Magnetic Tunnel Junction for Integrated Circuits: Scaling and Beyond

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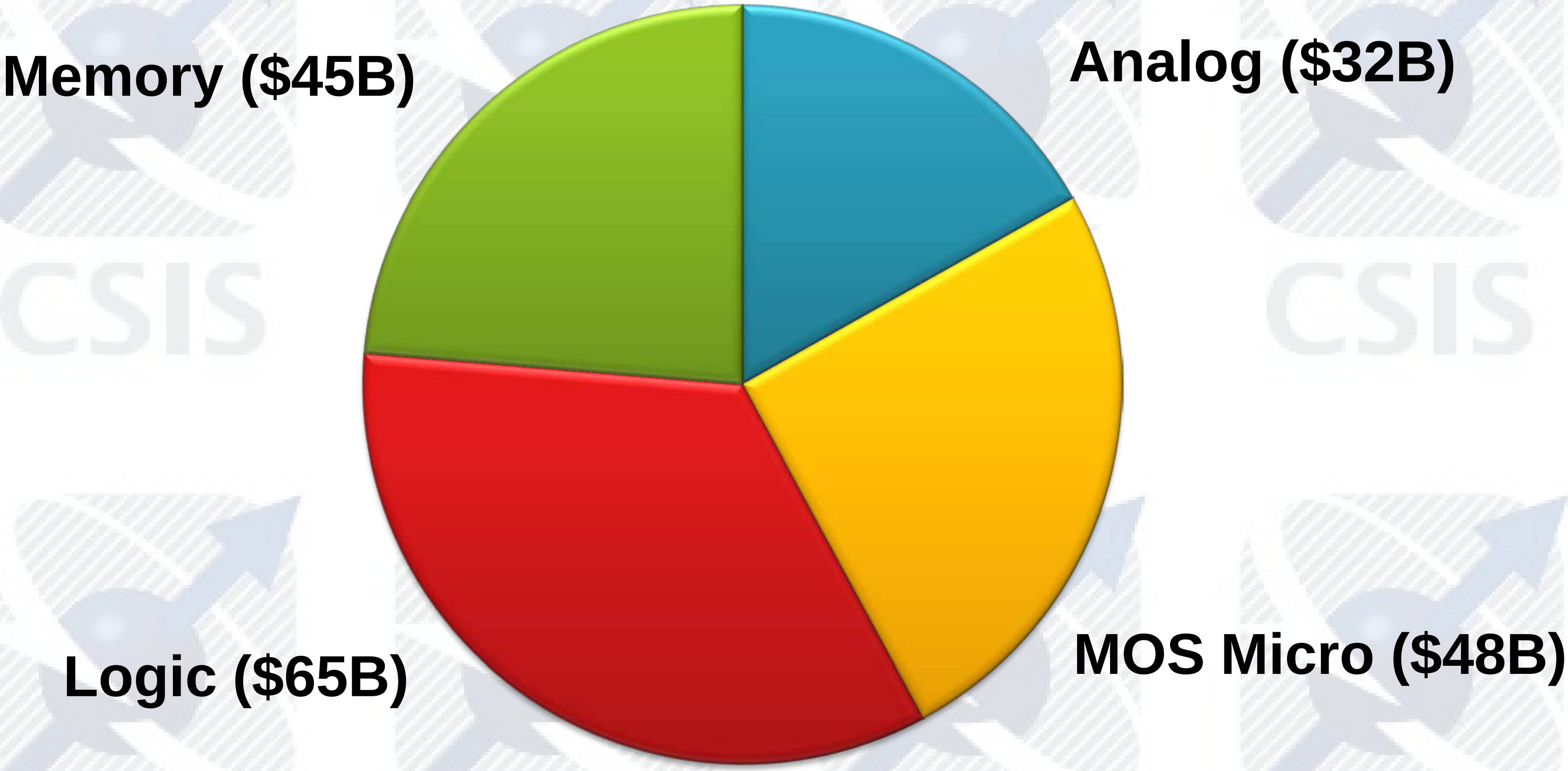
http://www.csis.tohoku.ac.jp/

OUTLINE

1. Integrated circuits - needs and challenges -
2. What magnetism can offer
   - current status of magnetic tunnel junction -
3. Research directions
4. Further future

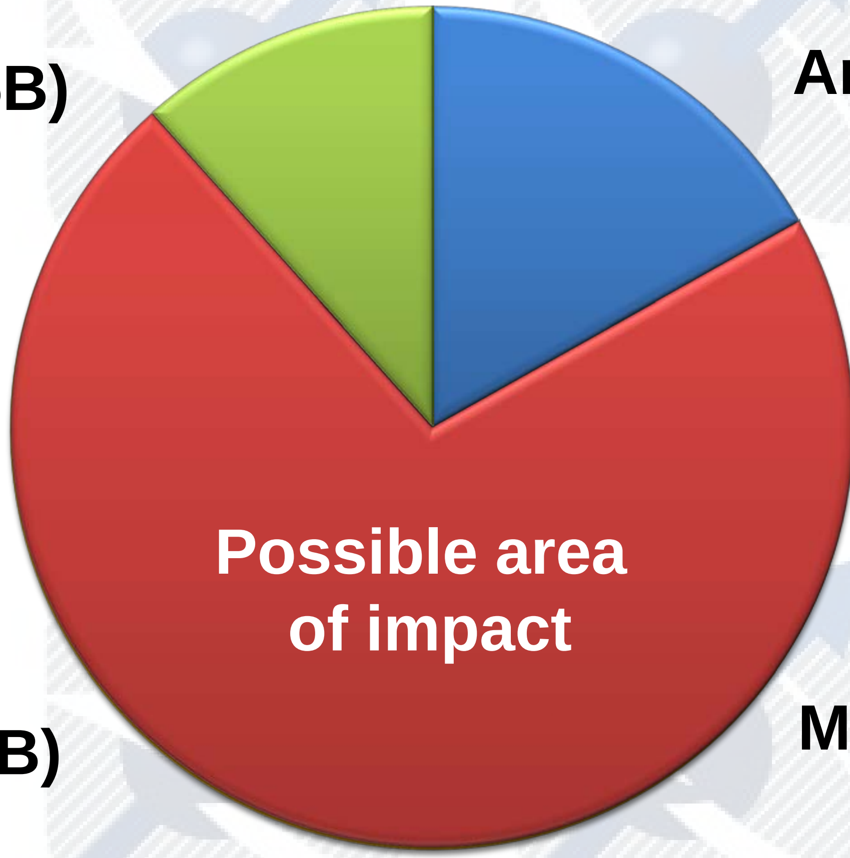
Semiconductor sales 2009



TOTAL $190B

WSTS 2010

Semiconductor sales 2009

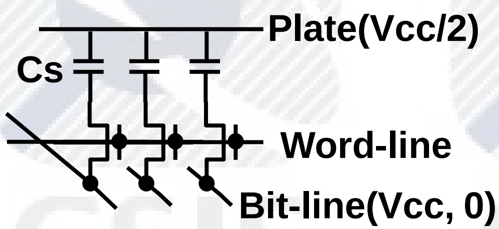


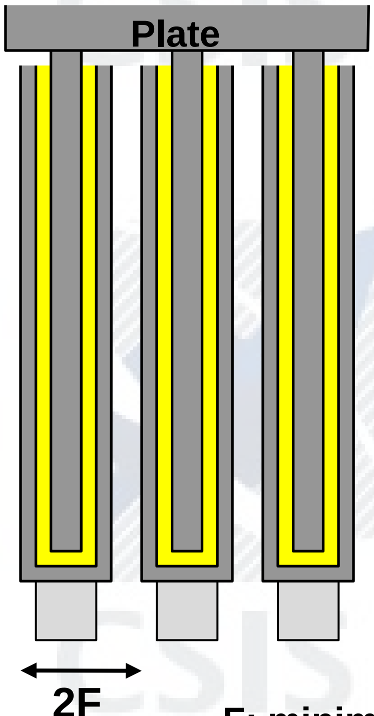
TOTAL $190B

WSTS 2010

DRAM Scaling

Difficult to obtain enough storage capacitance (C_s), even using a cylindrical shaped capacitor structure with high aspect ratio, high-k insulator and metal electrodes in a1T1R cross-point cell ($4F^2$).





F; minimum feature size

C_s > 20-30 fF

- **Leakage current through MOSFET (No capacitor leakage)**
- **Refresh time**
- **Parasitic bit-line capacitance**
- **Sense amplifier margin**
- **Soft error**

Relative permittivity of thin film

Insulator	ε	available
SiO2	3.9	yes
SiN	5-10	yes
Ta2O5	20-25	yes
BST	>200	no

In 25 nm generation (F=25nm)

ε of capacitor insulator > 70

even if the cylinder height is 1000nm.

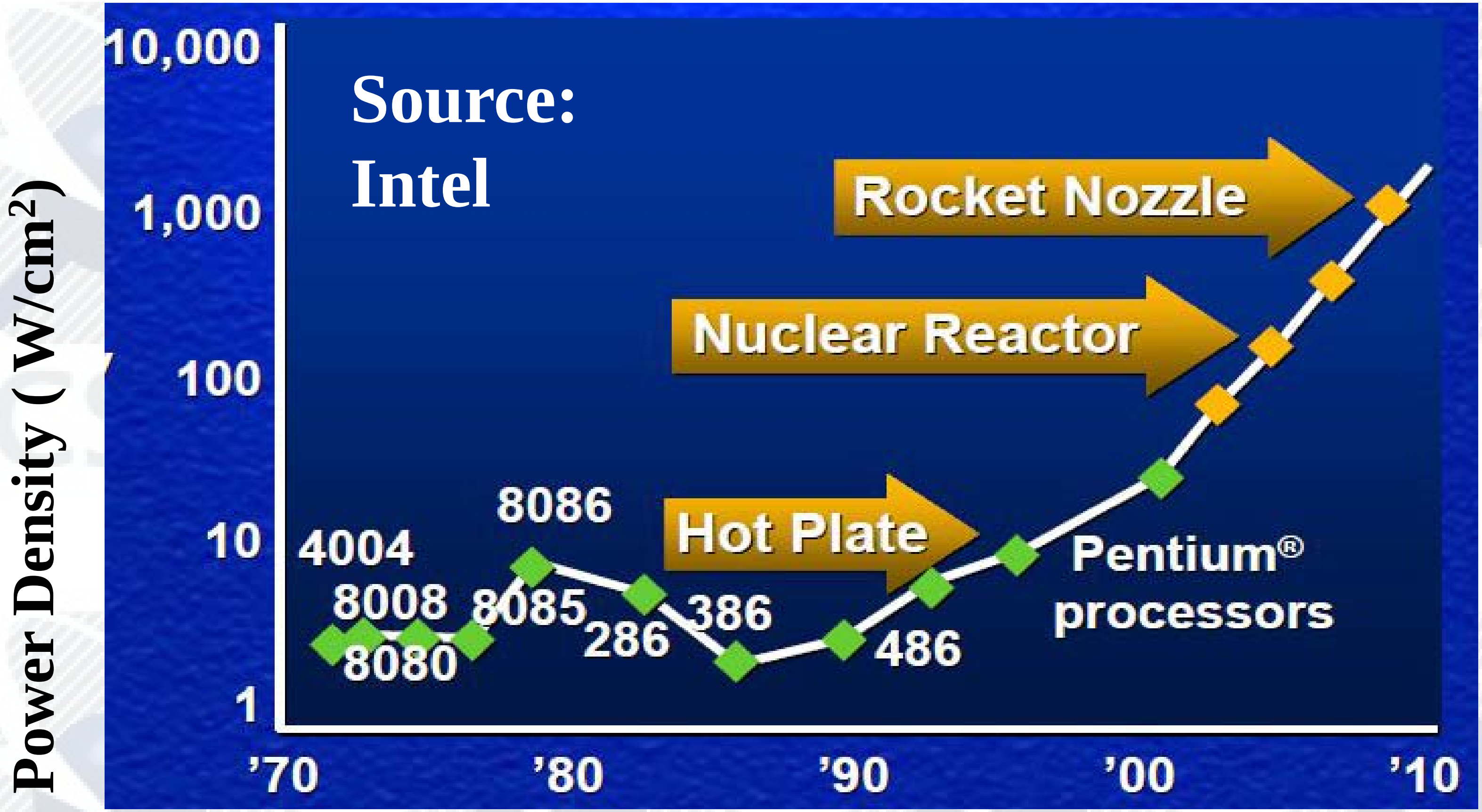
→ aspect ratio = 40

FEAURE SIZE

…hickness < 10nm

→ High resistance

Processing Power



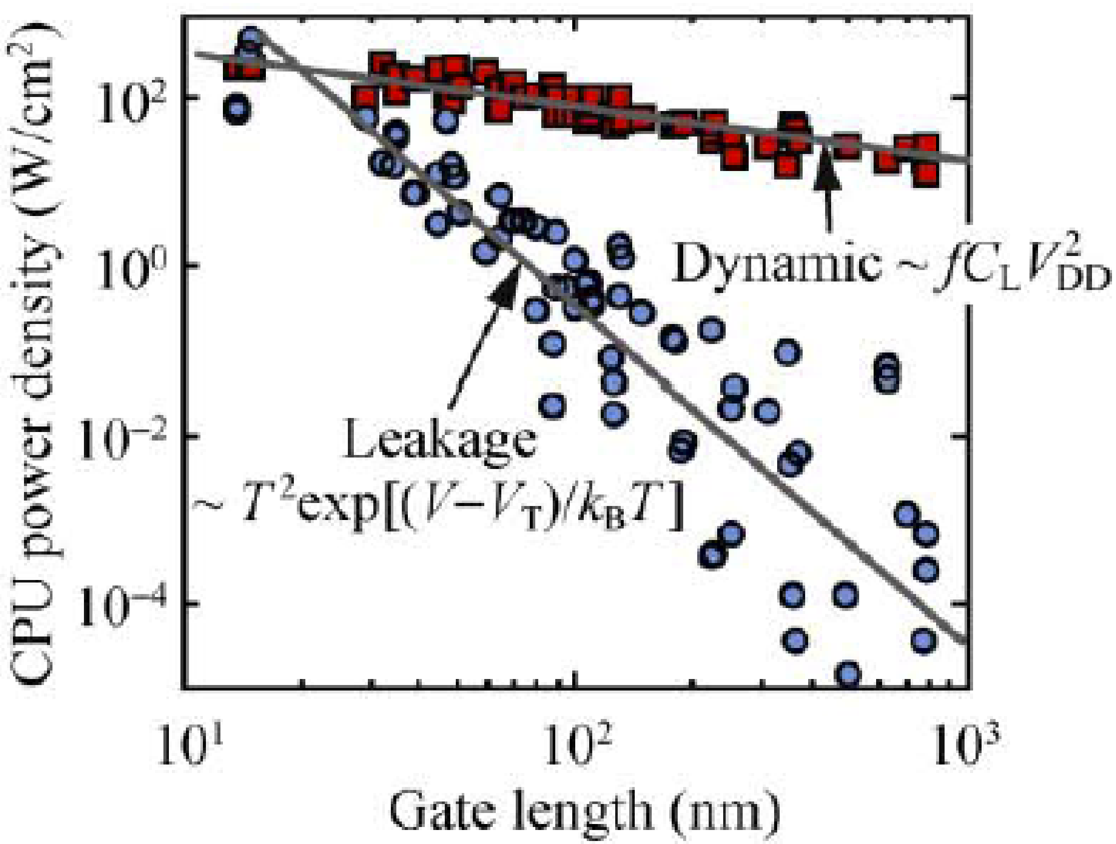
Explosive increase of power consumption

$$P \propto C_L f^3$$

POWER and DELAY

global delay)

High-performance transistor "leaks"

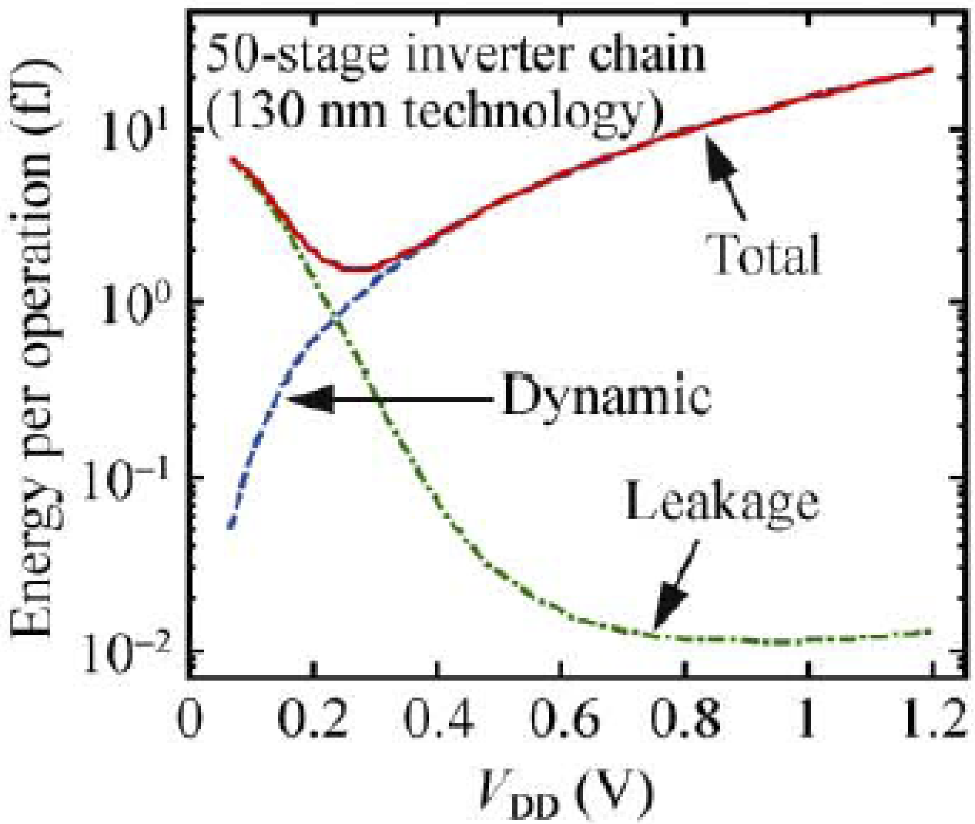


E. Pop, *Nano Res.* **3**, 147 (2010)

Leakage requires "power gating;" basically shuts the power off the part that is not in use. Requires cost assessment (p … gating).

STATIC POWER

Low voltage to counter active power



E. Pop, *Nano Res.* **3**, 147 (2010)

DYNAMIC POWER

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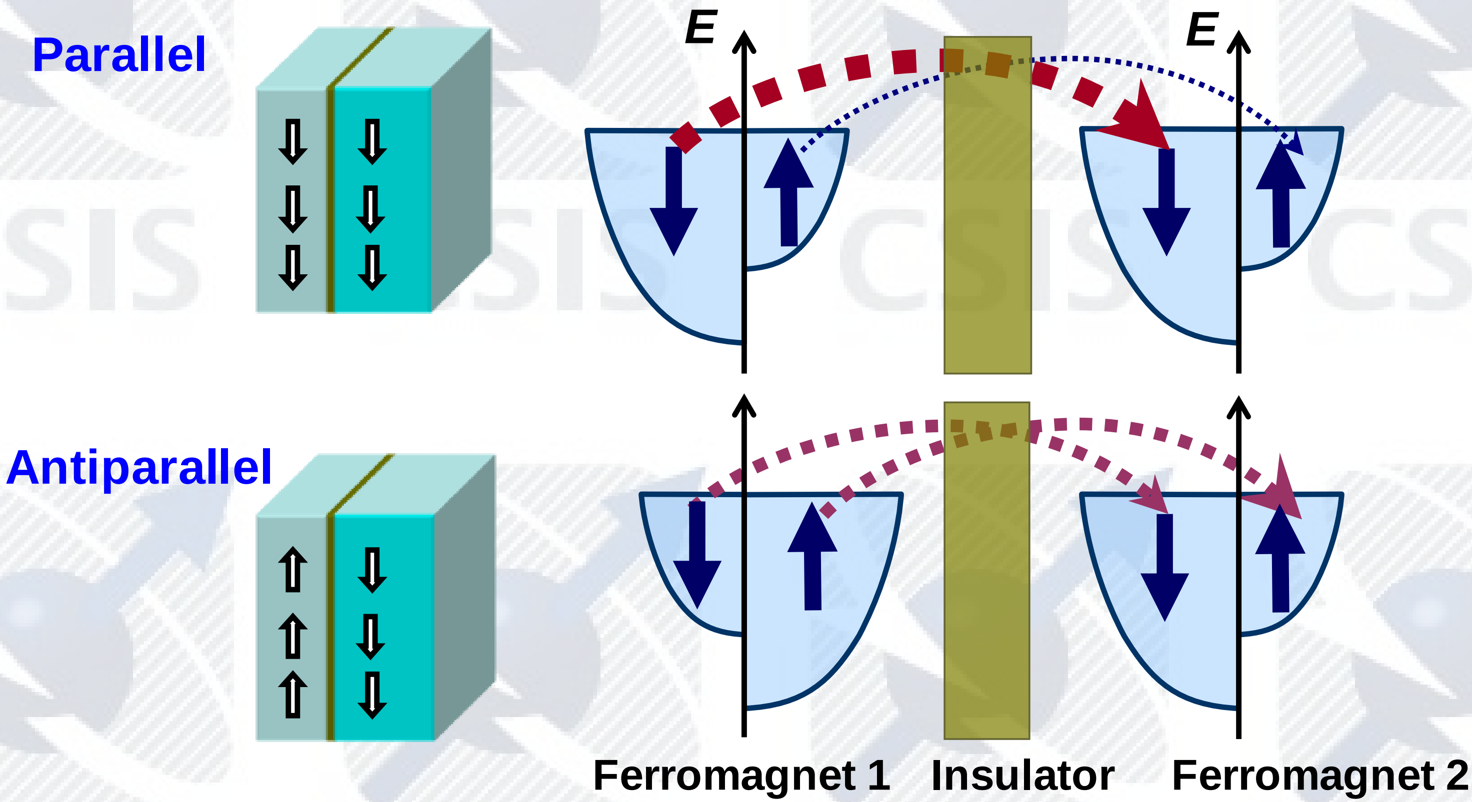
Magnetic Tunnel Junction

$$\text{Tunnel MagnetoResistance (TMR)} = \frac{R_{AP} - R_P}{R_P} = \frac{2P^2}{1-P^2}$$



Room temperature TMR: Miyazaki and Tezuka (Tohoku U.), *J. Mag. Mag. Mat.* 1995 and Moodera *et al. Phys. Rev. Lett.* 1995.

For a review on integrated circuit application, see e.g. S. Ikeda *et al. IEEE Trans. ED.*54, 991 (2007)

MTJ Development (I)

Volume 54A, number 3 PHYSICS LETTERS

TUNNELING BETWEEN FERROMAGNETIC FILMS

M. JULLIERE
Institut National des Sciences Appliquées, 35031 Rennes Cedex, France

Received 25 June 1975

Fe-Ge-Co junctions conductance G(V) is studied when mean magnetizations of the two ferromagnetic
rallel or antiparallel. Conductance measurement, in these two cases, is related to the spin polarizations of
tion electrons.

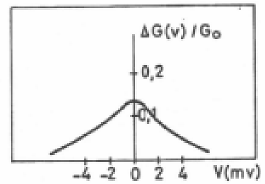


Fig. 2. Relative conductance $(\Delta G/G)_{V=0}$ of Fe-Ge-Co junctions at 4.2 K. ΔG is the difference between the two conductance values corresponding to parallel and antiparallel magnetizations of the two ferromagnetic films.

M. Julliere, Phys. Lett. 1975

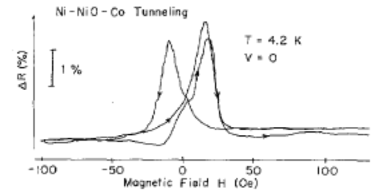


Fig. 1. Magnetic field H dependence of the resistance R at $V = 0$ and at 4.2 K normalized by that at $H = 0$ in a Ni–NiO–Co junction.

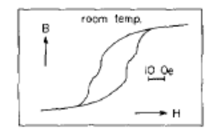


Fig. 2. Induction B versus H in the Ni–NiO–Co junction in Fig. 1 at room temperature.

IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-18, NO. 2, MARCH 1982 707

Electron Tunneling Between Ferromagnetic Films

S. MAEKAWA AND U. GÄFVERT

S. Maekawa and U. Gafvert, IEEE Trans. Mag. (1982)

ELSEVIER

Journal of Magnetism and Magnetic Materials 139 (1995) L231–L234

Journal of magnetism and magnetic materials

Giant magnetic tunneling effect in $Fe/Al_2O_3/Fe$ junction

T. Miyazaki, N. Tezuka
Department of Applied Physics, Faculty of Engineering, Tohoku University, Sendai 980-77, Japan

Received 28 October 1994

Room temperature TMR:

Miyazaki and Tezuka (Tohoku U.),

***J. Mag. Mag. Mat.* 1995 and**

Moodera *et al. Phys. Rev. Lett.* 1995.

VOLUME 74, NUMBER 16 PHYSICAL REVIEW LETTERS 17 APRIL 1995

Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions

J. S. Moodera, Lisa R. Kinder, Terrilyn M. Wong, and R. Meservey
Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 29 November 1994)

MTJ Development (II)

Spin-transfer torque

Switching:

•J. Slonczewski, *J. Magn. Magn. Mat.* **159**, L1 (1996).
•L. Berger, *Phys. Rev. B* **54**, 9353 (1996).

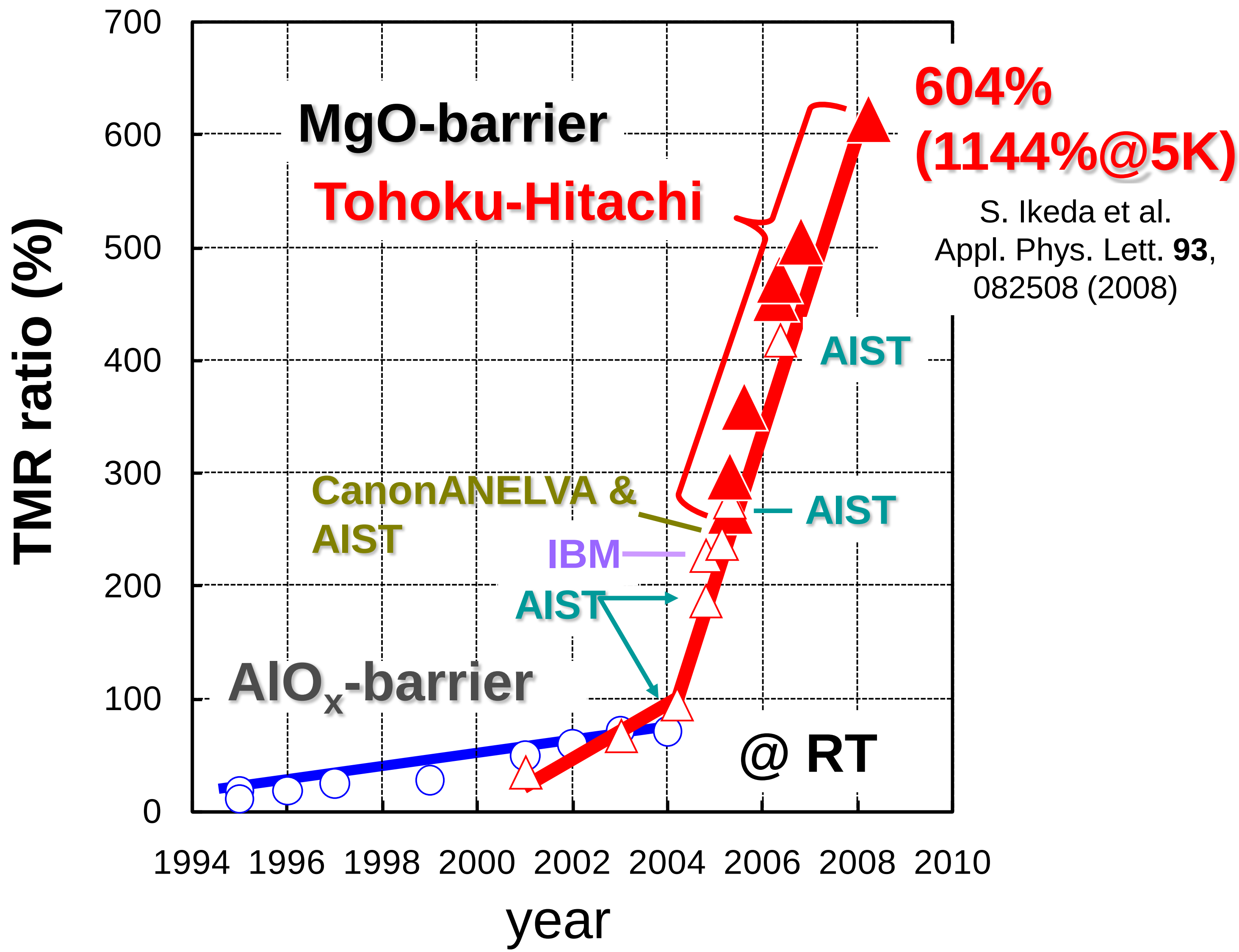
Domain wall motion:

•L. Berger, *J. Appl. Phys.* **55**, 1954 (1984), *J. Appl. Phys.* **71**, 2721 (1992).

MgO-MTJ

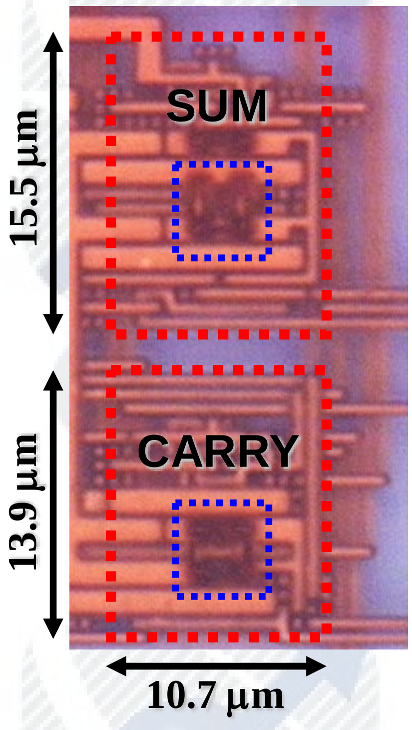
•W. H. Butler, X.-G. Zhang, T. C. Schulthess, and J. M. MacLaren, *Phys. Rev. B* **63**, 054416 2001.
•J. Mathon and A. Umersky, *Phys. Rev. B* **63**, 220403R 2001.

TMR ratio of MgO-MTJs



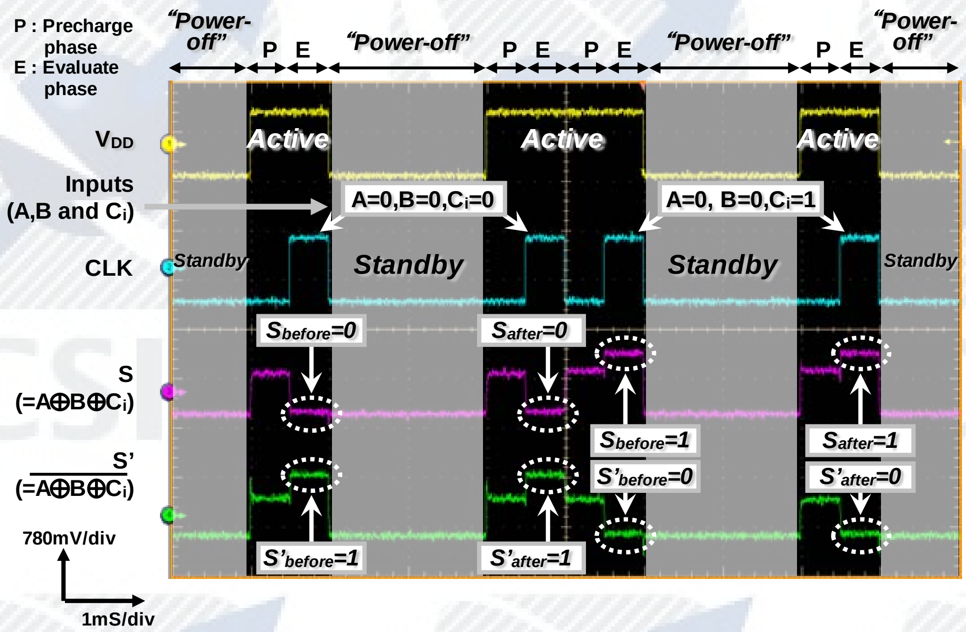
Nonvolatile Logic-in-Memory

Full adder block (for image processing)



0.18 μm CMOS/MTJ Process

MTJ: 100 x 200 nm²



S. Matsunaga, … H. Ohno, T. Hanyu, APEX, 1, 091301 (2008)

Nonvolatile: **ultimate power gating** (no static power)

Memory in the back end + part of logic

(reduced # of tr. = suppression of delay and dynamic power)

MTJ for VLSI: A wish list

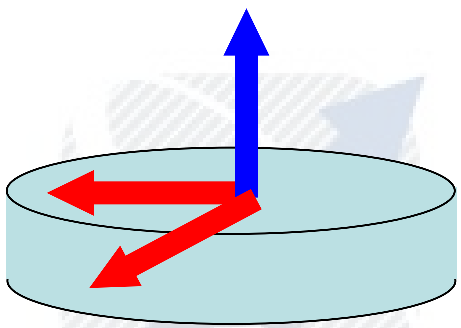
1. Small footprint (*F* nm)
2. High output (TMR ratio > 100%)
3. Nonvolatility (E/k_BT >40)
4. Low switching current ($I_C < F$ μA)
5. Back-end-of-the-line compatibility (350 ^{o}C)
6. Endurance
7. Fast read & write
8. Low resistance for low voltage operation
9. Low error rate
10. Low cost

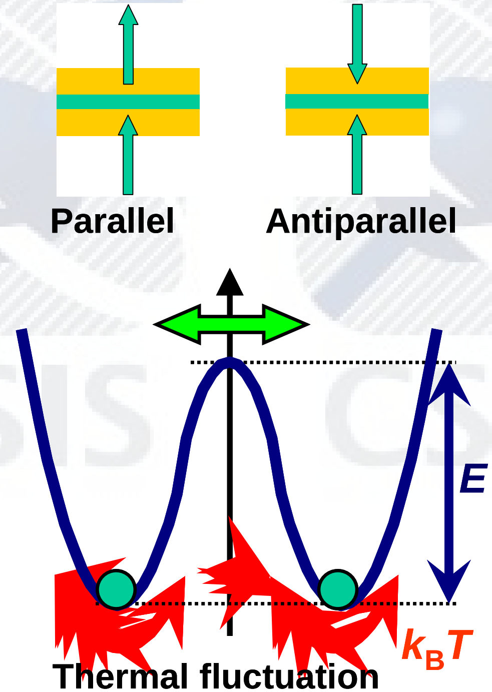
I_{c0} and $\Delta = E/k_B T$

perpendicular

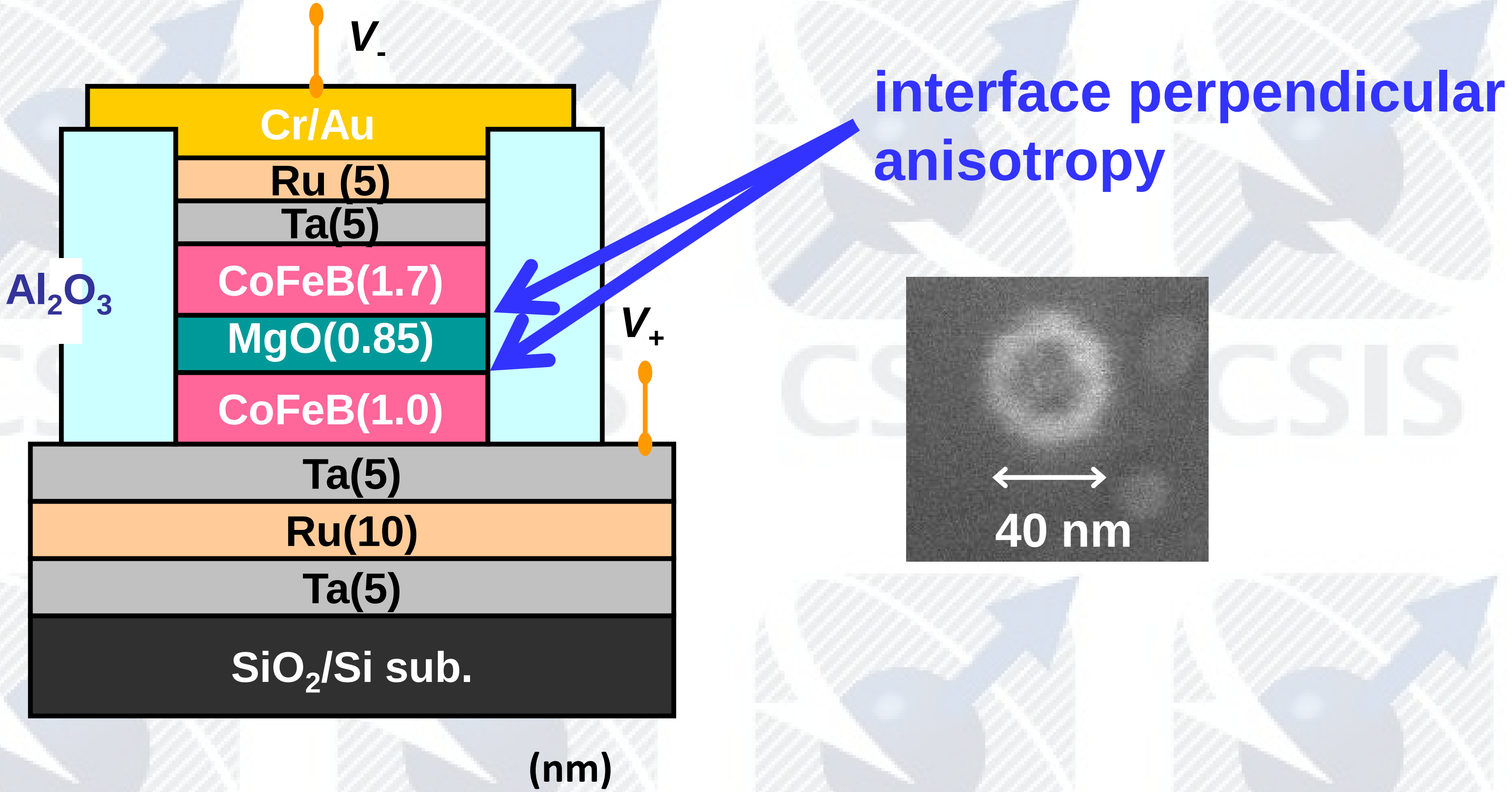
$$E = \frac{1}{2} M_S H_K V$$

$$I_{C0} = \frac{2\alpha\gamma e}{\mu_B g}\left(\frac{1}{2} M_S H_K V\right)$$





Perpendicular MgO-CoFeB MTJ



J_{C0} = 3.9 MA/cm^2 (I_{C0} = 49 μA) , E/k_BT = 43, TMR ratio 124%

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

Comparison of MTJs

Type	Stack structure (nm)	Size (nm)	MR (%)	RA (Ωμm²)	J_{C0} (MA/cm²)	I_{C0} (μA)	$\Delta=E/k_BT$	I_{C0}/Δ	T_a (°C)	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(~1.7)**	**40 φ**	**>110**	**<18**	**<4**	**<50**	**>≈40**	**≈1.2**	**350**	**S. Ikeda et al., Nat. Mat. 9 (2010) 721. K. Miura, et. al. HC-02, MMM 2010**

MMM 2010
DT-05 . (Poster session)
M. Yamanouchi *et al.*

DP-13. (Poster session)
H. Yamamoto *et al.*

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Scaling

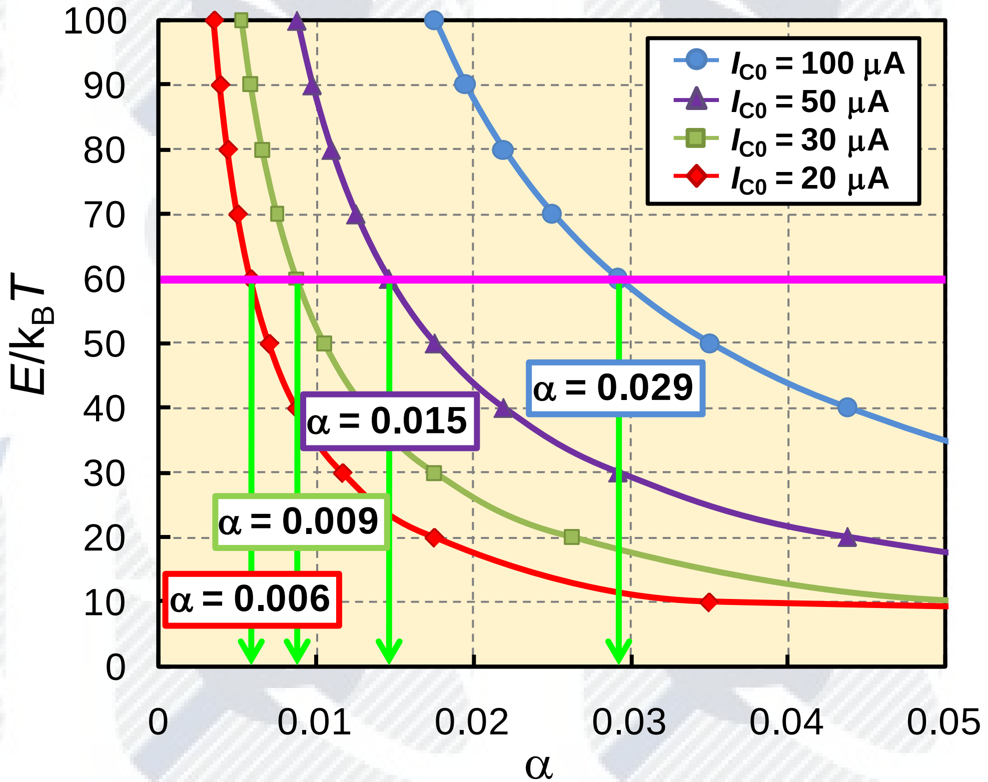
perpendicular

$$E = \frac{1}{2} M_S H_K V$$

$$I_{C0} = \frac{2\alpha\gamma e}{\mu_B g}\left(\frac{1}{2} M_S H_K V\right)$$

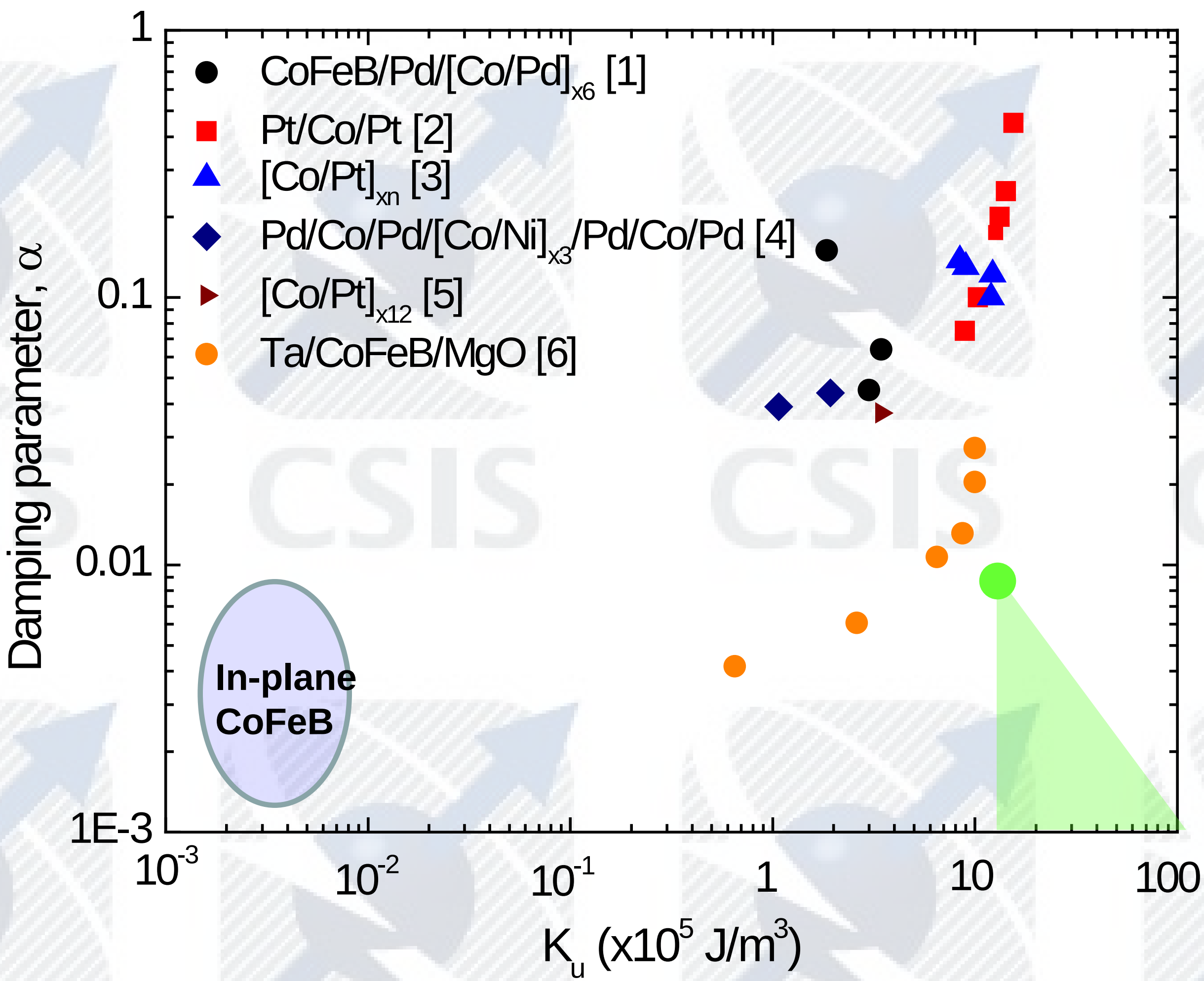
$$\propto \alpha E$$

High $K_u = \frac{1}{2} M_S H_K$ and low α



$$I_{C0} = 3.4\times10^{3}\alpha\,[\mu\text{A}]\ \text{for}\ E = 60k_BT$$

α versus K_u



Ref. [1] E. P. Sajitha, et. al., IEEE Transactions on Magnetics, **46**, 2056 (2010)
[2] S. Mizukami, et. al., App. Phys. Lett., **96**, 152502 (2010)
[3] A. Barman, et. al., J. App. Phys., **101**, 09D102 (2007)
[4] J.-M. Beaujour, et. al., Phys. Rev. B., **80**, 180415R (2009)
[5] N. Fujita, et. al., J. Magn. Magn. Mater., **320**, 3019 (2008)
[6] S. Ikeda, et. al., Nat. Mat., **9**, 721 (2010)

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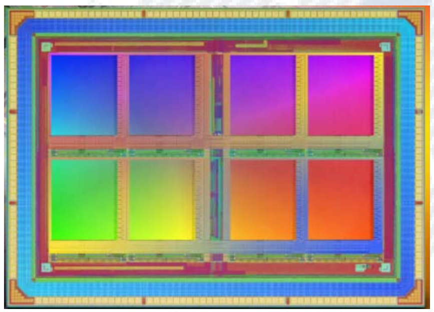
Magnetization manipulation by

Magnetic field

write/read heads for HDD
1st generation MRAM

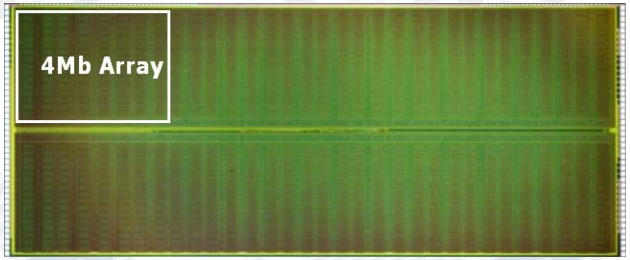
http://www.hitachigst.com/



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).



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

Spin torque MRAM
Spin torque oscillator
Race-track memory

Electric field

Spin-transfer switching

$$VIt = 0.5\ (\mathrm{V}) \times 30\ (\mu\mathrm{A}) \times 1\ (\mathrm{ns}) = 15\ (\mathrm{fJ})$$

Electric field switching

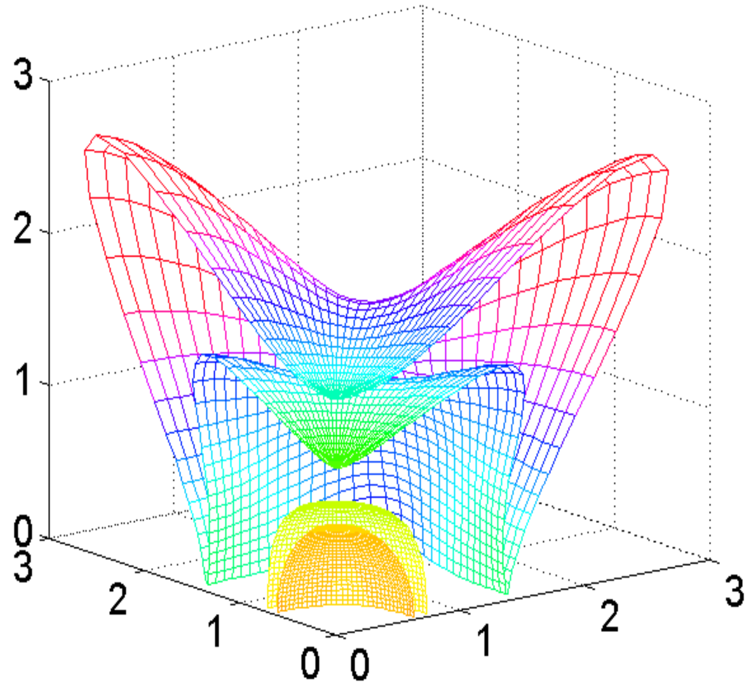
$$CV^2 = S \times d \times \varepsilon \times E^2$$

$$= \pi\left(\frac{30\ (\mathrm{nm})}{2}\right)^2 \times 5\ (\mathrm{nm}) \times 9.8\ \varepsilon_0 \times (5\ (\mathrm{MV/cm}))^2$$

$$= 0.08\ (\mathrm{fJ})$$

Spin-split valence band of (Ga,Mn)As

Ferromagnetic semiconductor (Ga,Mn)As: Mn gives rise to localized spin and hole



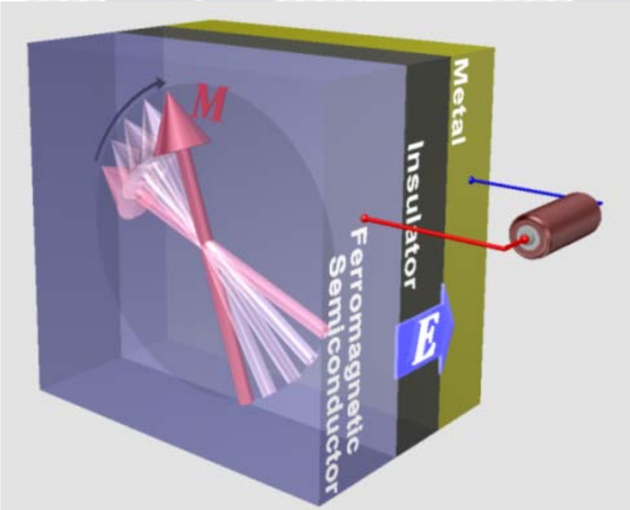
T. Dietl et al. *Science* 2000

$k_{x,y,z}$ [$10^7 cm^{-1}$]

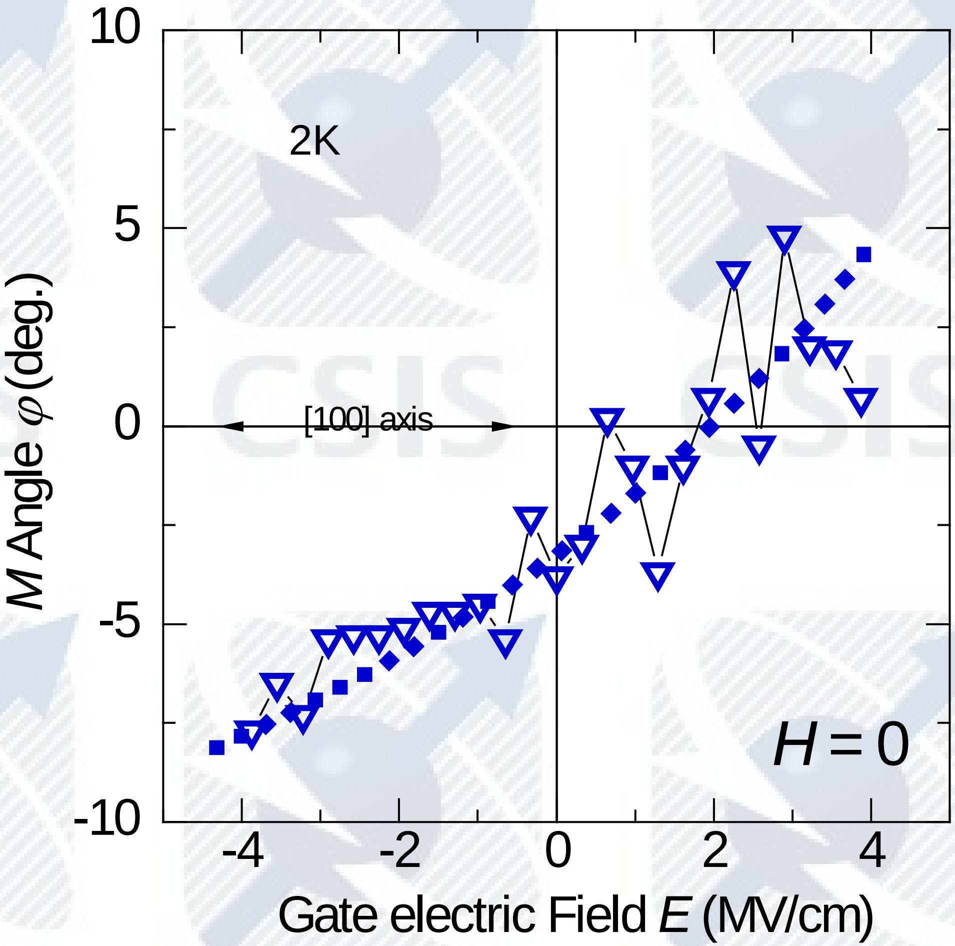
Material, Ferromagnetism and Functionalities; See

H. Ohno, *Science*, 1998, T. Dietl et al. *Science* 2000, H. Ohno et al. *Nature* 2000, D. Chiba et al. *Science* 2003, M. Yamanouchi et al. *Nature* 2004, D. Chiba, *Nature* 2008

Electric-field control of magnetization direction

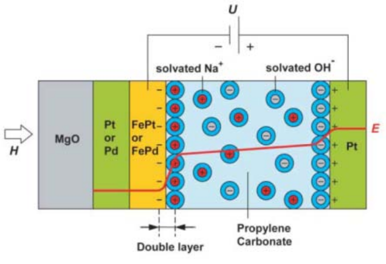


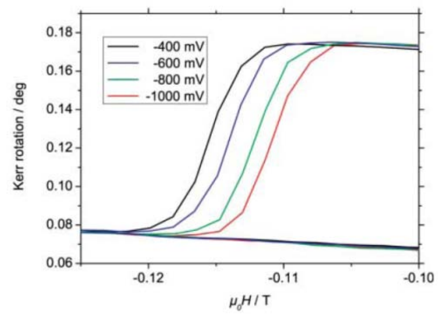
Ferromagnetic Semiconductor (Ga,Mn)As

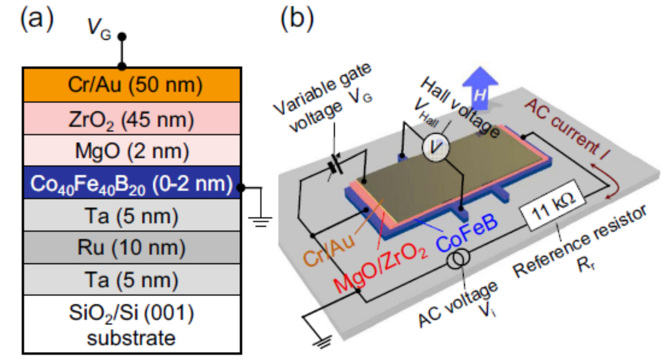


D. Chiba *et al.* Nature (2008)

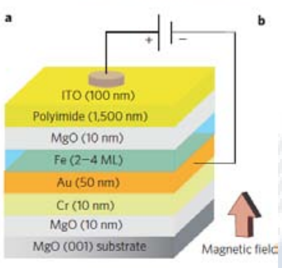
Electric-field effects on metals

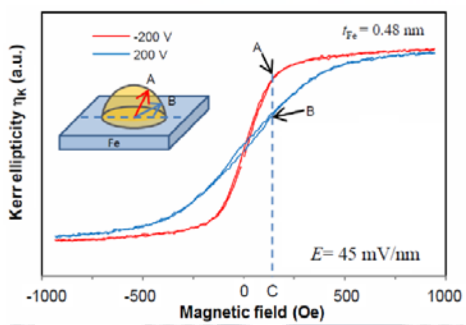


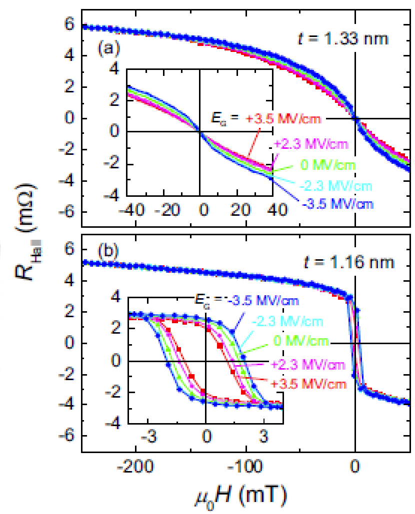


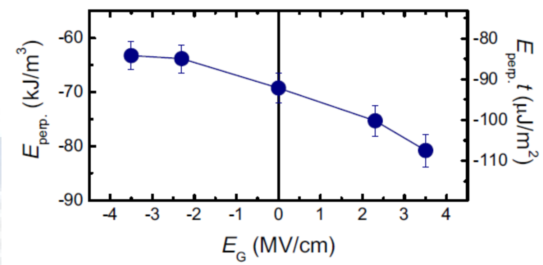


FePt, FePd: M. Weisheit *et al.*, Science (2007).









Fe/Au: T. Maruyama *et al.*, Nature Nanotechnology (2009).

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

All at room temperature

Summary

- MTJ is much better positioned now than before with 30 nm dimension in sight. Once ready this could trigger a major paradigm shift.
- Material science determines the scaling, requiring understanding of involved physics.

  Eg. K_U, α, high speed switching
- Processing (and related fields) requires further development.
- One of the future directions is electric field switching (session AA). This may further reduce the power for switching drastically.