Magnetoresistance and spin-transfer torque in magnetic tunnel junctions

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IEEE Distinguished Lecturer 2012

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IEEE Magnetics Society

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FIELD OF INTEREST

"Treatment of all matters in which the dominant factors are the fundamental developments, design, and certain applications of magnetic devices. This includes consideration of materials and components as used therein, standardization of definitions, nomenclature, symbols, and operating characteristics; and exchange of information as by technical papers, conference sessions, and demonstrations."

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- Approx. 3000 members in 33 chapters
- USA, Canada, South America
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PUBLICATIONS

- Society Newsletter
- IEEE Transactions on Magnetics
- IEEE Magnetics Letters

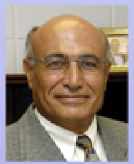
For more information and to join visit
www.ieeemagnetics.org

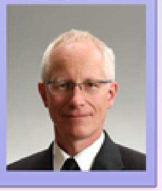
ACTIVITIES/OUTREACH

Conferences:
- **INTERMAG**
- MMM/Intermag (joint w/ AIP)
- TMRC

- Education:
  - Graduate Student Summer Schools

- Awards
  - Student Travel Grants to attend conferences
  - Best Student Presentation at Intermag
  - Achievement Award





- Distinguished Lecturers 2012
- Shinji Yuasa, "Magnetoresistance and spin torque in magnetic tunnel junctions"
- George C. Hadjipanayis, "Science and Technology of Modern Permanent Magnet Materials"
- Gerrit Bauer, "Spin Caloritronics"
- Masahiro Yamaguchi, "Soft Magnetic Thin Film Applications at Radio Frequencies"

12th Joint MMM-Intermag Conference

2013
Intermag
MMM

January 14 to January 18, 2013 (Abstracts:June 2012)

Location: Chicago, Illinois USA
Hyatt Regency Hotel

Chairperson: Paul Crowell
crowell@umn.edu

Program Co-Chair: Ilya Krivorotov
ikrivoro@uci.edu

Program Co-Chair: Werner Scholz
werner.scholz@seagate.com

Program Co-Chair: Shinji Yuasa
yuasa-s@aist.go.jp

IEEE

AIP American Institute of Physics

Collaborations

TOSHIBA **Toshiba Corp.** (H. Yoda)
(STT-MRAM)

Canon **Canon Anelva Corp.**
(sputtering deposition process)

Osaka University (Y. Suzuki)
(rf & high-speed experiments)

cnrs THALES **CNRS/Thales** (A. Fert, V. Cros, J. Grollier)
(spin-torque oscillator)

Outline

(1) Spintronics

(2) Tunnel magnetoresistance (TMR)

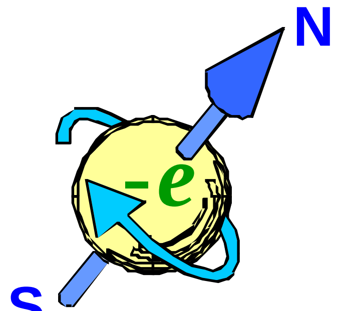
- Magnetoresistance
- Tunnel magnetoresistance in magnetic tunnel junction (MTJ)
- Giant TMR in MgO-based MTJ
- CoFeB / MgO / CoFeB structure for device applications

(3) Spin-transfer torque (STT)

- Physics of spin-transfer torque
- Spin-transfer torque MRAM (STT-RAM or Spin-RAM)
- Microwave applications

What is *spintronics*?

Electric Charge



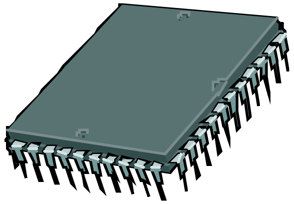
Electron

Spin (a small magnet)

Electronics

- power amplification
- logic operation

basically volatile



Transistor, LSI

TMR

& *STT*

Magnetics

- magnetic recording

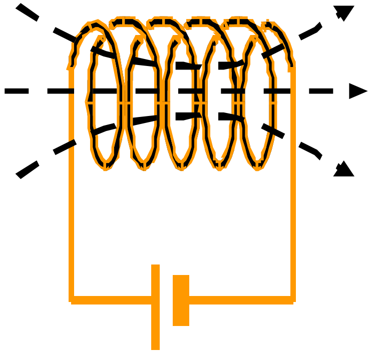
non-volatile

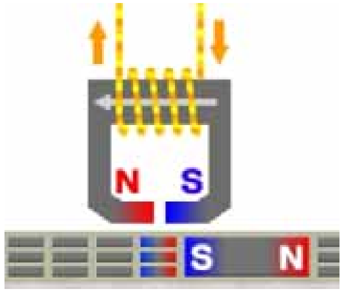
Hard Disk Drive (HDD)

Spintronics

Both ***charge*** and ***spin*** of electrons are utilized for new functions.

Difference between conventional magnetics and spintronics ?

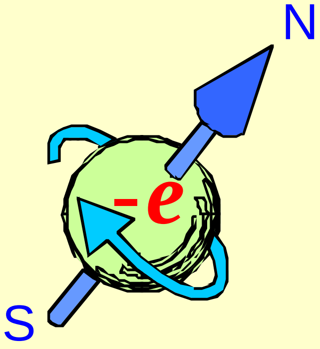




Magnetics

Coupling between charge and spin
by *induction coil*

Most of the energy is wasted.



Spintronics

Coupling between charge and spin
by *quantum mechanical effects*
(*e.g.* **tunnel magnetoresistance**, **spin-transfer torque**)

Highly efficient !

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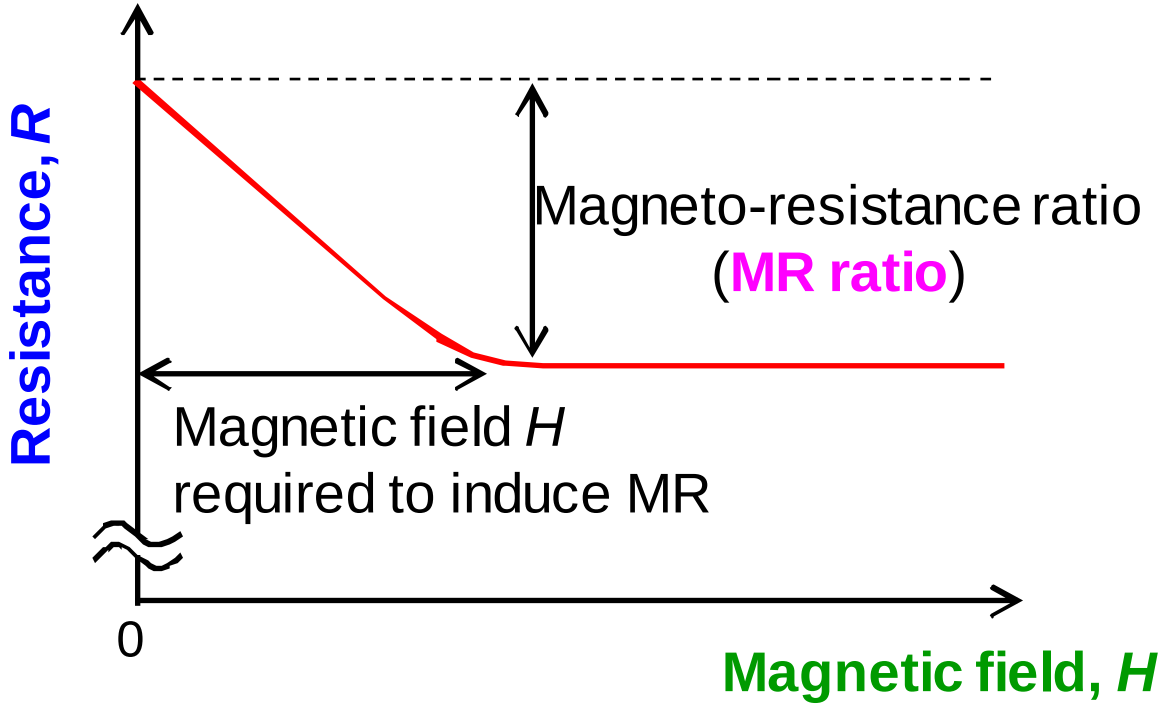
Magneto-Resistance (MR)

Change in electric resistance induced by magnetic field.



MR converts **magnetic signals** into **electric signals**.

(*cf*. **STT** converts **electric signals** into **magnetic signals**.)

MR ratio at **RT & a low *H* (~1 mT)** is important for device applications.

Magnetoresistance

MR ratio @ RT & low *H*

Year

1857

AMR effect

MR = 1 - 2%

Lord Kelvin

1985

GMR effect

MR = 5 - 15%

A. Fert, P. Grünberg

(*Nobel Prize 2007*)

1990

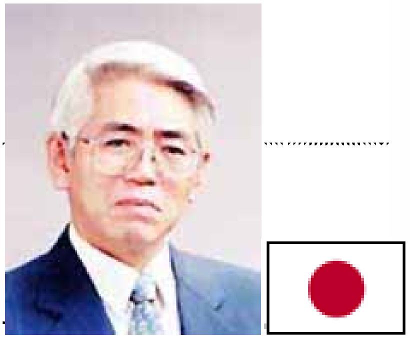
1995

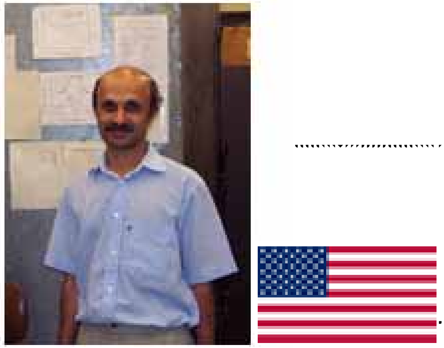
TMR effect

(Al-O barrier)

MR = 20 - 70%

T. Miyazaki, J. Moodera





2000

2005

2010

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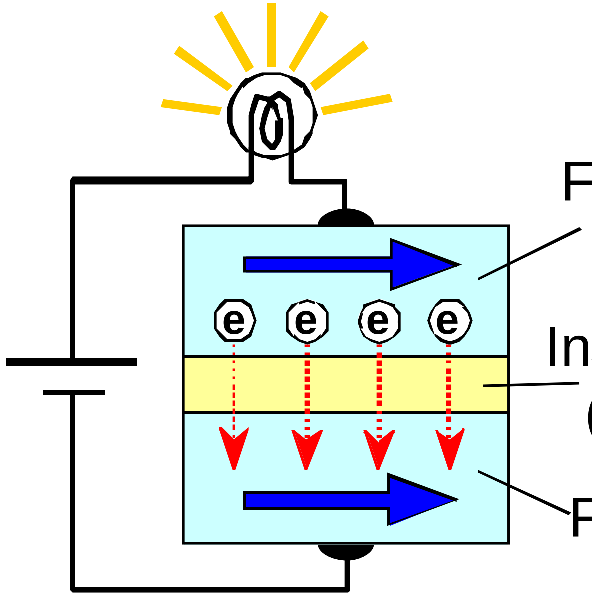
Tunnel MagnetoResistance (**TMR**) effect in magnetic tunnel junction (**MTJ**)



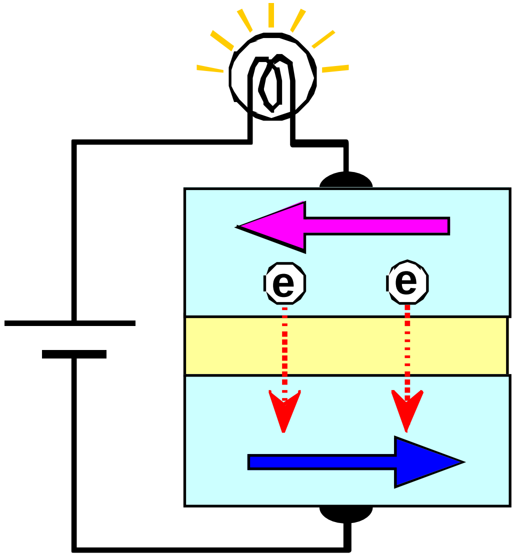
Ferromagnetic electrode

Insulator (*nm – thick*)
(***tunnel barrier***)

Ferromagnetic electrode

Parallel (P) state

Resistance R_P : **low**



Antiparallel (AP) state

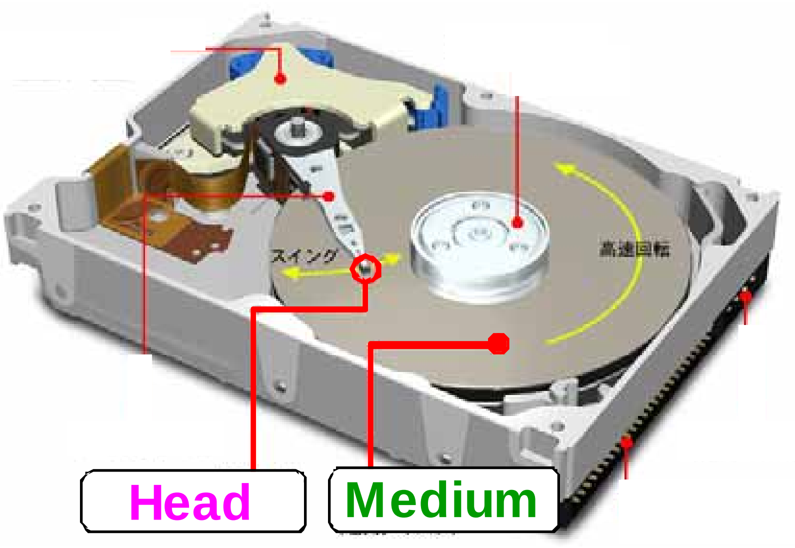
Resistance R_{AP} : **high**

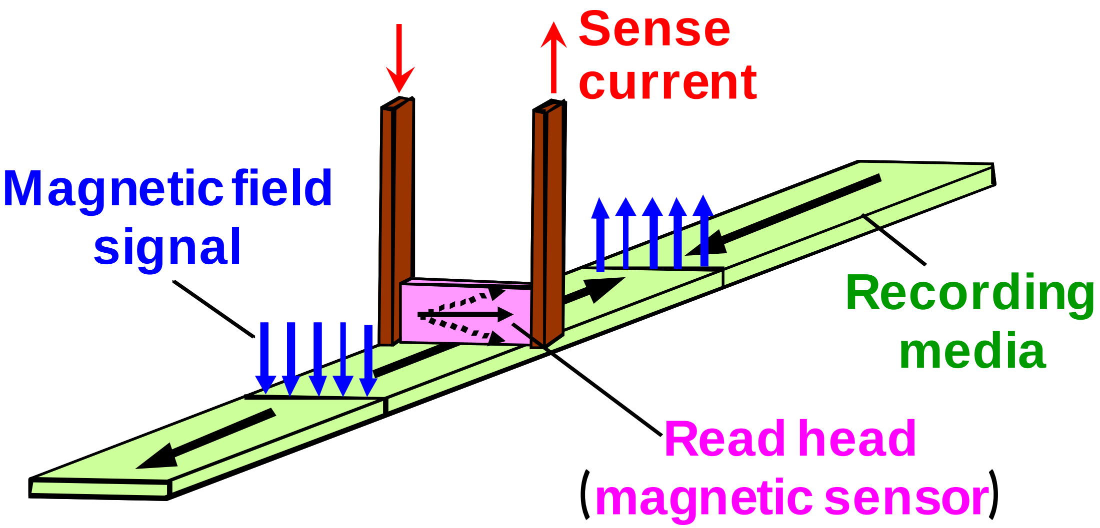
MR ratio $\equiv (R_{AP} - R_P) / R_P \times 100\%$ (performance index)

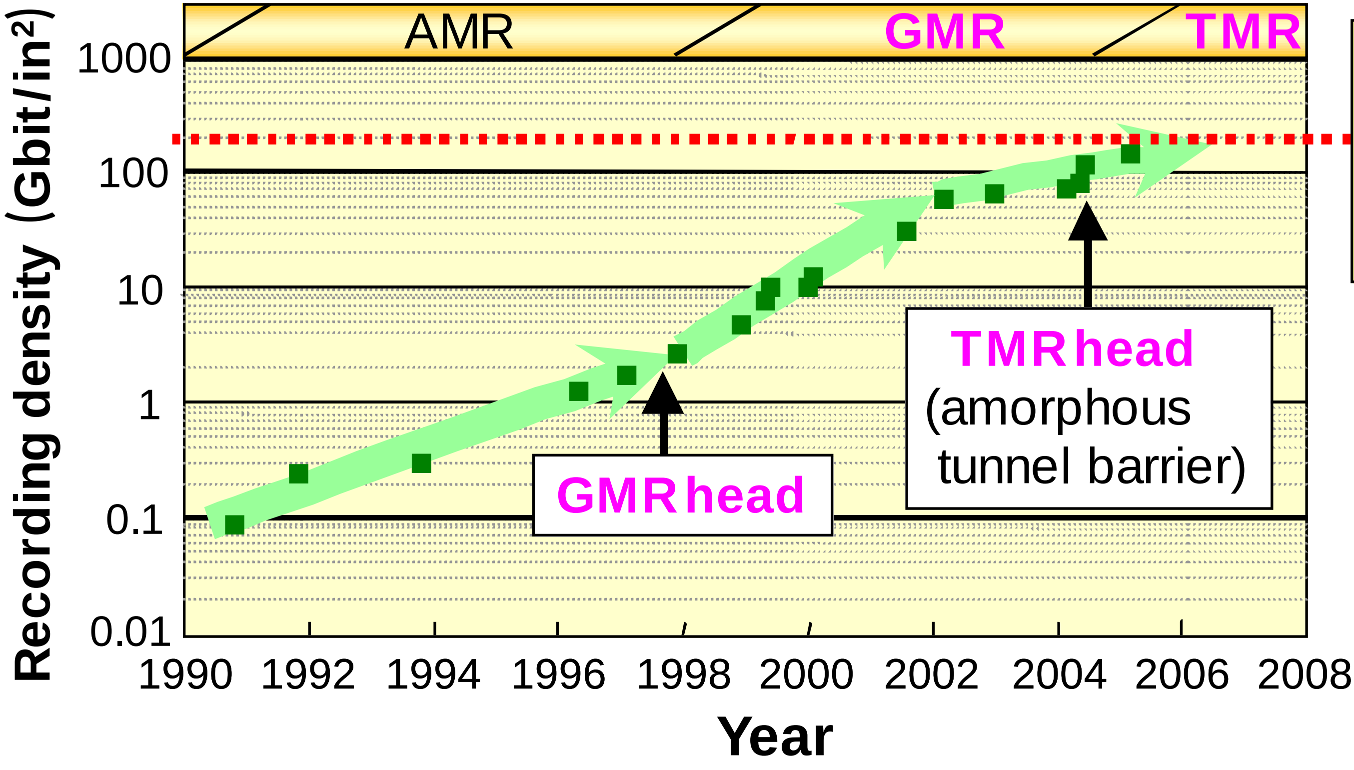
3d ferromagnet
Amorphous Al-O
3d ferromagnet

→ **MR ratios of 20 – 70% at RT**

Read head of hard disk drive (HDD)







Higher MR ratio is required for > 200 Gbit/inch².

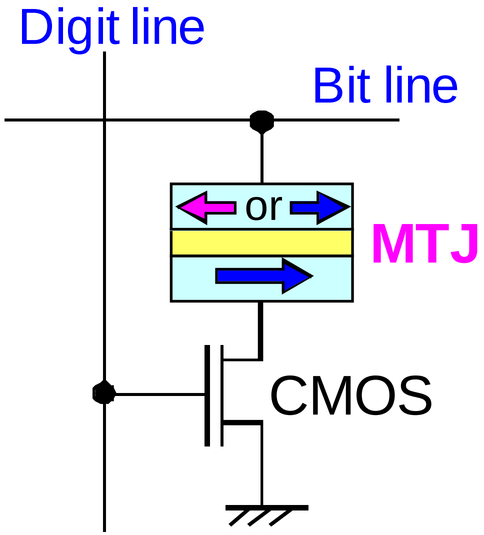
Non-volatile Magnetoresistive Random Access Memory (MRAM)

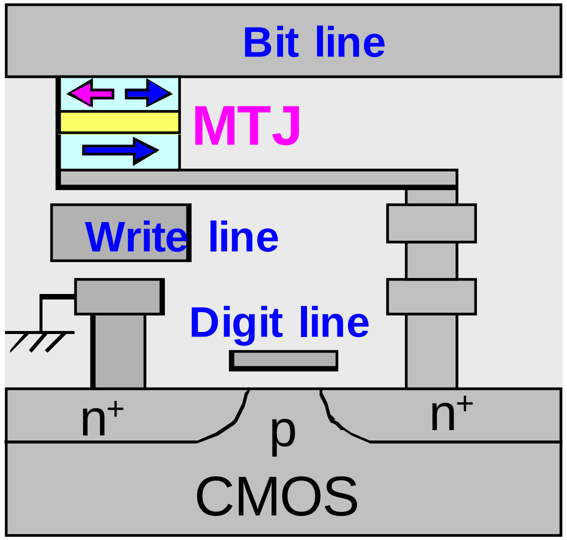
Parallel：“0”

Antiparallel：“1”

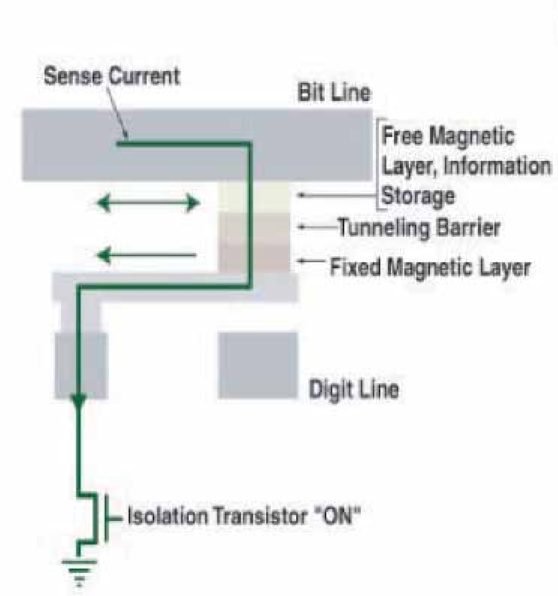
Non-volatile

magnetic memory

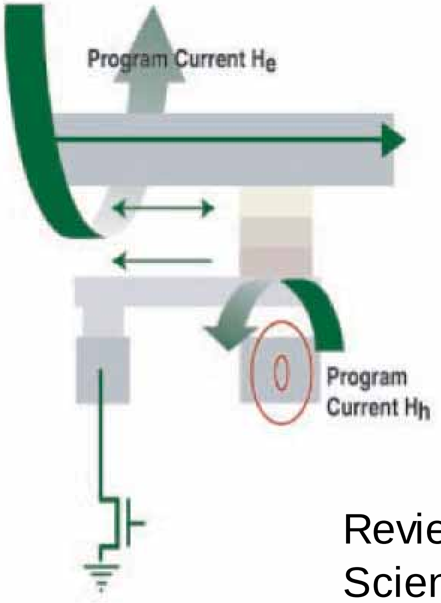




Read out

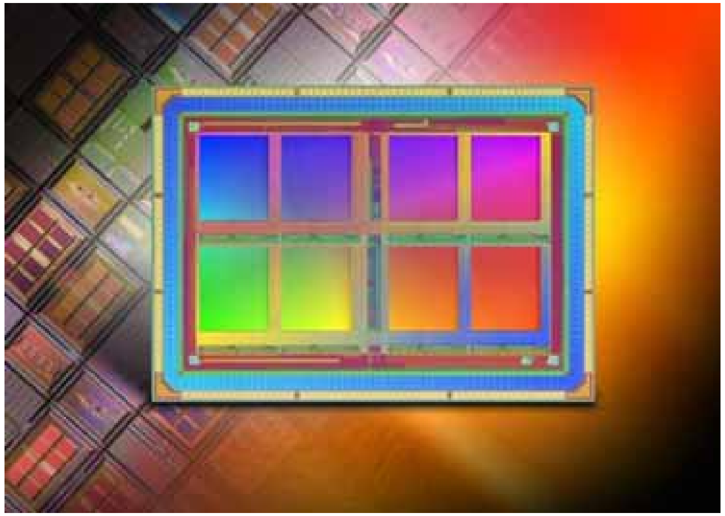


Writing



Review:
Science 294, 1488 (2001).

Non-volatile Magnetoresistive Random Access Memory (MRAM)



Freescale (US)'s 4 Mbit – MRAM based on Al-O MTJs
(volume production since 2006)

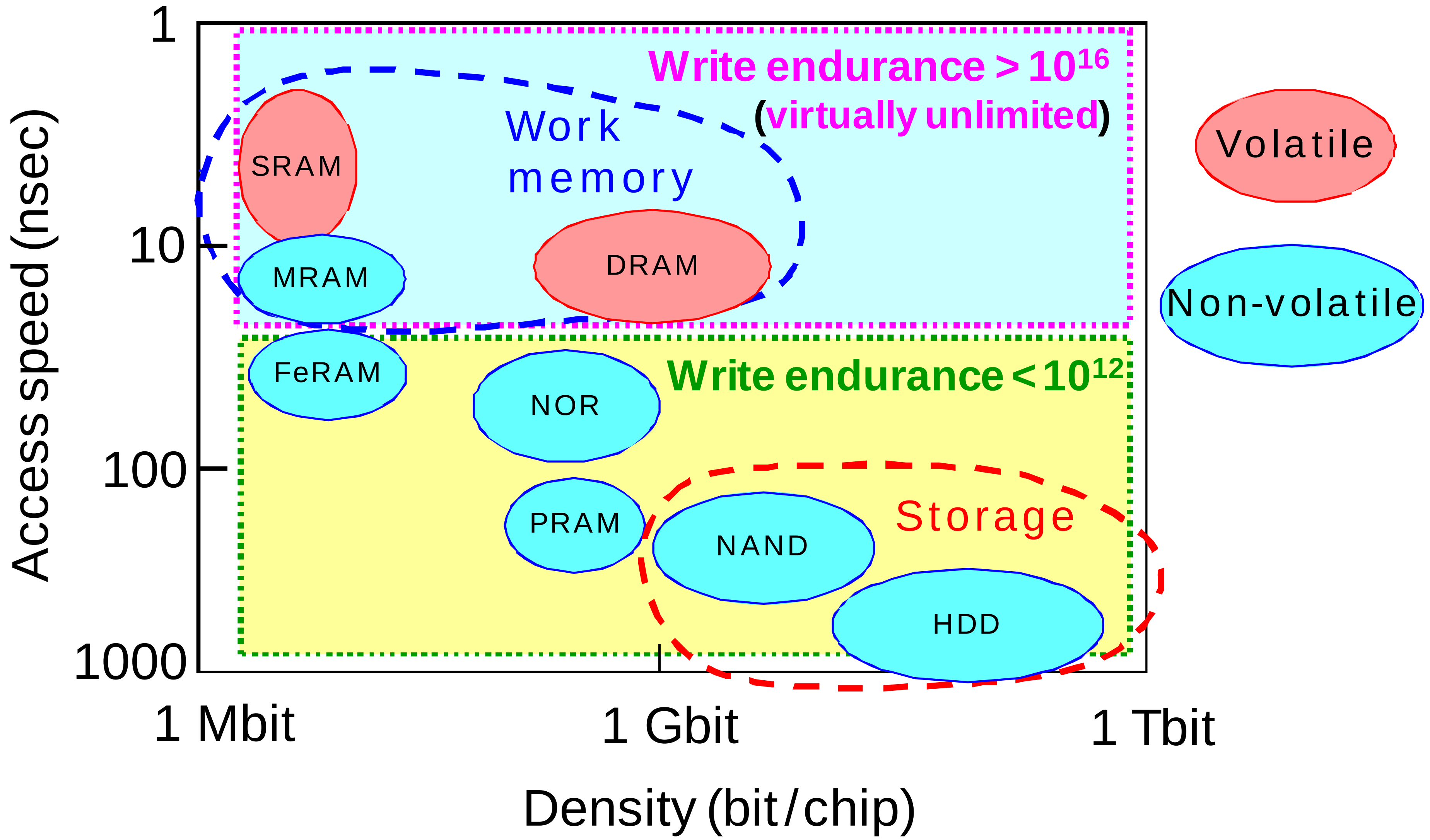
<Advantages>

Non-volatile, high speed, write endurance > 10^{16}

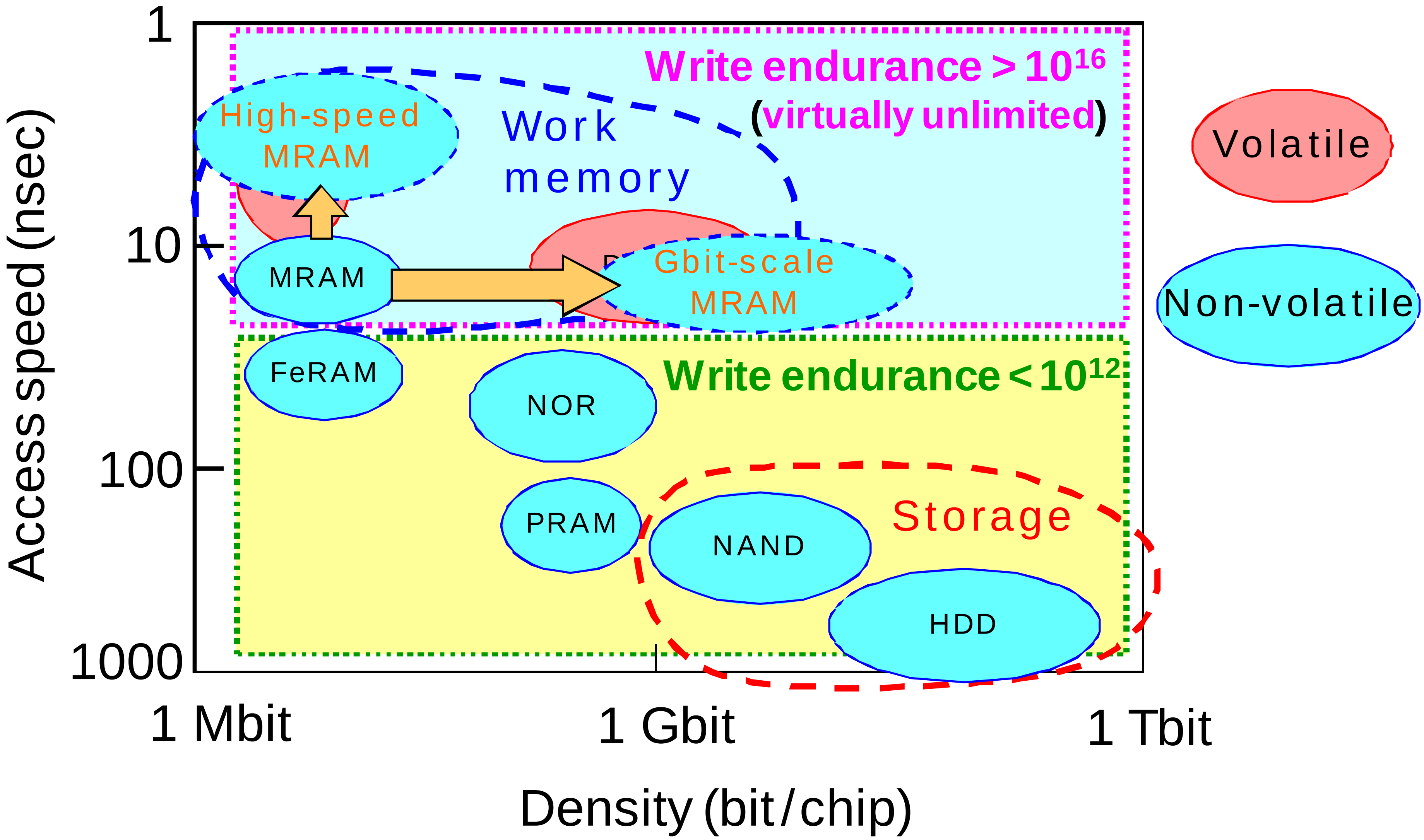
<Disadvantage>

***High-density* MRAM is difficult to develop.**

Three important properties for memory device: speed, density, and write endurance



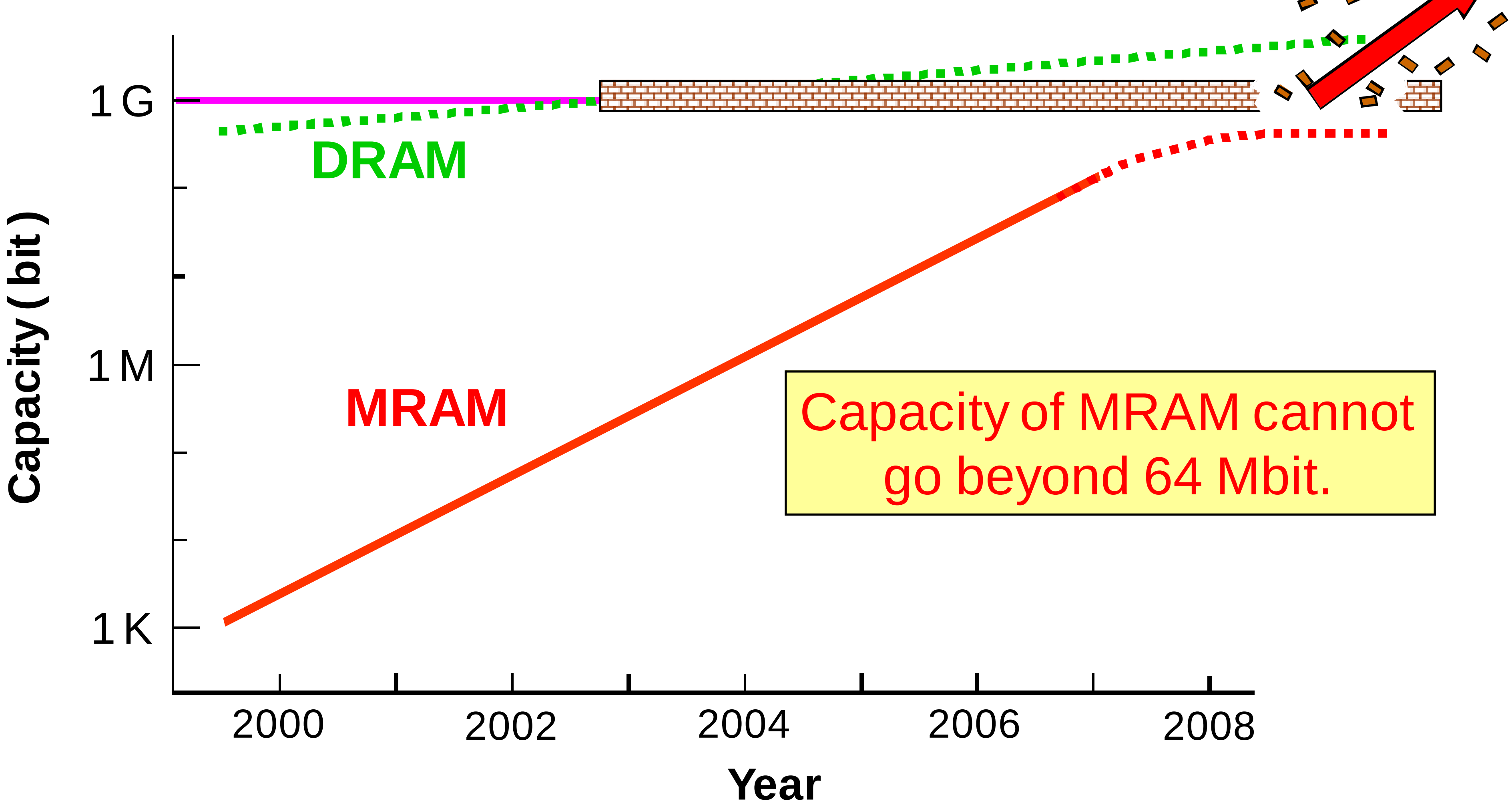
Three important properties for memory device: speed, density, and write endurance



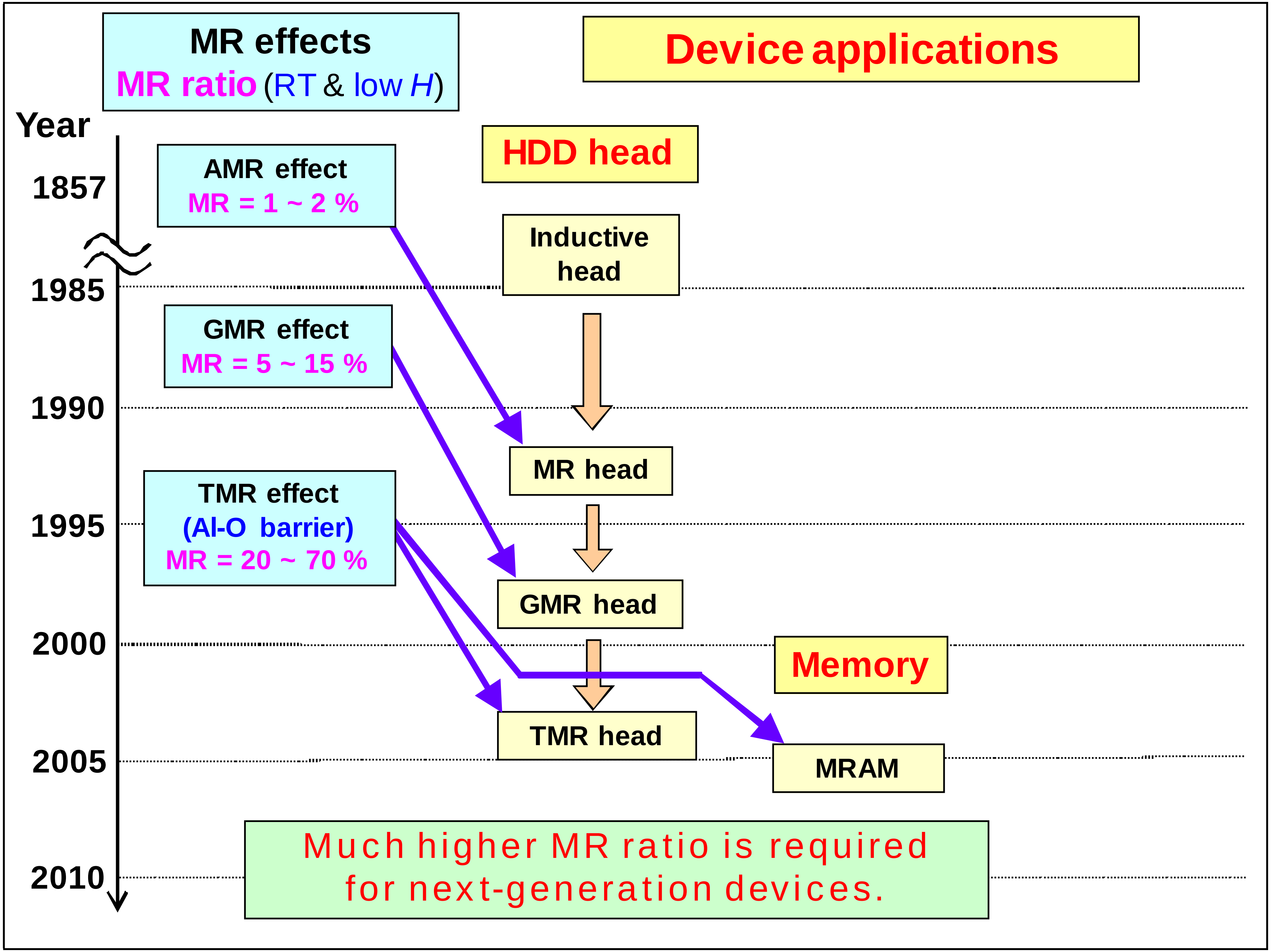
How can we develop Gbit-scale MRAM ?

Major requirement for Gbit-MRAM

- **Large output voltage ⇒ MR ratio >> 100%**
- **Reduction of writing power ⇒ spin-torque switching**



Capacity of MRAM cannot go beyond 64 Mbit.



MR effects

MR ratio (RT & low *H*)

Device applications

Year

1857

1985

1990

1995

2000

2005

2010

AMR effect
MR = 1 ~ 2 %

GMR effect
MR = 5 ~ 15 %

TMR effect
(Al-O barrier)
MR = 20 ~ 70 %

HDD head

Inductive head

MR head

GMR head

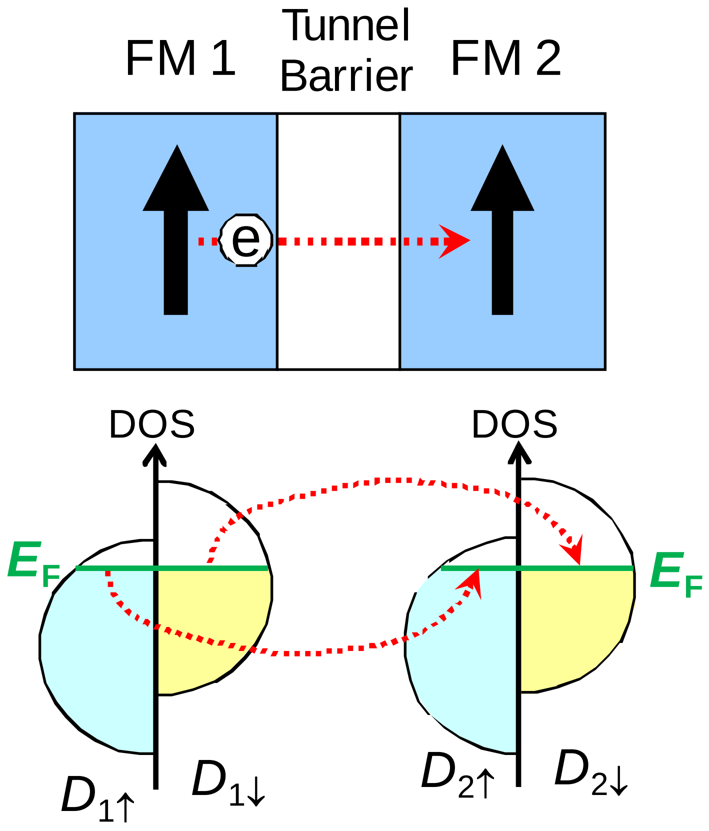
TMR head

Memory

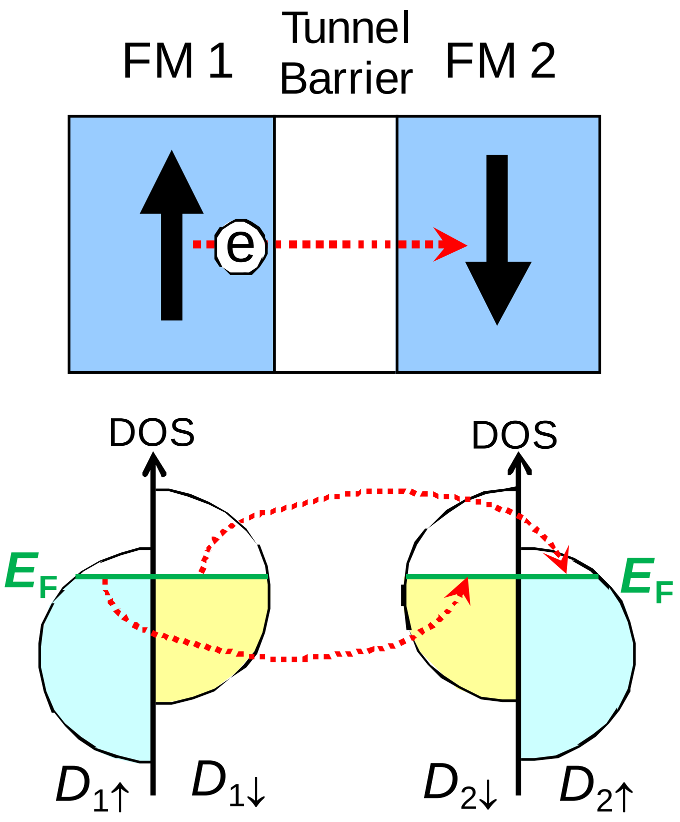
MRAM

Much higher MR ratio is required for next-generation devices.

Simple model for TMR effect : Julliere's model



P alignment



AP alignment

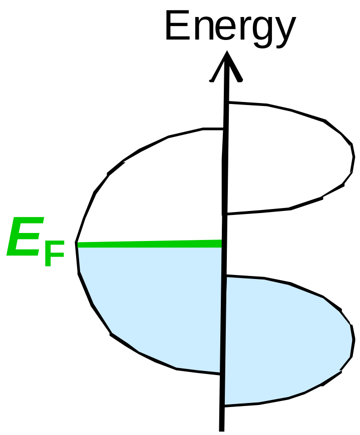
$$MR \equiv \frac{(R_{AP} - R_P)}{R_P} = \frac{2P_1P_2}{1-P_1P_2}, \qquad P_\alpha = \frac{(D_{\alpha\uparrow}(E_F) - D_{\alpha\downarrow}(E_F))}{(D_{\alpha\uparrow}(E_F) + D_{\alpha\downarrow}(E_F))}, \qquad \alpha = 1,2$$

Spin Polarization, *P*

How can we attain giant MR ratio ?

(1) Electrode material with full spin-polarization

$|P| = 1$



"Half Metal"

(E.g.) some Heusler alloys, Fe_3O_4, CrO_2, $LaSrMnO_3$ perovskite

Room-temperature MR ratios for half-metal electrodes have never exceeded those for simple 3d alloys such as Co-Fe.

(2) Crystalline tunnel barrier such as MgO(001)

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- Physics of spin-transfer torque
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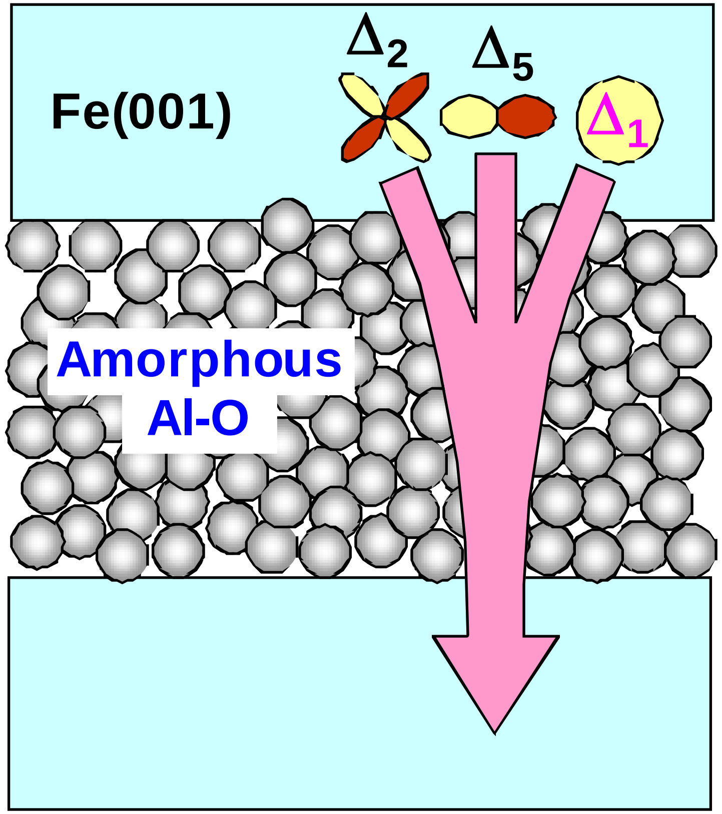
Amorphous Al-O barrier *vs.* crystal MgO barrier (theory)

Amorphous Al-O barrier

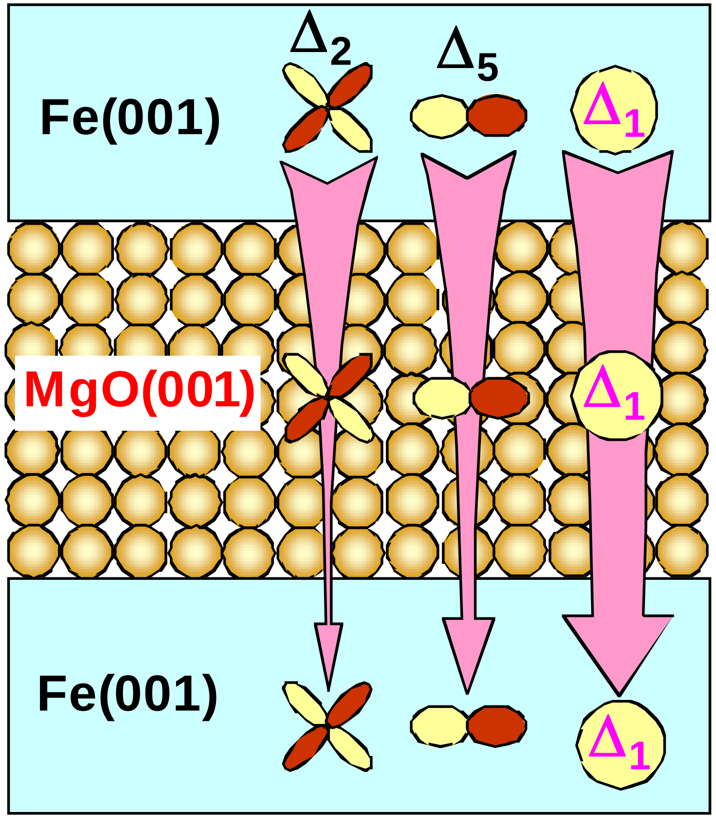
(conventional MTJ)



Incoherent tunneling of various Bloch states.

→ **MR < 100% at RT**

Crystal MgO(001) barrier

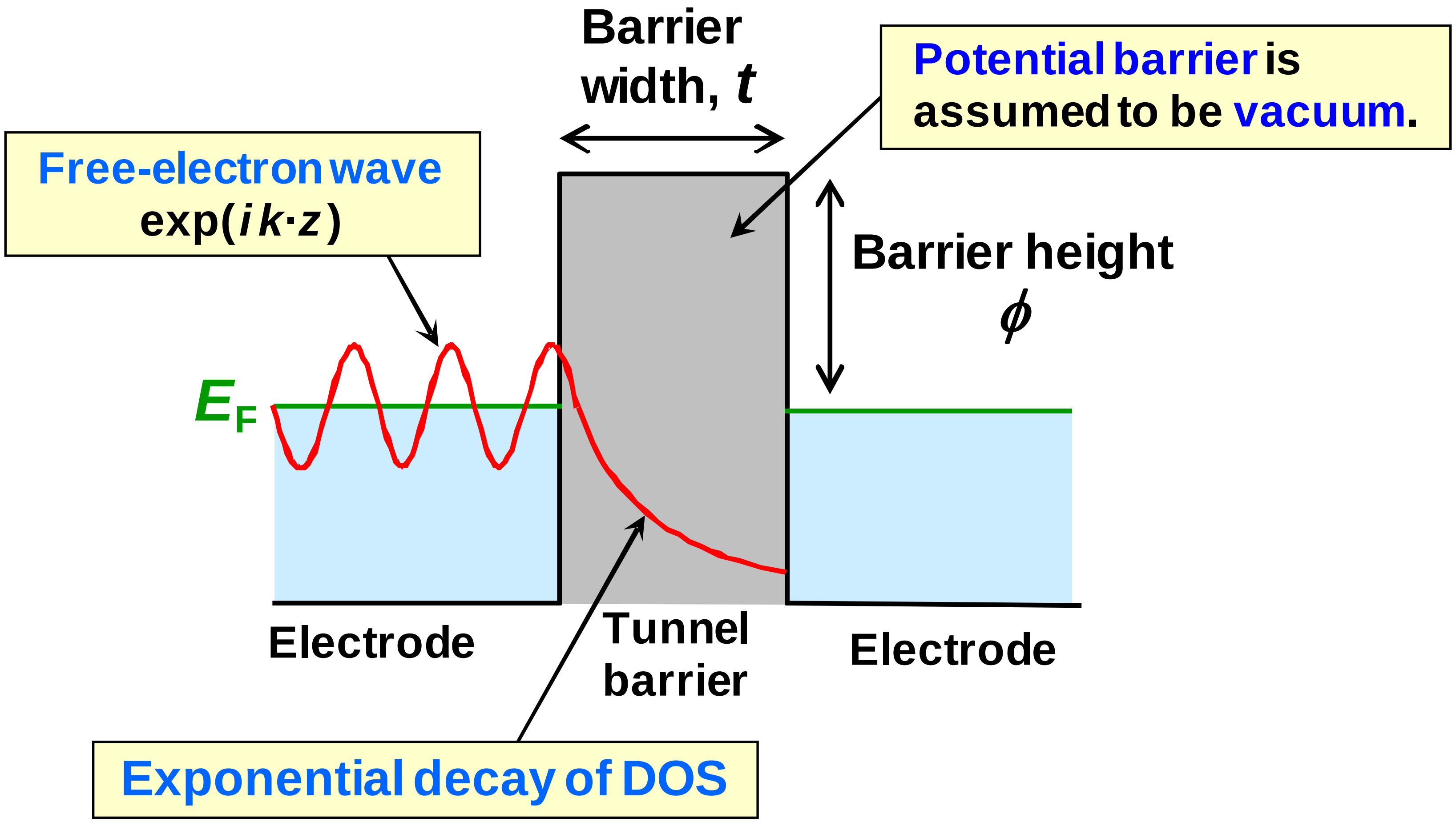


Dominant tunneling of fully spin-polarized Δ_1 Bloch states

→ **MR >> 1000% (theory)**

Butler *et al*. *PRB* 2001; Mathon *ibid* 2001.

What we learn about "*tunneling effect*" at an undergraduate course



Barrier width, *t*

Potential barrier is assumed to be vacuum.

Free-electron wave exp(*ik·z*)

Barrier height ϕ

E_F

Electrode

Tunnel barrier

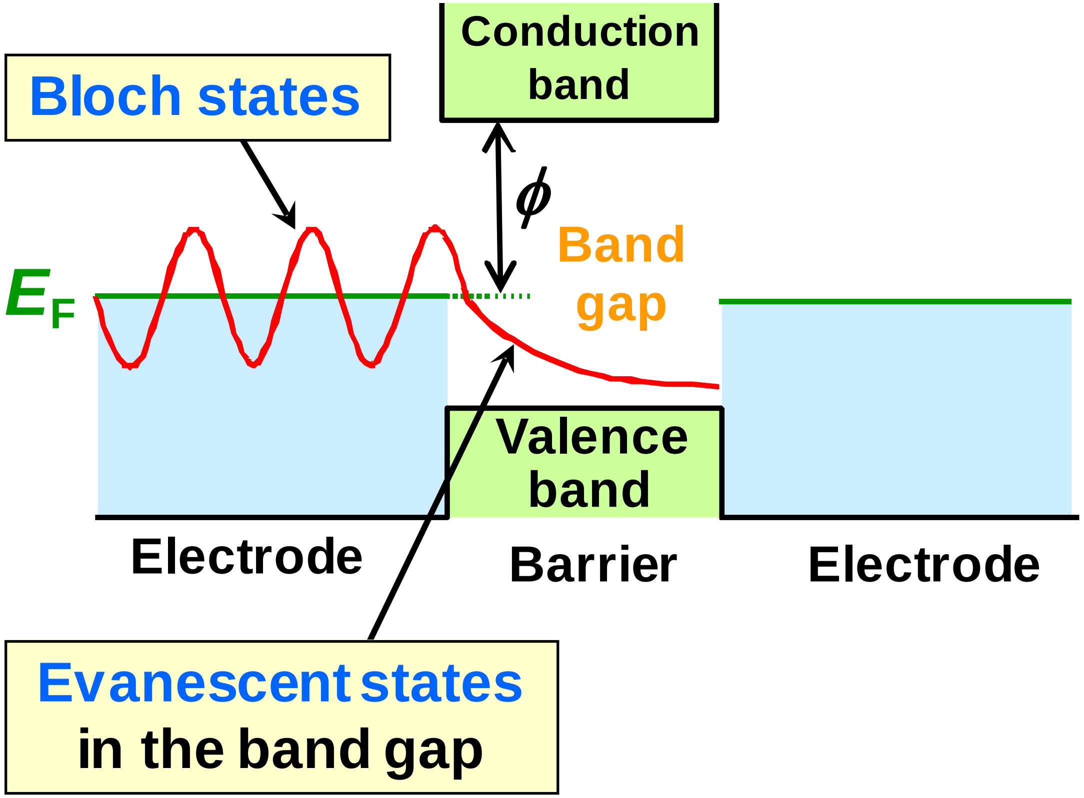
Electrode

Exponential decay of DOS

Tunneling transmittance (*T*) decays exponentially as a function of *t*.

(WKB approx.) $T \propto \exp(-\sqrt{8m\phi/\hbar^2}\times t)$ *m*: effective mass

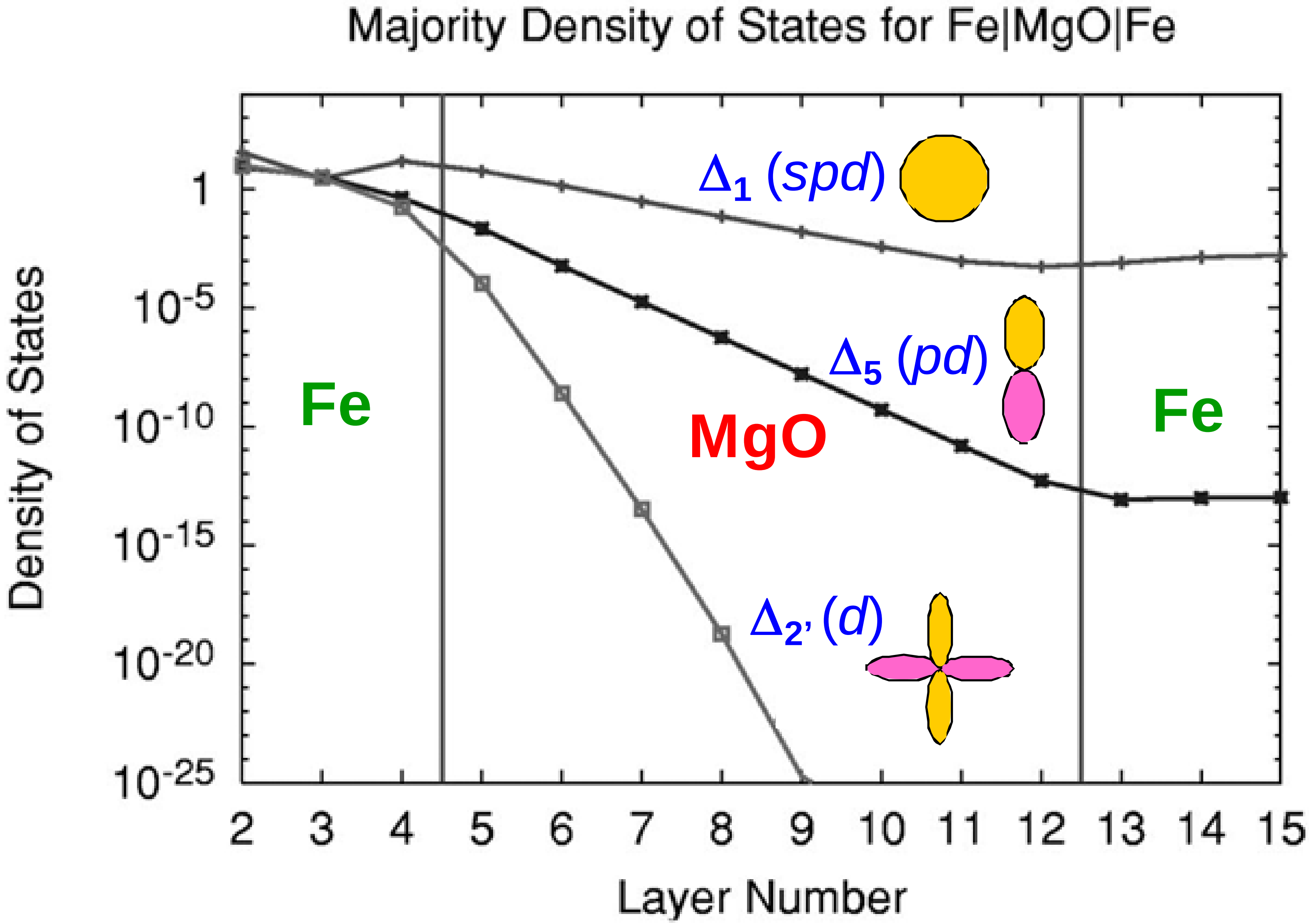
Realistic tunneling effect



Both Bloch states and evanescent states have
(i) specific orbital symmetry & (ii) specific band dispersion.
(complex wave vector $k = k_r + i\kappa$)

Bloch states and evanescent states couple at interface.

Decay of evanescent state largely depends on orbital symmetry.

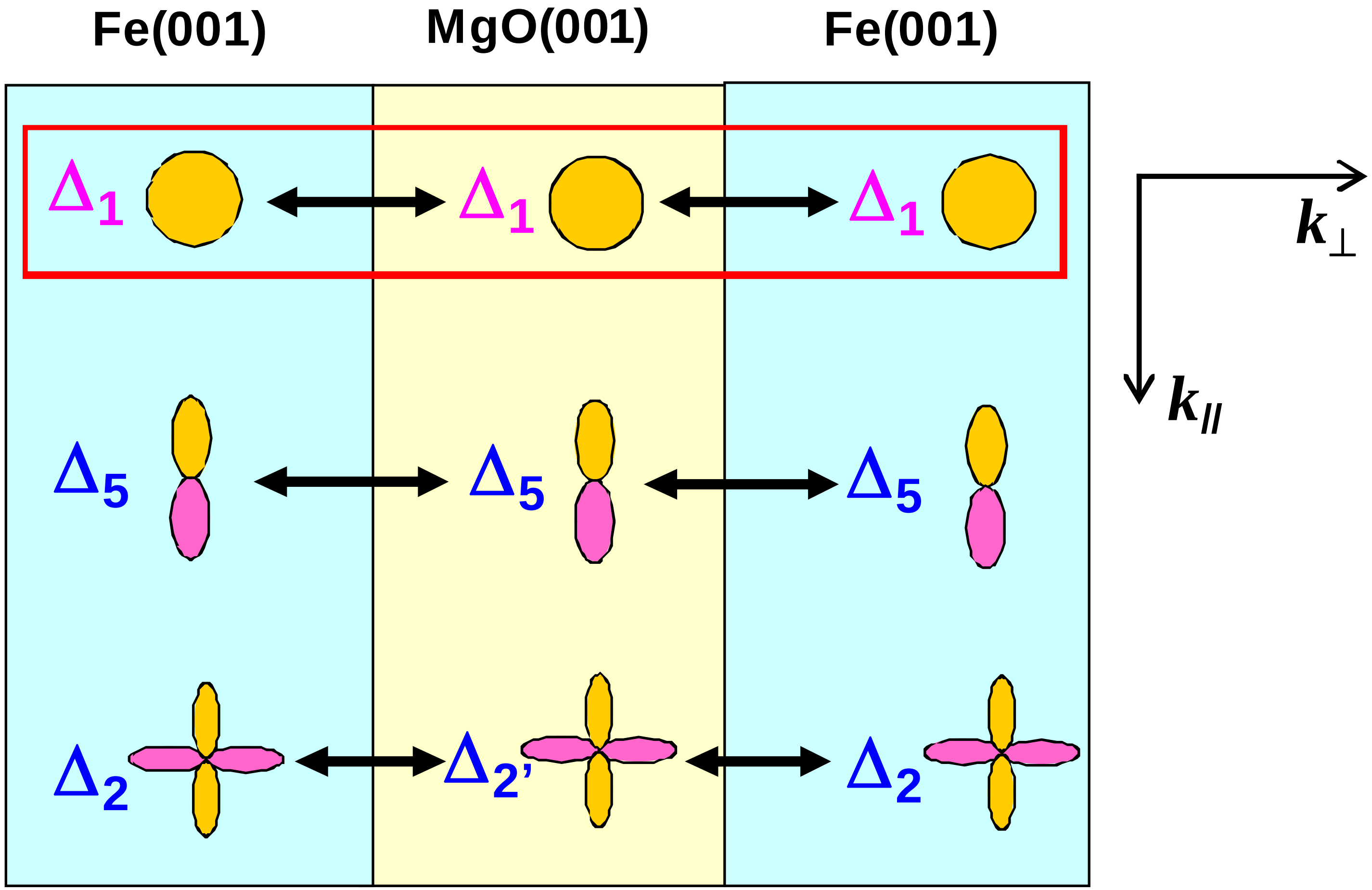


Butler (2001).

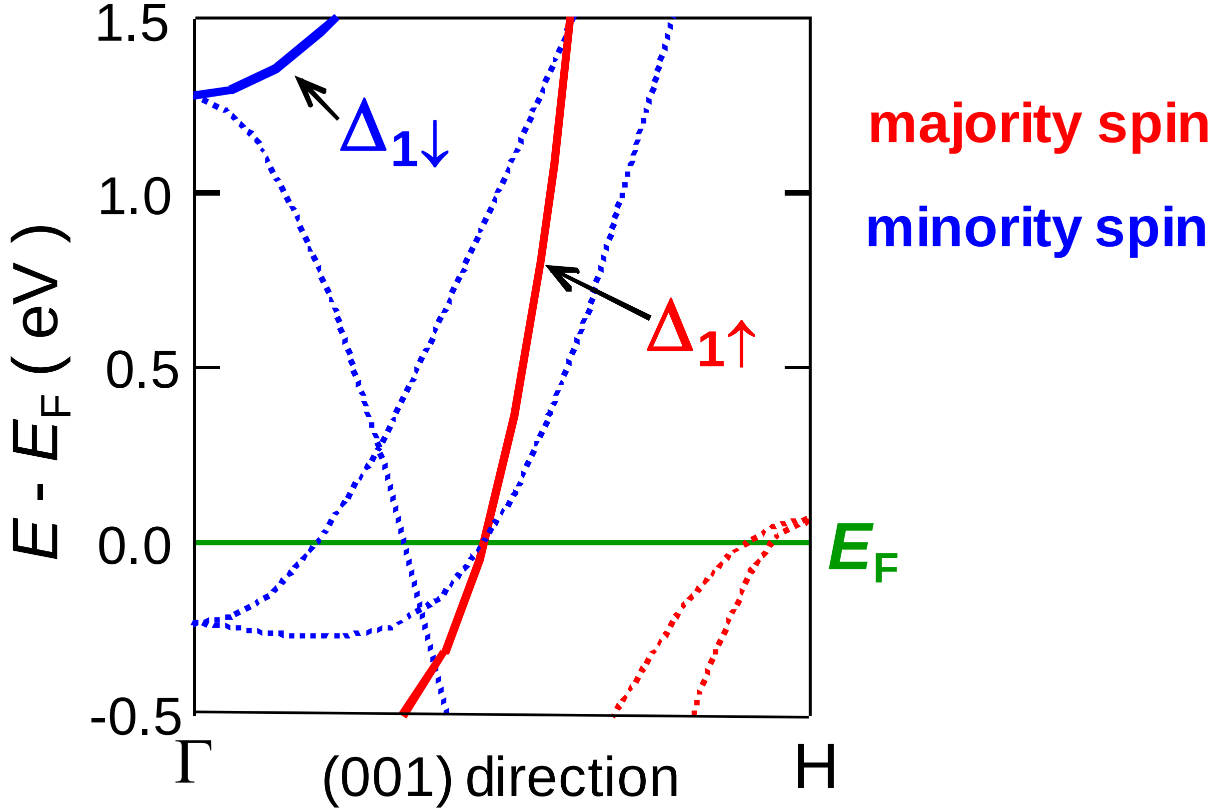
$$\Delta_1 : s + p_z + d_{2z^2 - x^2 - y^2}$$

Coupling between Bloch states and evanescent states

Ideal coherent tunneling for $k_{//} = 0$ direction



Fully spin-polarized Δ_1 band in bcc Fe(001)



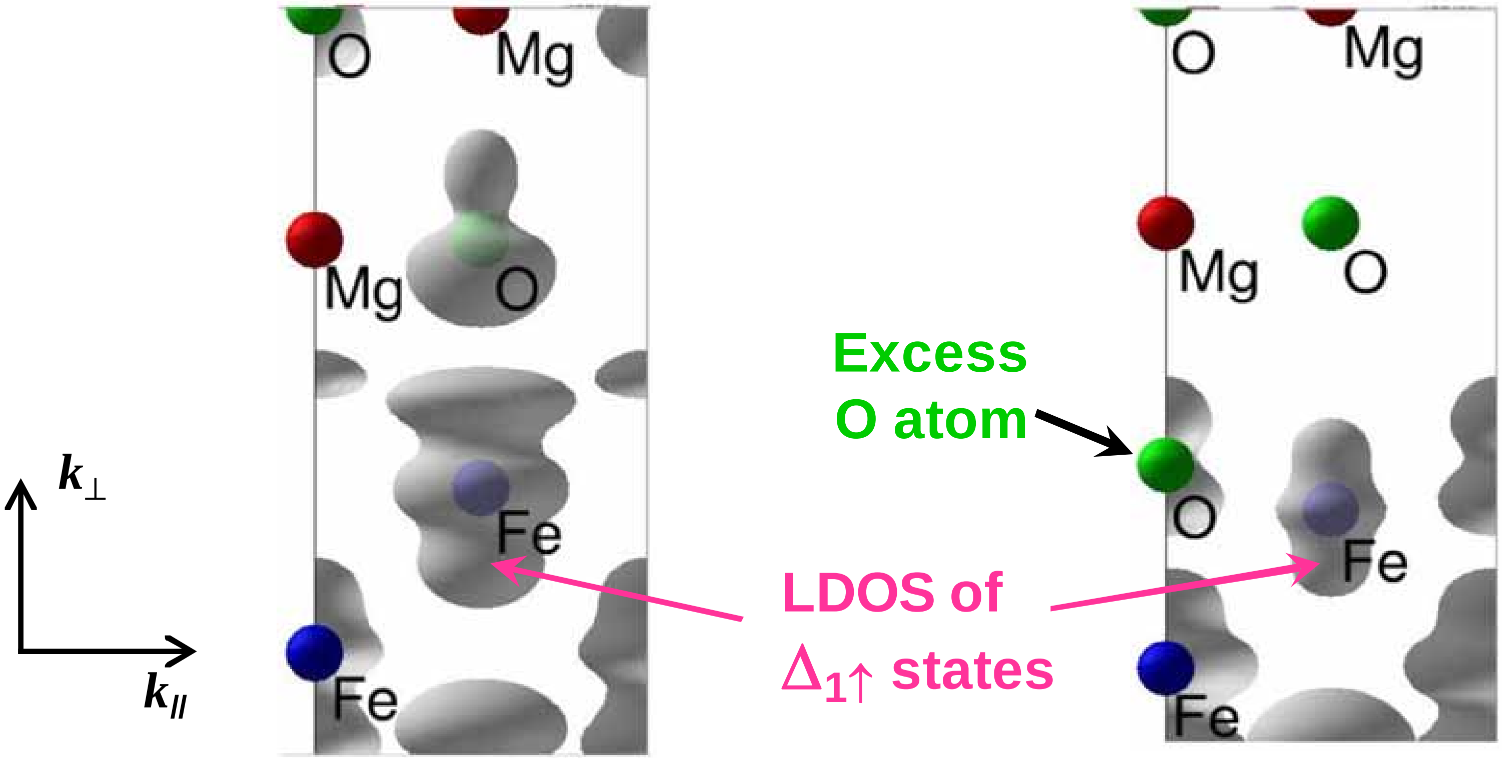
Fully spin-polarized Δ_1 band

⇒ Giant MR ratio is theoretically expected.

Not only bcc Fe but also many other bcc alloys based on Fe or Co have fully spin-polarized Δ_1 band. (*e.g.* bcc $Fe_{1-x}Co_x$, some Heusler alloys)

Importance of interface (theory)

X.-G. Zhang, *et al*., *PRB* **68**, 092402 (2003).



Ideal interface

Fe- $\Delta_{1\uparrow}$ states couple with MgO-Δ_1 states at $k_{//} = 0$.

MR ratio > 1000%

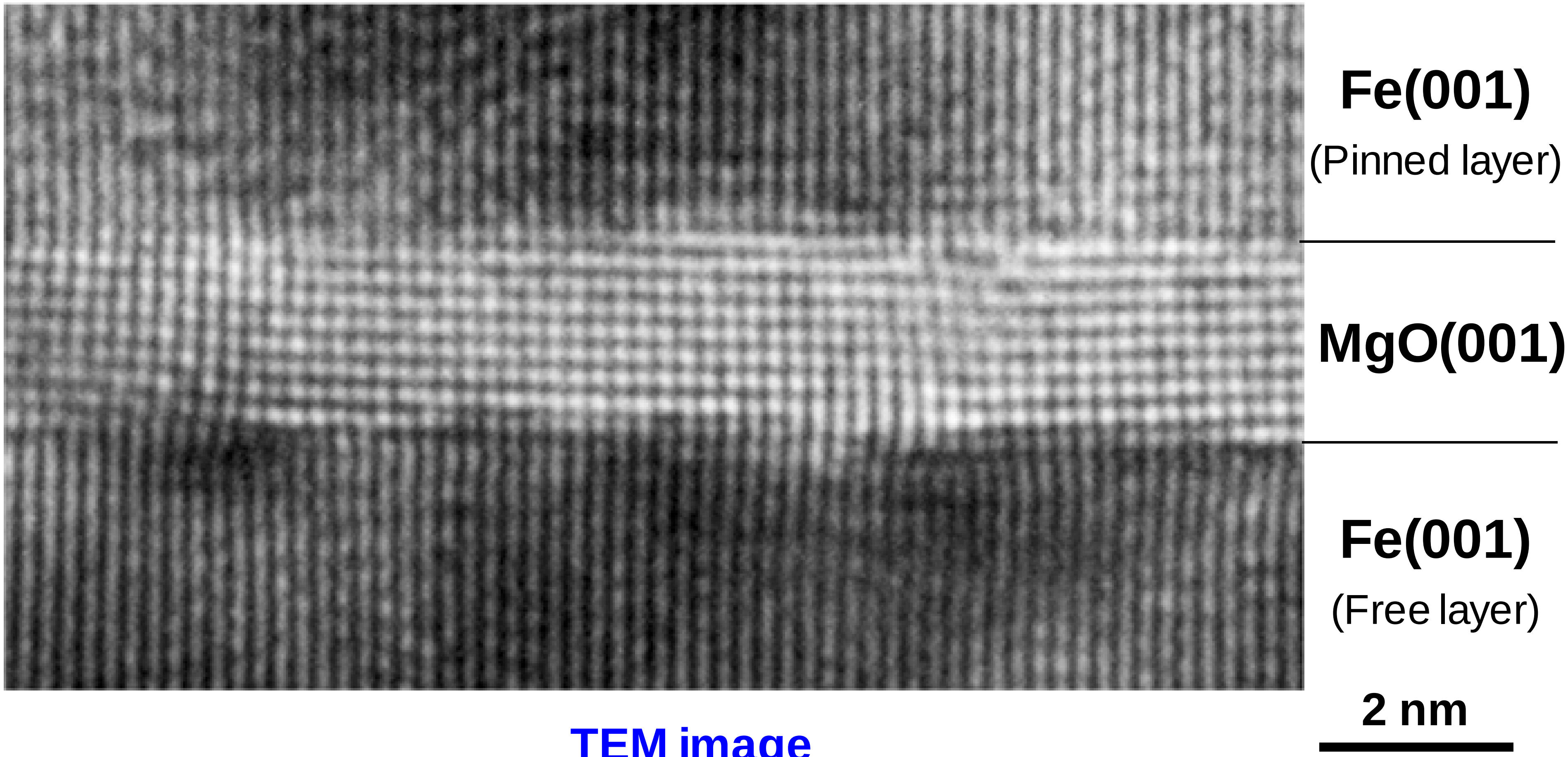
Oxidized interface

Fe- $\Delta_{1\uparrow}$ states do not couple with MgO-Δ_1 states at $k_{//} = 0$.

MR ratio < 100%

Fully epitaxial Fe/MgO/Fe MTJ grown by MBE

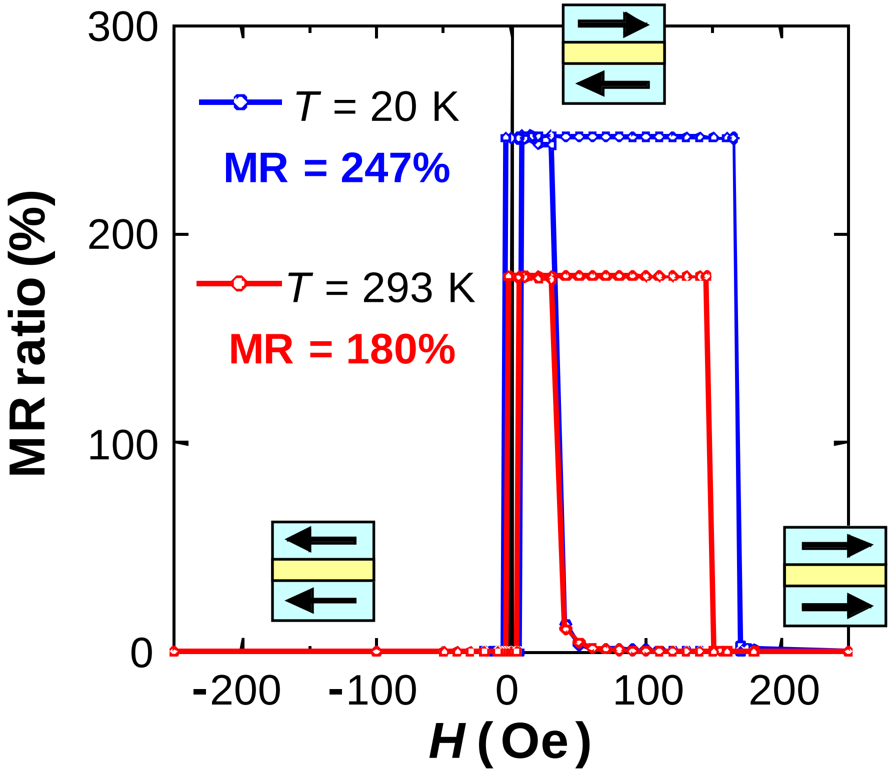
Yuasa *et al*., *Nature Mater.* **3**, 868 (2004).



TEM image

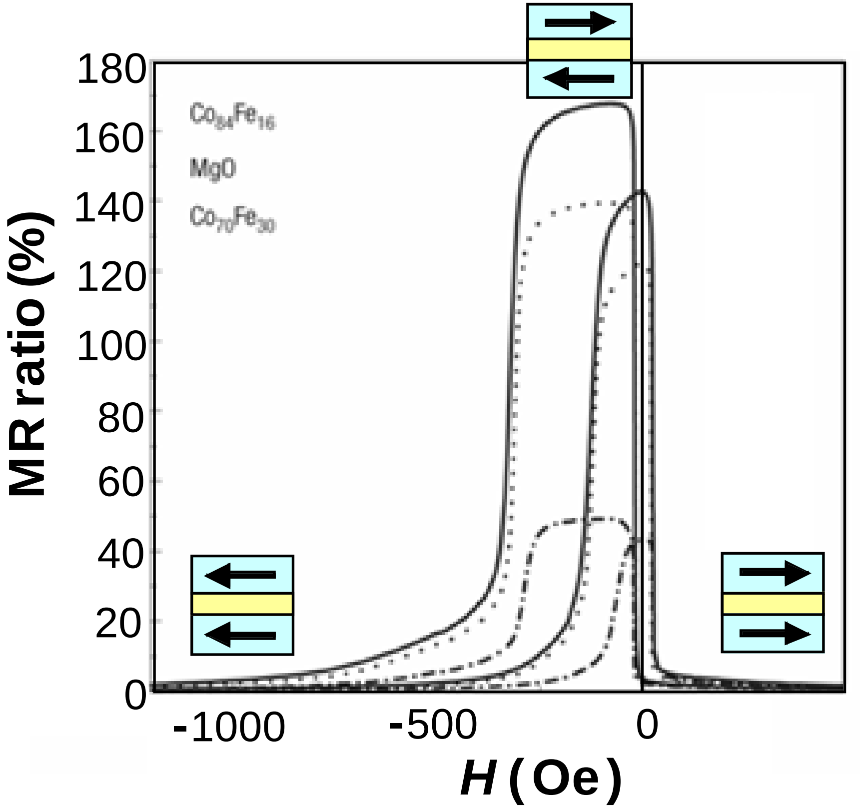
Experimental demonstrations of giant TMR

Single-crystal MgO(001) barrier

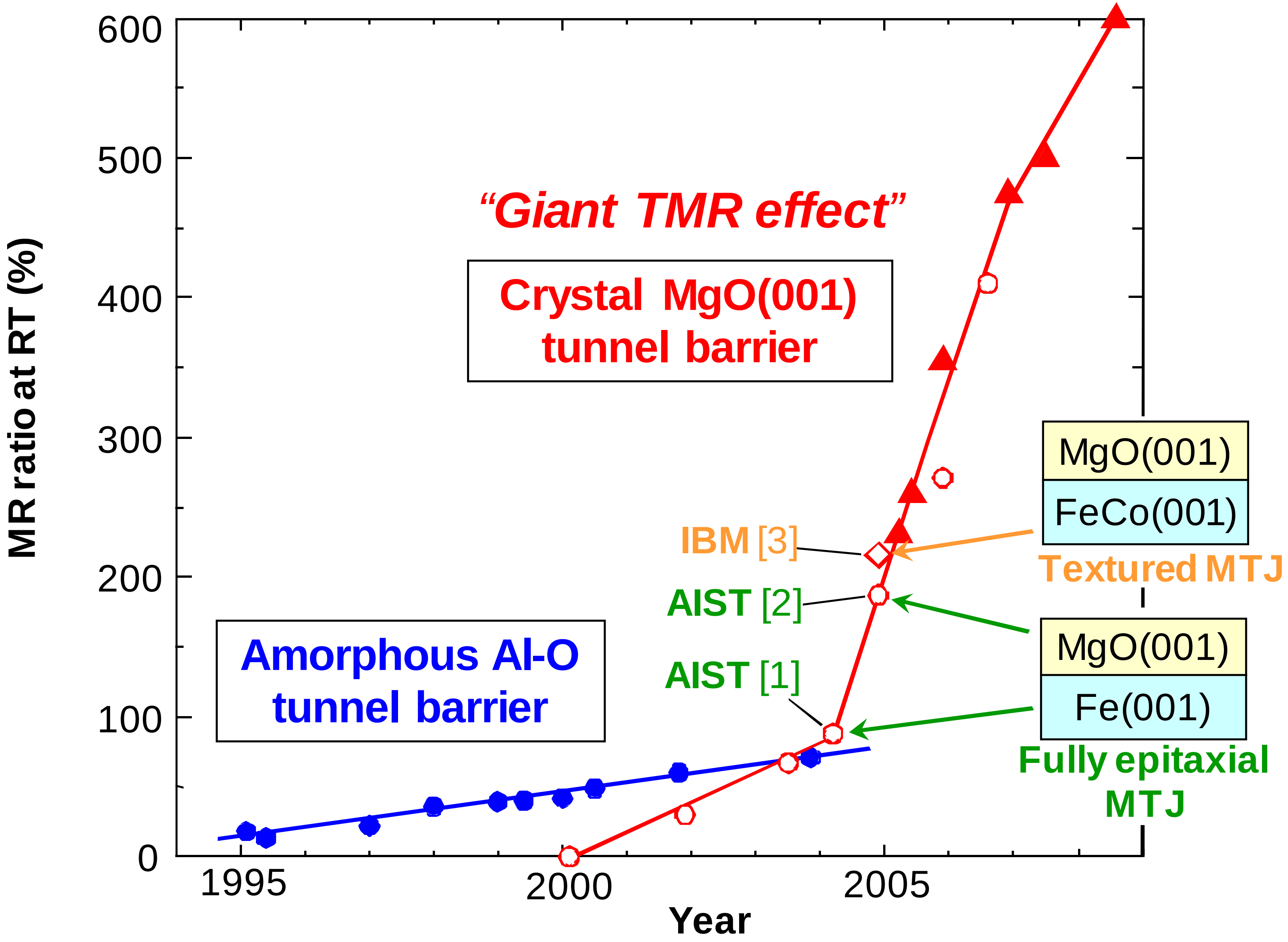


Yuasa *et al*., *Nature Mater.* **3**, 868 (2004).

Textured MgO(001) barrier



Parkin (IBM), *Nature Mater.* **3**, 862 (2004).

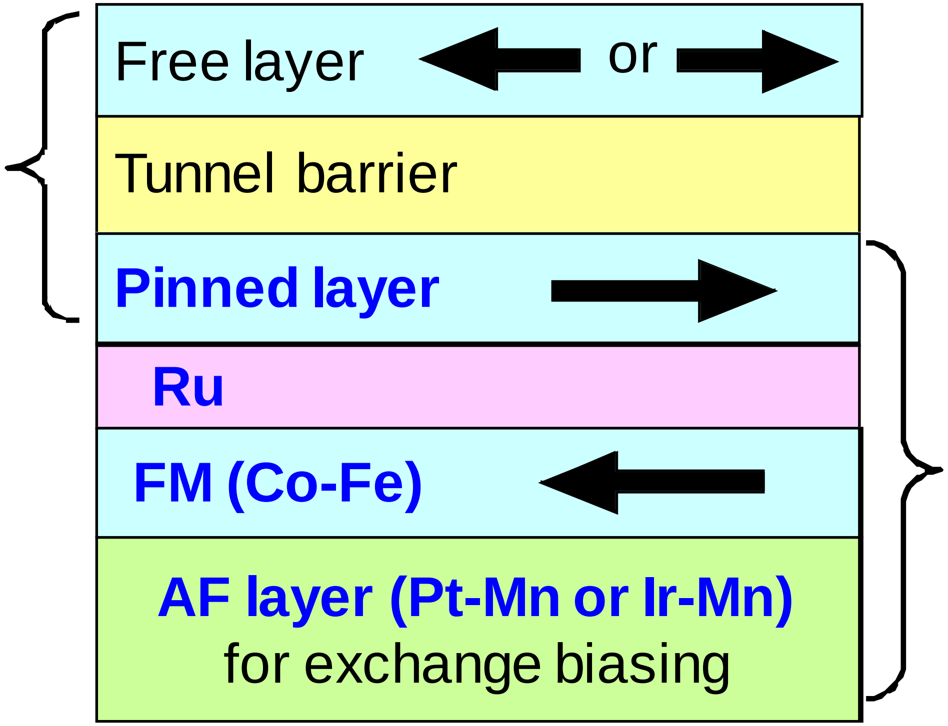


[1] Yuasa, *Jpn. J. Appl. Phys.* **43**, L558 (2004). [2] Yuasa, *Nature Mater.* **3**, 868 (2004).

[3] Parkin, *Nature Mater.* **3**, 862 (2004).

Fundamental problem on thin film growth

MTJ structure for practical applications



MTJ

Free layer ← or →

Tunnel barrier

Pinned layer →

Ru

FM (Co-Fe) ←

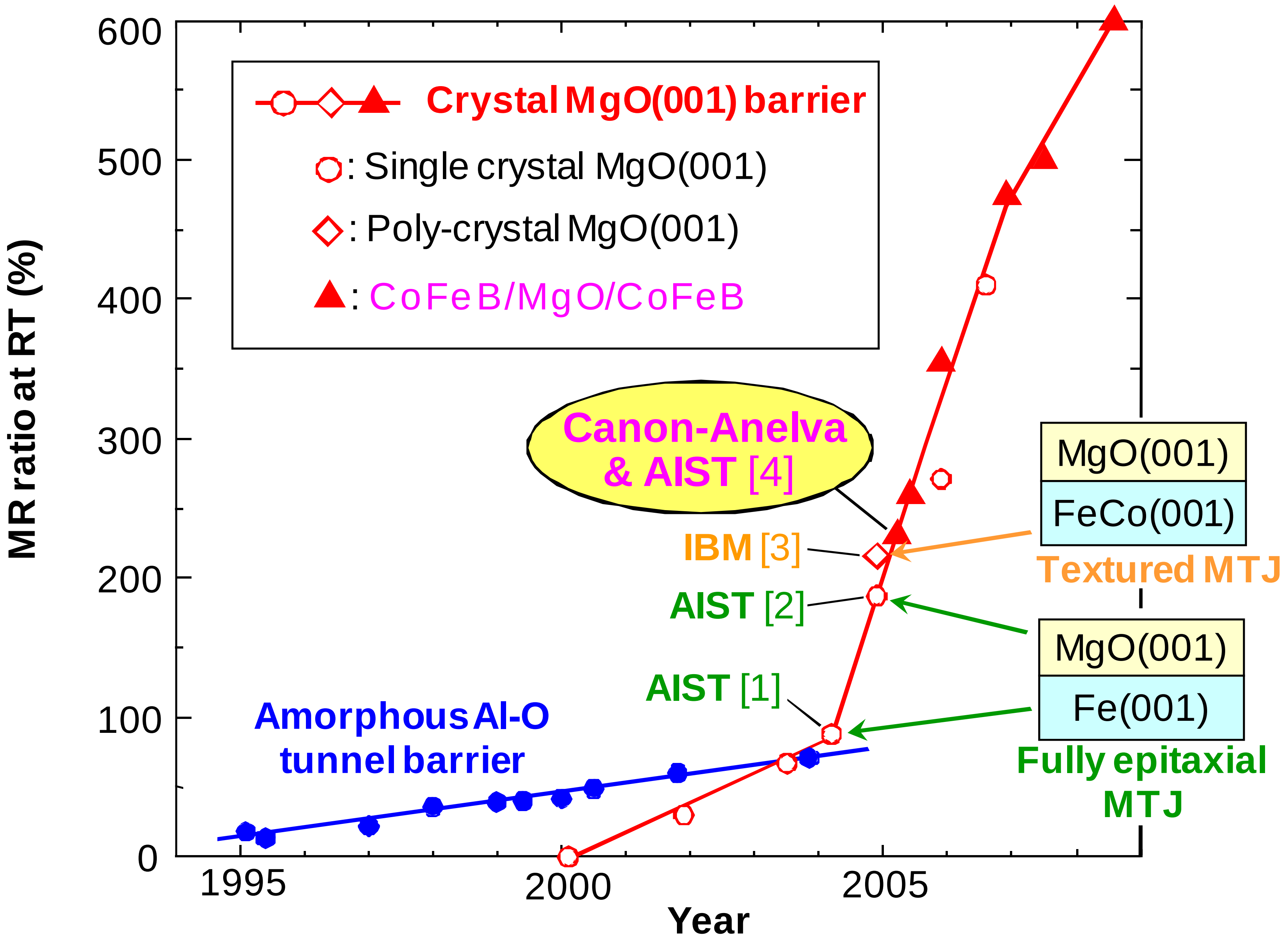
AF layer (Pt-Mn or Ir-Mn)
for exchange biasing

This structure is based on **fcc (111)**.

MgO(001) cannot be grown on **fcc (111)**.

4-fold symmetry

3-fold symmetry



[1] Yuasa, *Jpn. J. Appl. Phys.* **43**, L558 (2004). [2] Yuasa, *Nature Mater.* **3**, 868 (2004).

[3] Parkin, *Nature Mater.* **3**, 862 (2004). [4] Djayaprawira, SY, *APL* **86**, 092502 (2005).

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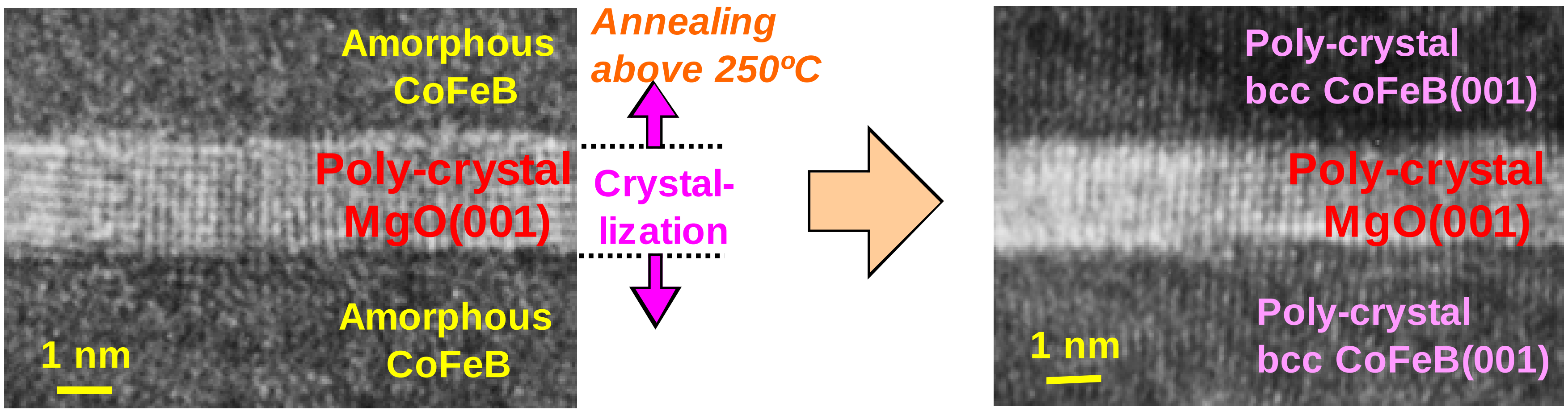
CoFeB/MgO/CoFeB structure for device applications

Canon-Anelva, AIST

Djayaprawira, SY, *Appl. Phys. Lett.* **86**, 092502 (2005).
Yuasa & Djayaprawira, *J. Phys. D: Appl. Phys.* **40**, R337 (2007).

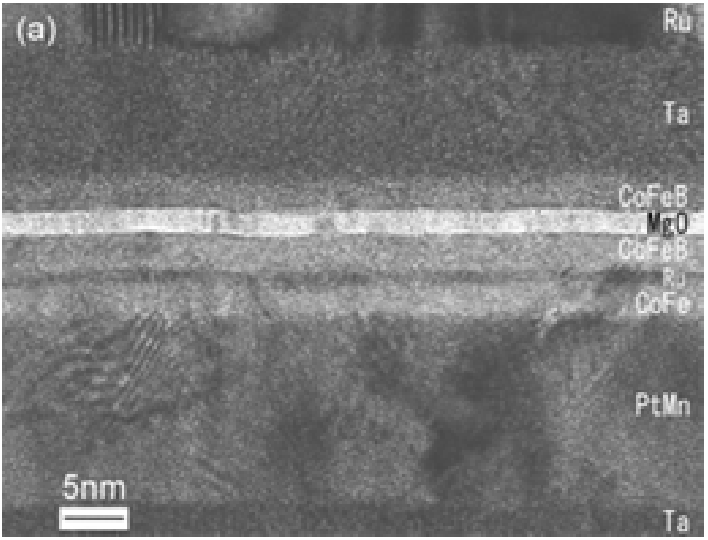


As-grown state

After annealing

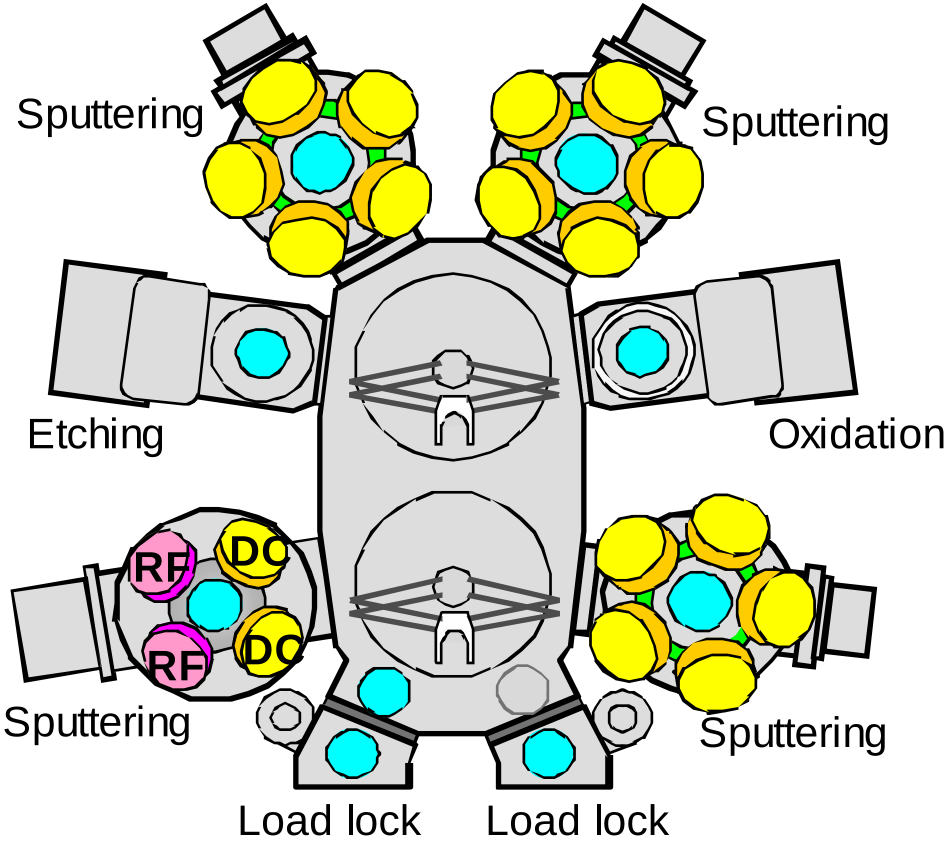
MgO-MTJ
(**4-fold symmetry**)

Practical bottom structure: fcc(111)
(**3-fold symmetry**)

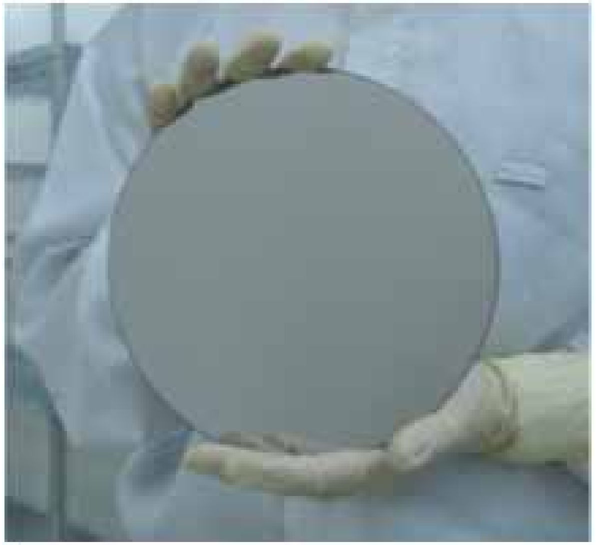


Core technology for device applications

Mass-manufacturing technology for HDD industry

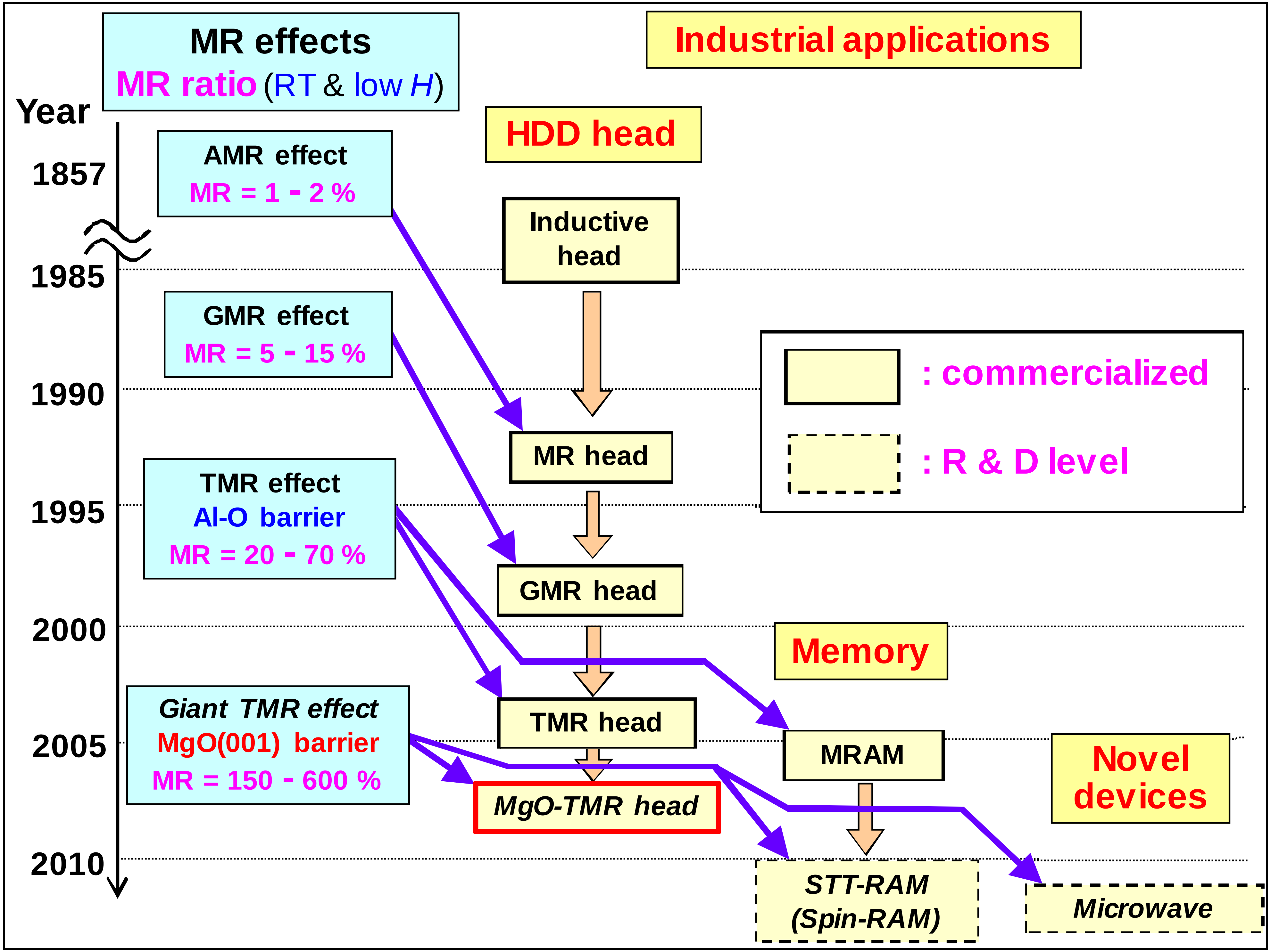


Canon-Anelva C-7100
sputtering system



ϕ200–300 mm wafer

All the HDD manufacturers use this type of sputtering machine for the production of HDD magnetic heads.



MR effects

MR ratio (RT & low *H*)

Industrial applications

Year

1857

1985

1990

1995

2000

2005

2010

AMR effect
MR = 1 - 2 %

GMR effect
MR = 5 - 15 %

TMR effect
Al-O barrier
MR = 20 - 70 %

Giant TMR effect
MgO(001) barrier
MR = 150 - 600 %

HDD head

Inductive head

MR head

GMR head

TMR head

MgO-TMR head

Memory

MRAM

STT-RAM (Spin-RAM)

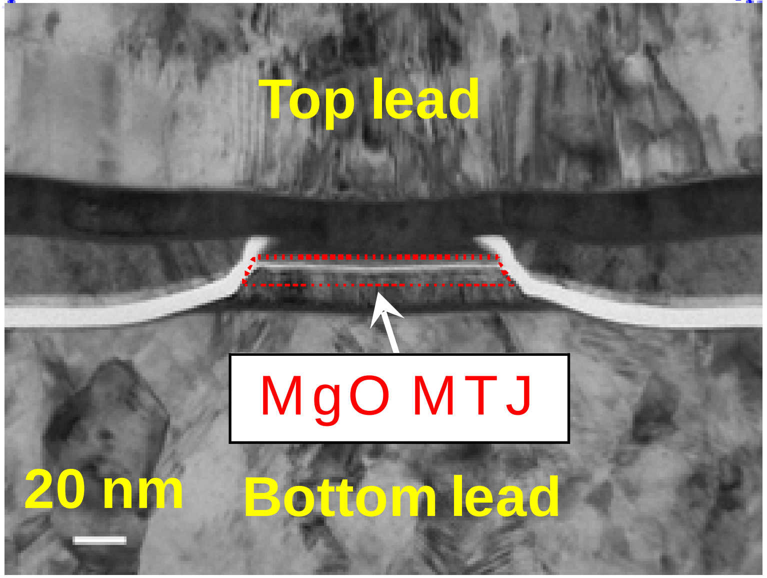
Novel devices

Microwave

: commercialized

: R & D level

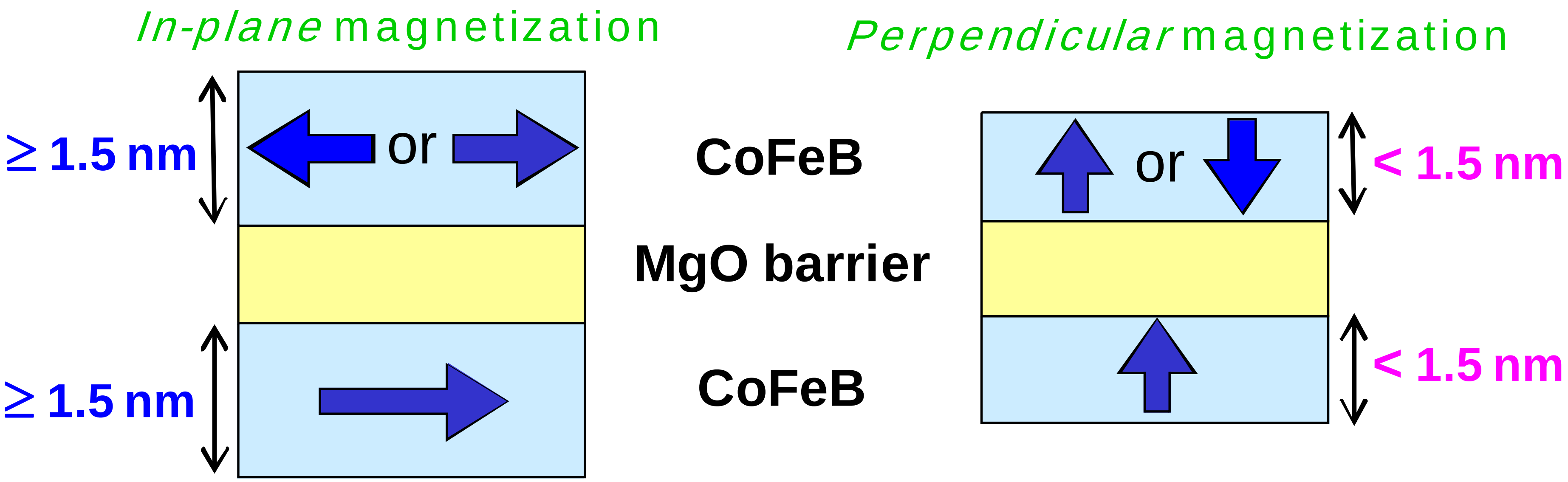
MgO-TMR head for ultrahigh-density HDD



TEM image

- **Volume production** since 2007.
- **700 Gbit/inch^2** achieved (×**5 increase**).
- Applicable up to 1 – 2 Tbit/inch^2.
- World market of **HDD**: **25 billion USD**
  head: **5 billion USD**

Ultrathin CoFeB electrode can have perpendicular magnetization.



In-plane magnetization

Perpendicular magnetization

≥ 1.5 nm

≥ 1.5 nm

or

CoFeB

MgO barrier

CoFeB

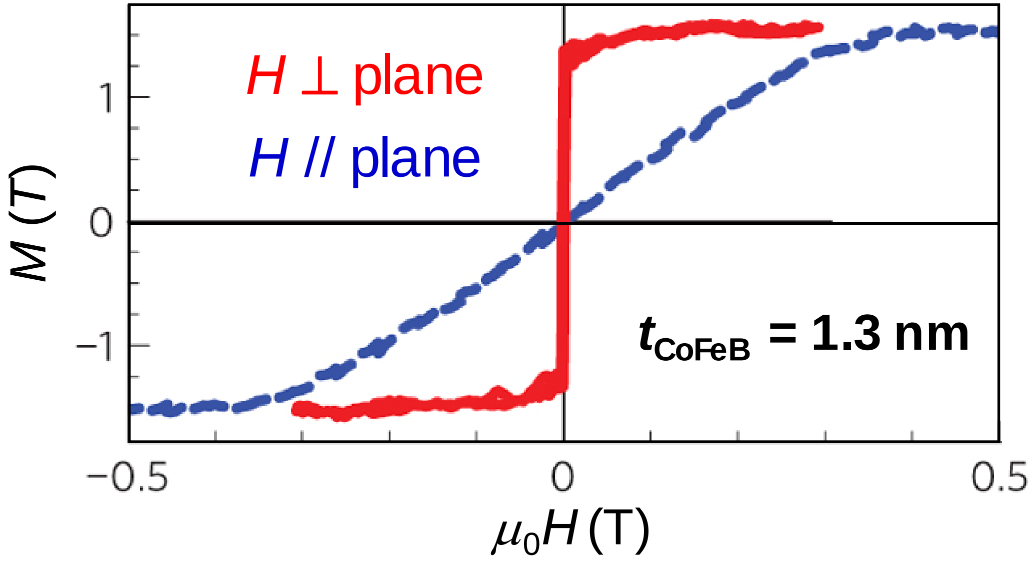
or

< 1.5 nm

< 1.5 nm

Since Djayaprawira, SY, *et al*.,
APL **86**, 092502 (2005).

S. Ikeda, H. Ohno *et al*.,
Nature Mater. **9**, 721 (2010).



Outline

(1) Spintronics

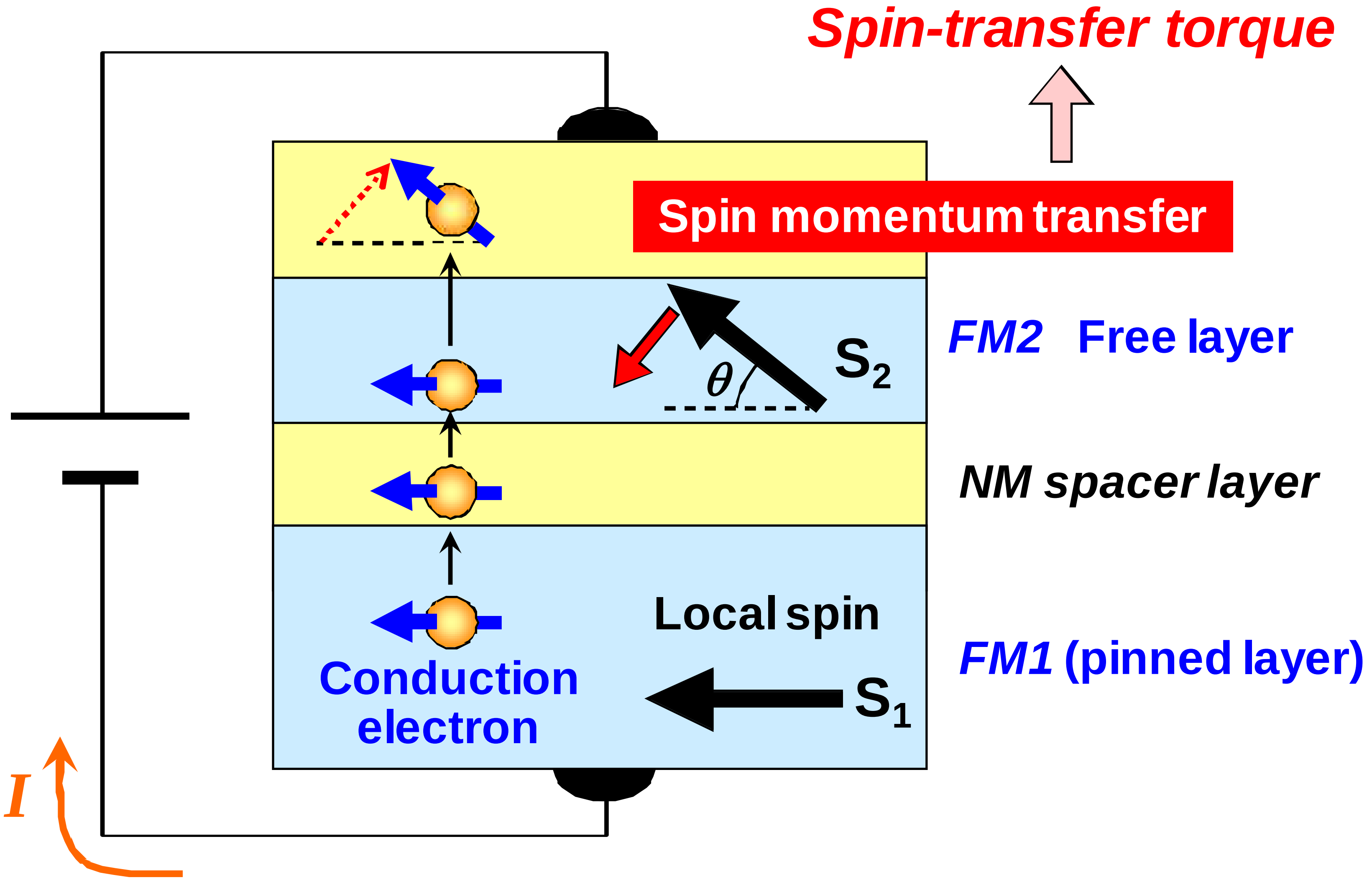
(2) Tunnel magnetoresistance (TMR)

- Magnetoresistance
- Tunnel magnetoresistance in magnetic tunnel junction (MTJ)
- Giant TMR in MgO-based MTJ
- CoFeB/MgO/CoFeB structure for device applications

➡ **(3) Spin-transfer torque (STT)**

- Physics of spin-transfer torque
- Spin-transfer torque MRAM (STT-RAM or Spin-RAM)
- Microwave applications

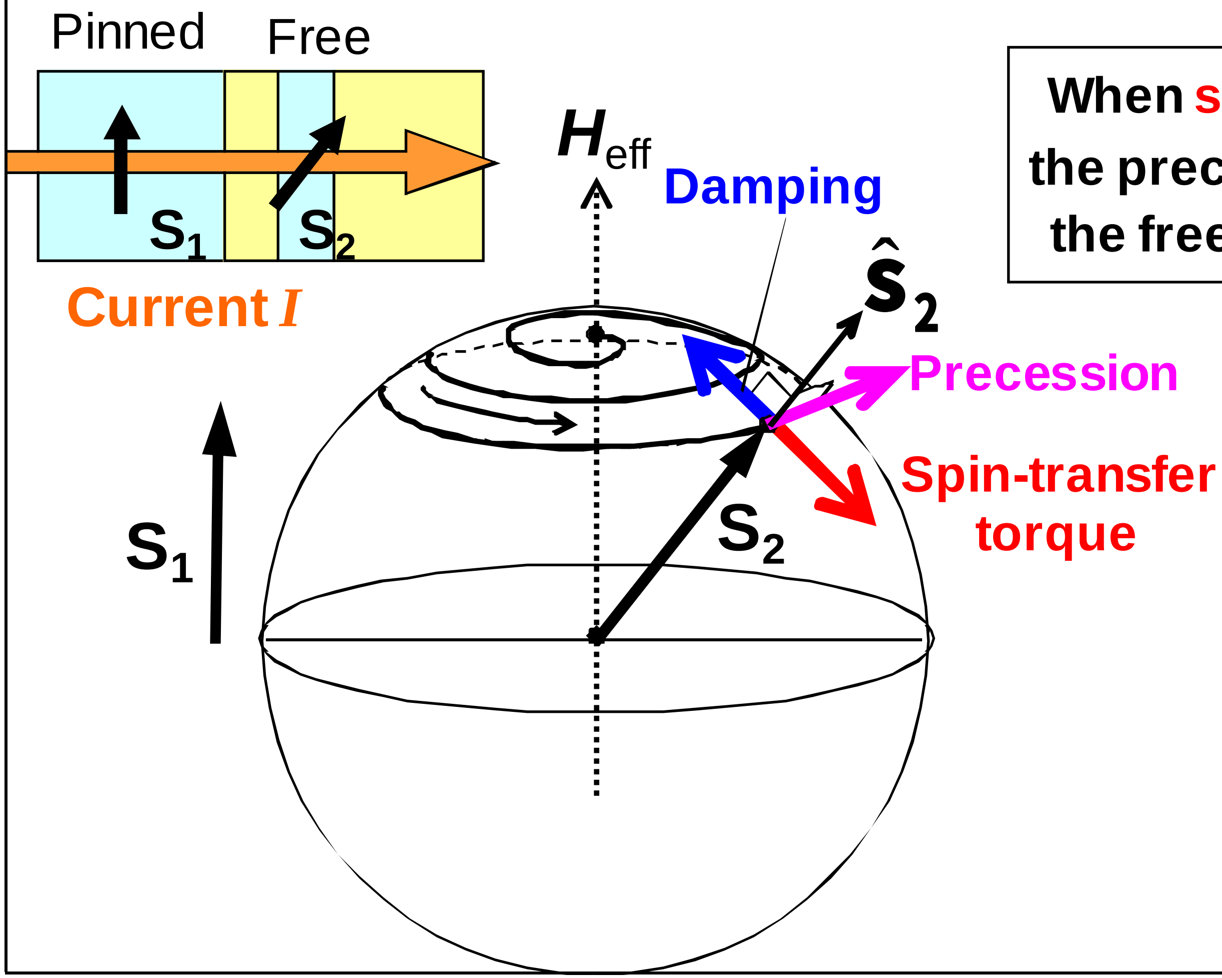
Spin-transfer torque in magnetic nano-pillar



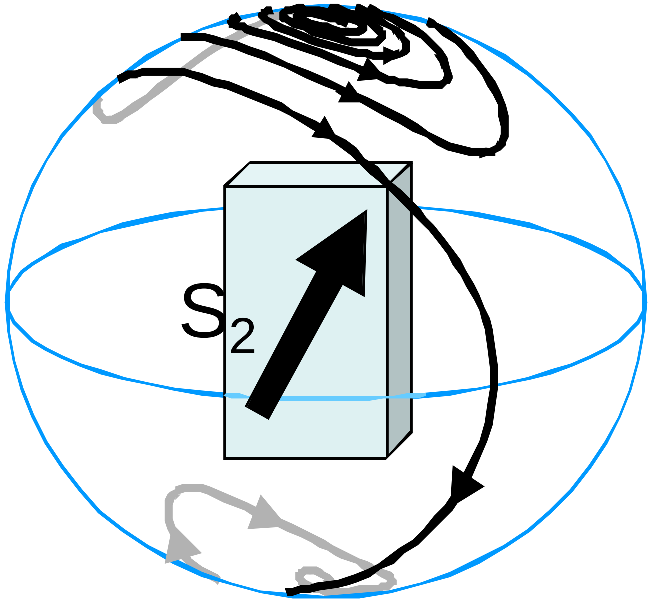
Theory of spin-transfer torque

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

$$\dot{\mathbf{S}}_2 = \underbrace{\gamma \mathbf{S}_2 \times \mathbf{H}_{eff}}_{\text{Precession}} \underbrace{- \alpha \hat{\mathbf{s}}_2 \times \dot{\mathbf{S}}_2}_{\text{Damping}} + \underbrace{\gamma \beta_{ST} I_e \hat{\mathbf{s}}_2 \times (\hat{\mathbf{s}}_2 \times \hat{\mathbf{s}}_1)}_{\text{Spin-transfer}}$$



When spin torque > damping torque, the precession angle is amplified, and the free-layer moment (S_2) switches.



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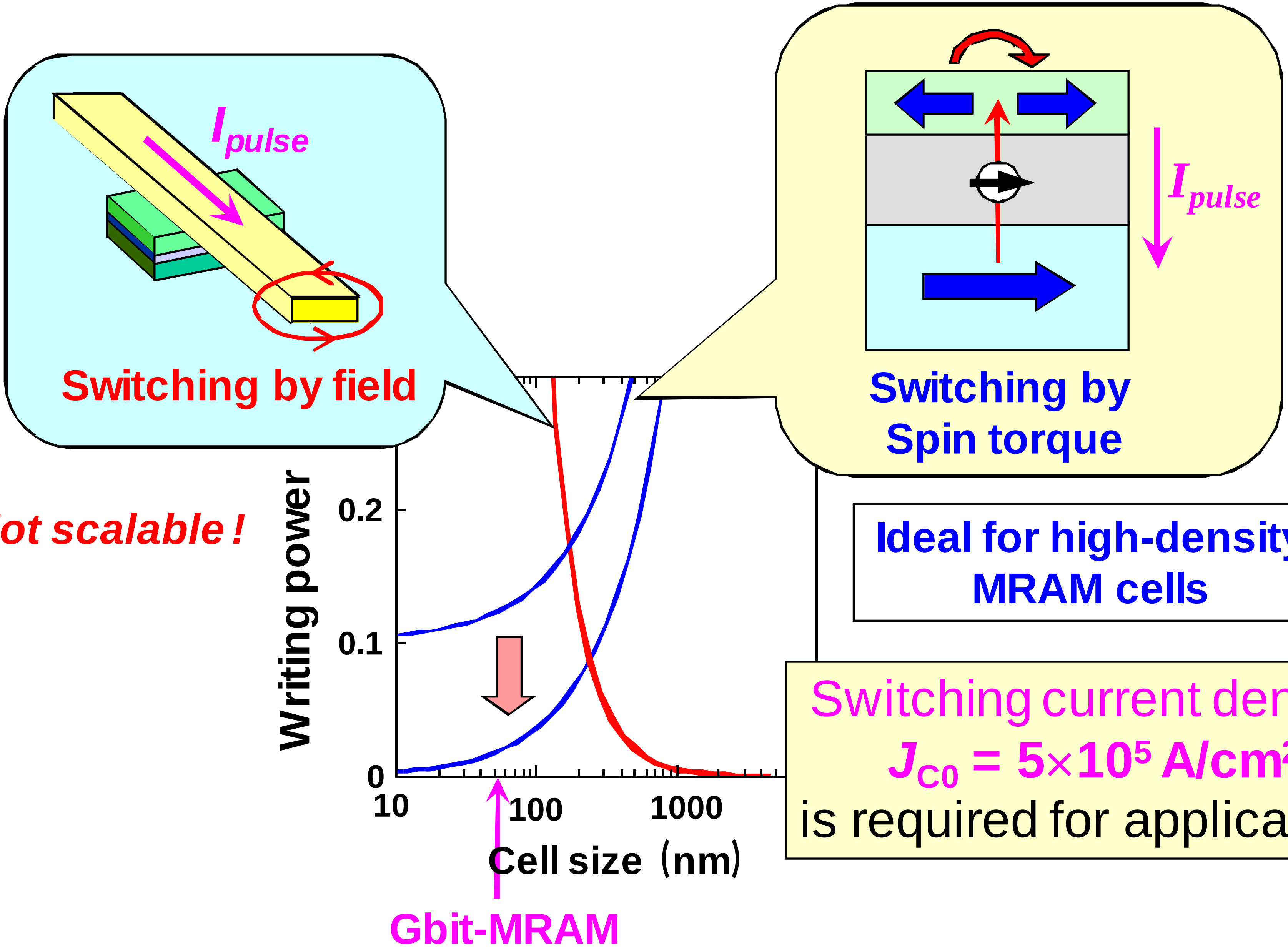
(3) Spin-transfer torque (STT)

- Physics of spin-transfer torque
- ➡ Spin-transfer torque MRAM (STT-RAM or Spin-RAM)
- Microwave applications

Writing (magnetization switching) by spin-transfer torque



Not scalable !

Ideal for high-density MRAM cells

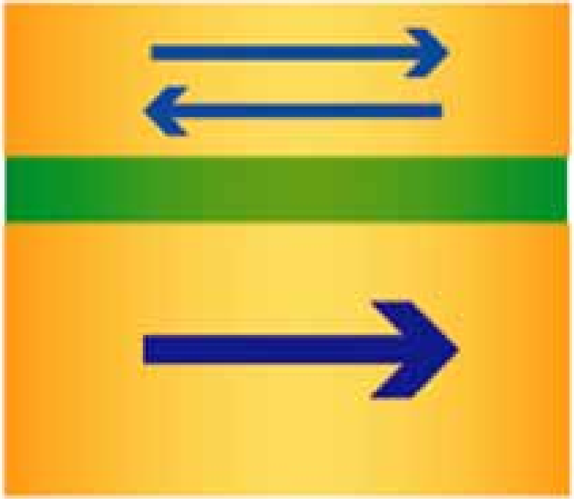
Switching current density

$J_{C0} = 5\times10^5\ \mathrm{A/cm^2}$

is required for application.

In-plane magnetization *vs*. Perpendicular magnetization

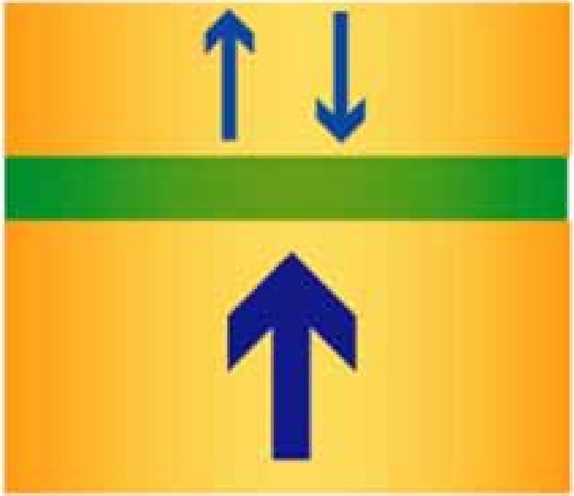
In-plane magnetization



<Materials>

- CoFeB
- Co-Fe
- Ni-Fe

Perpendicular magnetization

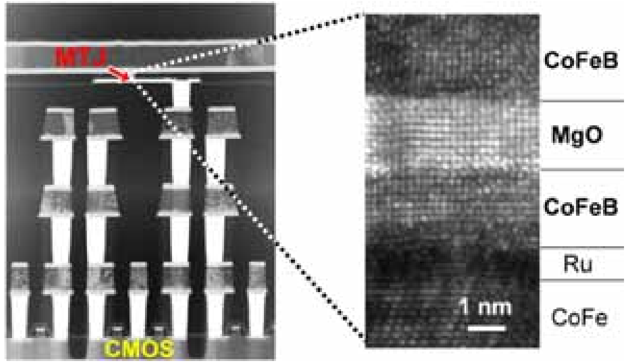


<Materials>

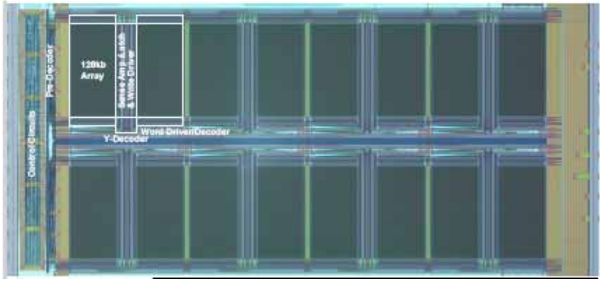
- $L1_0$-ordered alloy (*e.g*. FePt)
- Multilayer, **superlattice**
- RE-TM alloy (*e.g*. Tb-Co)
- HCP alloy (*e.g*. Co-Cr)
- ultrathin CoFeB

Development of Spin-RAM

2005 Sony **(IEDM 2005)**
- in-plane MTJ cells
- 4 kb

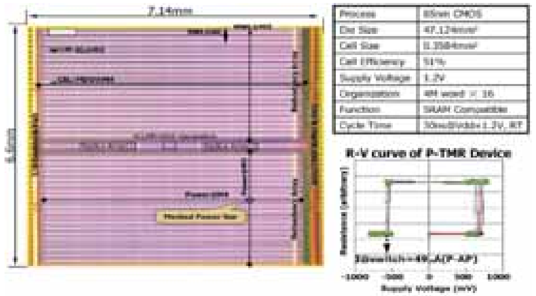


2007 Hitachi/Tohoku U. **(ISSCC 2007)**
- in-plane MTJ cells
- 2 Mb



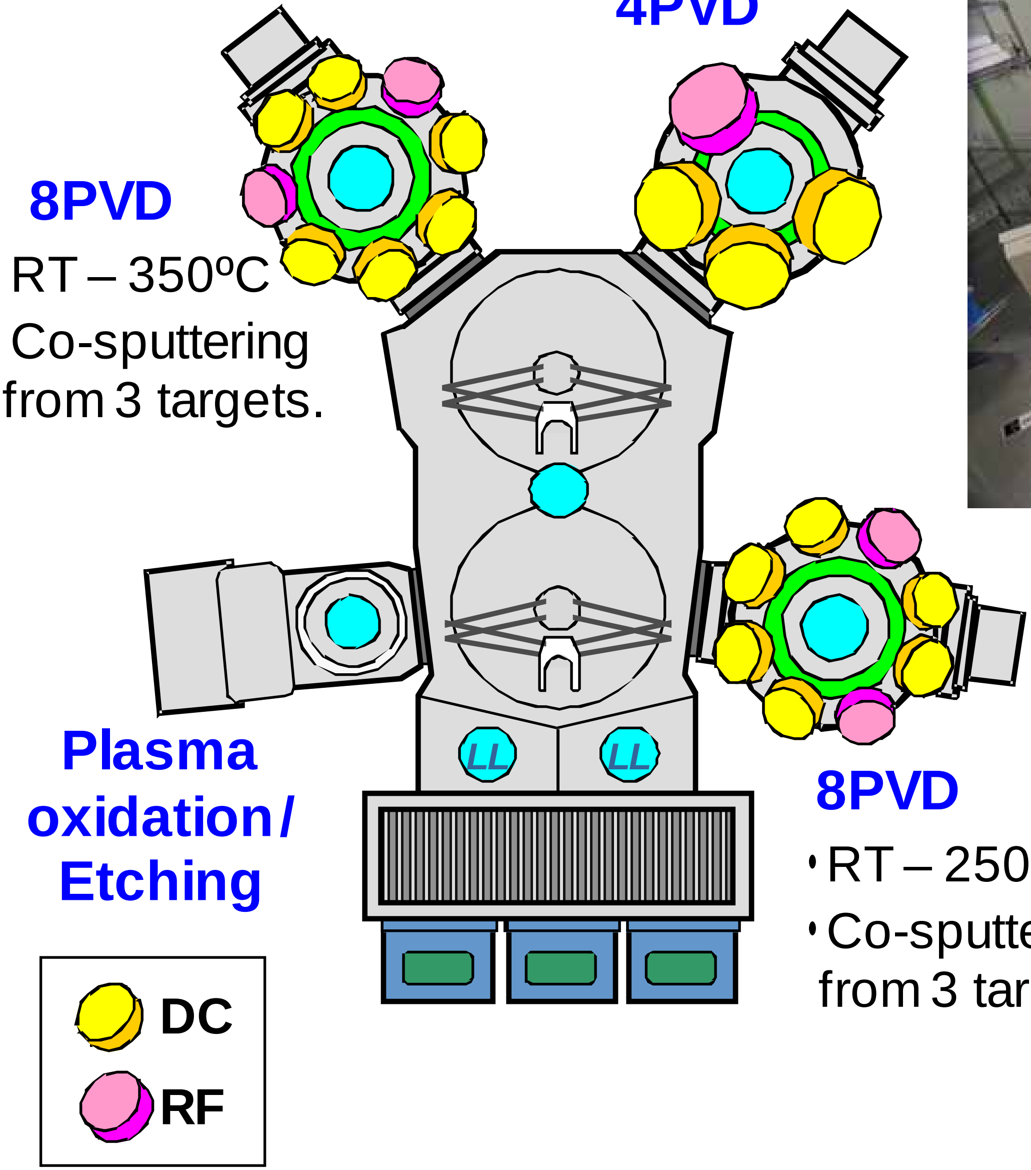
2008 Toshiba, AIST etc. **(IEDM 2008)**
- p-MTJ cells
- 1 kb

2010 Toshiba **(ISSCC 2010)**
- p-MTJ cells
- 64 Mb, 65 nm



Process	65nm CMOS
Die Size	47.12mm²
Cell Size	0.3584mm²
Cell Efficiency	51%
Supply Voltage	1.2V
Organization	4M word × 16
Function	SRAM Compatible
Cycle Time	30ns@Vdd=1.2V, RT

Canon-Anelva C-7100 sputtering system installed at AIST



4PVD

8PVD

- RT – 350ºC
- Co-sputtering from 3 targets.

Plasma oxidation / Etching

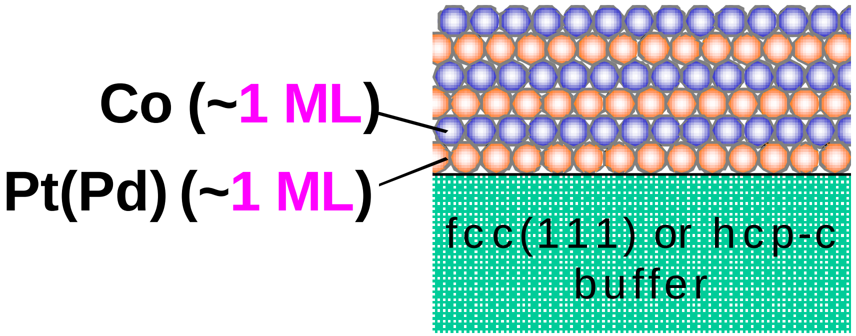
8PVD

- RT – 250ºC
- Co-sputtering from 3 targets.

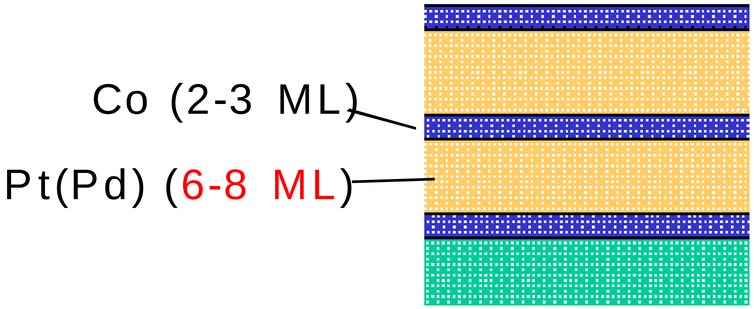
New perpendicular magnetic material : superlattice film

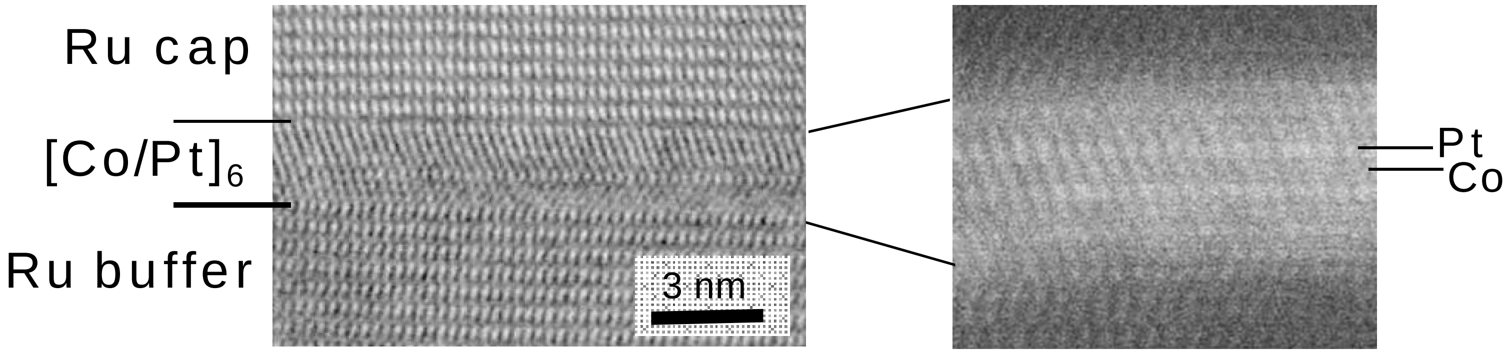
Yakushiji, SY *et al*., *Appl. Phys. Express* **3**, 053003 (2010).
Yakushiji, SY *et al*., *Appl. Phys. Lett.*, **97**, 232508 (2010).

fcc(111)-based superlattice film



***cf*. conventional magnetic multilayer with thick Pt(Pd) layers**

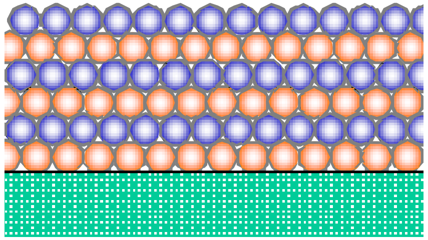


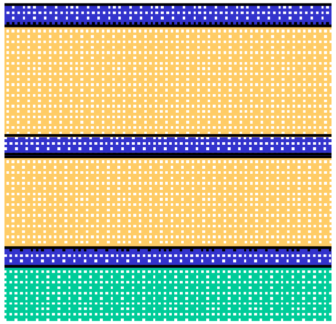


TEM

HAADF-STEM

Magnetic superlattice *vs.* conventional multilayer

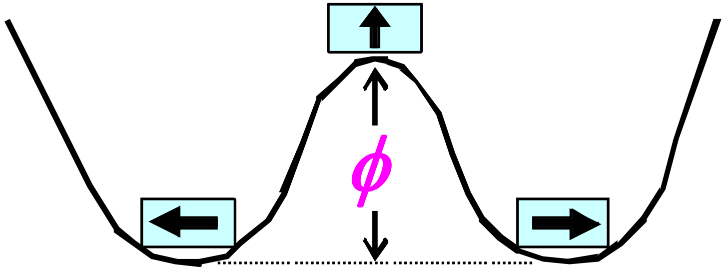




	Superlattice film	Conventional multilayer film
Thickness of total stack	Ultra-thin (**< 1.2 nm possible**)	Relatively thick **(> 3 nm)**
Structure	Artifical alloy	Mutilayer
K_u	Up to 12 Merg/cc (***tunable***)	~ 5 Merg/cc
Annealing stability	Very good > 370°C	Poor ~ 200°C
Origin of perp. magnetic anisotroy	Magneto-crystalline anisotropy	Interfacial anisotropy

Basic requirements for Gbit-scale Spin-RAM

➡ (1) $\Delta \equiv \phi / k_B T > 60 – 80$ for cell size < 50 nm



(2) MR ratio > 100 – 150% and low *RA* product

(3) Switching current density, $J_{C0} = 5\times10^5$ A/cm^2

(4) Switching speed **<** 20 ns to replace DRAM

< 1 – 3 ns to replace SRAM

Thermal stability of MTJ, $\Delta = K_u V / k_B T$

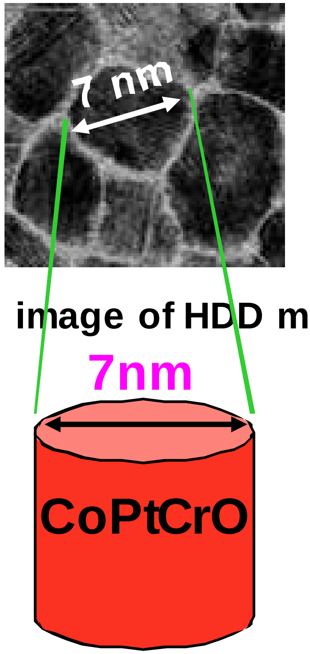
When cell size is smaller than 50 nm,
the uniaxial **shape anisotropy** cannot yield $\Delta > 60$.

MTJ with *in-plane* magnetization is hopeless !

Perpendicular magnetic recording

HDD

500 Gbit/inch^2



TEM image of HDD media

$\Delta > 80$ for the grain size < 10 nm

Basic requirements for Gbit-scale Spin-RAM

(1) $\Delta \equiv \phi/k_B T > 60-80$ for cell size < 50 nm

➡ (2) MR ratio > 100 – 150% and low *RA* product

(3) Switching current density, $J_{C0} = 5\times10^5$ A/cm^2

(4) Switching speed **<** 20 ns to replace DRAM
< 1 – 3 ns to replace SRAM

MRA ratio and *RA* product required for Gbit Spin-RAM

- **MR > 100 – 150%** is required to attain a high read-out signal (voltage) with a small read-out current.

- **Low *RA*** is required to satisfy the impedance matching with the pass transistor (CMOS).

The MTJ resistance should be about **10 kΩ**.

1 Gbit (F = 65 nm) → $RA < 30\ \Omega\mu\mathrm{m}^2$, MR > 100%

5 Gbit (F = 30 nm) → $RA < 7\ \Omega\mu\mathrm{m}^2$, MR > 100%

10 Gbit (F = 20 nm) → $RA < 3.5\ \Omega\mu\mathrm{m}^2$, MR > 100%

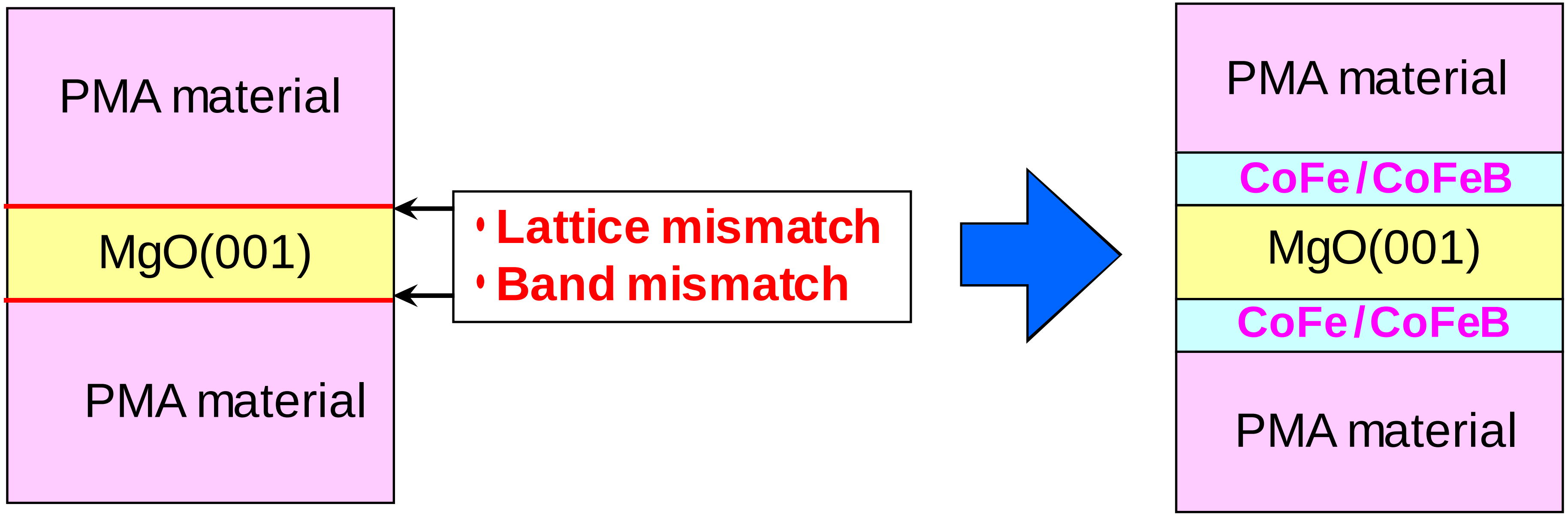
How to achieve high MR with perpendicular electrodes ?

<Issues>

(i) The Δ_1 band of perpendicular materials are not fully spin-polarized.

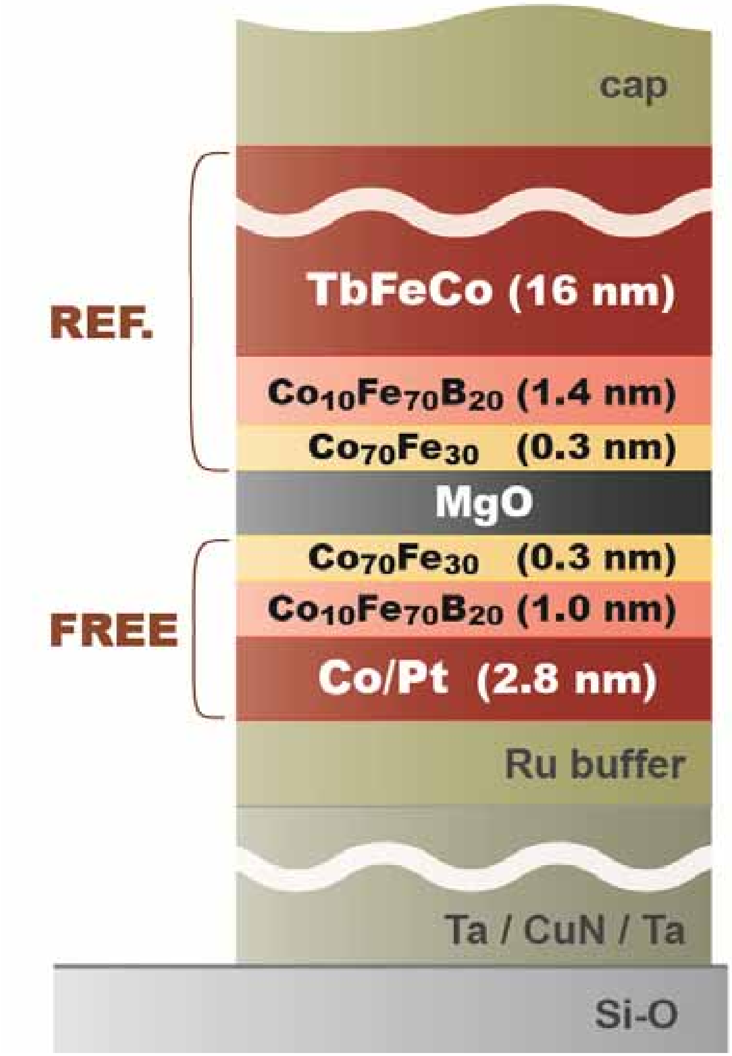
(ii) Lattice matching between perp. materials and MgO(001) is not good.

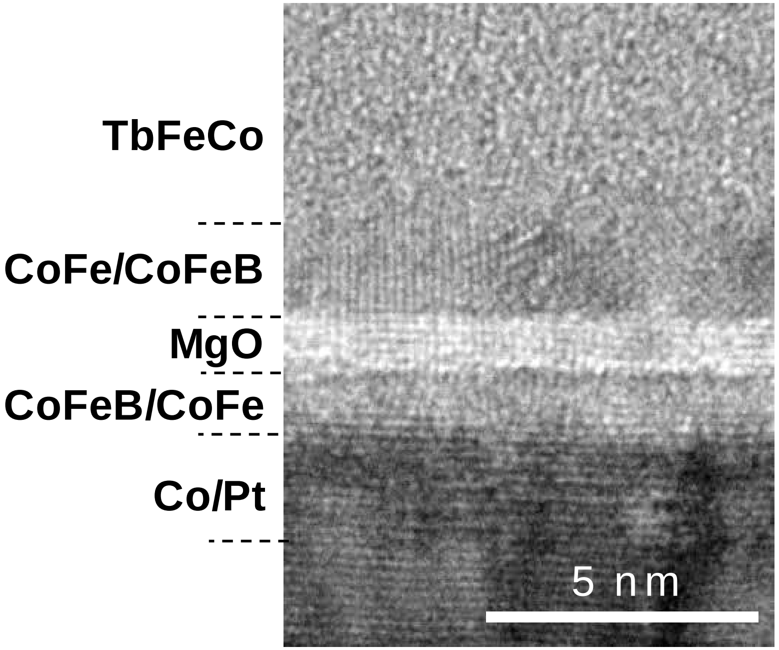
Insertion of CoFeB between MgO and PMA layer



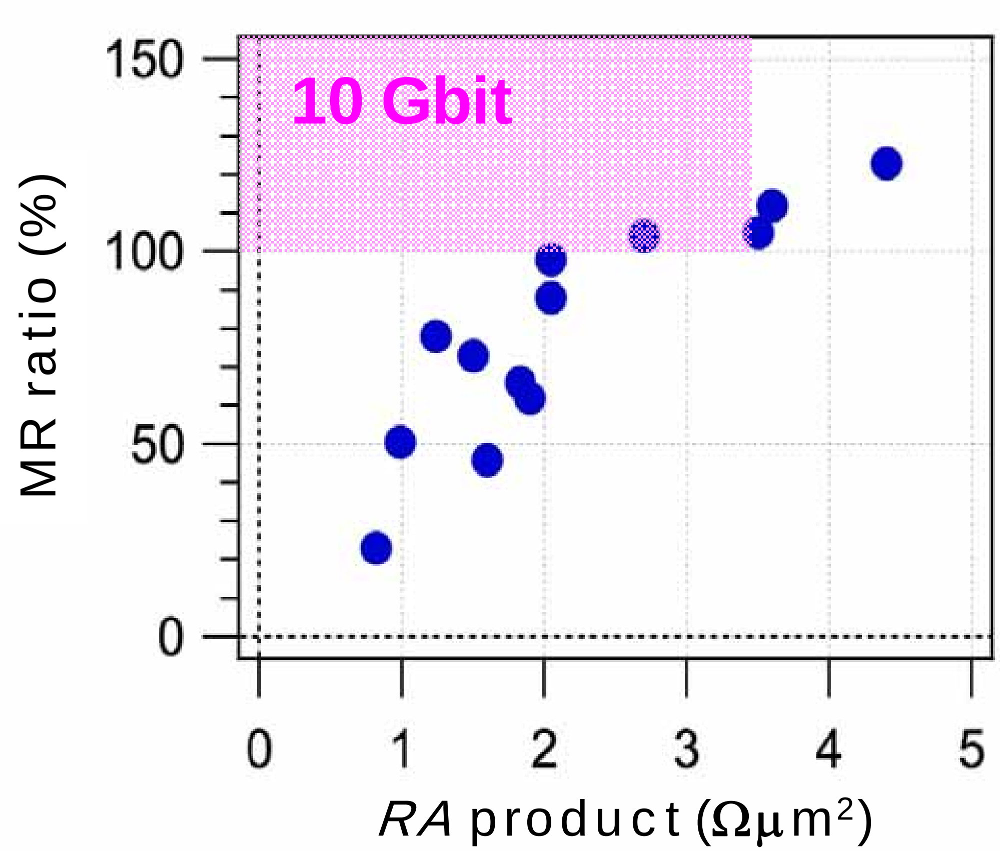
Typical structure of p-MgO-MTJ

Yakushiji, SY *et al*., *Appl. Phys. Express* **3**, 053003 (2010).
Yakushiji, SY *et al*., *Appl. Phys. Lett*., **97**, 232508 (2010).





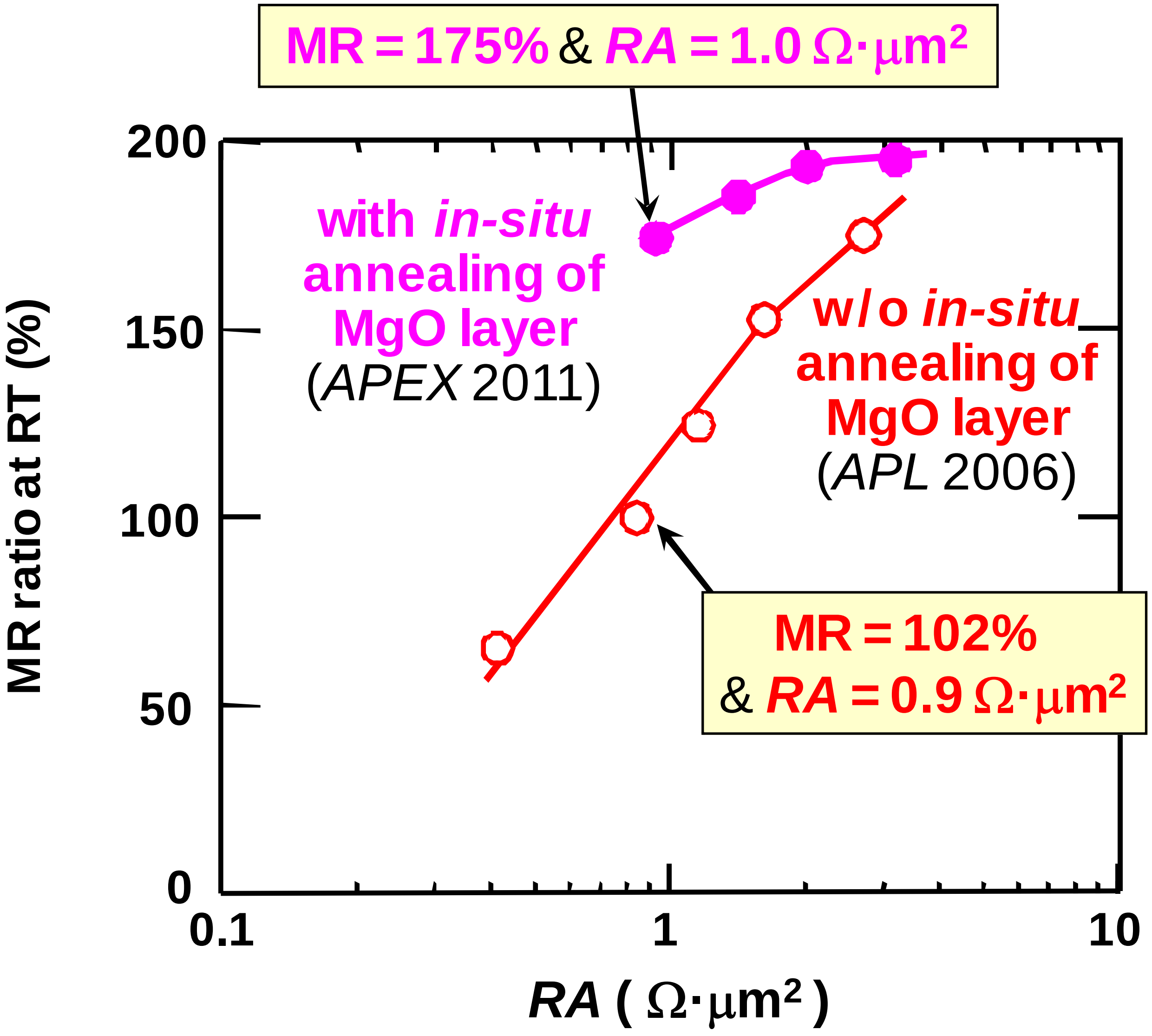
Can we simultaneously attain high MR & low *RA* ? – *Yes !*



The p-MTJs basically satisfy the requirements for 10 Gbit Spin-RAM **(*RA* < 3.5 Ωμm², MR > 100%)**.

The best properties attained with *in-plane* magnetization

Nagamine, SY *et al*., *Appl. Phys. Lett.* **89**, 162507 (2006).
Maehara, SY *et al*., *Appl. Phys. Express* **4**, 033002 (2011).



MR = 175% & *RA* = 1.0 Ω·μm²

with *in-situ* annealing of MgO layer (*APEX* 2011)

w/o *in-situ* annealing of MgO layer (*APL* 2006)

MR = 102% & *RA* = 0.9 Ω·μm²

Basic requirements for Gbit-scale Spin-RAM

(1) $\Delta \equiv \phi / k_B T > 60 – 80$ for cell size < 50 nm

(2) MR ratio > 100 – 150% and low *RA* product

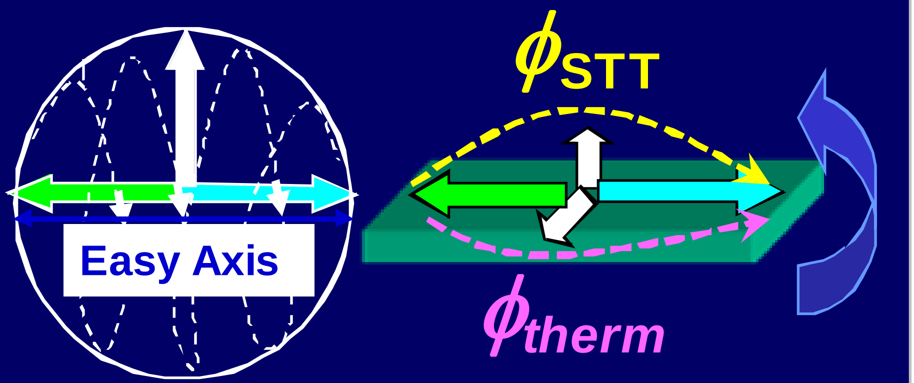
⇨ (3) Switching current density, $J_{C0} = 5 \times 10^5$ A/cm^2

(4) Switching speed **<** 20 ns to replace DRAM
< 1 – 3 ns to replace SRAM

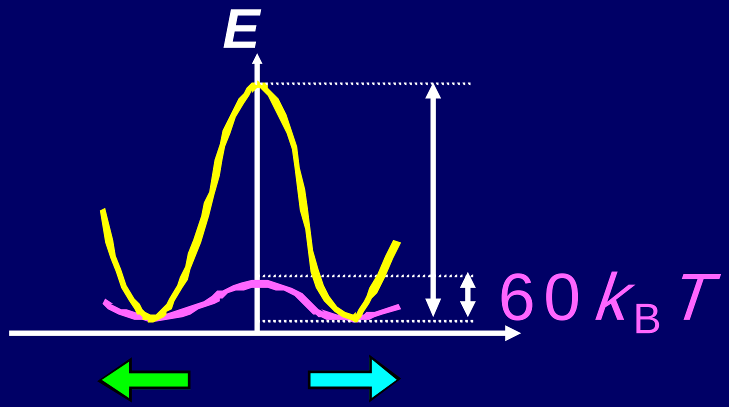
Potential barrier for magnetization switching

In-plane

$$Ic = \frac{2e}{\hbar}\frac{\alpha_{damp}}{g(\theta)}\left[2\Delta_{therm}\,k_BT + 2\pi M_s{}^2 tF^2\right]$$

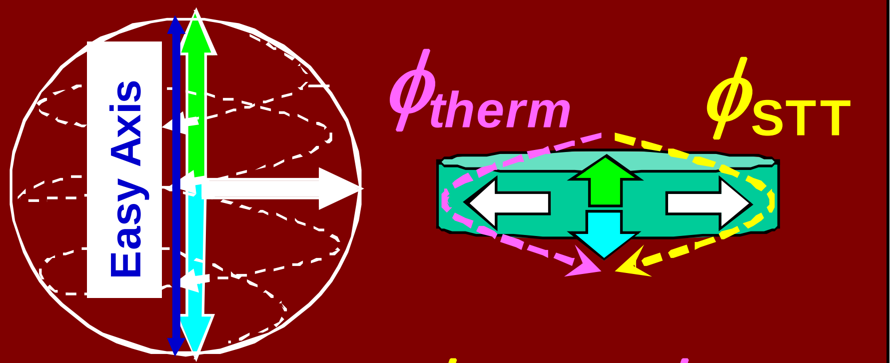


$$\phi_{STT} \sim 30\,\phi_{therm}$$

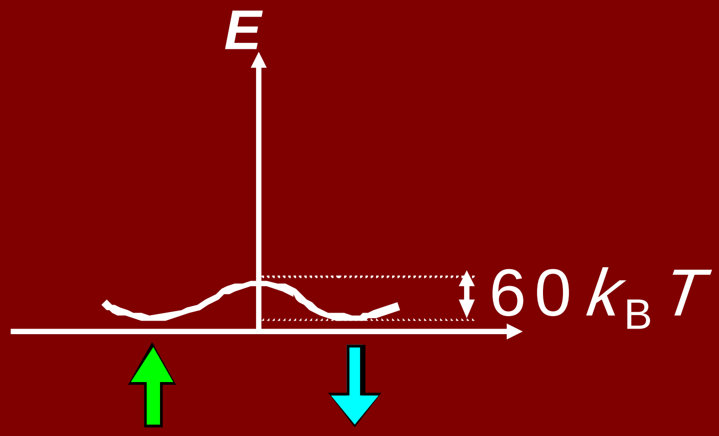


Perpendicular

$$Ic = \frac{2e}{\hbar}\frac{\alpha_{damp}}{g(\theta)}\left[2\Delta_{therm}\,k_BT\right]$$

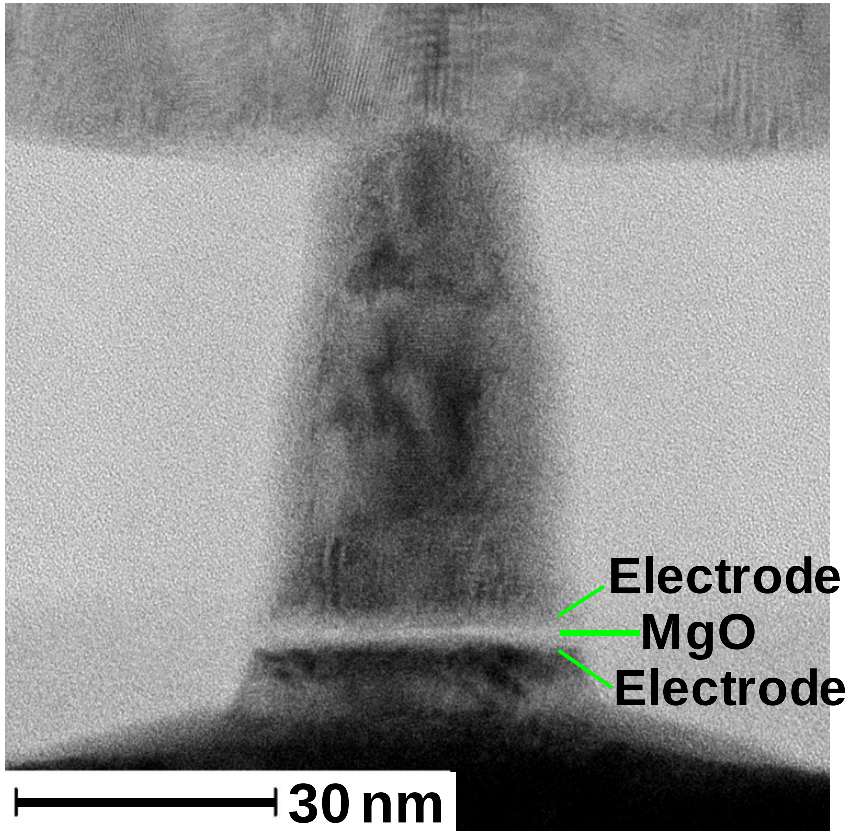


$$\phi_{STT} \sim \phi_{therm}$$

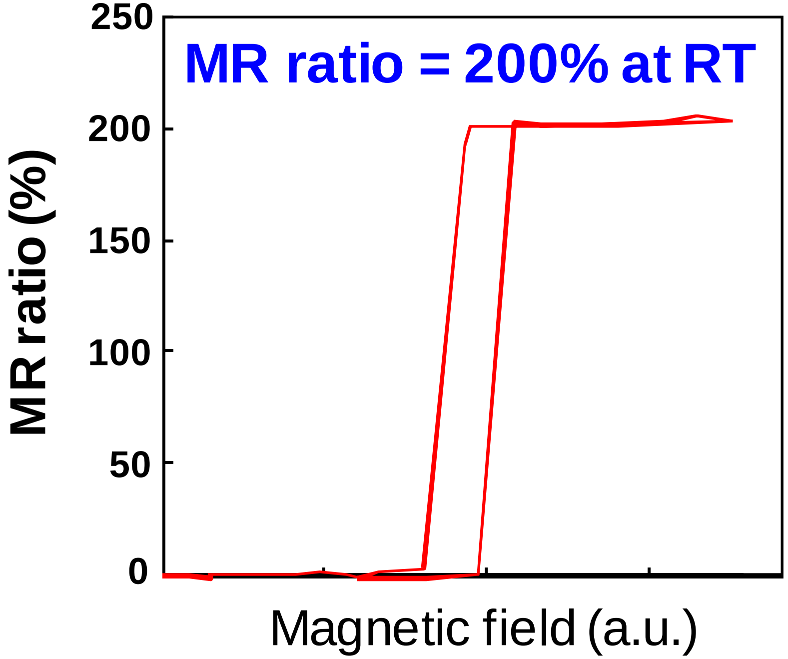


Our latest data **(Courtesy of Toshiba)**

NEDO – Spintronics Non-Volatile Devices Project
(Toshiba, AIST, *etc*.)



ϕ 30 nm MgO-MTJ with perp. magnetization



$J_{c0} = 5\times10^5$ A/cm^2

$\Delta = 45$

Basic requirements for Gbit-scale Spin-RAM

(1) $\Delta \equiv \phi / k_B T > 60-80$ for cell size < 50 nm

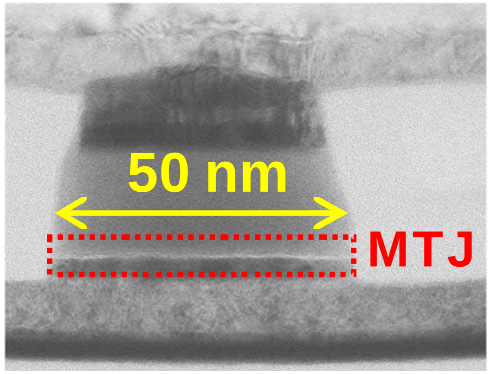
(2) MR ratio > 100 – 150% and low *RA* product

(3) Switching current density, $J_{C0} = 5\times10^{5}$ A/cm^{2}

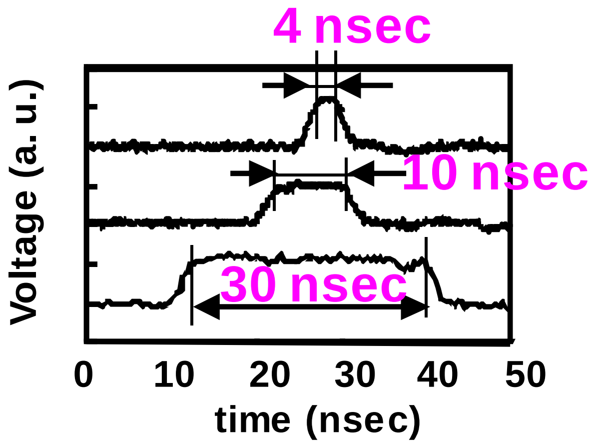
⇨ (4) Switching speed < 20 ns to replace DRAM
< 1 – 3 ns to replace SRAM

Demonstration of high-speed switching

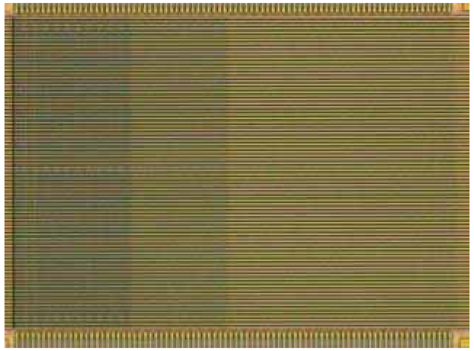
Kishi, SY *et al*. *IEDM 2008*, 12.6.
(Toshiba, AIST, *etc*.)



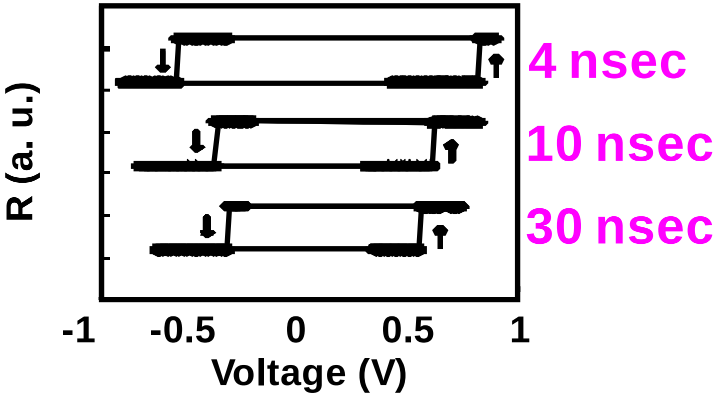
TEM image



Write pulses



CMOS-integrated
MTJ array

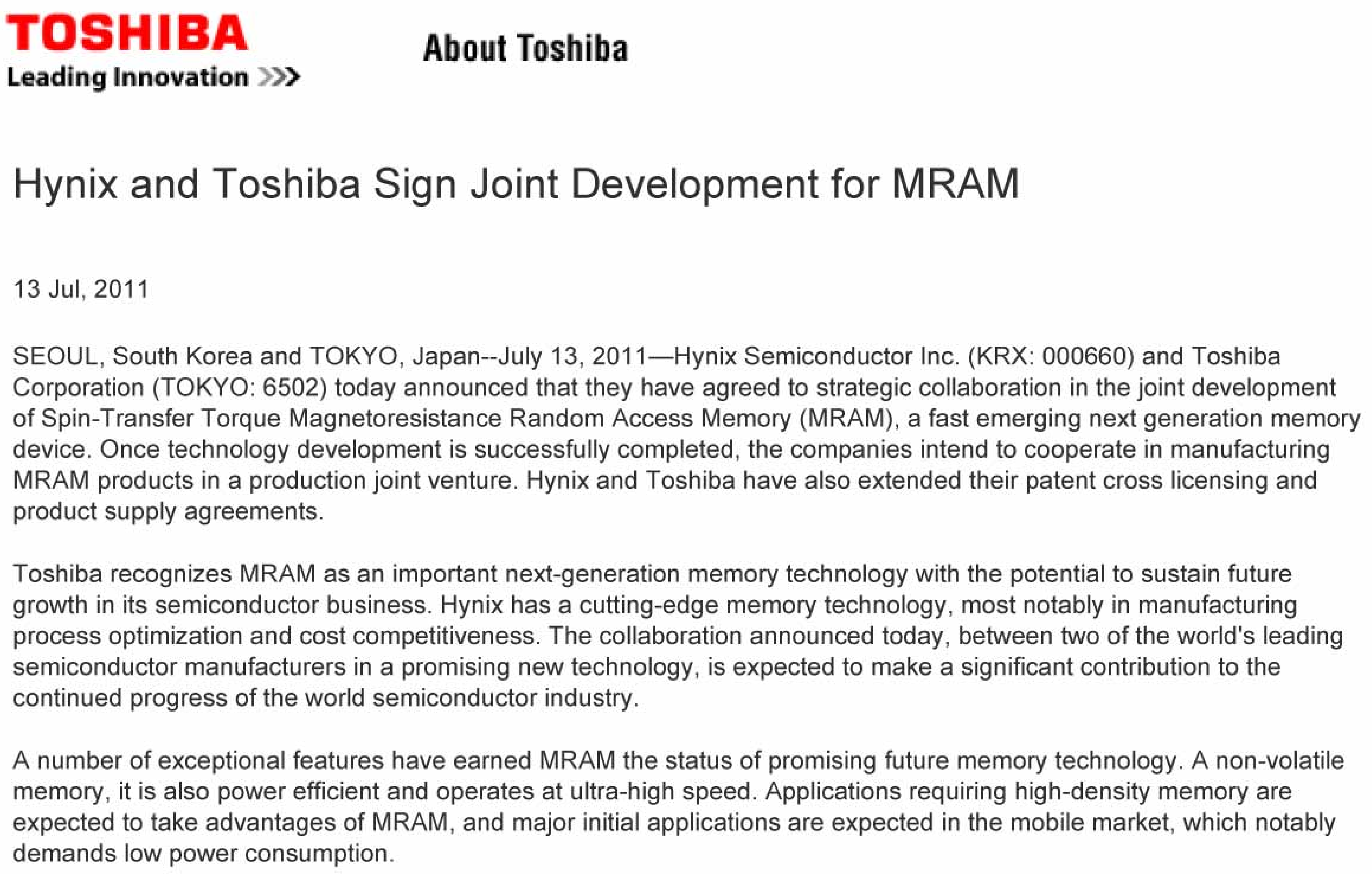


Spin-torque writing

Summary on Spin-RAM

		Perp. MTJ	**In-plane MTJ**
WRITE (I_c)	**<** drive current of CMOS	○	×
READ (MR & *RA*)	MR ratio > 100–150% & low *RA*	○	◎
STABILITY Δ for MTJ size < 50 nm	$\Delta > 60 – 80$	○	×
SPEED	**<** 20 ns writing	○	○
ENDURANCE	**>** 10^{16} write cycles	○	○

Toshiba – Hynix alliance to commercialize Spin-RAM



TOSHIBA
Leading Innovation >>>

About Toshiba

Hynix and Toshiba Sign Joint Development for MRAM

13 Jul, 2011

SEOUL, South Korea and TOKYO, Japan--July 13, 2011—Hynix Semiconductor Inc. (KRX: 000660) and Toshiba Corporation (TOKYO: 6502) today announced that they have agreed to strategic collaboration in the joint development of Spin-Transfer Torque Magnetoresistance Random Access Memory (MRAM), a fast emerging next generation memory device. Once technology development is successfully completed, the companies intend to cooperate in manufacturing MRAM products in a production joint venture. Hynix and Toshiba have also extended their patent cross licensing and product supply agreements.

Toshiba recognizes MRAM as an important next-generation memory technology with the potential to sustain future growth in its semiconductor business. Hynix has a cutting-edge memory technology, most notably in manufacturing process optimization and cost competitiveness. The collaboration announced today, between two of the world's leading semiconductor manufacturers in a promising new technology, is expected to make a significant contribution to the continued progress of the world semiconductor industry.

A number of exceptional features have earned MRAM the status of promising future memory technology. A non-volatile memory, it is also power efficient and operates at ultra-high speed. Applications requiring high-density memory are expected to take advantages of MRAM, and major initial applications are expected in the mobile market, which notably demands low power consumption.

http://www.toshiba.co.jp/about/press/2011_07/pr1302.htm

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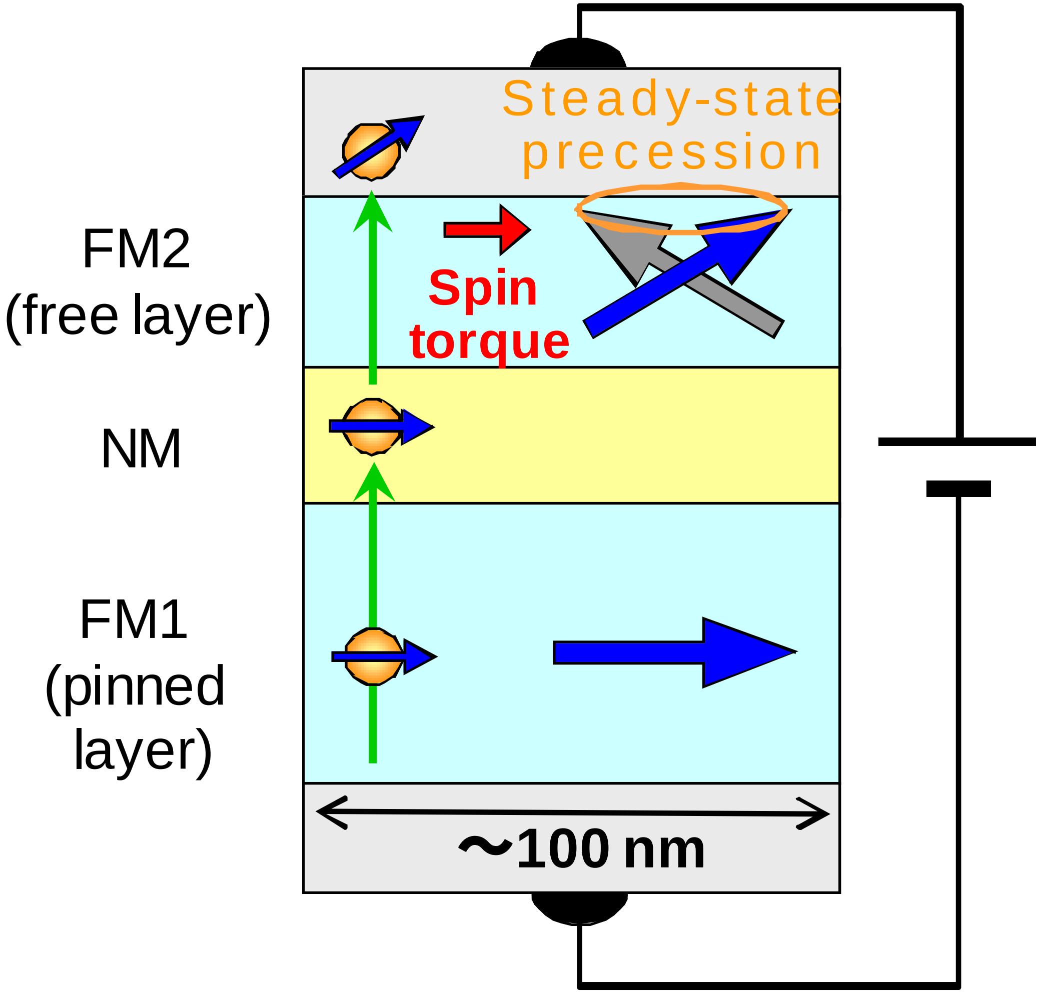
(3) Spin-transfer torque (STT)

- Physics of spin-transfer torque
- Spin-transfer torque MRAM (STT-RAM or Spin-RAM)
- Microwave applications

Steady-state precession induced by spin torque



DC current & voltage

Spin torque

Steady-state precession can be induced by adjusting *I* and *H*.
(ferromag. resonance (FMR))

Giant MR ratio

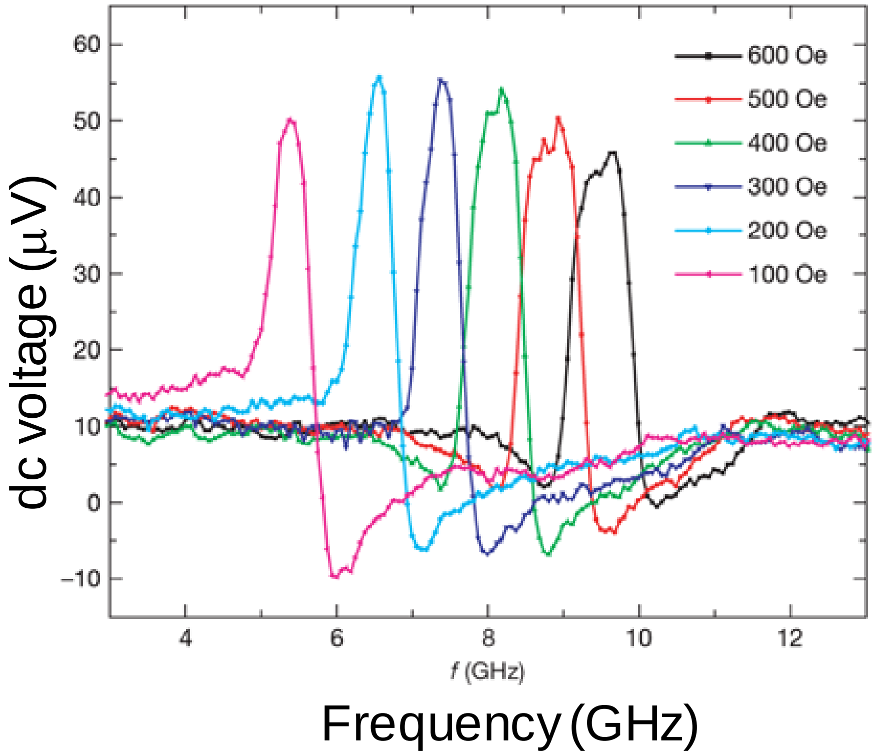
AC current & voltage
(FMR frequency)

MgO-MTJ is expected to act as a microwave oscillator and detector.

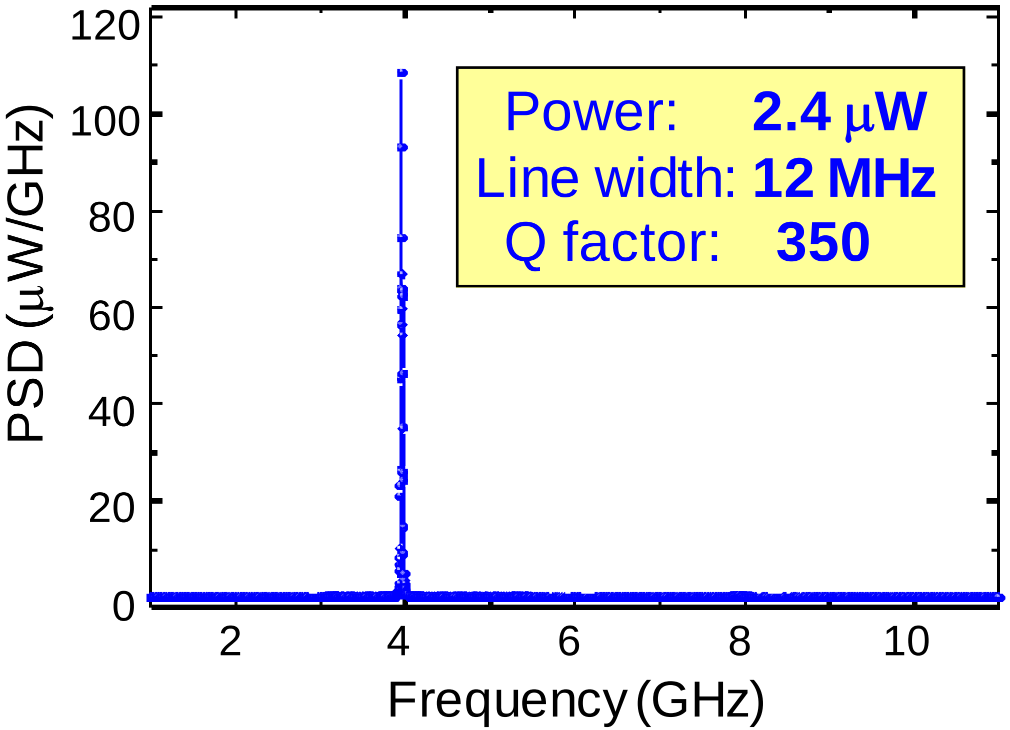
Microwave power ∝ (MR ratio)^2

Microwave functions of MgO-based MTJs

Tulapurkar, SY, *Nature* **438**, 339 (2005).
Kubota, SY *et al*., *Nature Phys.* **4**, 37 (2008).
Deac, SY *et al*., *Nature Physic* **4**, 803-809 (2008).
Dussaux, SY *et al*.**,** *Nature Comm.* **1**, 8 (2010).
H. Maehara, SY *et al*., *MMM 2010.*



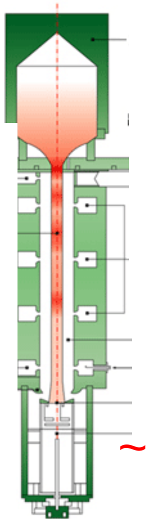
Spin-torque diode effect
(microwave detection)



Spin-torque oscillator (STO)
(microwave emission)

Advantages of STO over conventional microwave oscillators

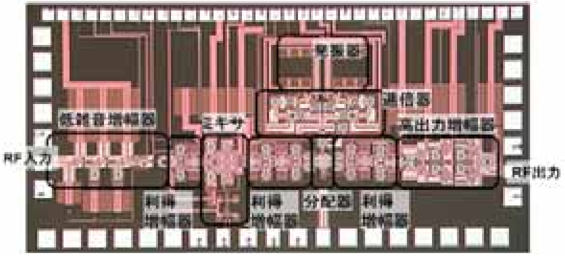
Klystron



Gunn diode oscillator

~10 cm ~1 cm

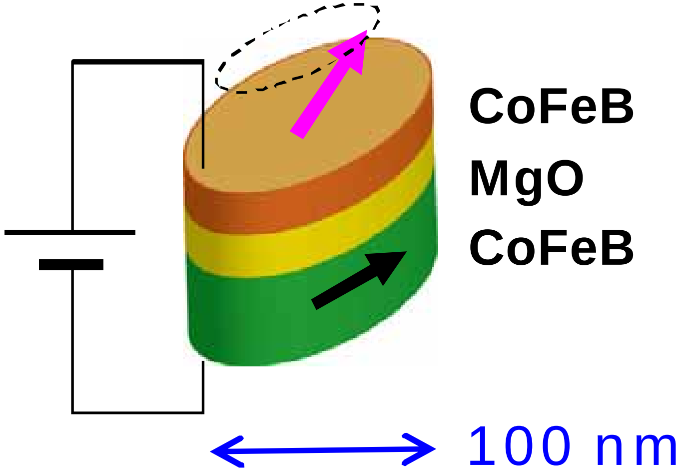
Large!



MMIC: low efficiency

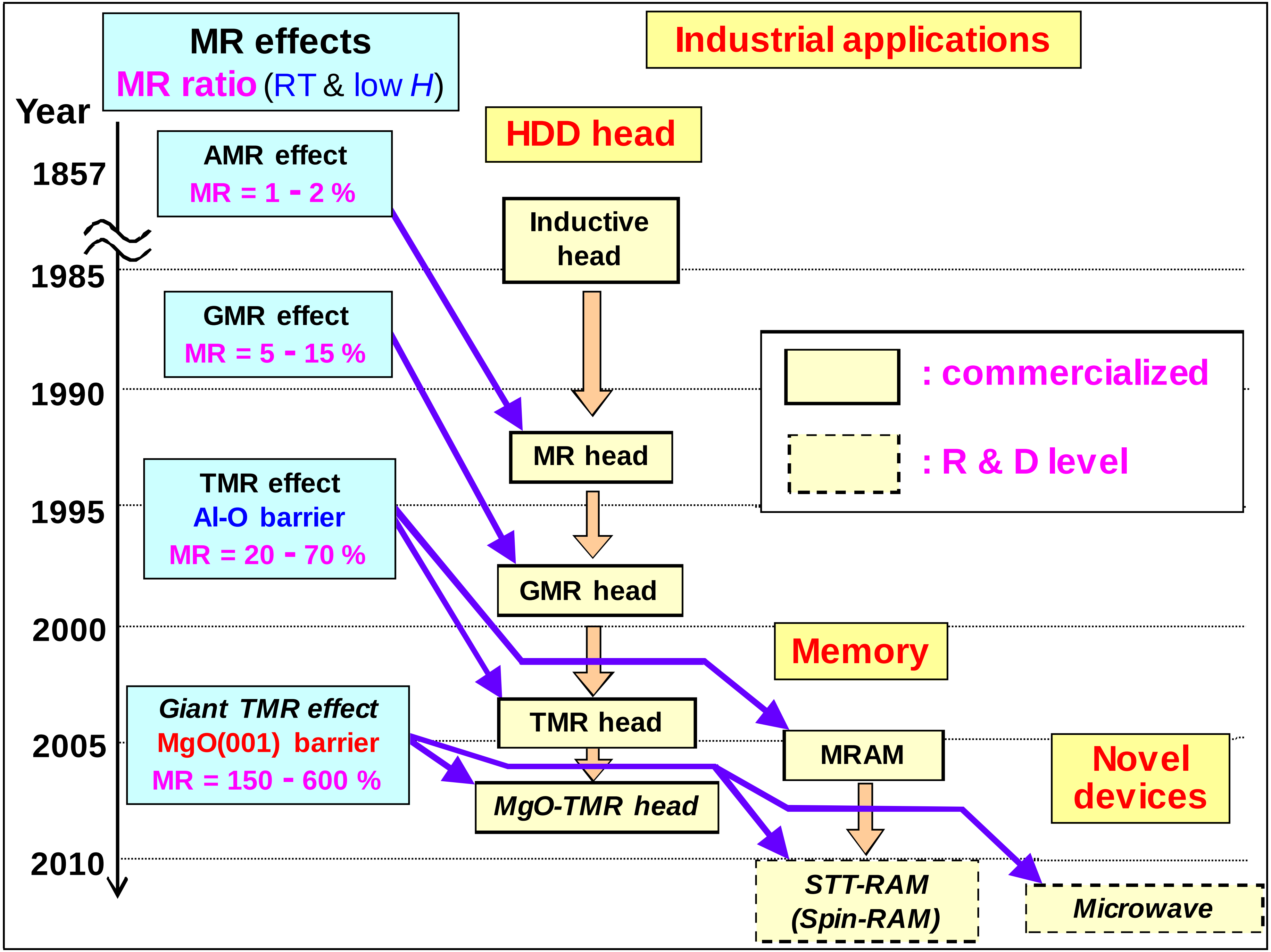
MMIC: Monolithic Microwave IC

MgO-MTJ-based STO



Ferromagnetic resonance
⇒ No resonance circuit is necessary.

Small **(~100 nm)**, cheap,
easily integrated in Silicon LSI



MR effects

MR ratio (RT & low *H*)

Industrial applications

Year

1857

1985

1990

1995

2000

2005

2010

AMR effect
MR = 1 - 2 %

GMR effect
MR = 5 - 15 %

TMR effect
Al-O barrier
MR = 20 - 70 %

Giant TMR effect
MgO(001) barrier
MR = 150 - 600 %

HDD head

Inductive head

MR head

GMR head

TMR head

MgO-TMR head

Memory

MRAM

STT-RAM (Spin-RAM)

Novel devices

Microwave

▭ **: commercialized**

⬚ **: R & D level**