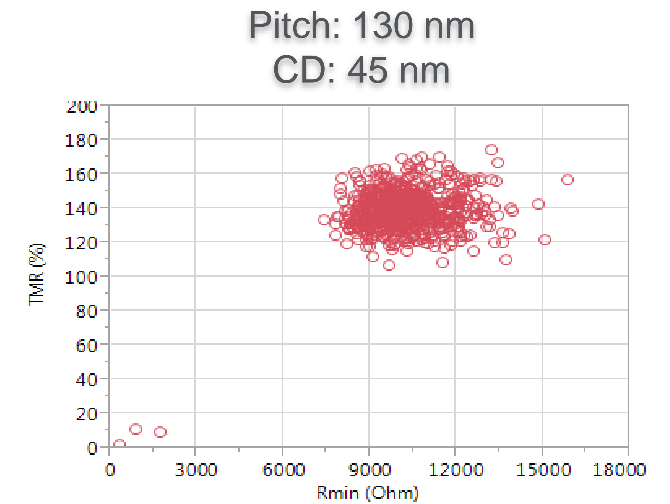
Pitch: 200 nm
CD: 55 nm



Pitch: 165 nm
CD: 50 nm



Pitch: 130 nm
CD: 45 nm



Applied Internal Data

TMR%[1] constant with CD. Resistance distributions CV[2] slightly worse for smallest CD

[1] TMR: Tunnel magneto-resistance
[2] CV : Coefficient of Variation

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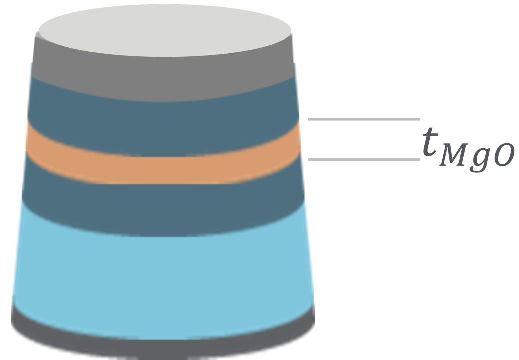
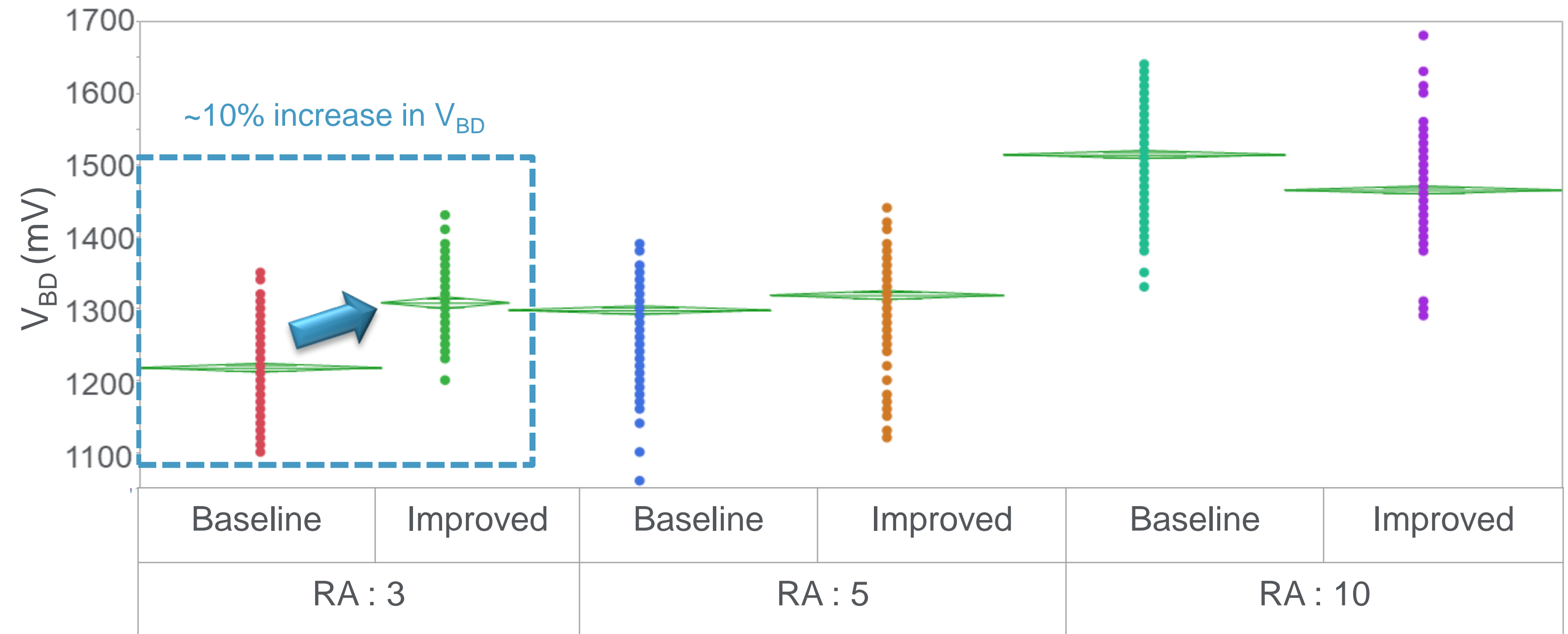
MgO Thickness (RA) Scaling

Reducing MgO tunnel oxide thickness to reduce Resistance and V_{DD}



$$RA \approx c * t_{MgO}{}^{n}$$

$$V_D = RA * J_c$$



t_{MgO}: *MgO Thickness*

Applied Internal Data

MgO tunnel oxide breakdown voltage improved by optimizing PVD process / in-situ treatment

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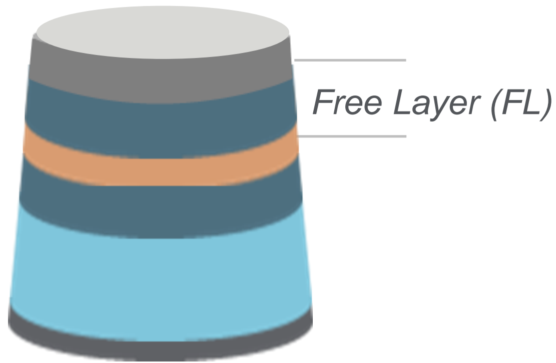
Data Retention at Low Programming Current (Spin Efficiency)

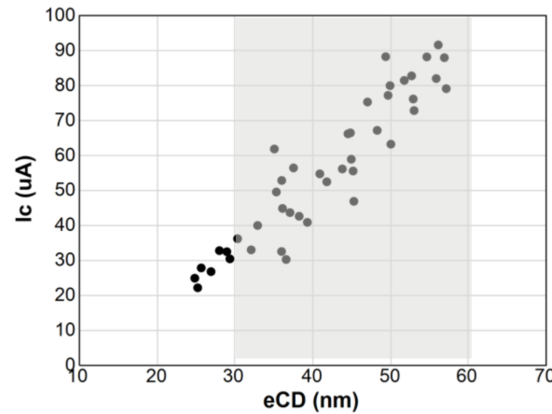
Key challenge: Maintaining data retention while reducing program current, as CD scales

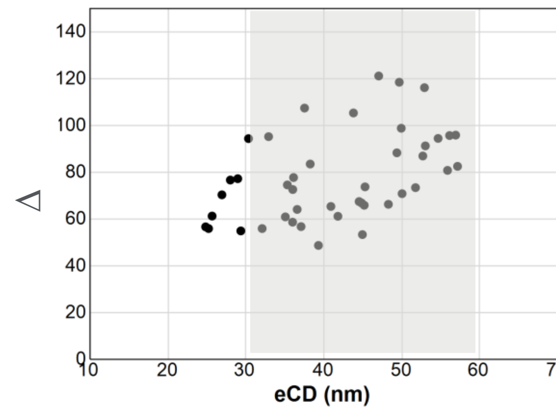


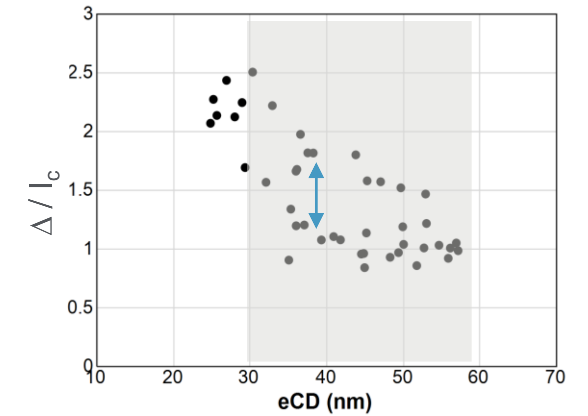
Proxy for Data Retention: $\Delta = \frac{H_k m_{free}}{2k_B T}$

Programming Current: $I_{c0} = \frac{2e}{\hbar}\frac{\alpha}{\eta} m_{free}\left(H_{k,eff}\right)$

Programming Current (I_c), Δ and spin efficiency (Δ/ I_c)







Upto 2X increase in Δ / I_c value by materials engineering*

** Multiple free layer configurations used in these plots*

Applied Internal Data

Materials Engineering of PVD Stack enables longer data retention while reducing programming current

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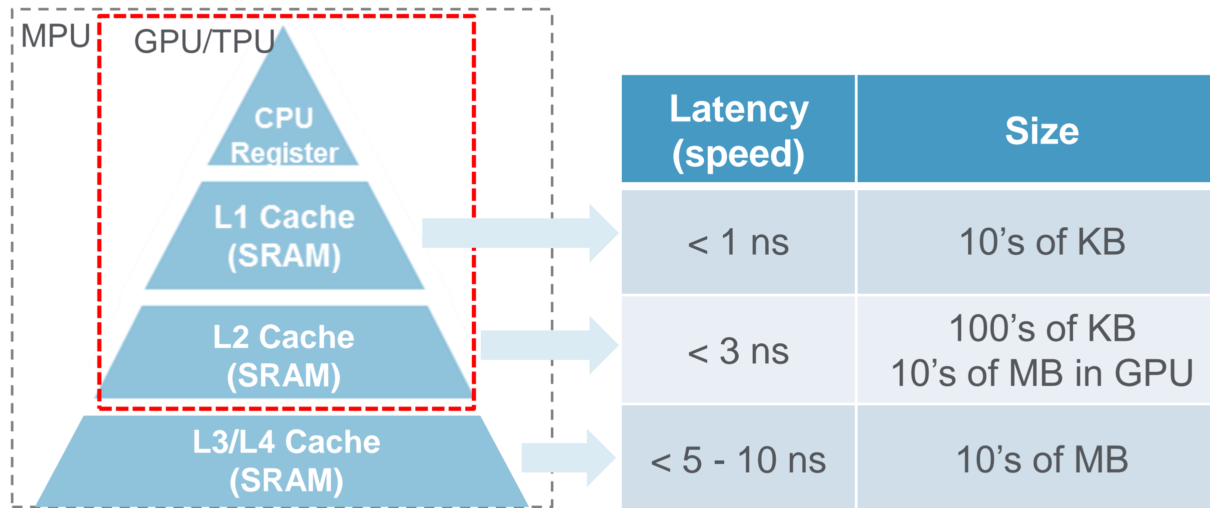
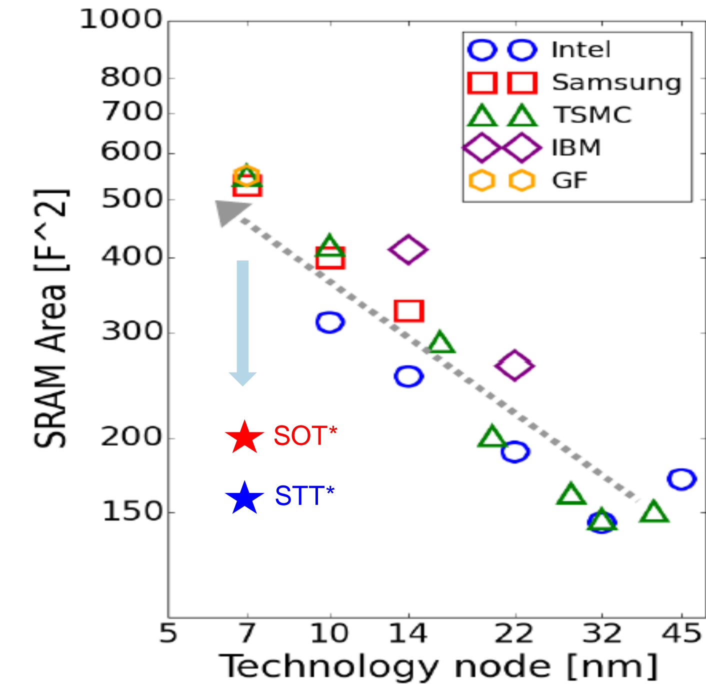
New Application: SRAM Cache Scaling and MRAM

SRAM cell area scaling challenged

Cache use in Processors



Latency (speed)	Size
< 1 ns	10's of KB
< 3 ns	100's of KB 10's of MB in GPU
< 5 - 10 ns	10's of MB



TDK, VLSI 2018

- MRAM has potential to replace SRAM as cache to increase density, if performance becomes comparable
- Additional applications possible due to non-volatility of MRAM

* Glossary
SOT : Spin Orbit Torque
STT : Spin Transfer Torque

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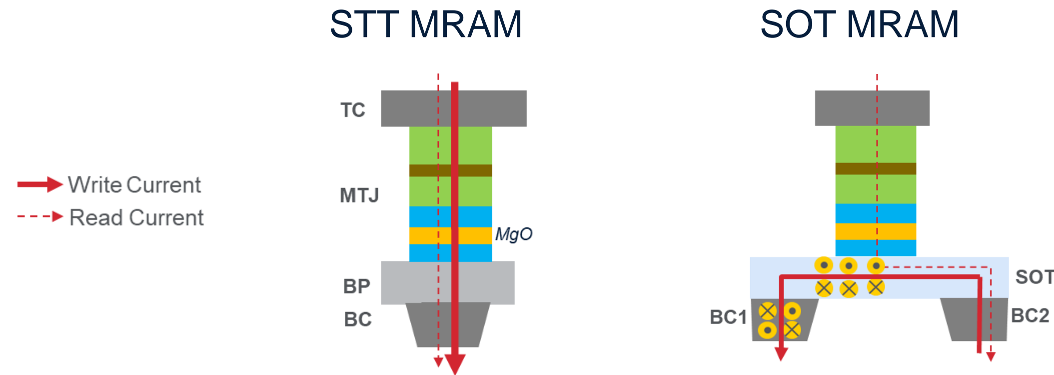
Beyond STT MRAM: SOT MRAM for L1/L2 Cache

Difference & Similarities between STT and SOT MRAM



	STT MRAM	SOT MRAM
Read	TMR Effect	TMR effect
Write	Spin Transfer Torque	**Spin Orbit Torque**

Fast write of < 1 ns possible for SOT MRAM, potentially with infinite endurance (> 1E12)

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Summary

- Multiple emerging memory technologies (STT MRAM, PCRAM and RERAM) entering manufacturing phase
  - Addressing different application (Embedded vs NV RAM vs SCM) in different markets (IOT, AI/Data Center)
- Manufacturing challenges with complex materials have previously limited new memory adoption → Innovative PVD and Etch Technologies enable High Volume Manufacturing
- Scaling path for STT MRAM beyond 22nm node is robust, with many options to improve performance and reduce bit cost that would further drive new applications
- STT / SOT MRAM are promising candidates for high performance non-volatile cache with higher density/capacity than 6T SRAM

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make possible