Heusler-alloy-based CPP-GMR devices with high MR outputs

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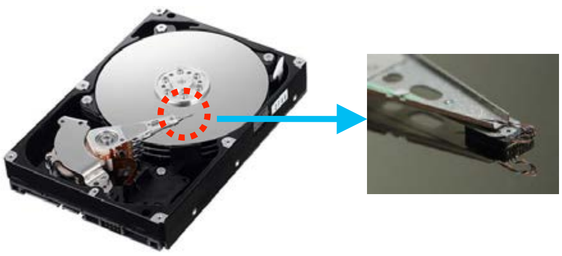
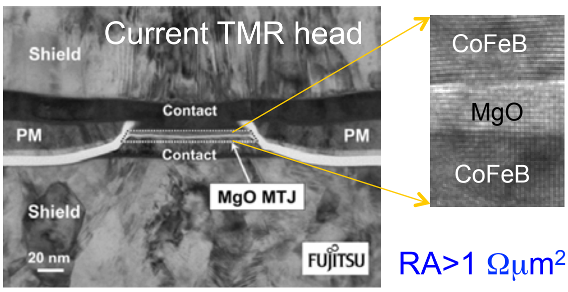
http://www.nims.go.jp/mmu/

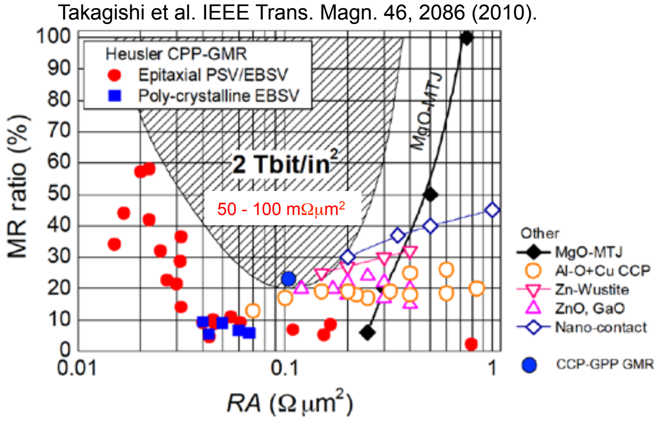
Read head for >2 Tbit/in^2





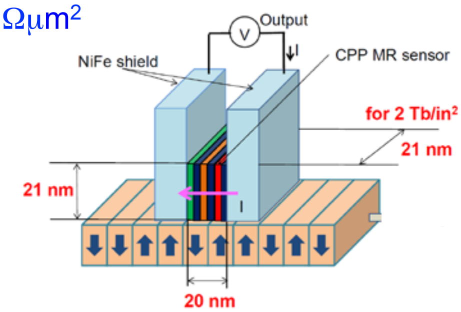
RA>1 Ωμm^2

Takagishi et al. IEEE Trans. Magn. 46, 2086 (2010).

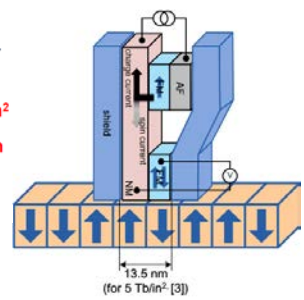


CPP-GMR

FM
NM
FM



CPP-GMR



Lateral SV

CPP-GMR and FM Heusler alloys

$$\Delta RA \approx 2\rho_F \underbrace{\frac{\beta^2}{1-\beta^2}}_{\text{bulk}} t_F + 4AR_{F/N} \underbrace{\frac{\gamma^2}{1-\gamma^2}}_{\text{interface}}$$

For 1 Tb/in^2

MR ~ 10-20%

$\Delta V = \Delta RA \times J =$ MR% x V_{BIAS}>12 mV

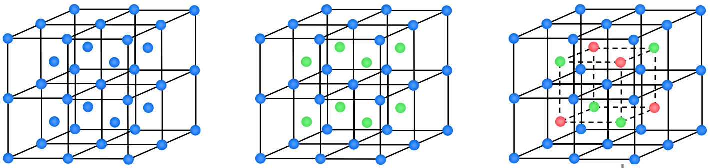
12% MR & J ~ 2×10^8 A/cm^2

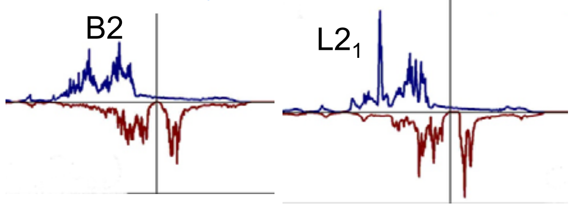
High damping against J

after Jeff Childress, HGST

Co_2FeZ or Co_2MnZ Heusler alloys

A2 X or Y or Z | B2 X(Y or Z) | $L2_1$ X_2YZ

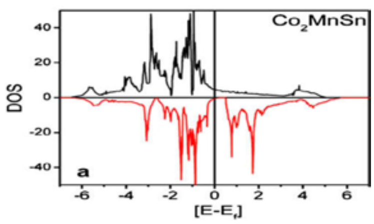




Search for highly spinpolarized FM alloys

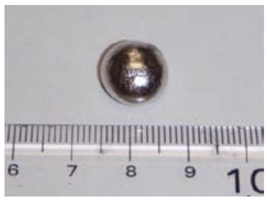
DOS calculation

DOS calculations: VASP



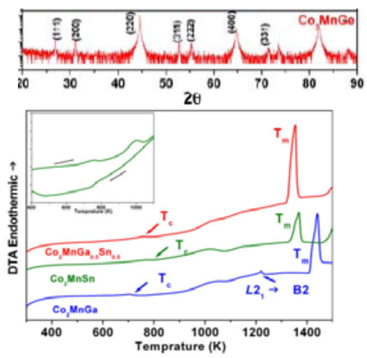
Alloy preparation

arc melting or induction meting



+ annealing

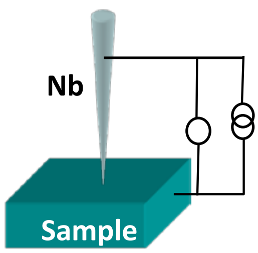
XRD & Thermal analysis

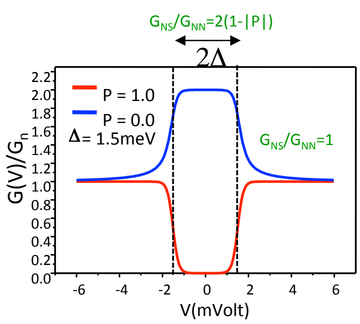


Tc, order-disorder temperature, melting point

Spin polarization

Point Contact Andreev Reflection (PCAR)



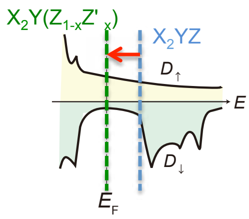


Conductance–bias

Spin polarization measured by PCAR

Quaternary alloys	P(%)	Ref.
$Co_2Mn(Ge_{0.75}Ga_{0.25})$	74	1
$Co_2Mn(Ga_{0.5}Sn_{0.5})$	72	2
$Co_2Fe(Si_{0.75}Ge_{0.25})$	70	3
$Co_2Fe(Ga_{0.5}Ge_{0.5})$	68	4
$Co_2(Cr_{0.02}Fe_{0.98})Ga$	67	5
$Co_2Mn(GeSn)$	67	6
$Co_2(Mn_{0.95}Fe_{0.05})Sn$	65	7
$(Co, Fe)_2MnGe$	65	8
$Co_2(Mn_{0.5}Fe_{0.5})Ga$	65	9
$Co_2(Cr_{0.02}Fe_{0.98})Si$	65	10
$Co_2Mn(Ti,Sn)$	64	11
$Co_2Mn(Al_{0.5}Sn_{0.5})$	63	12
$Co_2Mn(Ga_xSi_{1-x})$	63	13
$Co_2Fe(Al.Ga)$	63	14
$Co_2Mn(SiGe)$	63	15
$Co_2(Mn_{0.5}Fe_{0.5})Si$	61	16
$Co_2(Cr,Fe)Al$	60	17
$Co_2Mn(Al_{0.5}Si_{0.5})$	60	18
$Co_2Fe(Ga_{0.5}Si_{0.5})$	60	19
$Co_2Fe(Al_{0.5}Si_{0.5})$	60	20

Ternary alloys	P	Ref.
Co_2MnSi	56	21
Co_2MnGe	58	1
Co_2MnSn	60	12
Co_2MnAl	60	12
Co_2MnGa	60	1
Co_2CrAl	62	17
Co_2FeAl	59	17
Co_2FeSi	60	10
Co_2FeGa	58	22
Co_2CrGa	61	23
Co_2TiSn	57	24
Co_2VAl	48	25
Fe_2VAl	56	25



Metals and binary	P	Ref.
Fe	46	
Co	45	
FeCo	50	
$Co_{75}Fe_{25}$	58	
B2-FeCo	60	
$[Co/Pd]_n$	60	
Fe_4N	59	26
Co/Pt	56	27

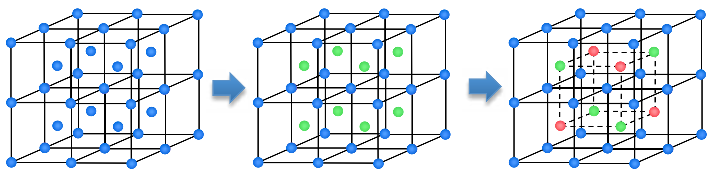
1. B. Varaprasad *et al.*, APEX**3** 023002 (2010).
2. B. Varaprasad *et al.*, Acta Matel.**57** 2702 (2009).
7. A. Rajanikanth *et al.*, JAP**103** 103904 (2008).
10. S.V. Karthik *et al.*, JAP**102** 043903 (2007).
12. A. Rajanikanth *et al.*, JAP**101** 09J508 (2007).
17. S.V. Karthik *et al.*, APL**89** 052505 (2006).
20. T.M. Nakatani *et al.*, JAP**102** 033916 (2007).
21. A. Rajanikanth *etal.*, JAP**105** 063916 (2009).
23. T.M. Nakatani *et al.*, JPD**41** 225002 (2008).
25. S.V. Karthik *et al.*, Acta Matel.**55** 3867 (2007).
26. A. Narahara *et al.*, APL**94** 202502 (2009).
27. A. Rajanikanth *et al.*, APL**97** 022505 (2010).
3-6, 8,9,11,13-17,18-20,22,24. To be submitted

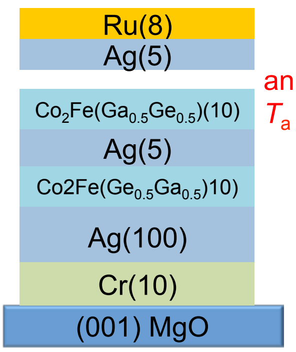
V. Varaprasad et al. Acta Mater (2012).

ΔRA increase by annealing

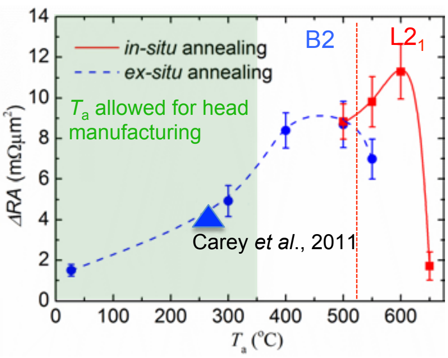
S. T. Li

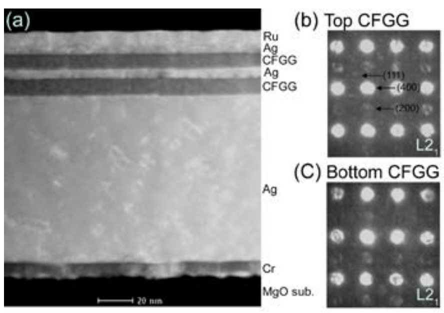
$Co_2Fe(Ga_{0.5}Ge_{0.5})$ B.S.D.Ch.S. Varaprasad et a. Acta Mater. 60, 6257 (2012).





anneal T_a

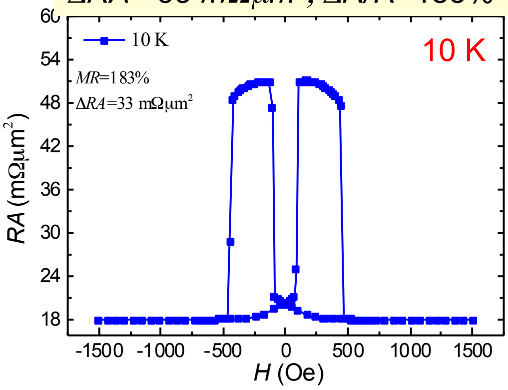




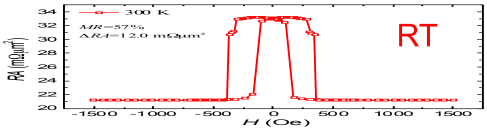
S. Li, Y.K. Takahashi, T. Furubayashi, and K. Hono, APL 103, 042405 (2013).

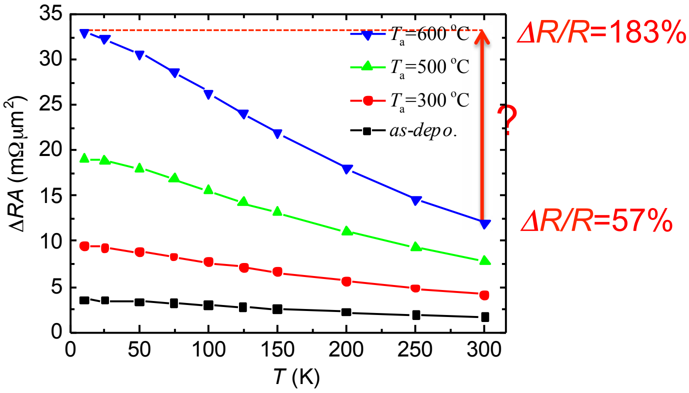
Large temperature dependence of MR

ΔRA= 33 mΩμm^2, ΔR/R=183%



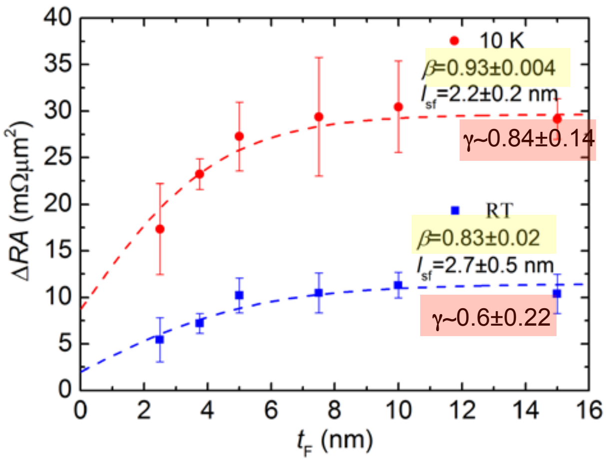
ΔRA= 12 mΩμm^2, ΔR/R=57%

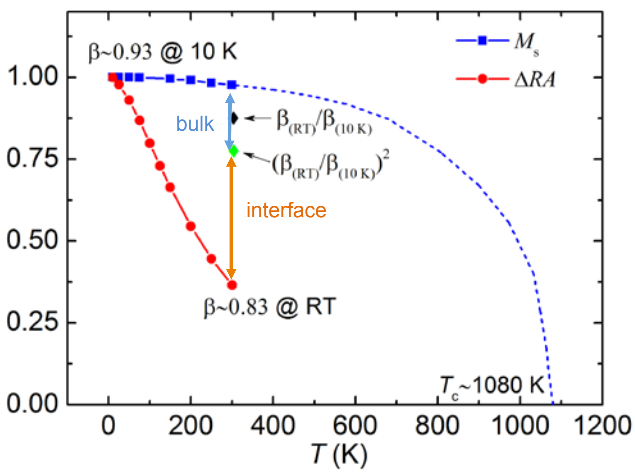




S. Li, Y.K. Takahashi, T. Furubayashi, and K. Hono, APL 103, 042405 (2013).

Origin of T dependence of *ΔRA*





$$\Delta RA \approx 2\rho_F \frac{\beta^2}{1-\beta^2} t_F + 4AR_{F/N} \frac{\gamma^2}{1-\gamma^2}$$

Which contributes to T-dependence of *ΔRA*, β or γ?

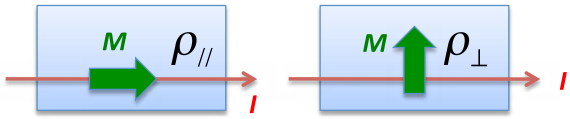
Eveluation of β using AMR measurements

Anisotropy magnetoresistance (AMR)

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

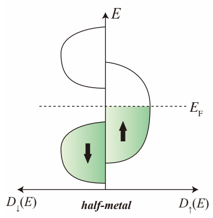
$\rho_{//} > \rho_{\perp}$: Positive

$\rho_{//} < \rho_{\perp}$: Negative



Ferromagnet

Theory of AMR and spin asymmetry by Kokado



$$\frac{\Delta\rho}{\rho} \propto \gamma(D_{\uparrow}^{(d)} - D_{\downarrow}^{(d)})(\sigma_{\downarrow} - \sigma_{\uparrow})$$

		$\gamma(D_{\uparrow}^{(d)} - D_{\downarrow}^{(d)})$	$(\sigma_{\downarrow} - \sigma_{\uparrow})$
Half-metal:	no $D_{\downarrow}(E_F)$	+	-
	no $D_{\uparrow}(E_F)$	-	+

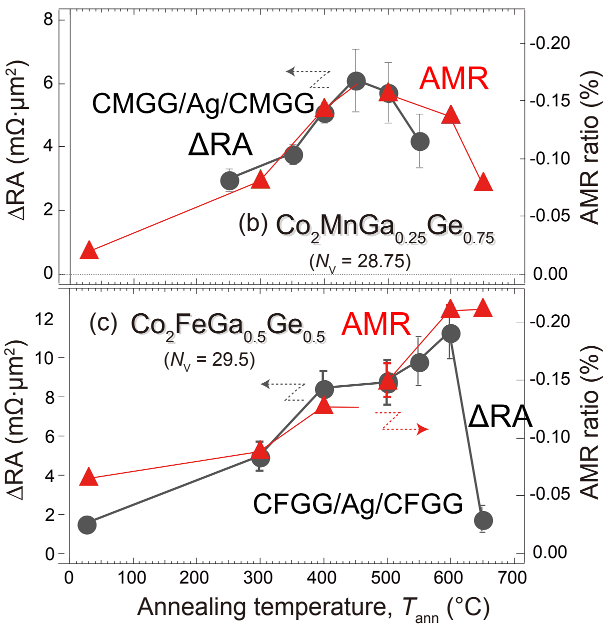
■ AMR is always ***negative*** in half-metal

$$\frac{D_{\downarrow}}{D_{\uparrow}} \propto 1 + \frac{\Delta\rho/\rho}{c}$$

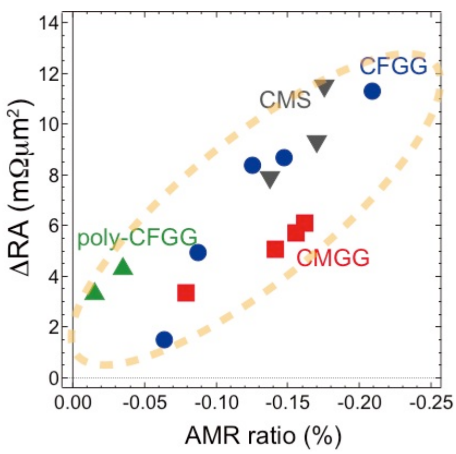
■$\Delta\rho/\rho < 0$, $|\Delta\rho/\rho|$↑ ➡ $D_{\downarrow}/D_{\uparrow}$↓ ➡ P↑.

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

ΔRA and AMR



Y. Sakuraba



Excellent correlation between AMR and ΔRA

⬇

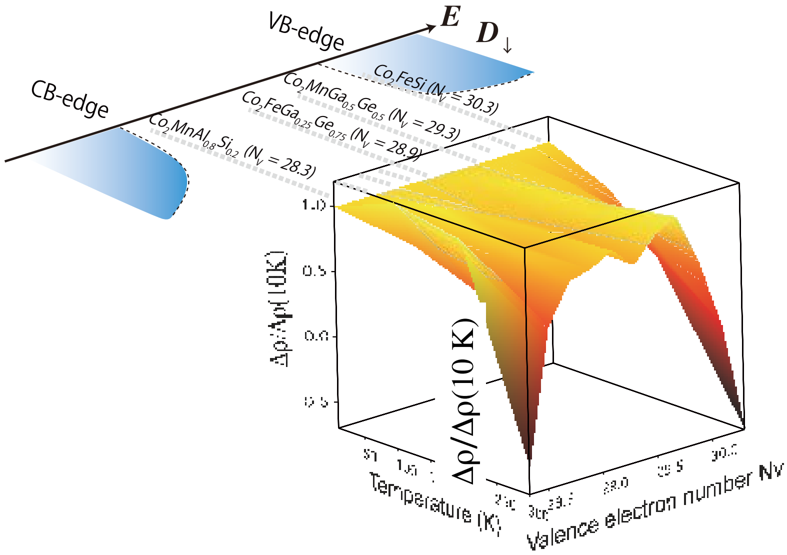
Facile way to estimate β

Y. Sakuraba et al. APL104, 172407 (2014).

Temperature dependence of $\Delta\rho$

Y. Sakuraba

$$\Delta\rho(T) = AMR(T) \times \rho(T)$$

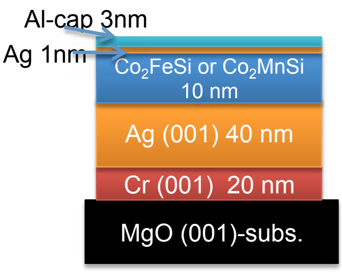


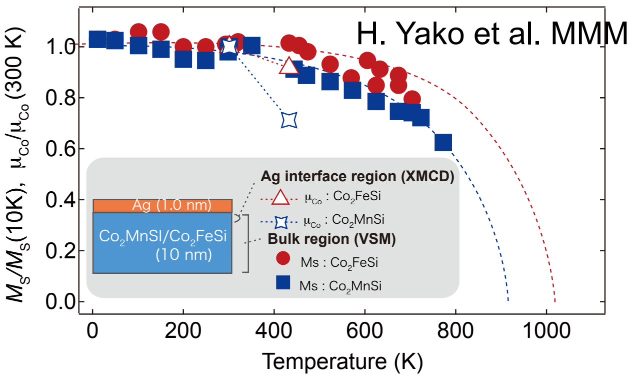
β of CFGG does not degrade at RT!

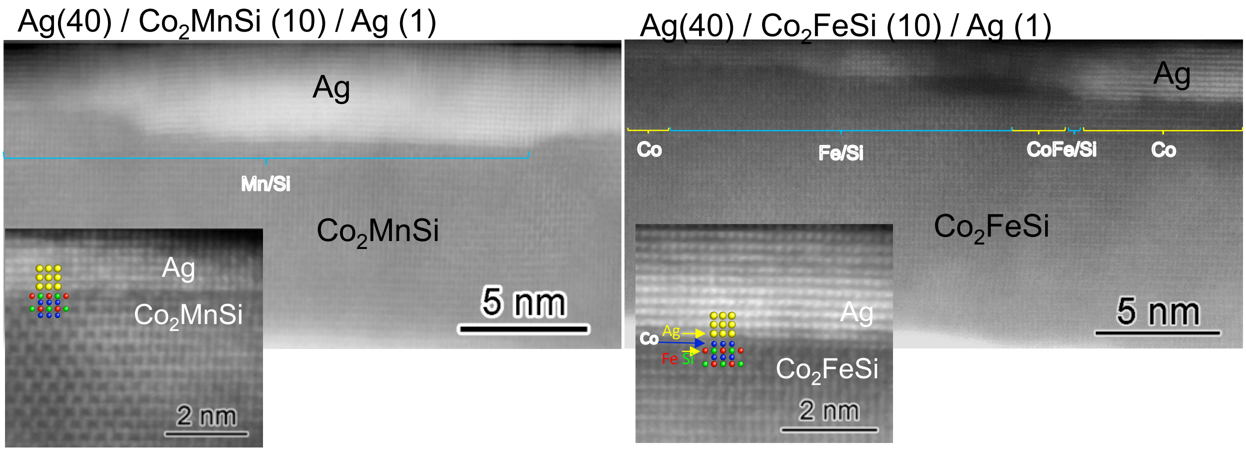
Y. Sakuraba et a. APL104, 172407 (2014).

T dependence of μ_{Co} at CMS & CFS/Ag interfaces

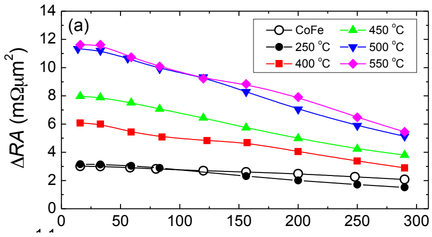
Y. Sakuraba

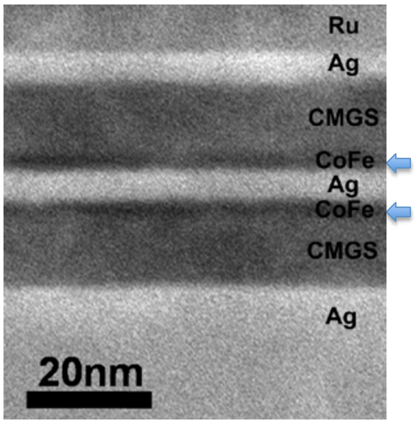


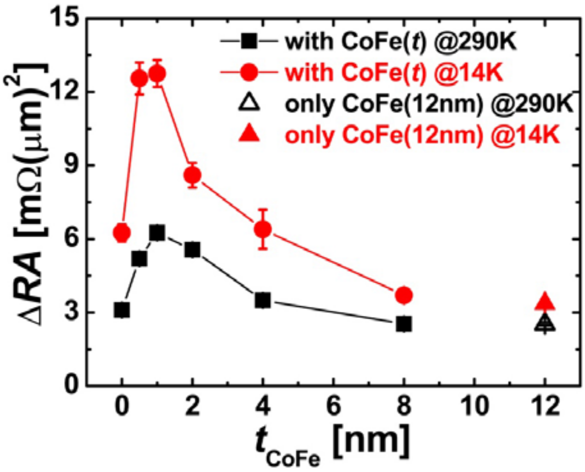




How to suppress the reduction of spin moment at Hesuer/Ag interface?



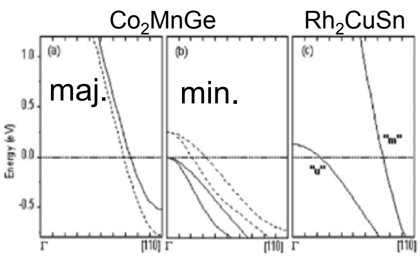


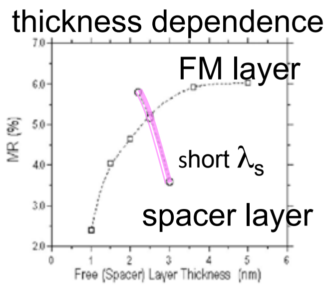


Insersion of thin FM layer for increasing exchange stiffness

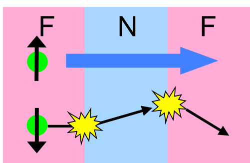
N. Hase et al. JAP 109, 07E112 (2011).

Band matching at FM/NM interface





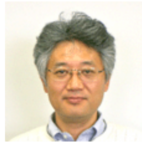
K. Nikolaev et al., Appl. Phys. Lett. 94, 222501(2009)



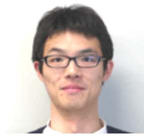
$$\Delta RA \propto AR_{F/N} \cdot \gamma^2/(1-\gamma^2)$$

small $R^{\downarrow}_{F/N}$ for up spin
large $R^{\uparrow}_{F/N}$ for down spin → large MR ratios

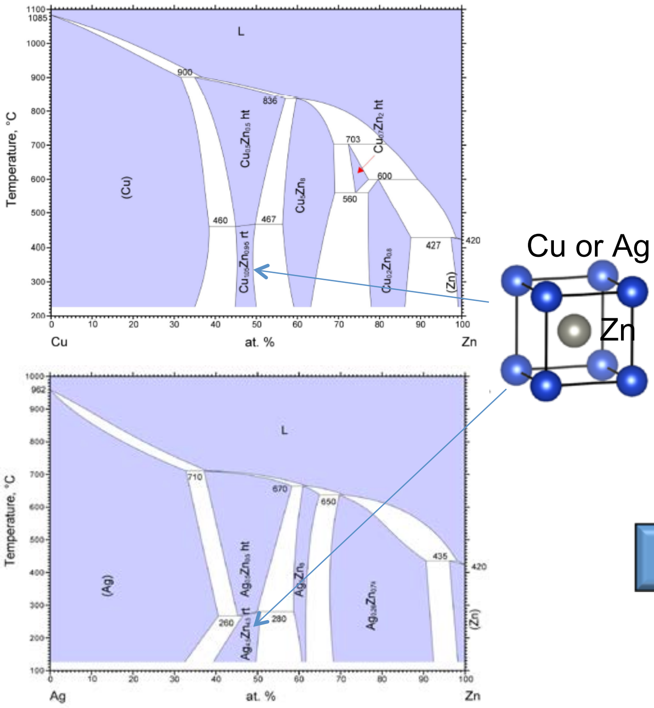
All B2 CPP-GMR

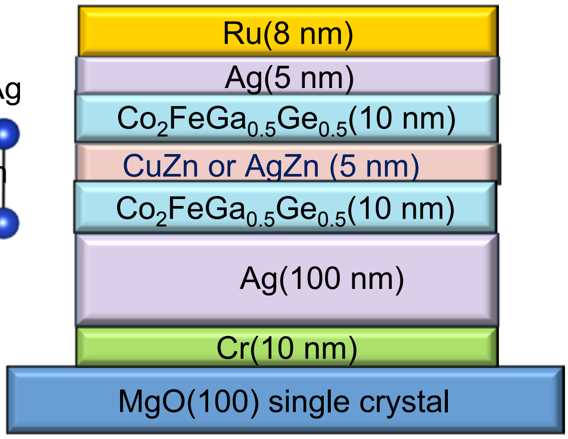


T. Furubayashi



Ye Du

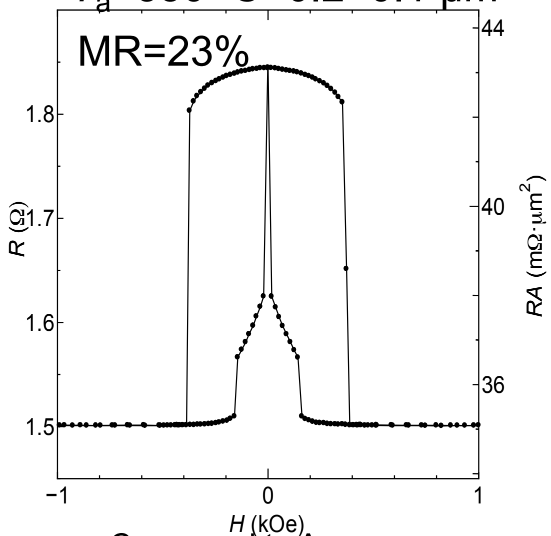


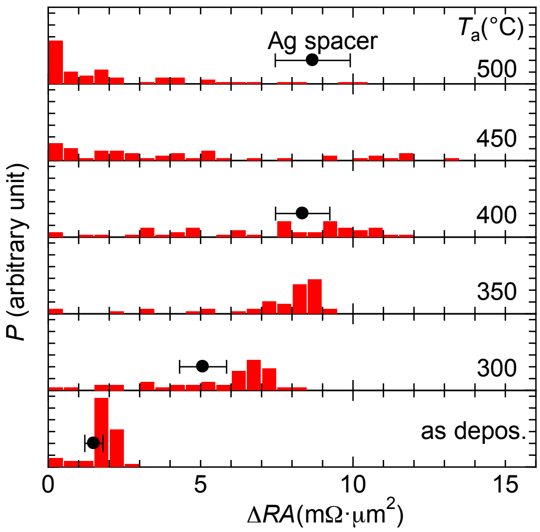


CFGG/CuZn/CFGG PSV

MgO/Cr(10)/Ag(100)/$Co_2FeGa_{0.5}Ge_{0.5}$(10)/CuZn(5)/$Co_2FeGa_{0.5}Ge_{0.5}$ (10)/Ag(5)/Ru(8) (nm)

T_a=350 ˚C 0.2×0.1 μm





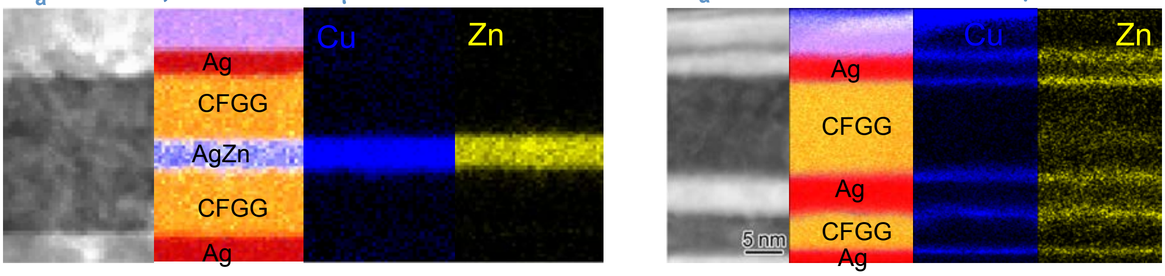
- Compared to Ag spacer*
  - larger ΔRA ~8 mΩ·μm² at low T_a=350 ˚C
  - larger $R_P A$ ~35 mΩ·μm² > ~20mΩ·μm²

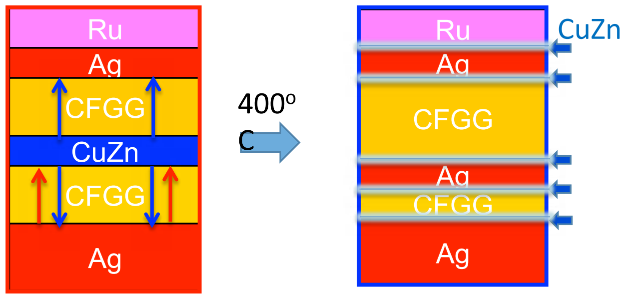
*H.S. Goripati at al., J. Appl. Phys., 113. 043901 (2013).

T. Furubayashi et al. JAP, submitted.

Why CuZn spacer causes high ΔRA at low T_a?

T_a= 350°C, ΔRA=9 mΩμm²　　T_a= 400°C, ΔRA=14 mΩμm²



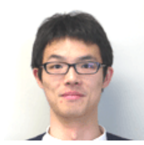


CuZn spacer is replaced with Ag spacer by interdiffusion!

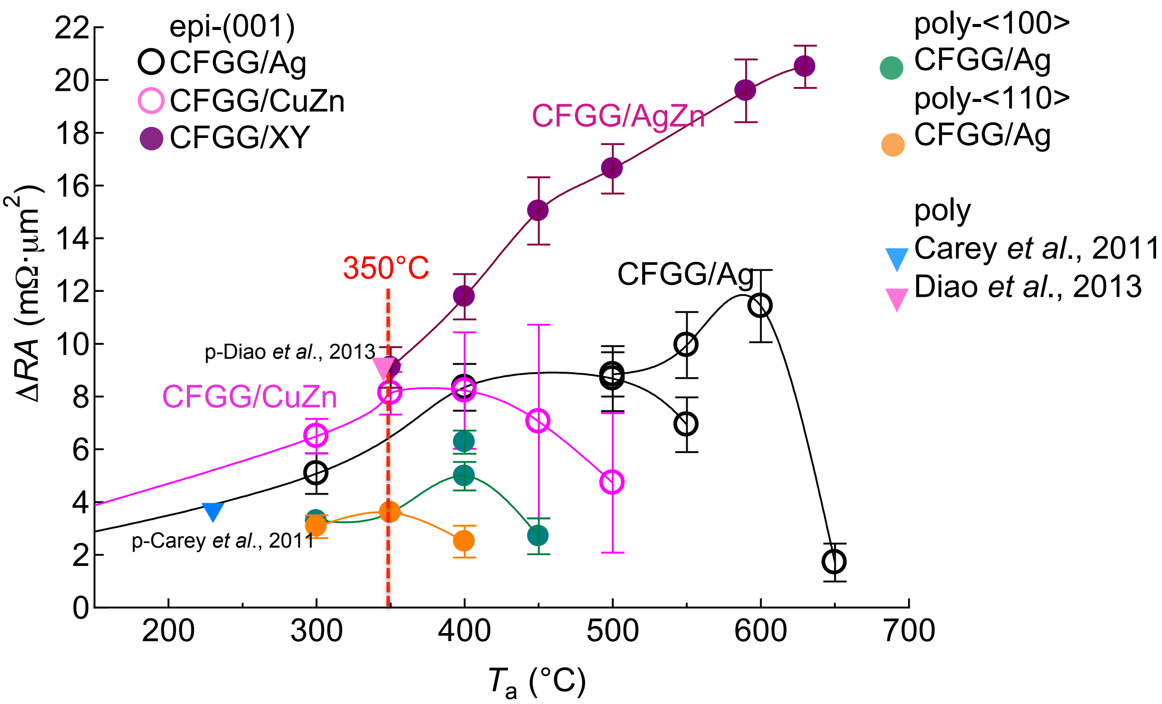
$$\Delta RA \approx 2\rho_F \frac{\beta^2}{1-\beta^2} t_F + 4AR_{F/N} \frac{\gamma^2}{1-\gamma^2}$$

- larger $R_P A$ compared to Ag space → $R_{F/N}$↑
- fast Zn diffusion may be responsible for high ΔRA at low T_a, 350°C

ΔRA and T_a of Heusler/NM/Heusler PSV

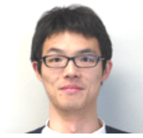


Du Ye



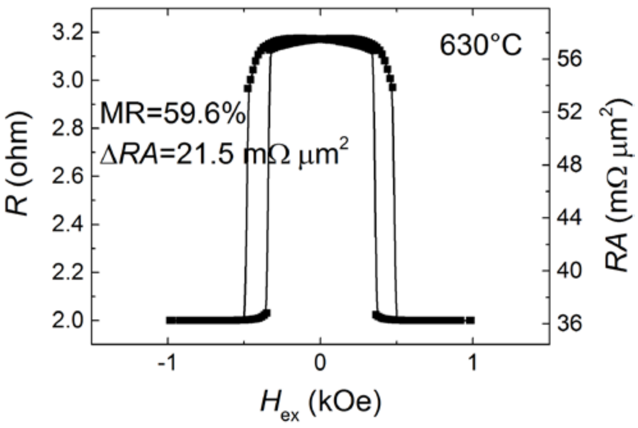
Y. Du et al. APL, submitted.

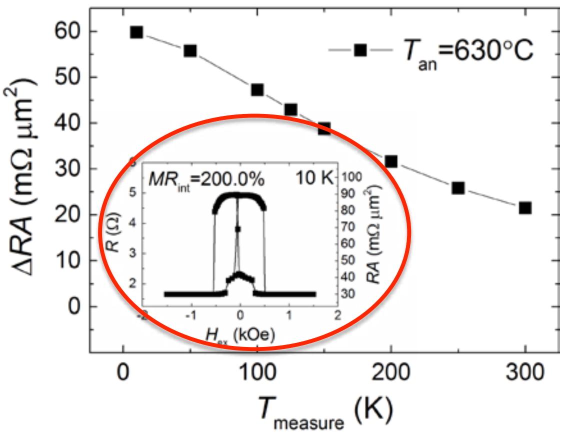
Very large ΔRA of CFGG/AgZn/CFGG PSV



Du Ye

MgO//Cr10/Ag100/CFGG10/AgZn5/CFGG10/Ag5/Ru8

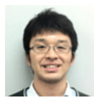




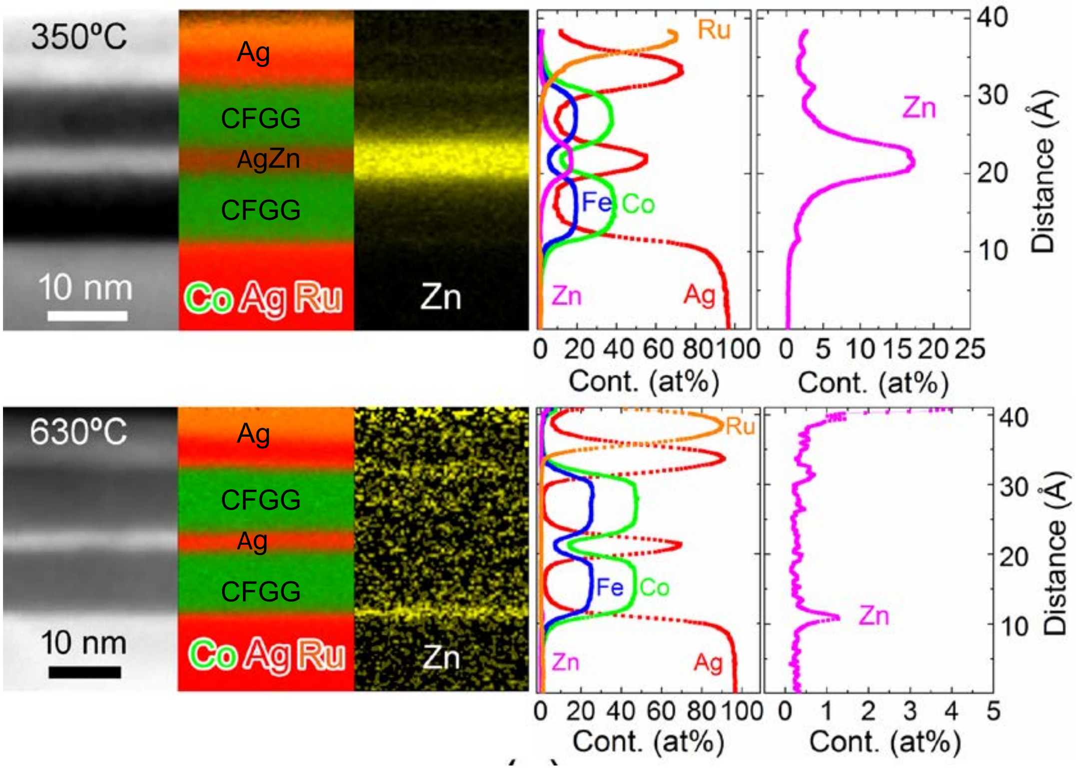
Selection of an appropriate spacer give large ΔRA – need of new materials search

Y. Du et al. APL, submitted.

Interlayer diffusion during annealing

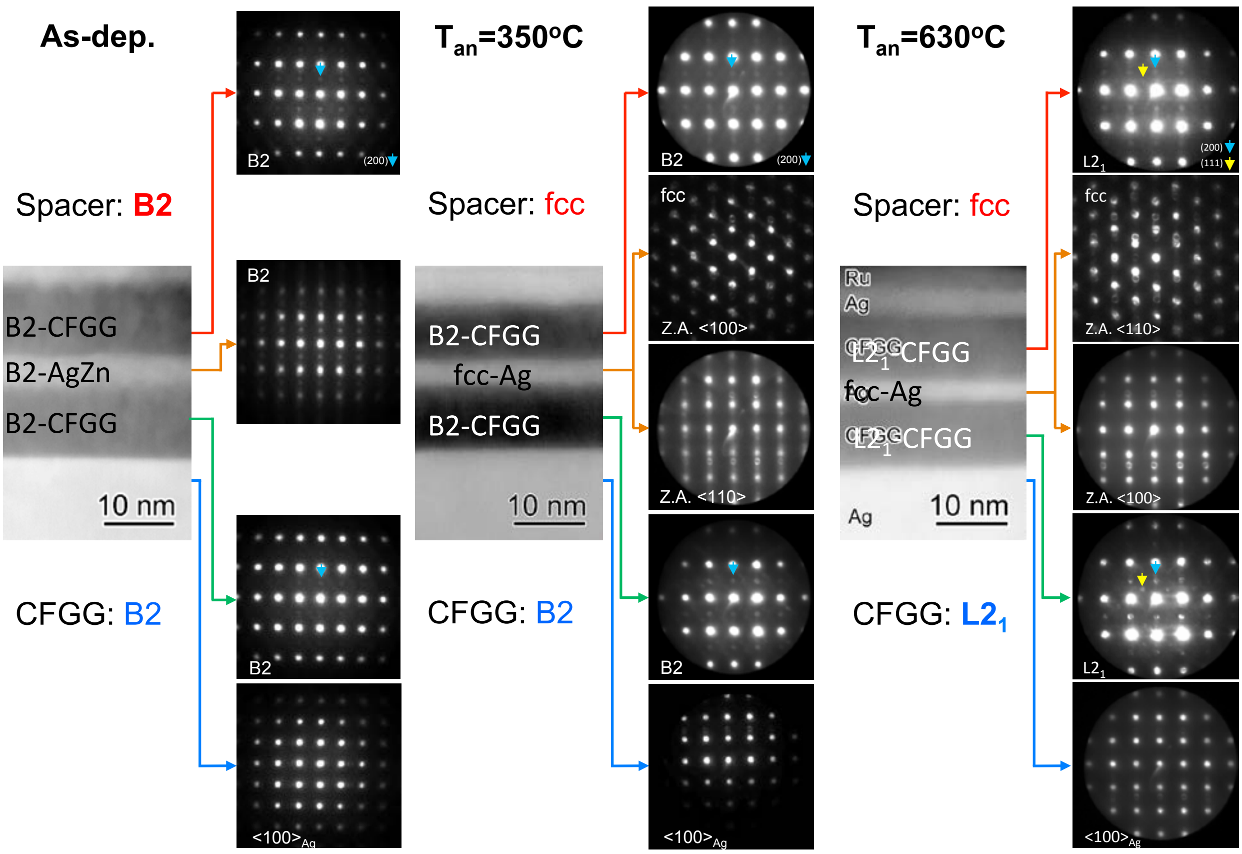


T. T. Sasaki



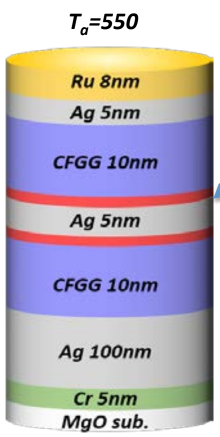
Y. Du et al. APL, submitted.

Structure of each layer in CFGG/XY/CFGG

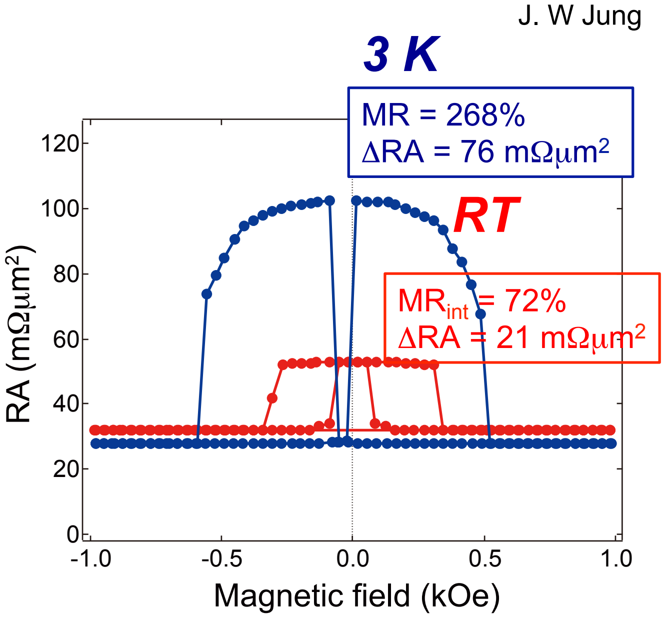


268% GMR by interface band matching?

J. W Jung



insertion of a matching layer

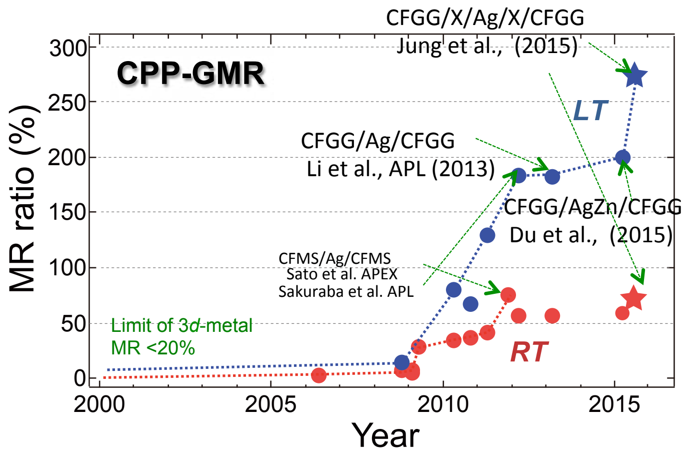


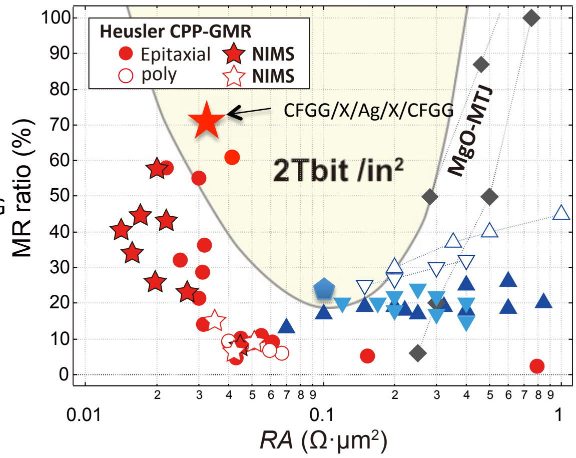
XY has an excellent band matching with Ag

λ_s of XY is only ~2 nm → interface insertion

J. W. Jung, MMM-Intermag Joint 2016.

Heusler alloy based CPP-GMR

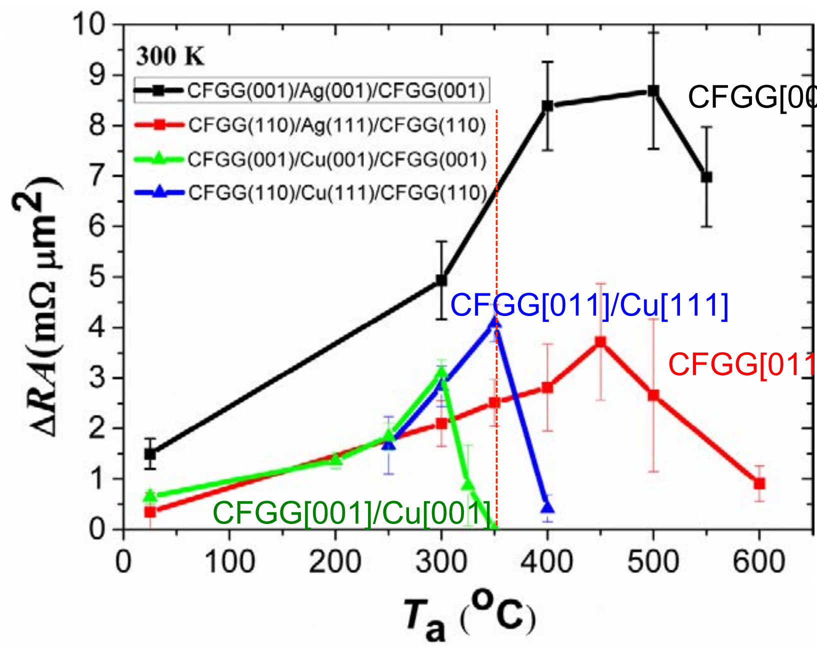




HGST, Intermag2015

CFGG/Ag orientation dependence of ΔRA

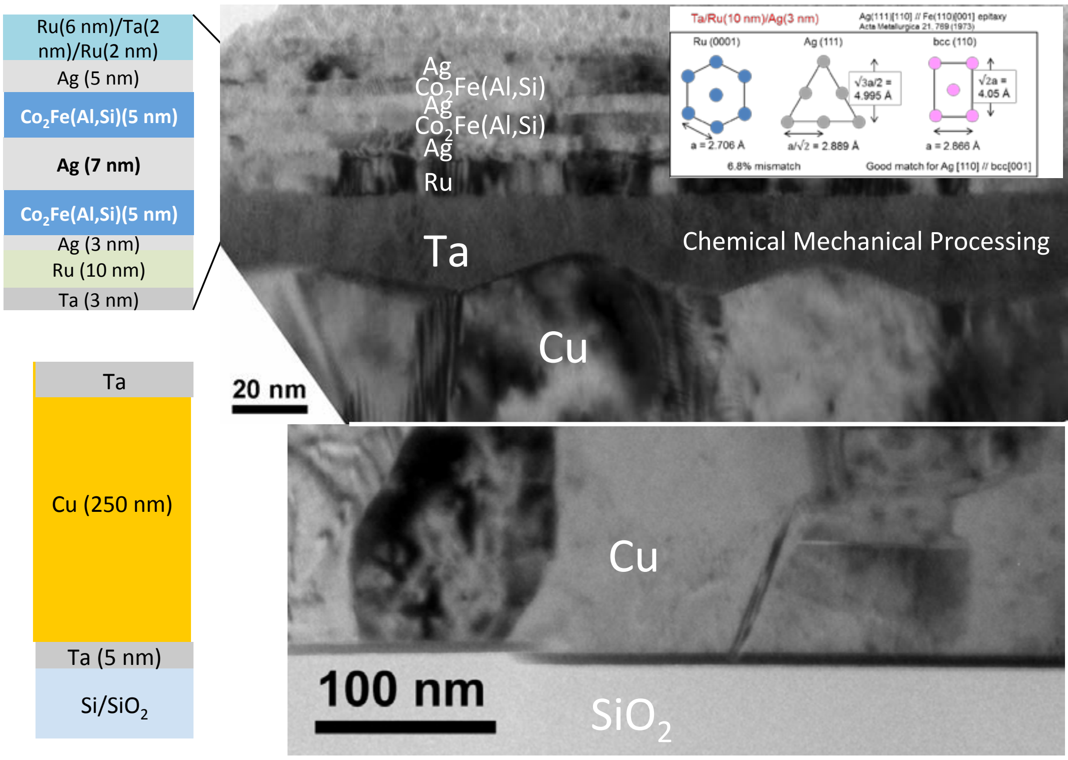
J. Chen



J.Chen et al. JAP, 115, 233905 (2014).

Polycrystalline CFAS PSV

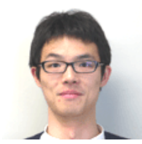
T. Nakatani



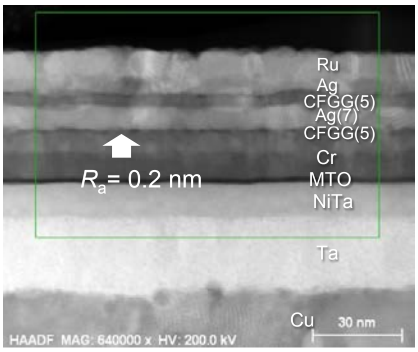
T.M. Nakatani et al. Acta Mater. 61, 3695 (2013).

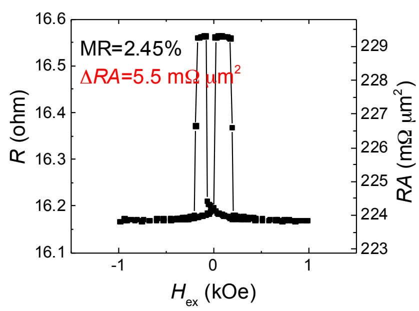
(001) polycrystalline PSV: MTO buffer

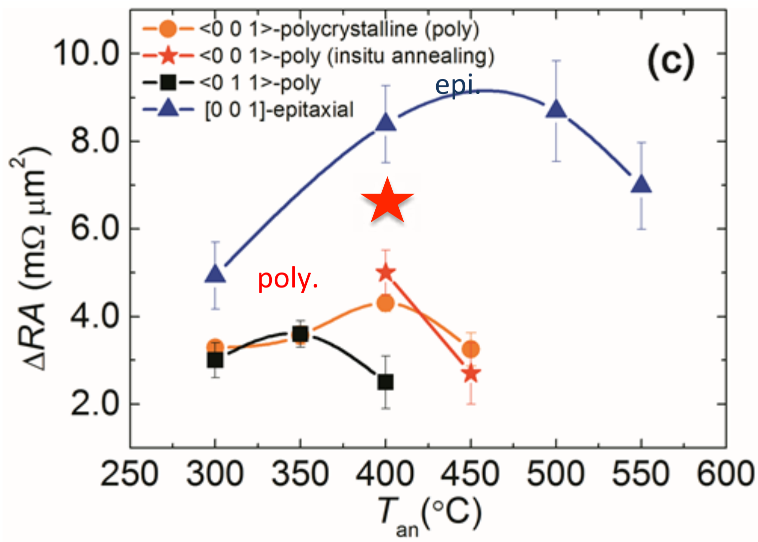
Si-SiO$_2$ subs./Ta/Cu(250)/Ta/NiTa/Mg$_{0.5}$Ti$_{0.5}$O buffer



Du Ye





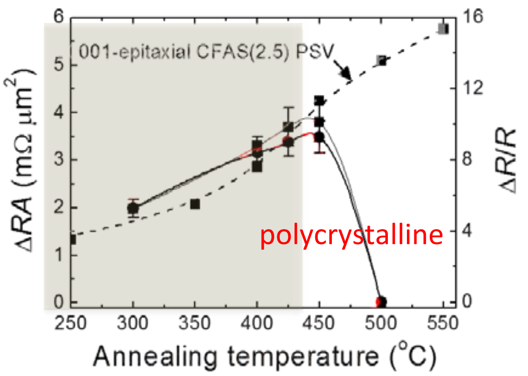


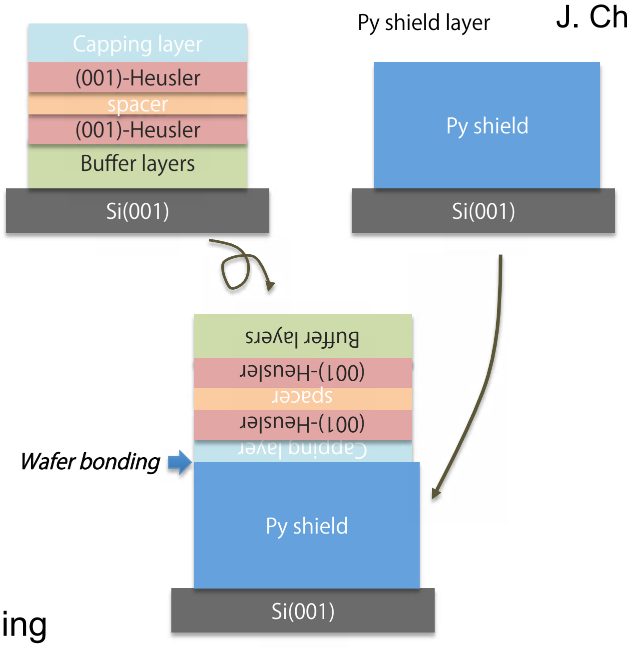
(001)-oriented device show higher DRA compared to (011)-oriented

Y. Du et al., APL 103, 202401 (2013).

Epitaxial device by wafer bonding

J. Chen



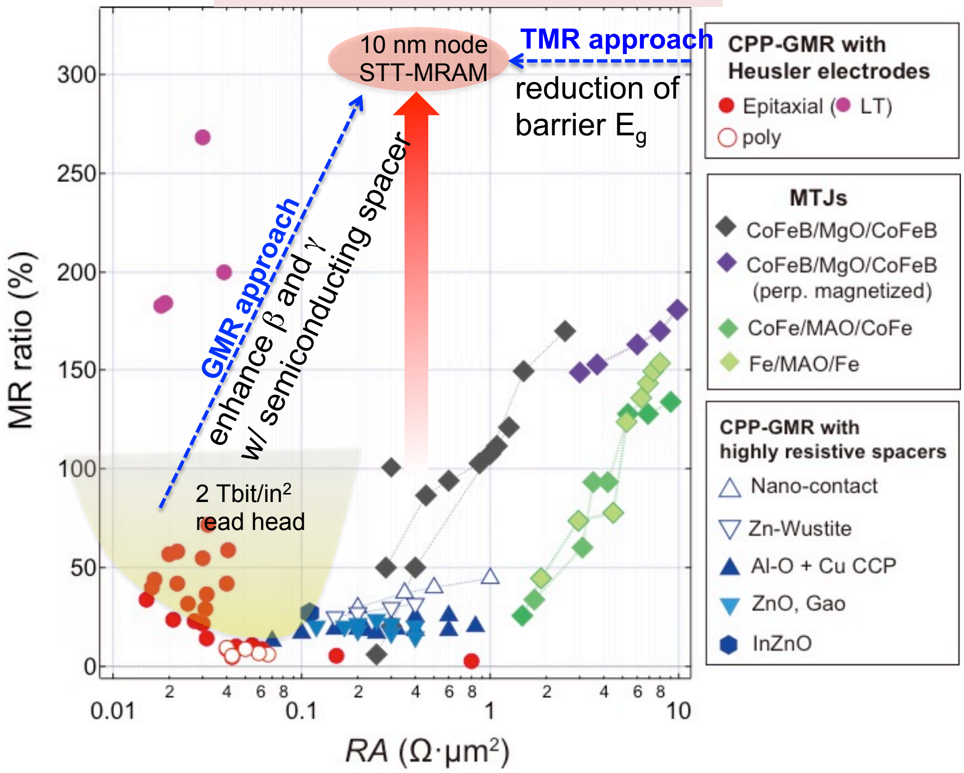


allows high temperature processing
high MR low RA will lead other applications of CPP-GMR

in collaboration with AIST

Future direction

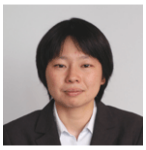
MR>300%, RA<0.8Ωμm²
for 10X STT-MRAM and spin-logic

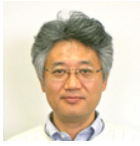


Acknowledgement

NIMS

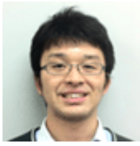

Y. Sakuraba


Y. K. Takahashi


T. Furubayashi


S. T. Li

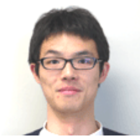

S. Bosu


T. T. Sasaki


J. W. Jung


T. Nakatani
(now HGST)

University of Tsukuba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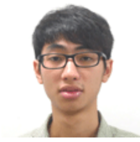
J. Chen


Ikhtiar

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