Magnetoresistance and spin-transfer torque in magnetic tunnel junctions

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IEEE Distinguished Lecturer 2012

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IEEE Magnetics Society

IEEE

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FIELD OF INTEREST

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PUBLICATIONS

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

For more information and to join visit
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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

Intermag 2013 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 Corp. (H. Yoda)
(STT-MRAM)

Canon Anelva Corp.
(sputtering deposition process)

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

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

Outline

(1) Spintronics

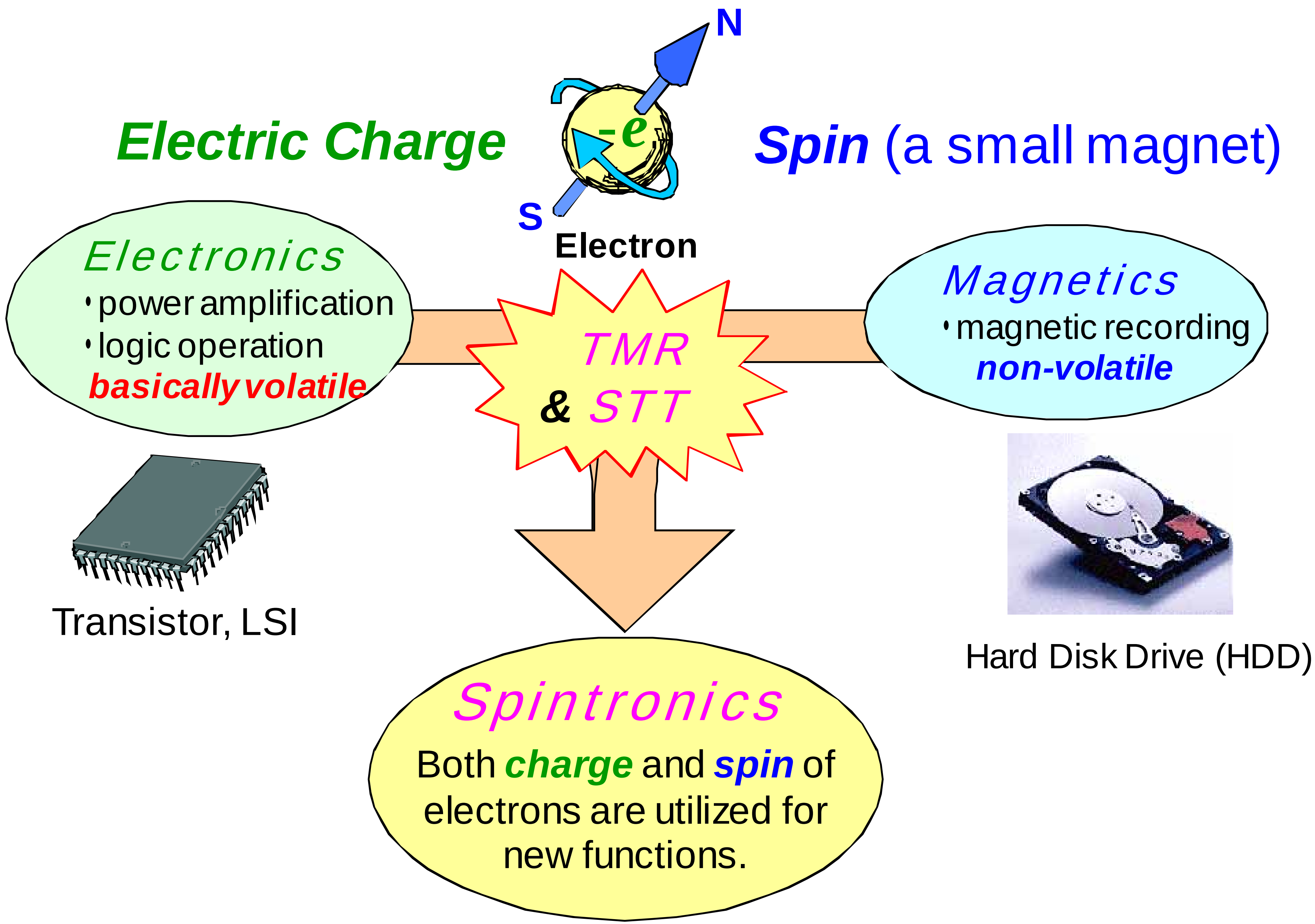
(2) Tunnel magnetoresistance (TMR)

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

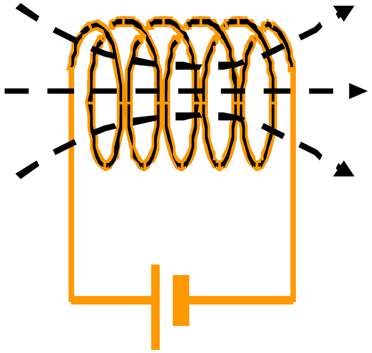
(3) Spin-transfer torque (STT)

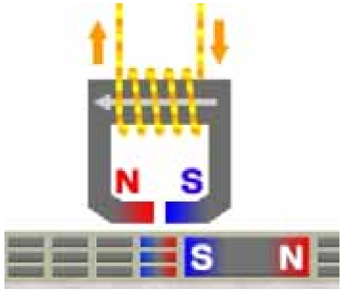
- Physics of spin-transfer torque
- Spin-transfer torque MRAM (STT-RAM or Spin-RAM)
- Microwave applications

What is *spintronics*?



Difference between conventional magnetics and spintronics ?

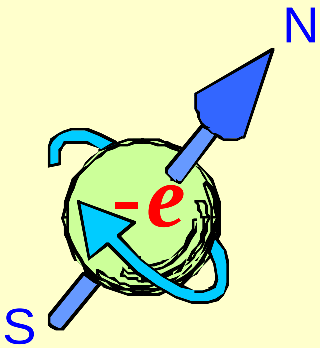




Magnetics

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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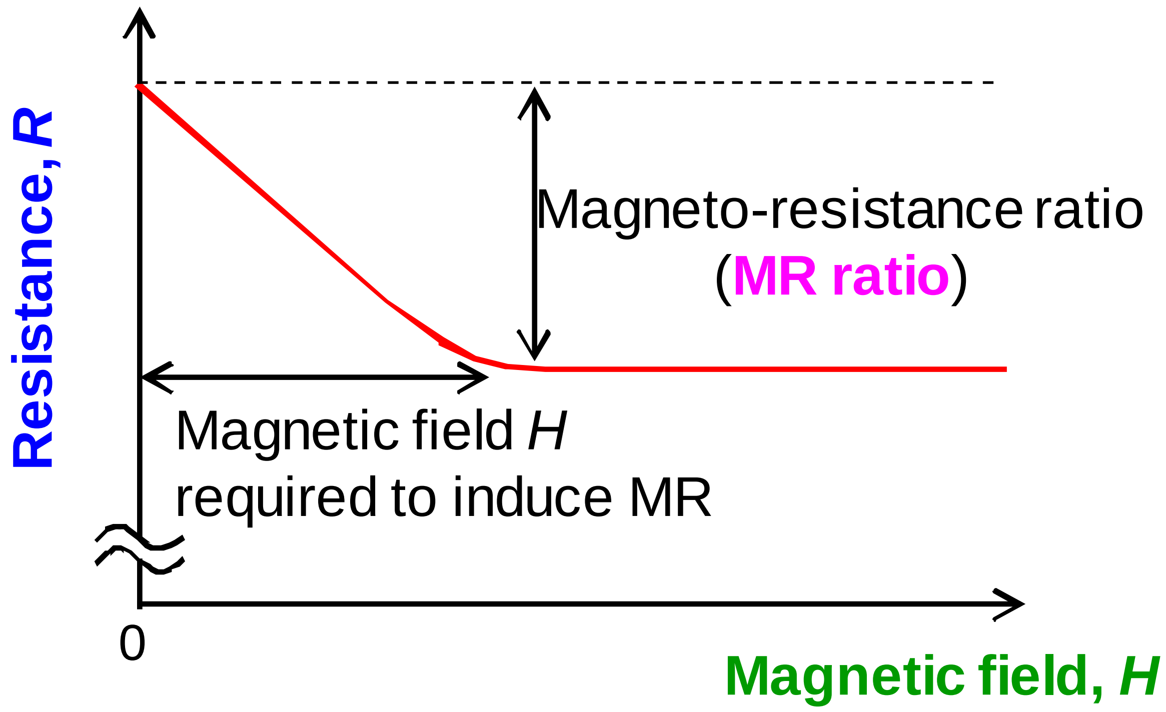
Magneto-Resistance (MR)

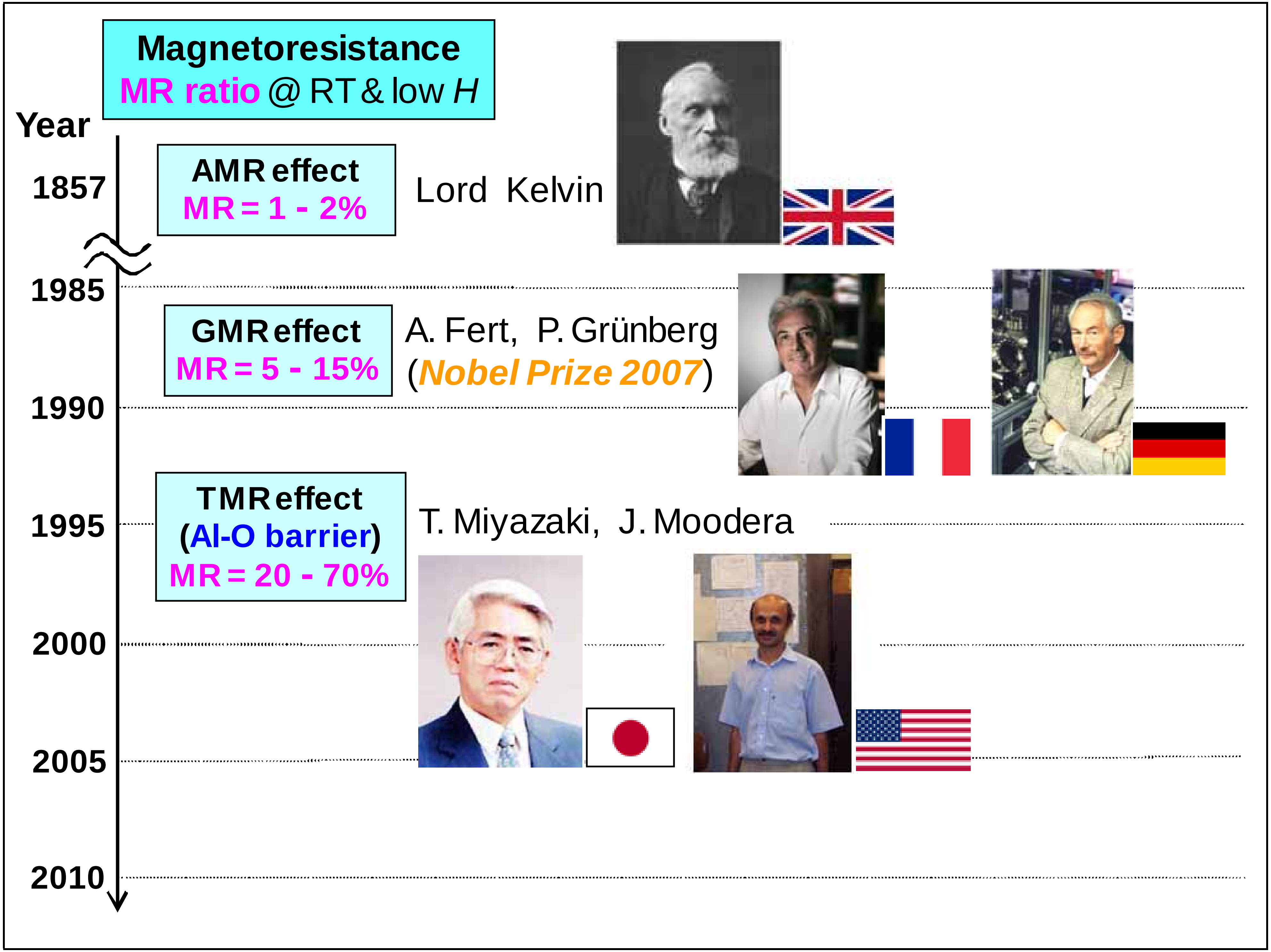
Change in electric resistance induced by magnetic field.



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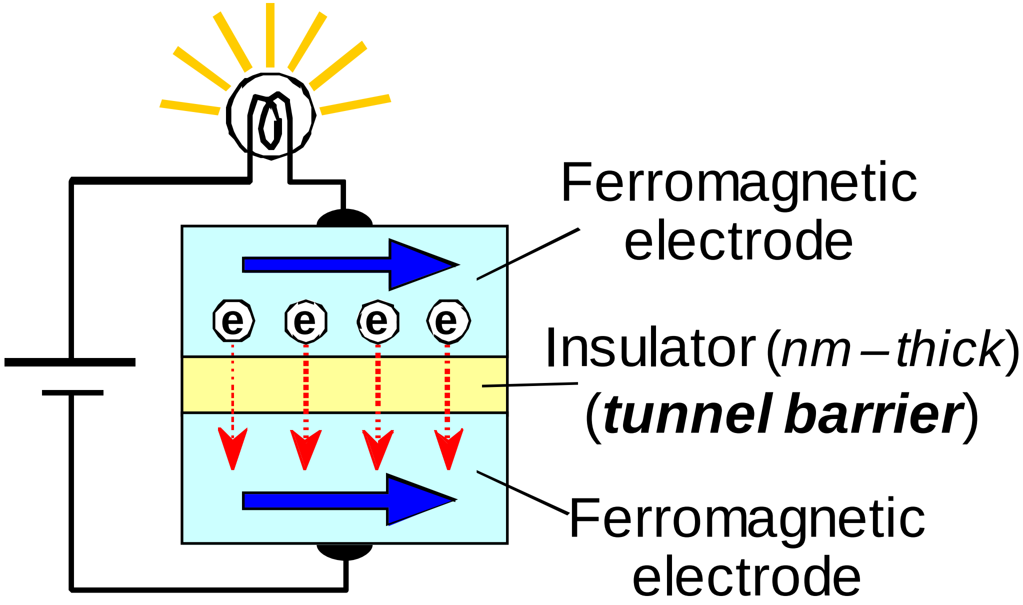
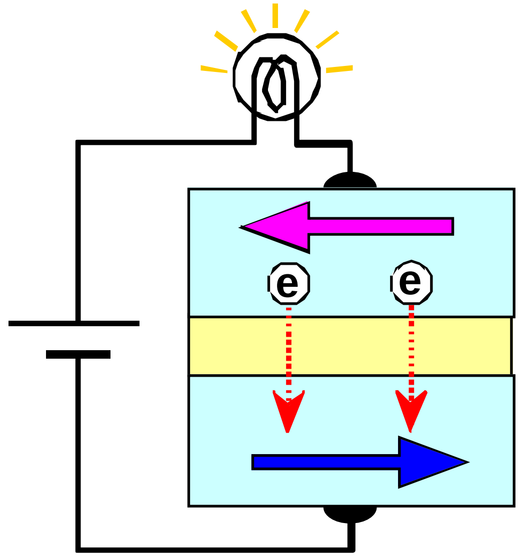
Tunnel MagnetoResistance (**TMR**) effect in magnetic tunnel junction (**MTJ**)



Parallel (P) state

Resistance $\boldsymbol{R}_{\mathbf{P}}$: **low**



Antiparallel (AP) state

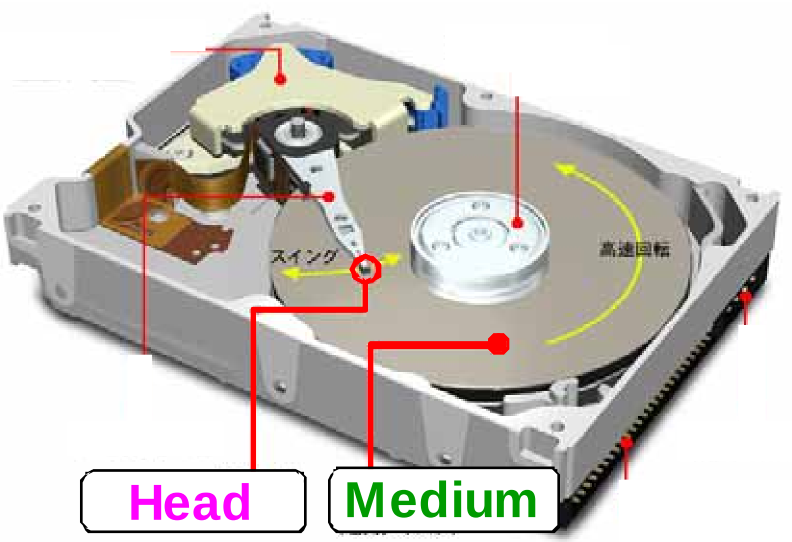
Resistance $\boldsymbol{R}_{\mathbf{AP}}$: **high**

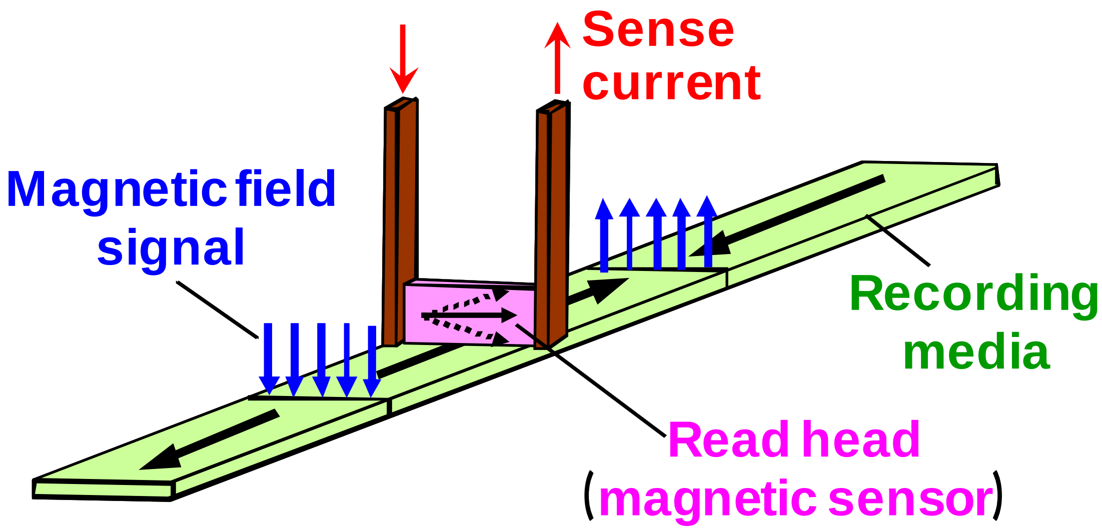
MR ratio $\equiv (R_{AP} - R_P) / R_P \times 100\%$ (performance index)

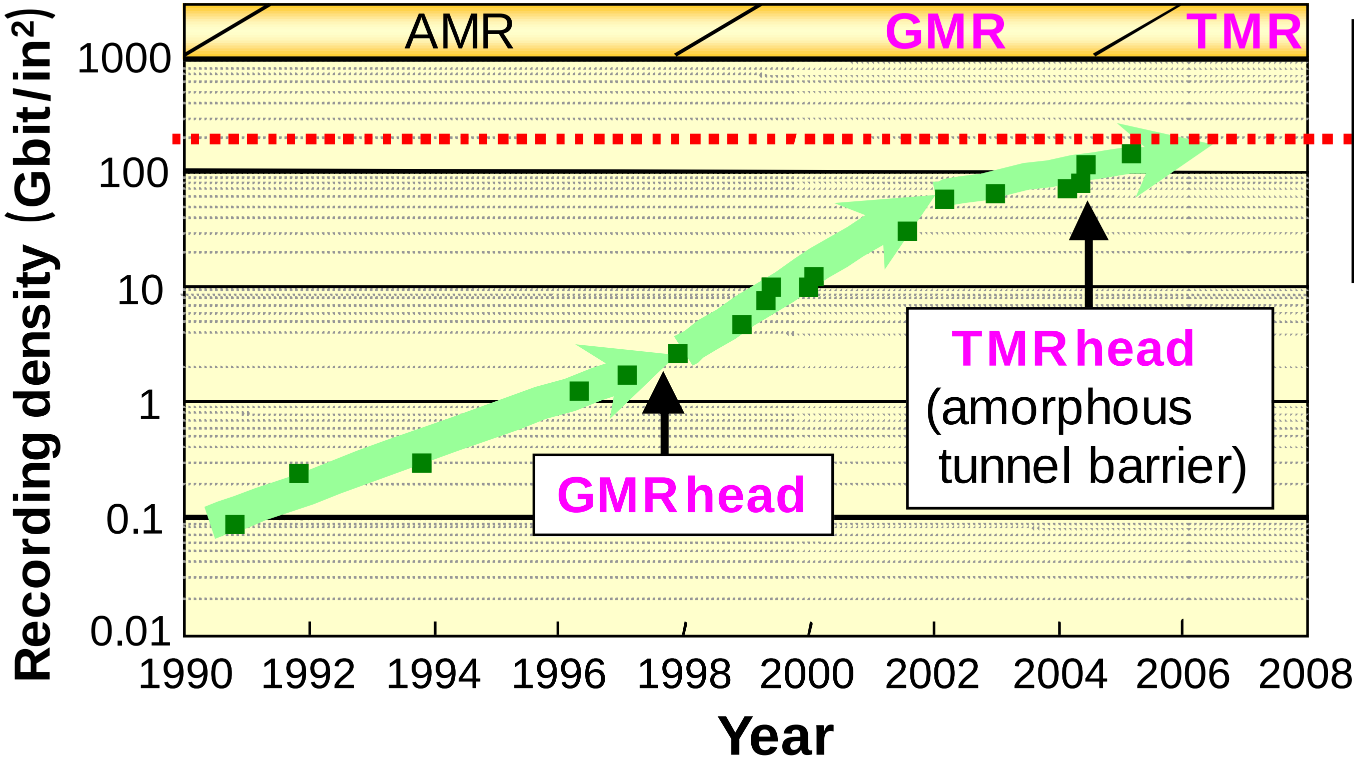
3d ferromagnet
Amorphous Al-O
3d ferromagnet

→ **MR ratios of 20 – 70% at RT**

Read head of hard disk drive (HDD)





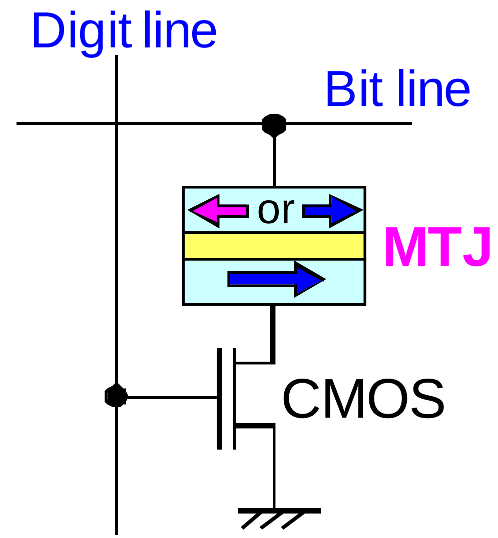


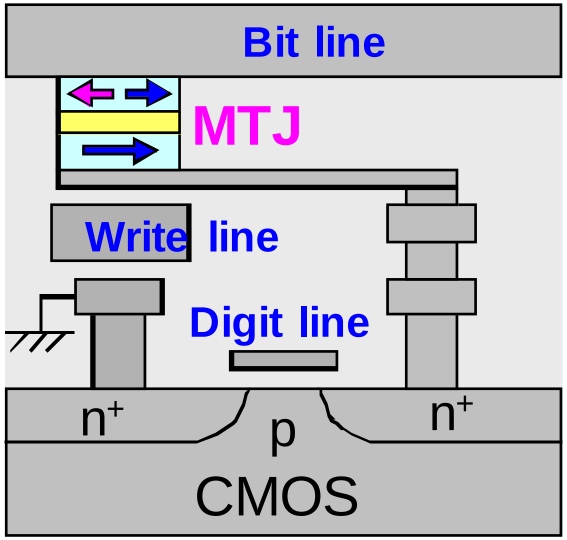
Higher MR ratio is required for > 200 Gbit/inch^2.

Non-volatile Magnetoresistive Random Access Memory (MRAM)

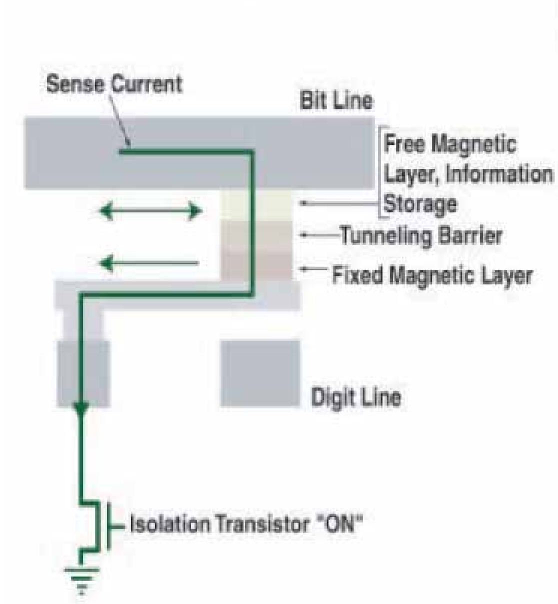
Parallel：“0”
Antiparallel：“1”

Non-volatile
magnetic memory

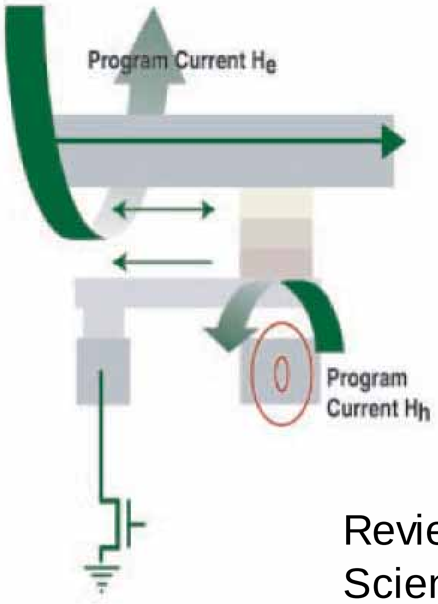




Read out

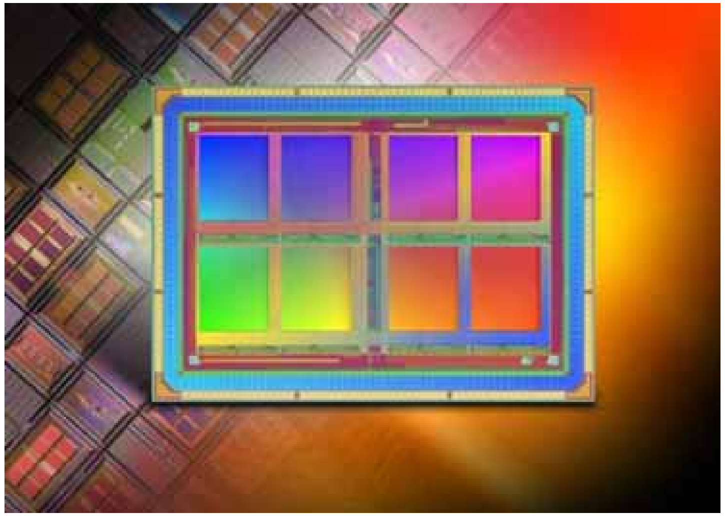


Writing



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)

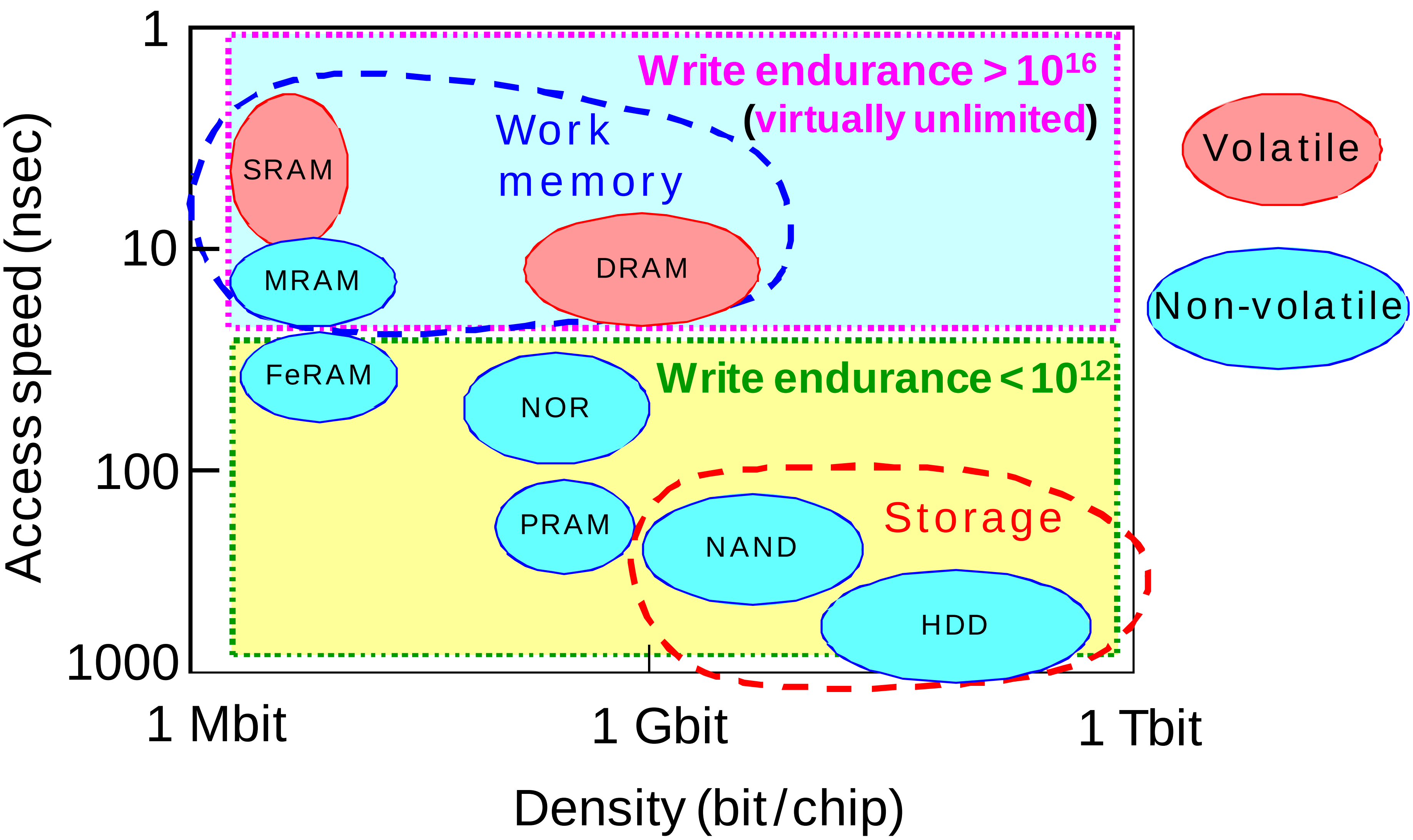
<Advantages>

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

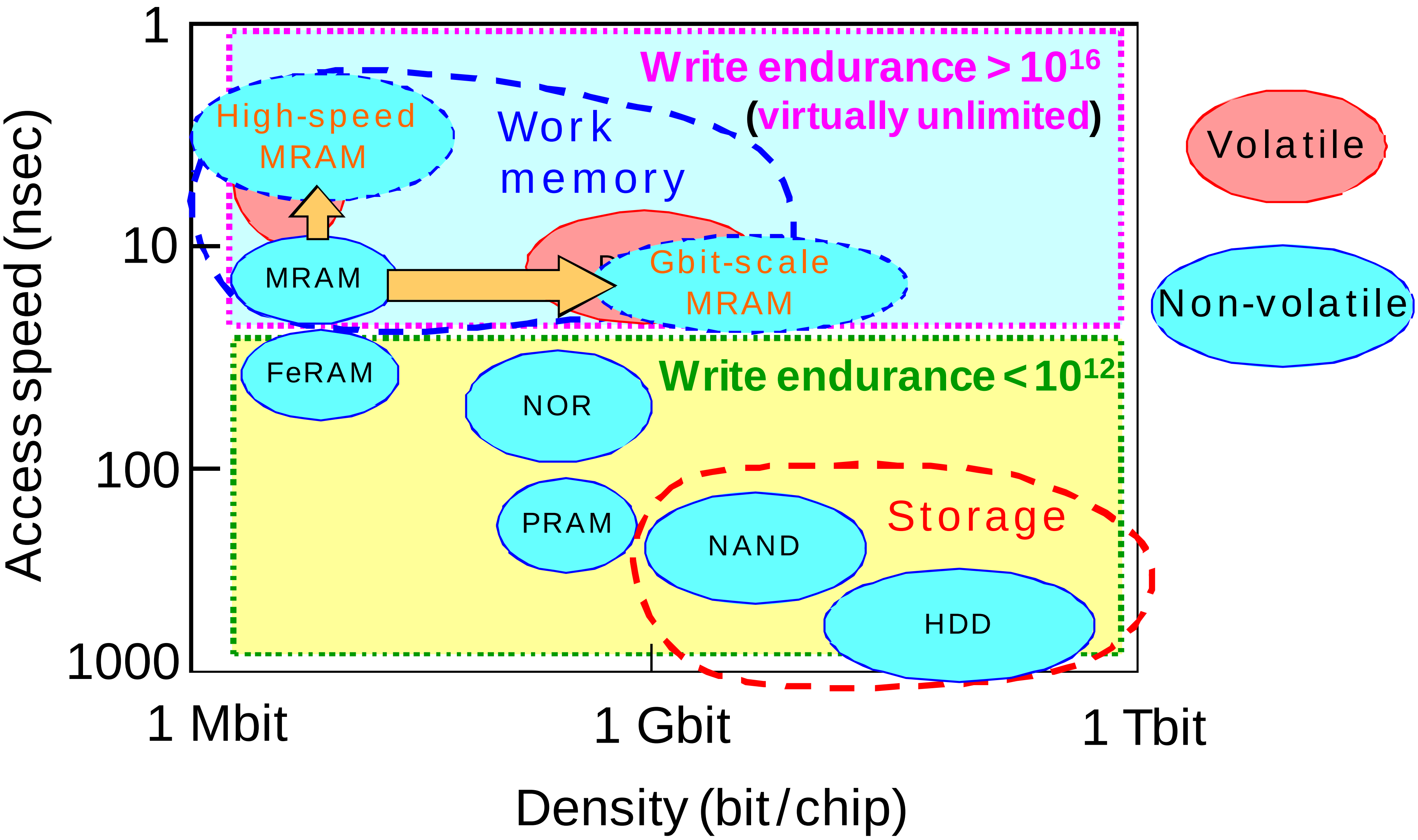
<Disadvantage>

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

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



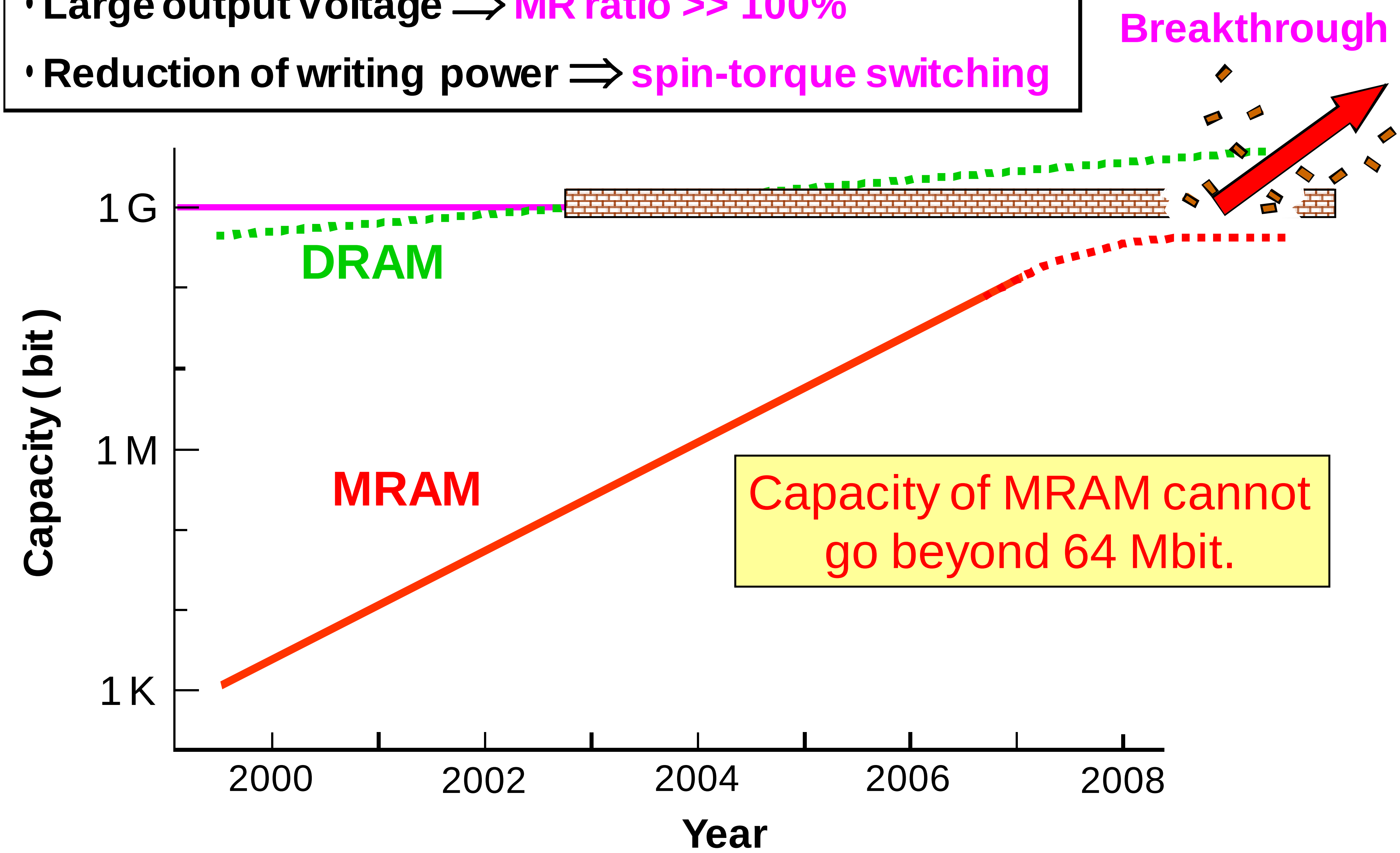
Three important properties for memory device: speed, density, and write endurance

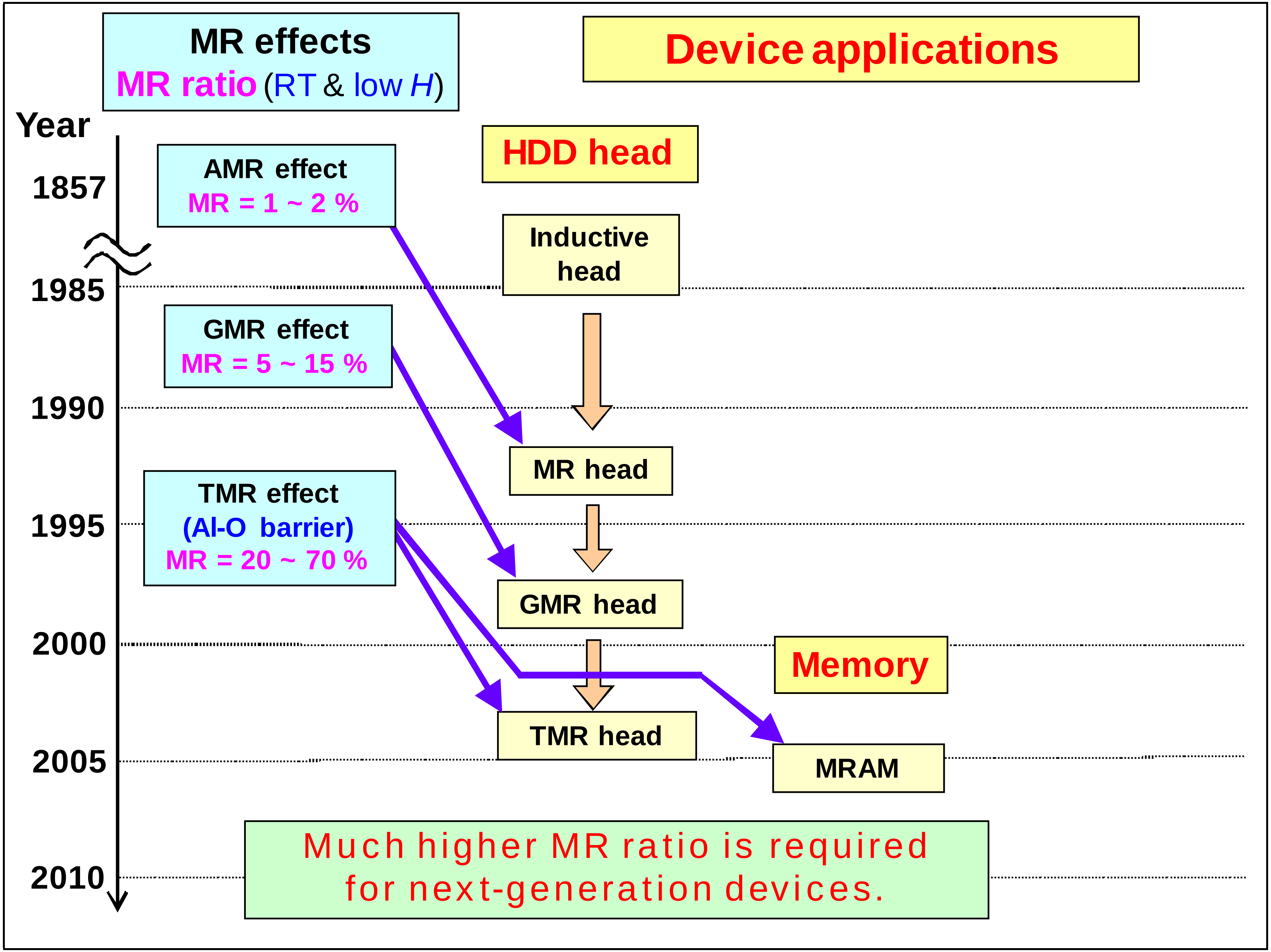


How can we develop Gbit-scale MRAM ?

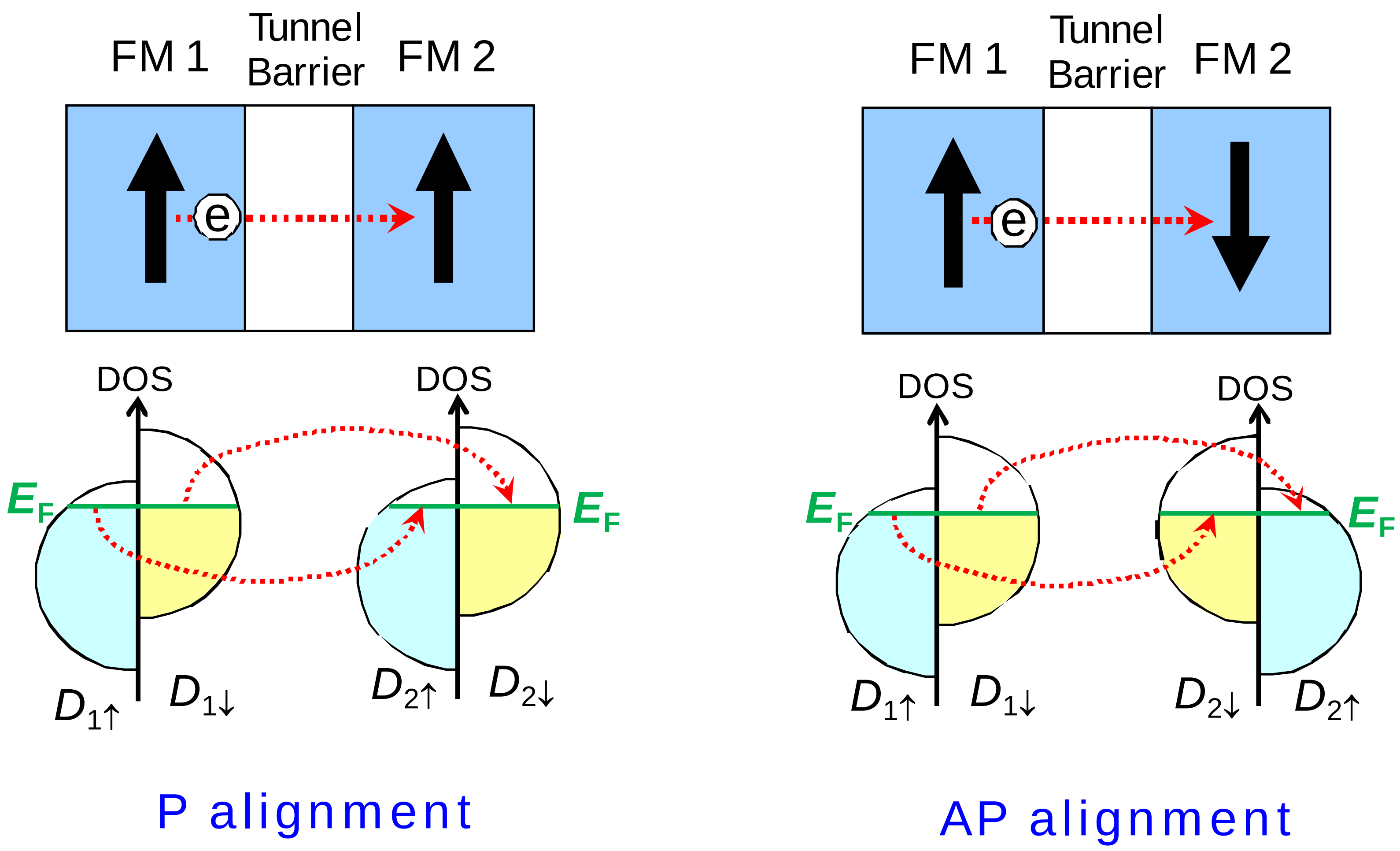
Major requirement for Gbit-MRAM

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




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

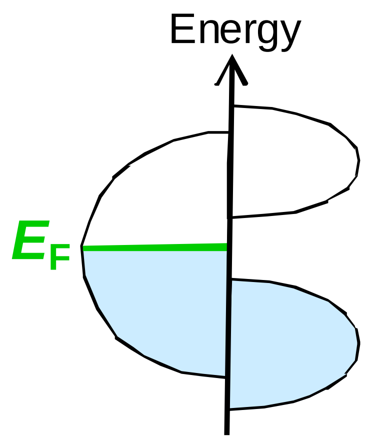


$$MR \equiv \frac{(R_{AP} - R_P)}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}, \qquad P_\alpha = \frac{(D_{\alpha\uparrow}(E_F) - D_{\alpha\downarrow}(E_F))}{(D_{\alpha\uparrow}(E_F) + D_{\alpha\downarrow}(E_F))}, \qquad \alpha = 1,2$$

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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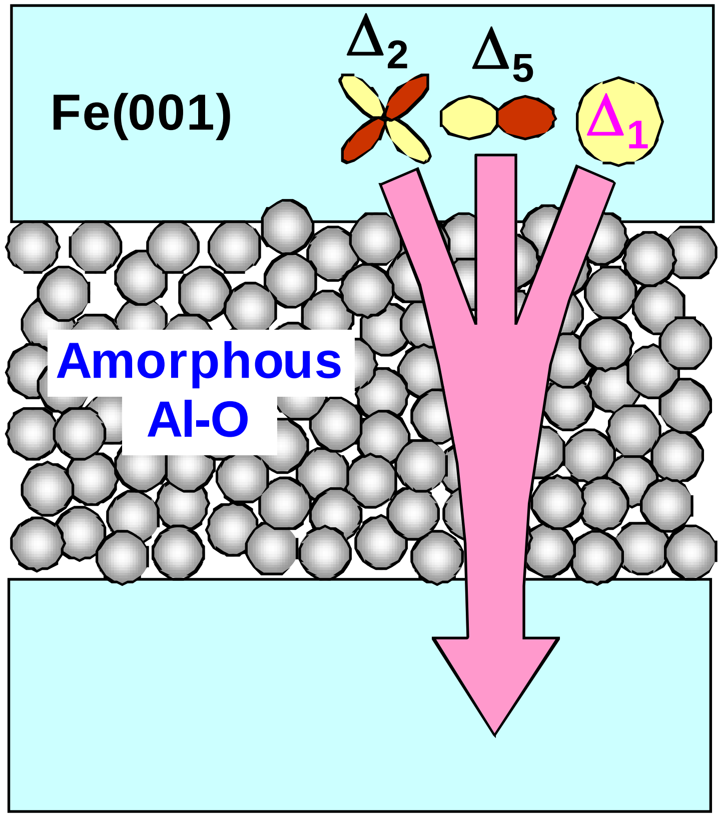
Amorphous Al-O barrier *vs.* crystal MgO barrier (theory)

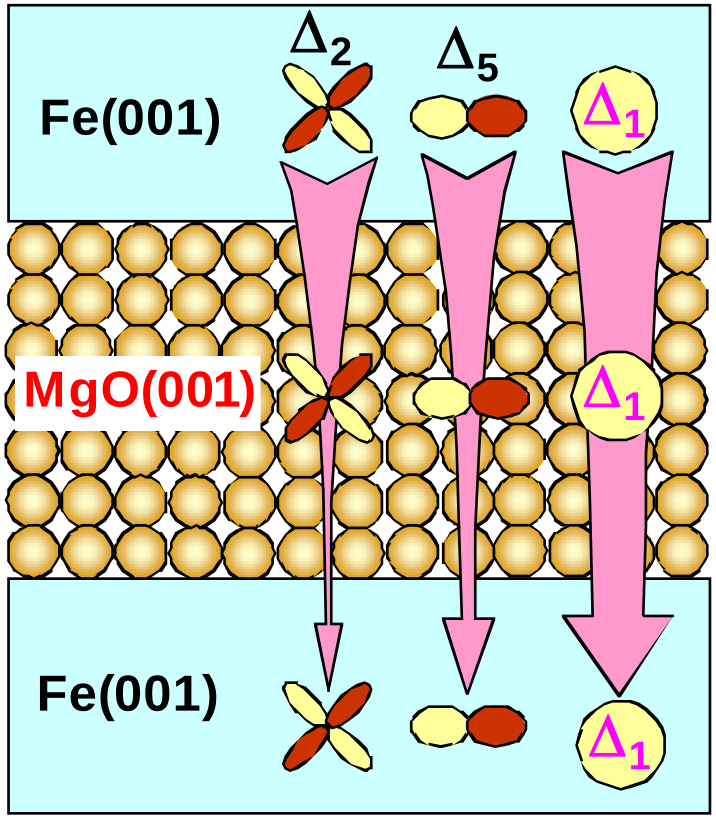
Amorphous Al-O barrier
(conventional MTJ)



Incoherent tunneling of various Bloch states.

MR < 100% at RT

Crystal MgO(001) barrier

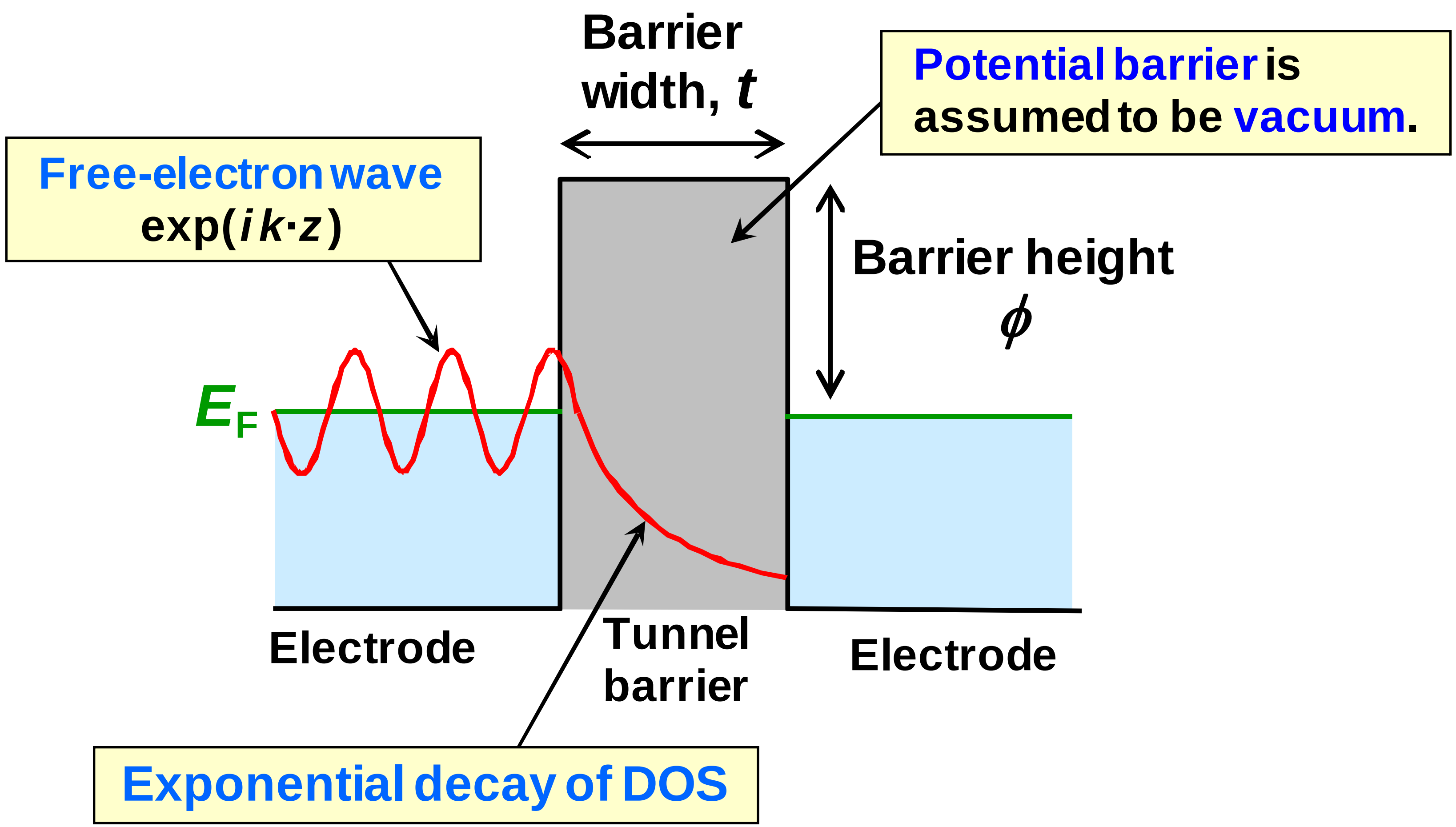


Dominant tunneling of fully spin-polarized Δ_1 Bloch states

MR >> 1000% (theory)

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

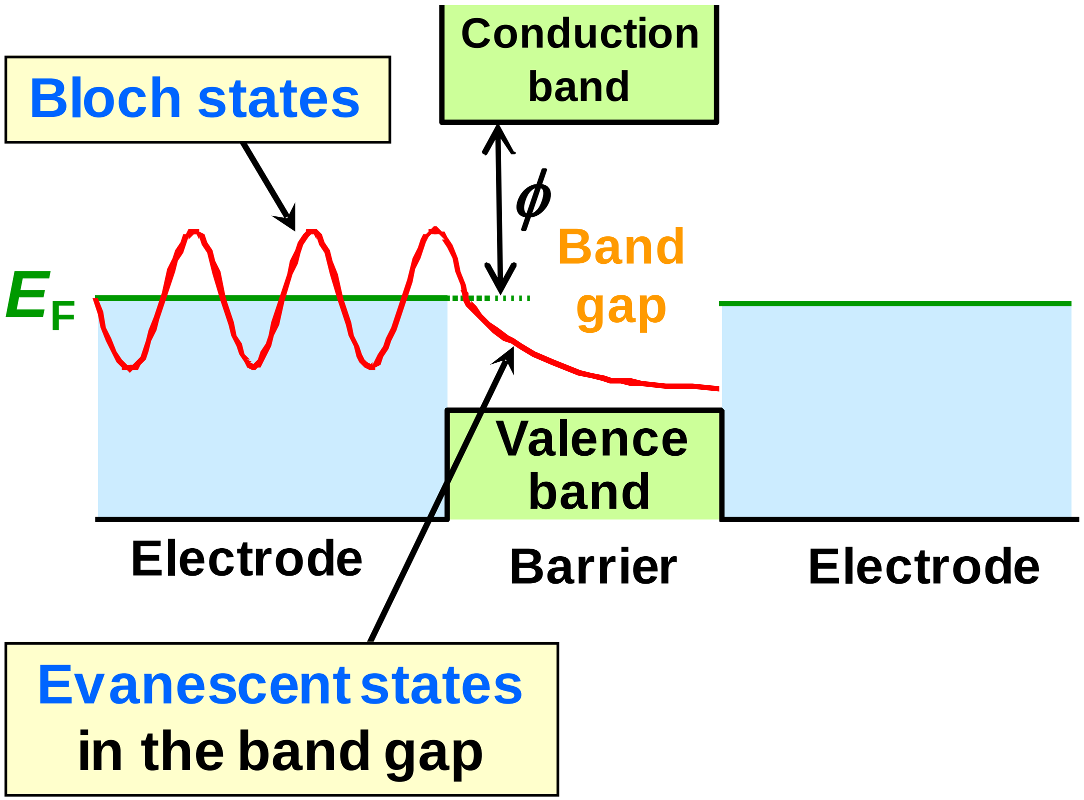
What we learn about "*tunneling effect*" at an undergraduate course



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

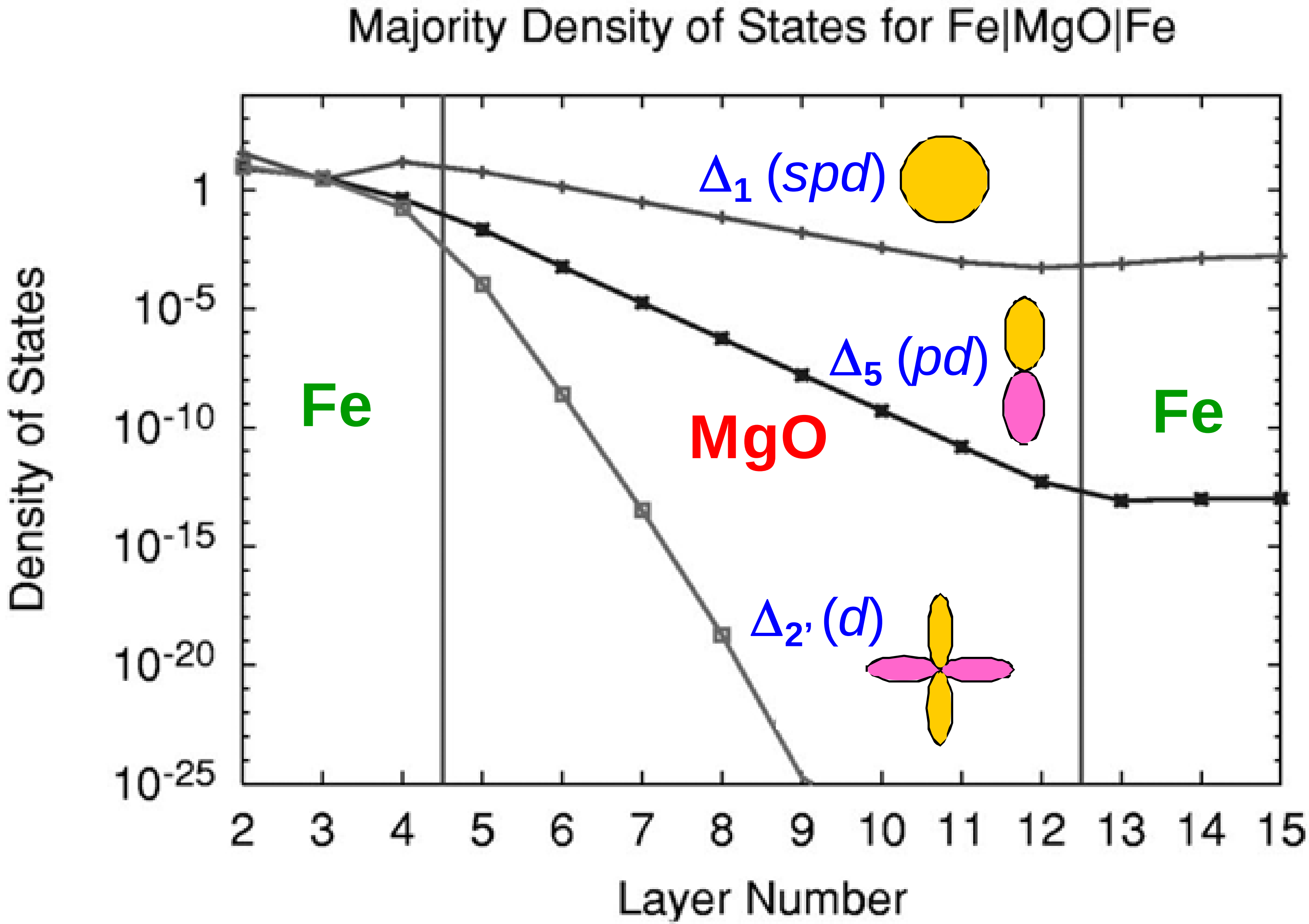
Realistic tunneling effect



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.

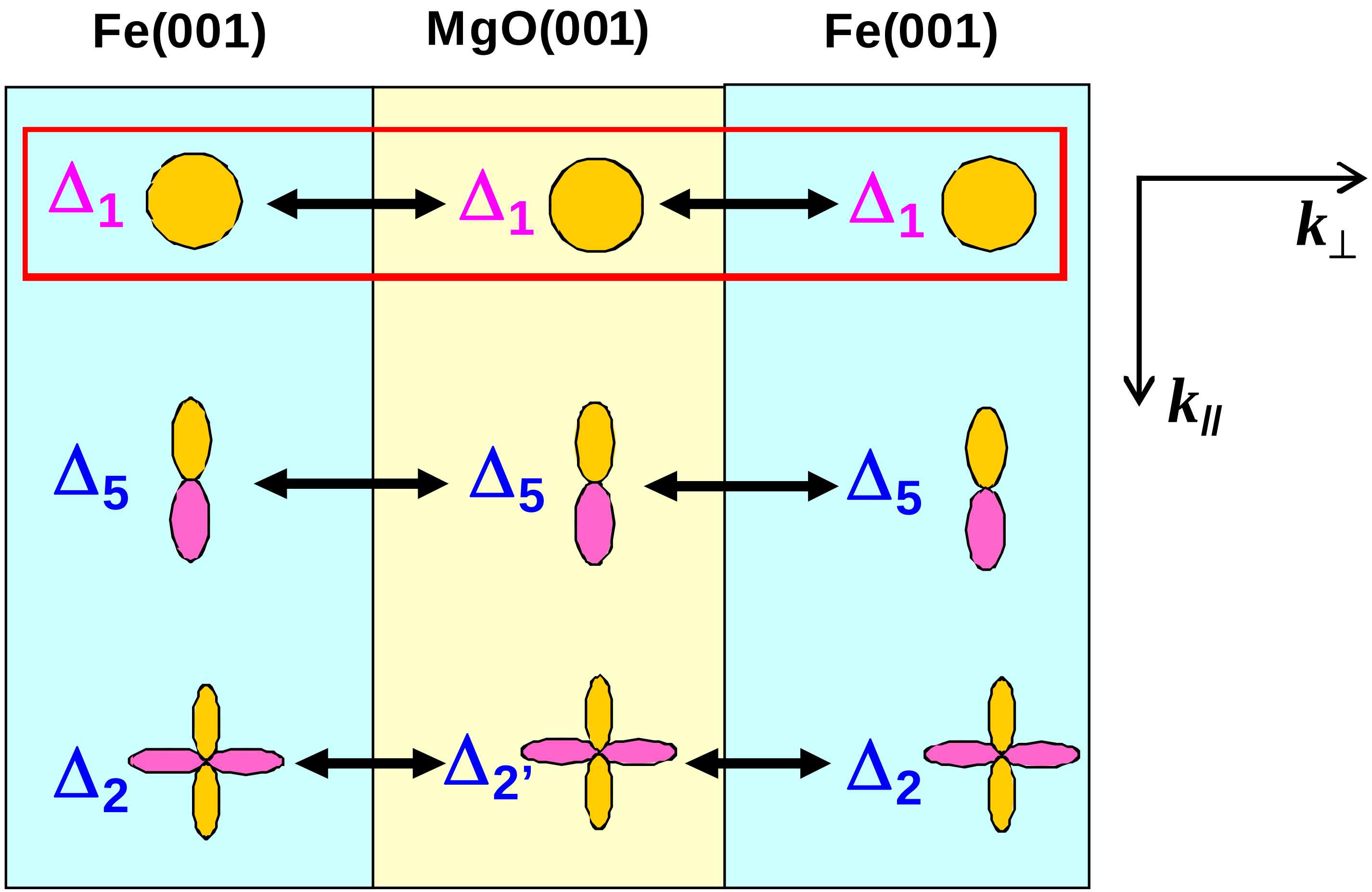


Butler (2001).

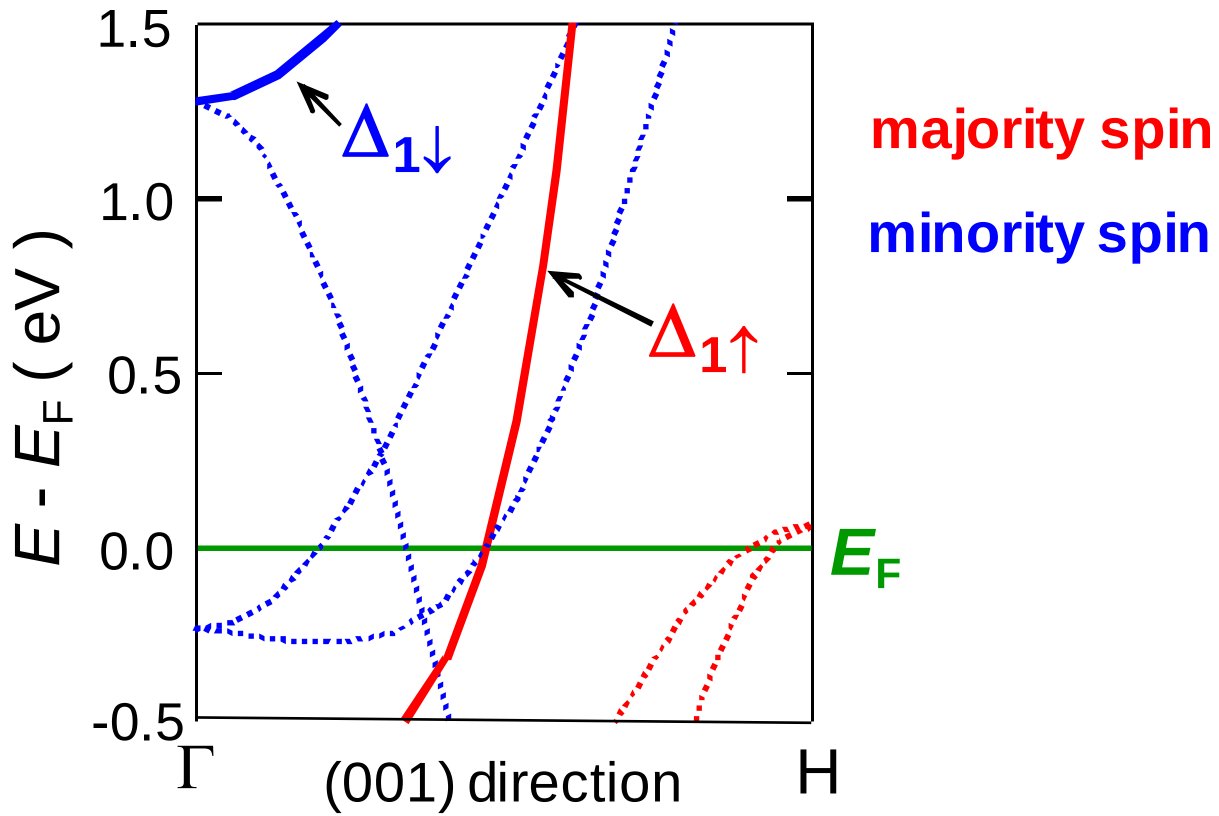
$$\Delta_1 : s + p_z + d_{2z^2-x^2-y^2}$$

Coupling between Bloch states and evanescent states

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



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



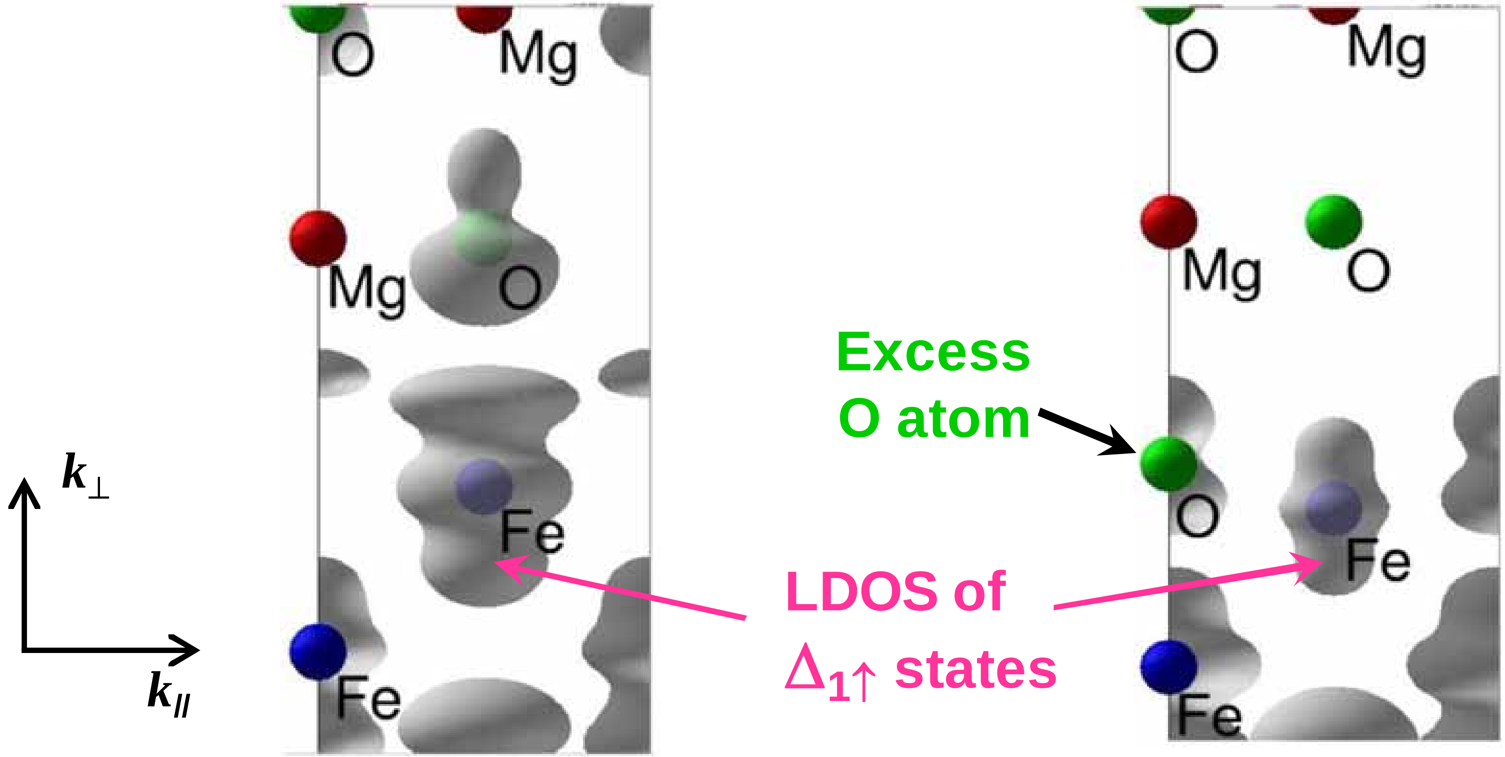
Fully spin-polarized Δ_1 band

⇒ 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%

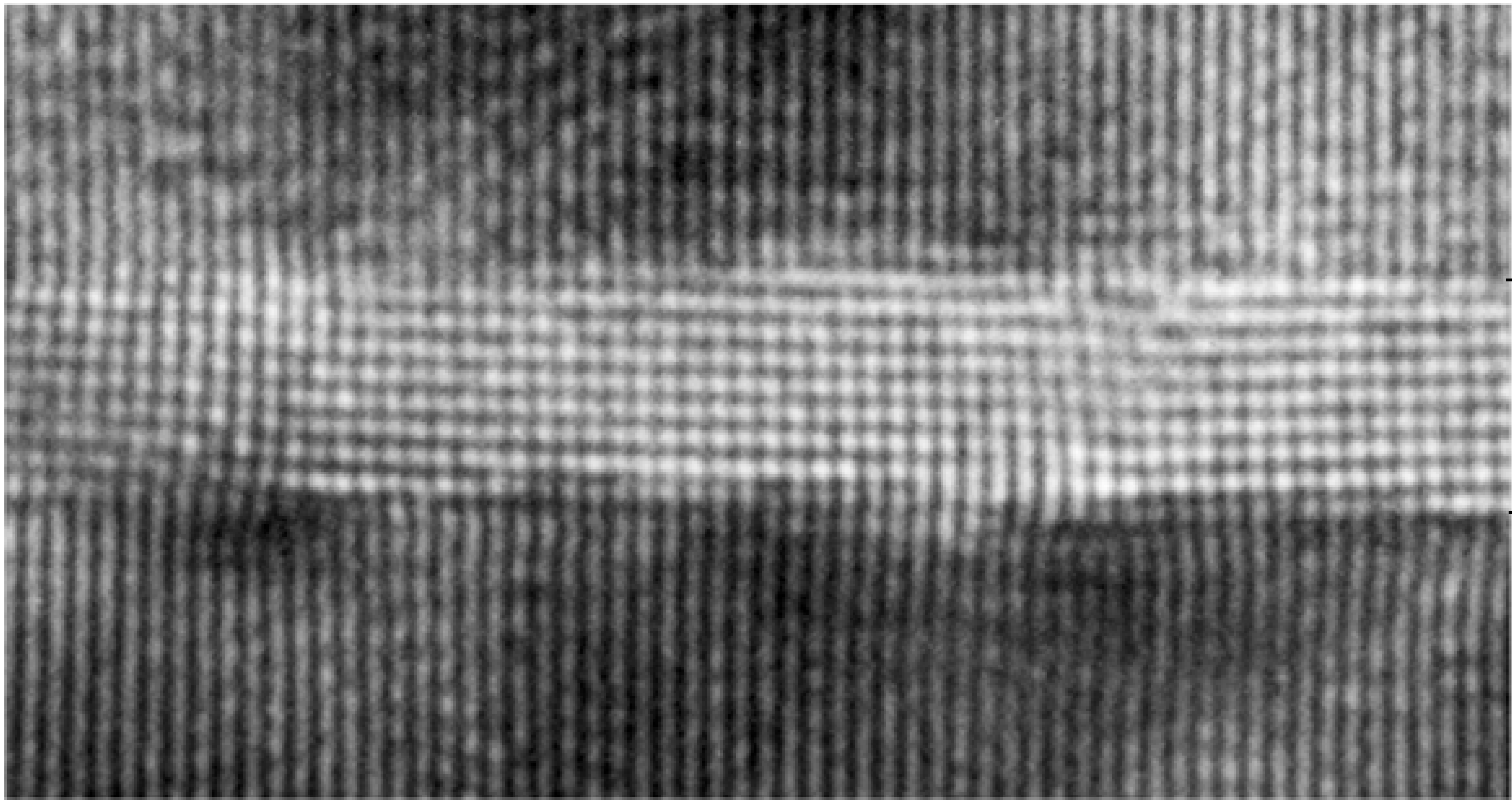
Oxidized interface

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).



Fe(001)
(Pinned layer)

MgO(001)

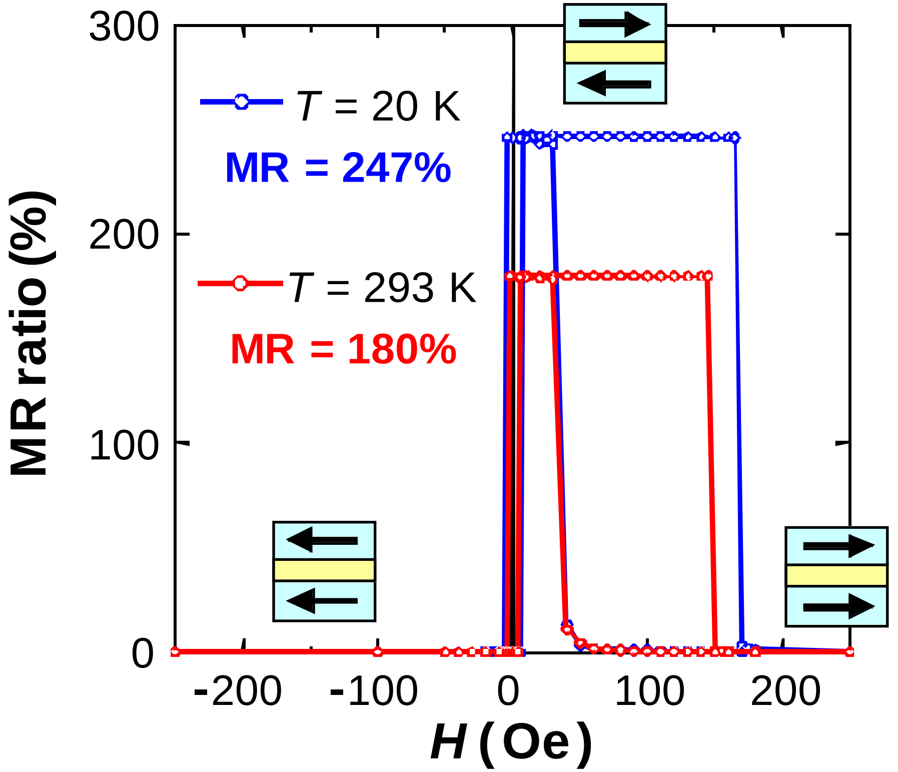
Fe(001)
(Free layer)

2 nm

TEM image

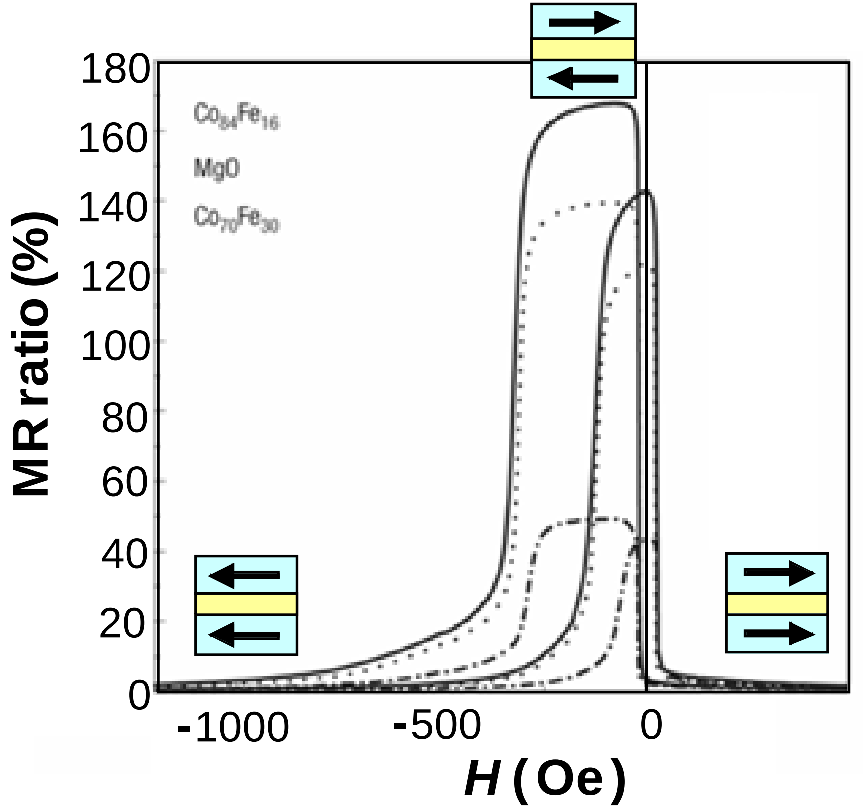
Experimental demonstrations of giant TMR

Single-crystal MgO(001) barrier

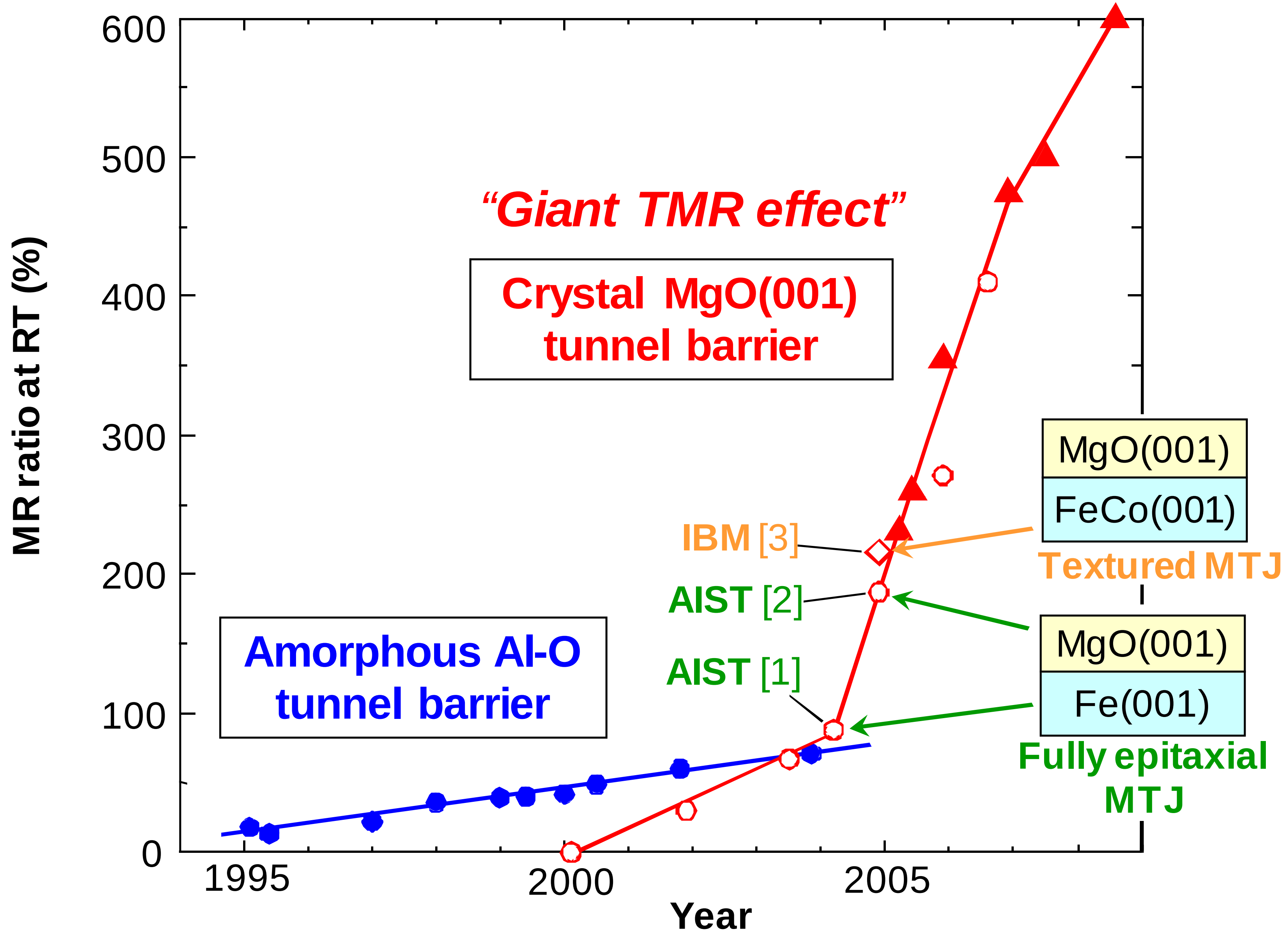


Yuasa *et al*., *Nature Mater.* **3**, 868 (2004).

Textured MgO(001) barrier



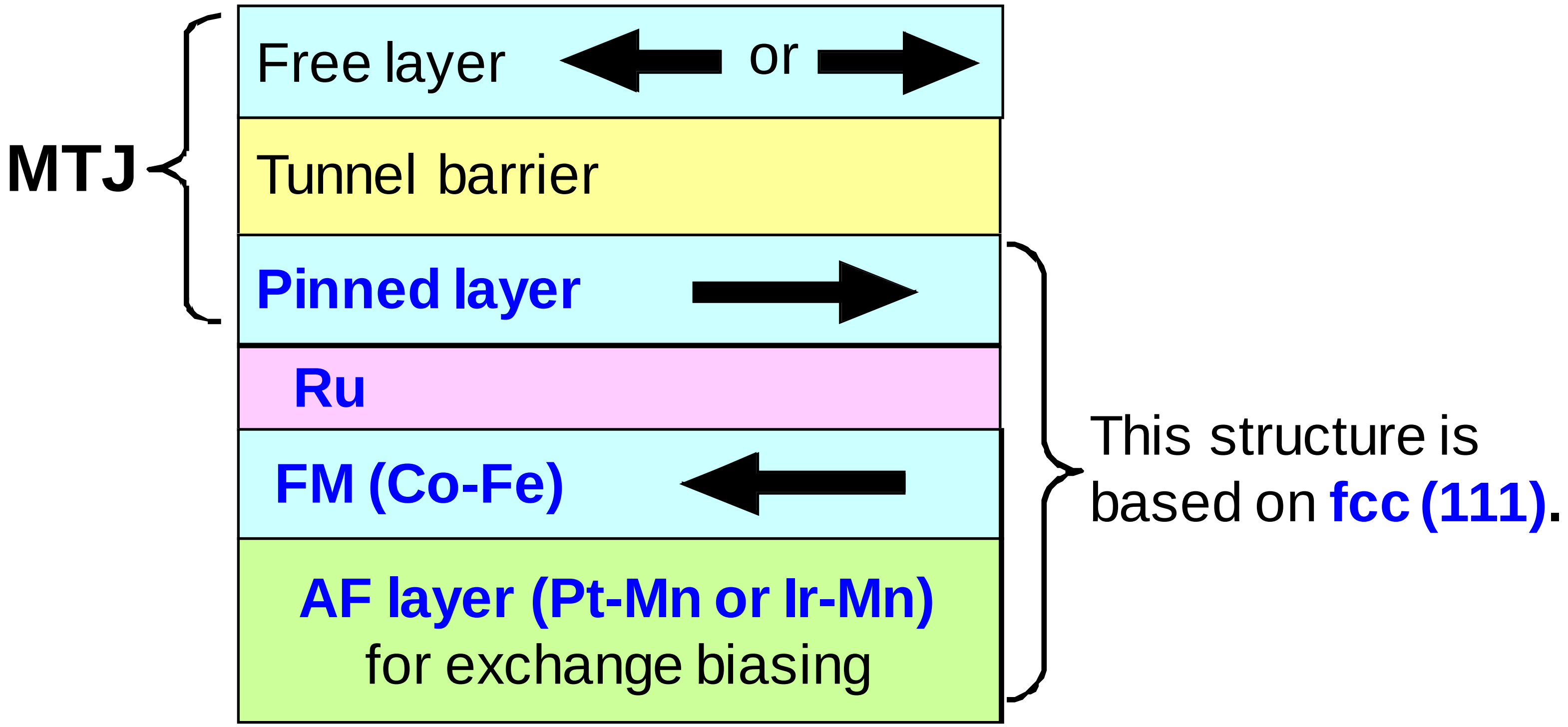
Parkin (IBM), *Nature Mater.* **3**, 862 (2004).



[1] Yuasa, *Jpn. J. Appl. Phys.* **43**, L558 (2004). [2] Yuasa, *Nature Mater.* **3**, 868 (2004).
[3] Parkin, *Nature Mater.* **3**, 862 (2004).

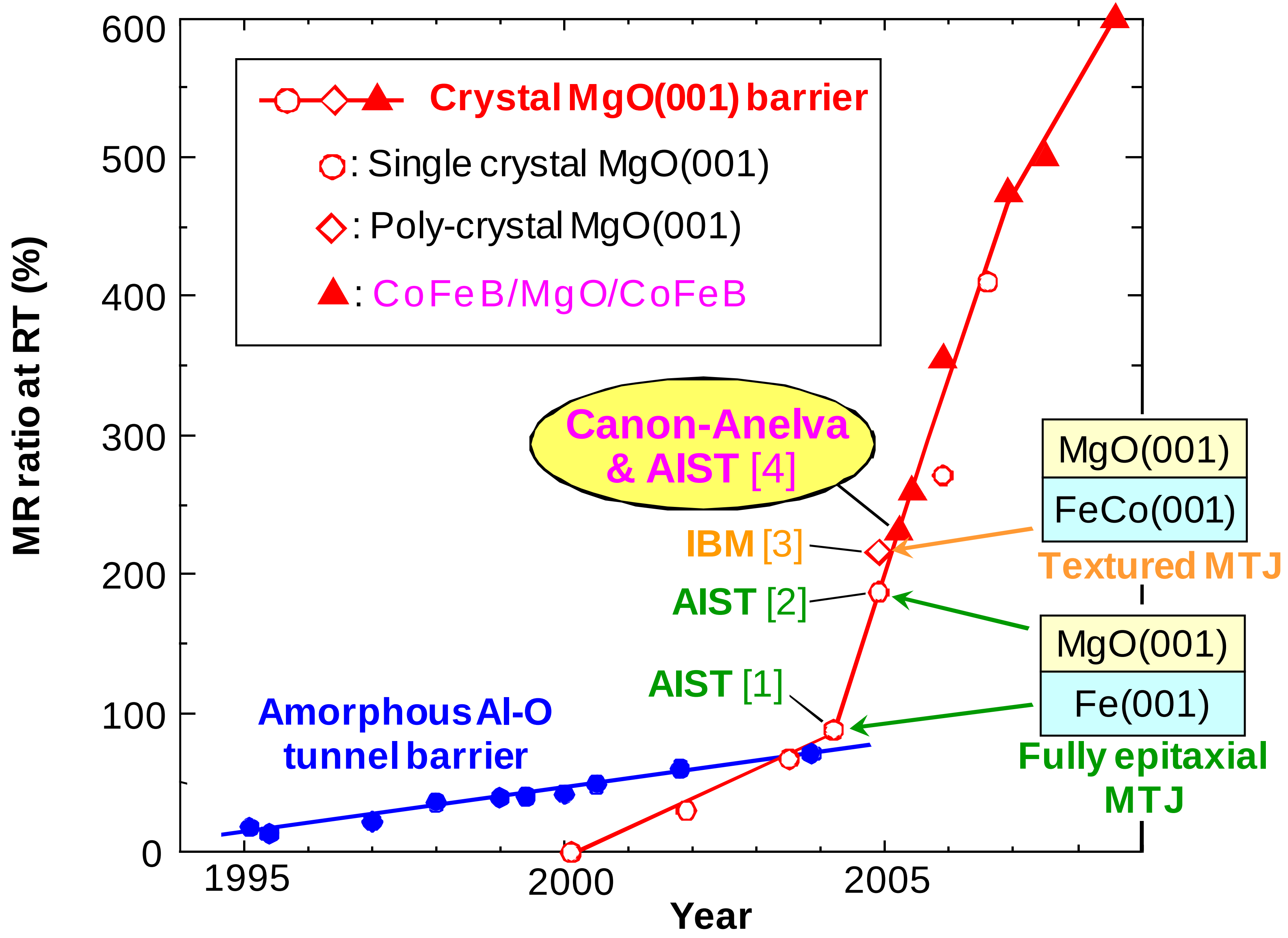
Fundamental problem on thin film growth

MTJ structure for practical applications



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

4-fold symmetry | **3-fold symmetry**



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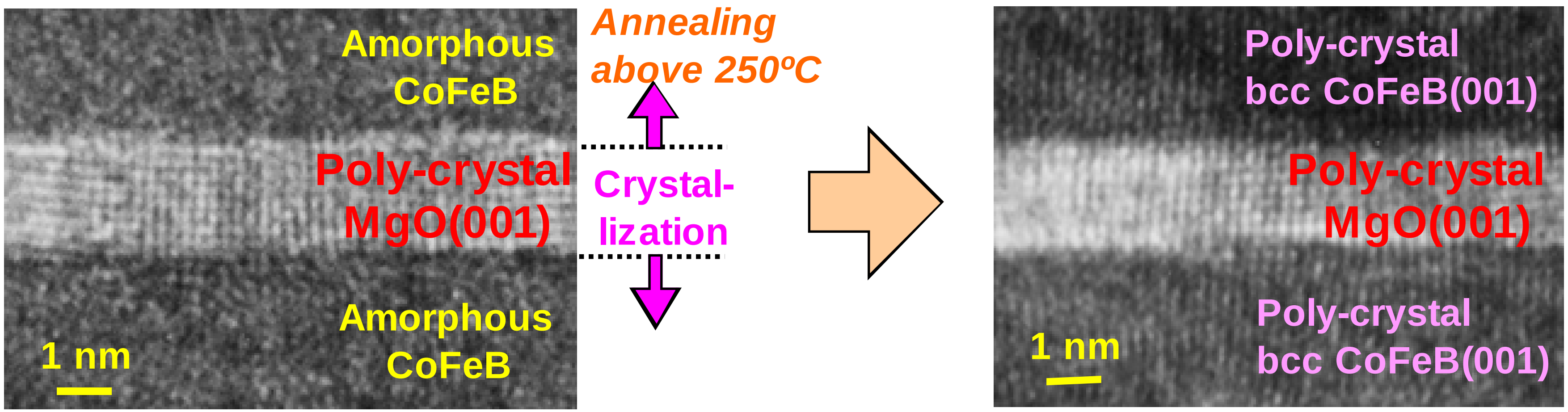
CoFeB/MgO/CoFeB structure for device applications

Canon-Anelva, AIST

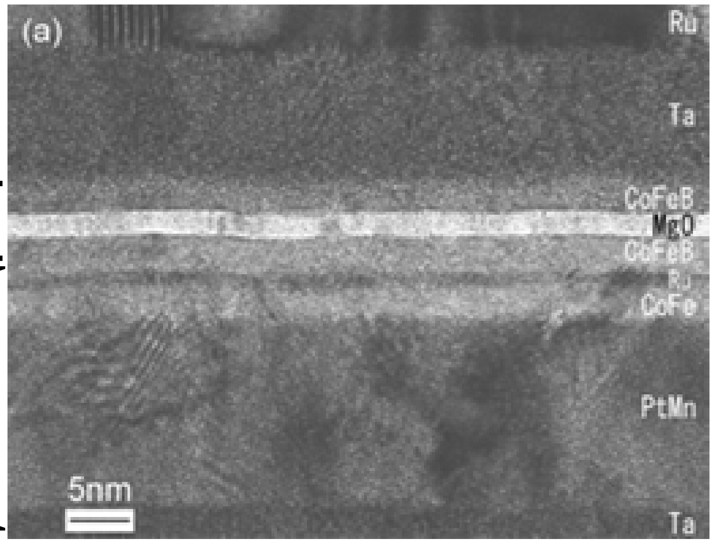
Djayaprawira, SY, *Appl. Phys. Lett*. **86**, 092502 (2005).
Yuasa & Djayaprawira, *J. Phys. D: Appl. Phys*. **40**, R337 (2007).



As-grown state | After annealing

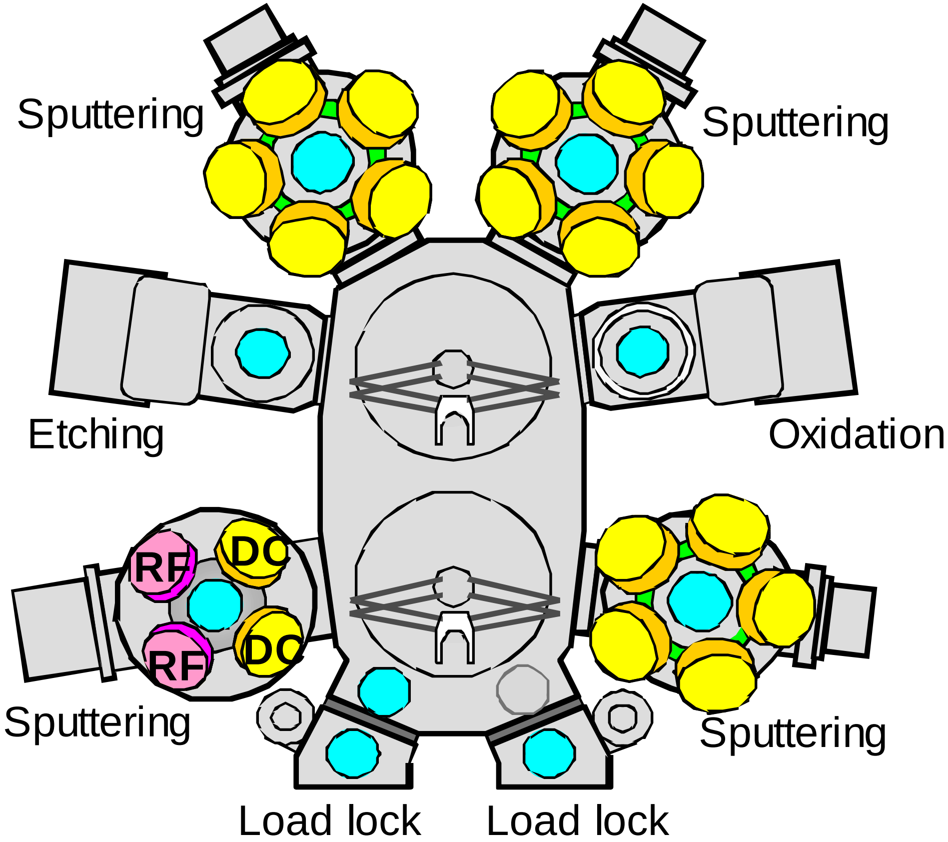
MgO-MTJ (**4-foldsymmetry**)

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

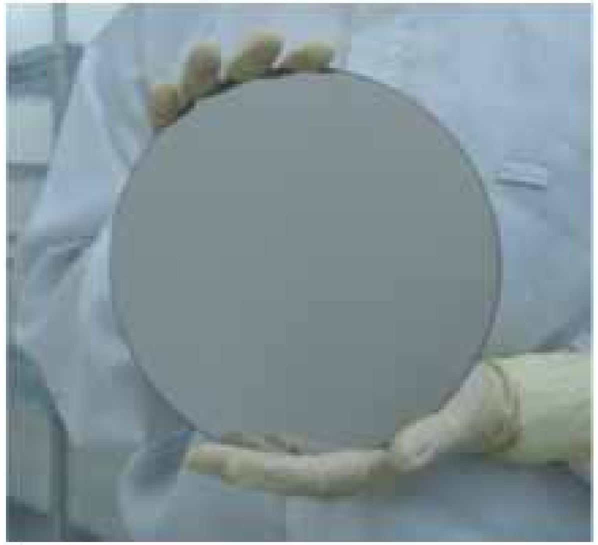


Core technology for device applications

Mass-manufacturing technology for HDD industry

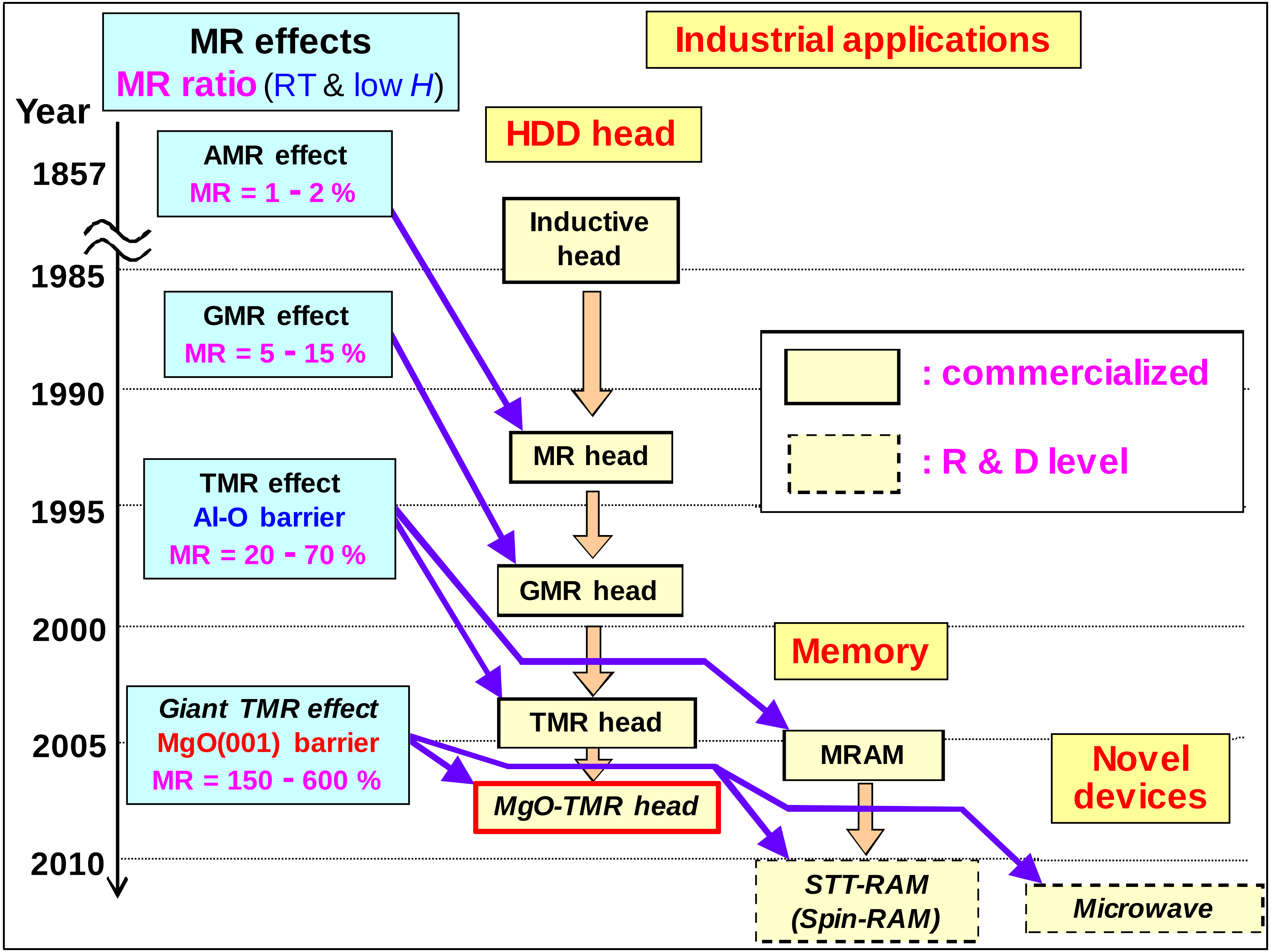


Canon-Anelva C-7100
sputtering system



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
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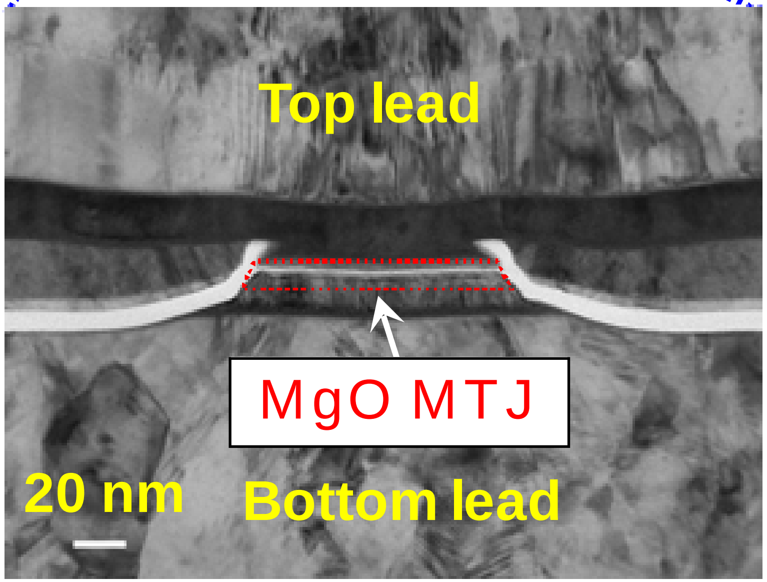
AMR effect
MR = 1 - 2 %
GMR effect
MR = 5 - 15 %
TMR effect
Al-O barrier
MR = 20 - 70 %
Giant TMR effect
MgO(001) barrier
MR = 150 - 600 %
HDD head
Inductive head
MR head
GMR head
TMR head
MgO-TMR head
: commercialized
: R & D level
Memory
MRAM
STT-RAM (Spin-RAM)
Novel devices
Microwave

MgO-TMR head for ultrahigh-density HDD

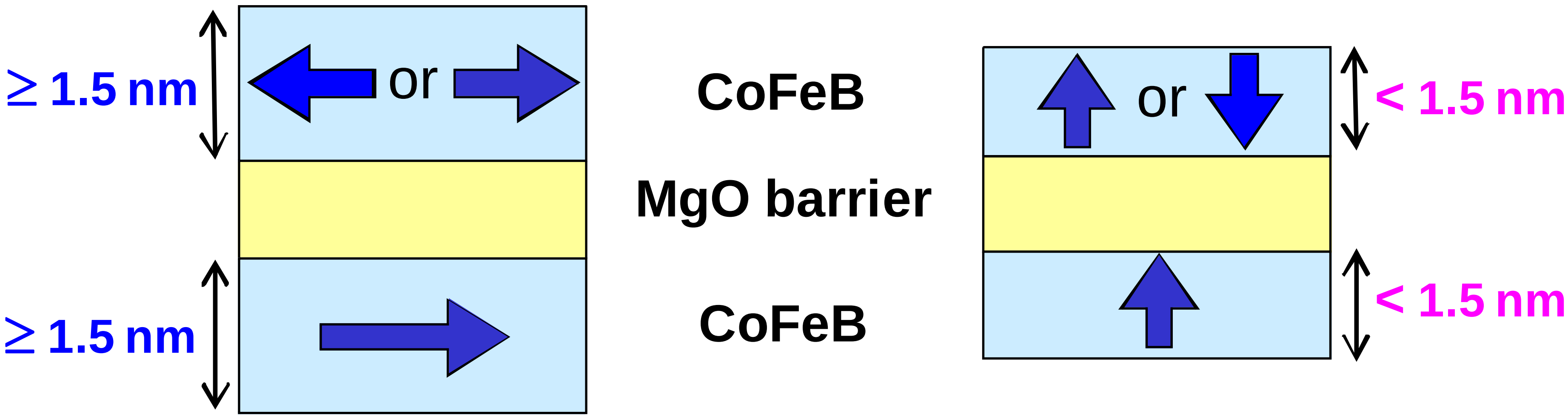


TEM image

- **Volume production** since 2007.
- **700 Gbit / inch²** achieved (×**5 increase**).
- Applicable up to 1 – 2 Tbit / inch².
- World market of **HDD**: **25 billion USD**
  head: **5 billion USD**

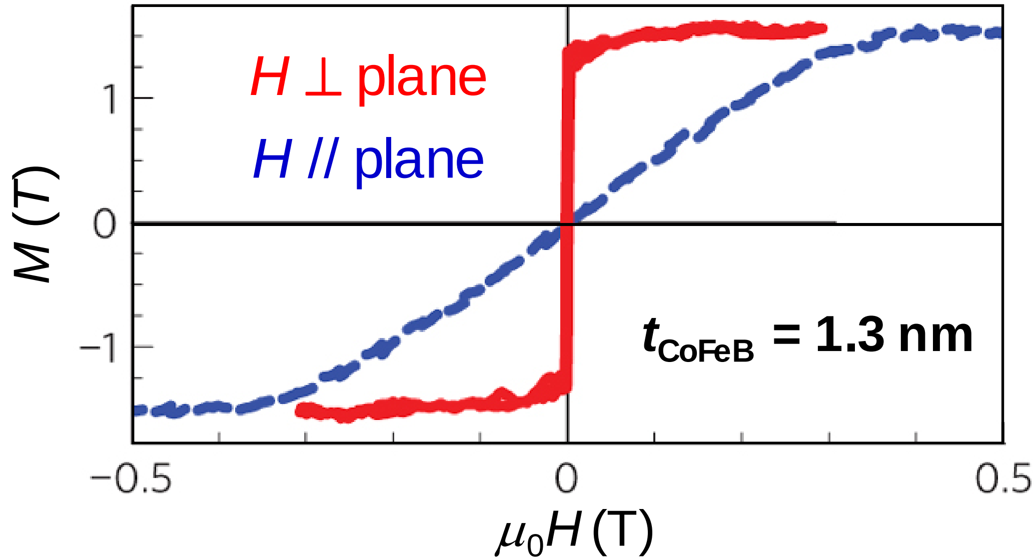
Ultrathin CoFeB electrode can have perpendicular magnetization.

In-plane magnetization　　　　*Perpendicular* magnetization



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

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



Outline

(1) Spintronics

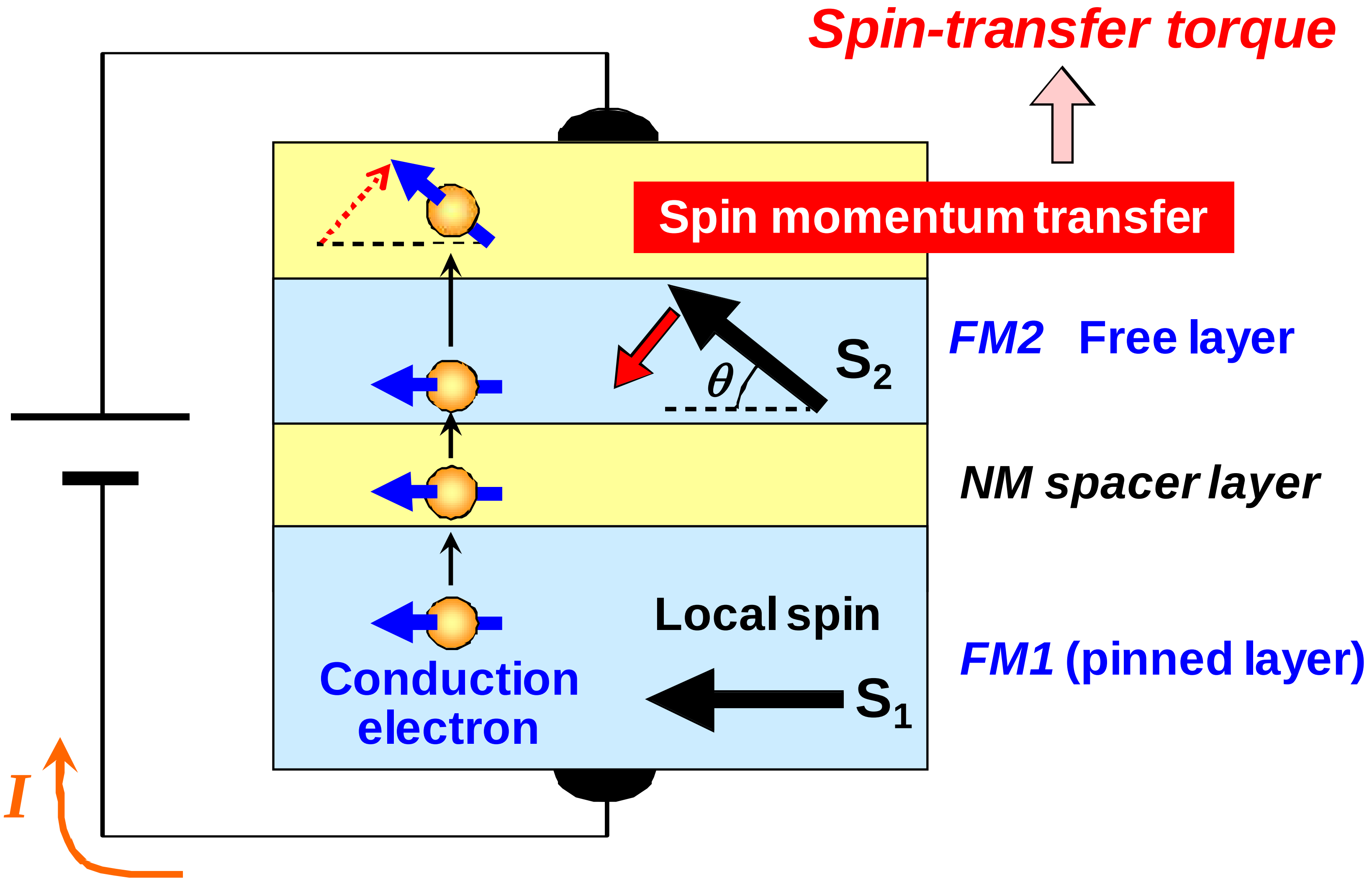
(2) Tunnel magnetoresistance (TMR)

- 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

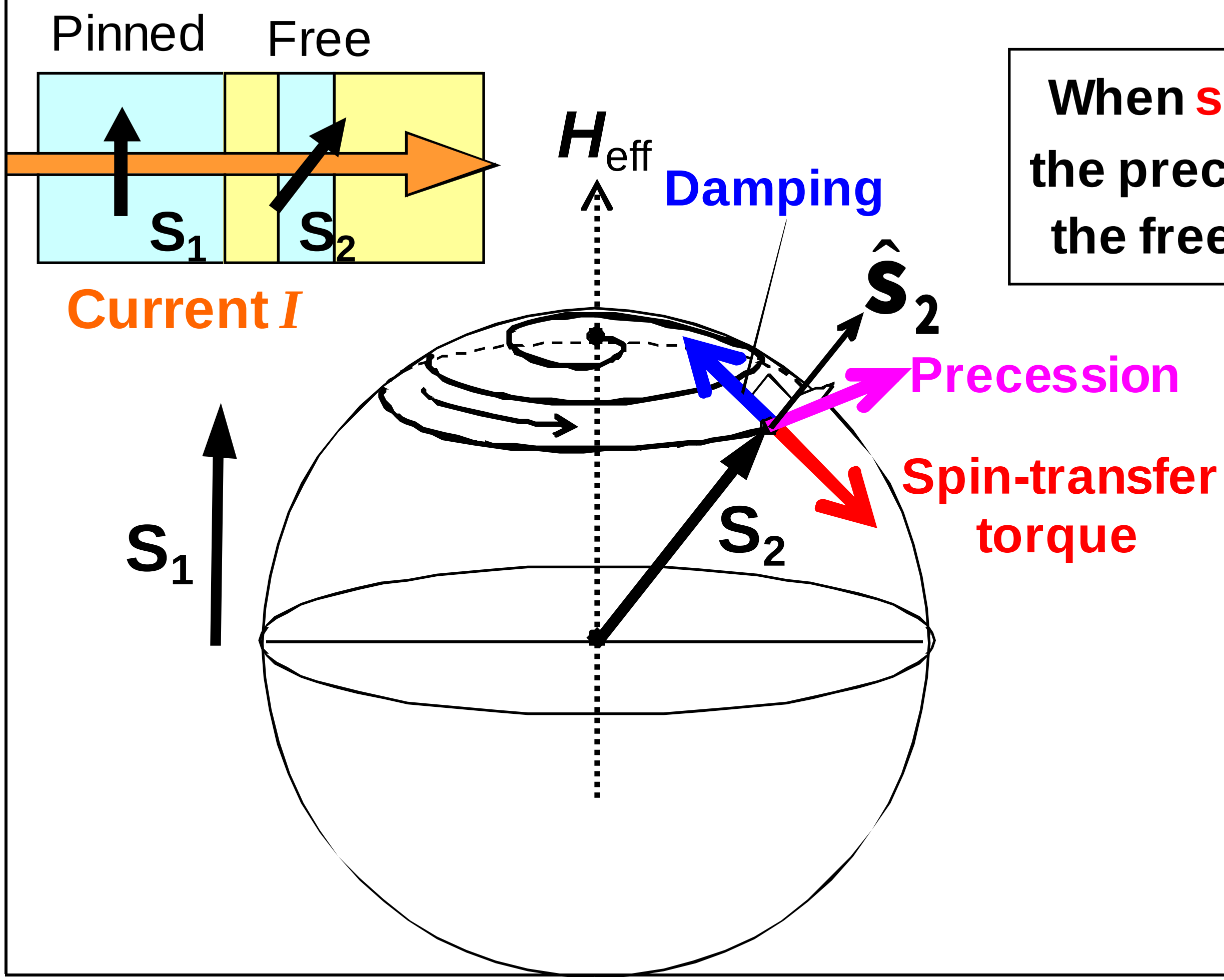
Spin-transfer torque in magnetic nano-pillar



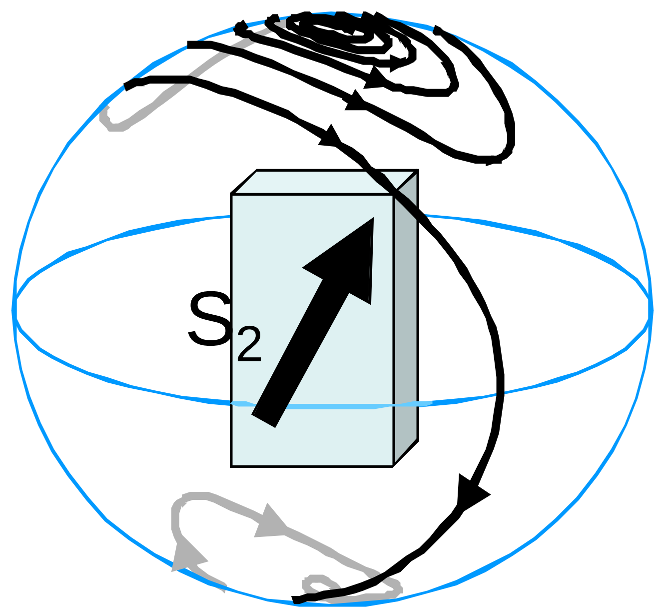
Theory of spin-transfer torque

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.



Outline

(1) Spintronics

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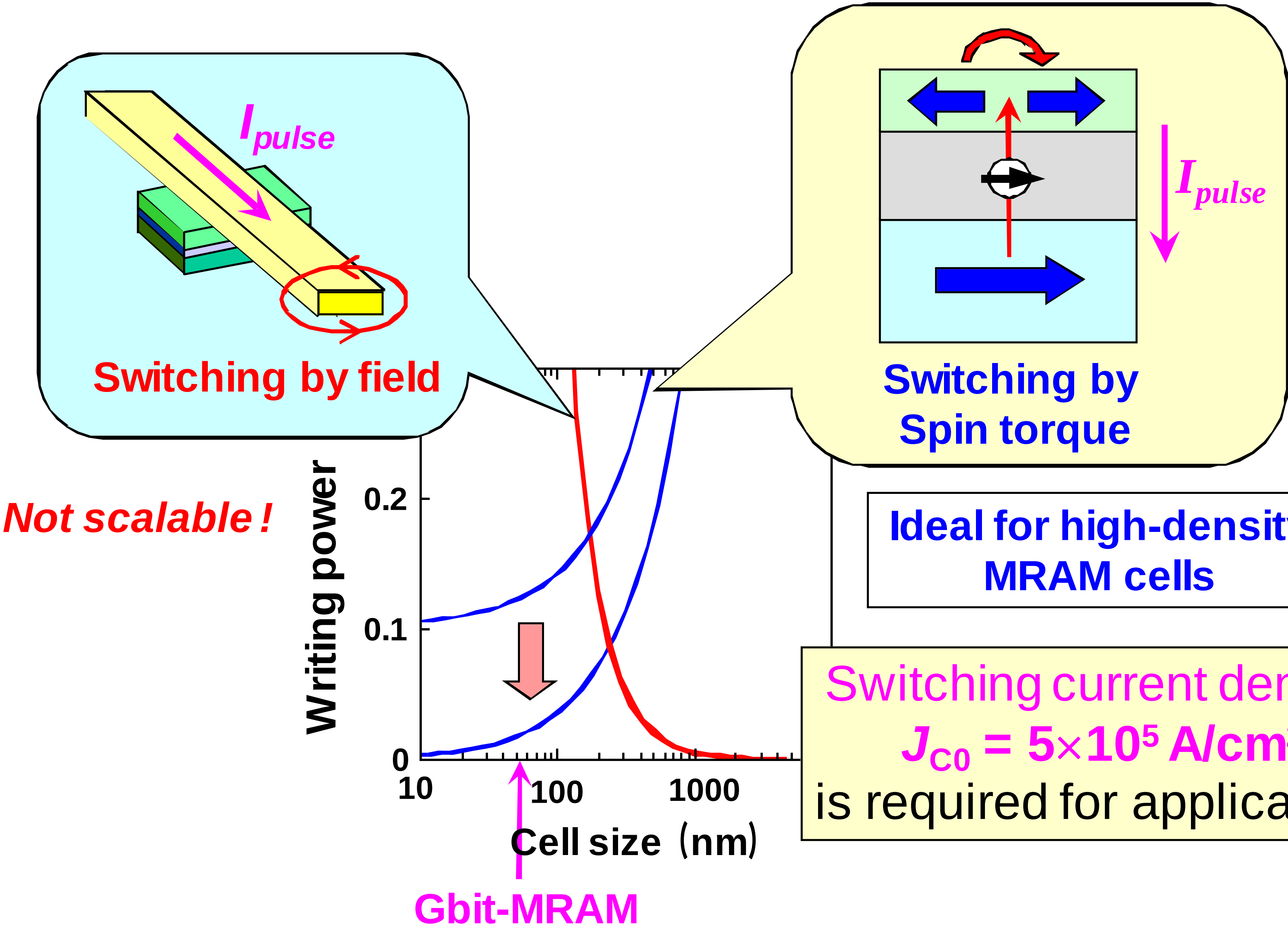
(3) Spin-transfer torque (STT)

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

Writing (magnetization switching) by spin-transfer torque

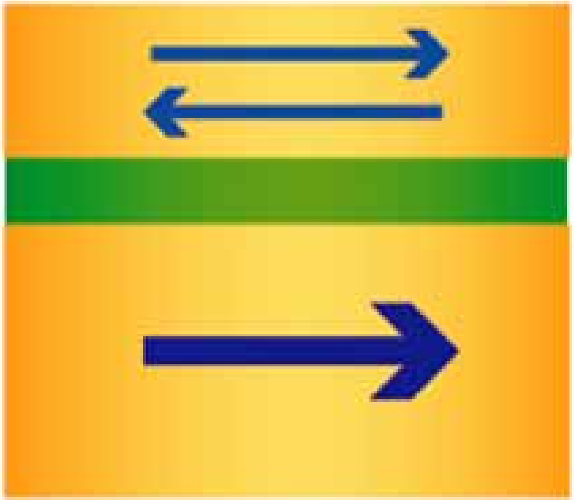


Ideal for high-density MRAM cells

Switching current density
$J_{C0} = 5\times10^{5}$ A/cm^{2}
is required for application.

In-plane magnetization *vs*. Perpendicular magnetization

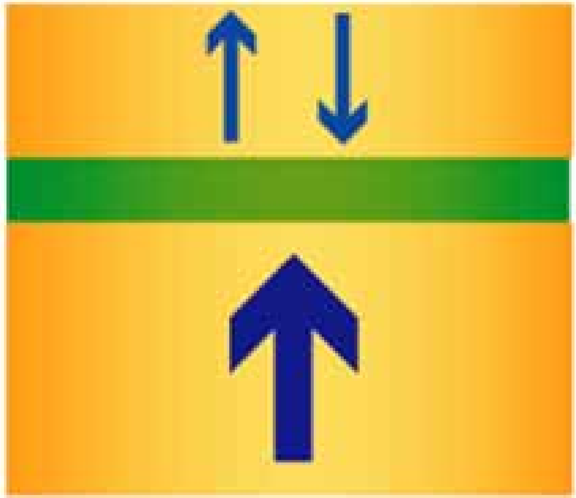
In-plane magnetization



<Materials>

- CoFeB
- Co-Fe
- Ni-Fe

Perpendicular magnetization

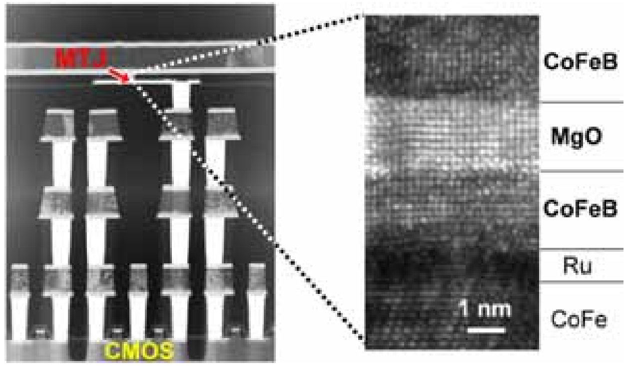


<Materials>

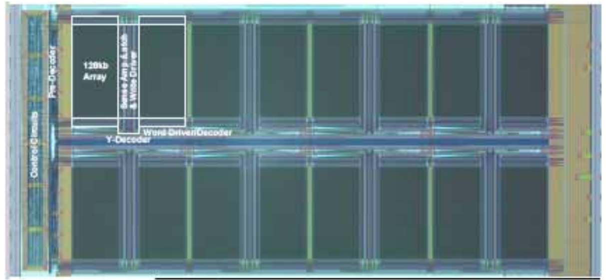
- $L1_0$-ordered alloy (*e.g*. FePt)
- Multilayer, **superlattice**
- RE-TM alloy (*e.g*. Tb-Co)
- HCP alloy (*e.g*. Co-Cr)
- ultrathin CoFeB

Development of Spin-RAM

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

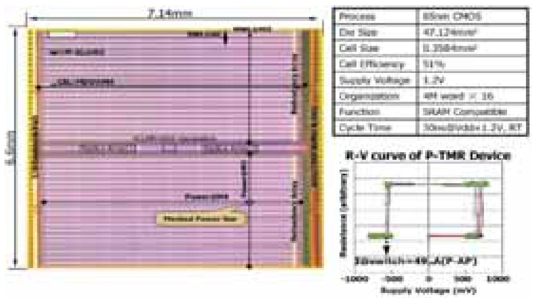


2007 Hitachi/Tohoku U. **(ISSCC 2007)**
- in-plane MTJ cells
- 2 Mb

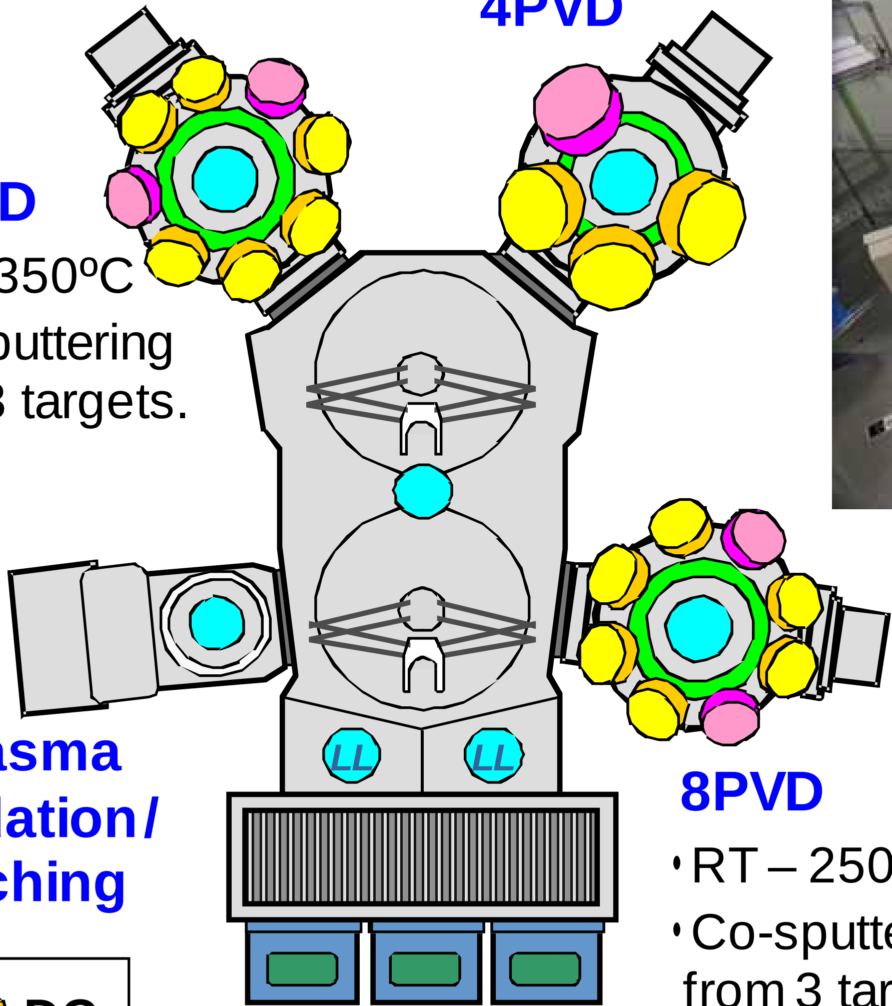


2008 Toshiba, AIST etc. **(IEDM 2008)**
- p-MTJ cells
- 1 kb

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



Canon-Anelva C-7100 sputtering system installed at AIST



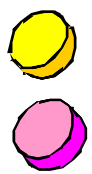
8PVD

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

8PVD

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

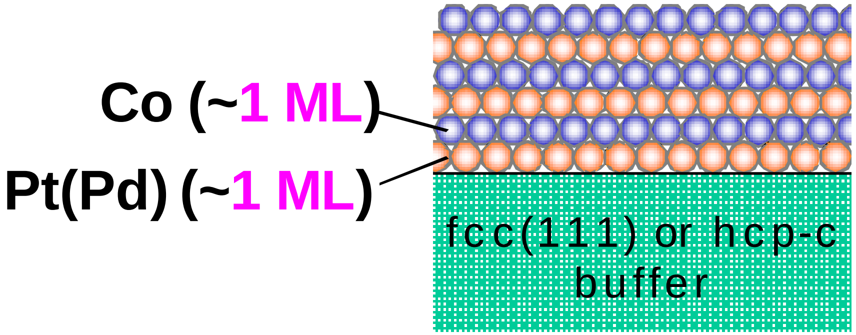
Plasma oxidation / Etching



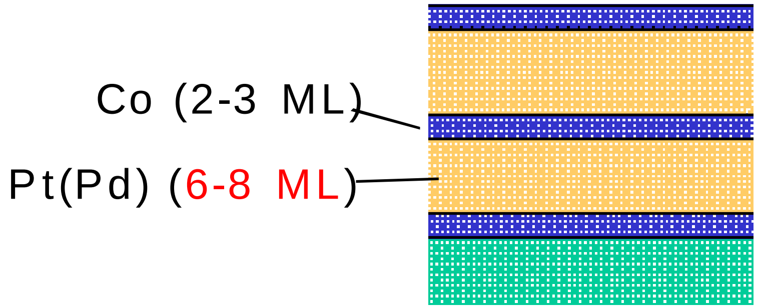
New perpendicular magnetic material : superlattice film

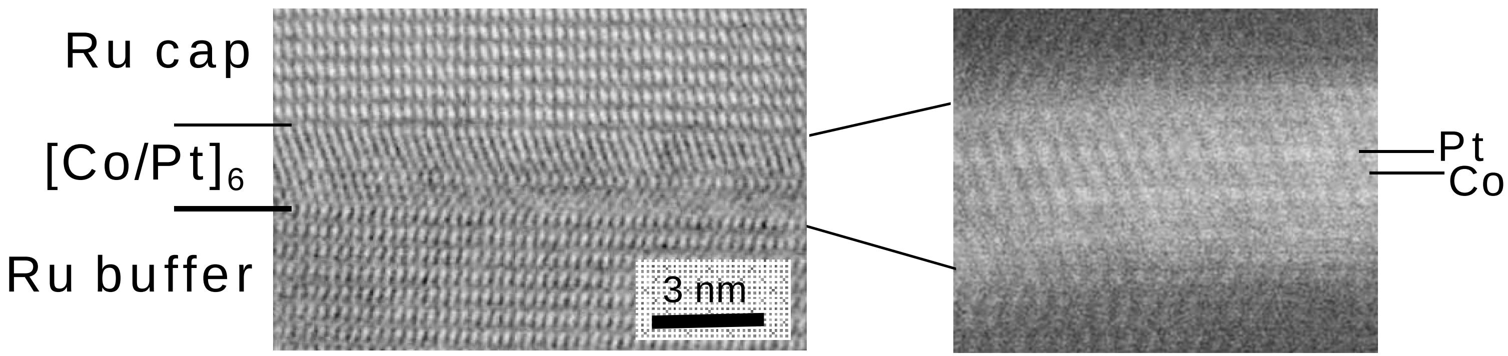
Yakushiji, SY *et al*., *Appl. Phys. Express* **3**, 053003 (2010).
Yakushiji, SY *et al*., *Appl. Phys. Lett*., **97**, 232508 (2010).

fcc(111)-based superlattice film



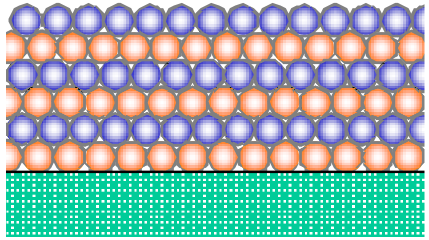
***cf*. conventional magnetic multilayer with thick Pt(Pd) layers**

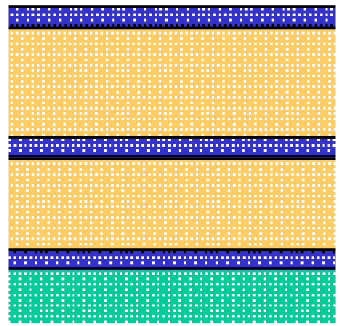




TEM **HAADF-STEM**

Magnetic superlattice *vs.* conventional multilayer

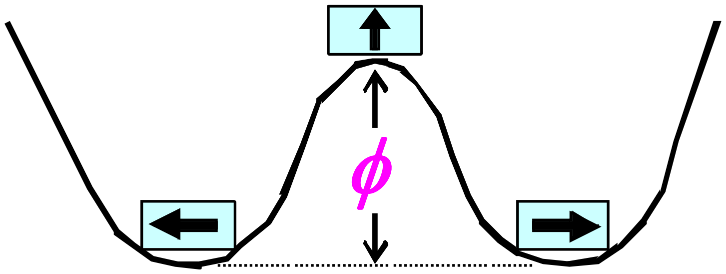




	Superlattice film	Conventional multilayer film
Thickness of total stack	Ultra-thin (**< 1.2 nm possible**)	Relatively thick **(> 3 nm)**
Structure	Artifical alloy	Mutilayer
K_u	Up to 12 Merg/cc (***tunable***)	~ 5 Merg/cc
Annealing stability	Very good > 370°C	Poor ~ 200°C
Origin of perp. magnetic anisotroy	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, $J_{C0} = 5 \times 10^5$ A/cm^2

(4) Switching speed < 20 ns to replace DRAM

< 1 – 3 ns to replace SRAM

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

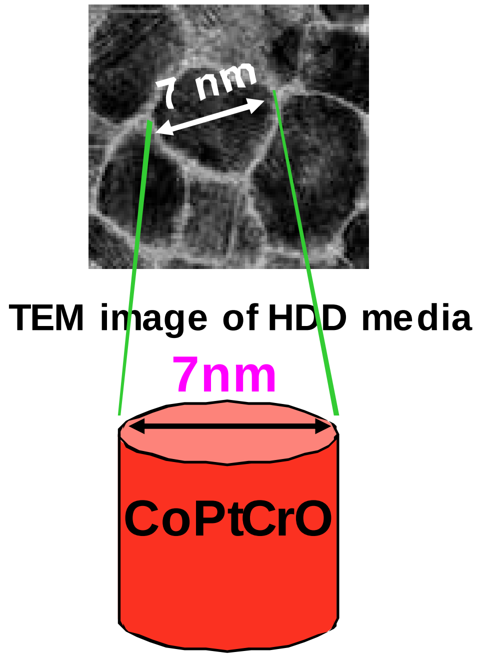
When cell size is smaller than 50 nm,
the uniaxial **shape anisotropy** cannot yield $\Delta > 60$.

MTJ with *in-plane* magnetization is hopeless !

Perpendicular magnetic recording

HDD

500 Gbit/inch^2



Δ > 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 $\Omega\mu m^2$, MR > 100%

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

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

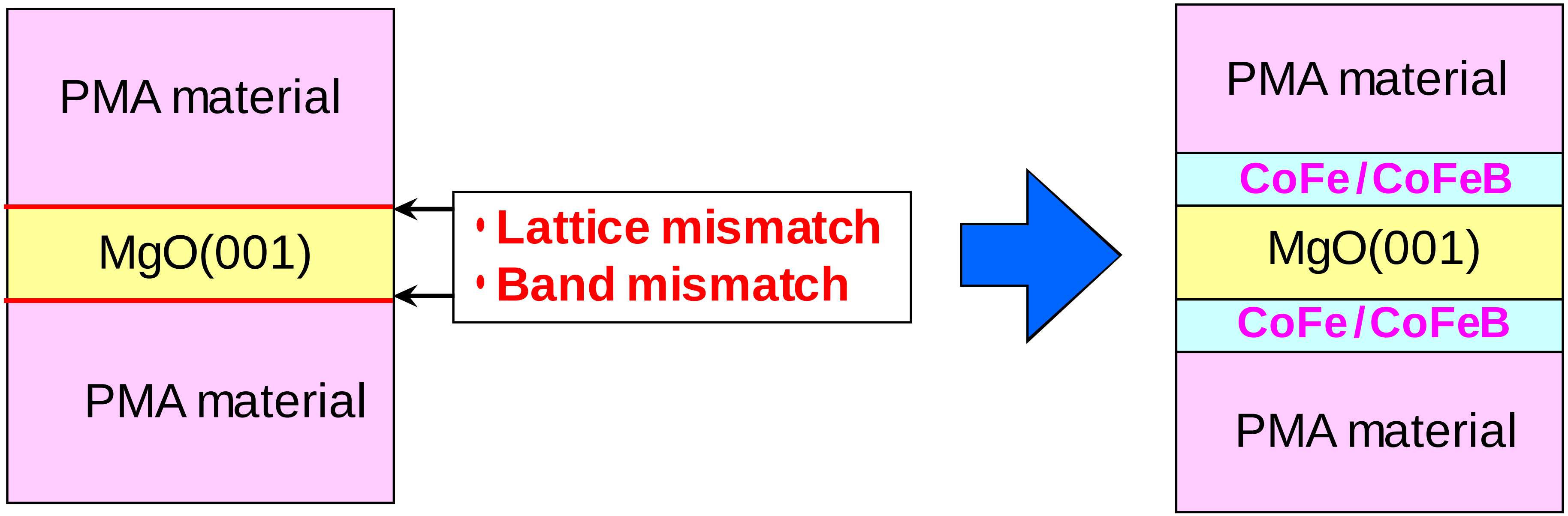
How to achieve high MR with perpendicular electrodes ?

<Issues>

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

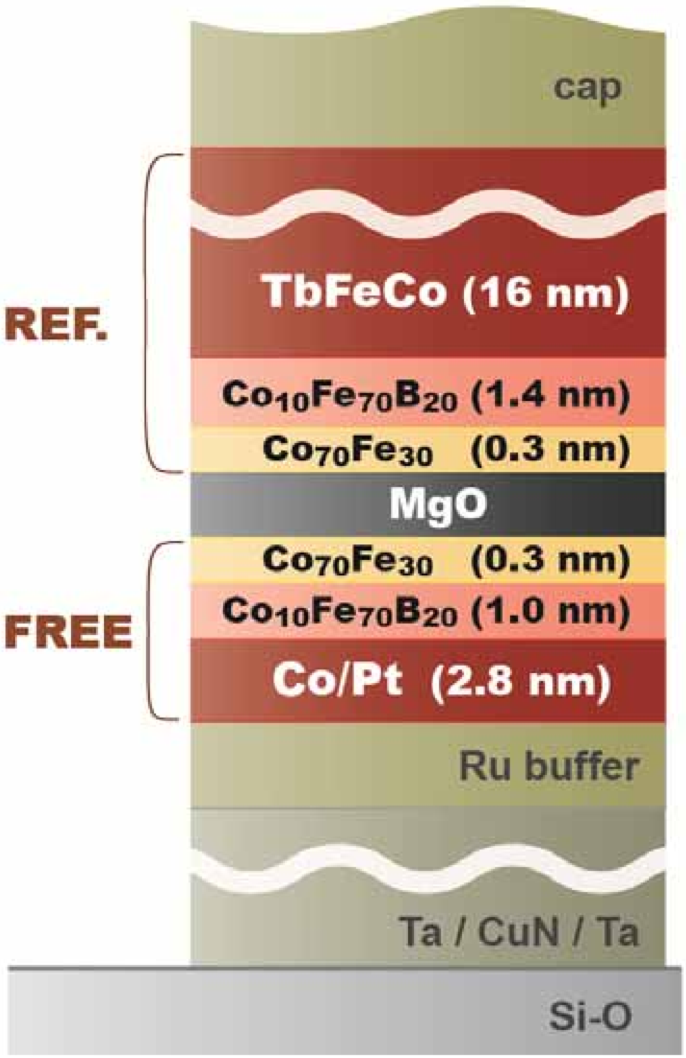
(ii) Lattice matching between perp. materials and MgO(001) is not good.

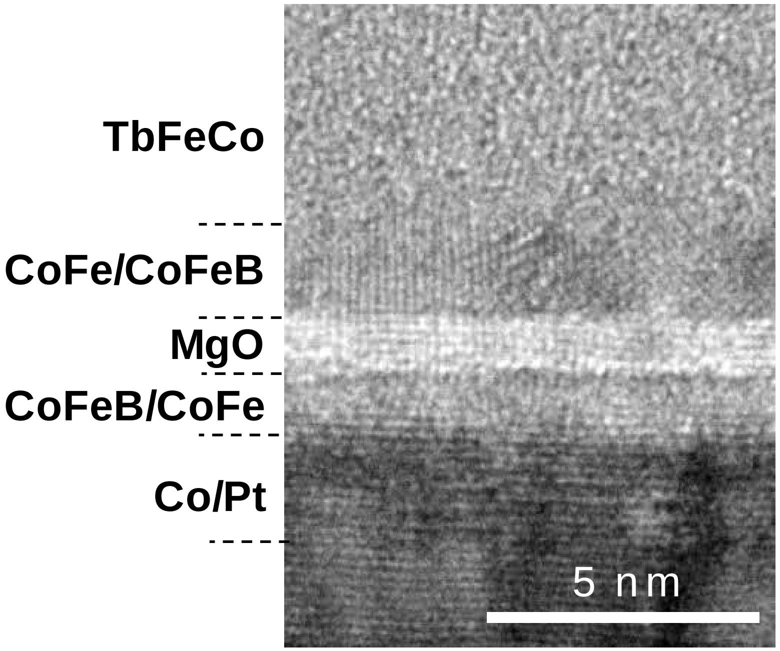
→ **Insertion of CoFeB between MgO and PMA layer**



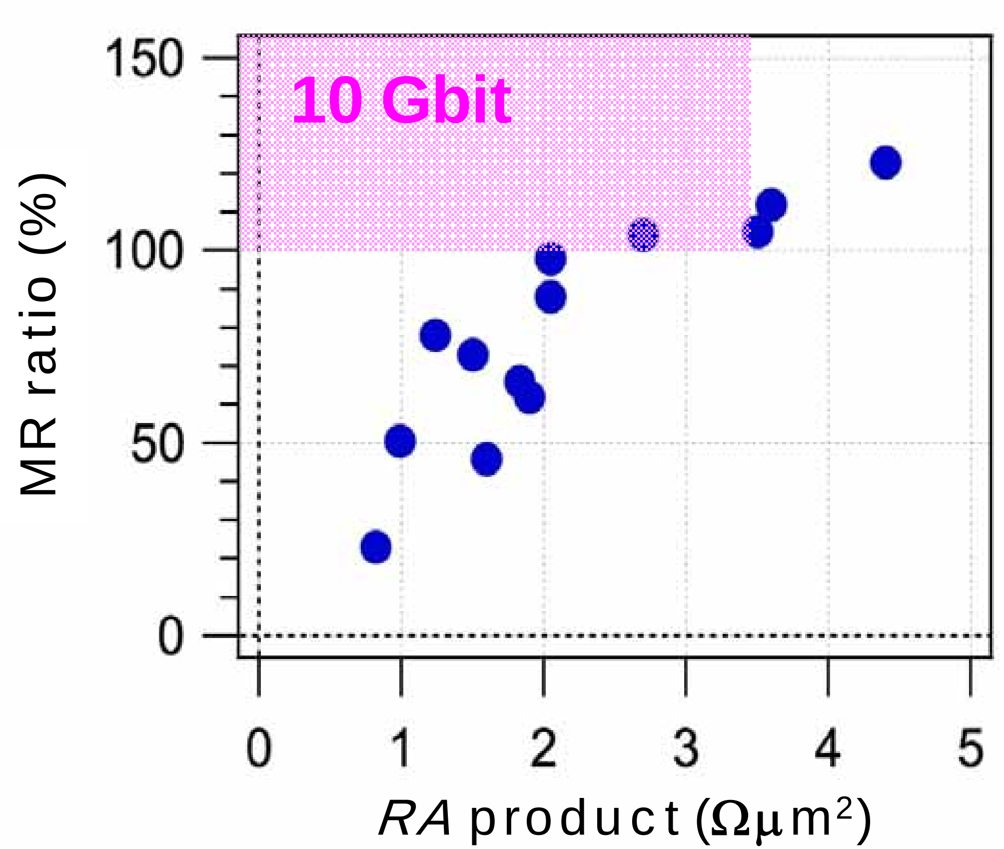
Typical structure of p-MgO-MTJ

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





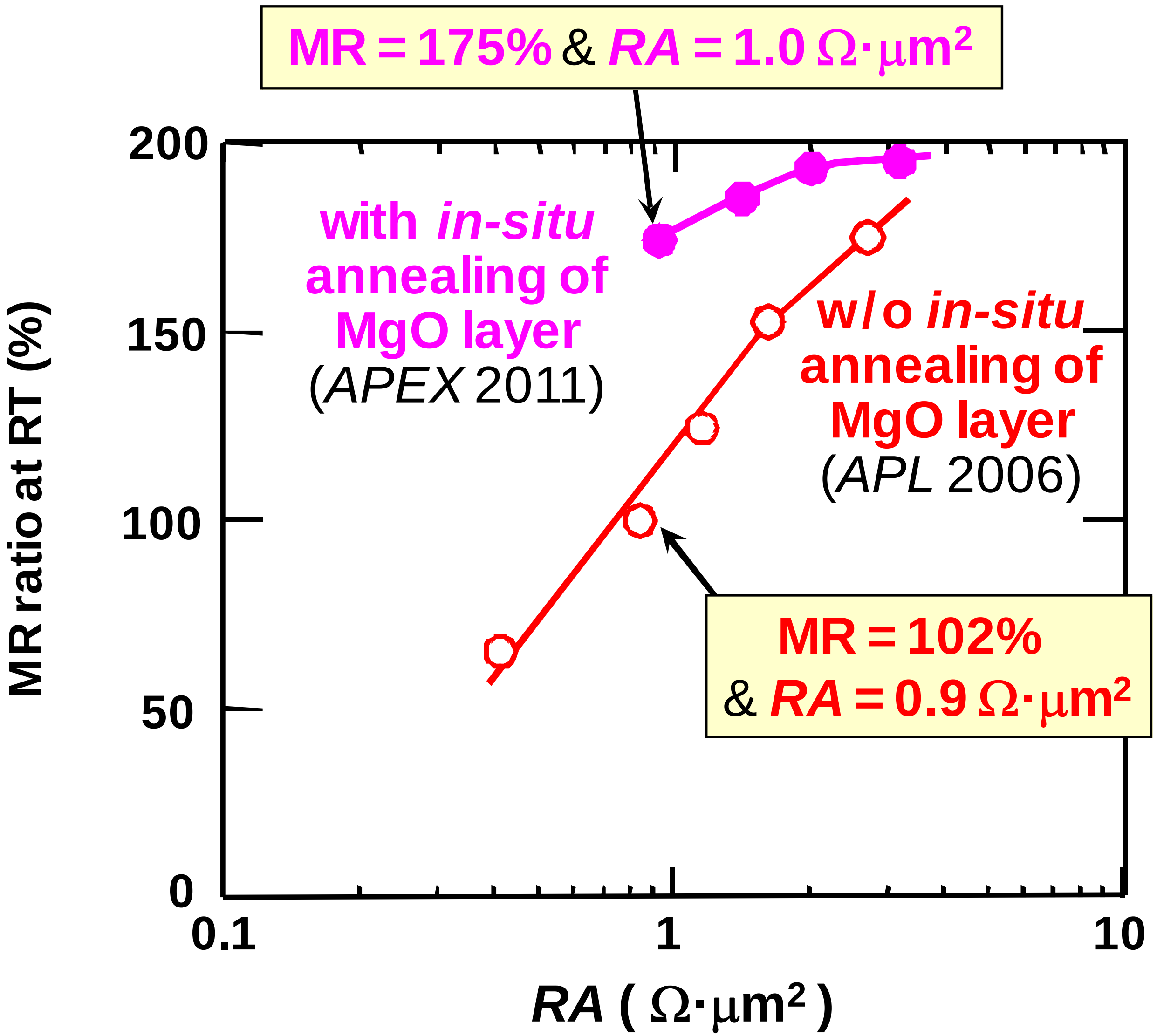
Can we simultaneously attain high MR & low *RA* ? – *Yes !*



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).



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

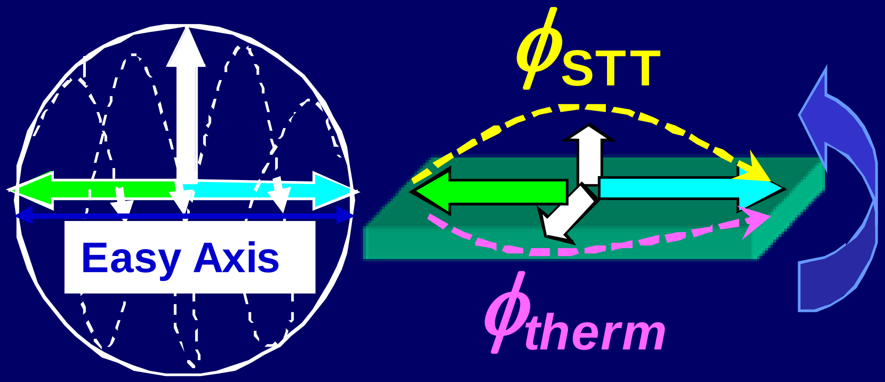
(4) Switching speed **<** 20 ns to replace DRAM

< 1 – 3 ns to replace SRAM

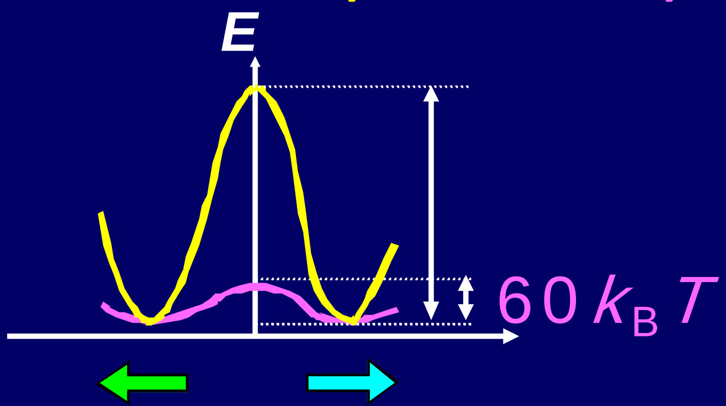
Potential barrier for magnetization switching

In-plane

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

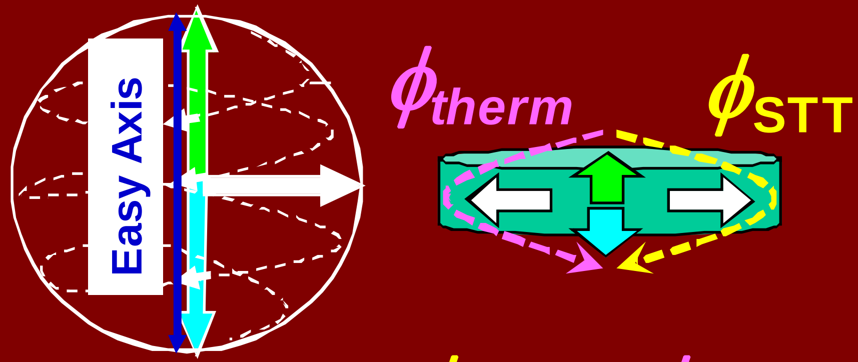


$\phi_{STT} \sim 30\,\phi_{therm}$

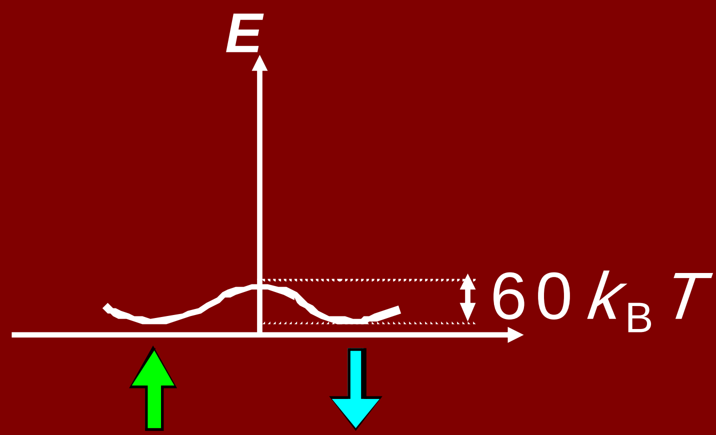


Perpendicular

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

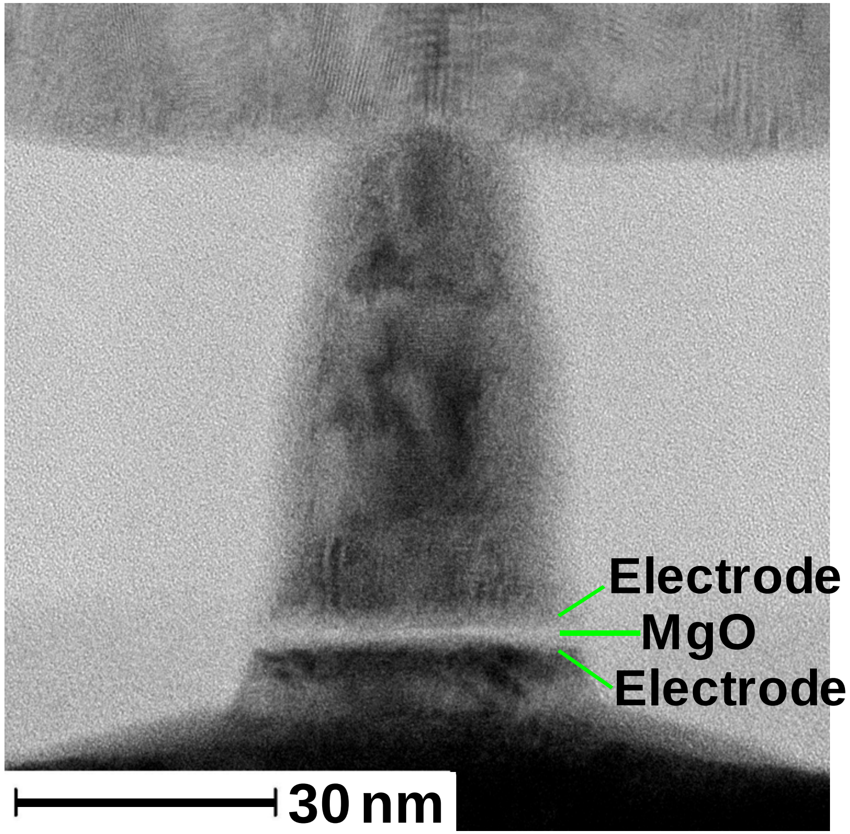


$\phi_{STT} \sim \phi_{therm}$

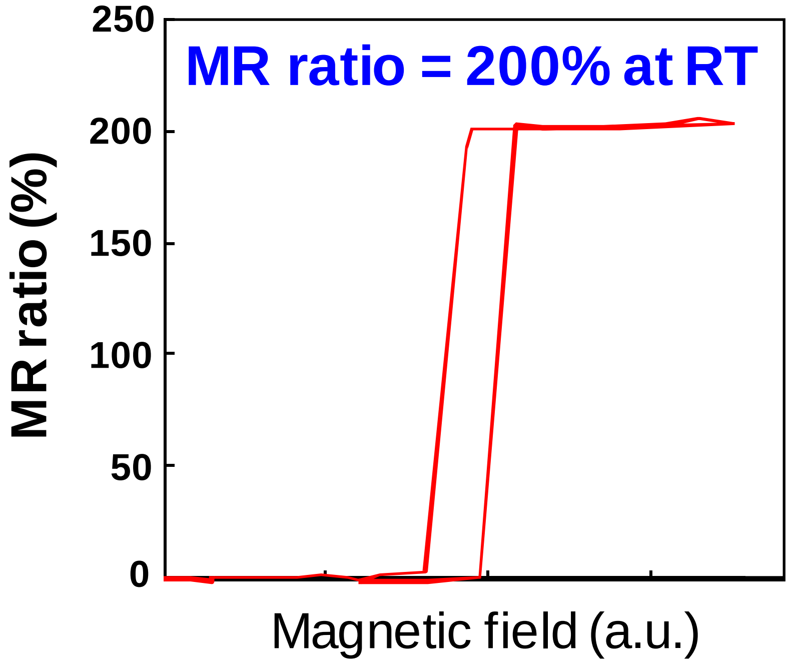


Our latest data (Courtesy of Toshiba)

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



ϕ 30 nm MgO-MTJ with perp. magnetization



$J_{c0} = 5 \times 10^5$ 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

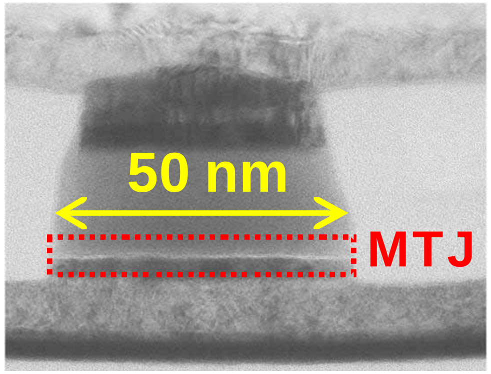
(2) MR ratio > 100 – 150% and low *RA* product

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

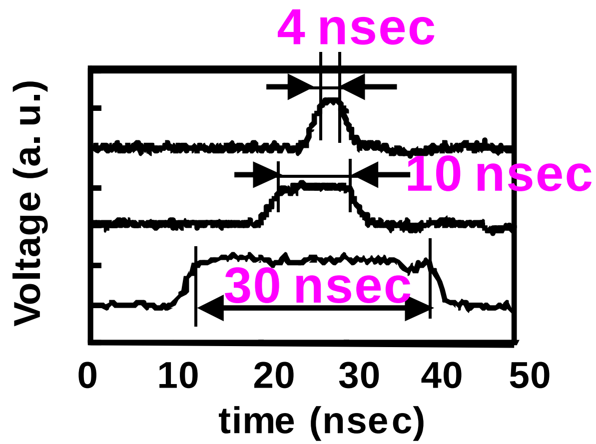
⇨ (4) Switching speed **<** 20 ns to replace DRAM
< 1 – 3 ns to replace SRAM

Demonstration of high-speed switching

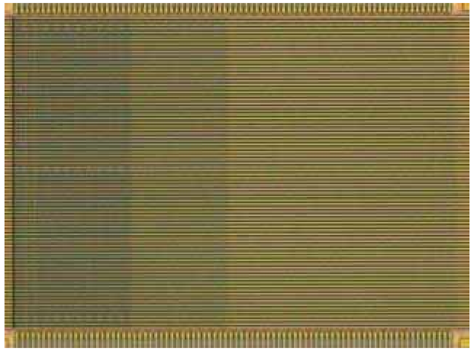
Kishi, SY *et al*. *IEDM 2008*, 12.6.
(Toshiba, AIST, *etc*.)



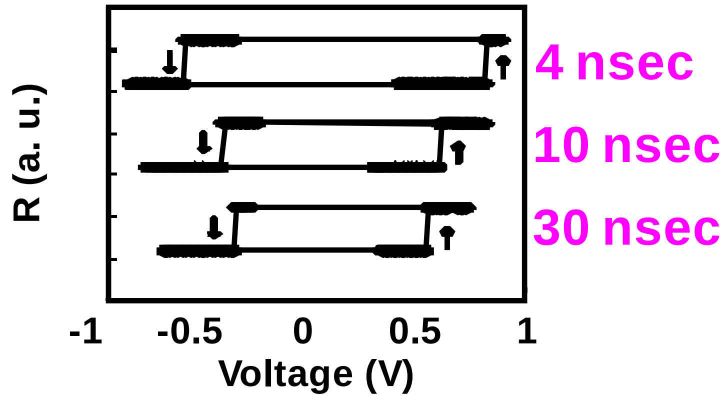
TEM image



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	Δ > 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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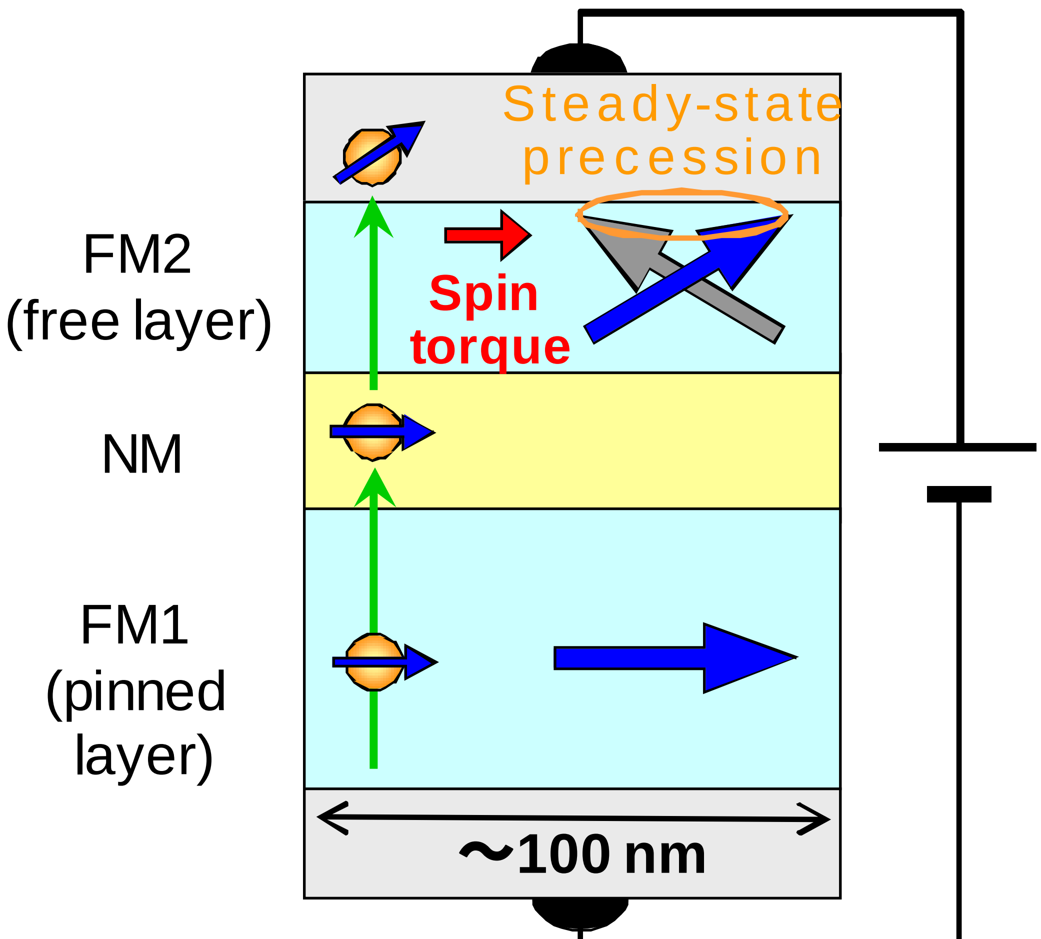
(3) Spin-transfer torque (STT)

- 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 ↕

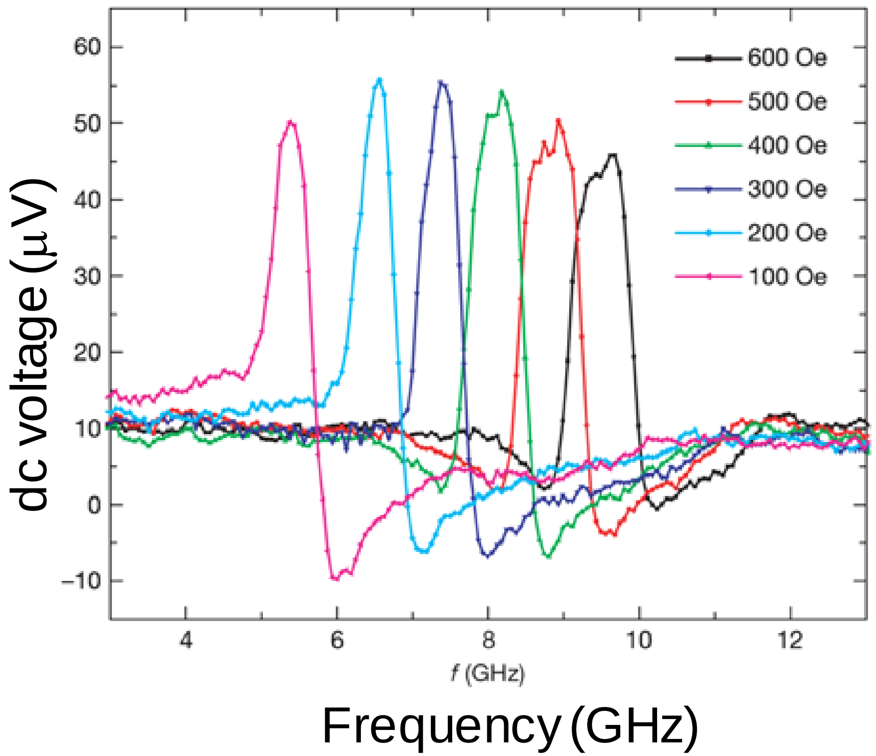
AC current & voltage
(FMR frequency)

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

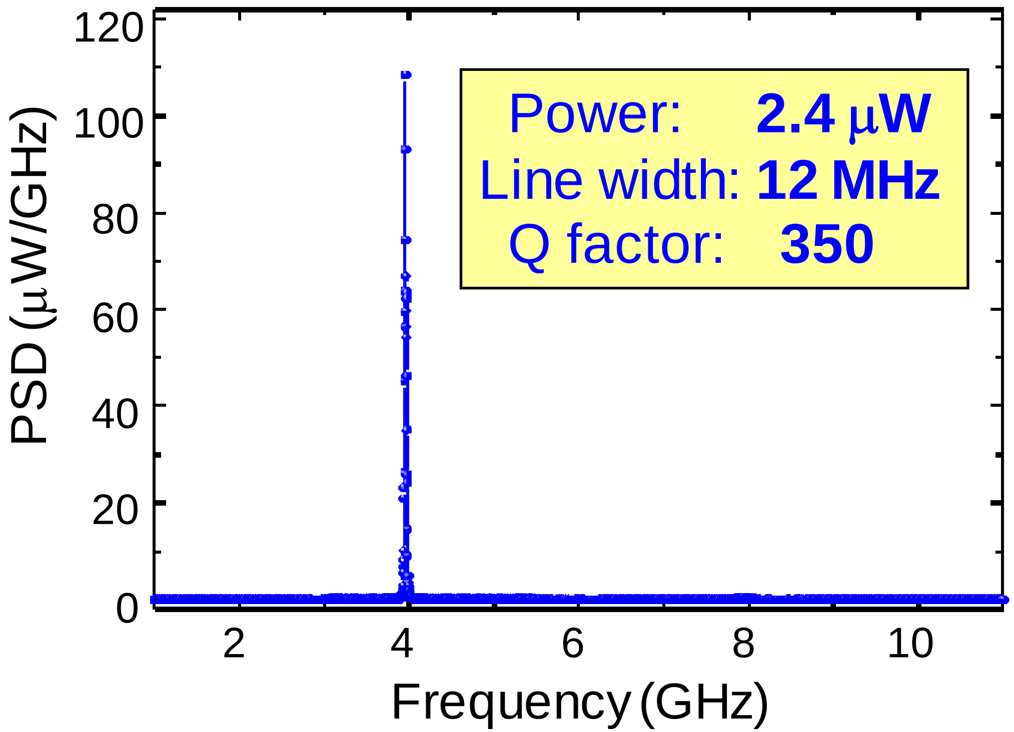
Microwave power ∝ (MR ratio)^2

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.*



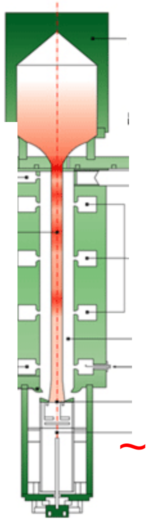
Spin-torque diode effect
(microwave detection)



Spin-torque oscillator (STO)
(microwave emission)

Advantages of STO over conventional microwave oscillators

Klystron

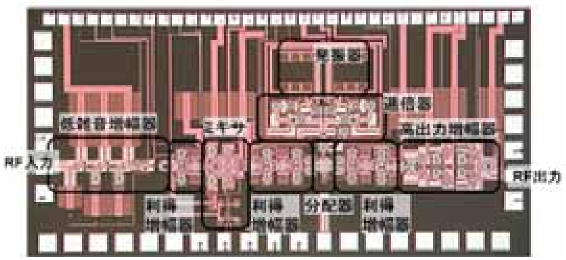


~10 cm

Gunn diode oscillator

~1 cm

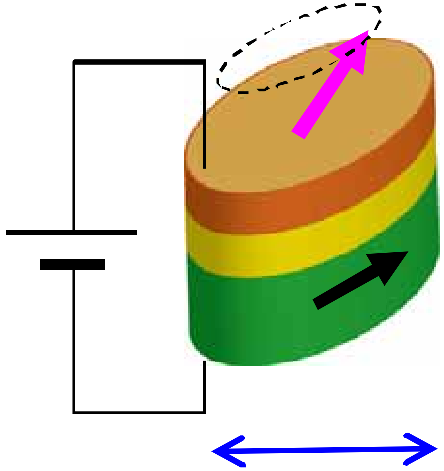
Large !



MMIC: low efficiency

MMIC: Monolithic Microwave IC

MgO-MTJ-based STO



CoFeB

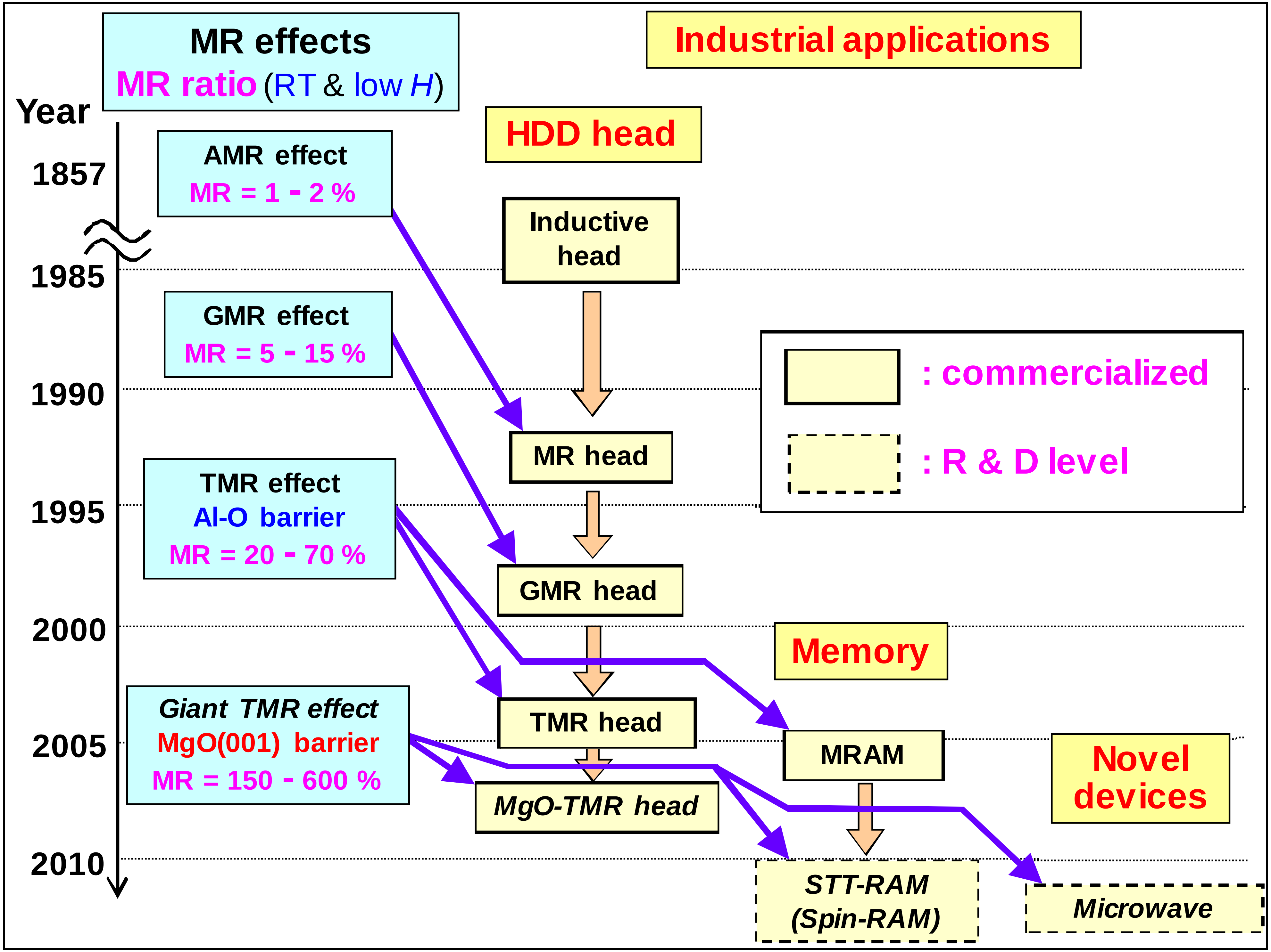
MgO

CoFeB

100 nm

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
: commercialized
: R & D level
Memory
MRAM
STT-RAM (Spin-RAM)
Novel devices
Microwave