TMRC 2011 at University of Minnesota
talk # C3, 8/30/2011

Heusler alloy CPP spin-valves for ultrathin reader applications

Tomoya Nakatani[1], N. Hase[2,1], H. S. Goripati[2,1], Y. K. Takahashi[1], T. Furubayashi[1], K. Hono[1,2]

[1]National Institute for Materials Science, Japan
[2]University of Tsukuba, Japan

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

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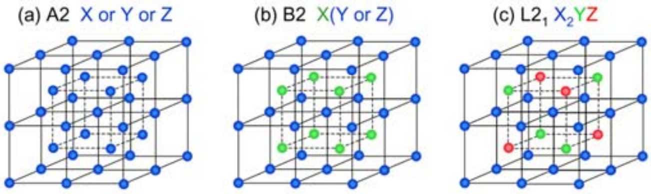
The University of Alabama 1831: O. Mryasov

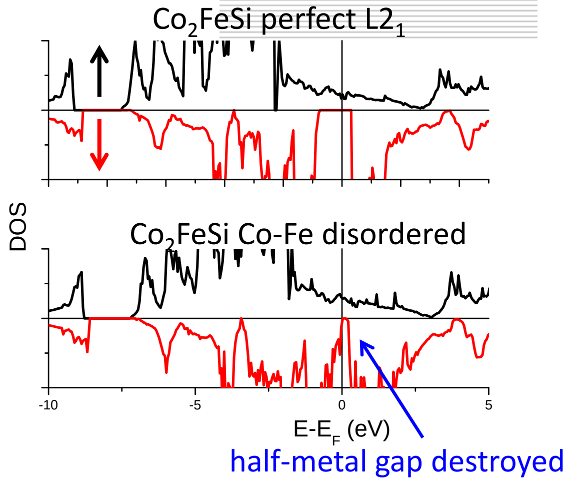
TOSHIBA Leading Innovation: H. Iwasaki, M. Takagishi, K. Koi

Hitachi Global Storage Technologies: J. R. Childress

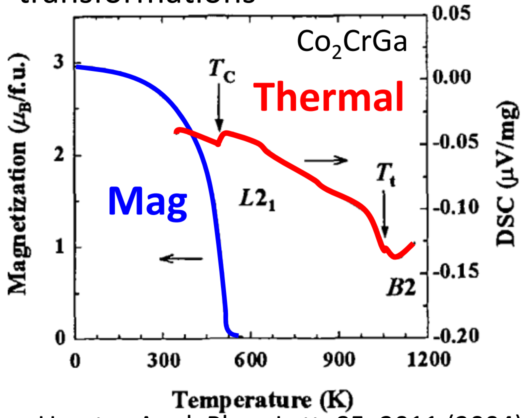
Half-metallic Heusler alloy



Co_2MnGe, Co_2FeSi etc.



Magnetic and order-disorder transformations



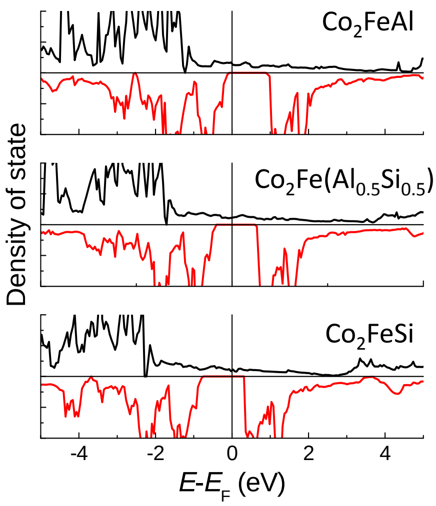
Umetsu Appl. Phys. Lett. 85, 2011 (2004)

Criterion for alloy choice

- Half-metallicity in calculation.
- High Curie temperature.
- High order-disorder temperature
  → high driving force for ordering

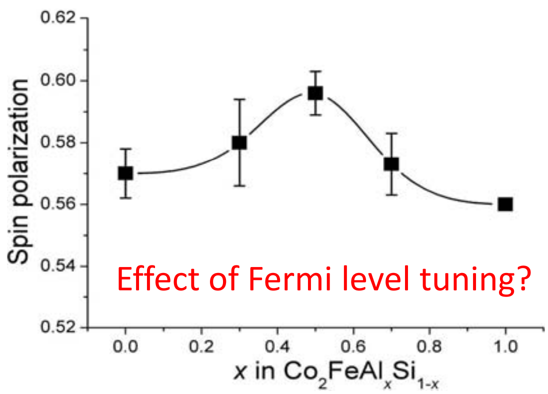
Quaternary Heusler alloy

- <u>Balance different properties</u>
  e.g. **Co_2(Cr,Fe)Al**: Co_2CrAl is HM but low Tc,
  Co_2FeAl has high Tc but not HM
- <u>Tune the Fermi level</u>
  e.g. **Co_2Fe(Al,Si), Co_2(Mn,Fe)Si**



Systematic change of E_F

Spin polarization by PCAR



Fecher, J. Phys. D, 40, 1572 (2007); Tezuka, Appl. Phys. Lett. 89, 112514 (2006); Balke, Phys. Rev. B 89, 252508 (2006); Nakatani, J. Appl. Phys. 102, 033916 (2007); Gercsi, J. Phys. Cond. Mat. 19, 326216 (2007).

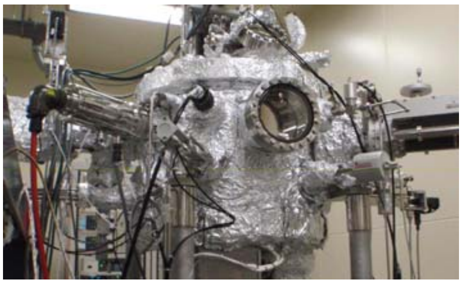
Purpose & outline

1. Study physical aspects of Heusler based-CPP-GMR using a $Co_2Fe(Al_{0.5}Si_{0.5})$ alloy.
   - Spin-dependent scattering
   - FM and spacer thickness for CPP-GMR
   - Annealing temperature for Heusler ordering
   - Spin torque noise

2. Search and develop new Heusler composition with large CPP-GMR output.

Experimental methods

UHV Magnetron sputtering



3 inch DC/RF cathode, 10 targets

- base 1×10^{-7} Pa
- RT deposition
- Deposited from alloy target
- Substrate heater

Fully epitaxial on MgO(001)

- Single crystalline → more intrinsic property
- Smooth interfaces

MgO//Cr(10 nm)/Ag(100 nm) underlayer

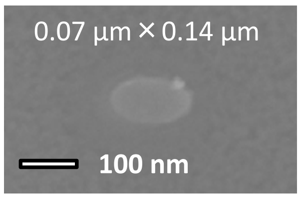
lead electrode

Roughness R_a = 1 Å

Device fabrication

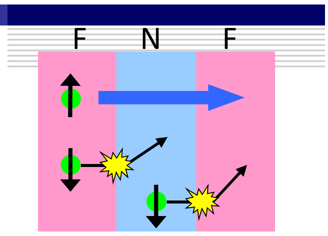
Photolithography + EB lithography

1 cm substrate



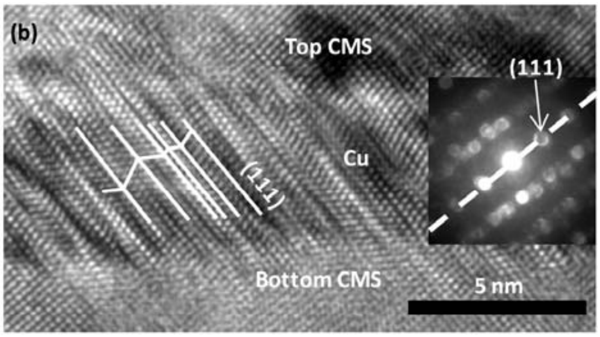
Material for the spacer layer

- Good conductivity → spin diffusion length
- Small lattice mismatch
- Thermal stability for annealing
- Band matching →



Large interfacial spin-dependent scattering

Twin in **Cu** spacer: Co_2MnSi/Cu 001 epi



Large lattice mismatch with Heusler: 10%

Kodama , J. Appl. Phys. 105, 07E905 (2009)
Furubayashi, JAP 107, 113917 (2010)

Ag

- ρ = 2 μΩcm
- SDL > 100 nm
- Lattice mismatch < 2% with Heusler
- Immiscible with Co, Fe or Si either
- Band matching ??

Furubayashi et al. APL (2008)

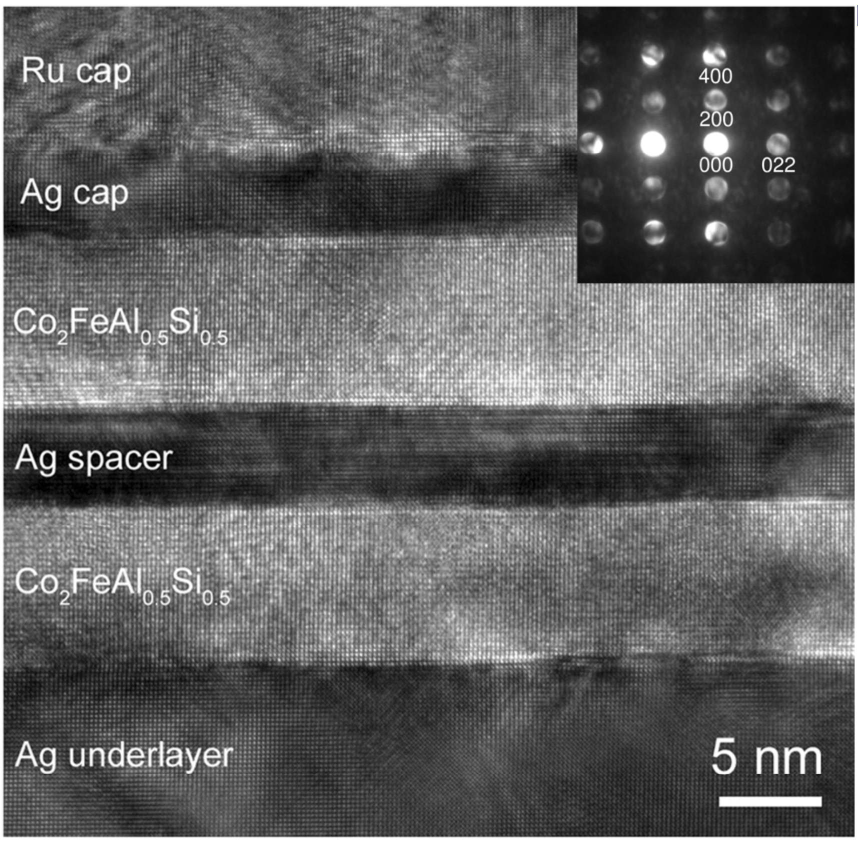
NiAl B2 intermetallic compound

- ΔRA comparable to Ag
- Short spin diffusion length
- Strong ferromagnetic interlayer coupling

Nakatani, to be published

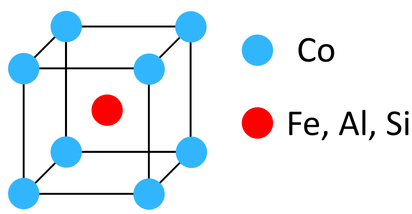
Cross-sectional TEM

Annealed at 500 °C



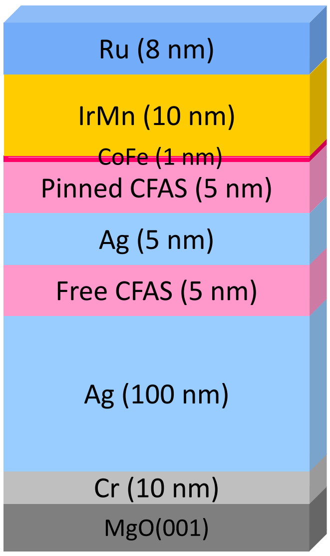
- Coherent epitaxial at CAFS/Ag interface.
- Free from strain.
- Very flat and sharp interfaces.
- B2 ordered CFAS layers.

B2 structure



Exchange biased spin-valve

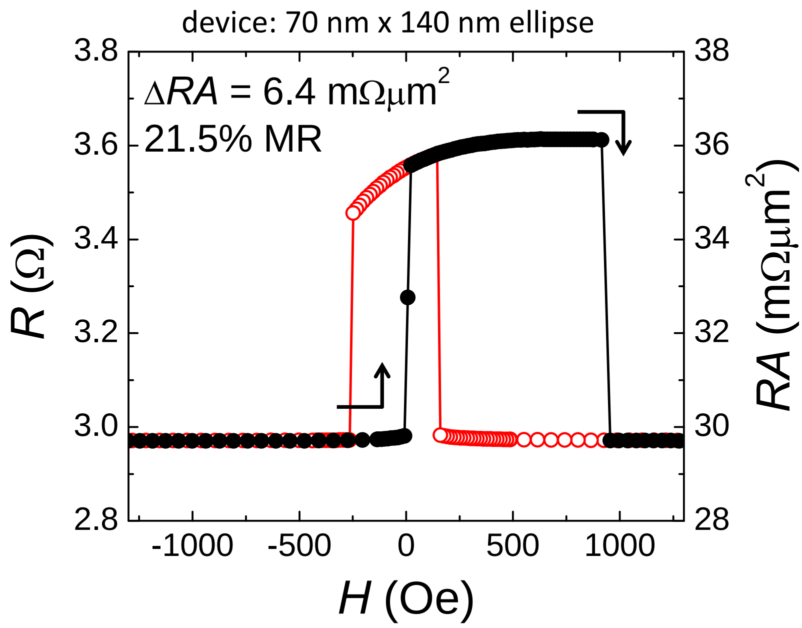
$Co_2Fe(Al_{0.5}Si_{0.5})$ Heusler (CFAS)



All deposition at RT

⇩

500 °C in 5 kOe



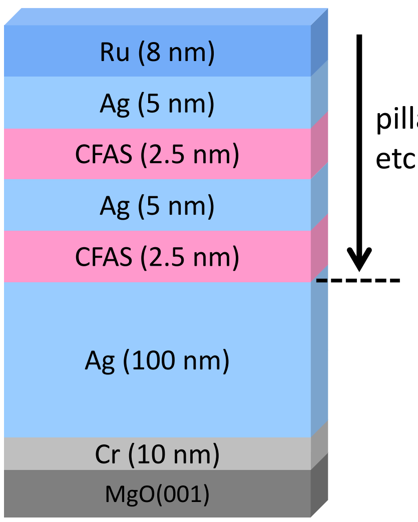
Large CPP-GMR outputs with CFAS/Ag

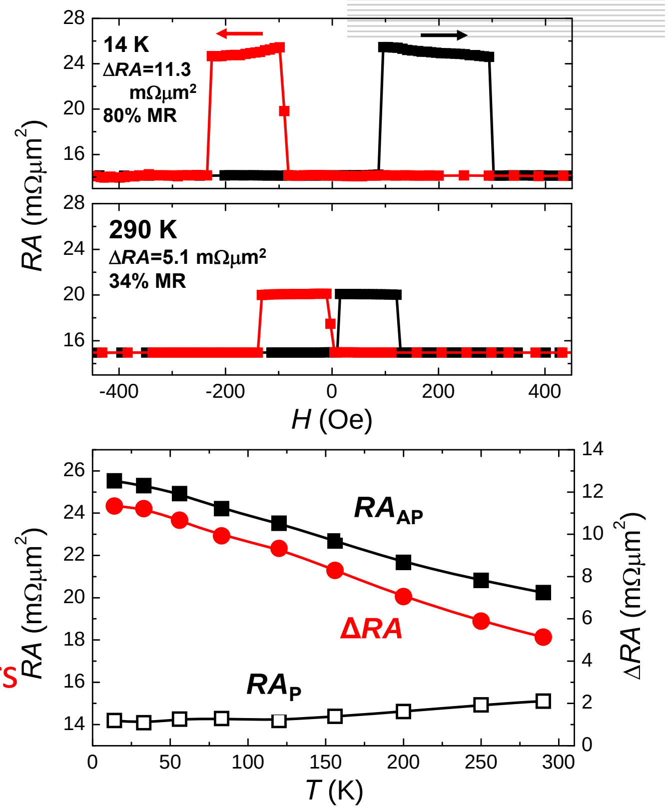
cf. poly-CoFe/Cu ΔRA < 1 mΩμm²

epi-CoFe/Ag ΔRA = 2 mΩμm²

Pseudo spin-valve

annealed at 500 °C



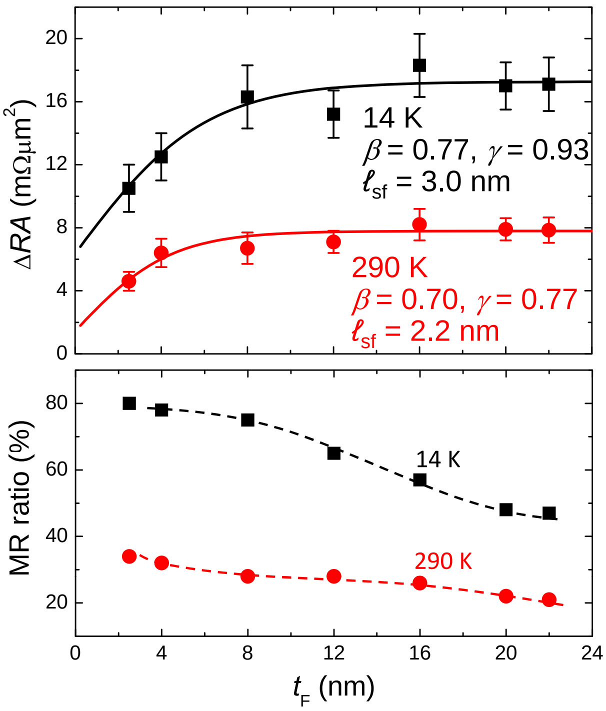


- AP state by dipole coupling
- Large ΔRA with 2.5 nm FM layers
- Large temperature dependence of ΔRA.

Nakatani, Appl. Phys. Lett. 82, 094444 (2010).

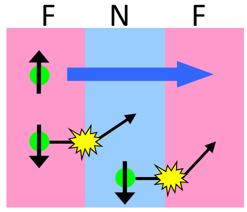
Spin-dependent scattering

CFAS/Ag/CFAS PSV annealed at 500 C



- Large bulk scattering
- High resistivity 70 μΩcm
- Short spin diffusion length
- Large interfacial scattering

Large ΔRA and ΔR/R with thin FM layers.

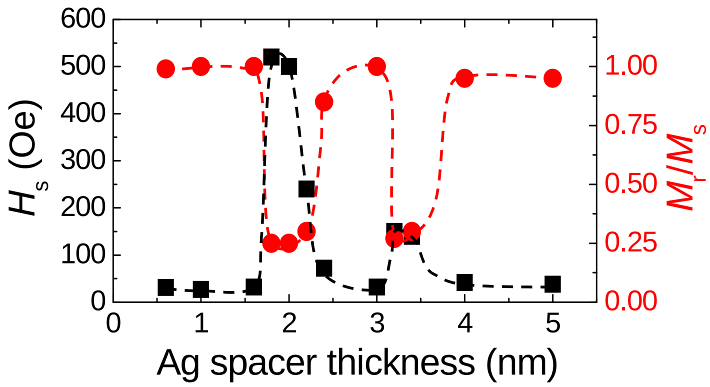


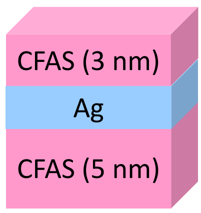
- Small interfacial R
  AR ~ 0.25 mΩμm^2
- Large γ

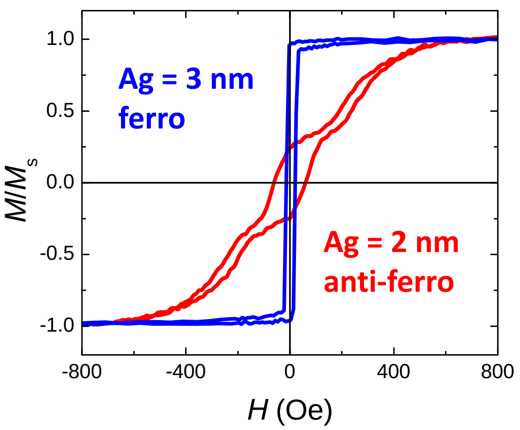
→ Beneficial for ultrathin reader

Nakatani, Appl. Phys. Lett. 82, 094444 (2010), J. Appl. Phys. 109, 07B724 (2011)

Ag spacer thickness: How thin can we reduce?



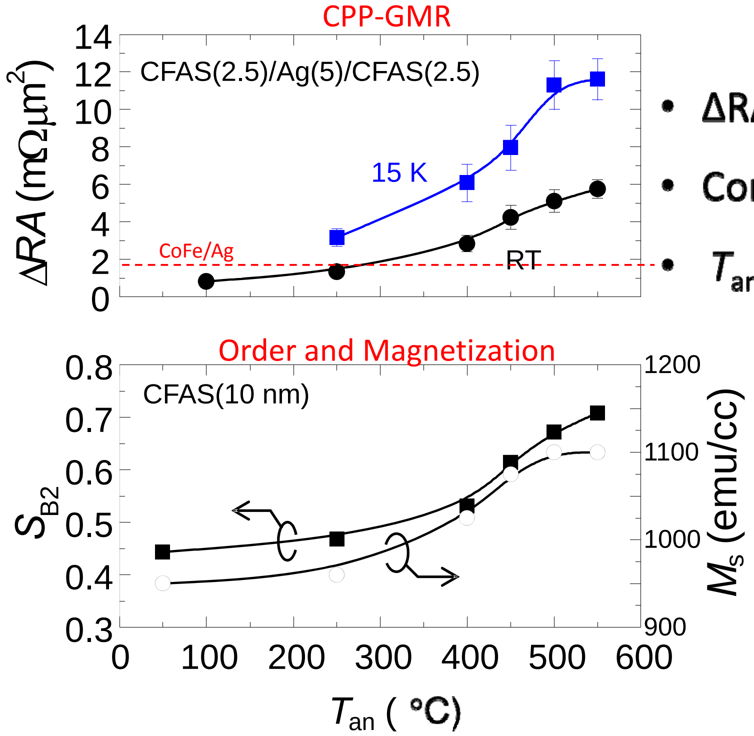




- Oscillatory AFM coupling
- Keep Ag > 4 nm for spin-valve.
- AFM coupled is usable for
  dual-free-layer sensor?

Presented at poster session of TMRC2011
To be presented at MMM by Nakatani (poster)

Annealing temperature dependence

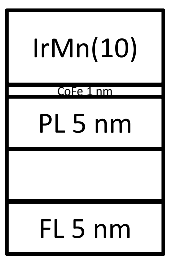


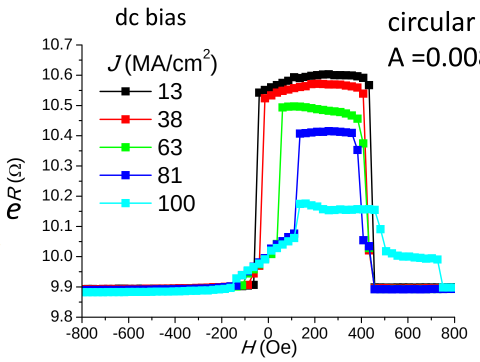
- ΔRA increases with T_{an}.
- Consistent with B2 order and M_s.
- T_{an}< 300 °C, ΔRA lower than CoFe.

Important to obtain highly ordered Heusler by low T_{an}.

submitted to proceedings of TMRC2011

Bias current density and spin torque noise

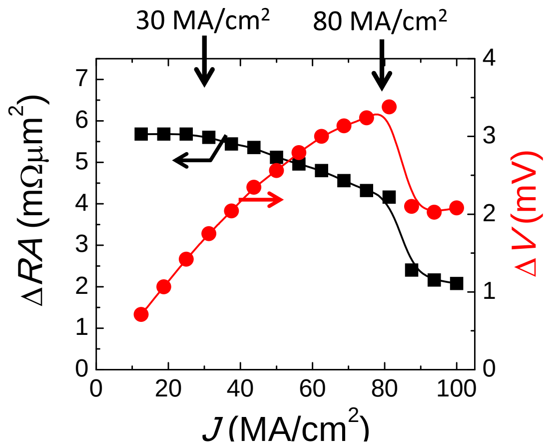




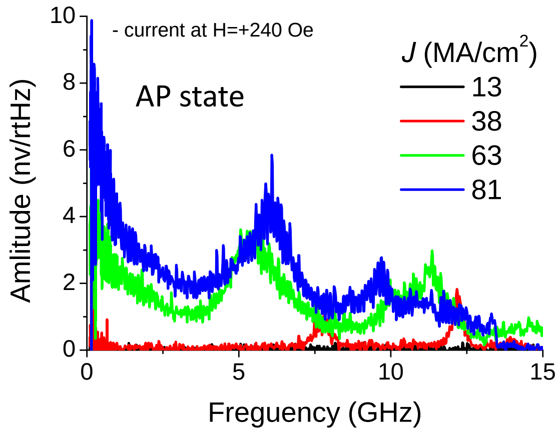
circular pillar
A =0.008 μm²

$J_{critical}$ ~ 40 MA/cm²

→Need to be improved.
***e.g.* 100 MA/cm² for read head**



CFAS: damping constant α = 0.005–0.01 by FMR



Summary of $Co_2Fe(Al_{0.5}Si_{0.5})$ CPP-SV

001-epitaxial CFAS/Ag/CFAS SVs

- ΔRA = 6 mΩμm^2, ΔR/R = 21% in EBSV with 5 nm CFAS (T_{an} = 500 C).
- Large contribution of interfacial scattering.
  - → Good band match at CFAS/Ag
  - → Advantageous for ultrathin reader.
- Ag spacer for SV must > 4 nm to decouple FL and PL.
  FM/NM/FM trilayer ~ 10 nm
- ΔRA: strong dependence on T_{an} → T_{an} > 400 C for B2 ordering.
- $J_{critical}$ = 40 MA/cm^2 for 1/*f*-like spin-torque noise.

Need Heusler materials with

⇨ **• Larger ΔRA and ΔR/R with thin FM thickness.**
• Lower annealing temperature for ordering.

Purpose & outline

1. Study physical aspects of Heusler based-CPP-GMR using a $Co_2Fe(Al_{0.5}Si_{0.5})$ alloy.

2. Search and development of new Heusler composition with large CPP-GMR output.

   $Co_2(Cr_{0.1}Fe_{0.9})Si$
   $Co_2Mn(Ga_{0.5}Sn_{0.5})$
   $Co_2Fe(Ge_{0.5}Ga_{0.5})$
   $Co_2Mn(Ge_{0.5}Ga_{0.5})$

Methods of alloy search

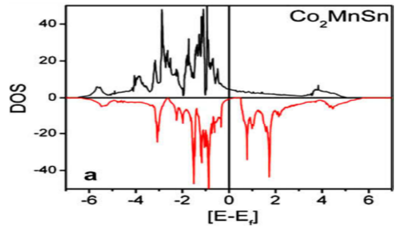
Alloy synthesis

arc melting or induction meting

+ annealing

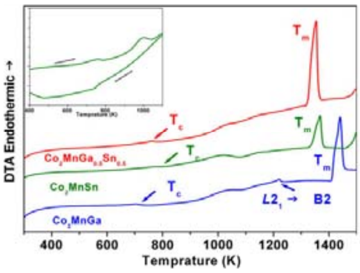
DOS calculation

Commercial package: VASP



Thermodynamically property

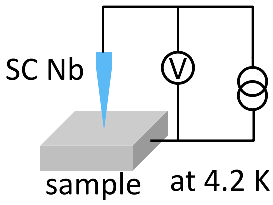
differential thermal analysis (DTA)



Tc, order-disorder temperature, melting point

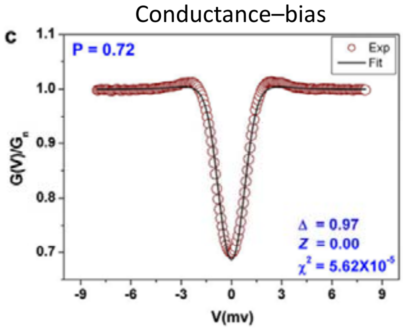
Spin polarization

Point Contact Andreev Reflection (PCAR)



Lock-in amp
Numerical dI/dV

Conductance–bias



$Co_2(Cr,Fe)Si$ alloy: effect of Cr doping

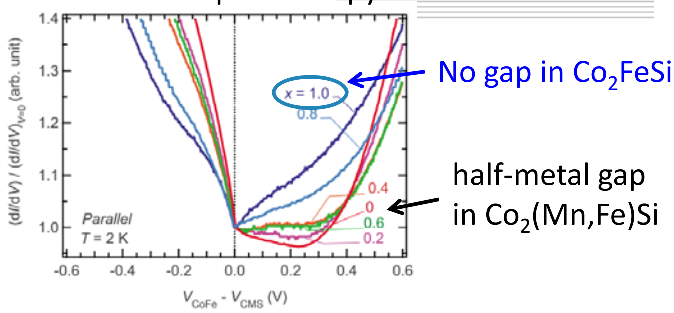
Co_2FeSi: Tc = 827 °C[1]

$T_{L2_1/B2}$=1145 °C[2]

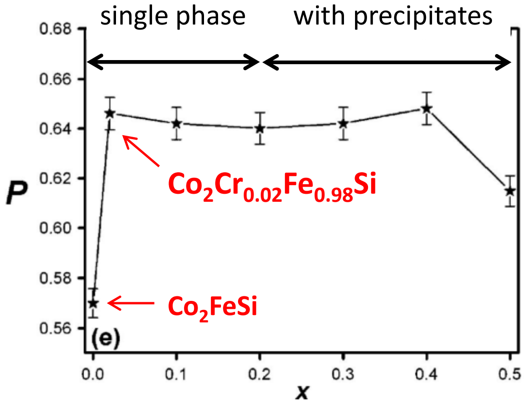
Predicted half-metal

[1] Wurmehl, Appl. Phys. Lett., 88, 032503 (2006).
[2] Umetsu, private communication.

Tunnel spectroscopy



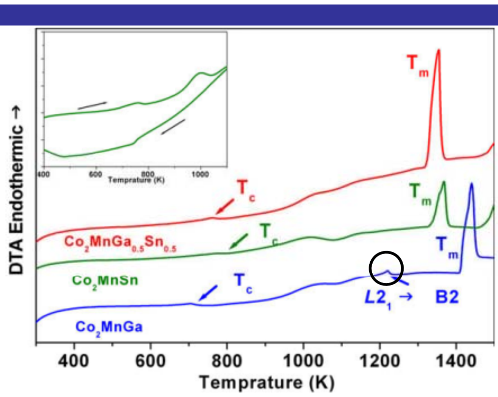
Kubota, Appl. Phys. Lett. 94, 122504 (2009).



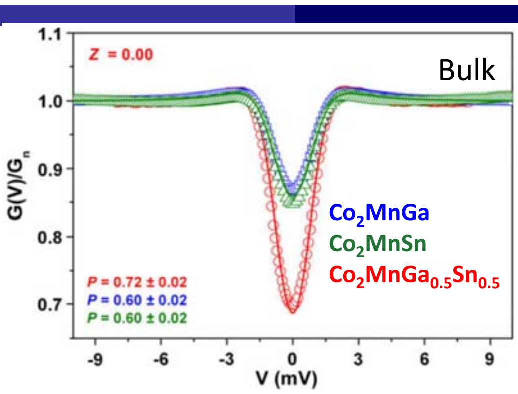
Karthik, J. Appl. Phys. 102, 043903 (2007).

- Enhancement of P by small Cr
- Improvement of ordering by Cr by XRD and Mössbauer

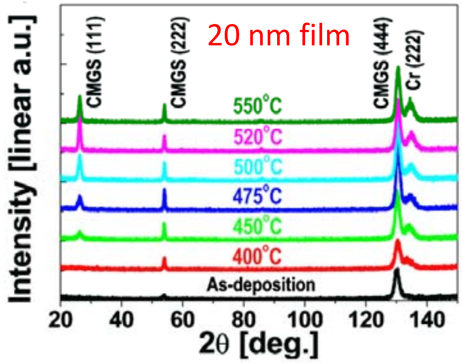
Intermetallic $Co_2MnGa_{0.5}Sn_{0.5}$



$L2_1$ is stable up to melting point
→ high driving force of $L2_1$ order.



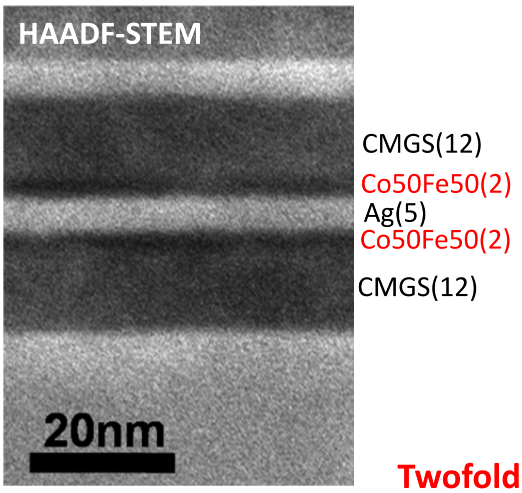
P = 0.72 for $Co_2MnGa_{0.5}Sn_{0.5}$

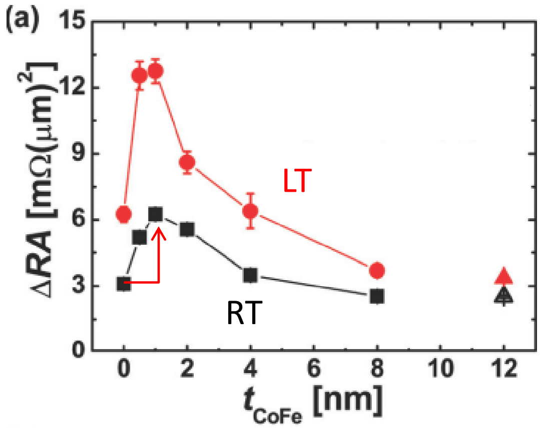


$L2_1$ order by >450 °C

Varaprasad, Acta Mater. 57, 2702 (2009).
Hase, J. Appl. Phys. 108, 093916 (2010).

Enhancement of CPP-GMR by inserting CoFe layers

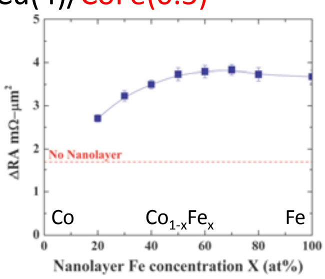




Twofold enhancement of ΔRA by 1 nm CoFe insertions.

Ref: RL(4)/CoFe(0.5)/Cu(4)/CoFe(0.5)
/FL(4)/CoFe(0.5)/cap
RL and FL = Co_2MnGe

Carey, J. Appl. Phys.
109, 093912 (2011)



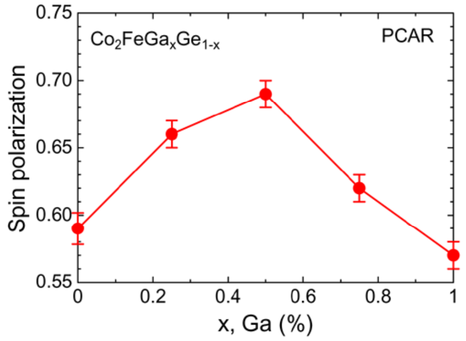
Practically useful to improve ΔRA without increasing thickness much.

Hase, J. Appl. Phys. 109, 07E112 (2011)

$Co_2Fe(Ge_{0.5}Ga_{0.5})$

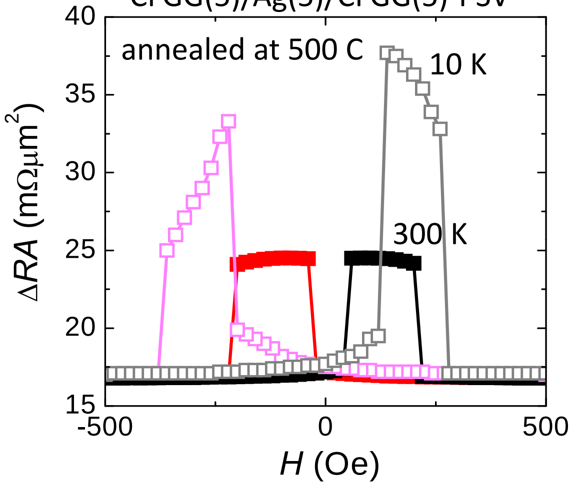
Tc = 827 °C

$T_{L2_1/B2}$=1027 °C



P = 0.69

Co_2Fe-based alloy
→high annealing possible
~ 500 °C

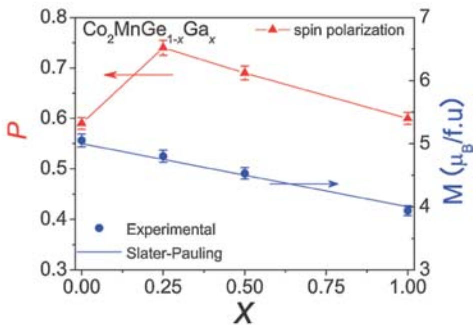


RT	10 K
ΔRA = 7.6 mΩμm²	ΔRA = 20 mΩμm²
ΔR/R = 44%	ΔR/R = 119%

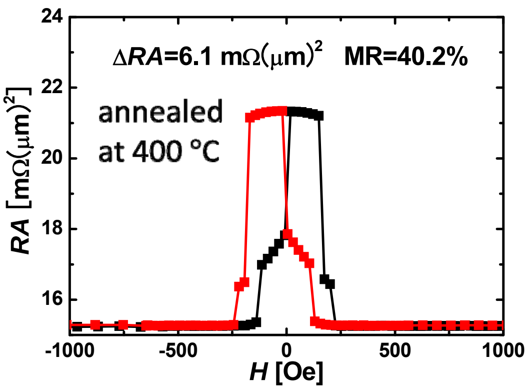
Largest ever reported
due to large β = 0.77 at RT.

Takahashi, Appl. Phys. Lett. 98, 072510 (2011).

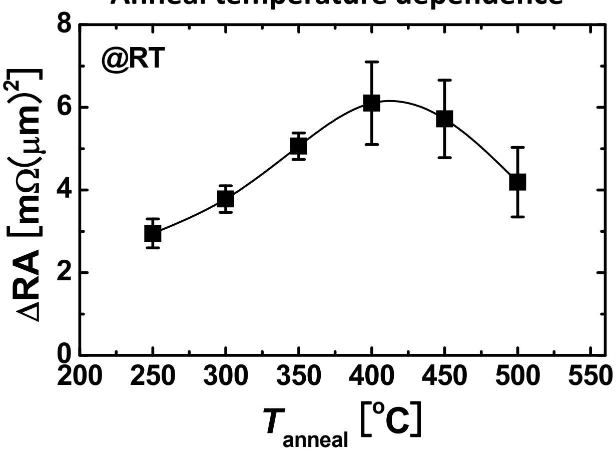
$Co_2Mn(Ge,Ga)$



Bulk $Co_2Mn(Ge_{0.75}Ga_{0.25})$
P = 74% (highest ever!)
Tc = 622 °C
Intemetallic (no $L2_1$–B2 transformation)



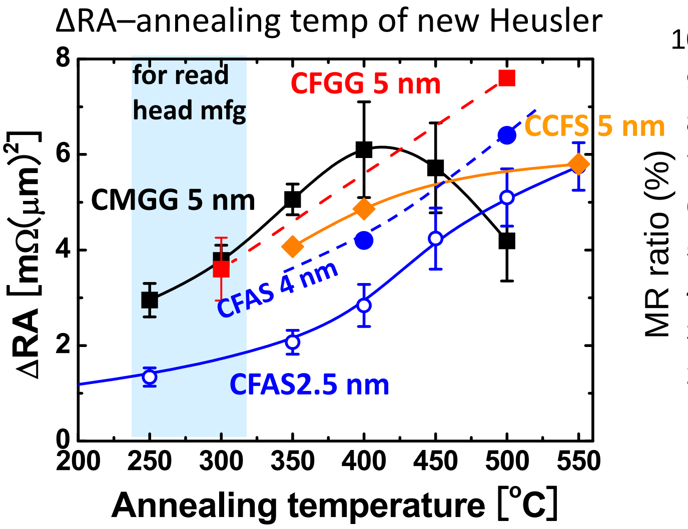
Anneal temperature dependence

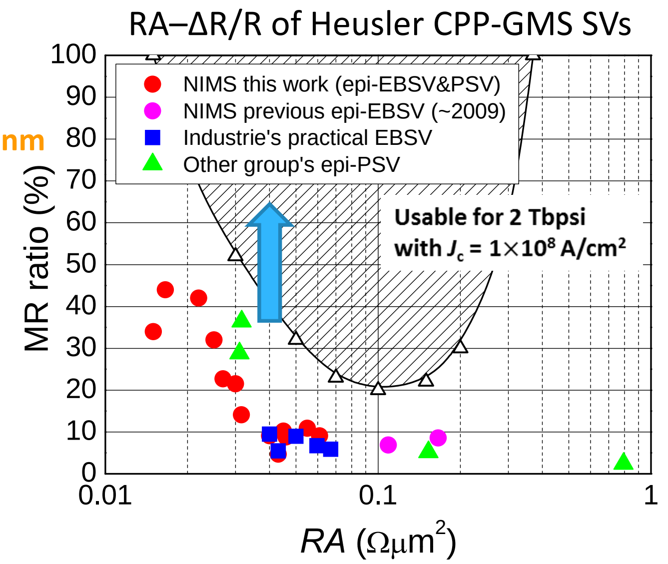


Large ΔRA and ΔR/R with low T_{an}
→ practically beneficial

To be presented at MMM by Naoki Hase (oral)

Summary





CFGG = $Co_2Fe(Ge_{0.5}Ga_{0.5})$
CMGG = $Co_2Mn(Ge_{0.75}Ga_{0.25})$
CCFS = $Co_2(Cr_{0.1}Fe_{0.9})Si$
CFAS = $Co_2Fe(Al_{0.5}Si_{0.5})$

Further improvement of β and γ (also, ρ_F and $AR_{interface}$) will enhance ΔRA with low *RA*.

Future direction

- Further search of new Heusler composition
  - High spin polarization
  - Ordering by low annealing temperature
- Spacer material with better band matching
- Fundamental questions:
  - Origin of temperature dependence
  - Mechanism of enhancement of ΔRA by CoFe insertion
  - Role of interfacial structure at FM/NM
  - Effect of crystalline orientation
- Poly-crystalline CPP-GMR films on Si/SiO_2 substrate
- Alternative reader structure
  - Dual-free-layer (scissors-type trilayer)
  - Non-local spin-valve