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Advanced magnetic tunnel junctions based on CoFeB/MgO interfacial perpendicular anisotropy

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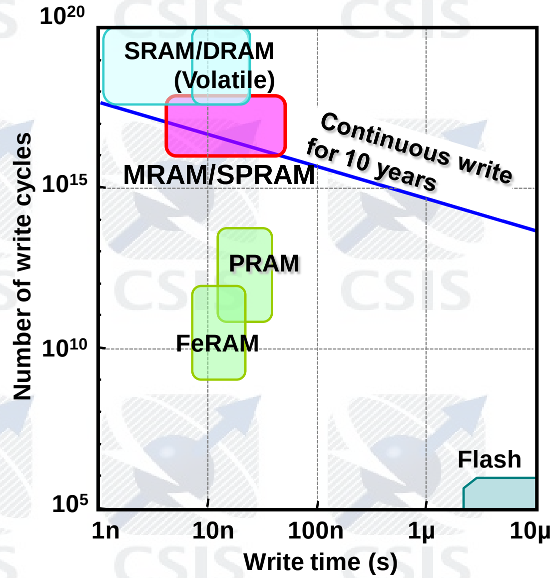
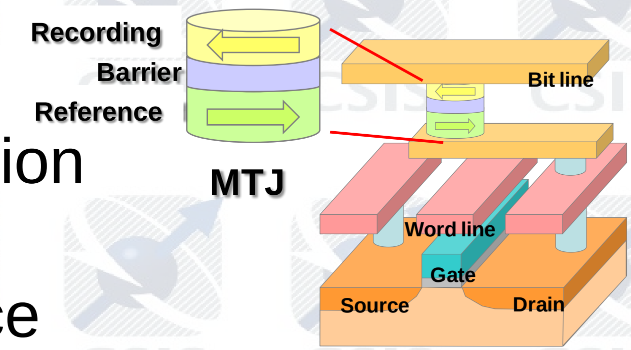
Spintronics devices

(Expectation as low power consumption devices)

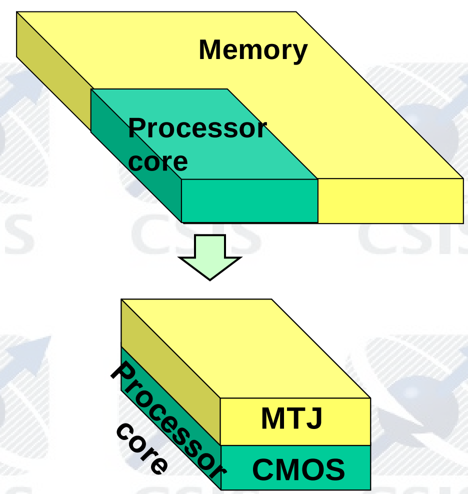
- **M**agnetoresistive RAMs (MRAMs)
  SPin transfer torque RAMs (SPRAMs)



- ✓ Nonvolatility
- ✓ High speed operation
- ✓ Virtually unlimited write endurance

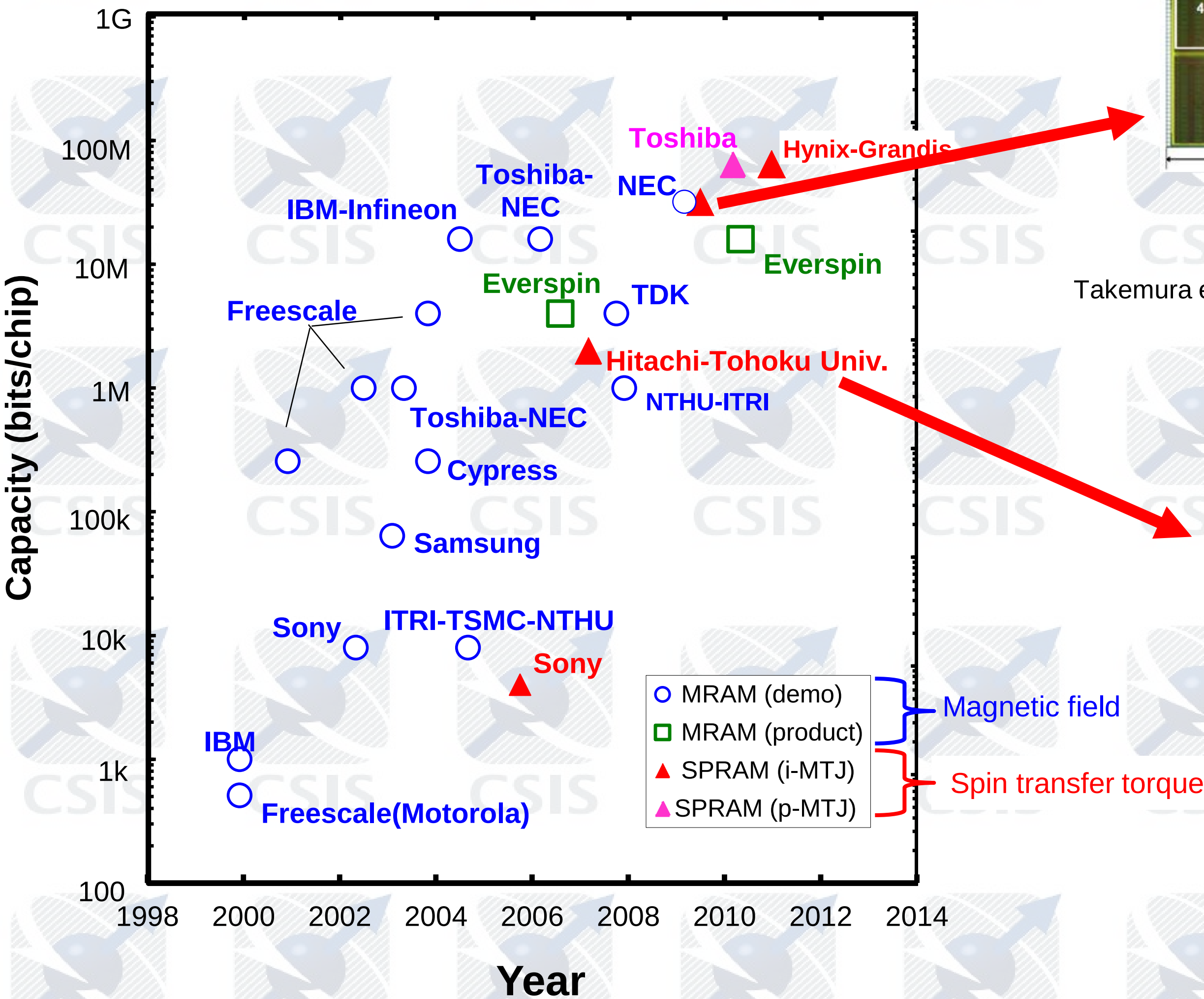


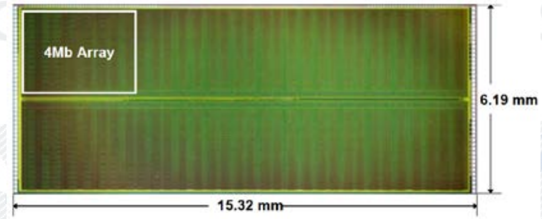
- Logic-in-memory architecture
  - ✓ Reduction of leak current (static power)
  - ✓ Reduction of interconnection delay



Mochizuki *et al.*, IEICE Transactions on Fundamentals, E88-A (2005) 1408.
Matsunaga *et al.,* Appl. Phys. Express, 1 (2008) 091301; *ibid.*, 2 (2009) 023004.
Sekikawa et al., IEDM 2008, Suzuki et al., VLSI Technology 2009
Ohno et al., IEDM 2010
Matsunaga *et al*. VLSI Circuit 2011

MRAM development

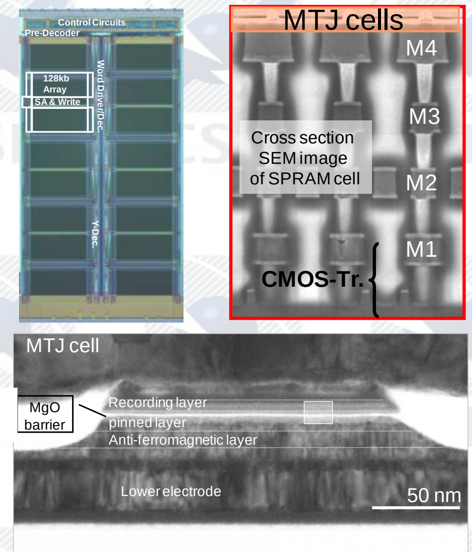




32Mb SPRAM

VLSI Circuit 2009

Takemura et al., IEEE J. Solid-State Circuits 45 (2010) 869.



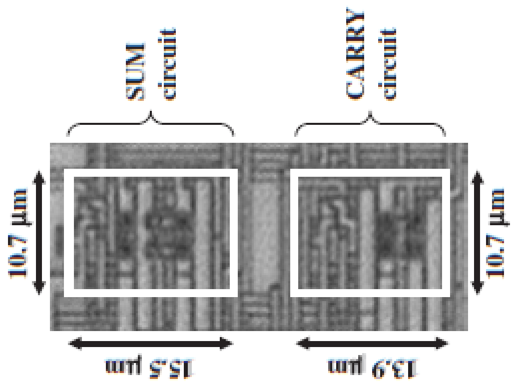
2Mb SPRAM

ISSCC 2007

Kawahara et al., IEEE J. Solid-State Circuits 43 (2008) 109.

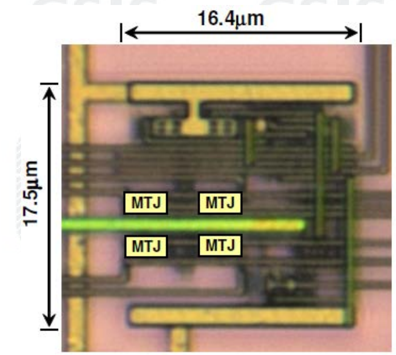
Ikeda et al., IEEE Trans. Electron Devices, 54 (2007) 991.

Nonvolatile circuits for logic-in-memory



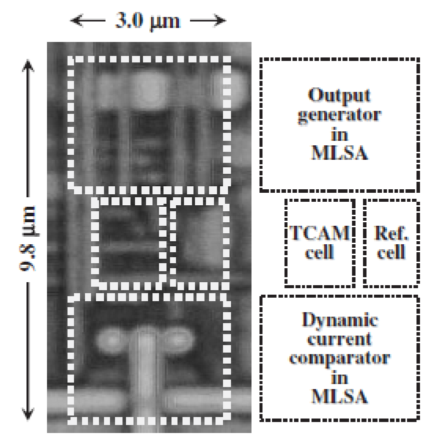
MTJ-Based Nonvolatile Full Adder

Matsunaga, …Hanyu *et al.*, Appl. Phys. Express 1 (2008) 091301.



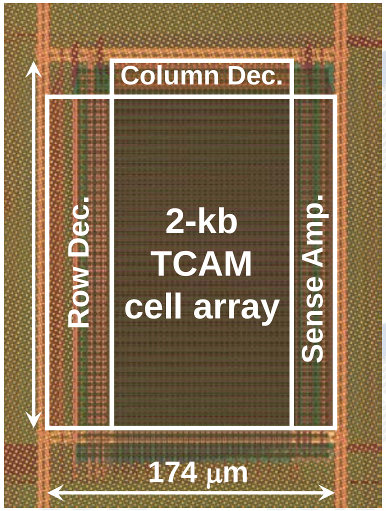
MTJ-Based Nonvolatile Lookup-Table Circuit Chip

Suzuki, …Hanyu,*et al*., VLSI Circuit Symposium 2009.



MTJ-Based Nonvolatile Ternary Content-Addressable Memory (TCAM) cell

Matsunaga, ... Hanyu *et al*., Appl. Phys. Express 2 (2009) 023004.



2kb-nonvolatile TCAM chip

Matsunaga, …Hanyu,*et al*., VLSI Circuit Symposium 2011.

Technology issues toward realization of nonvolatile VLISs

To realize nonvolatile VLISs (MRAM and logic-in-memory) using the leading edge technology node, there are still issues to be addressed.

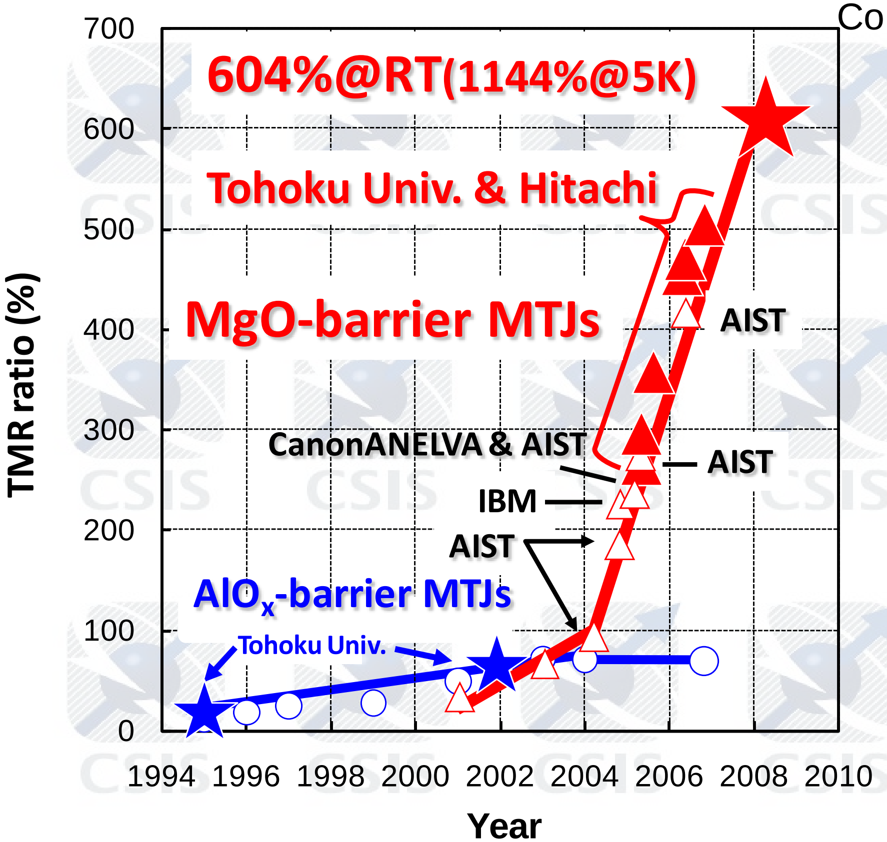
ISSUES

- High output (TMR ratio>100%)
- Low switching current ($I_C < F$ μA)
- Thermal stability for nonvolatility ($E/k_B T > 40$)
- Annealing stability in back-end-of-line process ($T_a > 350^oC$)

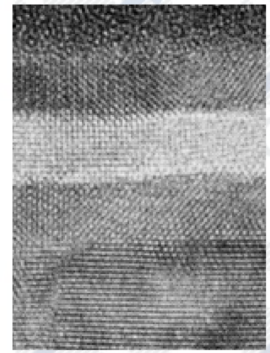
+ Scalability

- MTJs have to satisfy these requirements with scalability at the same time.
- In order to satisfy these requirements, we focus on the MTJs with perpendicular anisotropy electrodes.

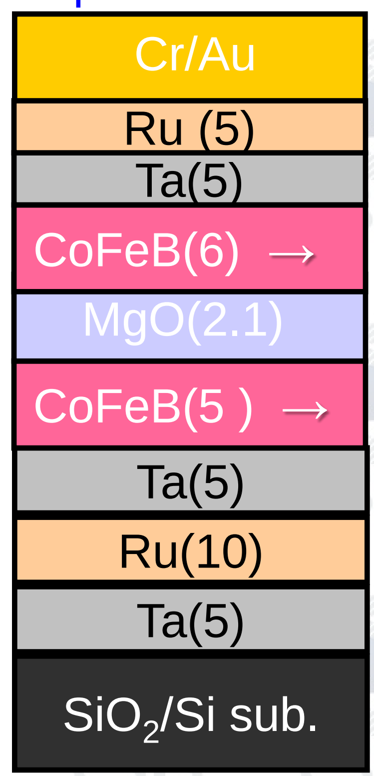
Progress of MTJs



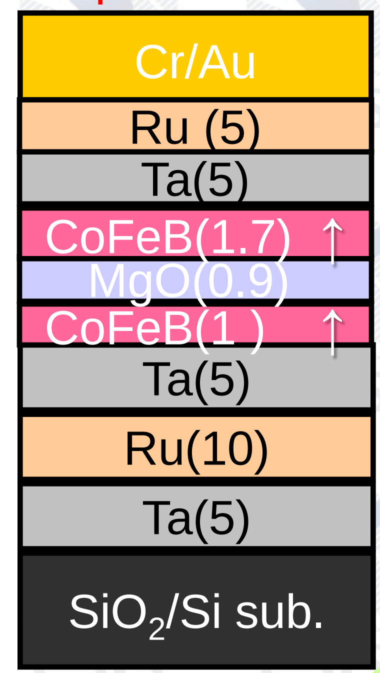
S. Ikeda et. al., Appl. Phys. Lett. **93**, 082508 (2008).
Nat. Mat., **9**, 721 (2010)



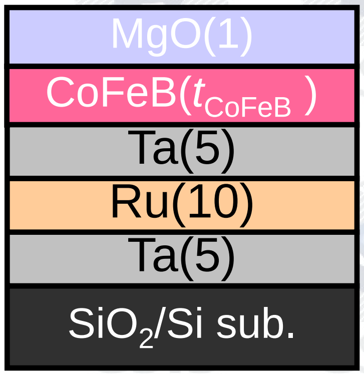
In-plane anisotropy pseudo-SV



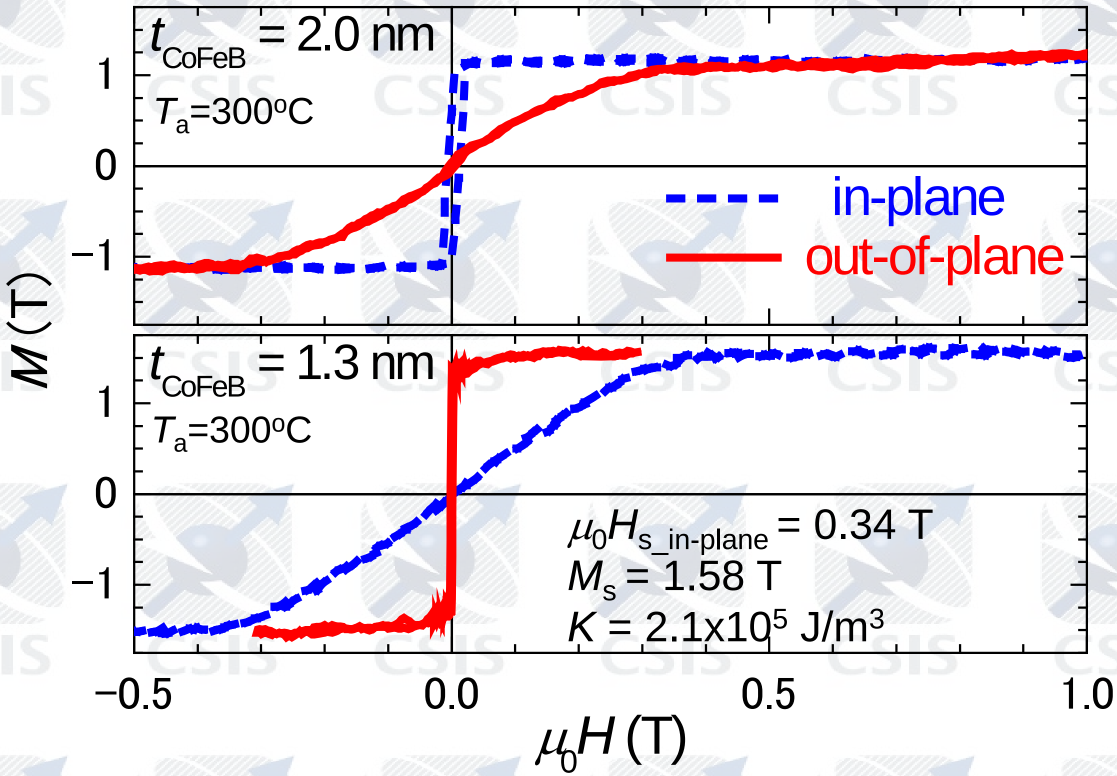
Perpendicular anisotropy pseudo-SV



M-H curves of CoFeB/MgO stack samples with different t_{CoFeB}



T_a=300 ^{o}C,
4 kOe, 1h

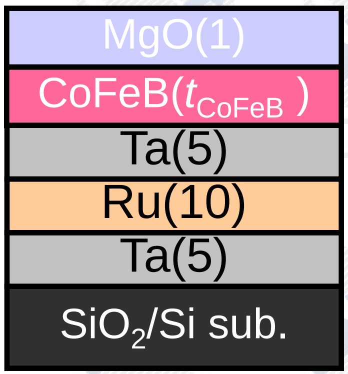


In-plane anisotropy

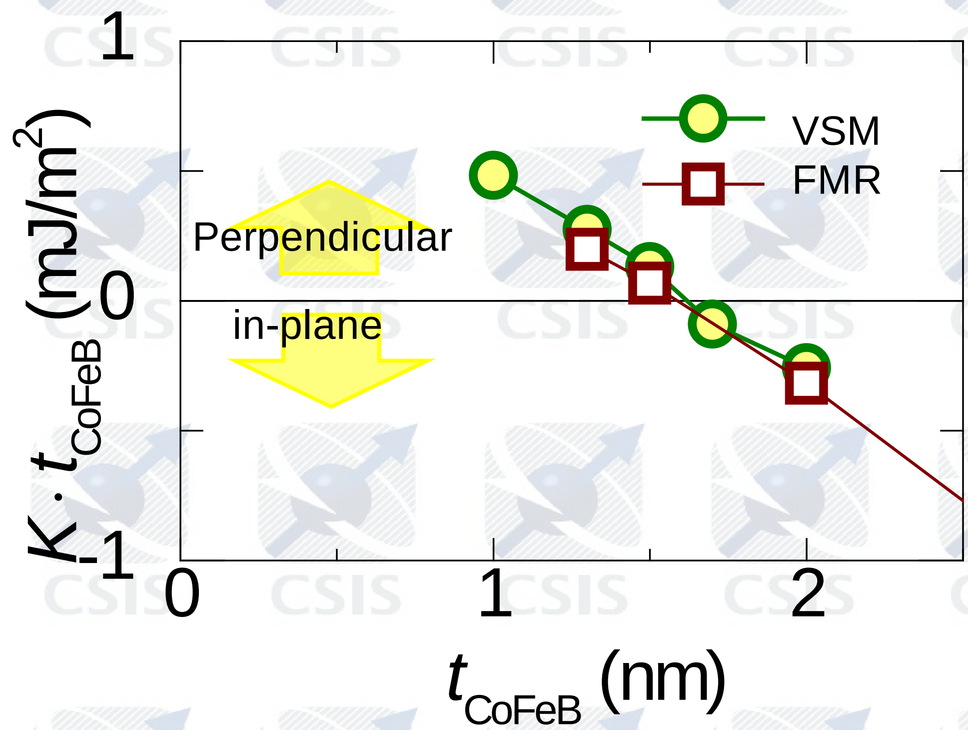
Perpendicular anisotropy

S. Ikeda et al., Nat. Mat. **9** (2010) 721.

t_{CoFeB} dependence of Kt_{CoFeB} in CoFeB/MgO stack



$T_a = 300^oC$



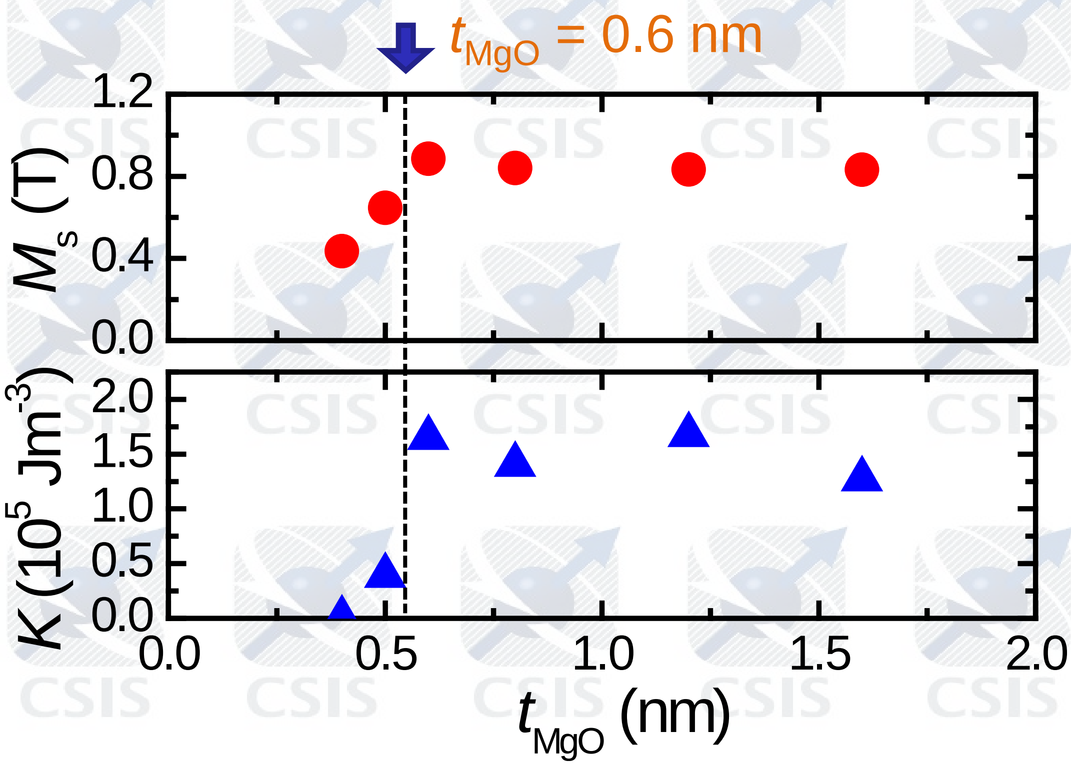
$$Kt_{CoFeB} = (K_b - M_S^2/2\mu_0)\, t_{CoFeB} + K_i$$

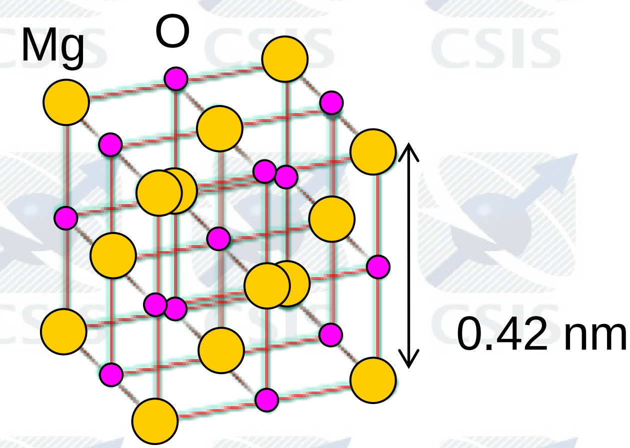
- From the y-intercept, $K_i = 1.3$ mJ/m^2.
- The CoFeB/MgO interfacial anisotropy K_i is dominant in the perpendicular anisotropy because K_b is negligible.

S. Ikeda et al., Nat. Mat. **9** (2010) 721.

t_{MgO} dependence of M_s and K

Saturation magnetization M_s and effective magnetic anisotropy energy density K are evaluated from the out-of-plane M-H curves.



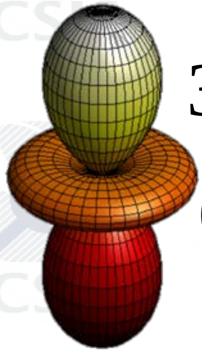


1 monolayer of MgO is ~0.21 nm

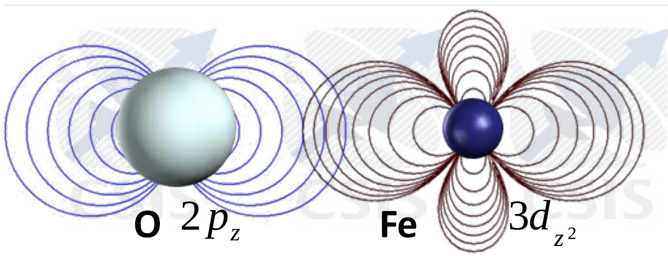
More than 3 monolayers of MgO is required to stabilize the perpendicular anisotropy induced by CoFeB-MgO interface.

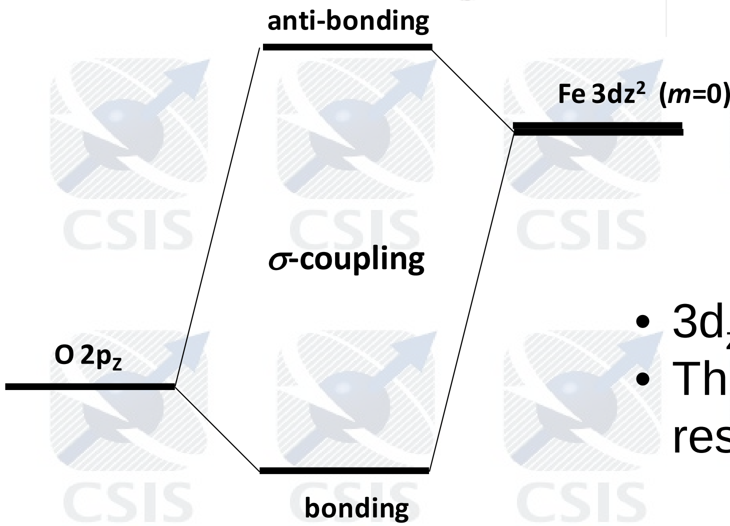
M. Yamanouchi *et al.*, J. Appl. Phys. **109** (2011) 07C712.

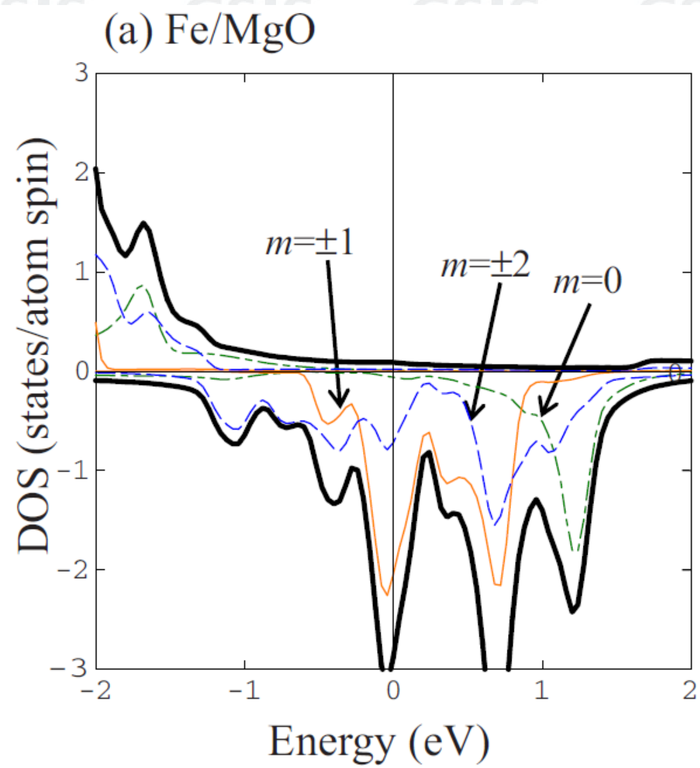
Possible factor of the perpendicular anisotropy in CoFeB/ MgO stack



$3d_{z^2}$: in-plane anisotropy
(m=0)



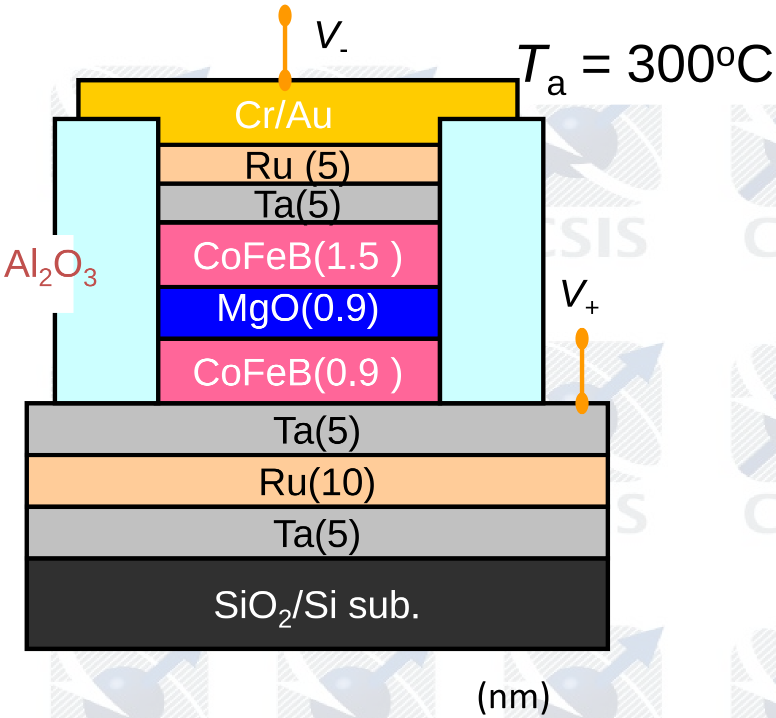


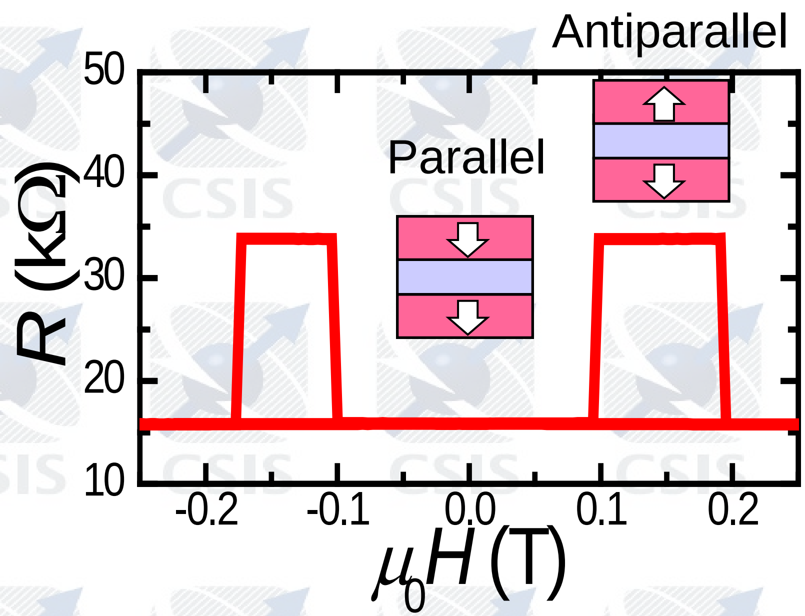


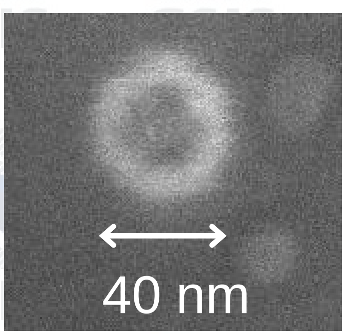
K. Nakamura *et al*., Phys. Rev. B, 81 (2010) 220409.
R. Shimabukuro *et al*., Physica E 42 (2010) 1014.

- $3d_{z^2}$ band of Fe is pushed up above the Fermi energy.
- The contribution of $3d_{z^2}$ orbital of Fe becomes small, resulting in appearance of perpendicular anisotropy.

TMR properties in CoFeB-MgO p-MTJs







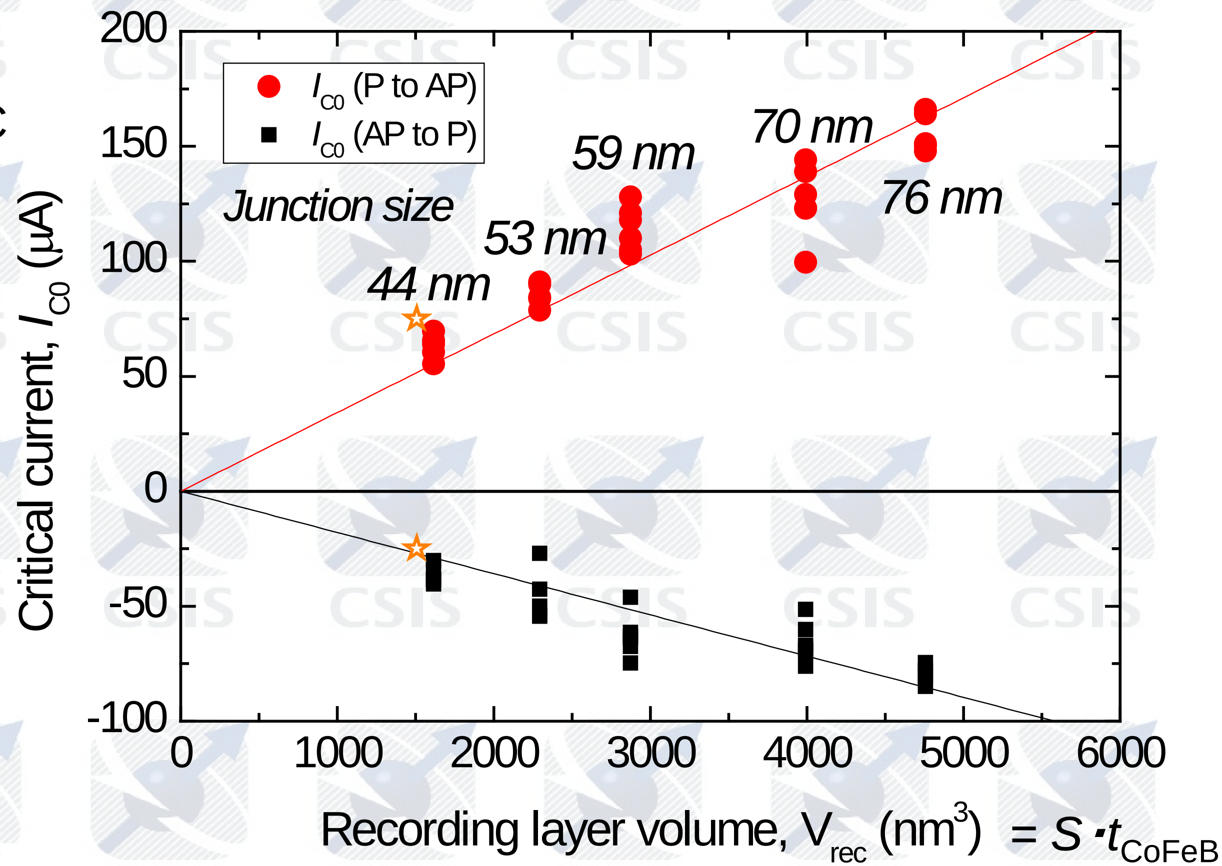
Clear hysteresis -> top and bottom CoFeB electrodes have perpendicular anisotropy.

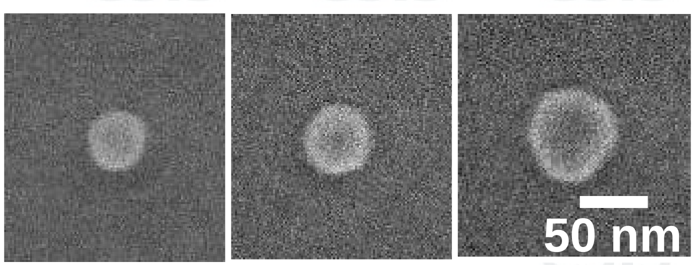
S. Ikeda et al., Nat. Mat. **9** (2010) 721.

Junction size dependence of I_{c0}

T_a=300°C

w/o H_{ex}

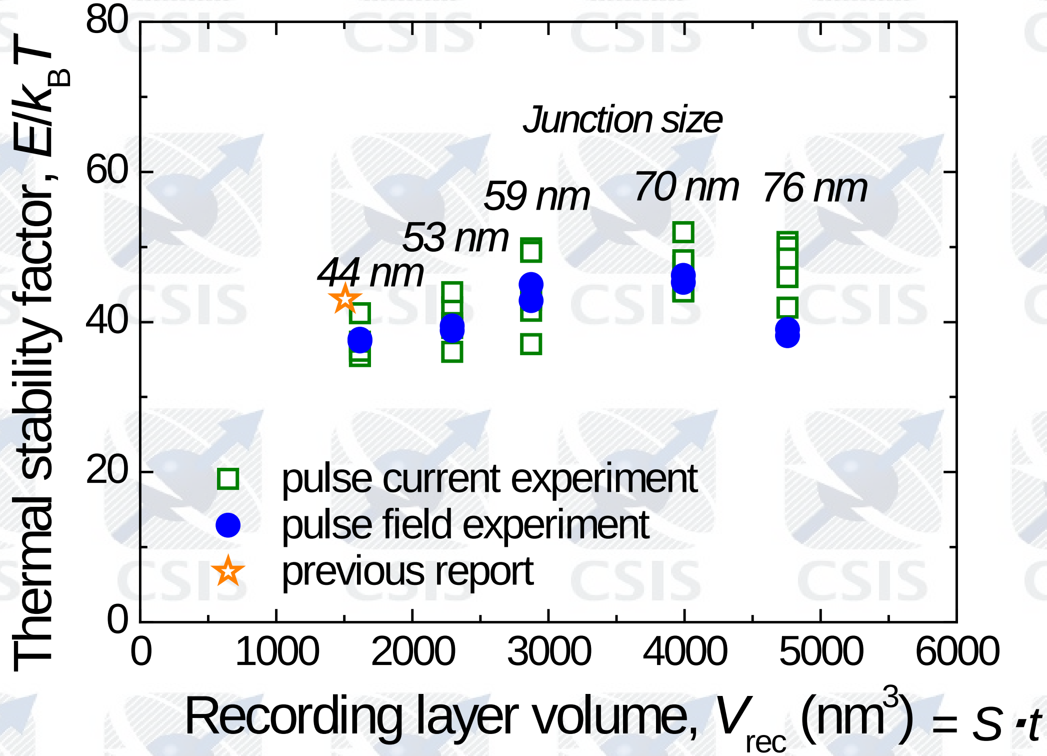




I_{c0} linearly decreases with junction area S (volume V_{rec}).
We confirmed scalability of switching current for spin transfer torque.

H. Sato et al., Appl. Phys. Lett. **99** (2011) 042501.

Junction size dependence of E/k_BT



E/k_BT maintained almost constant values even though the junction diameter was varied from 40 nm to 80.

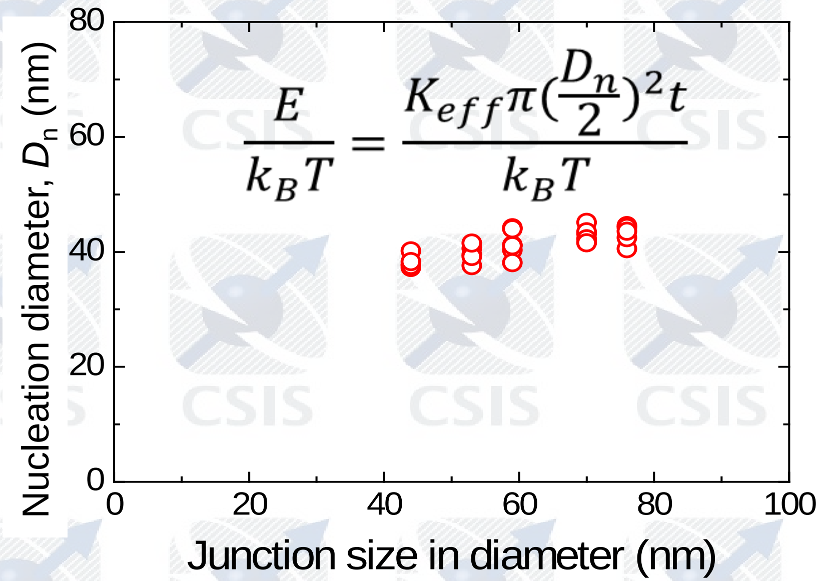
I_{C0} reduces in proportion to the volume of the recording layer but the E/k_BT values are not affected much by the volume down to 40 nm in diameter.

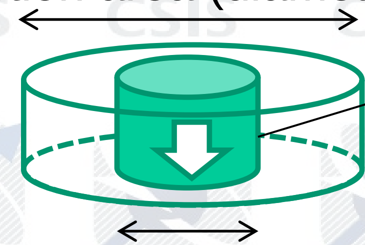
H. Sato et al., Appl. Phys. Lett. **99** (2011) 042501.

Origin of the junction size dependence of I_{C0} and E/k_BT

No clear reduction in E/k_BT with different junction size

Nucleation type magnetization reversal





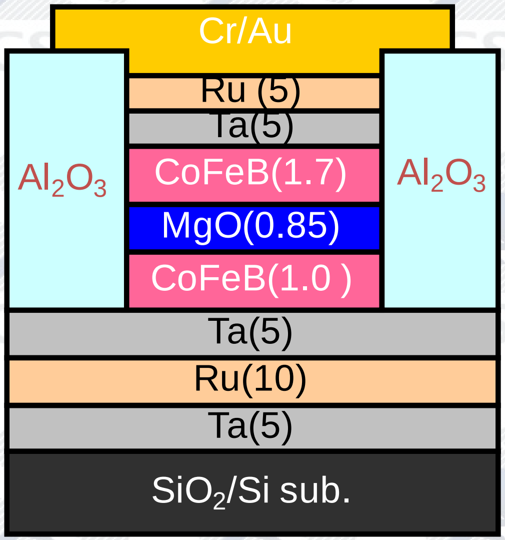
D_n showed almost constant values of 40 nm in diameter, which is almost independent of junction size.

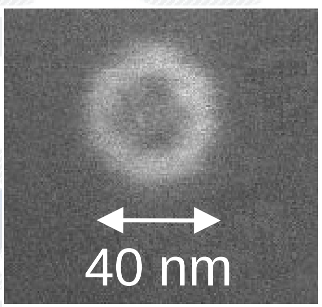
$$I_{C0}=J_{C0}S=J_{C0}(\pi(D^2-D_n^2)/4)+\pi(D_n/2)^2) \propto S$$

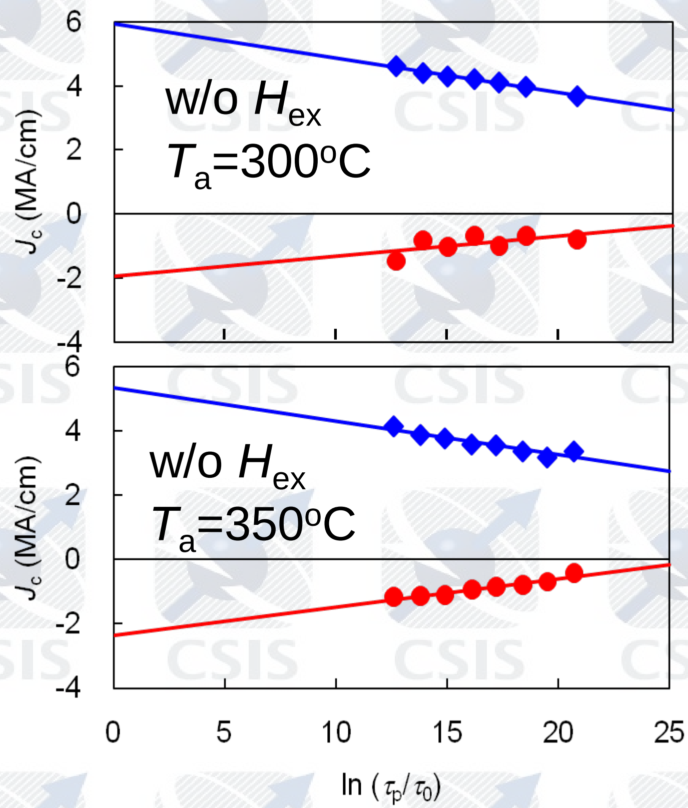
$$E/k_BT=K_{eff}\pi(D_n/2)^2/k_BT \propto D_n^2$$

H. Sato et al., Appl. Phys. Lett. **99** (2011) 042501.

J_{c0} and E/k_BT of MTJs with 40 nm diameter







T_a(°C)	TMR ratio (%)	*RA* (Ωμm²)	J_{c0} (MA/cm²)	E/k_BT
300	124	18	3.9	43.1
350	113	16	3.8	39.1

- J_{c0} and E/k_BT are maintained after annealing at 350°C.
- This MTJ system has a back end of the line (BEOL) compatibility.

S. Ikeda *et al.*, Nat. Mat. 9, (2010) 721.
K. Miura *et al.*, MMM 2010, HC-02.

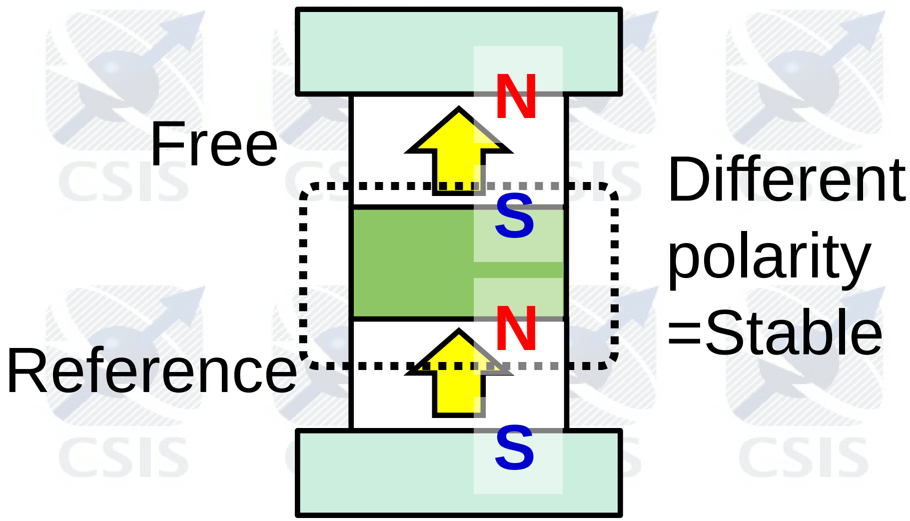
Comparison of MTJs

Type	Stack structure (nm)	Size (nm)	MR (%)	RA ($\Omega\mu m^2$)	J_{C0} (MA/cm^2)	I_{C0} (μA)	$\Delta=E/k_BT$	I_{C0}/Δ	T_a (^oC)	Ref.
i-MTJ	CoFeB(2)/Ru(0.65)/CoFeB(1.8) SyF	100x200	>130	~10	2	~400	65	~6.2	300-350	J. Hayakawa et al., IEEE T-Magn., 44, 1962 (2008)
p-MTJ	L10-FePt(10)/Fe(t)/Mg(0.4)/MgO(1.5)/L10-FePt(t)	Blanket	120 (CIPT)	11.8k	-	-	-	-	500	M. Yoshizawa et al., IEEE T-Magn., 44, 2573 (2008)
p-MTJ	L10-FePt/CoFeB/MgO(1.5)/CoFeB/Co based superlattice	Blanket	202 (CIPT)	-	-	-	-	-	-	H. Yoda et al., Magnetics Jpn. 5, 184 (2010) [in Japanese].
p-MTJ	[Co/Pt]CoFeB/CoFe/MgOCoFe/CoFeB/TbFeCo	Blanket	85-97 (CIPT)	4.4-10	-	-	-	-	225	K. Yakushiji et al., APEX 3, 053033 (2010)
p-MTJ	[CoFe/Pd]/CoFeB/MgO/CoFeB/[CoFe/Pd]	800x800 N	100 (113)	18.7k (20.2k)	-	-	-	-	350 (325)	K. Mizunuma et al., MMM&INTERMAG2010
p-MTJ	CoFeB (1)/ TbCoFe (3)	130 φ	~15		4.7	650	107	6.08	-	M. Nakayama et al., APL 103, 07A710 (2008)
p-MTJ	$L1_0$-alloy	50-55 φ	-	-	-	49	56	0.88	-	T. Kishi et al., IEDM 2008
p-MTJ	Fe based $L1_0$ (2)/CoFeB (0.5)	-	-	-	-	9	-	-	-	H.Yoda et al., Magnetics Jpn. 5, 184 (2010) [in Japanese].
p-MTJ	**CoFeB/MgO/ CoFeB**	**40 φ**	**113 (124)**	**16 (18)**	**3.8 (3.9)**	**48 (49)**	**39 (43)**	**1.23 (1.14)**	**350 (300)**	**S. Ikeda et al., Nat. Mat. 9 (2010) 721. K. Miura et al., MMM2010,HC-02**

These p-MTJ technologies will be a promising building block for nonvolatile VLSIs using spin-transfer torque switching.

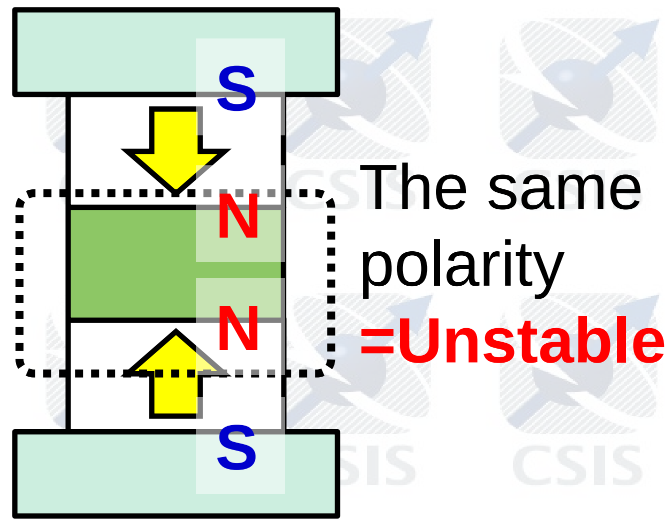
Issue for p-MTJs

Bit Information "0"



Parallel state
Low resistance

Bit Information "1"



Antiparallel state
High resistance

The thermal stability $\Delta_p = E/k_B T$ of anti-parallel state in p-MTJs becomes low by comparison with parallel state.

Enhancement of thermal stability

$$\Delta_{P, AP} = \Delta\,[1 \pm H_s/H_{c0}]^2$$

Conventional structure

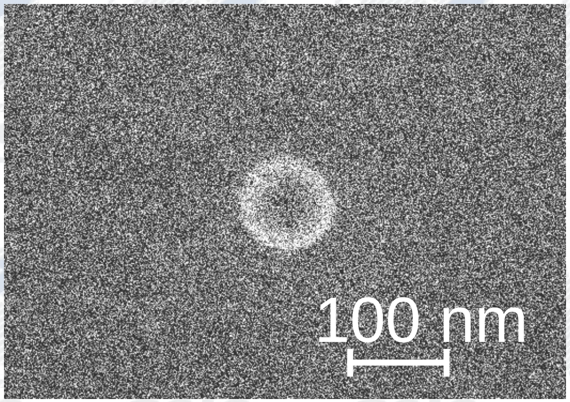
Stepped structure

H_s decreases by employing step structure with large reference layer.

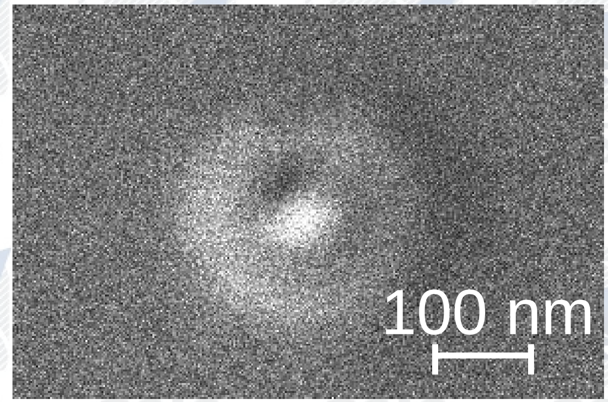
Δ_{AP} increases with decreasing diameter of reference layer.

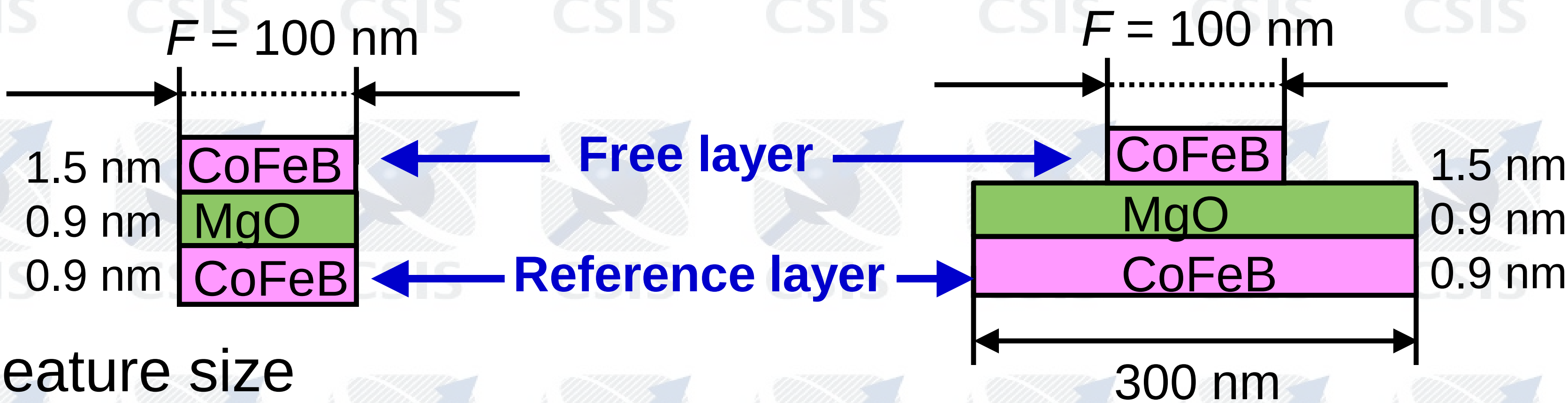
Two types of p-MTJs

Conventional structure



Stepped structure



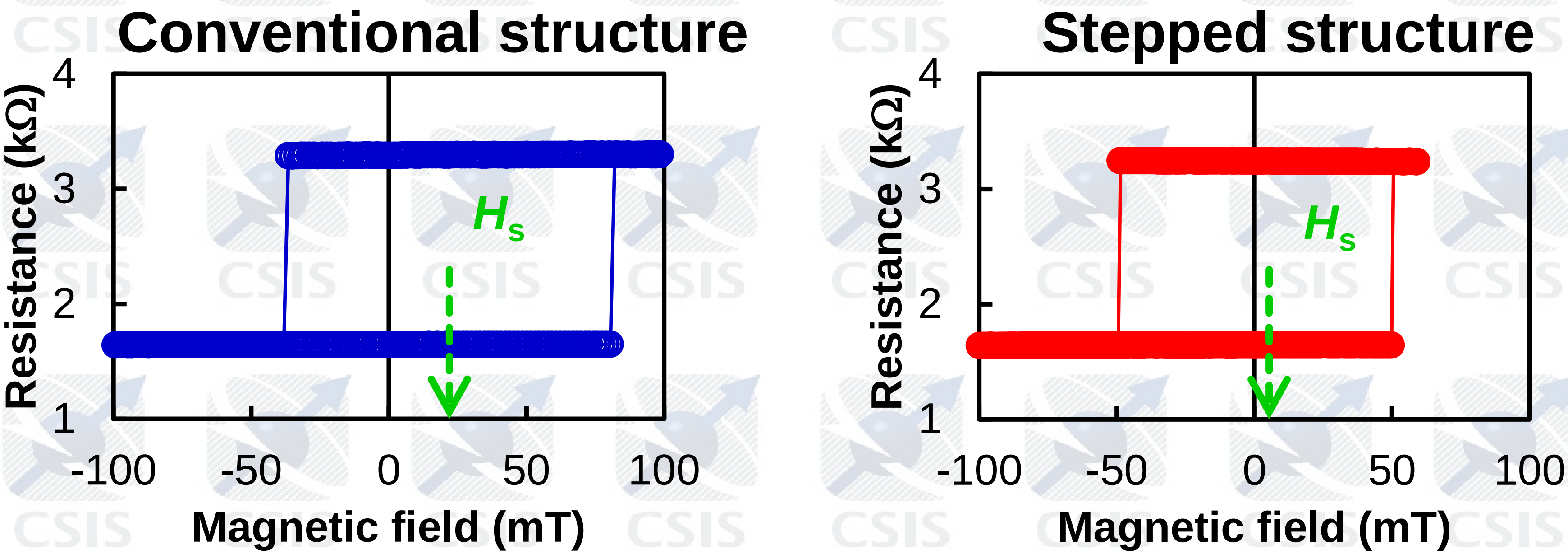


F : Feature size

Slide 19

K. Miura et al., 2011 VLSI Technology, 11B-3.

H_s in two types of p-MTJs



	Conventional structure	Stepped structure
TMR ratio (%)	100	97
RA (Ωμm^2)	13	13
H_s (mT)	22	5

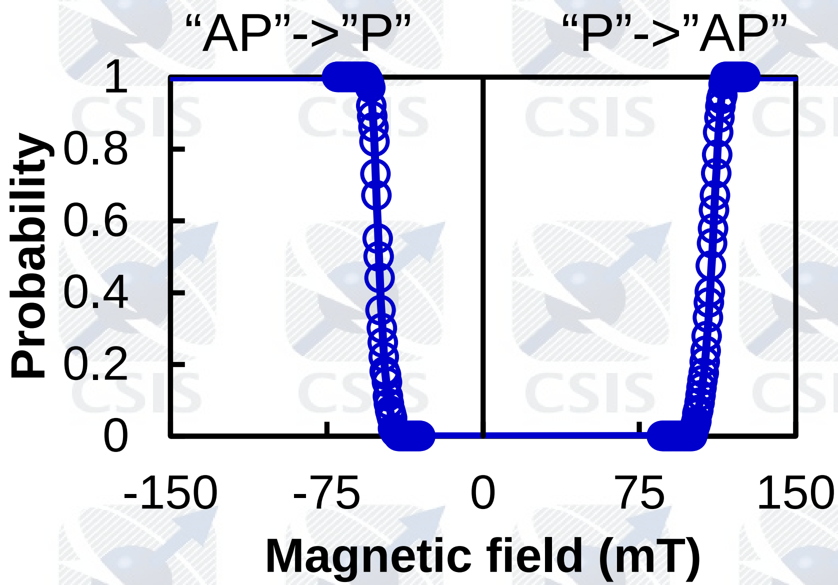
H_s can be reduced by using stepped structure.

K. Miura et al., VLSI Technology 2011, 11B-3.

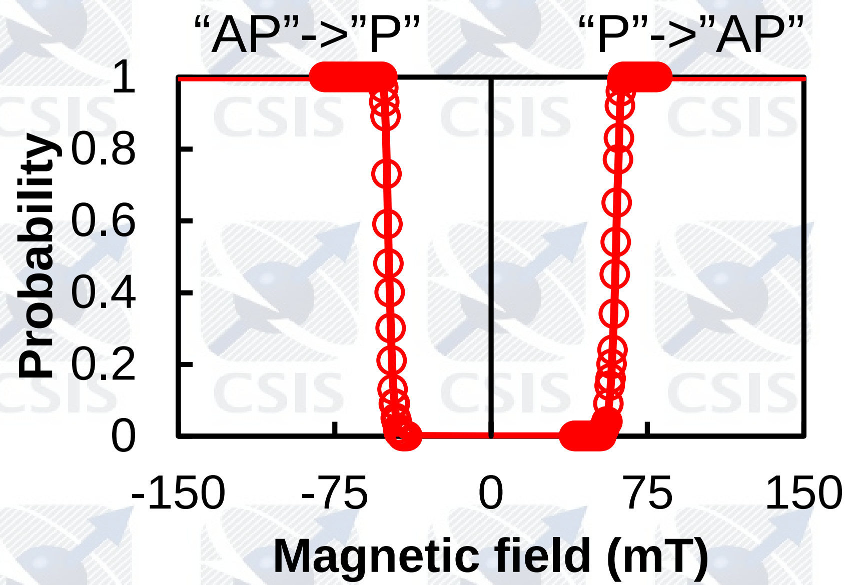
Δ_P and Δ_{AP} in two types of p-MTJs

$$\text{Probability} = 1 - \exp\left\{1 - \frac{\tau_p}{\tau_0}\exp\left[\Delta\left(1 - \frac{H - H_s}{H_{c0}}\right)^2\right]\right\} \quad \Delta_{P,AP} = \Delta\left(1 \pm \frac{H_s}{H_{c0}}\right)^2$$

Conventional structure



Stepped structure

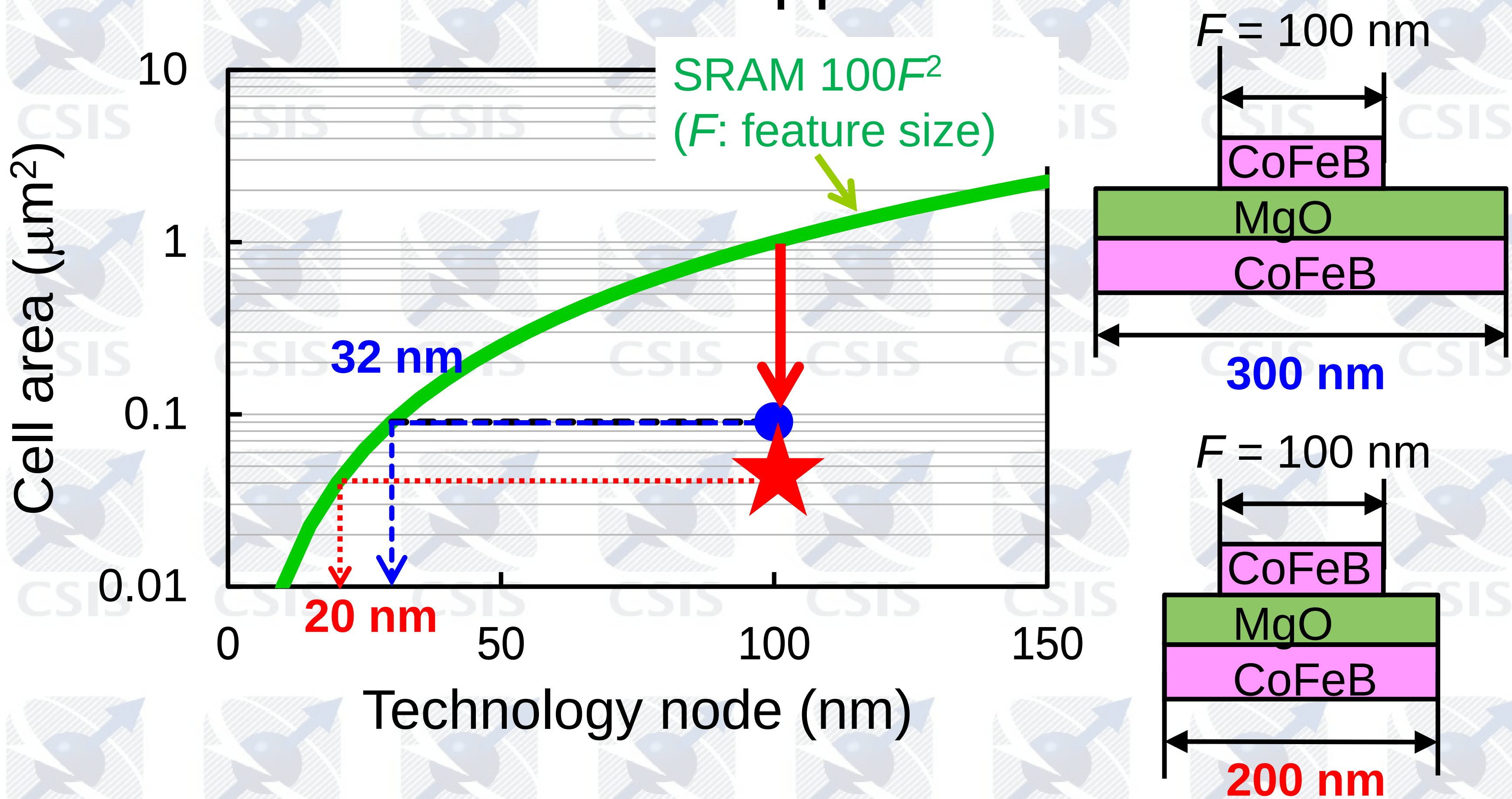


	Conventional structure	Stepped structure
Δ_P	71.2	72.9
Δ_{AP}	46.5	70.1

Δ_{AP} in stepped structure increases.

K. Miura et al., VLSI Technology 2011, 11B-3.

Cell area of stepped structure



Cell area of 0.09 μm^2 (300nmϕ) in the stepped structure corresponds to SRAM cell area at 32 nm technology node.

Cell area can be down to 0.04 μm^2 (200nmϕ) without degrading the retention time over 10 years, which corresponds to SRAM cell area at 20 nm technology node.

K. Miura et al., VLSI Technology 2011, 11B-3.

Summary

- We have demonstrated that the critical current I_{c0} in CoFeB/MgO perpendicular anisotropy MTJs (p-MTJs) can be scaled down with decreasing recording layer volume.
- The thermal stability factor E/k_BT can be maintained at about 40 even though the recording volume was reduced to 40 nm. The magnetization reversal in CoFeB/MgO p-MTJs is dominated by nucleation type magnetization reversal (nucleation diameter ~40 nm).
- CoFeB/MgO p-MTJs show the high TMR ratio of more than 100%, high thermal stability at dimension as low as 40 nm diameter and a low switching current of 49 μA at the same time .
- CoFeB/MgO p-MTJ with step structure shows the enhancement of thermal stability in antiparallel state, which achieves thermal stability for data retention time over 10 years.