Workshop on "Heusler Alloys for Spintronic Devices"
July 30, 2015 @C-SPIN, Univ. of Minnesota, Minneapolis, USA

CPP-GMR and Related Phenomena in Half-Metallic Heusler Alloy Systems

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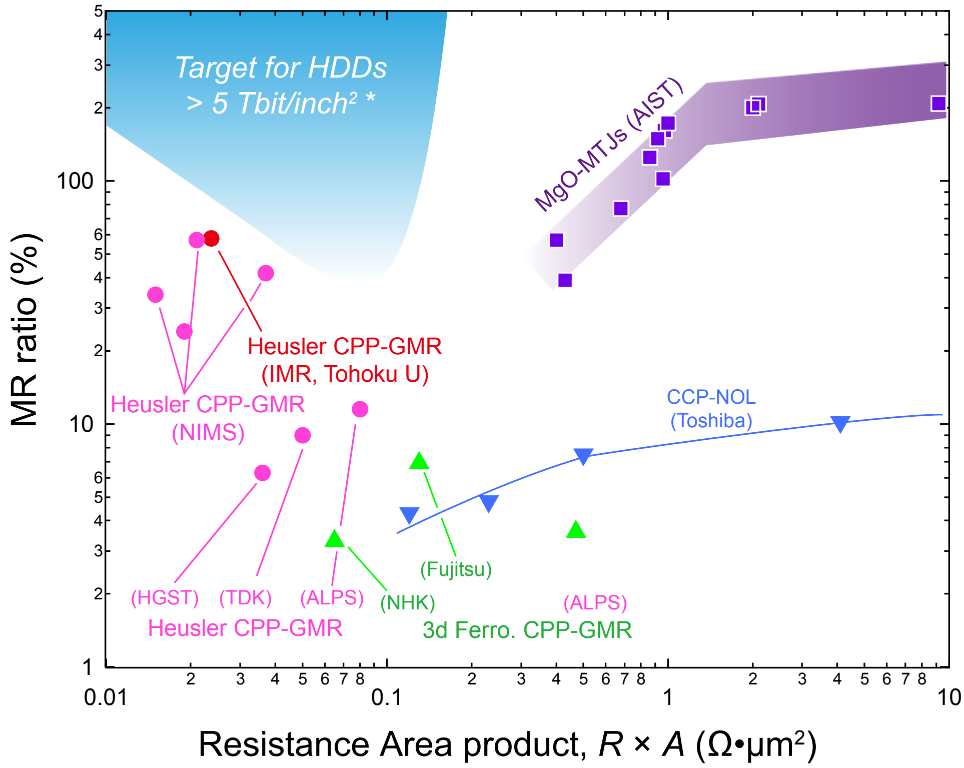
Research activities on Heusler alloys in my group

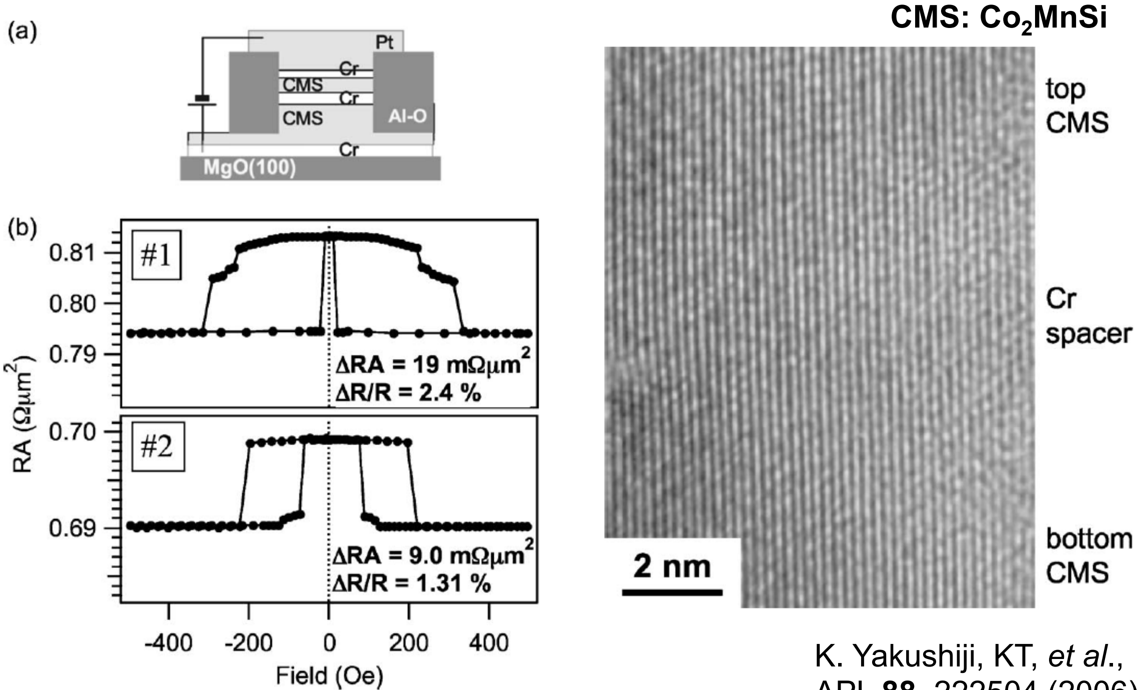
- ***CPP-GMR*** **with $Co_2Fe_{1-x}Mn_xSi$ electrodes**
- ***Spin torque oscillation*** **with CPP-GMR devices**
- ***Giant Peltier effect*** **in CPP-GMR devices**
- ***Perpendicular magnetization*** **of Heusler alloy thin films**
- ***Antiferromagnetic*** **Heusler alloy films to replace IrMn in spin valves**

High MR ratio with low resistance



CMS/Cr/CMS fully-epitaxial CPP-GMR device

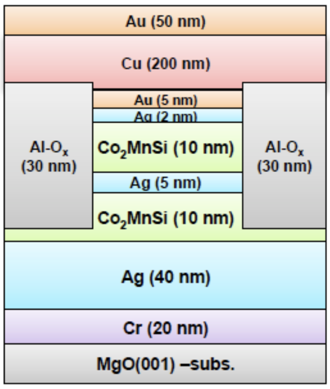
CMS: Co_2MnSi

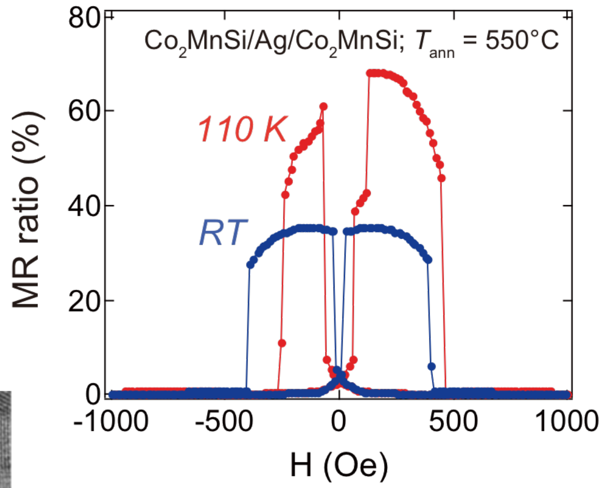


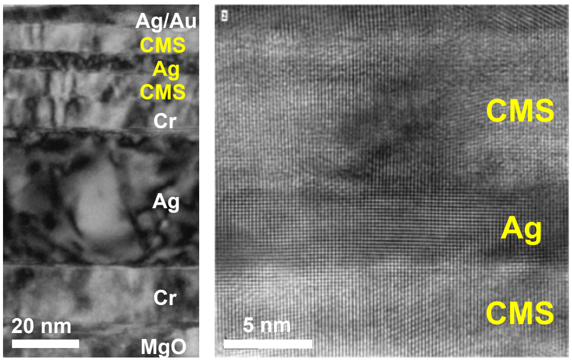
K. Yakushiji, KT, *et al.*, APL **88**, 222504 (2006).

The first experimental report on Heusler-based CPP-GMR devices with large Δ*RA* values.

CMS/Ag/CMS fully-epitaxial CPP-GMR device







Fully-epitaxial growth in CMS/Ag/CMS

Breakthrough of CPP-GMR

A high MR ratio (36.4%@RT) was observed.

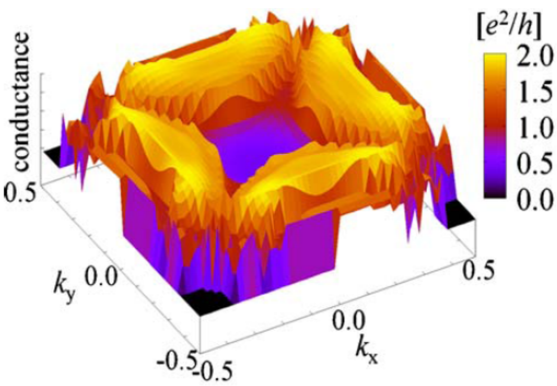
T. Iwase, KT *et al.*, Appl. Phys. Exp., 2 (2009) 063003.
Y. Sakuraba, KT *et al.*, Phys. Rev. B82 (2010) 094444.

Ag spacer? or Cr spacer?

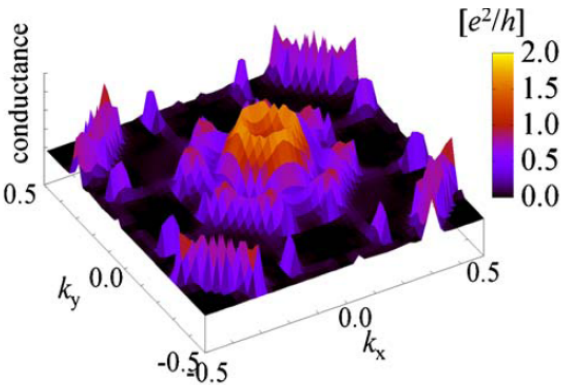
Majority spin conductance in the parallel state

Sakuraba, Miura, KT, *et al.*, PRB **82**, 094444 (2010).

Co_2MnSi/Ag

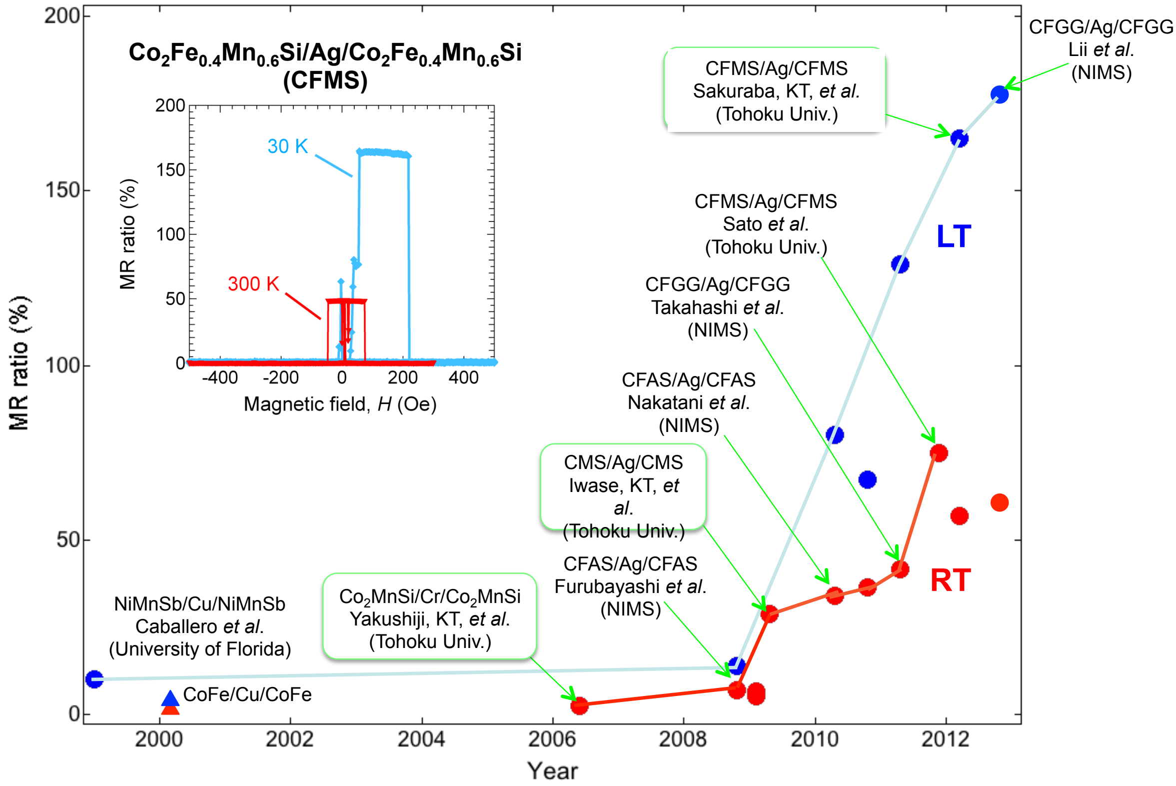


Co_2MnSi/Cr



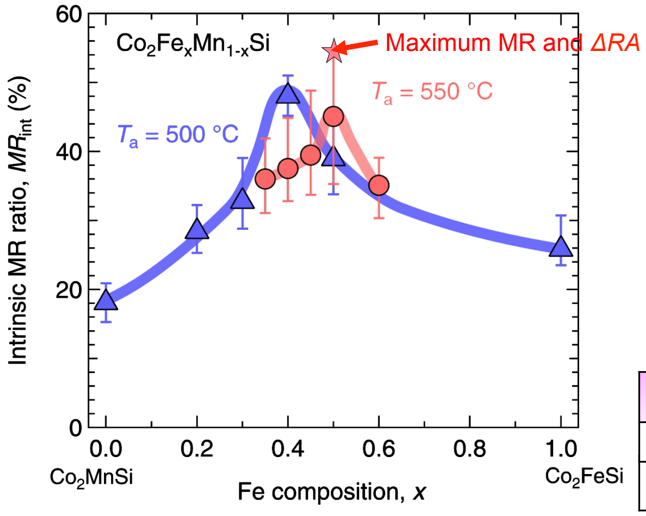
Matching of the Fermi surface is important.

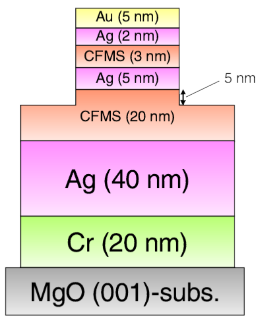
Development of CPP-GMR for Heusler alloys



CPP-GMR with $Co_2Fe_xMn_{1-x}Si$ electrodes

Fe:Mn composition ratio x dependence





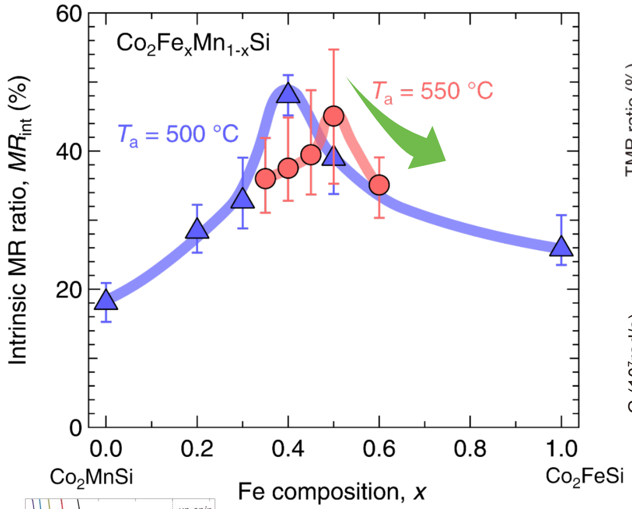
T_a	x_{best}	MR_{int}	RA	ΔRA
500	0.4	51 %	25.1 mΩ·μm²	12.8 mΩ·μm²
550	0.5	55 %	31.4 mΩ·μm²	17.2 mΩ·μm²

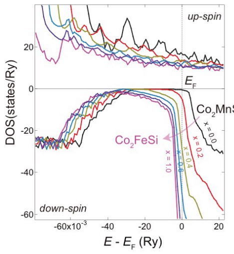
Y. Sakuraba, M. Ueda *et. al.* Appl. Phys. Lett. **101**, 252408(2012).

- The best composition x = 0.4 at T_a = 500℃
  0.5 at T_a = 550℃
- The highest ΔRA of 17.2 mΩ·μm² was observed in $Co_2Fe_{0.5}Mn_{0.5}Si$.

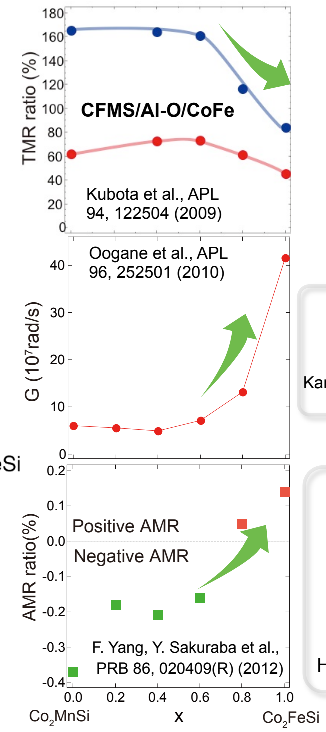
CPP-GMR with $Co_2Fe_xMn_{1-x}Si$ electrodes

Discussion - Fe:Mn composition ratio *x* dependence (x > 0.4-0.5)





Reduction of MR ratio at x > 0.4-0.5 can be explained by electronic structure of CFMS.



$G = \alpha\gamma M_s \propto D(E_F)$

Half-metal often has **small *G***

Kambersky: Can. J. Phys. 48, 2906 (1970)

Kokado et al. (J. Phys. Soc. Jpn. 81, 024705 (2012))

$$\frac{\Delta\rho}{\rho} = \frac{\rho_{//} - \rho_{\perp}}{\rho_{//}} \times 100(\%)$$

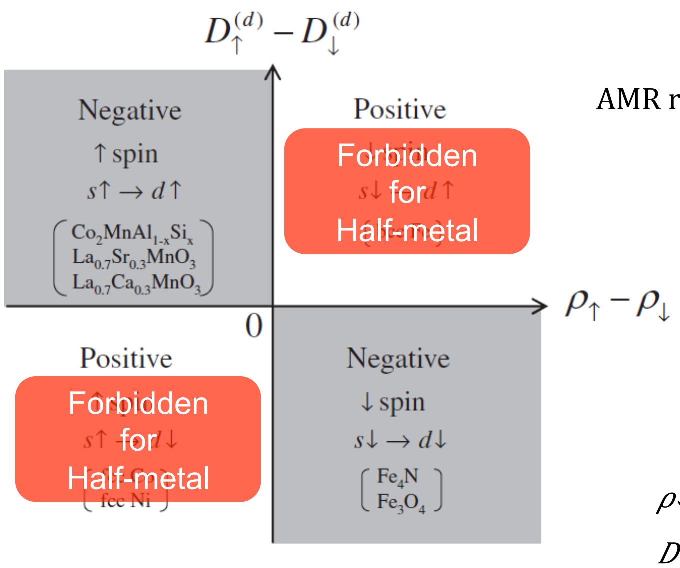
$$\propto \gamma(D_{\uparrow}^{(d)} - D_{\downarrow}^{(d)})\left(\frac{1}{\rho_{\downarrow}} - \frac{1}{\rho_{\uparrow}}\right)$$

Half-metal : AMR must be ***negative***

Half-metallic materials & AMR effect

s-d scattering procedures and the sign of AMR ratio

S. Kokado, *et al.*, JPSJ **81**, 024705 (2012).



AMR ratio$\equiv\Delta\rho/\rho$

$= \gamma(\rho_{s\downarrow\to d\uparrow} - \rho_{s\downarrow\to d\downarrow})/\rho_{\downarrow\downarrow} + \rho_{\downarrow}$

$\propto \gamma(D_{\uparrow}^{(d)} - D_{\downarrow}^{(d)})(1/\rho_{\downarrow}$

with

$\rho_{\sigma} = \rho_{s\sigma} + \rho_{s\sigma\to d\sigma}$

$\gamma = (3/4)(\lambda/H_{ex})^2$

ρ_{σ} :Resistivity of σ spin

$D_{\uparrow}^{(d)}$: Density of states of d-electron

λ: Spin-orbit coupling constant

H_{ex}: exchange field of the d-states

Half-metallic materials

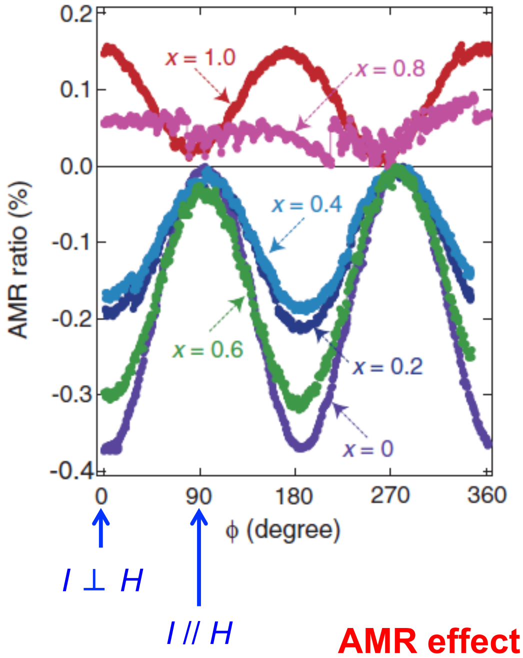
↓

Negative sign of AMR ratio

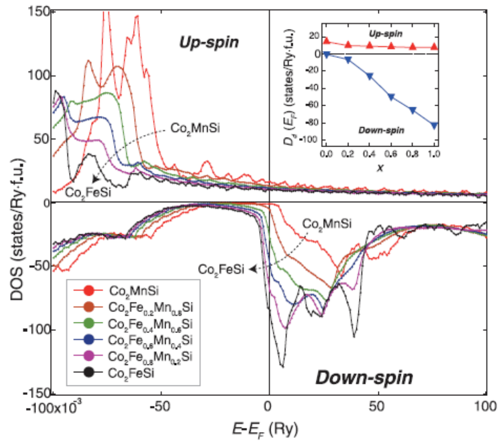
AMR effects of Heusler alloy films

AMR curves of $Co_2Fe_xMn_{1-x}Si$ films

Yang, Sakuraba, KT, *et al.*, PRB **86**, 020409(R) (2012).



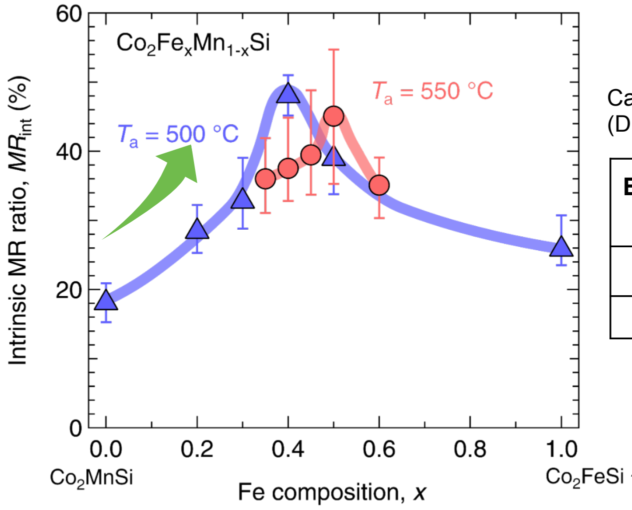
DOS of $Co_2Fe_xMn_{1-x}Si$ alloys (calc.)



AMR effect is a fingerprint for half-metallicity.

CPP-GMR with $Co_2Fe_xMn_{1-x}Si$ electrodes

Discussion - Fe:Mn composition ratio *x* dependence



Calculated exchange stiffness by first-principles calculations (Dr. Miura, Tohoku univ.)

Exchange stiffness of Co [meV]	Co_2MnSi/Ag	Co_2FeSi/Ag
Interface	137	x 2.5 → 340
Bulk	414	536

bulk spin-asymmetry — interface spin-asymmetry

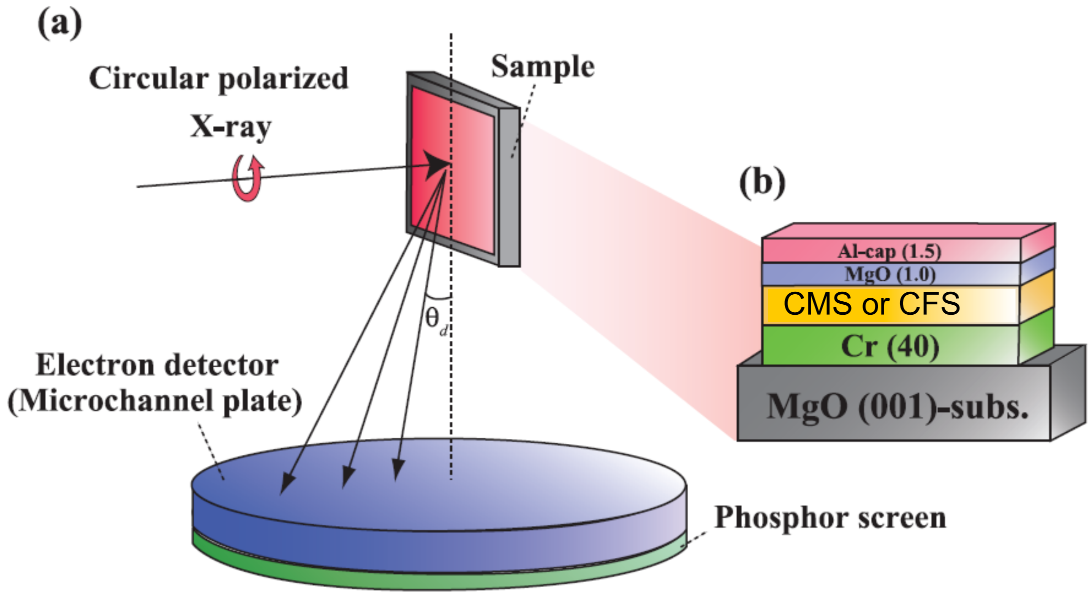
$$\Delta RA \propto \left(\beta \rho^*_{CFMS} t_{CFMS} + \gamma R^*_{CFMS/Ag} A\right)^2$$

bulk contribution — Interface contribution

Systematic analysis of γ is necessary to clarify the improvement of interfacial exchange stiffness.

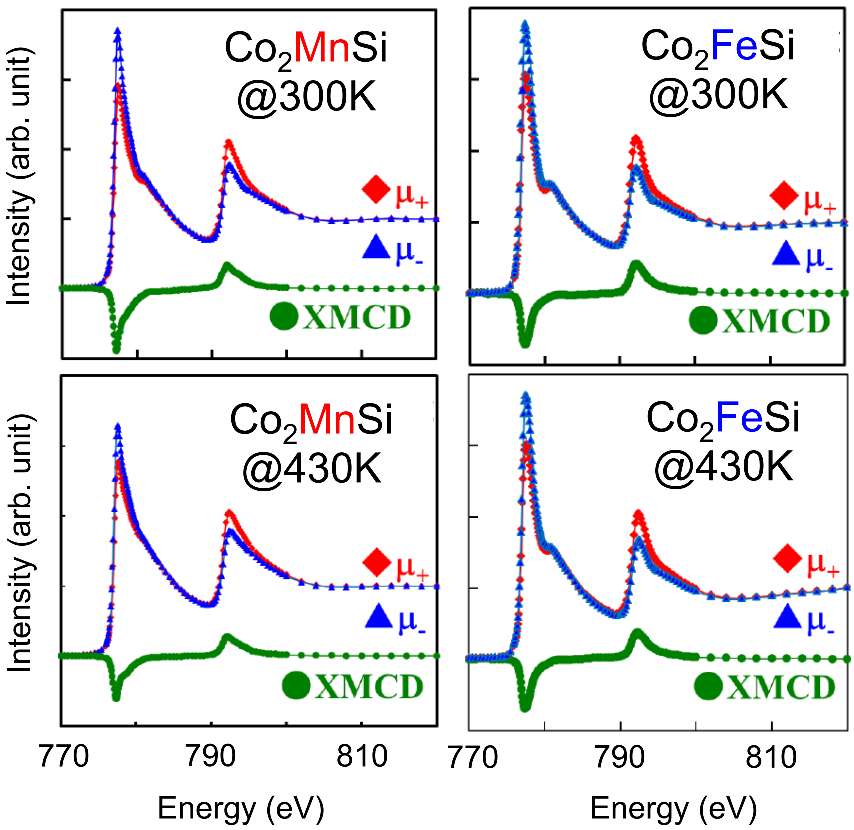
Depth-resolved XMCD measurements

Measured@BL-16A, Photon Factory, KEK
Collaboration with Prof. Amemiya, Dr. Sakamaki



Soft x-ray → penetration depth (~ 5 nm or less)
Depth-dependence of magnetic moments can be measured.

Exchange stiffness constants at interfaces



XAS and XMCD spectra

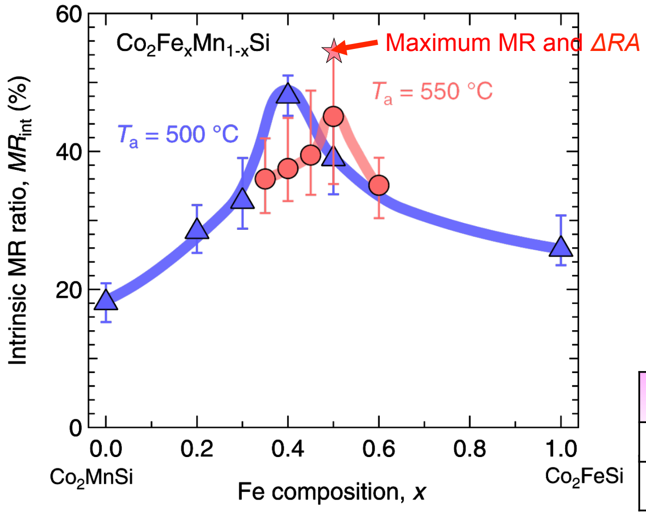
@Co $L_{2,3}$ edges

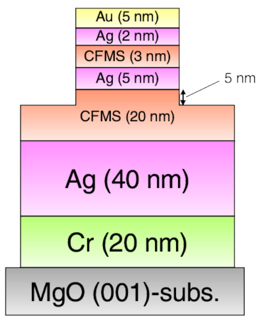
“Bulk” moment & “Interface” moment

Temperature dependence of Co-moment at the interface;
Larger for the Co_2MnSi/Ag case than that for the Co_2FeSi/Ag case

CPP-GMR with $Co_2Fe_xMn_{1-x}Si$ electrodes

Fe:Mn composition ratio *x* dependence





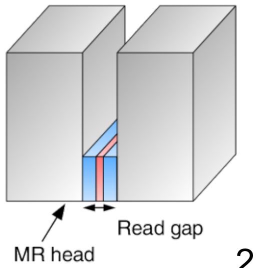
T_a	x_{best}	MR_{int}	*RA*	*ΔRA*
500	0.4	51 %	25.1 mΩ·μm²	12.8 mΩ·μm²
550	0.5	55 %	31.4 mΩ·μm²	17.2 mΩ·μm²

Y. Sakuraba, M. Ueda *et. al.* Appl. Phys. Lett. **101**, 252408(2012).

x = 0 → 0.5 : Interface contribution increases → MR increases.
x = 0.5 → 1 : Half-metallicity disappears → MR decreases.

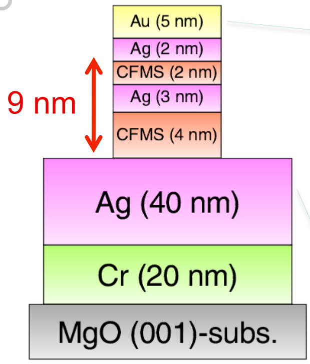
Challenge for a thinner layer thickness

Requirement of total thickness for read sensor

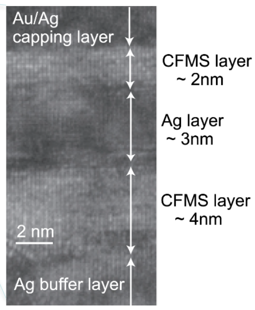


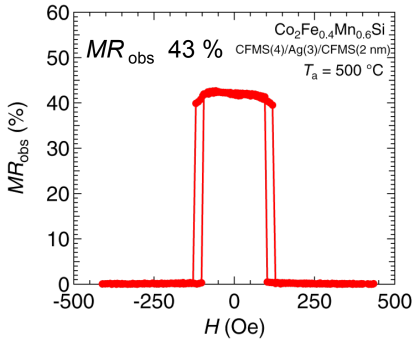
Required read gap < 21 nm (2 Tb/in²)
10.5 nm (5 Tb/in²)

CFMS(4)/Ag(3)/CFMS(2) : 9 nm



TEM image





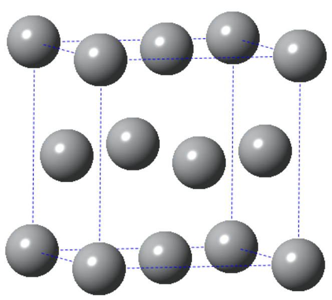
MR_{int}	RA	ΔRA
58 %	21.7 mΩ·μm²	12.5 mΩ·μm²

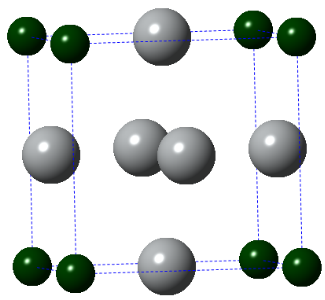
Even 9nm-thick trilayer show large MR ratio over 50%.

Approach for higher output –new spacer material–

fcc Ag

$L1_2$ Ag_3Mg





$a = b = c = 0.409$ nm

Resistivity = 1.6 μΩcm

$a = b = 0.410$ nm
$c = 0.419$ nm

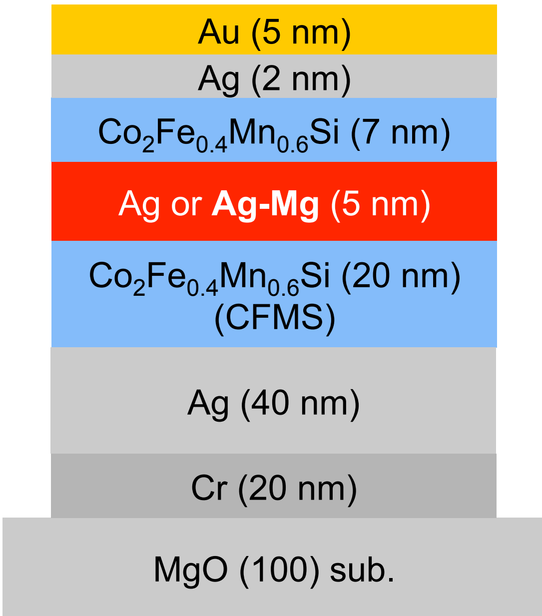
Resistivity ~ 5 μΩcm

Fujiwara *et al*., JPSJ (1958)

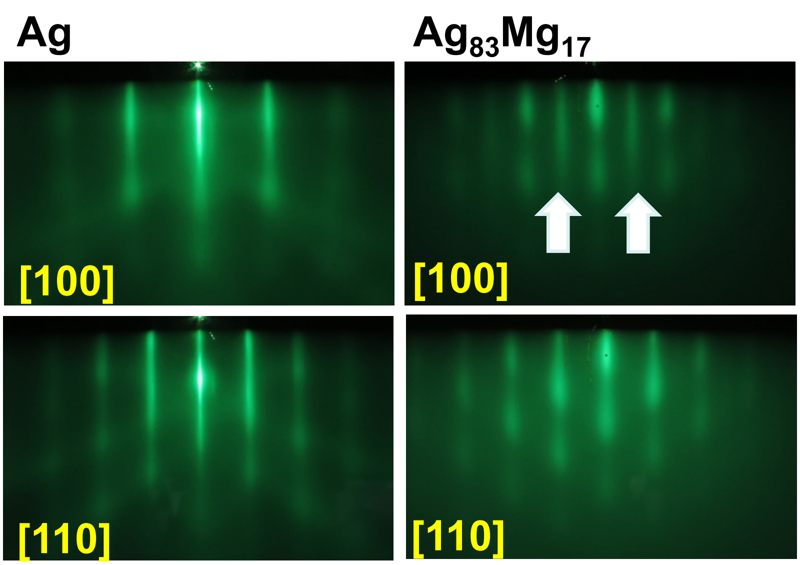
Lattice mismatch is similar (Ag ~ 2%, $L1_2$ Ag_3Mg ~ 3%).

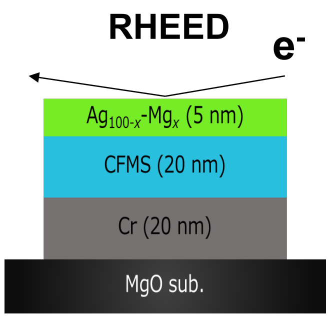
Experimental procedures

- Film deposition: Magnetron sputtering
- *In situ* annealing
  @650ºC after the Cr depo.
  @500ºC after the top CFMS depo.
- Ag-Mg layer
  Deposited by co-sputtering
- Fabrication of CPP-pillar:
  Electron-beam lithography & Ar ion dry etching
- Characterization :
  XRD, RHEED,
  Direct-current 4-probe measurement



RHEED patterns of a thin Ag-Mg film





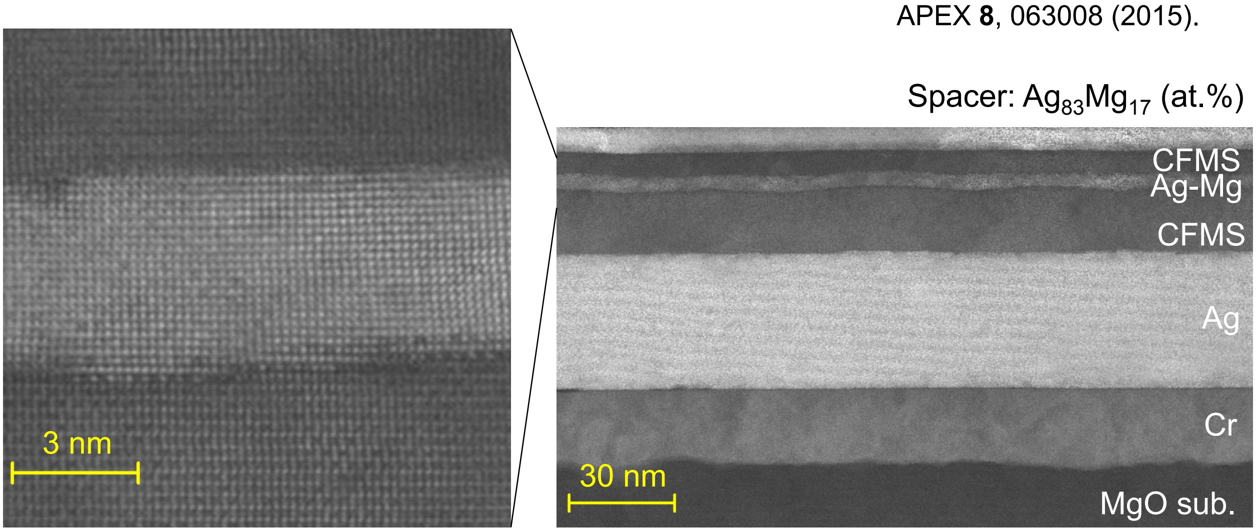
*Ag-Mg depo.@RT

Superlattice diffraction was observed for the surface of $Ag_{83}Mg_{17}$ (~ Ag_5Mg) layer deposited at room temperature

Cross-sectional HAADF-STEM for Ag-Mg spacer

H. Narisawa, T. Kubota, KT, APEX **8**, 063008 (2015).

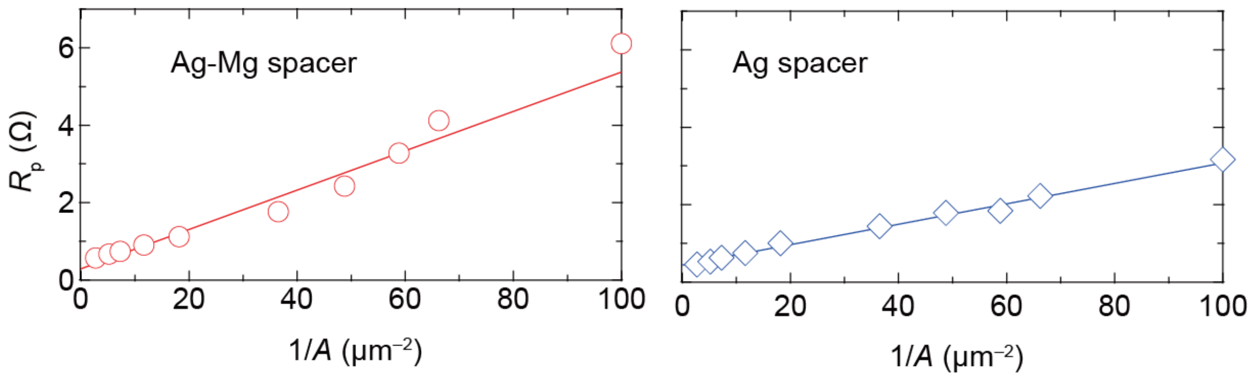
Spacer: $Ag_{83}Mg_{17}$ (at.%)



CFMS/Ag-Mg/CFMS → Flat and sharp interfaces

$Ag_{83}Mg_{17}$ spacer layer → Ordered locally at interfaces

RA in CFMS/Ag/CFMS

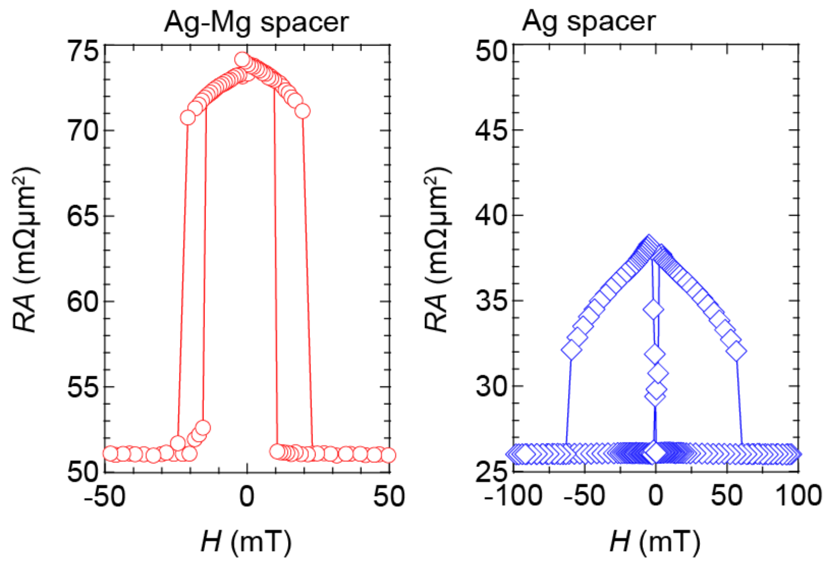


RA = 51 ± 4 mΩμm^2
R_{para} = 0.30 ± 0.14 Ω

RA = 26 ± 1 mΩμm^2
R_{para} = 0.43 ± 0.04 Ω

RA for Ag-Mg spacer is twice larger than that for pure Ag spacer.

CPP-GMR in CFMS/Ag-Mg/CFMS



Large *ΔRA* for Ag-Mg compared to that for Ag

$^*MR_{int} = \Delta R / (R_p - R_{para})$

Spacer	RA (mΩμm²)	MR_{obs} (%)	MR_{int} (%)	ΔRA (mΩμm²)
Ag	26	35 (38)	48 (54)	13 (15)
$L1_2$ Ag-Mg	51	36 (40)	44 (48)	**23 (25)**

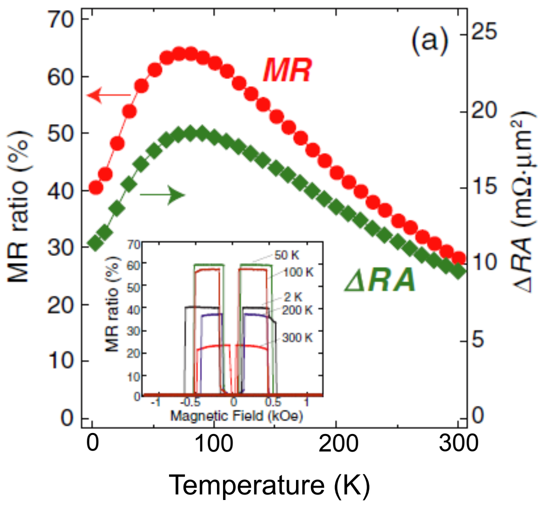
Temperature dependence of CPP-GMR

Ag spacer
→ Maximum ~80 K

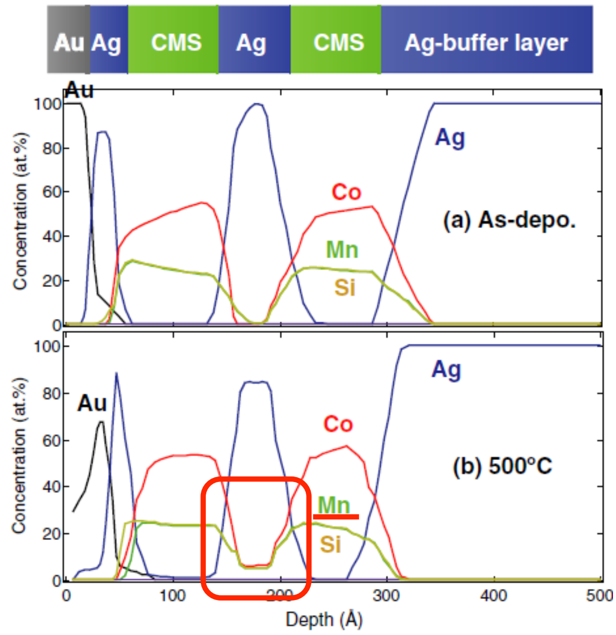
Ag-Mg spacer
→ Maximum disappears.

Temp. dependence; effect of Mn-diffusion

Previous work on
$Co_2MnSi/Ag/Co_2MnSi$



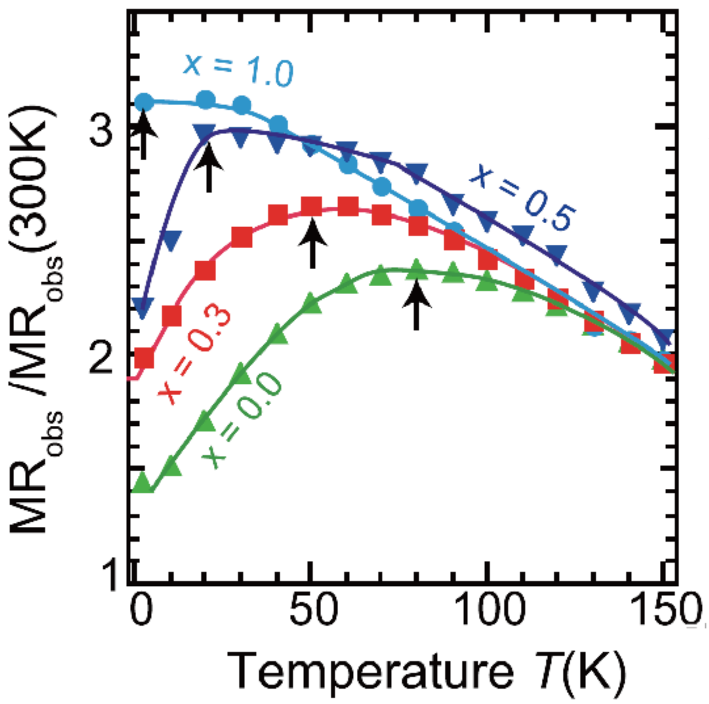
Depth profiles of the film composition (RBS)



Diffusion of Mn probably causes a maximum of the temp. dependence.

Y. Sakuraba, *et al*., J. Phys. D. (2011).

Temperature dependence of CPP-GMR

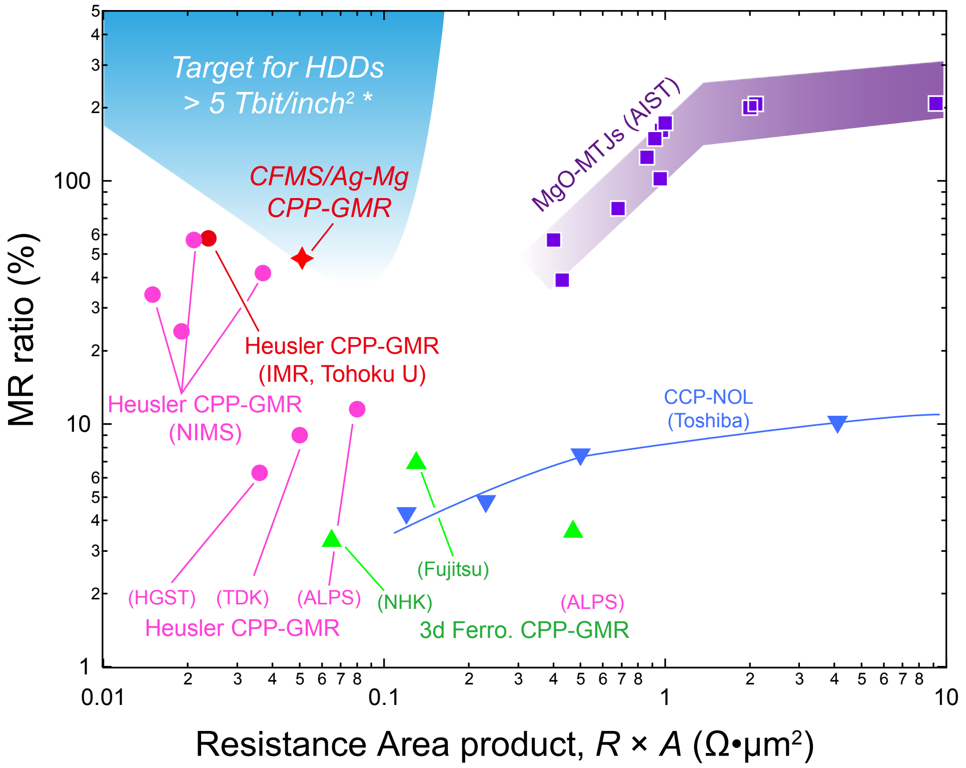


$Co_2Fe_xMn_{1-x}Si$

Y. Sakuaba, KT, *et al*.,
Appl. Phys. Lett. **101**, 252408 (2012).

Related to Kondo physics?
L. O'Brien et *al*.,
Nature Commun., 5:3927 (2014).

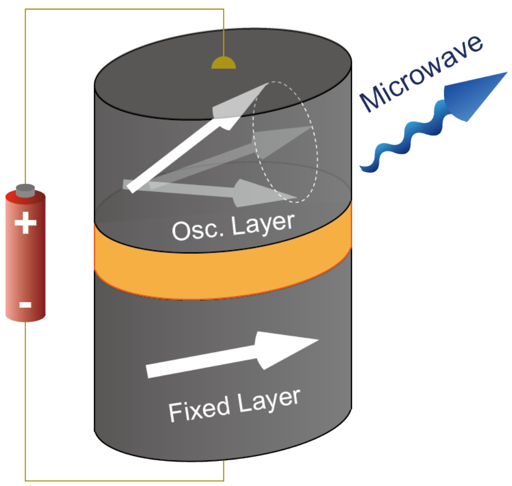
High MR ratio with low resistance



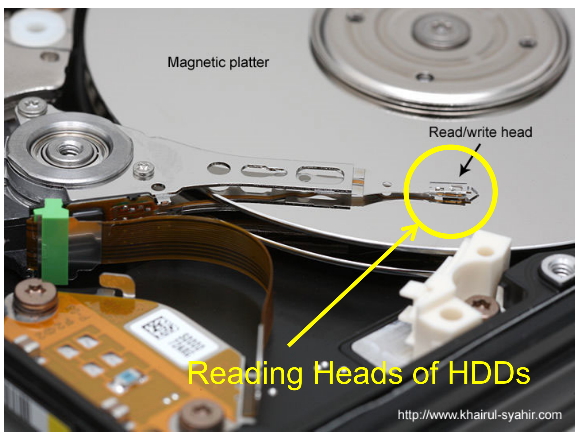
Device applications using CPP-GMR devices

Heusler-alloy-based CPP-GMR devices

Spin torque oscillators

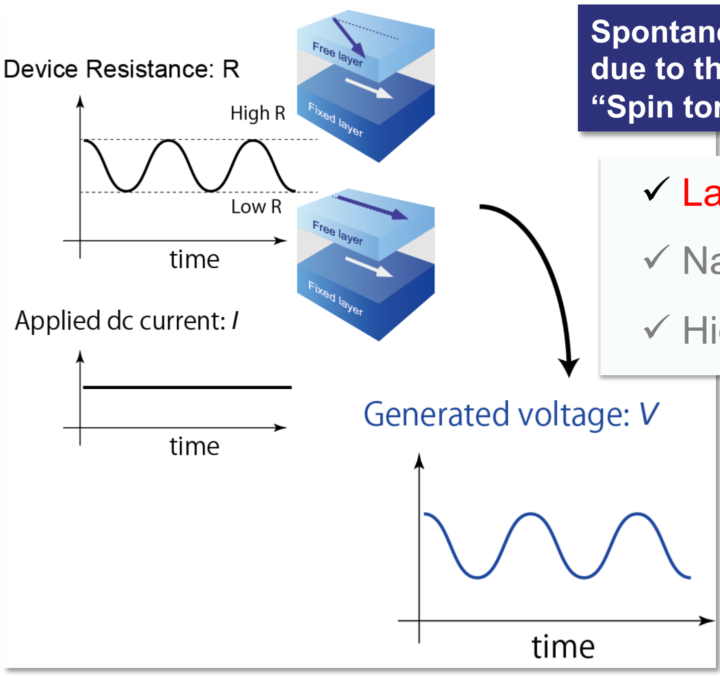


Read Heads in HDDs



Spin torque oscillator (STO)

What is Spin Torque Oscillation?



Spontaneous magnetization precession due to the balance between "Spin torque" and "Damping torque"

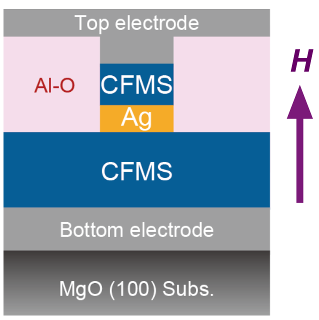
- ✓ Large Output Power
- ✓ Narrow Oscillation Linewidth
- ✓ High Oscillation Frequency

$$Output\ \ power \propto (MR)^2$$

Half-metallic Heusler alloy showing large MR

Heusler CPP-GMR STO (Pillar)

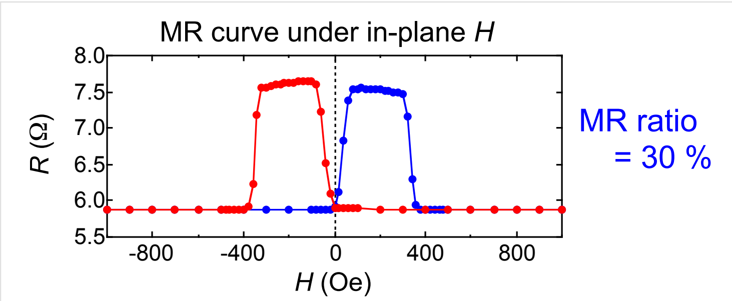
Pillar-type



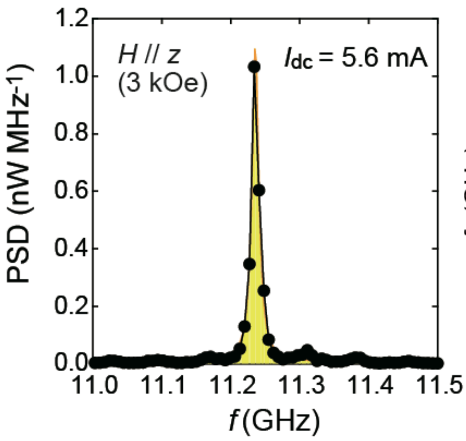
Pillar size:
100 x 170 nm²

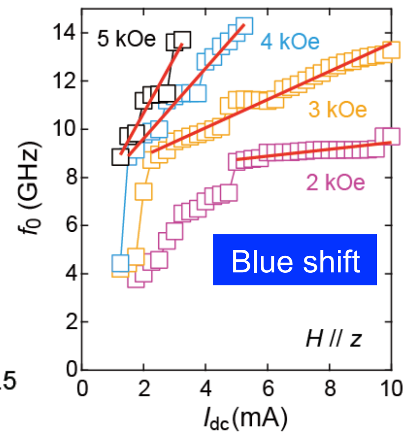
Out-of Plane Precession Mode

T. Seki *et al.*, APL **105**, 092406 (2014)



MR ratio = 30 %

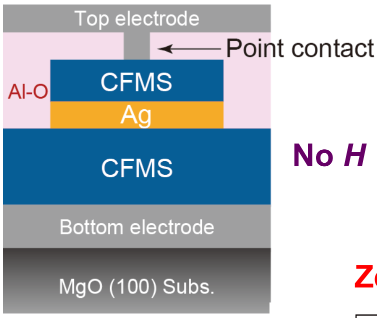




P_{out} = 23.7 nW, Q = 1124

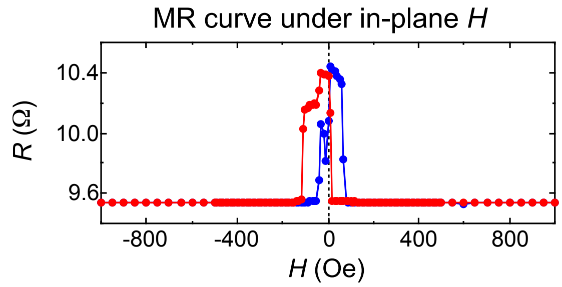
Heusler CPP-GMR STO (Point Contact)

Point Contact-type



No *H*

Contact size: 140 nm ϕ

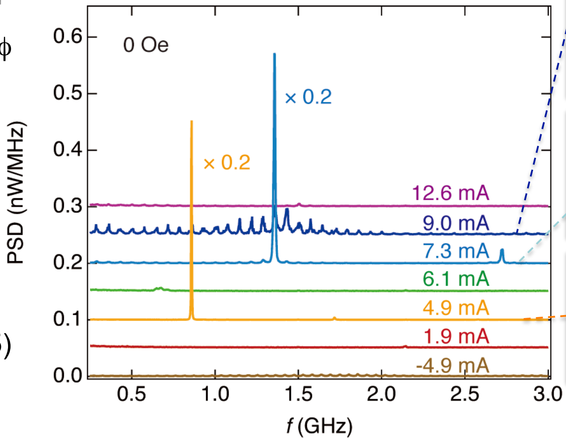


MR ratio = 10 %

Vortex-like Mode

T. Yamamoto *et al.*, APL **106**, 092406 (2015)

Zero-field spin torque oscillation



Region III: Incoherent
Multiple peak structure
Chaotic dynamics?

Region II: Coherent
f_0 = 1.36 GHz
Δf = 9 MHz

Region I: Coherent
f_0 = 0.86 GHz
Δf = 3 MHz

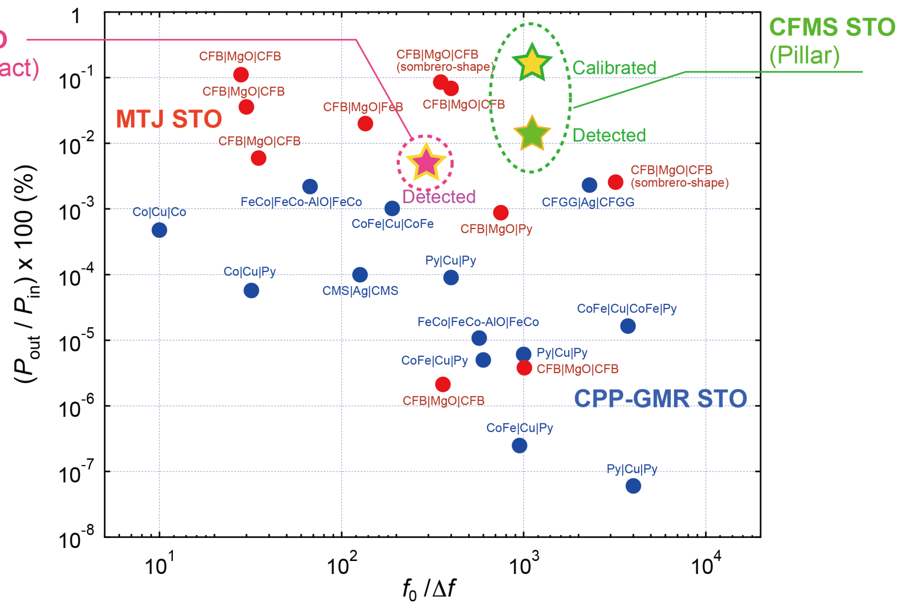
Heusler CPP-GMR STO

Nanopillar	P_{out} = 23.7 nW	Δf = 10 MHz	H = 3 kOe (//z)

T. Seki *et al.*, APL **105**, 092406 (2014)

Point Contact	P_{out} = 11.6 nW	Δf = 3 MHz	H = 0 Oe

T. Yamamoto *et al.*, APL **106**, 092406 (2015)



Summary

Half-metallic Heusler alloys for spintronics

- CPP-GMR in $Co_2Fe_xMn_{1-x}Si/Ag/Co_2Fe_xMn_{1-x}Si$
  - Composition dependence:
    Max. of CPP-GMR @ x=0.4~0.5
  - Spacer: Ag → Ag-Mg
    Enhancement of ΔRA
  - Temperature dependence of CPP-GMR
    Maximum for CMS/Ag/CMS, CFMS/Ag/CFMS
    No Maximum for CFS/Ag/CFS, CFMS/Ag-Mg/CFMS
- STO with CPP-GMR devices with CFMS/Ag/CFMS
  - nanopillar-type; high output power and high Q
  - point contact-type; high output power and high Q
    with no applied field

Magnetic Materials Laboratory

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