Tunnel Magnetoresistance Effect and Its Applications

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Collaborators

Osaka University

(High-frequency experiment)

Canon ***Canon Anelva Corp.***

(R & D of manufacturing technology)

TOSHIBA ***Toshiba Corp.***

(R & D of Spin-MRAM)

Funding agencies

JST

NEDO 技術開発機構

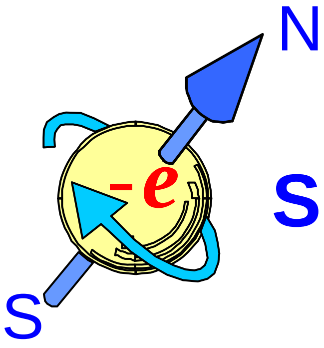
Outline

(1) Introduction

(2) Epitaxial MTJs with a crystalline MgO(001) barrier

(3) CoFeB / MgO / CoFeB MTJs for device applications

Spintronics



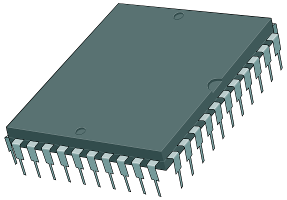
Charge **Spin**

Electron

Electronics
- diode
- transistor

Magneto-resistance

Magnetics
- magnetic recording
- permanent magnet



LSI

Since 1988

Spintronics

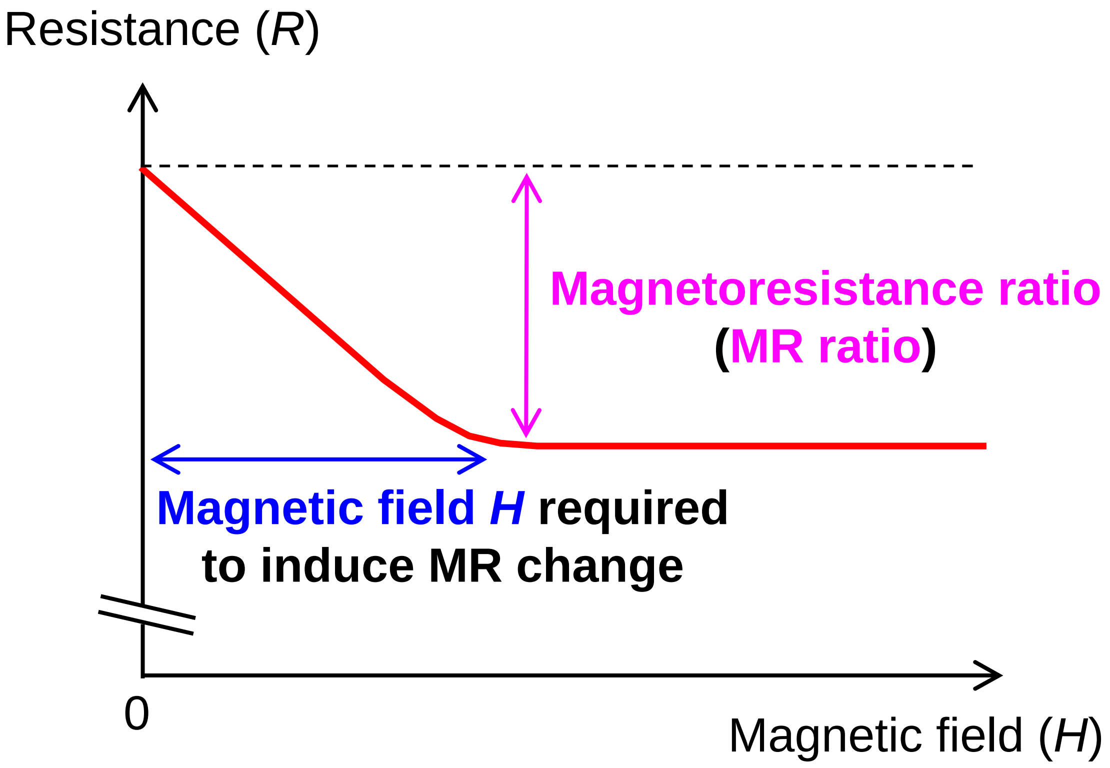
Both charge and spin of the electron is utilized for novel functionalities.

Hard Disk Drive (HDD)

What is "*magnetoresistance*" ?

A change in resistance by an application of *H*.

Magneto-Resistance ; **MR**



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

Magnetoresistance

MR ratio (**RT** & **low *H***)

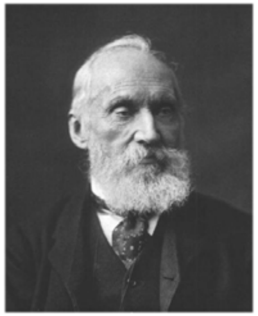
Year

1857

AMR effect

MR = 1 ~ 2 %

Lord Kelvin



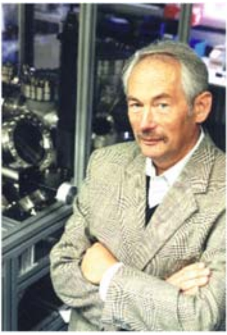
1985

GMR effect

MR = 5 ~ 15 %

A. Fert, P. Grünberg

(**Nobel Prize 2007**)



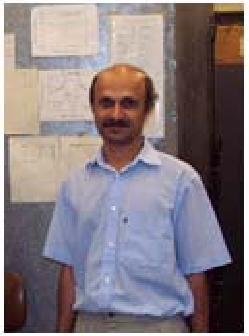
1990

1995

TMR effect

MR = 20 ~ 70 %

T. Miyazaki, J. Moodera

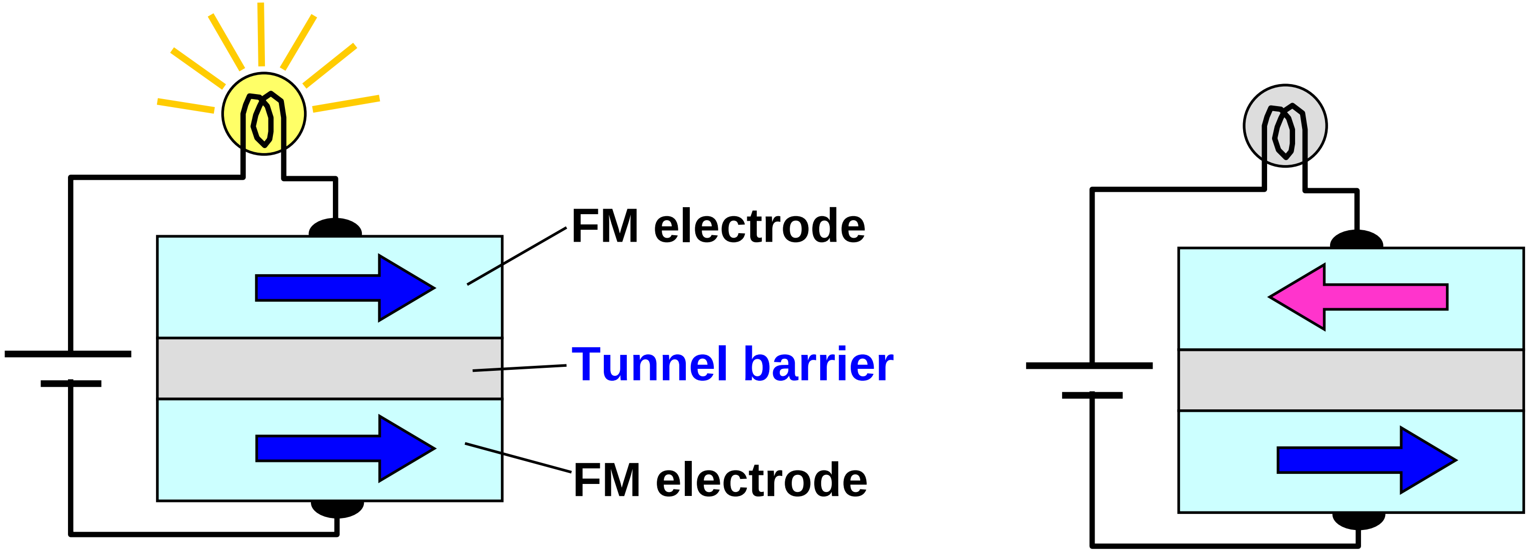


2000

2005

2010

Tunnel magnetoresistance (TMR) effect



Parallel (P) state

Tunnel Resistance R_P : **low**

Antiparallel (AP) state

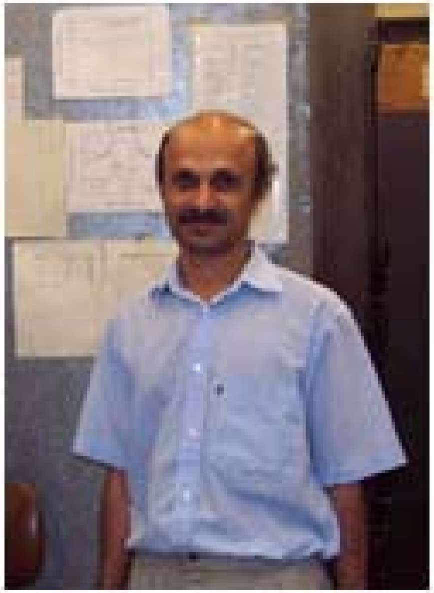
Tunnel Resistance R_{AP} : **high**

Magnetic tunnel junction (MTJ)

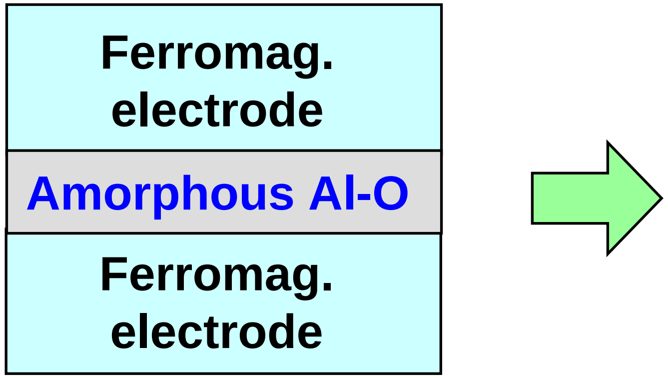
MR ratio $\equiv (R_{AP} - R_P) / R_P$ (performance index)

Room-temperature TMR in 1995

T. Miyazaki
(Tohoku Univ.)



J. S. Moodera
(MIT)



Ferromag. electrode

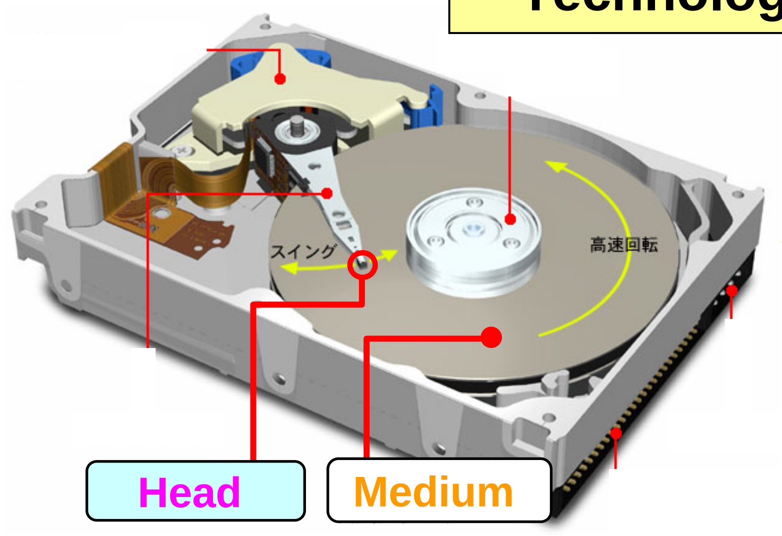
Amorphous Al-O

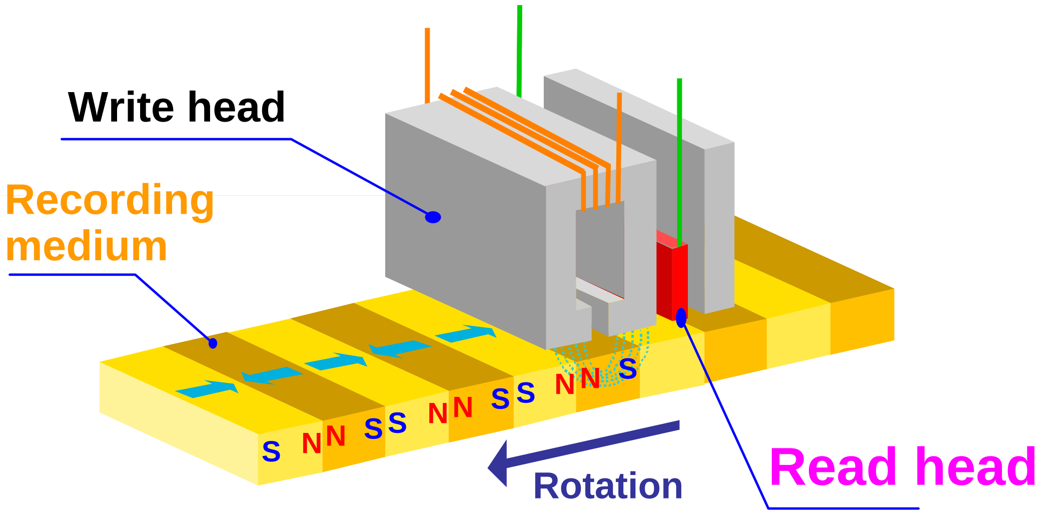
Ferromag. electrode

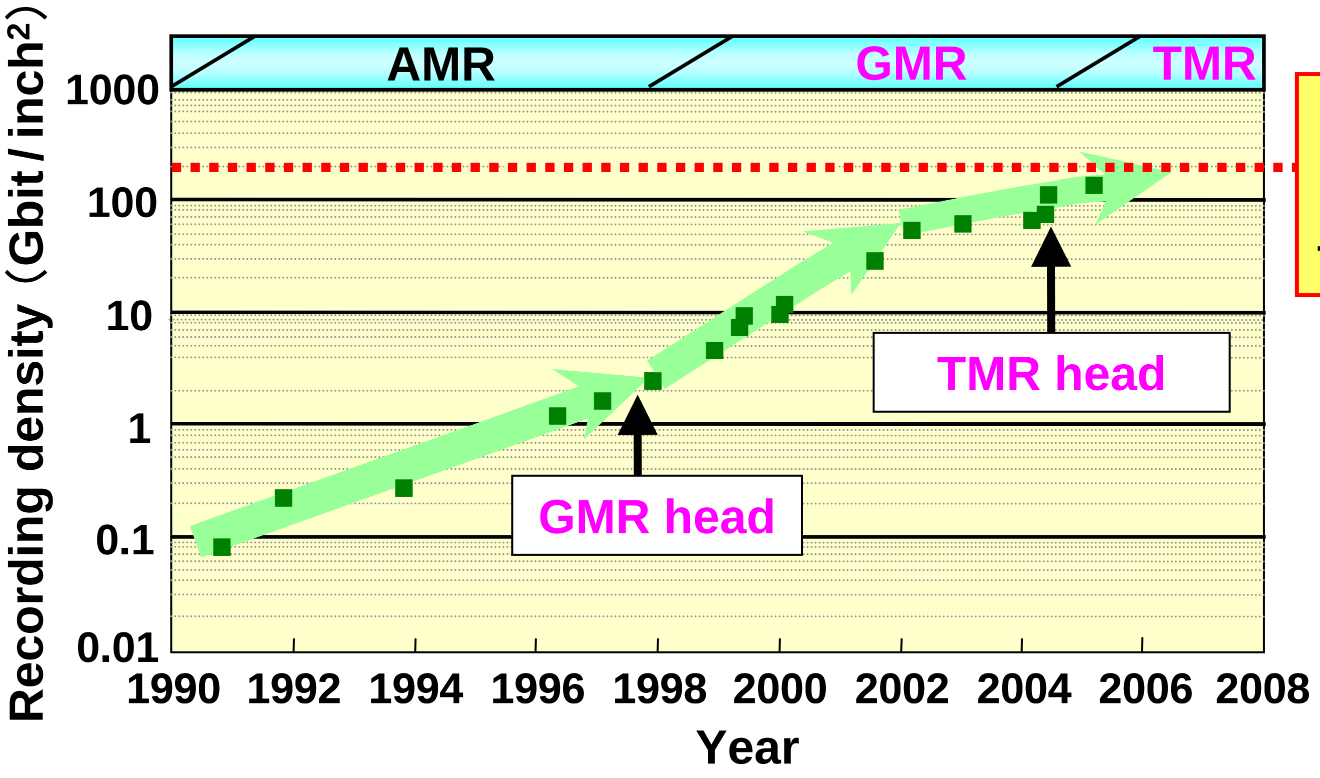
Al-O – based MTJ

MR ratios of 20 – 70% at RT

Technologies for HDD read head

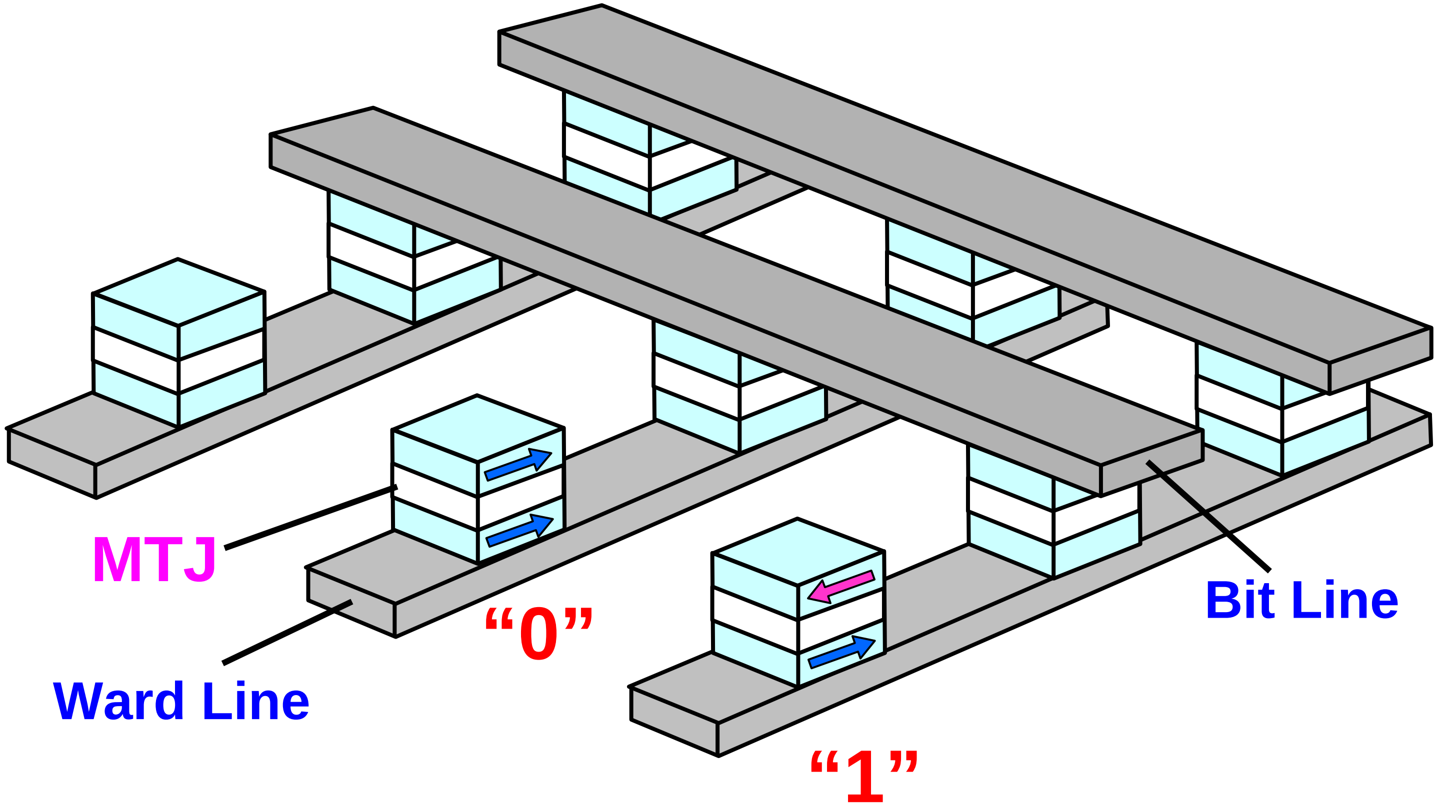






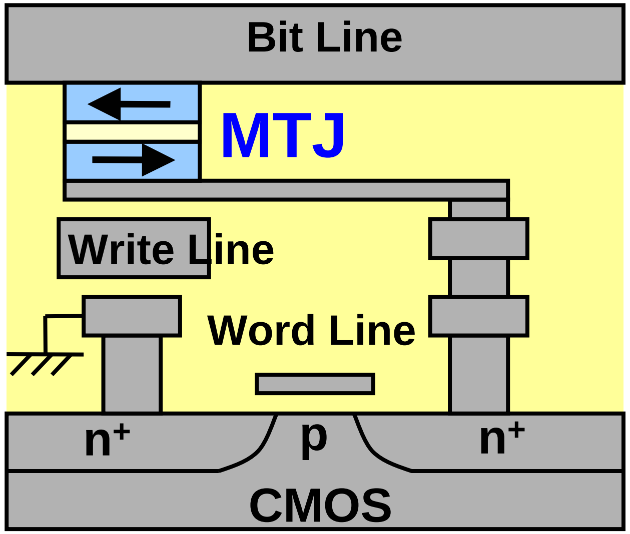
Next-generation read head is indespensable for > 200 Gbit / inch^2.

Magnetoresistive Random Access Memory (MRAM)

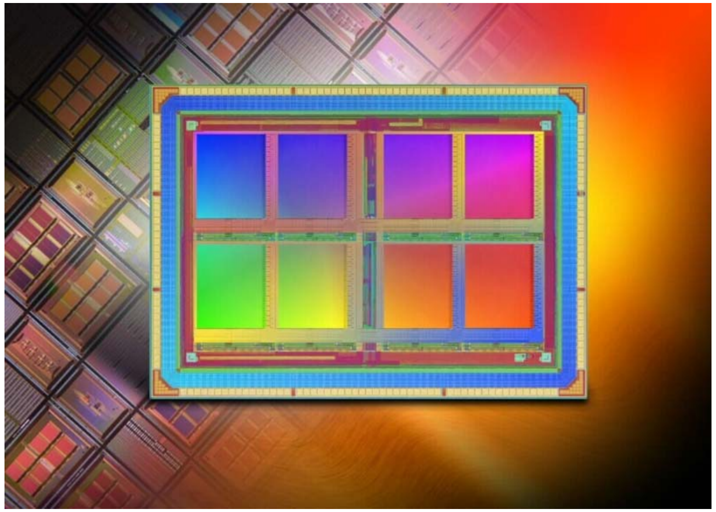


Non-volatile memory

Magnetoresistive Random Access Memory (MRAM)



Cross-section structure



Freescale's 4 Mbit-MRAM
based on Al-O MTJs
Volume production since 2006.

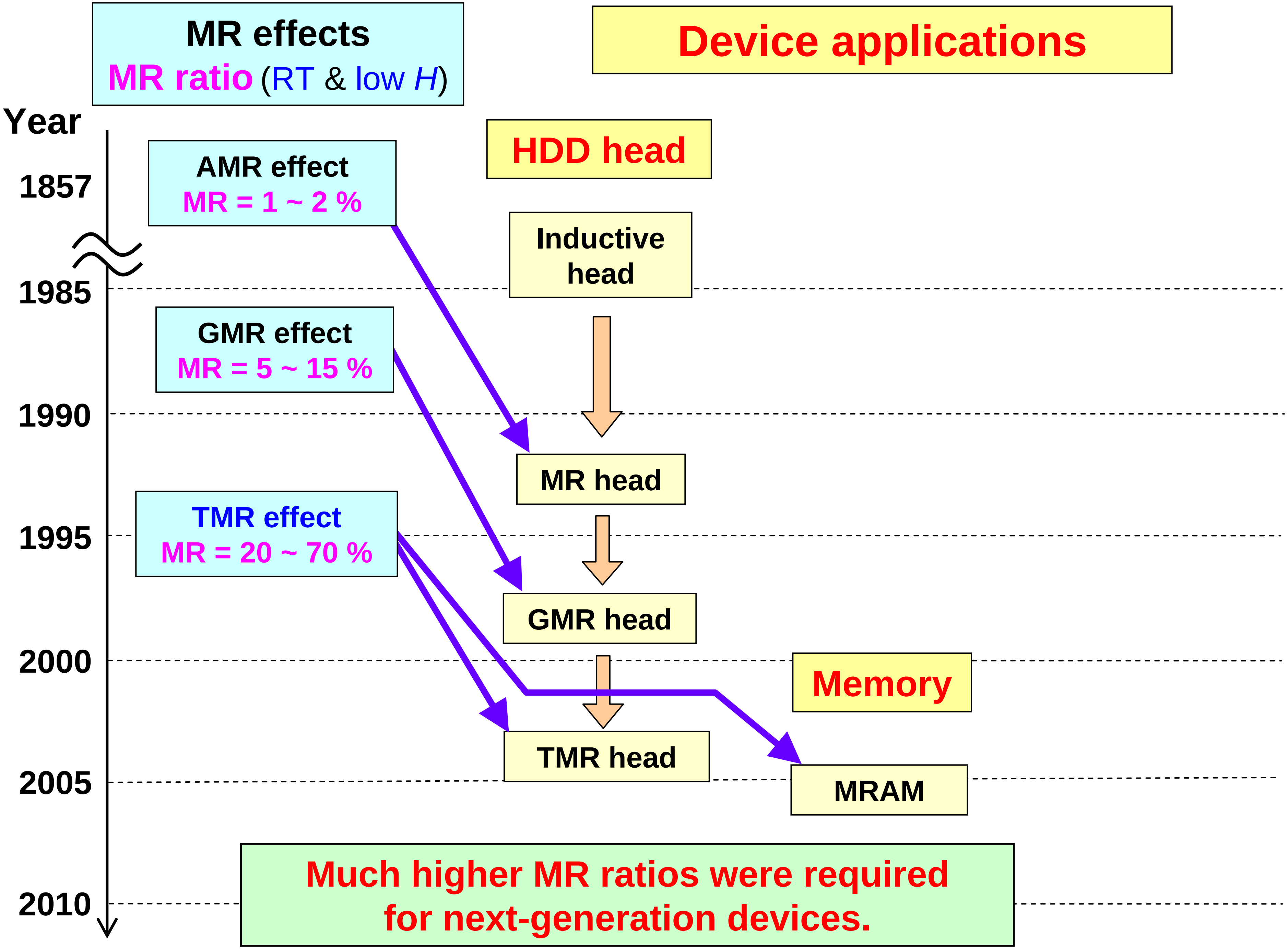
<Advantages>

Non-volatile, high speed, infinite write endurance, etc.

<Disadvantage>

High-density MRAM is difficult to develop.

MR ratios > 150% at RT are required for developing Gbit-MRAM.



MR effects

MR ratio (RT & low *H*)

Device applications

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AMR effect
MR = 1 ~ 2 %

GMR effect
MR = 5 ~ 15 %

TMR effect
MR = 20 ~ 70 %

HDD head

Inductive head

MR head

GMR head

TMR head

Memory

MRAM

Much higher MR ratios were required for next-generation devices.

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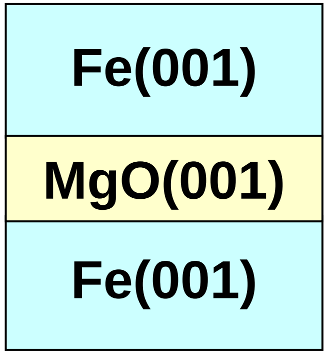
Theoretical prediction of giant TMR effect in Fe/MgO/Fe



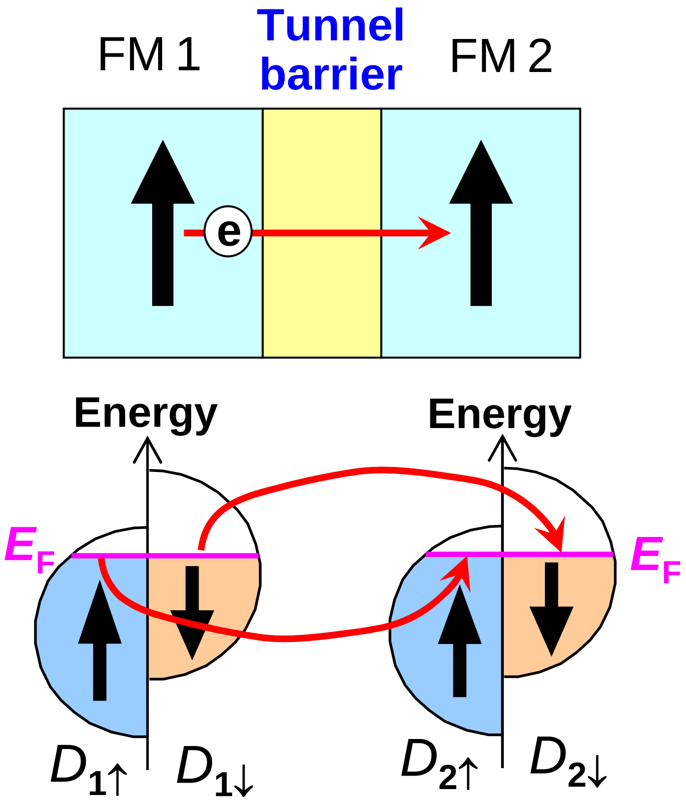
Fully epitaxial MTJ

< First-principle calculations >

- Butler *et al*., *Phys. Rev*. B **63**, 056614 (2001).
- Mathon & Umerski, *Phys. Rev*. B **63**, 220403 (2001).

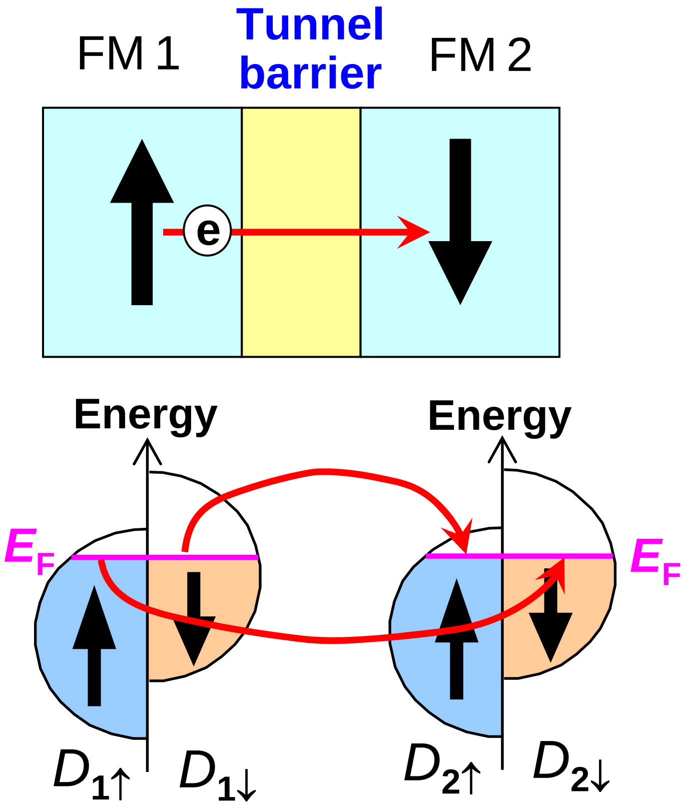
MR ratio > 1000%

Spin polarization *P*



Parallel (P) state

Tunnel resistnce: R_P



Antiparallel (AP) state

Tunnel resistnce: R_{AP}

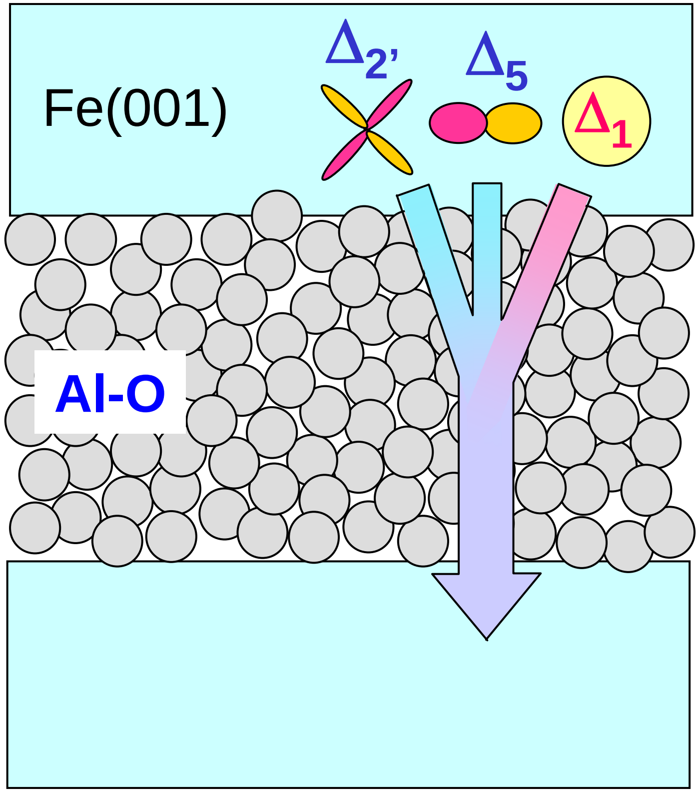
$$\mathbf{MR} \equiv (R_{AP} - R_P) / R_P = 2P_1P_2 / (1 - P_1P_2), \quad P_\alpha = \frac{\left(D_{\alpha\uparrow}(E_F) - D_{\alpha\downarrow}(E_F)\right)}{\left(D_{\alpha\uparrow}(E_F) + D_{\alpha\downarrow}(E_F)\right)}, \quad \alpha = 1, 2.$$

Spin polarization *P*

Tunneling process in MTJs

Amorphous Al-O barrier

No symmetry

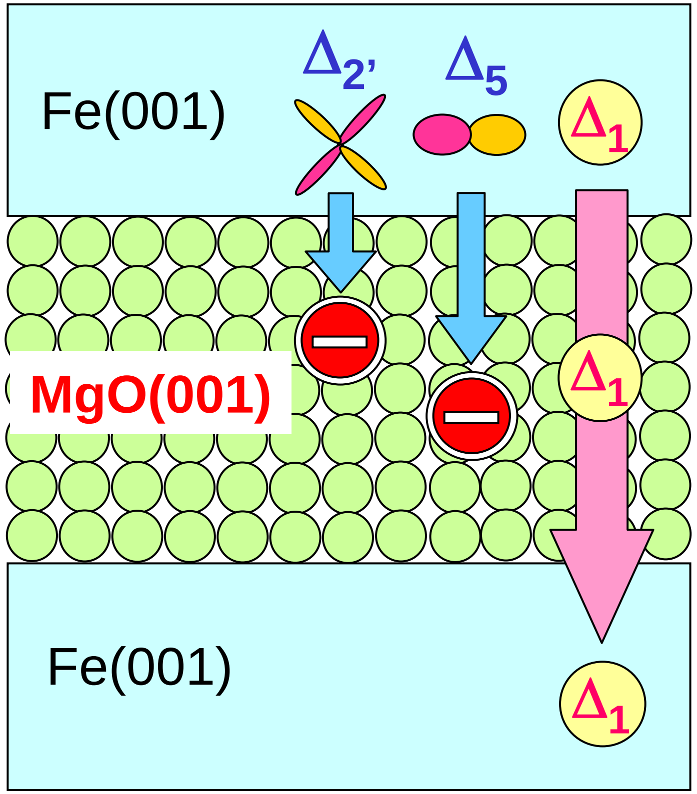


Various Bloch states tunnel incoherently.

MR ratio < 100% at RT

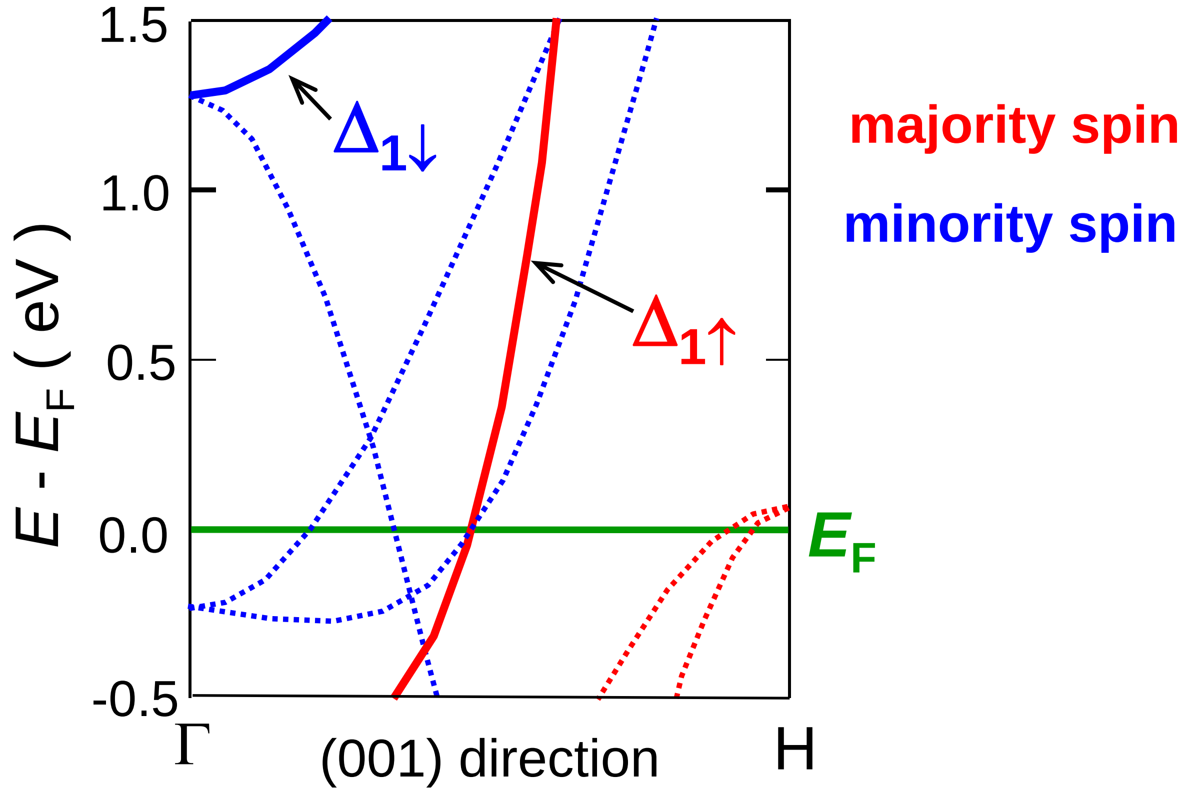
Crystalline MgO(001) barrier

4-fold symmetry



Only the Bloch states with Δ_1 symmetry tunnel dominantly.

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

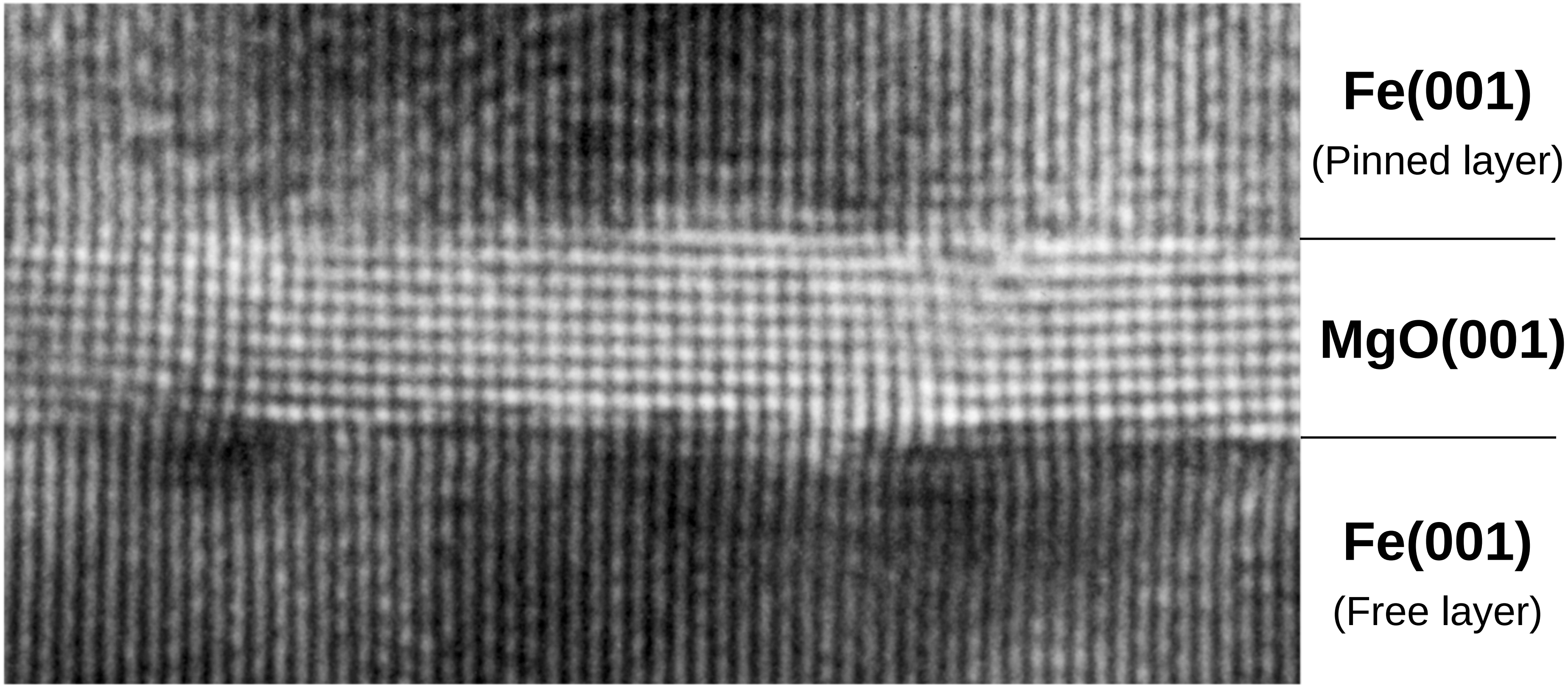


Fully spin-polarized Δ_1 band

⇒ 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 $Fe_{1-x}Co_x$, Heusler alloys)

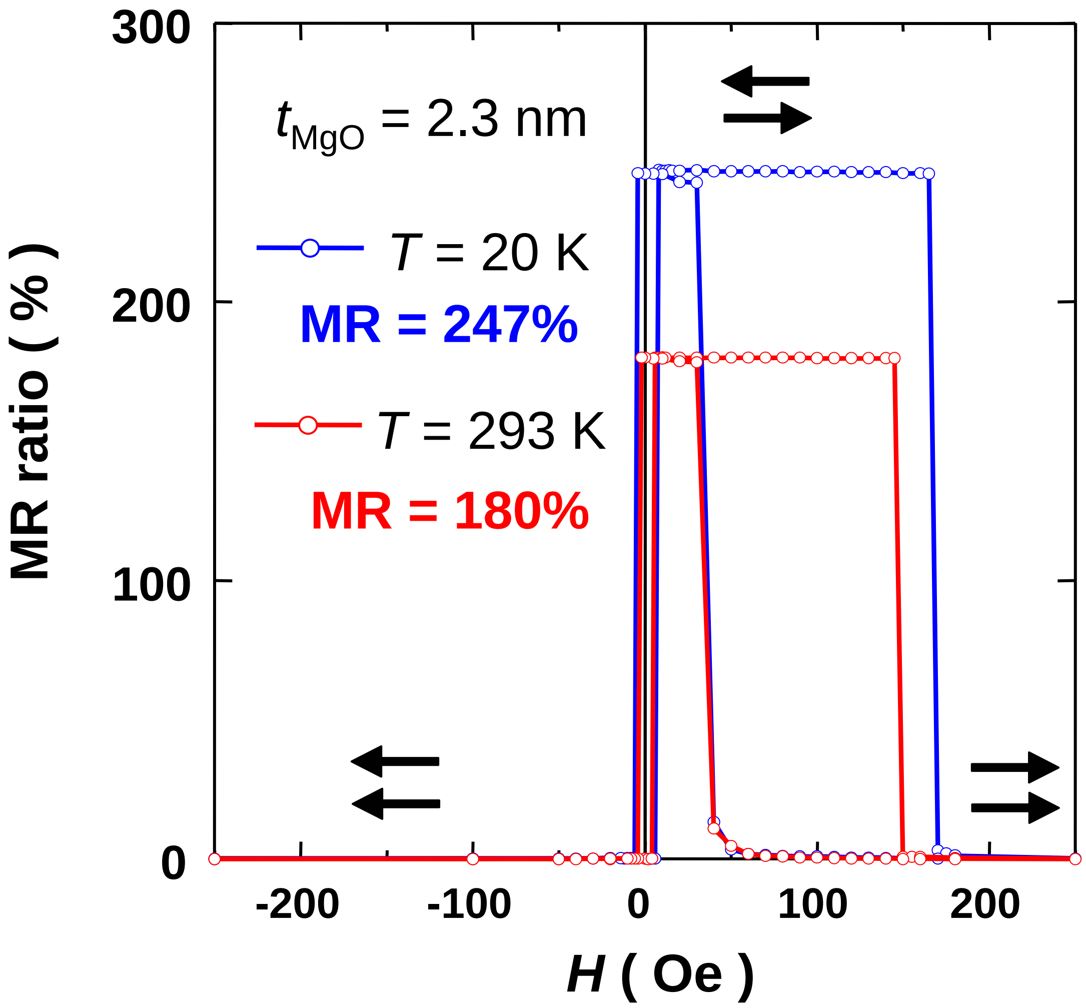
Fully epitaxial Fe/MgO/Fe MTJ grown by MBE



TEM image

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

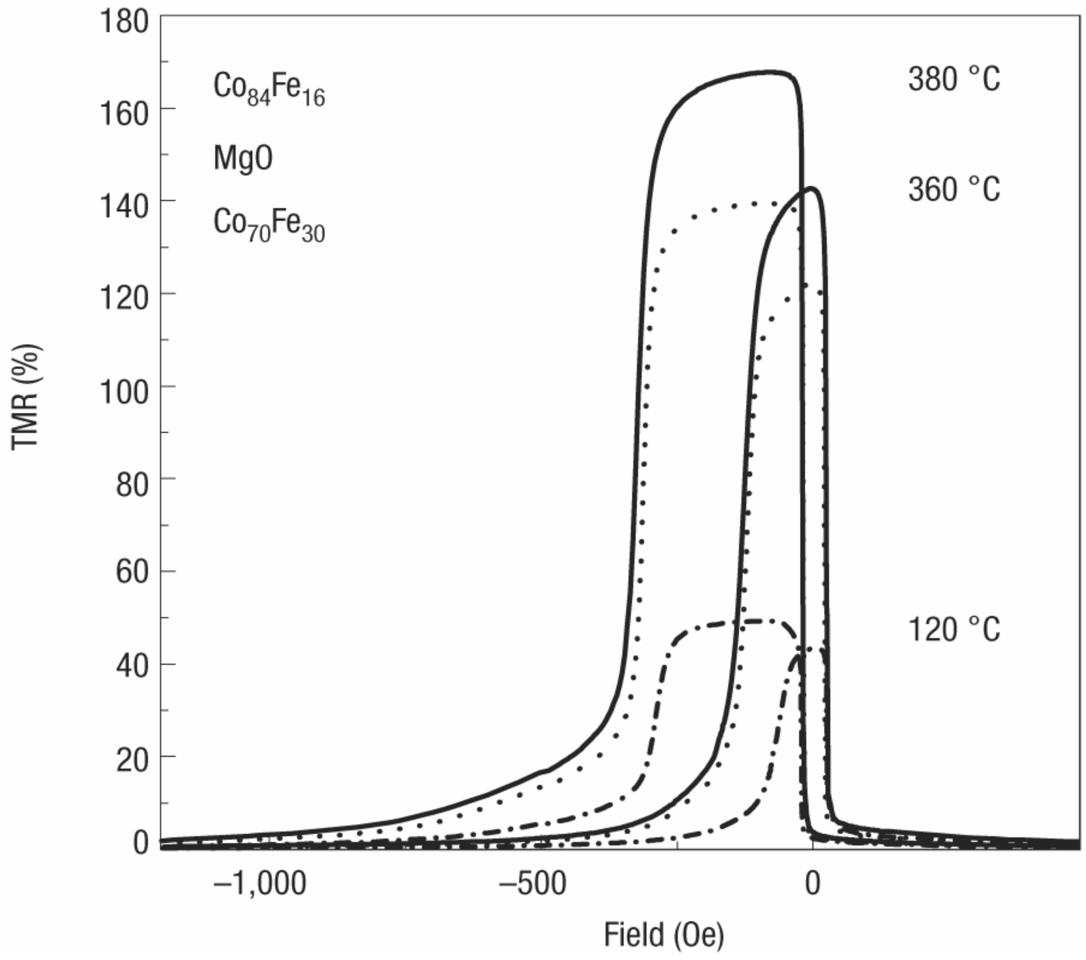
Magnetoresistance of epitaxial Fe/MgO/Fe MTJ



MTJs with a single-crystal MgO(001) barrier

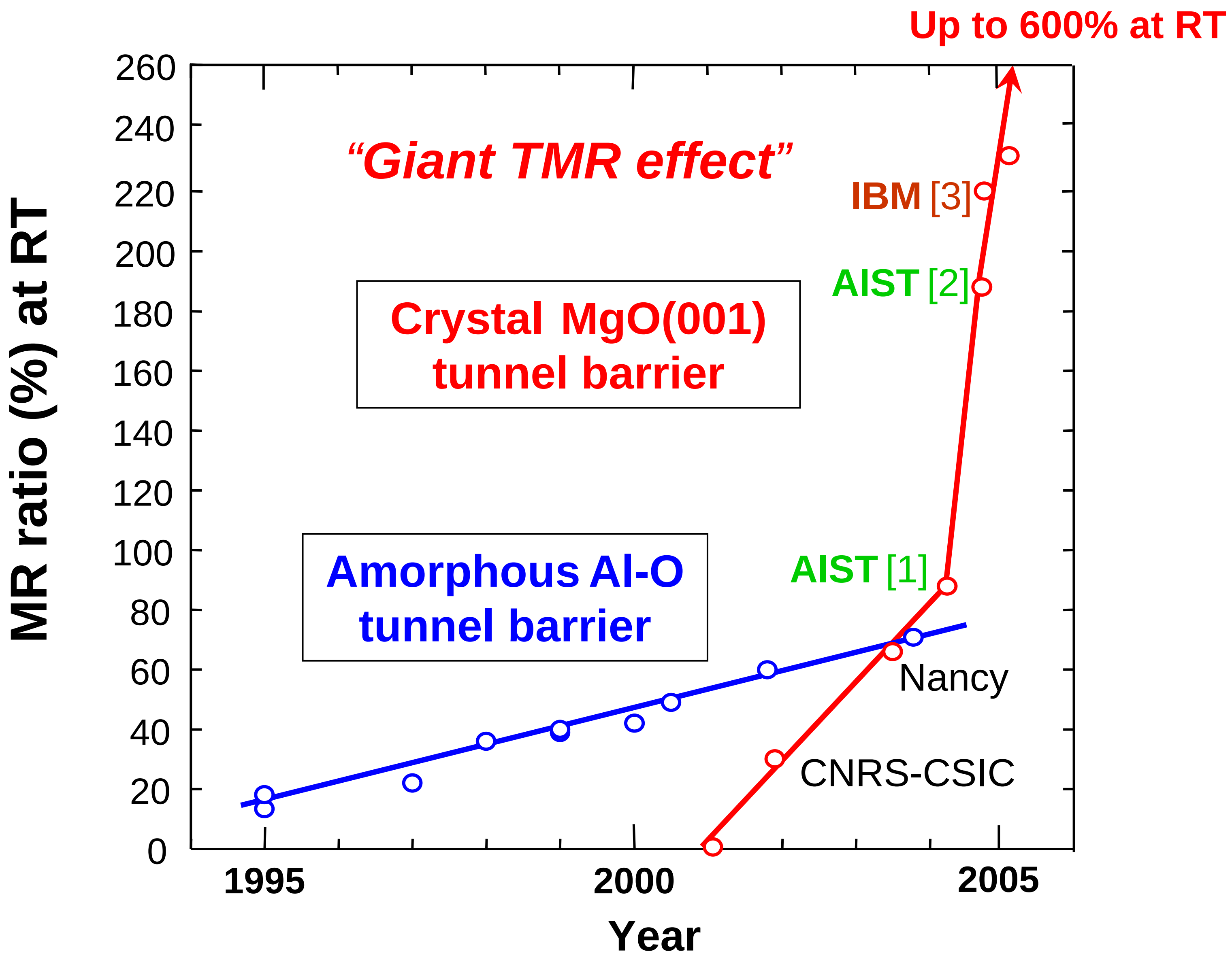
S. Yuasa *et al*., *Nature Materials* **3**, 868 (2004).

Magnetoresistance of textured MgO-based MTJ



MTJs with a (001)-oriented poly-crystal (textured) MgO barrier

S. S. P. Parkin *et al*., *Nature Materials* **3**, 862 (2004).



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

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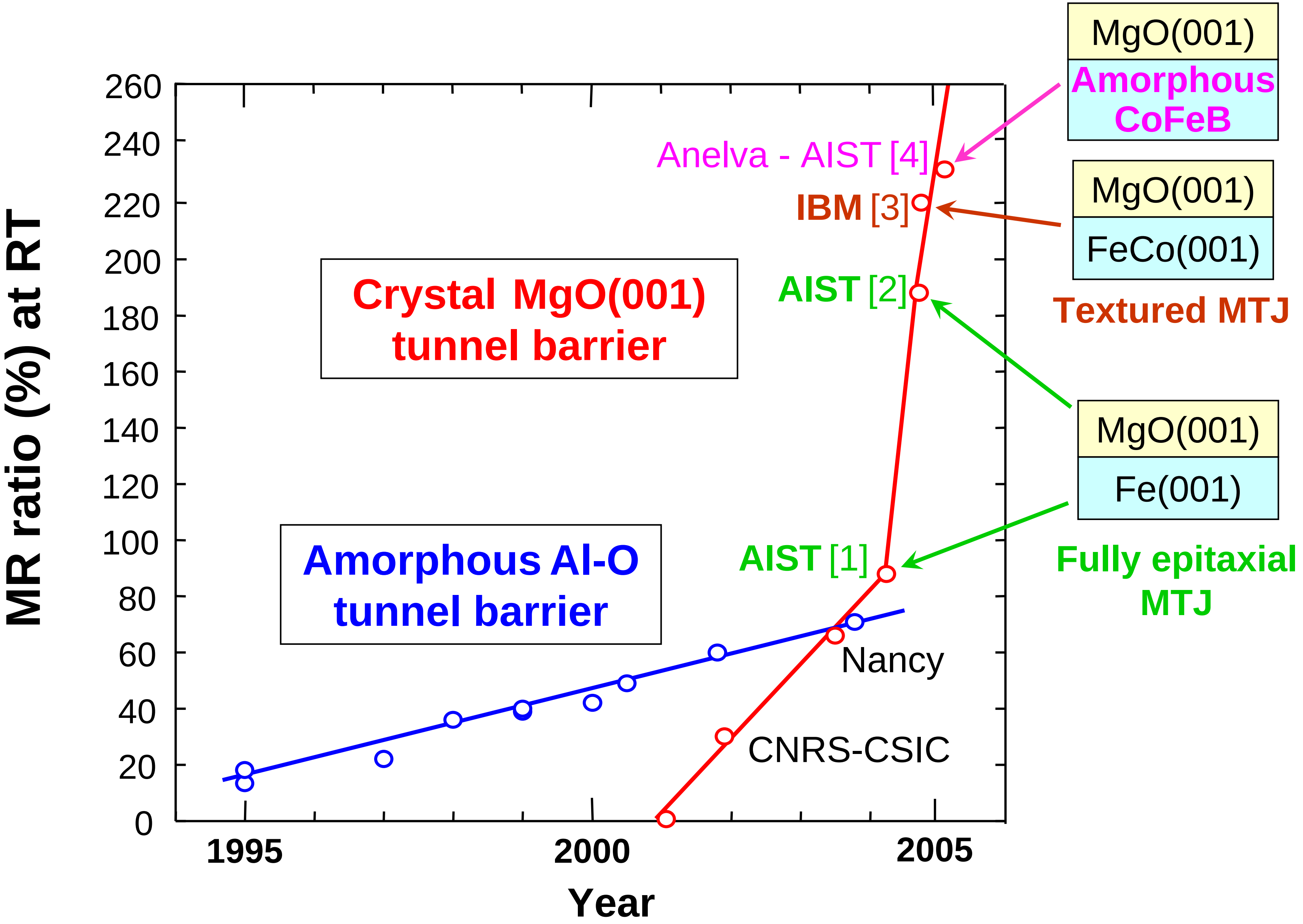
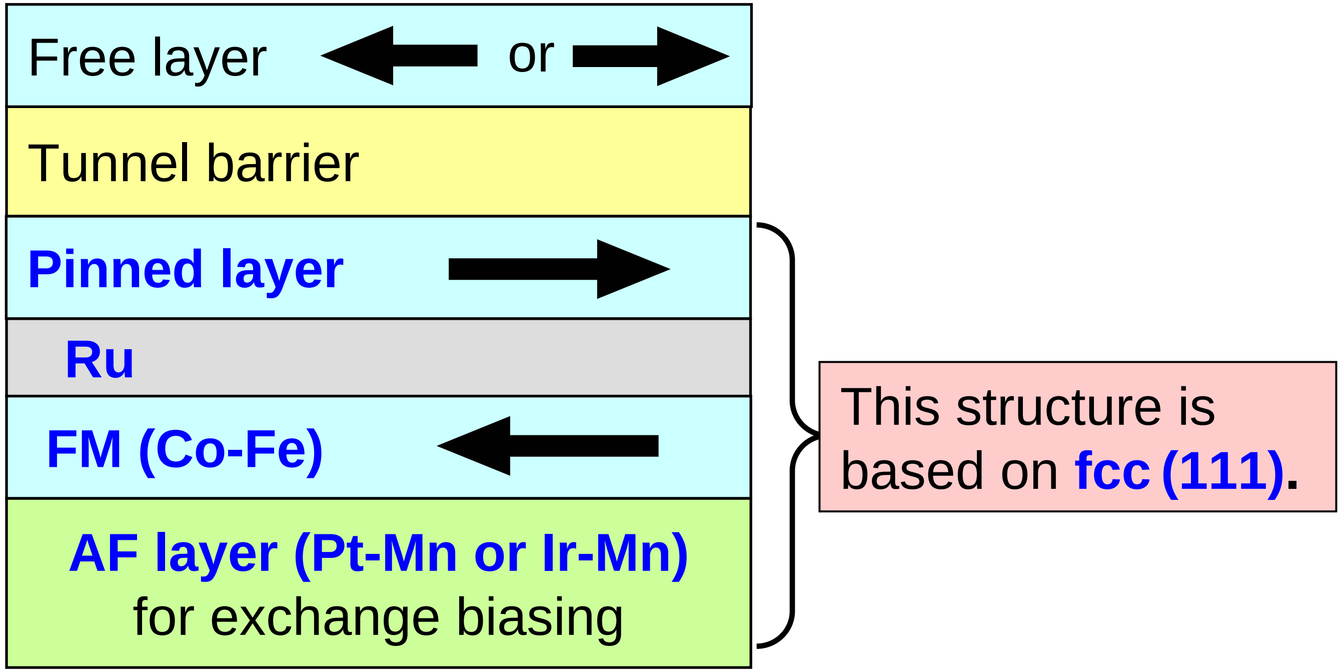


[1] Yuasa, *Jpn. J. Appl. Phys*. **43**, L558 (2004). [2] Parkin, *Nature Mater.* **3**, 862 (2004).

[3] Yuasa, *Nature Mater.* **3**, 868 (2004). [4] Djayaprawira, SY, *APL* **86**, 092502 (2005).

MTJ structure for practical applications

For MRAM & HDD read head



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)**.

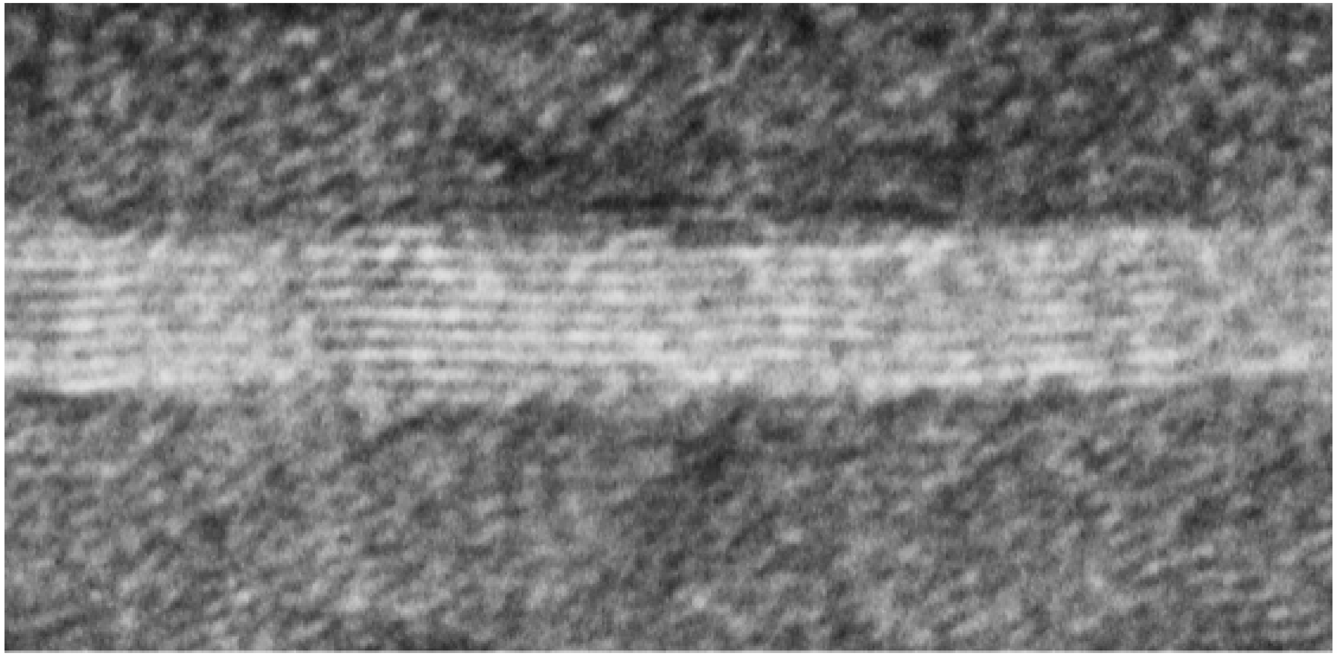
MgO(001) cannot be grown on **fcc (111)**.

4-fold symmetry

3-fold symmetry

MTJ structure in as-grown state

Collaboration with ***Canon-Anelva***



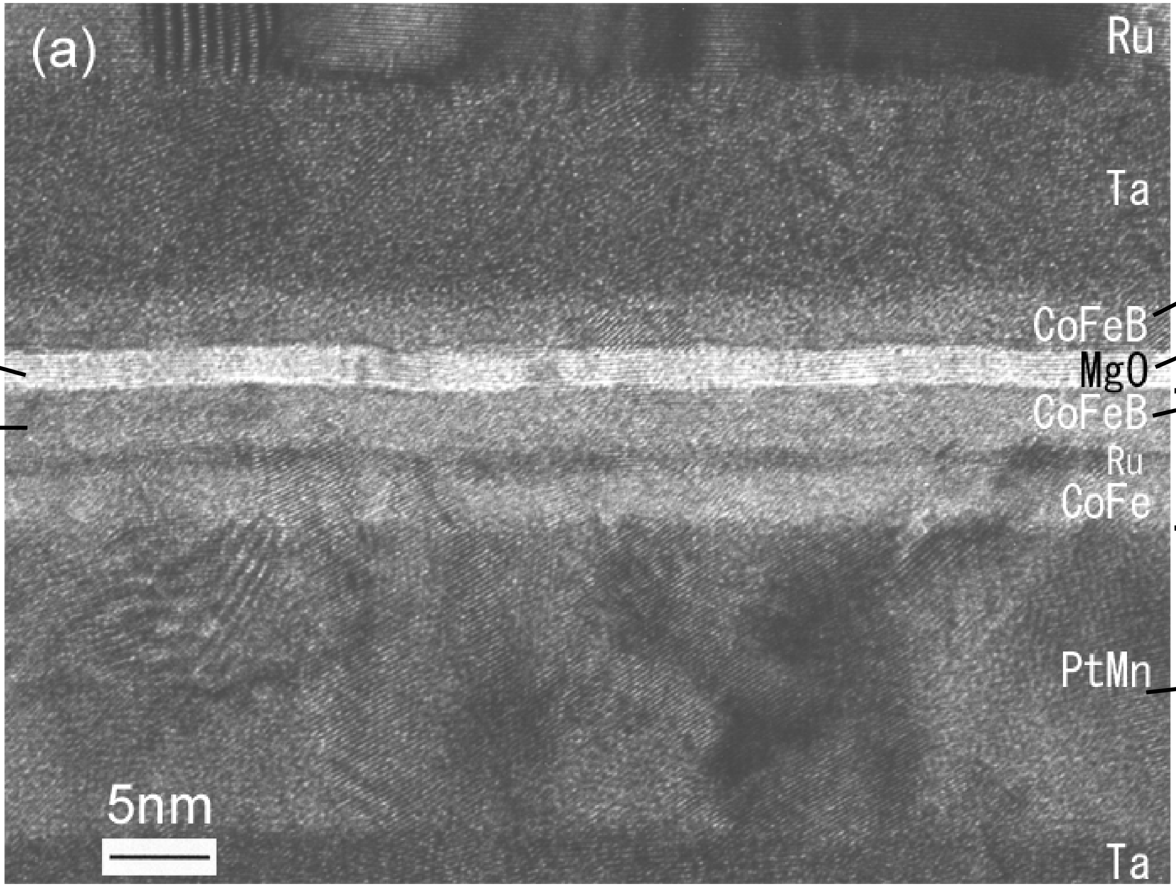
TEM image

Djayaprawira, SY, *Appl. Phys. Lett*. **86**, 092502 (2005).

◆**Ideal for device applications**

This structure can be grown on any kind of underlayers by sputtering deposition at RT + post - annealing.

CoFeB / MgO / CoFeB - MTJ with practical structure



Crystalline symmetry

4-fold

Amorphous

3-fold

Free layer

Tunnel barrier

Pinned layer

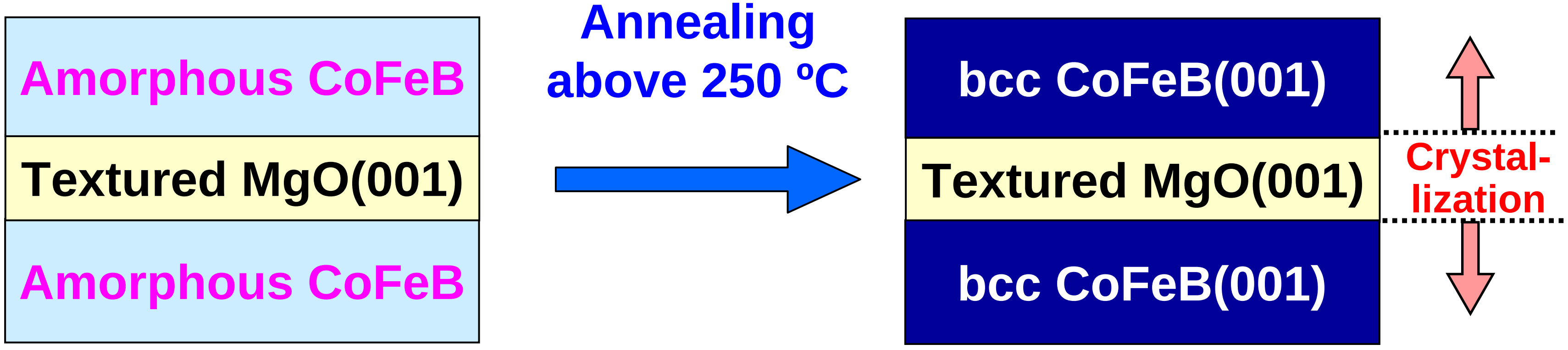
SyF structure

AF layer for exchange-biasing

Standard bottom structure for MRAM and HDD head

Crystallization of CoFeB by post - annealing

S. Yuasa *et al*., *Appl. Phys. Lett*. **87**, 242503 (2005).


Amorphous CoFeB

Textured MgO(001)

Amorphous CoFeB

Annealing above 250 ºC

bcc CoFeB(001)

Textured MgO(001)

bcc CoFeB(001)

Crystal-lization

As-grown MTJ

Crystallization of CoFeB

MgO(001) layer acts as a template to crystallize amorphous CoFeB.

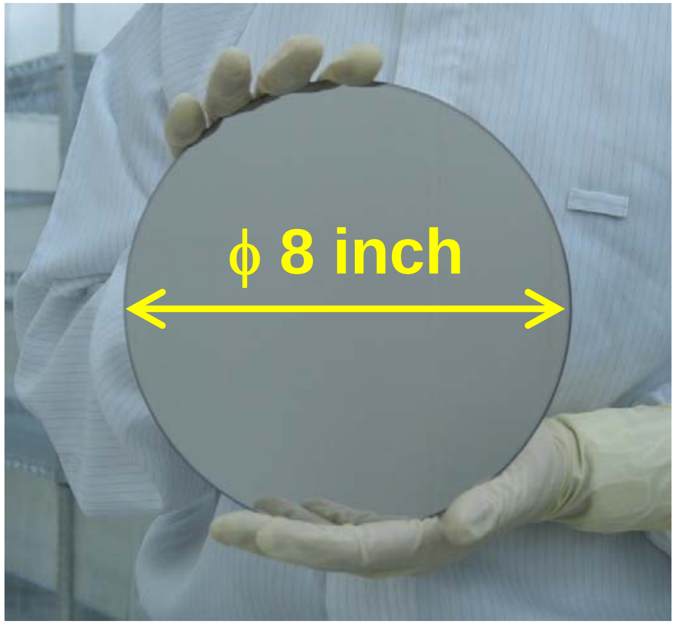
"Solid Phase Epitaxy"

Because the Δ_1 band in bcc CoFeB(001) is fully spin-polarized, CoFeB/MgO/CoFeB MTJs show the giant TMR effect.

Sputtering deposition

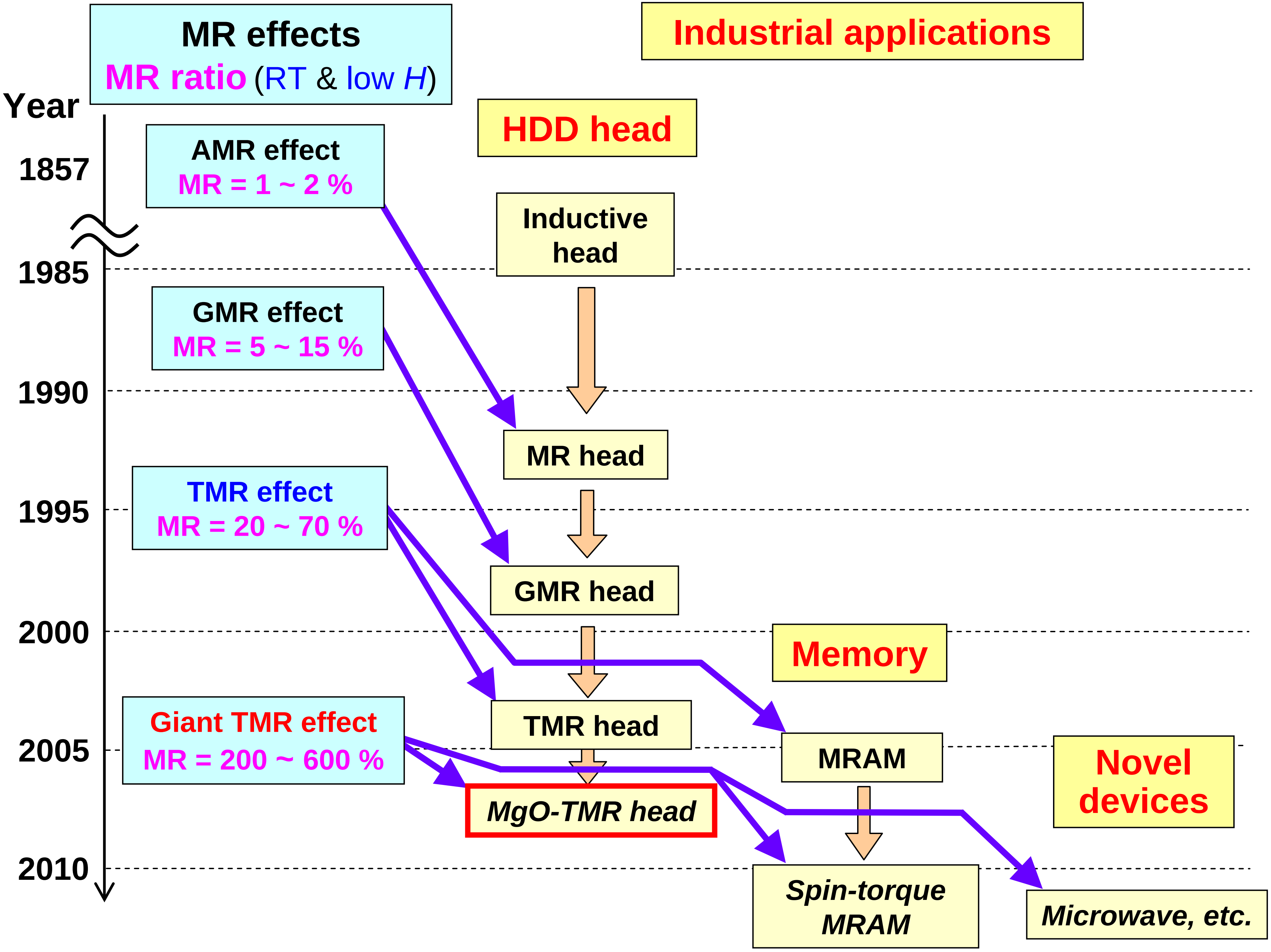
Canon-ANELVA C-7100 system

Standard sputtering machine
in HDD industry



Thermally oxidized
Si wafer (8 or 12 inch)

100 wafers a day !



MR effects
MR ratio (RT & low *H*)

Industrial applications

Year

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AMR effect
MR = 1 ~ 2 %

GMR effect
MR = 5 ~ 15 %

TMR effect
MR = 20 ~ 70 %

Giant TMR effect
MR = 200 ~ 600 %

HDD head

Inductive head

MR head

GMR head

TMR head

MgO-TMR head

Memory

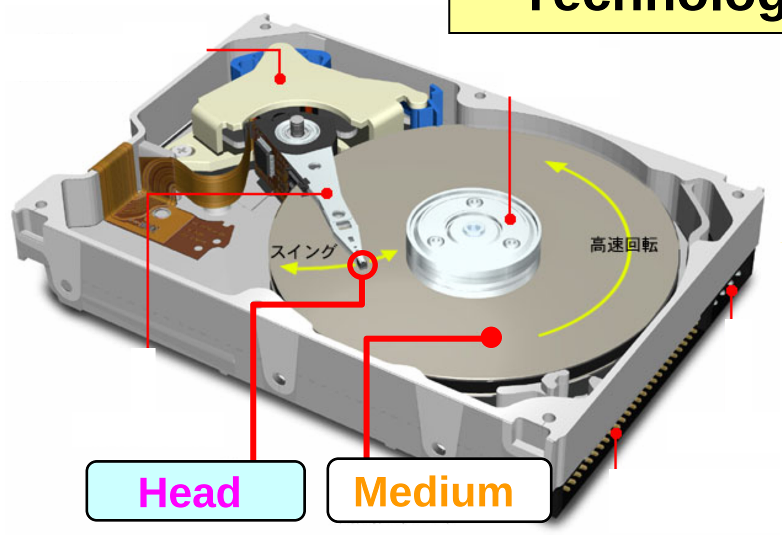
MRAM

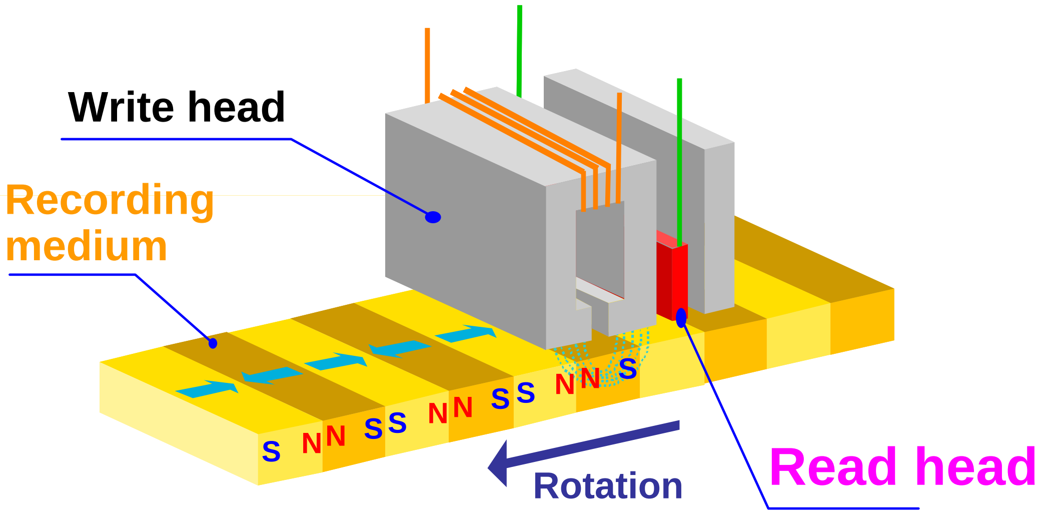
Spin-torque MRAM

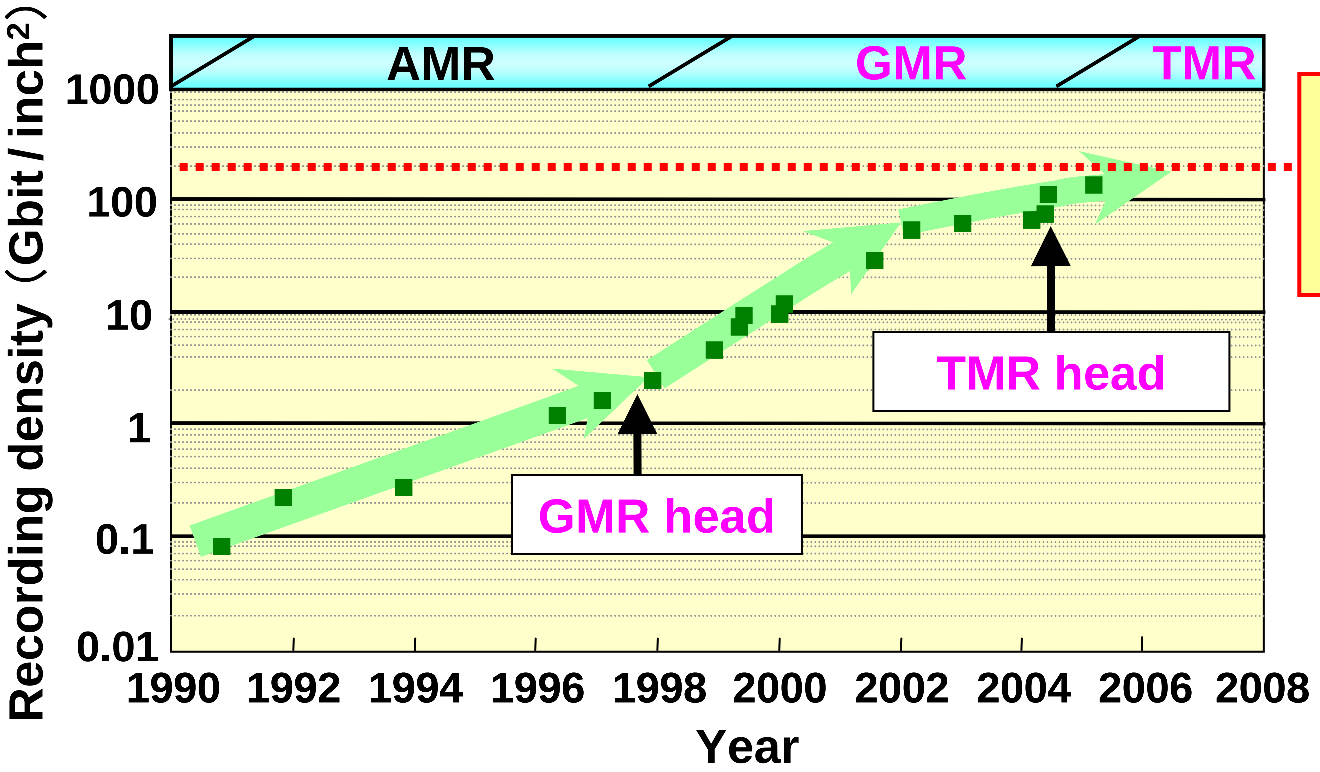
Novel devices

Microwave, etc.

Technologies for HDD read head

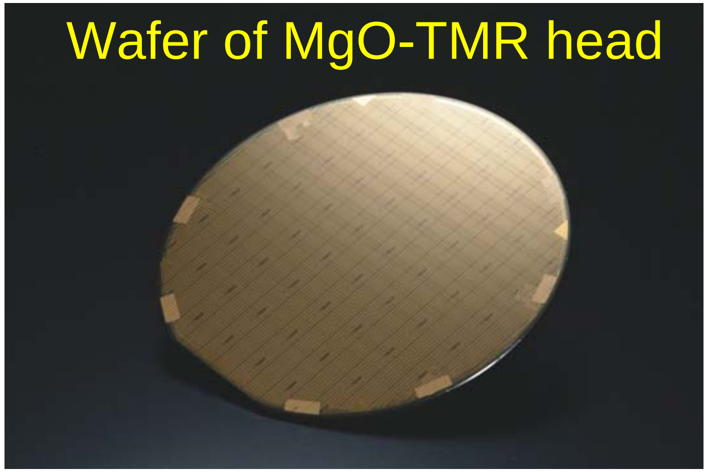






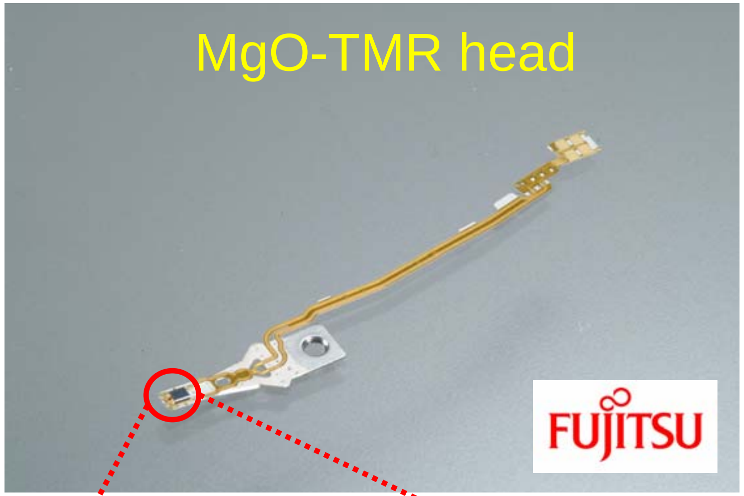
Next-generation read head is indespensable for > 200 Gbit / inch^2.

MgO-TMR head for ultrahigh-density HDD

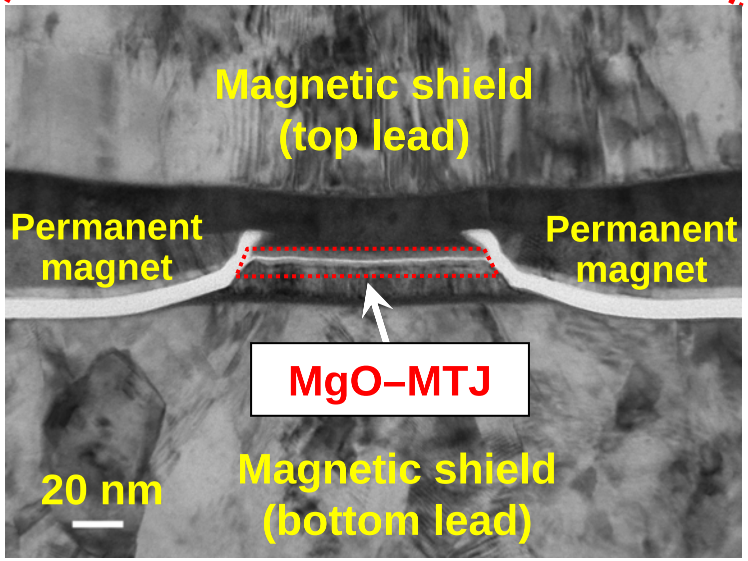

Wafer of MgO-TMR head

Cut

Inte-gration

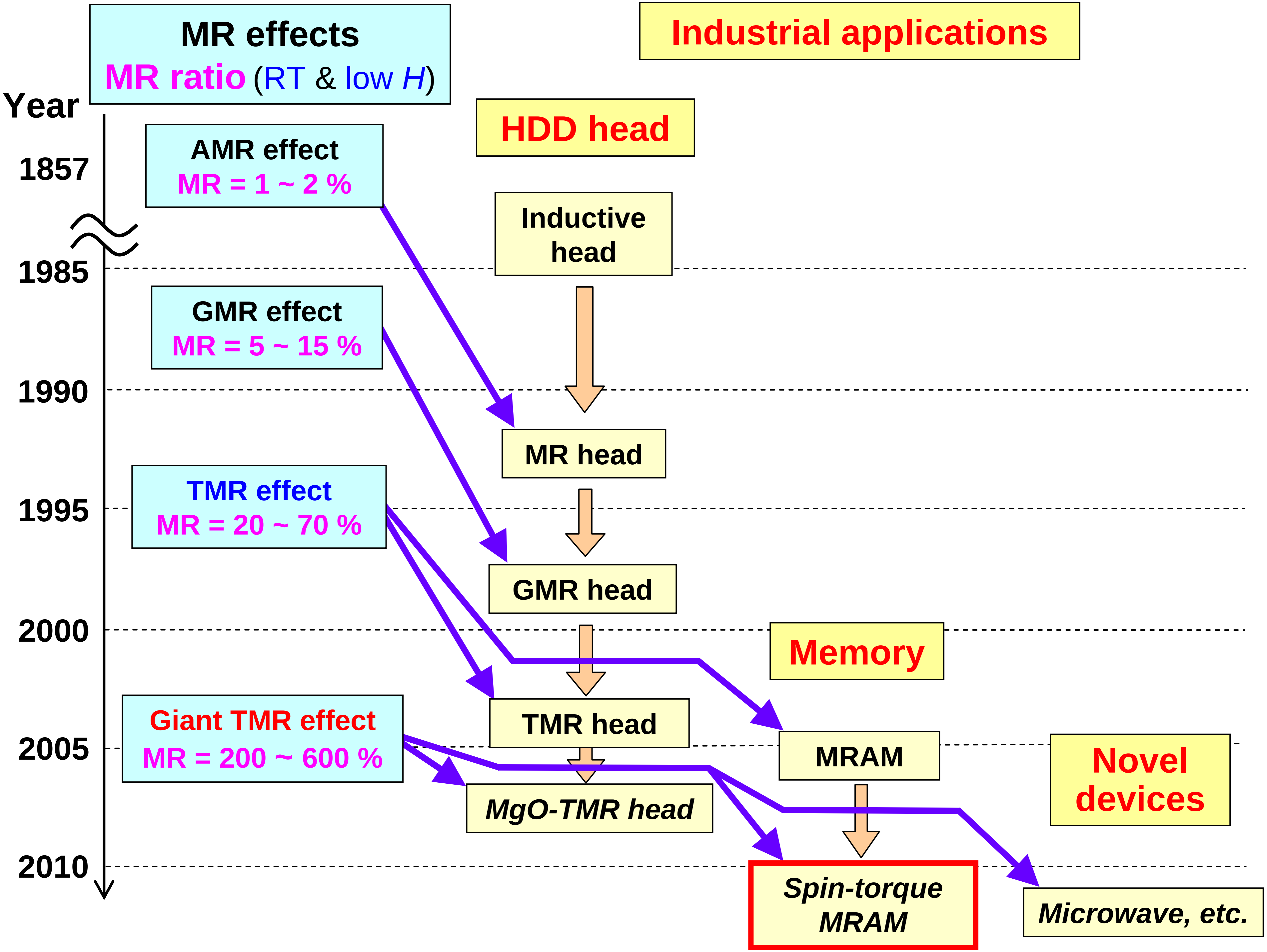

MgO-TMR head

Inte-gration



TEM image

- **Commercialized in 2007**.
- Density **> 250 Gbit / inch^2** achieved.
- Applicable up to **1 Tbit / inch^2**.



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TMR head

MgO-TMR head

Memory

MRAM

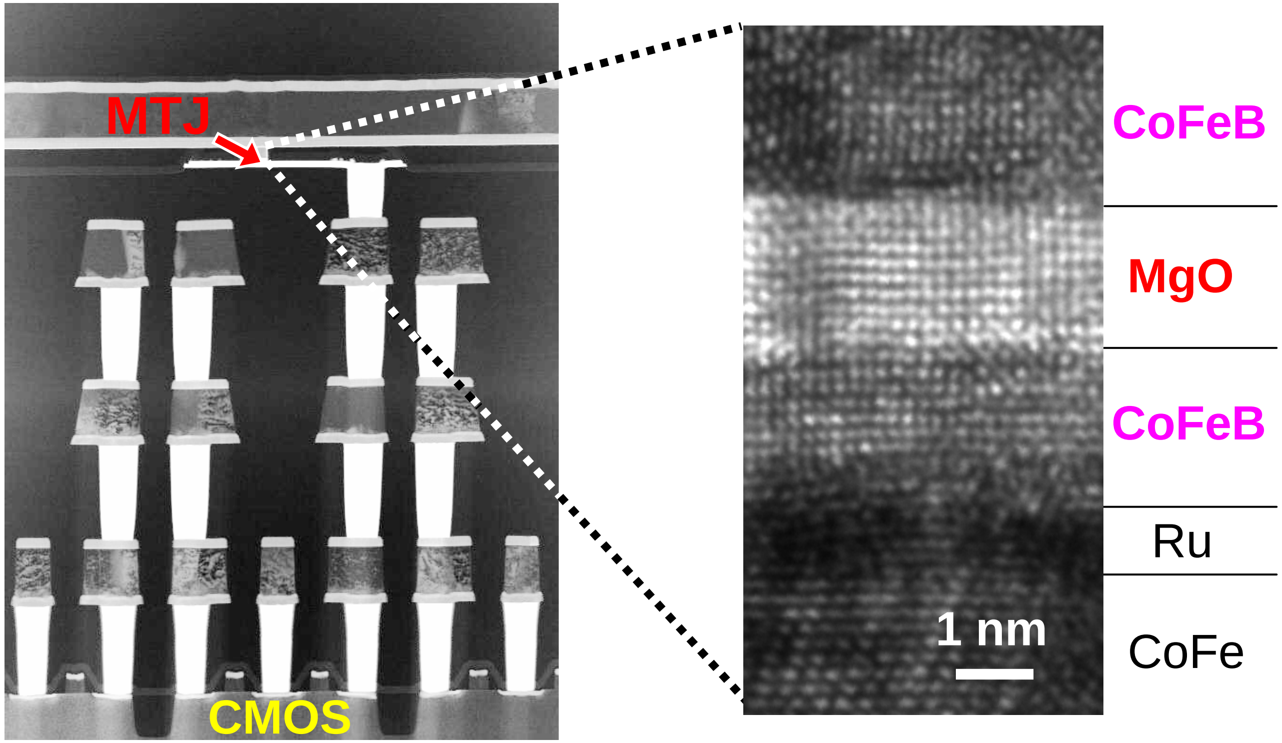
Spin-torque MRAM

Novel devices

Microwave, etc.

Spin-torque MRAM（SpinRAM）

M. Hosomi *et al.*(Sony), *Technical Digest of IEDM 2005,* 19.1.

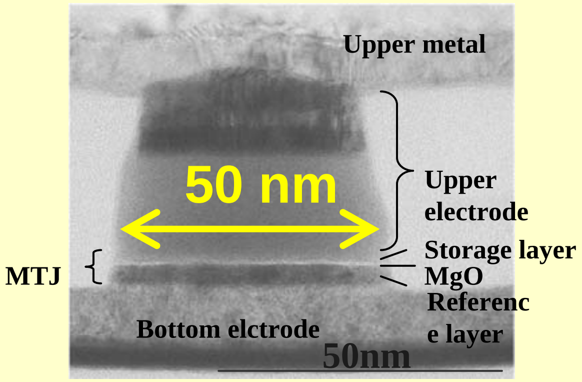


Write current density, $J_{C0} \sim 2 \times 10^6$ A/cm^2

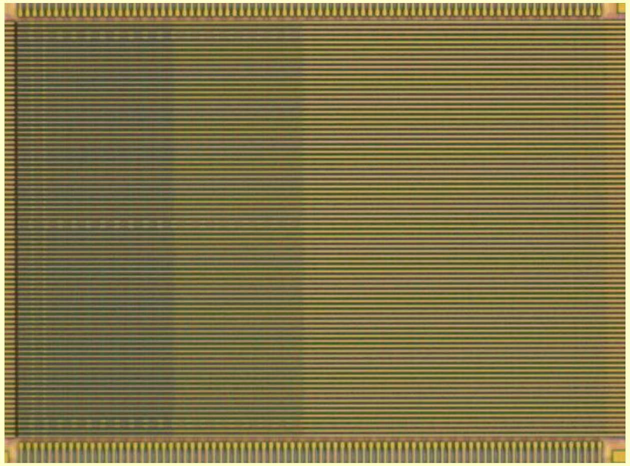
J_{C0} of 5×10^5 A/cm^2 is required for Gbit-scale SpinRAM.

SpinRAM having **perpendicular magnetization**

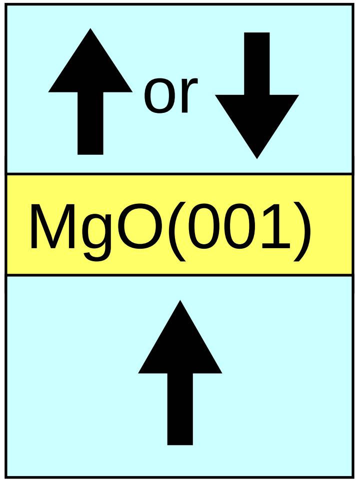
T. Kishi (Toshiba), SY *et al*., *IEDM* (2008) 12.6.



A TEM image of 50 nm-sized MTJ



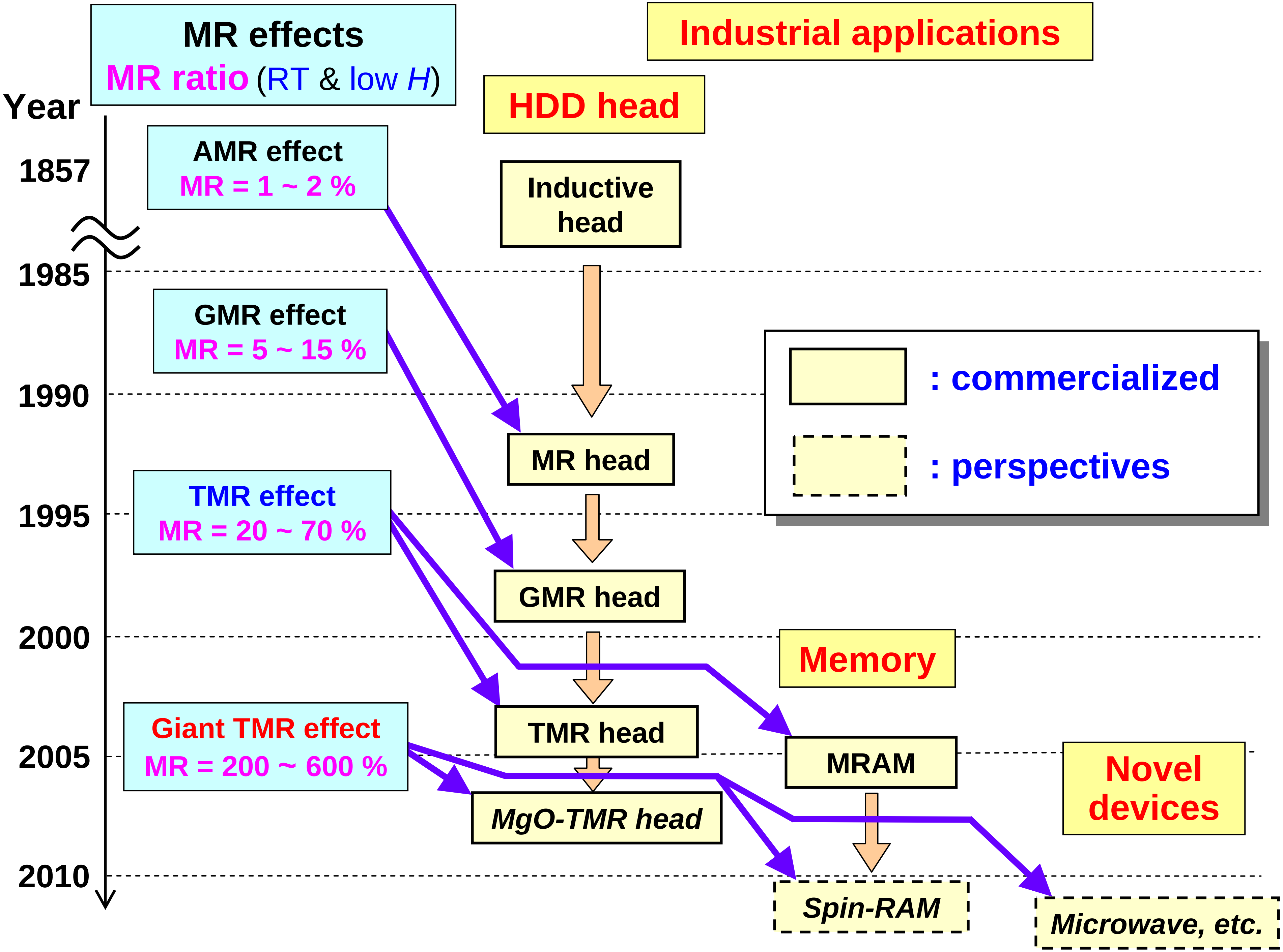
A CMOS integrated MTJ array



Perpendicularly-magnetized electrodes

$J_{C0} <$ 10^6 A/cm^2 achieved !

Perpendicularly magnetized MTJ is a promising technology for Gbit-scale Spin-RAM.



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▭ **: commercialized**

⬚ **: perspectives**