Collection of Selected Presentation Materials from Recent Talks

Spintronic Devices for Nonvolatile VLSIs

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Work supported by the FIRST Program from JSPS
and partly by R & D for Next-Generation Information Technology of MEXT

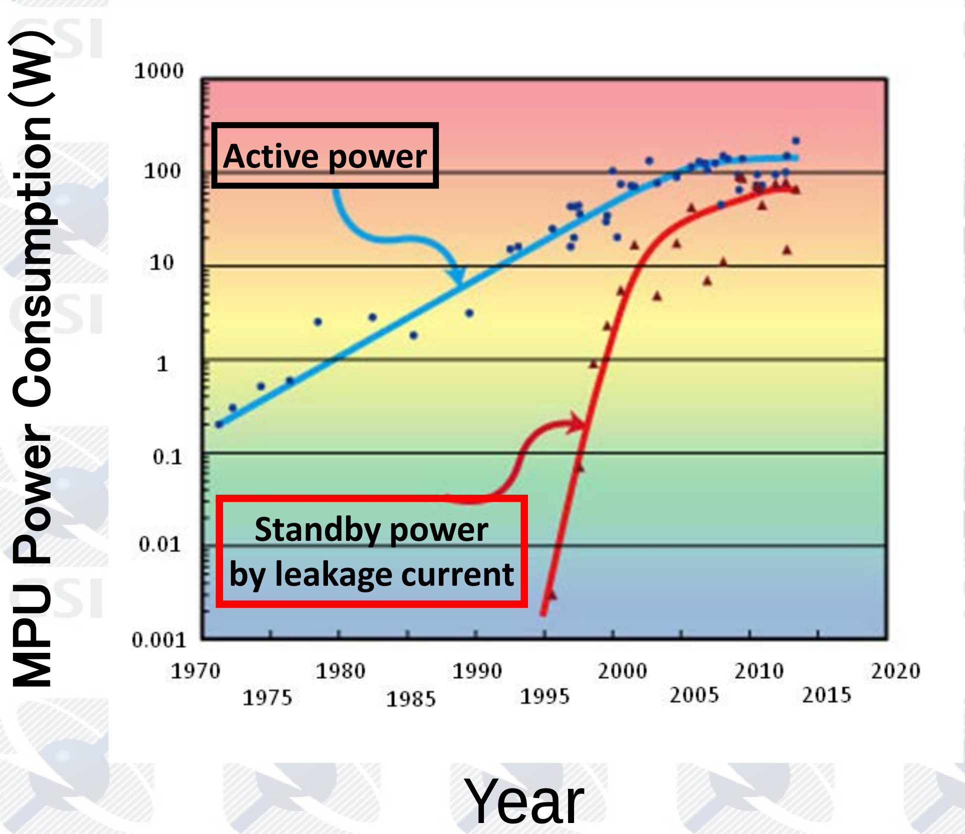
http://www.csis.tohoku.ac.jp/

Outline

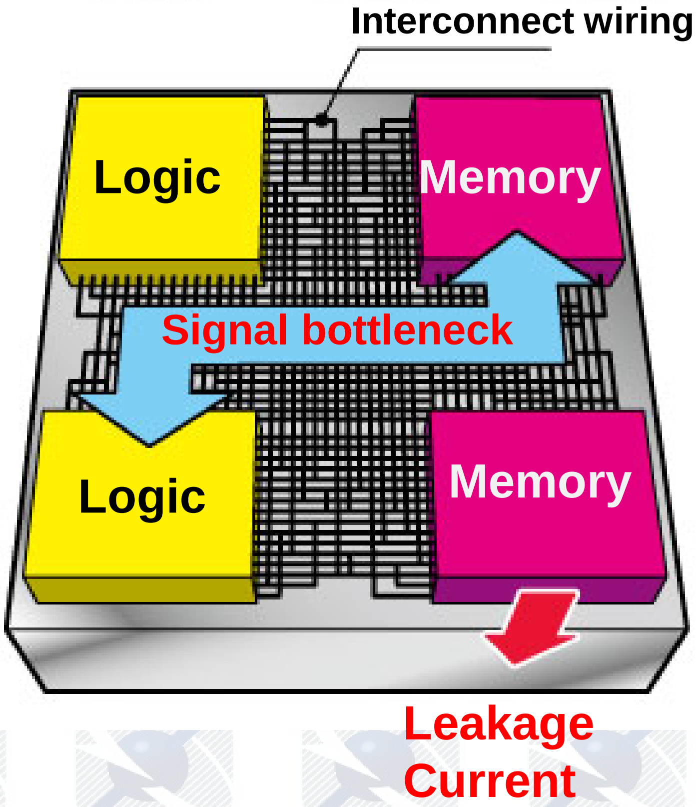
1. Introduction
2. Magnetic Tunnel Junction (MTJ)
3. Electrical Switching of MTJ
4. Three-terminal Domain Wall Device
5. Summary

Challenges VLSI Technology Face

Power Consumption



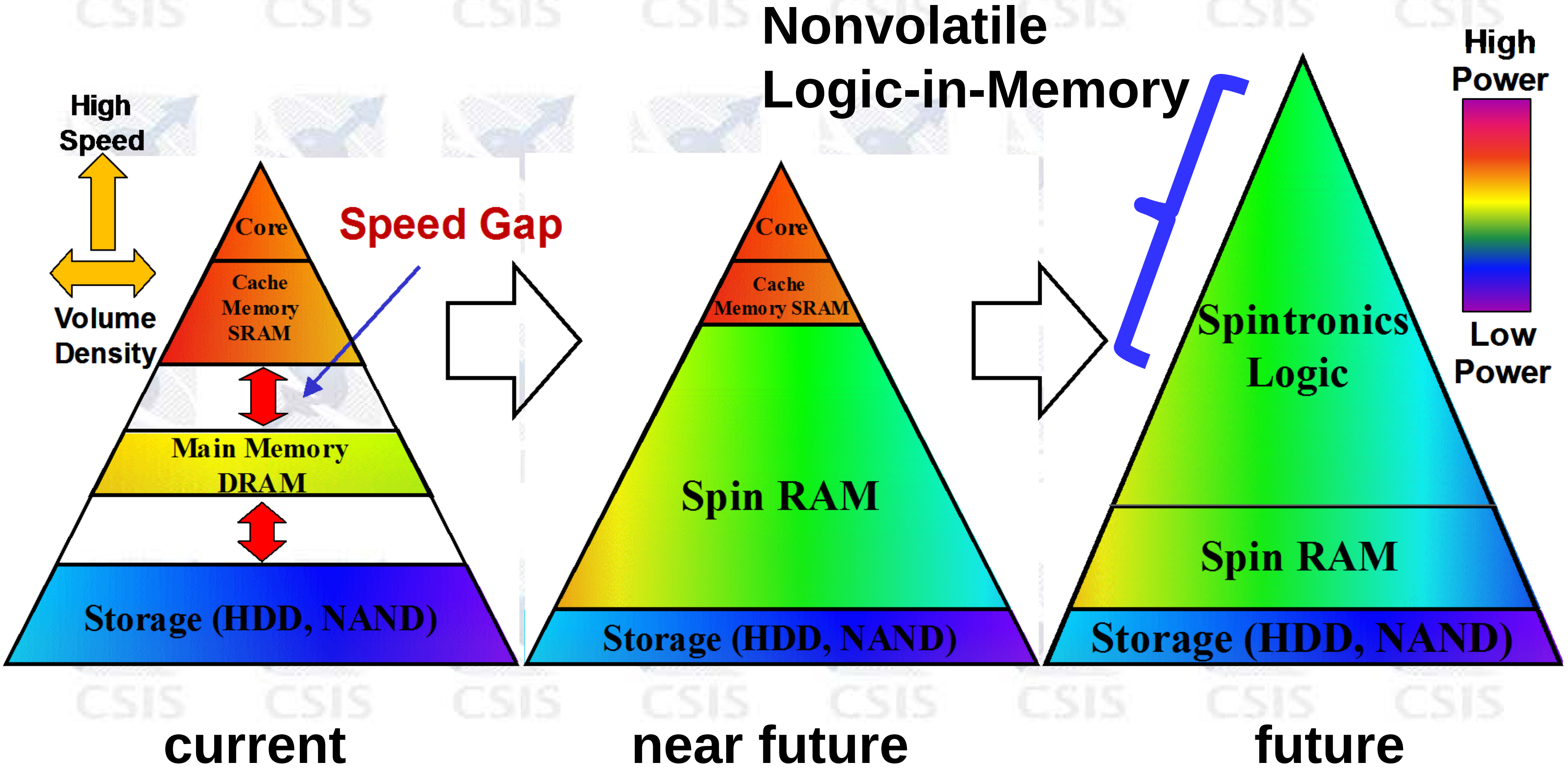
Interconnection Delay



Nonvolatile working memory is in need

Features of non-volatile for memory device	Flash	FRAM	Spin Device
Access Speed	△	○	○
Non destructive Read	○	△	○
Write Endurance	×	△	○
Scalability	○	△	○
Operation Voltage	×	△	○

System (Memory) Hierarchy



Nonvolatile
Logic-in-Memory

High
Speed

Volume
Density

Core
Cache
Memory
SRAM

Speed Gap

Main Memory
DRAM

Storage (HDD, NAND)

current

Core
Cache
Memory SRAM

Spin RAM

Storage (HDD, NAND)

near future

Spintronics
Logic

Spin RAM

Storage (HDD, NAND)

future

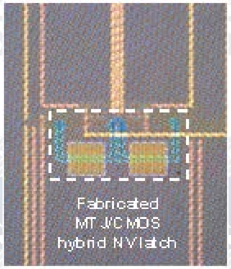
High
Power

Low
Power

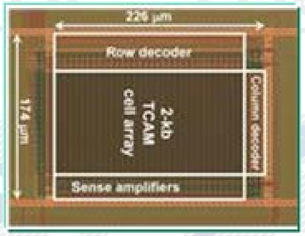
Magnetic tunnel junction based memory elements to counter dynamic and static power, and interconnection delay

H. Ohno et al., IEDM 2010 (invited)

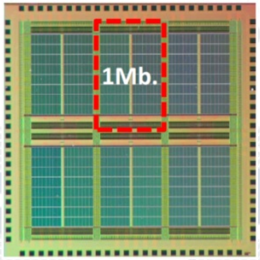
Non-volatile CMOS VLSIs with spintronics



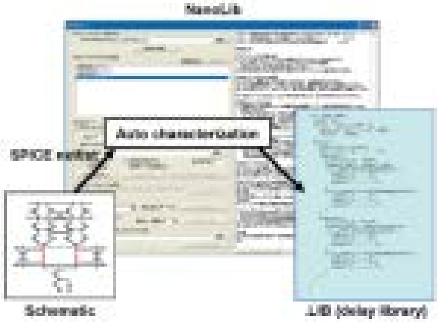
600MHz
MTJ/CMOS Latch
(**Fastest** nonvolatile latch)
(IEDM 2011）



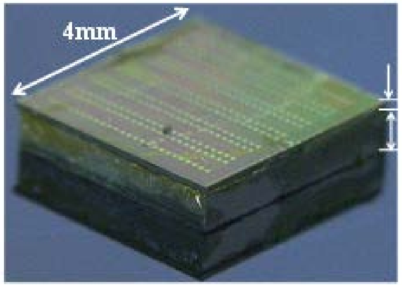
Nonvolatile TCAM
(**Most compact** TCAM cell, 4T-2MTJ)
（VLSI 2011）



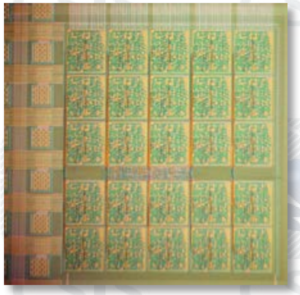
1Mb Array Three Terminal **DW** Cell
(**High endurance**)
(VLSI 2012)



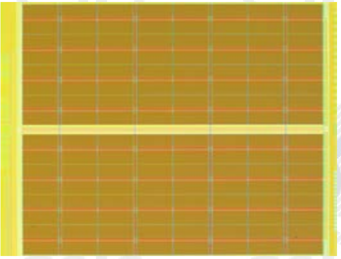
First Auto **Design Tool** for Spintronics CMOS
(2011）



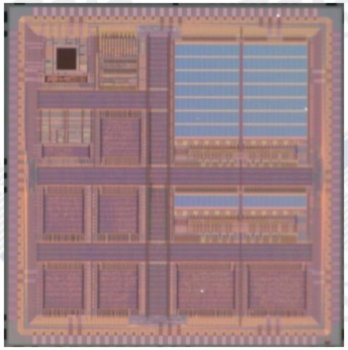
Nonvolatile FPGA with TSV
(**First 3D** Spintronics CMOS Processor)
（VLSI 2012）



Nonvolatile GPU
(**Largest Scale** Spintronics Random Logic 500kgate/chip)
（ISSCC 2013）

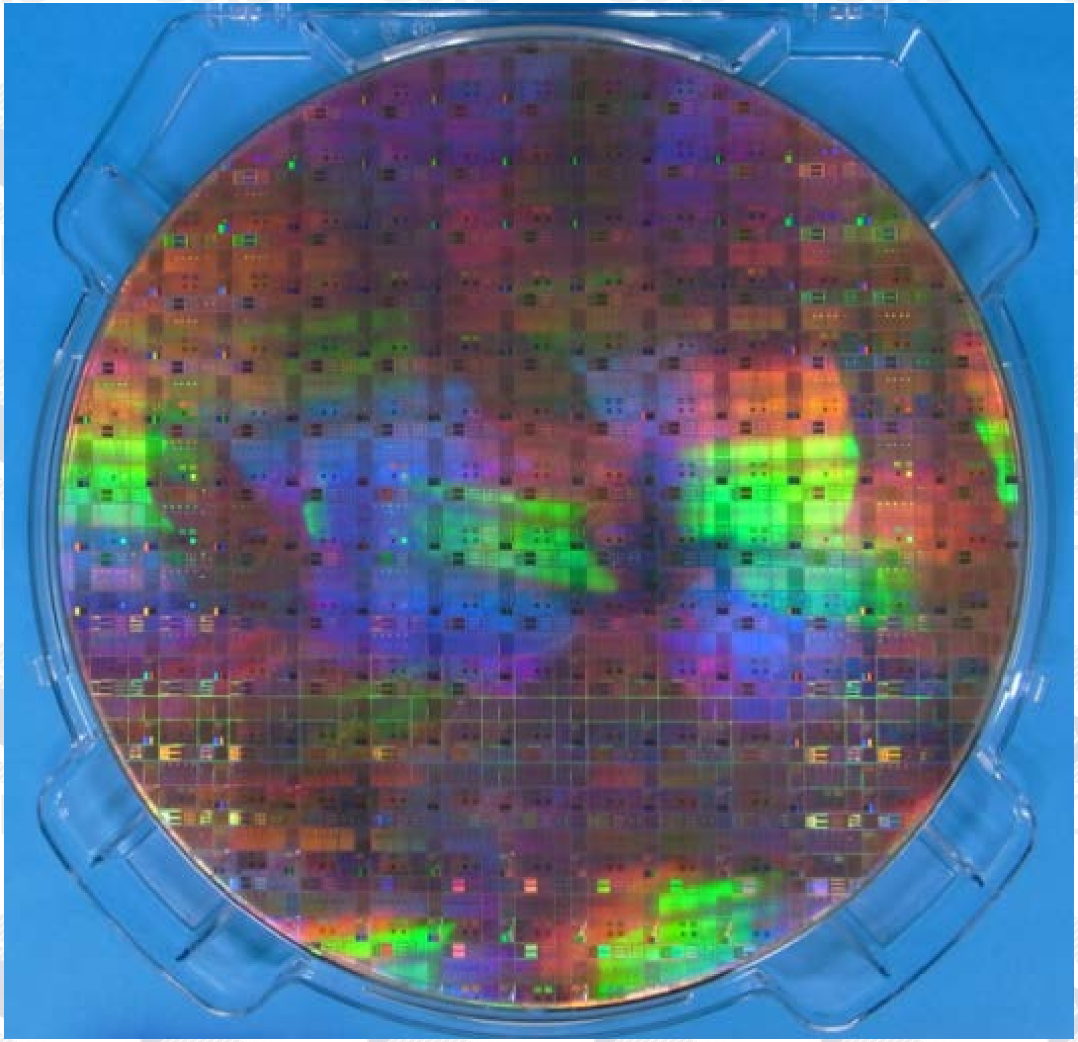


1.5nsec / 1Mbit
Embedded MRAM
(**Fastest** nonvolatile 1Mbit memory)
（VLSI 2013）

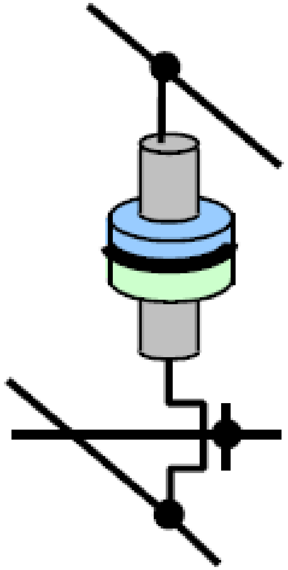


Nonvolatile microcomputer
(**First** nonvolatile microcomputer)
（ISSCC 2014）

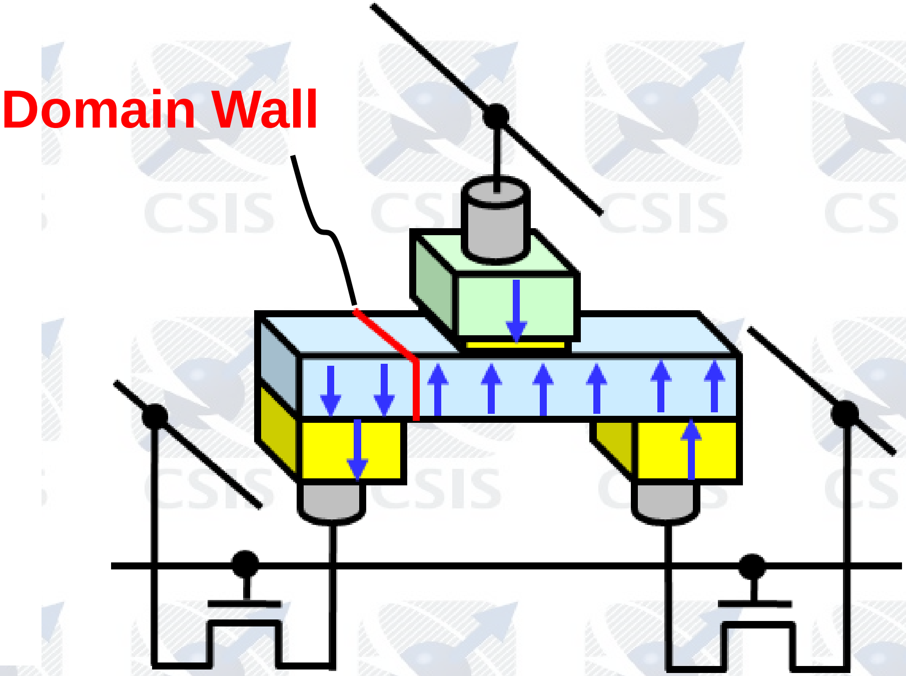
On 300 mm wafers



Magnetic Tunnel Junctions (MTJs)



two terminal



three terminal

Nonvolatile, fast, low voltage and high endurance

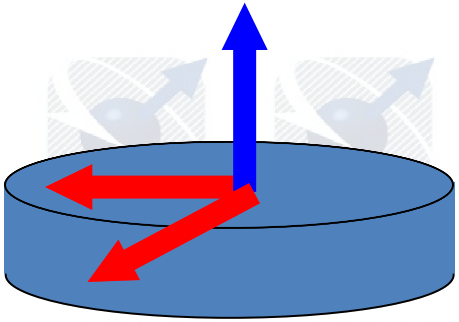
Switching Current I_{c0} and Energy Barrier $\Delta = E/k_BT$

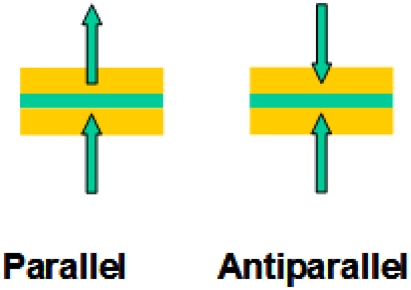
perpendicular

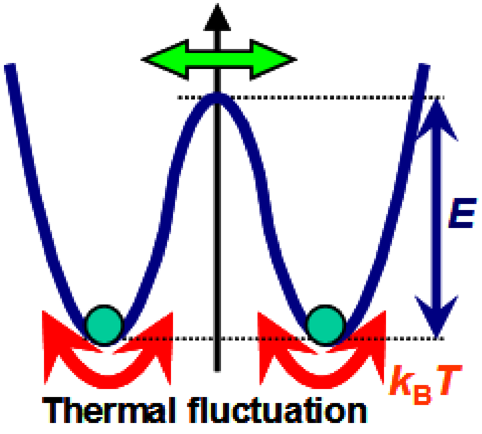
$$E = \left(\frac{1}{2} M_S H_K\right) V = \underline{K_{eff}} V$$

$$I_{C0} = \frac{2\alpha\gamma e}{\mu_B g}\left(\underline{K_{eff}} V\right)$$

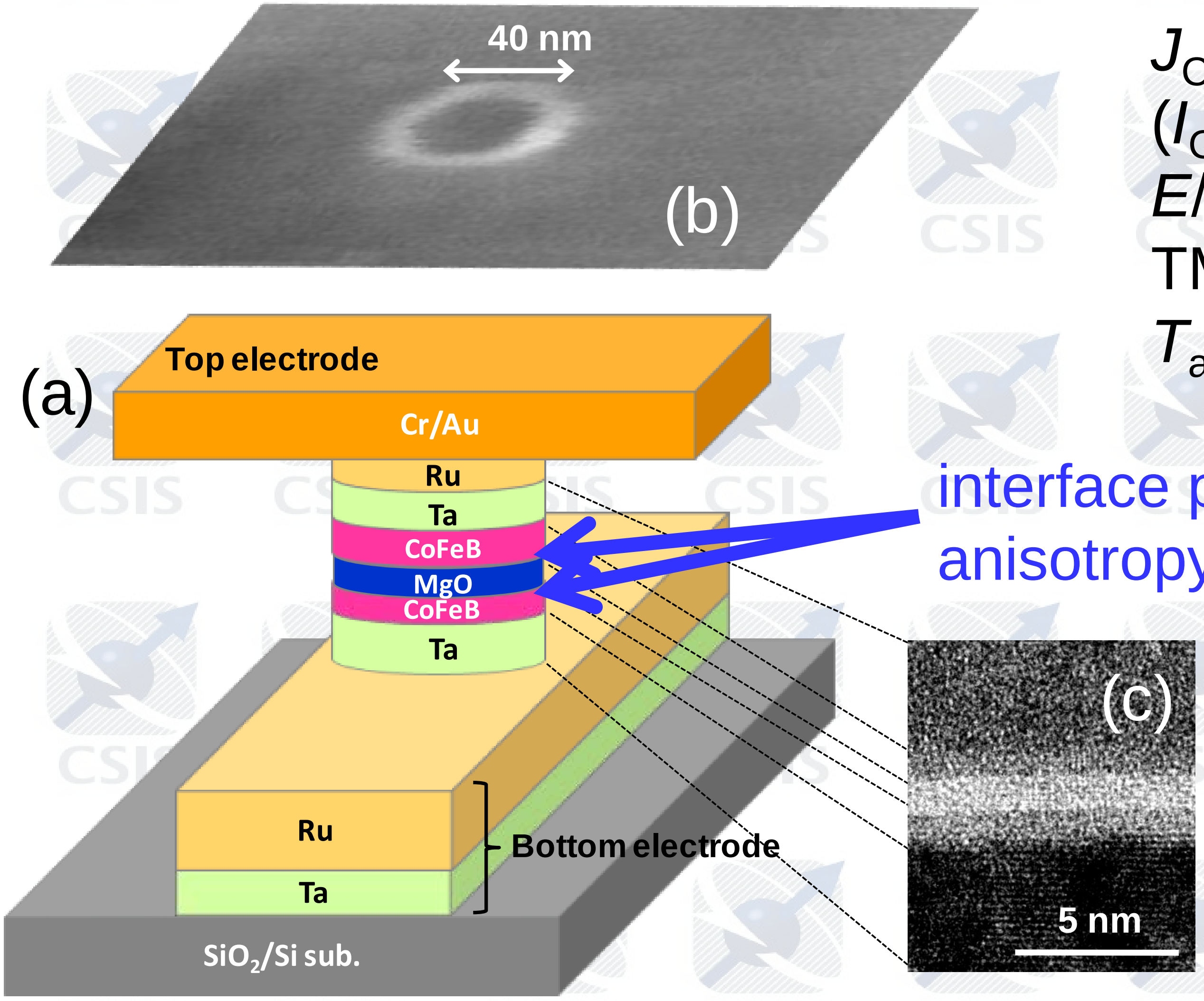
$$\propto \alpha E$$







Perpendicular MgO-CoFeB MTJ

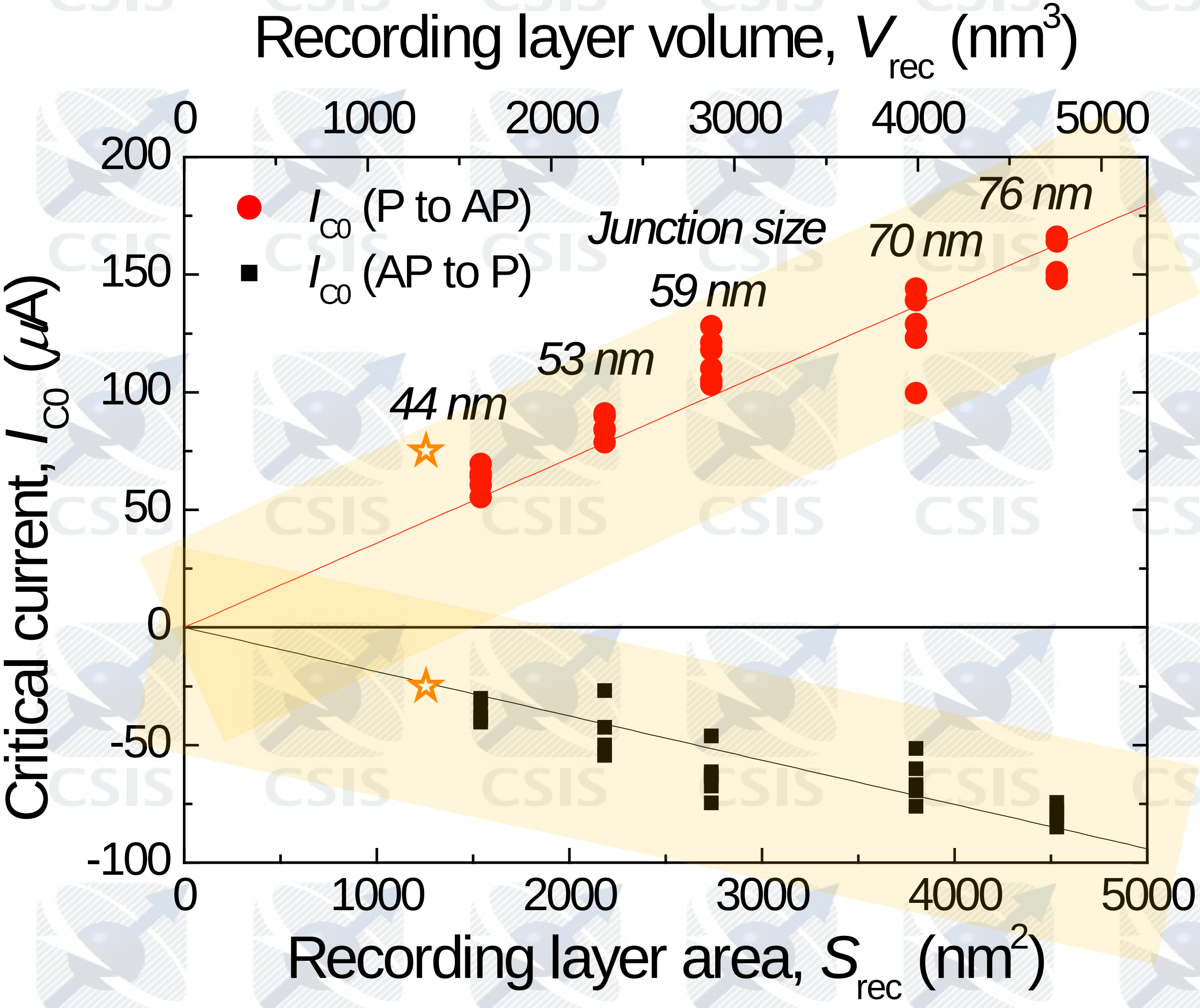


interface perpendicular anisotropy

J_{C0} = 3.8 MA/cm^2
(I_{C0} = 48 μA)
E/k_BT ~ 40
TMR ratio = 110%
T_a = 350^{o}C

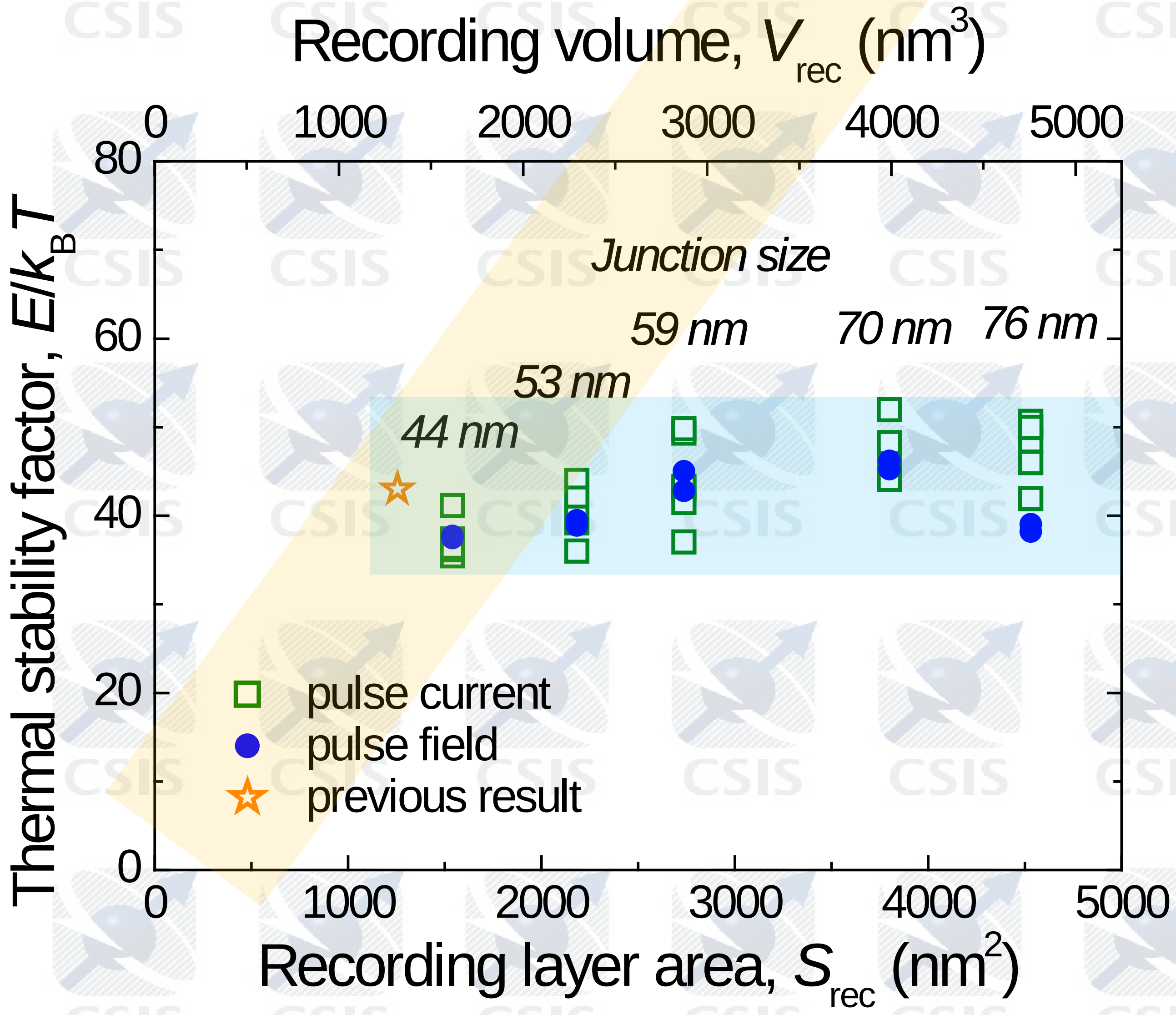
S. Ikeda *et al*., Nature Mat. **9**, 721 (2010)

Size dependence of I_{C0}



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

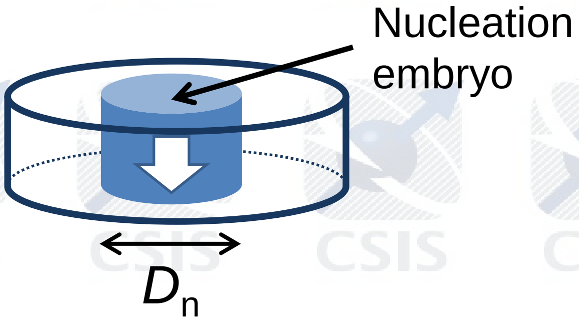
Size dependence of $\Delta = E/k_B T$

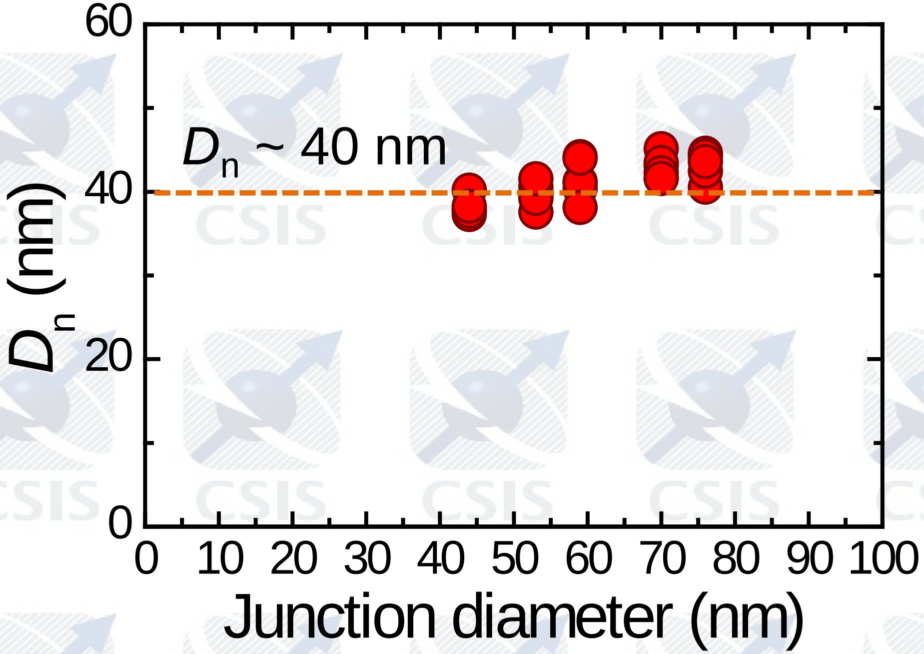


$$E \neq KV$$

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

Nucleation diameter





$$\Delta = \frac{K_{eff}\left(D_n/2\right)^2 t}{k_B T}$$

Our results along with others suggest $D_n \approx \delta_W = \pi\sqrt{\frac{A_S}{K_{eff}}}$

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

E and layer thickness

$$E = K_{eff} V = K_{eff} \pi \left(D_{\mathrm{n}} / 2 \right)^2 t$$

⇩

$$E \approx K_{eff} \pi \left(\delta_{\mathrm{W}} / 2 \right)^2 t$$

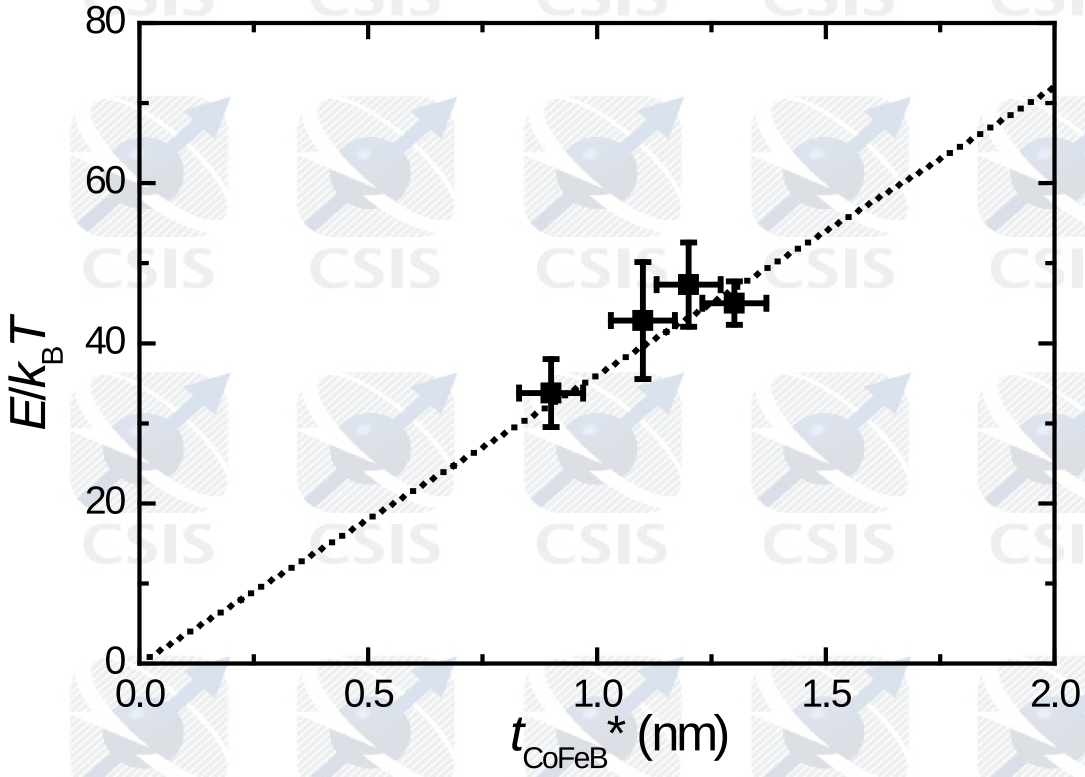
$$= \frac{\pi^3 A_S t}{4}$$

$$\propto t$$

H. Sato *et al*., IEEE Magn. Lett. **3**, 3000204 (2012).

$$\left(K_{eff} = \frac{K_{\mathrm{i}}}{t} + K_{\mathrm{b}} - \frac{M_{\mathrm{S}}^2}{2\mu_0} \right)$$

CoFeB thickness dependence of E/k_BT



- t_{CoFeB}^* (= t_{rec}) was determined by subtracting magnetically dead layer (0.4 nm) at CoFeB/Ta interface.

$$E \approx K_{eff}\pi(\delta_w/2)^2 t_{rec}$$
$$= \pi^3 A_s t_{rec}/4$$

- A linear relationship between E/k_BT and t_{rec}
- The slope of 36 nm^{-1} ⇒ $A_s^* \approx 19$ pJ/m

H. Sato *et al.*, IEEE Magn. Lett. **3**, 3000204 (2012).

Domain patterns of CoFeB

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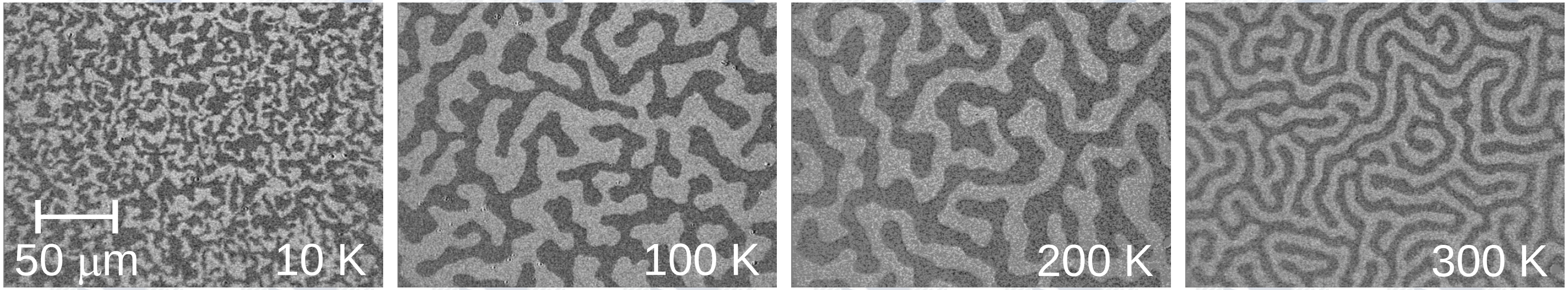
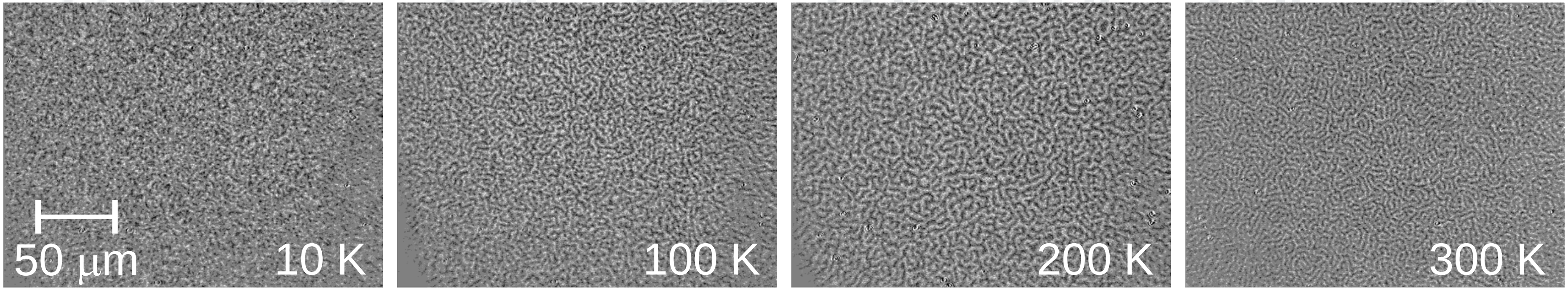
Magneto-optical Kerr effect (MOKE) images after demagnetization

sample A (t = 1.1 nm), as-deposited



sample B (t = 1.3 nm), annealed at 350°C



***T* ≥ 100 K**

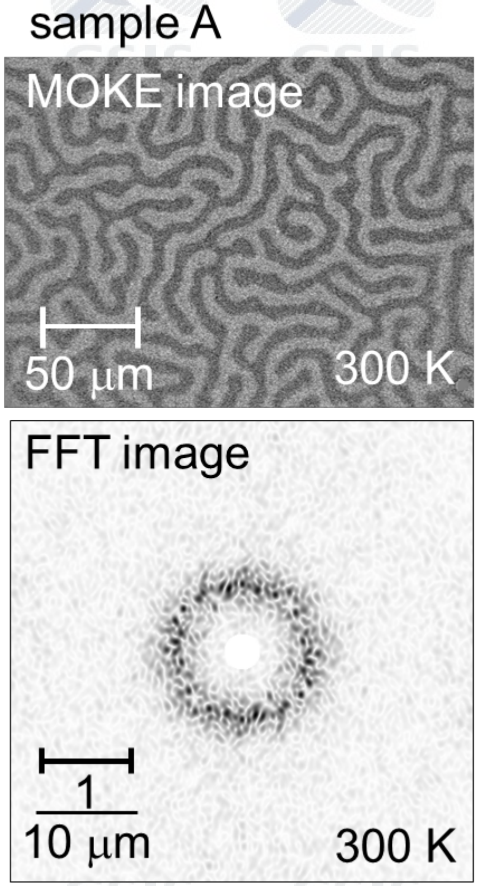
- Domain walls moved smoothly
- Labyrinth patterns were formed

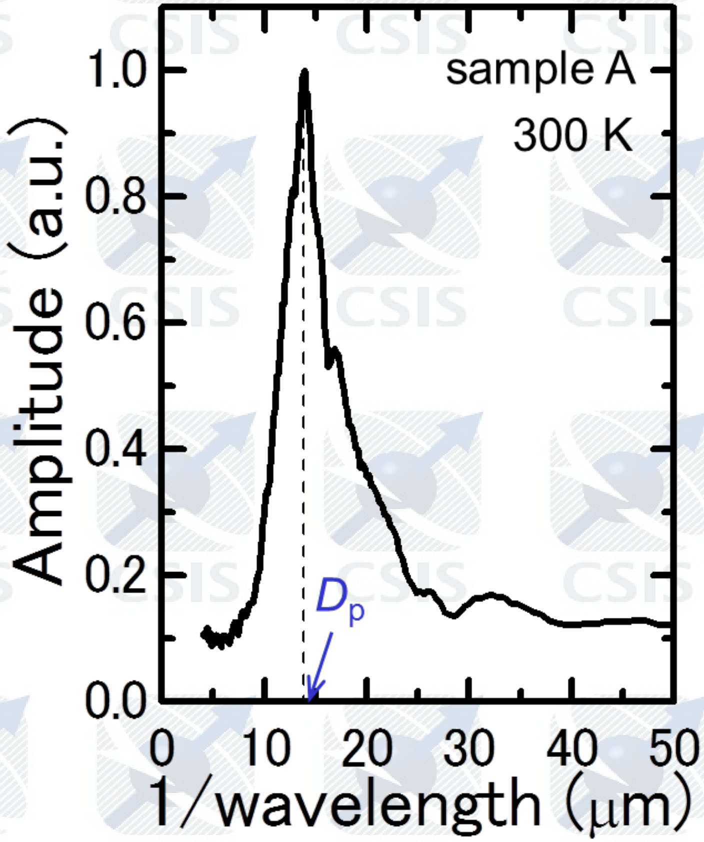
***T* ≤ 50 K**

- Domain walls were strongly pinned
- Complex patterns were formed

M. Yamanouchi *et al*., IEEE Magn. Lett. **2**, 3000304 (2011).

Domain patterns of CoFeB

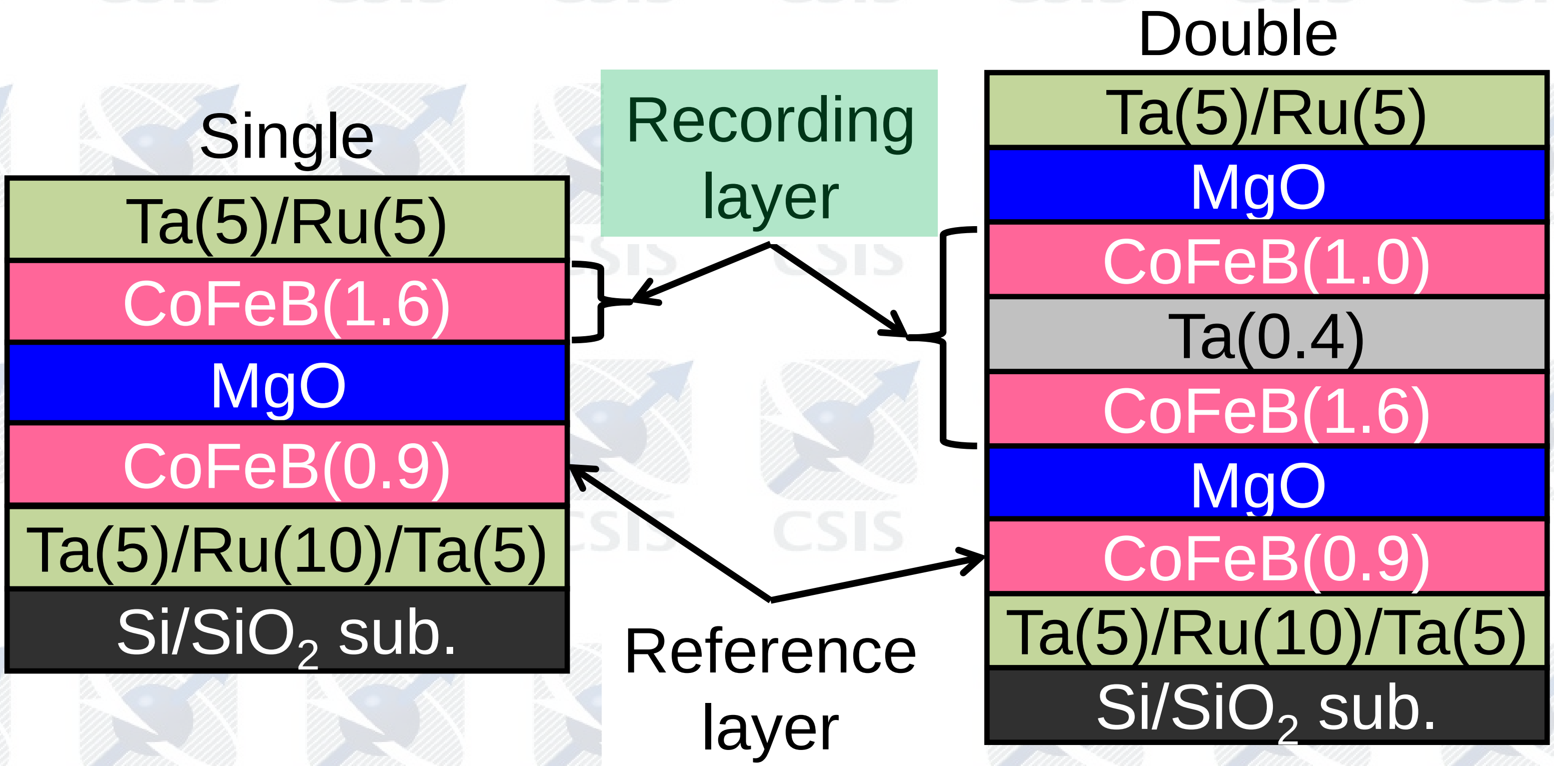




	A_s (pJ/m) at 300 K	δ_w (nm) at 300 K
sample A (t = 1.1 nm, As-deposited)	8.4	43
sample B (t = 1.3 nm, 350°C)	31	67

M. Yamanouchi *et al*, IEEE Magn. Lett., **2**, 300304 (2011)

Double interface structure



Single

Ta(5)/Ru(5)

CoFeB(1.6)

MgO

CoFeB(0.9)

Ta(5)/Ru(10)/Ta(5)

Si/SiO$_2$ sub.

Recording layer

Reference layer

Double

Ta(5)/Ru(5)

MgO

CoFeB(1.0)

Ta(0.4)

CoFeB(1.6)

MgO

CoFeB(0.9)

Ta(5)/Ru(10)/Ta(5)

Si/SiO$_2$ sub.

(70 nmϕ)	**Single**	**Double**
E/k_BT	51	**95**
J_{C0} (MA/cm^2)	3.3	3.2

H. Sato, *et al*., Appl. Phys. Lett. **101**, 022414 (2012).

Double MgO

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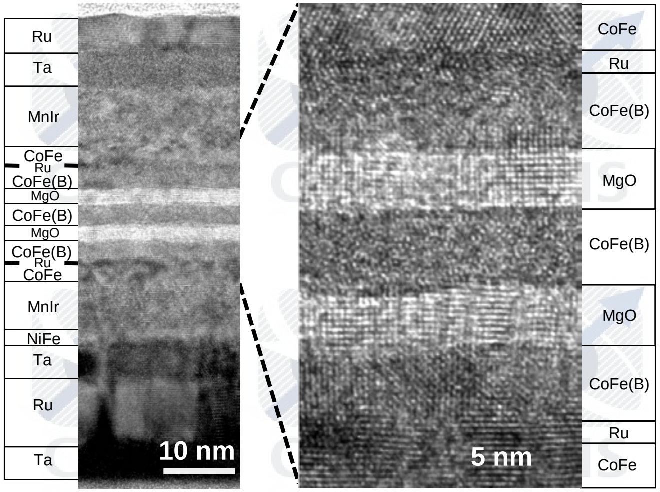
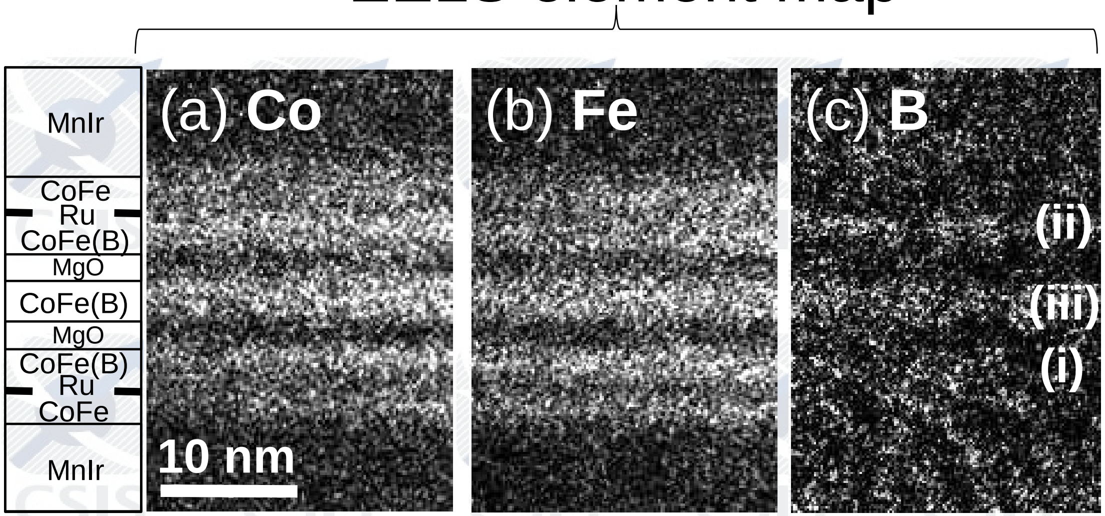
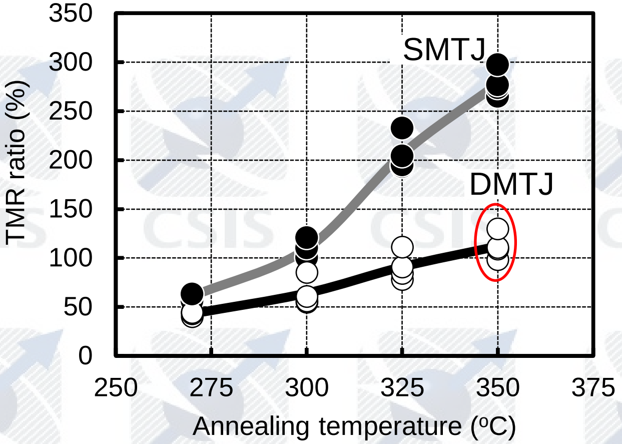
Double-MgO MTJ (DMTJ)
annealed at T_a = 350 °C



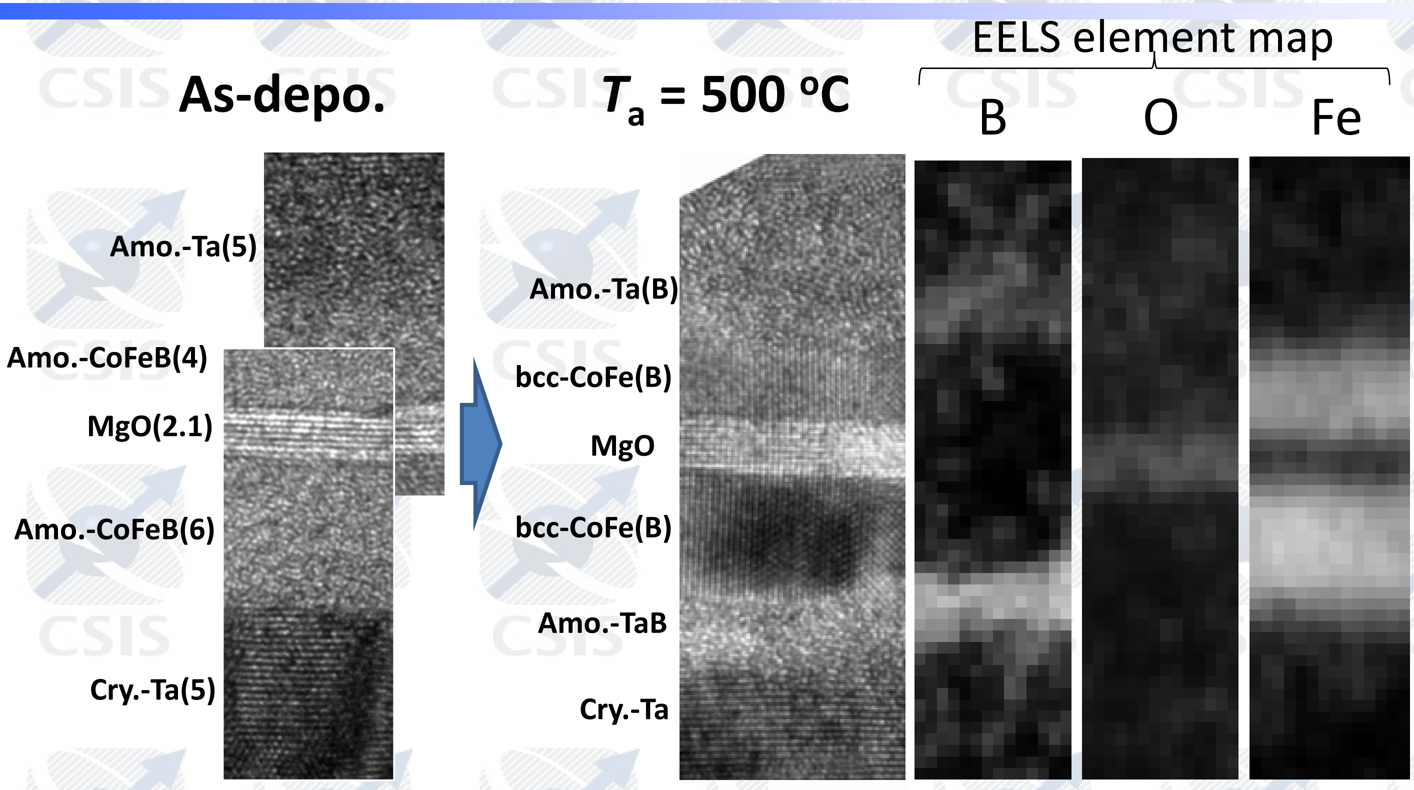
EELS element map

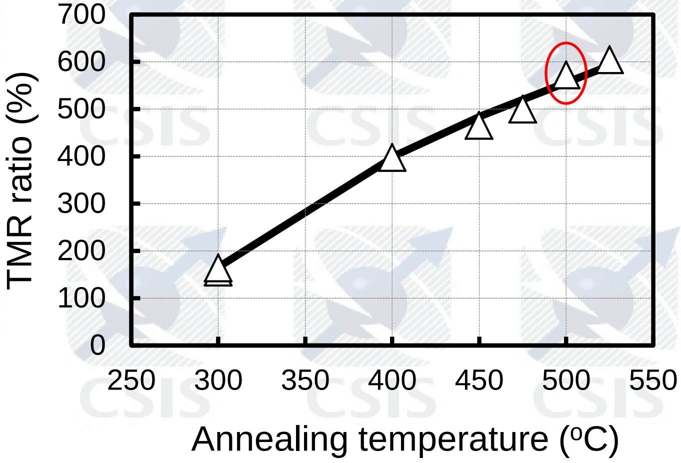




H. D. Gan et al., Appl. Phys. Lett. 96 (2010) 192507.

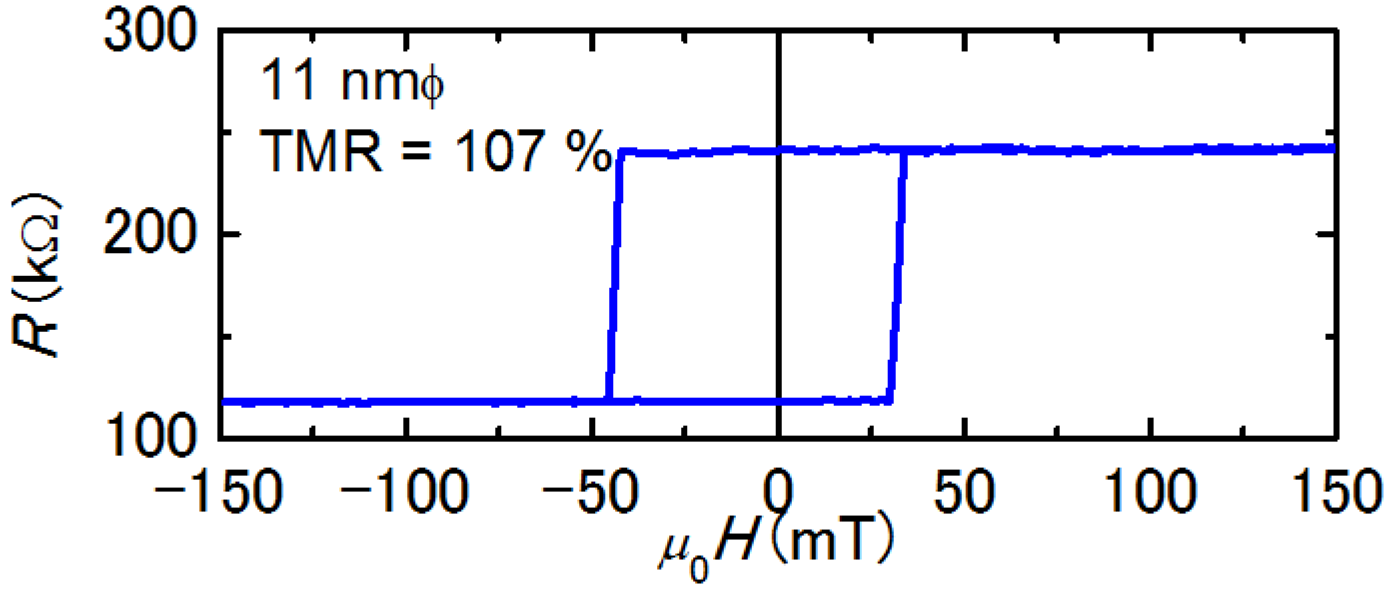
Single MgO

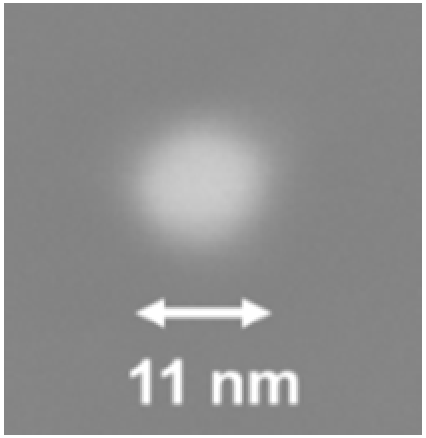




S. Ikeda et al., Appl. Phys. Lett. 93(2008) 082508.
S. V. Karthik et al., J. Appl. Phys. 106 (2009) 023920.

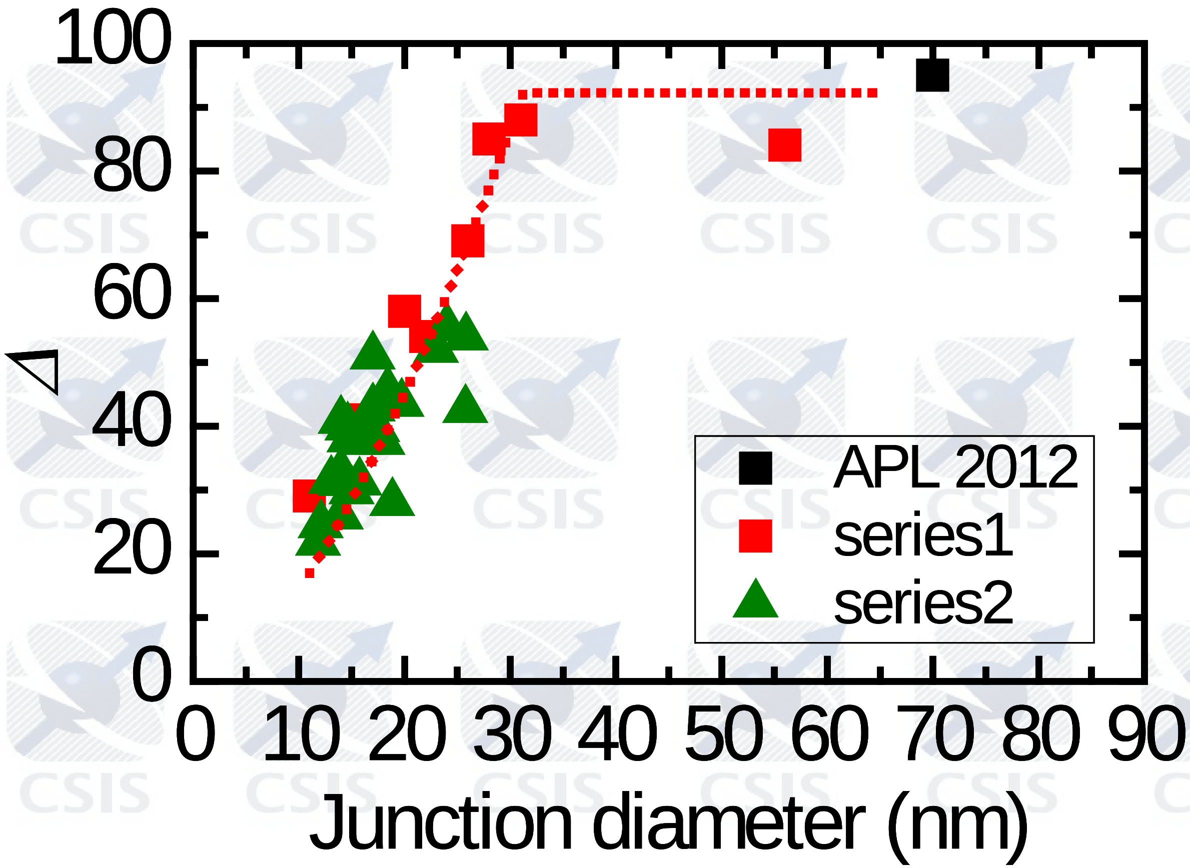
11 nmϕ MTJ (smallest MTJ to date)





H. Sato *et al. Appl. Phys. Lett*. **105**, 062403 (2014)

Device size dependence of Δ



Dotted line reproduces the trend well

Interface engineering to further enhance Δ

H. Sato *et al*., *Appl. Phys. Lett.* **101**, 022414 (2012).
H. Sato *et al*., IEDM 2013, p. 3.2.1.
H. Sato *et al. Appl. Phys. Lett*. **105**, 062403 (2014)

Demagnetization coefficient *N*

$$E = K_{eff}\, t \left(\frac{D}{2} \right)^2 \pi$$

$$K_{eff} = \frac{K_i}{t} + K_b - \frac{M_S^2}{2\mu_0} \underline{\left(N_z - N_x \right)}$$

Reported properties of nano p-MTJs

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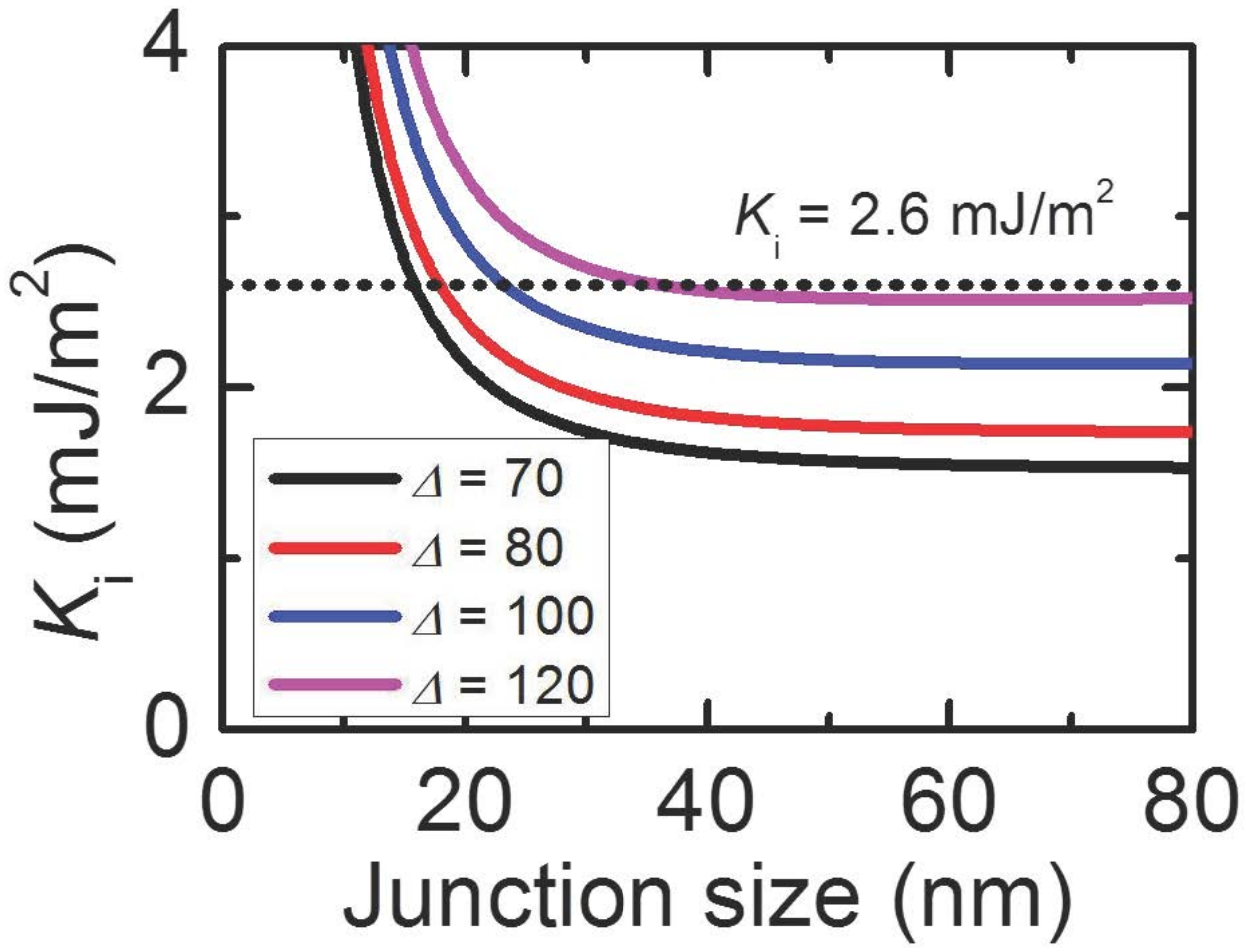
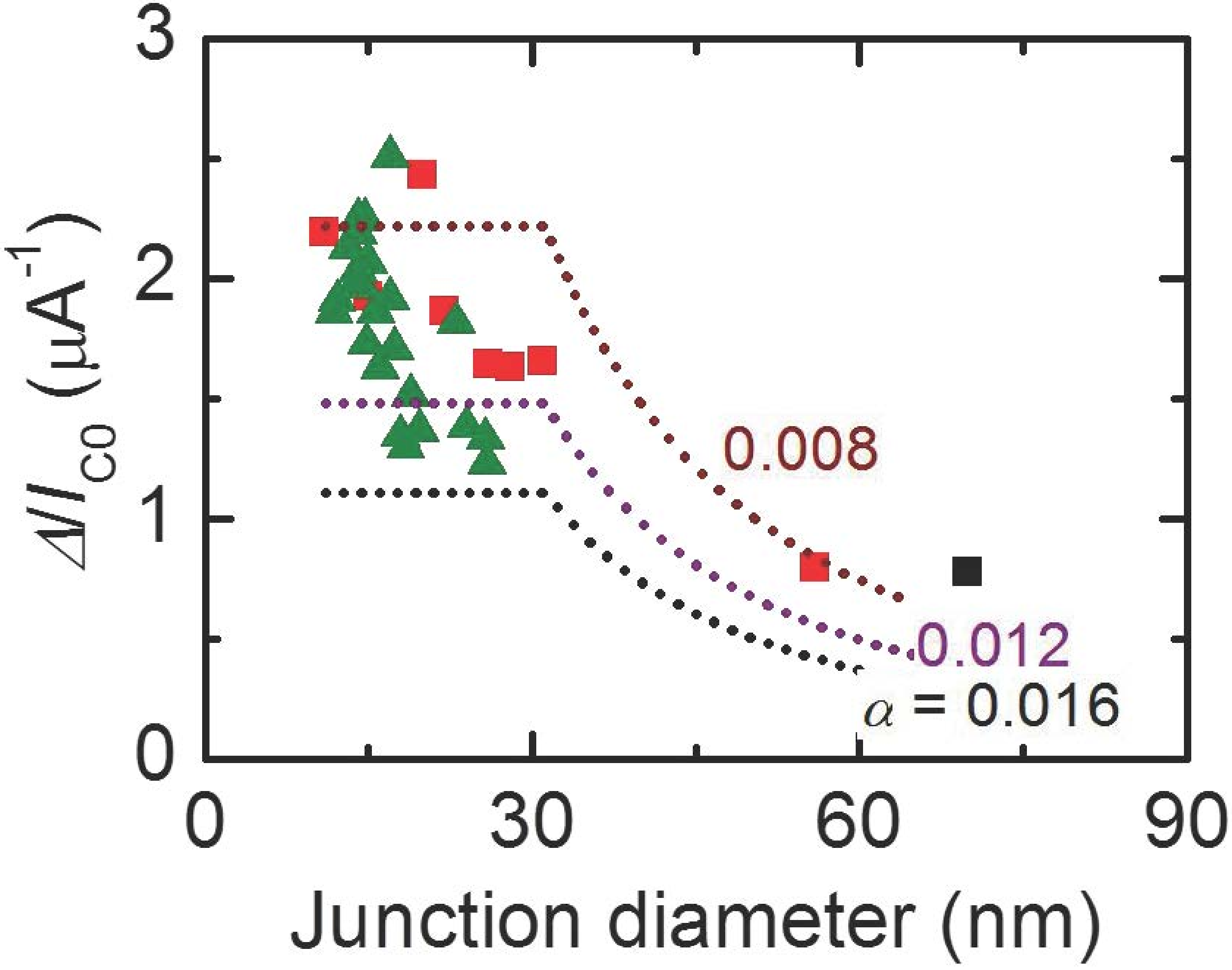
Material	Size (nm)	TMR ratio (%)	I_{C0} or I_C (μA)	E/k_BT	Ref
CoFeB	40	124	49	43	[1]
CoFeB	17x40	100 (CIPT)	50	35	[2]
CoFeB	20	57	29	29	[3]
undisclosed	30	73	25	61	[4]
CoFeB	27	130	12	80	[5]
			19	147	
undisclosed	15	-	~0.6 V	~42	[6]
CoFeB/Ta/CoFeB	20	127	24	58	[7]
	15	101	22	41	[7]
	11	107	13	28	[7]

[1] S. Ikeda *et al*., Nature Mater. 9, 721 (2010).
[2] W. Kim *et al*., 2011 IEDM, p24.1.1
[3] M. Gajek *et al*, Appl. Phys. Lett. 100, 132408 (2012).
[4] E. Kitagawa *et al*., 2012 IEDM, p. 29.4.2.
[5] L. Thomas *et al*., J. Appl. Phys. 115, 172615 (2014).
[6] J. H. Kim et al., 2014 VLSI Tech., P.76.
[7] H. Sato *et al*., 2013 IEDM, p. 61., Appl. Phys. Lett. 2014

Interface anisotropy – junction size, K_i and Δ



Size dependence of $\Delta I/I_{C0}$



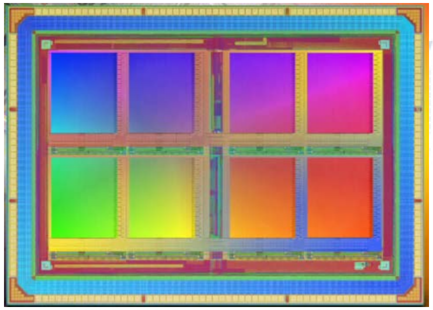
H. Sato *et al.*, *Appl. Phys. Lett.* **101**, 022414 (2012).
H. Sato *et al.*, IEDM 2013, p. 3.2.1.
H. Sato *et al. Appl. Phys. Lett*. **105**, 062403 (2014)

Magnetization manipulation by

Magnetic field

write/read heads for HDD
1st generation MRAM

http://www.hitachigst.com/

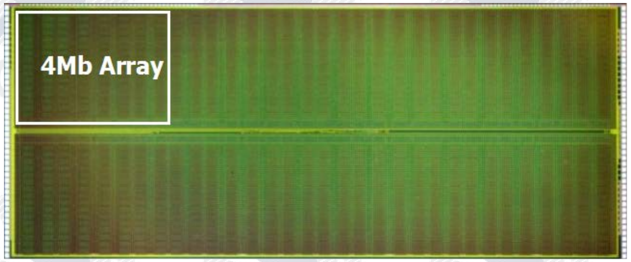


http://www.everspin.com/

Spin current

L. Berger, J. Appl. Phys. 55, 1954 (1984).
J. Slonczewski, J. Magn. Magn. Mat. 159, L1 (1996).
L. Berger, Phys. Rev. B 54, 9353 (1996).

Spin torque MRAM
Spin torque oscillator
Race-track memory



R. Takemura *et al*., VLSI Circ. Dig. p.84 (2009)

Electric field

Switching Energy

Spin-transfer switching

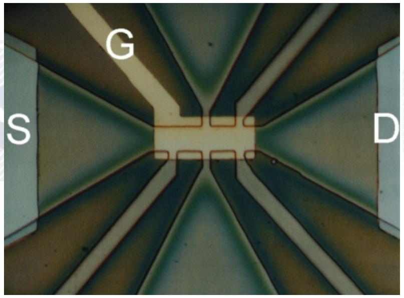
$$VIt = 0.25\ (\mathrm{V}) \times 30\ (\mu\mathrm{A}) \times 1\ (\mathrm{ns})$$
$$= 8\ (\mathrm{fJ})$$

Electric field switching

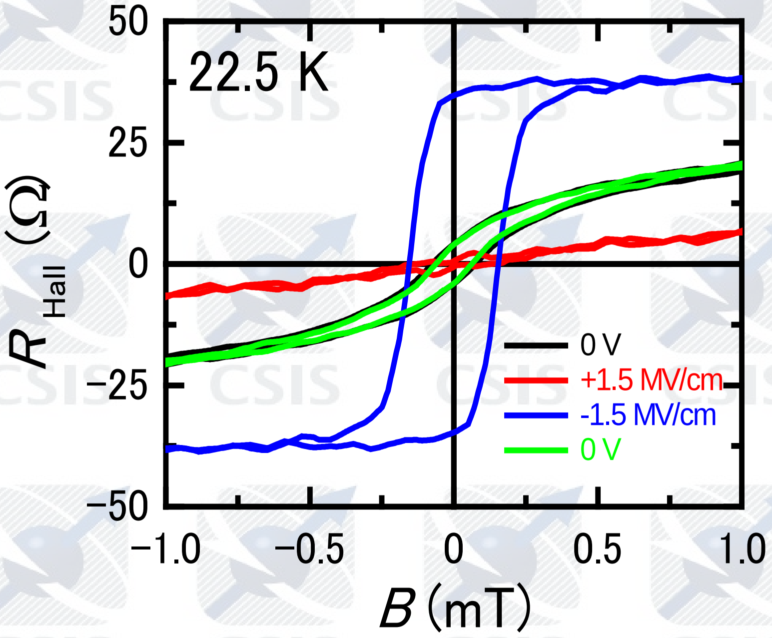
$$CV^2 = \mathrm{S} \times \mathrm{d} \times \varepsilon \times \mathrm{E}^2$$
$$= \pi\left(\frac{30\ (\mathrm{nm})}{2}\right)^2 \times 5\ (\mathrm{nm}) \times 9.8\ \varepsilon_0 \times (5\ (\mathrm{MV/cm}))^2$$
$$= 0.08\ (\mathrm{fJ})$$

Electric-field control of magnets

Ferromagnetic transition

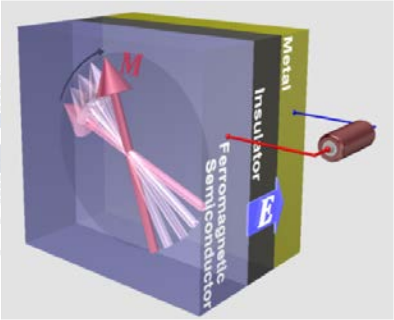


Ferromagnetic semiconductor (In,Mn)As

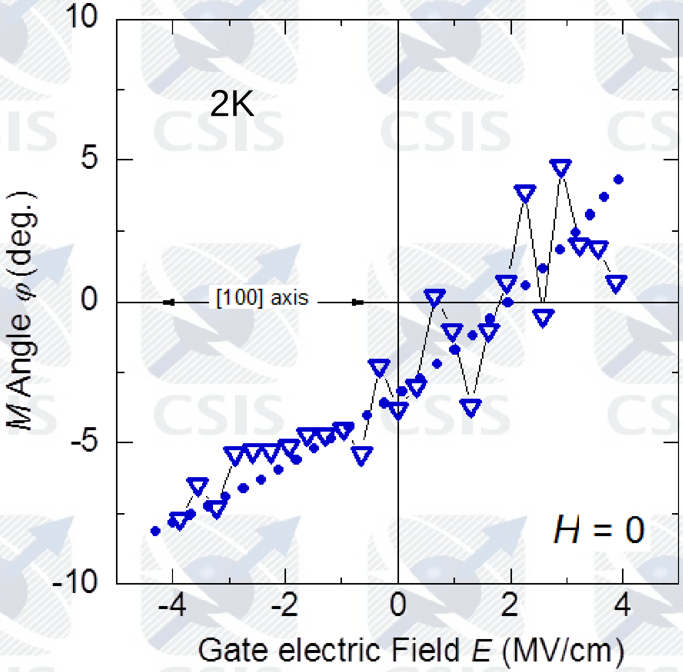


H. Ohno *et al.*, *Nature* 408, 944 (2000)

Magnetization direction

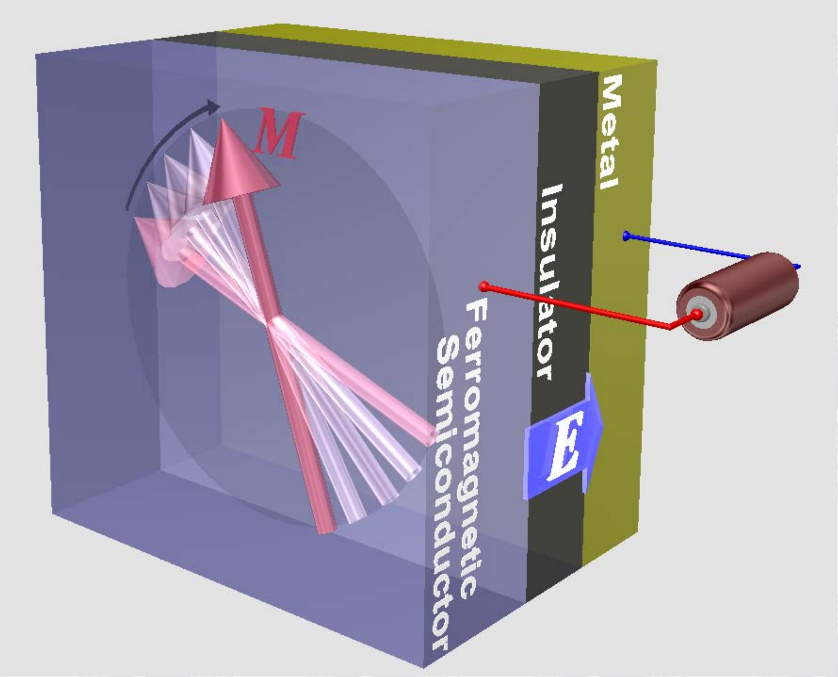


Ferromagnetic Semiconductor (Ga,Mn)As



D. Chiba *et al.*, *Nature* 455, 515 (2008)

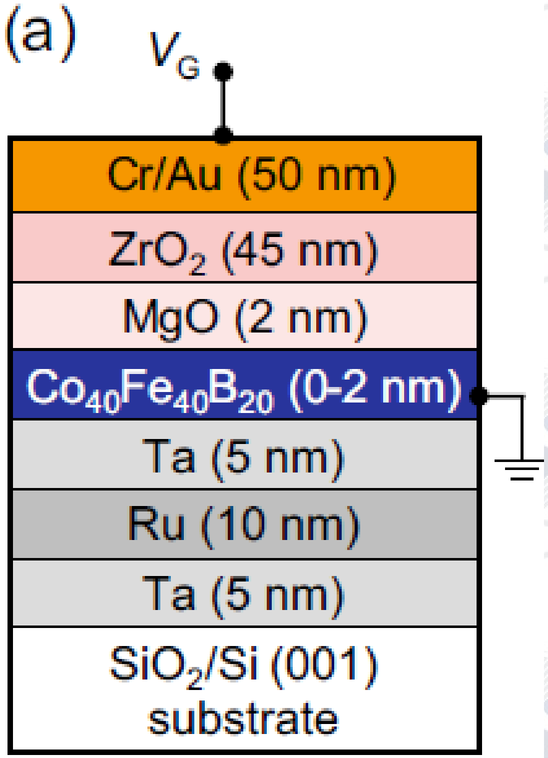
Magnetization switching by anisotropy



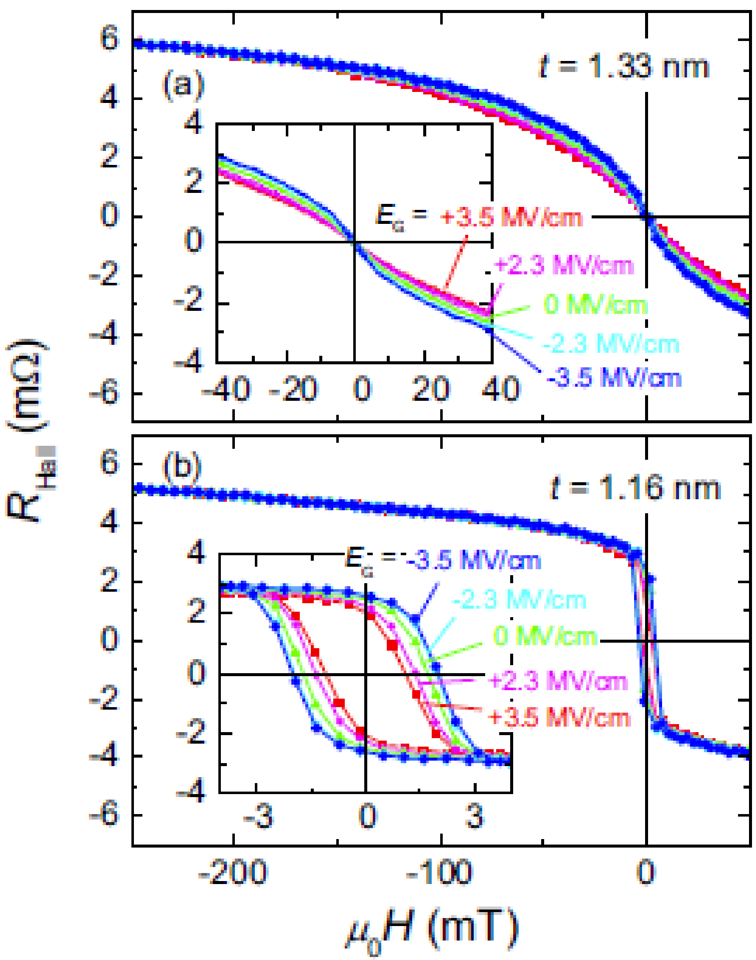
(1) *perpendicular* to *in-plane* and back

(2) controlling *in-plane* anisotropies

Electric-field effects on metals



Room temperature



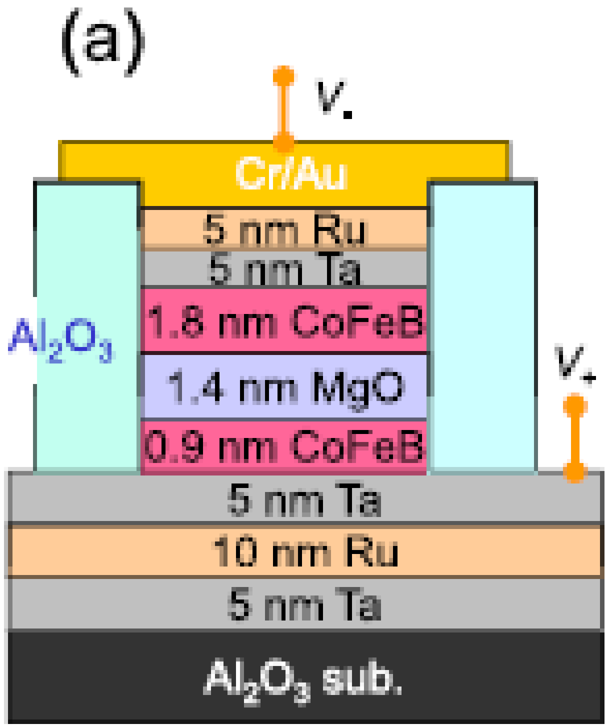
$30\ \mu eV/m^2$ per V/nm

Electric-field modulation of anisotropy in CoFeB

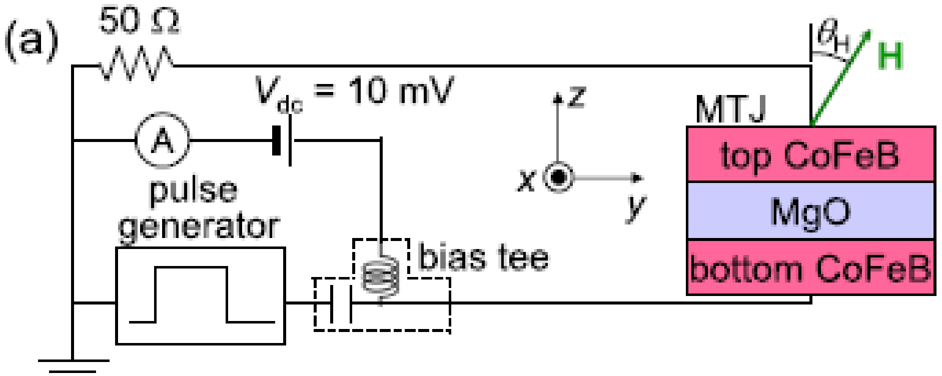
M. Endo, S. Kanai, S. Ikeda, F. Matsukura, and H, Ohno, *Appl. Phys. Lett.* 96, 212503 (2010).

See also; FePt, FePd: M. Weisheit *et al.*, Science (2007). Fe/Au: T. Maruyama *et al.*, Nature Nanotechnology (2009).

Electrical switching of *perpendicular* CoFeB

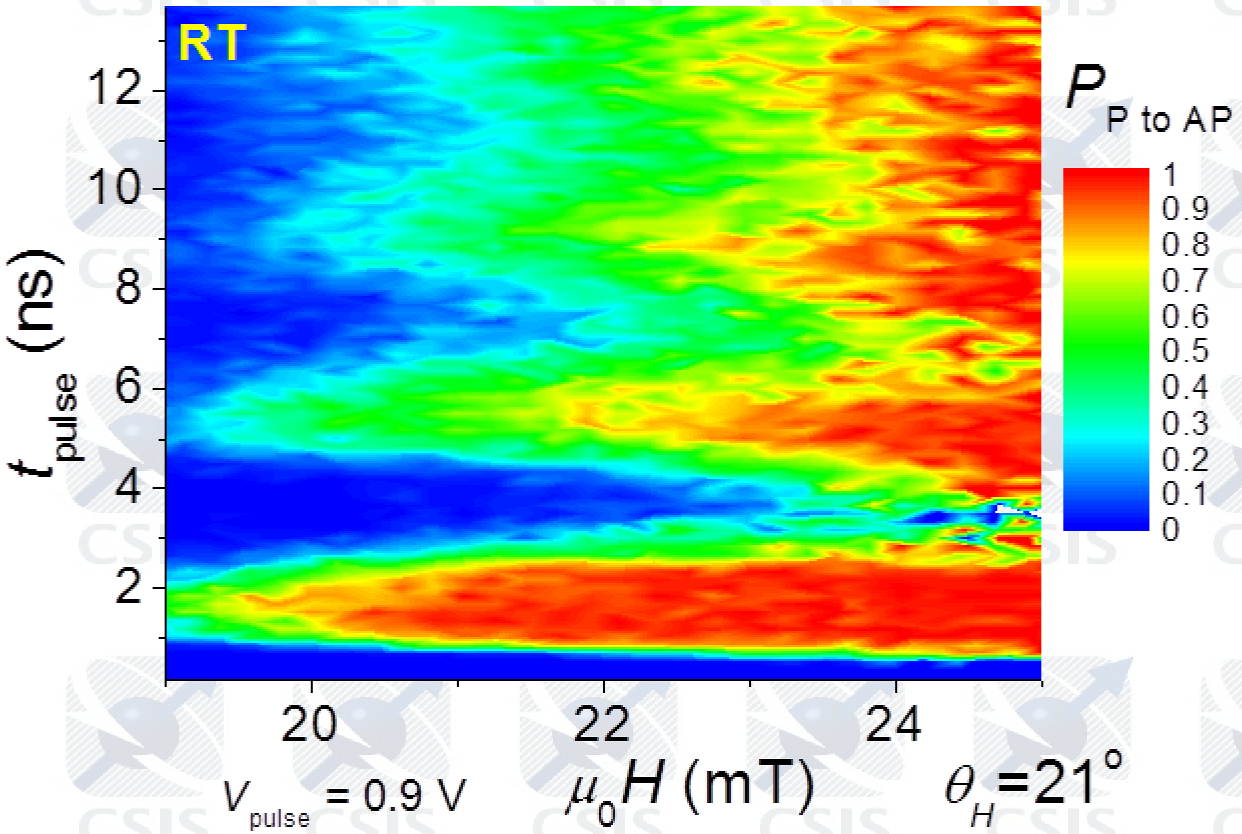


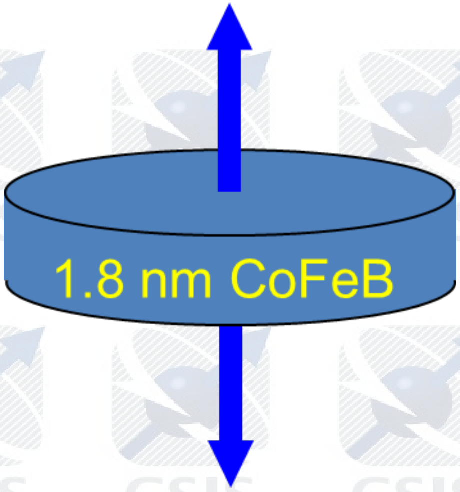
70 nmϕ



S. Kanai *et al*., *Appl. Phys. Lett.* **101**, 122403 (2012)

Electrical switching of *perpendicular* CoFeB



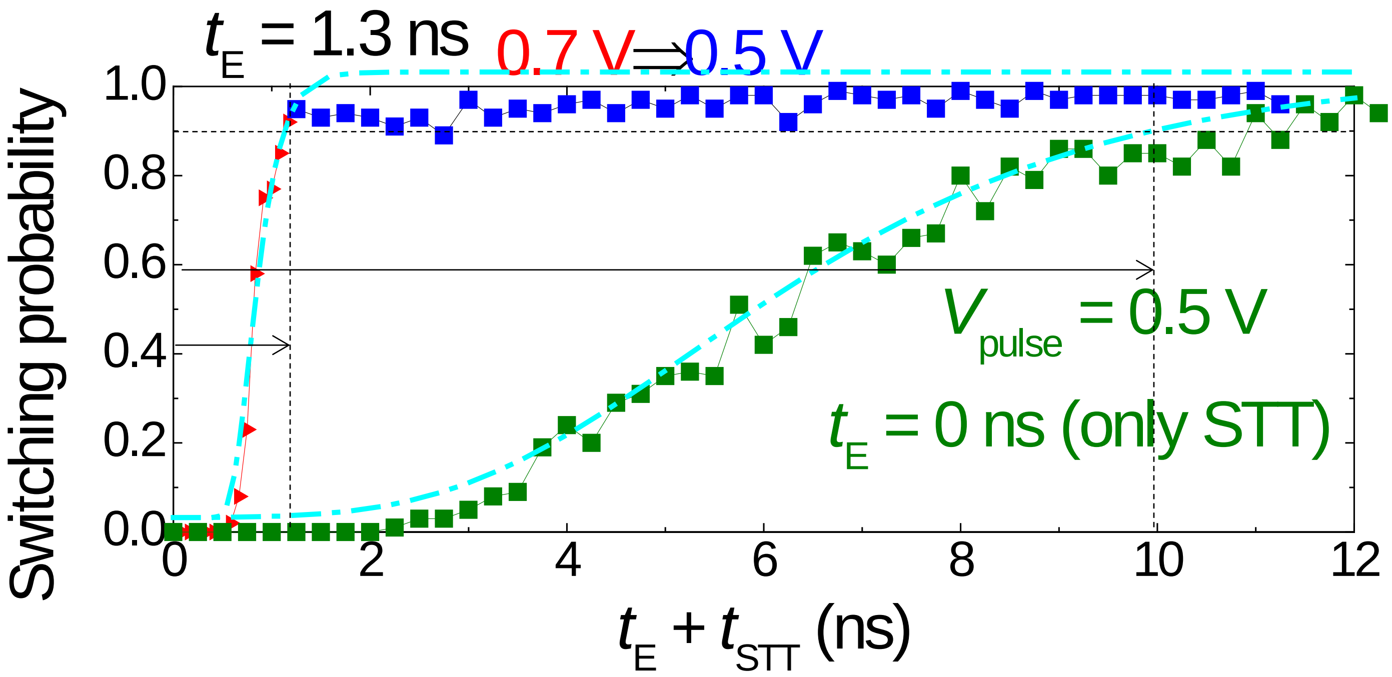


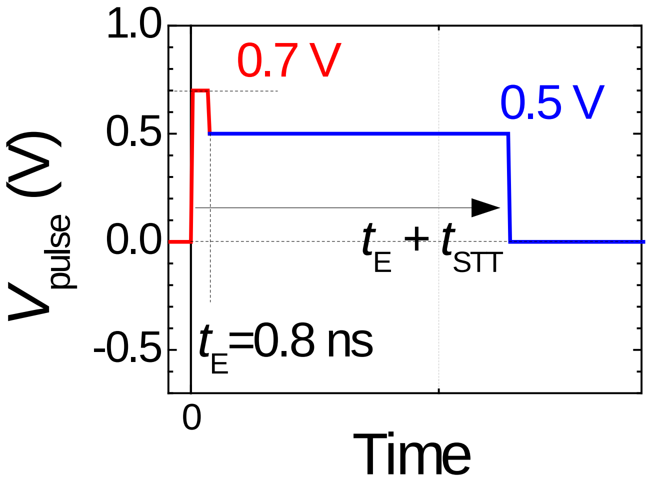
under constant magnetic field

S. Kanai, *et al.*, *Appl. Phys. Lett.* **101**, 122403 (2012)
S. Kanai, *et al.*, *Appl. Phys. Lett.* **103,** 072408 (2013)

See also Y. Shiota et al. *Nature Materials*, 2011 for ultrathin FeCo
W. G. Wang et al. *Nature Materials* 2012 for electric-field assisted switching

Electrical switching plus STT



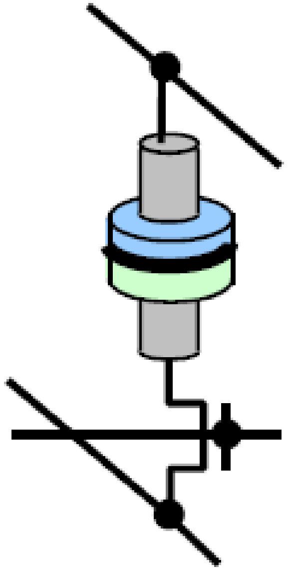


S. Kanai, et al., *Appl. Phys. Lett.* **104**, 212406 (2014)

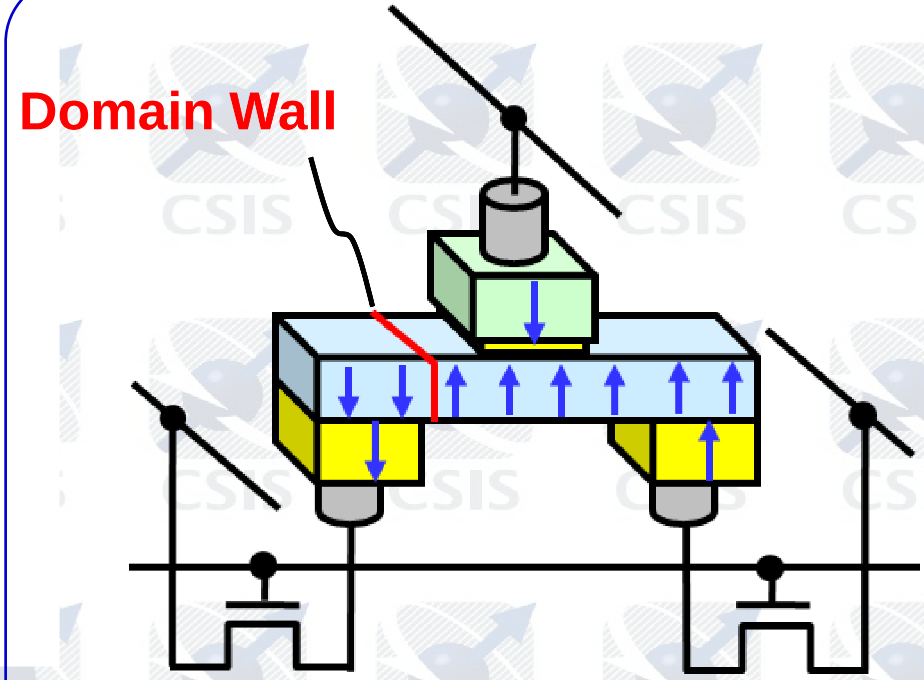
Remaining challenges

- ✓ Toggle: read before write
- ✓ Scaling: $E=KV$, $\Delta K_i=E/S$
- ✓ Configuration: two terminal vs. three
- ✓ Switching probability
- ✓ Pulse: shape and timing control

Two and three terminal devices



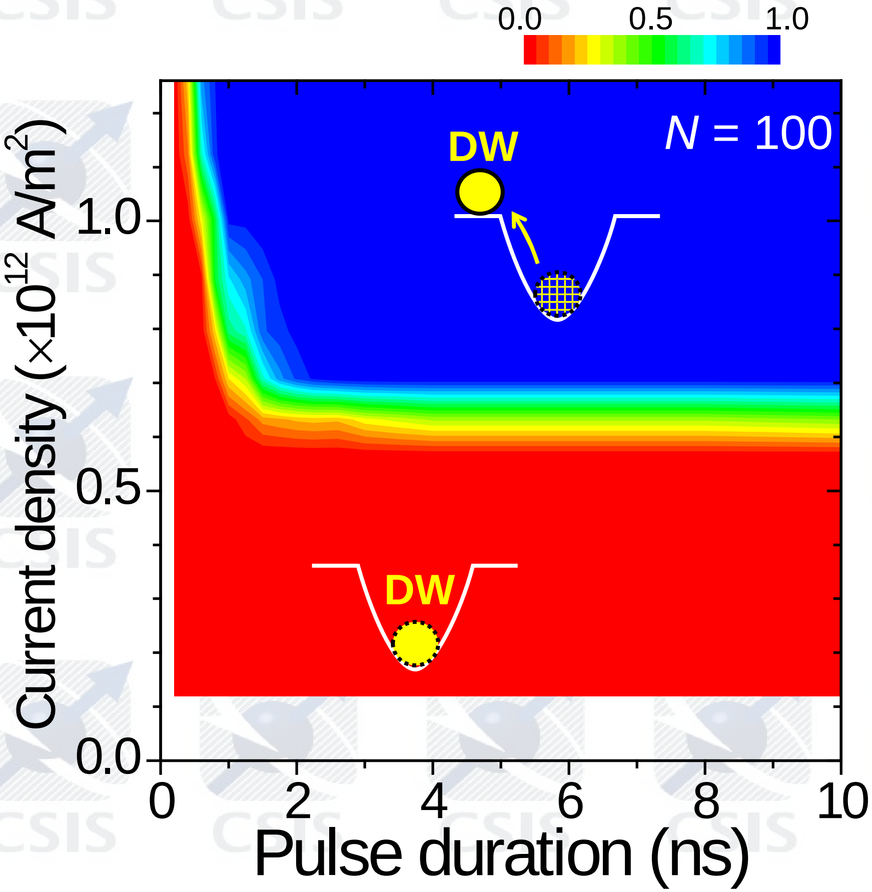
two terminal

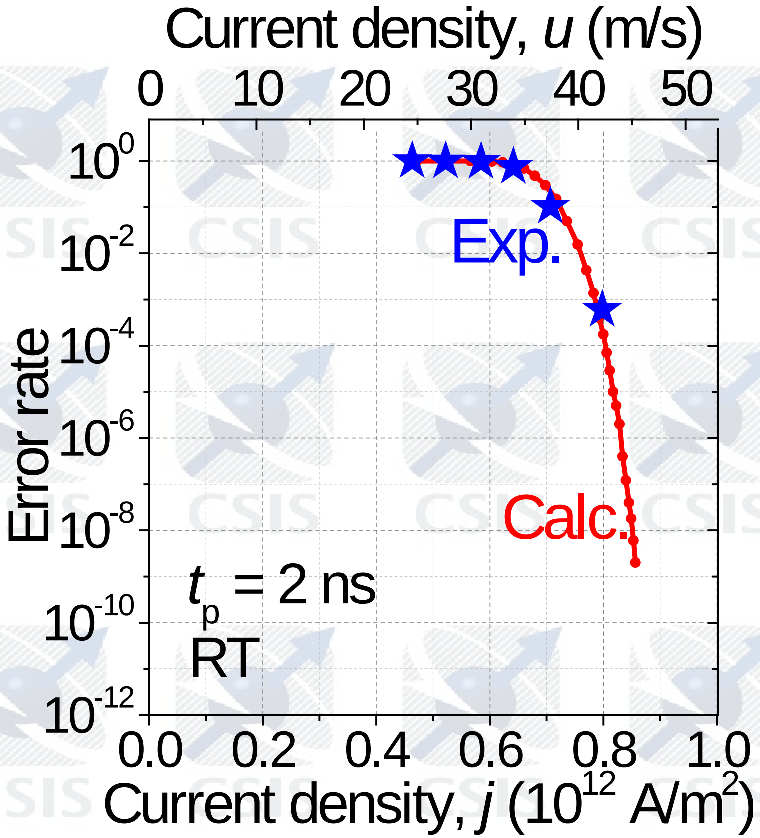


three terminal

Nonvolatile, fast, low voltage and high endurance

Depinning probability of DW by ns pulses



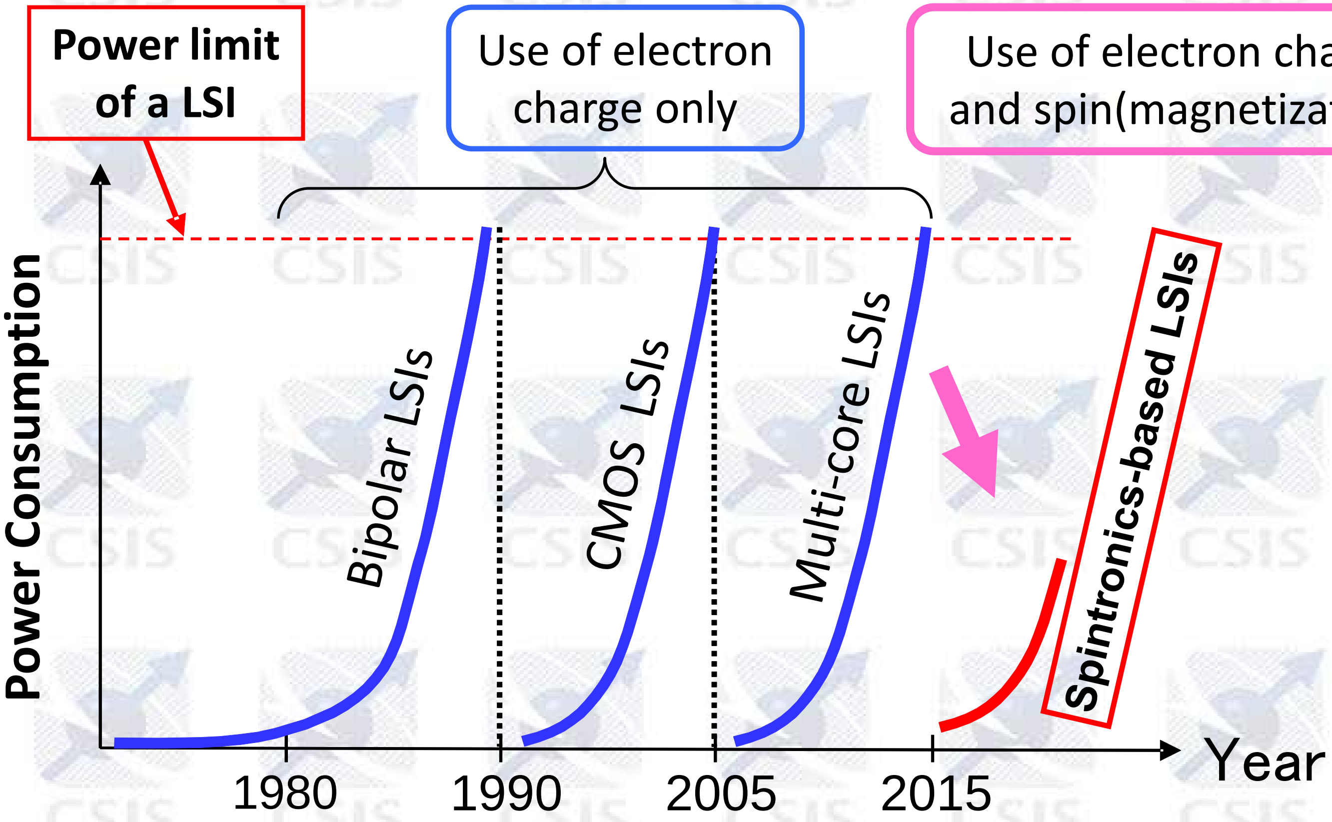


- Critical current density shows constant down to ~2 ns.
- Error rate decreases above a threshold more steeply than MTJs.

S. Fukami, H.O. *et al*., *Nat. Commun.* **4**, 2293 (2013).

A New Paradigm in VLSI

Whenever power consumption of LSI increased to hit a limit of heat dissipation, a paradigm shift in LSI technology has taken place by bringing in new technology.



Summary

Spintronics devices are an indispensable ingredient in developing CMOS VLSI with low power and high performance.

Two terminal device

- Size dependence of energy barrier of perpendicular CoFeB-MgO MTJ between 30 and 11 nm; size dependence of demagnetization.
- Size dependence of Δ/I_{C0} suggests additional reduction of dissipative path as size reduces.
- Electric-field manipulation of magnetization

Three terminal device

- Depinning probability that determines error rate was explored and shown to follow a function steeper than that known for MTJs.