
Tunnel Magnetoresistance Effect and Its Applications

AIST
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Collaborators

Osaka University
(High-frequency experiment)

Canon Anelva Corp.
(R & D of manufacturing technology)

Toshiba Corp.
(R & D of Spin-MRAM)

Funding agencies

JST
NEDO
(1) Introduction

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

(3) CoFeB / MgO / CoFeB MTJs for device applications
Both charge and spin of the electron is utilized for novel functionalities.
What is “magnetoresistance”? A change in resistance by an application of $H$.

Magneto-Resistance; MR

MR ratio at RT & a low $H$ ($\sim 1$ mT) is important for practical applications.
Year | Magnetoresistance
---|---
1857 | AMR effect  
     | MR = 1 ~ 2 %
1985 | GMR effect  
     | MR = 5 ~ 15 %
1990 | TMR effect  
     | MR = 20 ~ 70 %
1995 | A. Fert, P. Grünberg  
     | Nobel Prize 2007
2000 | T. Miyazaki, J. Moodera
2005 |  
2010 |  

Lord Kelvin

A. Fert, P. Grünberg

T. Miyazaki, J. Moodera
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 $≡ (R_{AP} − R_P) / R_P$ (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
Next-generation read head is indispensable for > 200 Gbit / inch².

Technologies for HDD read head

Recording density (Gbit / inch²)

Year


GMR head

TMR head

AMR

GMR

TMR

Recording medium

Write head

Read head

Rotation
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.
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 >


MR ratio > 1000%
Spin polarization $P$

Parallel (P) state
Tunnel resistance: $R_P$

Antiparallel (AP) state
Tunnel resistance: $R_{AP}$

$$MR \equiv \frac{R_{AP} - R_P}{R_P} = 2P_1P_2 / (1 - P_1P_2), \quad P_\alpha = \frac{D_\alpha^{\uparrow}(E_F) - D_\alpha^{\downarrow}(E_F)}{D_\alpha^{\uparrow}(E_F) + D_\alpha^{\downarrow}(E_F)}, \quad \alpha = 1, 2.$$
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 $\Delta_1$ symmetry tunnel dominantly.
Fully spin-polarized $\Delta_1$ band in bcc Fe(001)

$\Rightarrow$ 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 $\Delta_1$ band.
(e.g. bcc Fe$_{1-x}$Co$_x$, Heusler alloys)
Fully epitaxial Fe/MgO/Fe MTJ grown by MBE

Fe(001) (Pinned layer)

MgO(001)

Fe(001) (Free layer)

TEM image

Magnetoresistance of epitaxial Fe/MgO/Fe MTJ

$MR = 247\%$

$MR = 180\%$

$T_{MgO} = 2.3$ nm

$T = 20$ K

$T = 293$ K

MTJs with a single-crystal MgO(001) barrier

Magnetoresistance of textured MgO-based MTJ

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

"Giant TMR effect"

Crystal MgO(001) tunnel barrier

Amorphous Al-O tunnel barrier

MR ratio (%) at RT

Year

Up to 600% at RT

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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 \textit{fcc} (111).

\textbf{MgO}(001) cannot be grown on \textit{fcc} (111).

4-fold symmetry
3-fold symmetry
MTJ structure in as-grown state

Collaboration with Canon-Anelva

**Ideal for device applications**

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

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CoFeB / MgO / CoFeB - MTJ with practical structure

Standard bottom structure for MRAM and HDD head
Crystallization of CoFeB by post-annealing


Amorphous CoFeB
Textured MgO(001)
Amorphous CoFeB

Annealing above 250 °C

bcc CoFeB(001)
Textured MgO(001)
bcc CoFeB(001)

As-grown MTJ

Crystallization of CoFeB

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

“Solid Phase Epitaxy”

Because the Δ₁ 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!
Next-generation read head is indispensable for > 200 Gbit / inch².
MgO-TMR head for ultrahigh-density HDD

Wafer of MgO-TMR head

- Commercialized in 2007.
- Density > 250 Gbit/inch² achieved.
- Applicable up to 1 Tbit/inch².

MgO-TMR head

TEMP image

Permanent magnet

Permanent magnet

Magnetic shield (top lead)

Magnetic shield (bottom lead)

20 nm

MgO–MTJ

Integrating...
Year

1857

≈

1985

1990

1995

2000

2005

2010

Industrial applications

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

AMR effect
MR = 1 ~ 2 %

GMR effect
MR = 5 ~ 15 %

TMR effect
MR = 20 ~ 70 %

Giant TMR effect
MR = 200 ~ 600 %

HDD head

MR head

GMR head

Memory

TMR head

MRAM

Spin-torque MRAM

Novel devices

Inductive head

MgO-TMR head

AMR effect

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1985

1995

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GMR effect

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TMR effect

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Giant TMR effect

MR = 200 ~ 600 %

1995

2000

2005

2010

1995

2000

2005

2010

Spin-torque MRAM

Microwave, etc.
Spin-torque MRAM (SpinRAM)


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

$J_{C0}$ of $5 \times 10^5$ A/cm$^2$ is required for Gbit-scale SpinRAM.
SpinRAM having **perpendicular magnetization**


A TEM image of 50 nm-sized MTJ

Perpendicularly-magnetized electrodes

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

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