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Cobalt-based Heusler alloys for spintronics

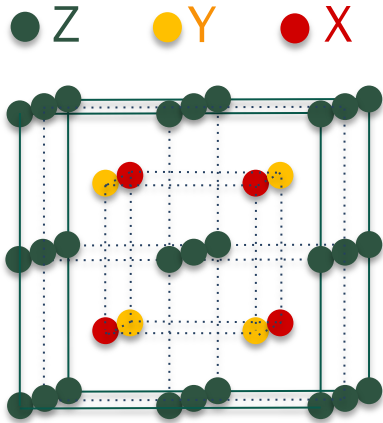
Half-metallicity and ultra-low damping investigation of the Co_2MnX series

*C. GUILLEMARD, C. ROJAS-SANCHEZ, S. PETIT-WATELOT, L. PASQUIER,
A. M. BATAILLE, F. BERTRAN, S. ANDRIEU*

Outline

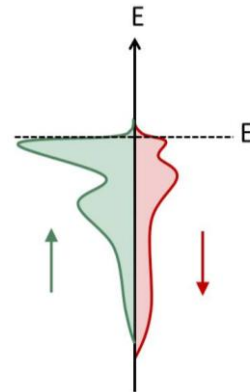
- I. Co_2MnX Heusler alloys & spintronics
- II. *In situ* SR-PES on the Cassiopée beamline
 - Elaboration of Co_2MnX
 - Spin-Resolved Photoemission Spectroscopy
- III. Ferromagnetic resonance
 - Out-of-plane geometry
 - Low magnetic damping results
- IV. Summary

Heusler alloys

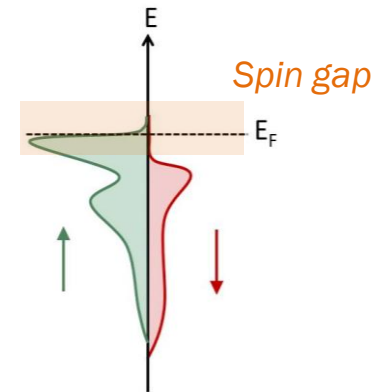


Some are predicted
Half Metal Magnet

R. A. De Groot, *Phys. Rev. Lett.*
50, 1983



Standard
Ferromagnet



Half Metal Magnet
(HMM)

Full Heusler Z_2YX :

Co_2MnSi , Rh_2YbPb ...

$$\eta = \frac{D_{\uparrow}(E_F) - D_{\downarrow}(E_F)}{D_{\uparrow}(E_F) + D_{\downarrow}(E_F)} = 1 \rightarrow 100\% \text{ spin polarization at } E_F$$



$$TMR = \frac{2\eta_1\eta_2}{1 - \eta_1\eta_2} \rightarrow \infty$$

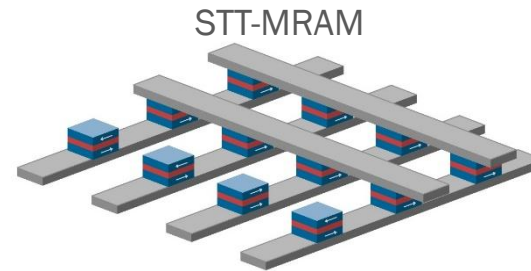
Exp: 1996 %

H. Liu et al, *App. Phys. Lett.* **101**, 2012

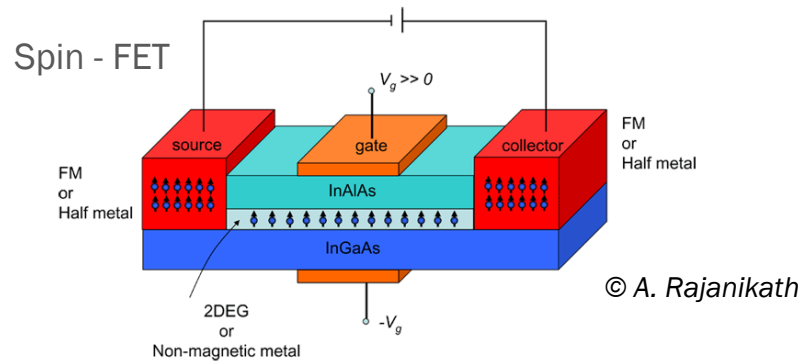
Interest for spintronic devices :

Information storage and processing

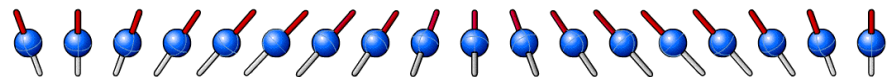
- MRAM
 - ↗ TMR / GMR
 - ↘ J_C (STT)



- STNO
- Spin injection



- Magnonics : Long length SW propagation



Motivations

Co₂MnX Heuslers good candidates :

- ✓ Predicted HMM (*ab initio* calc.)
- ✓ Ultra-low damping materials (down to 10⁻⁵)
- ✓ High T_C
- ✓ Lattice parameter close to MgO (tunnel barrier)

Our strategy :

- Elaboration of epitaxial Co₂MnX thin films by MBE
- To confirm the predicted HMM behavior of Heuslers and tune the electronic structure (by switching X_{IV} by X_{III}, X_V etc.)
- Measurement of the Gilbert damping by VNA-FMR
- Link the HMM behavior and damping value

Outline

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The Cassiopée Beamline

Mott detection SR-PES

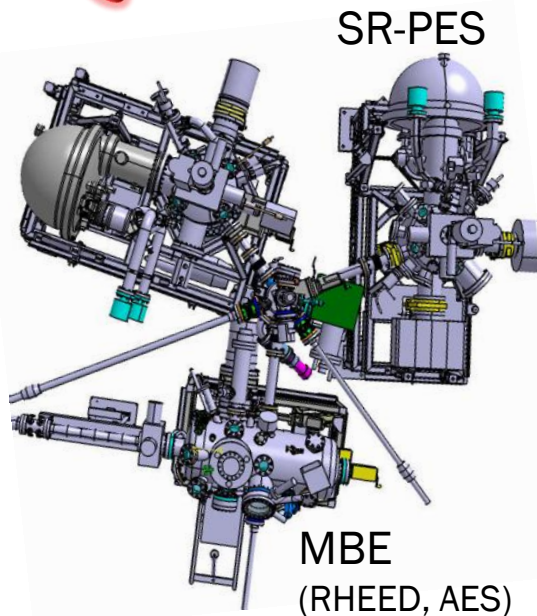


SOLEIL : 2,75 GeV storage ring, Saint Aubin, Fr.

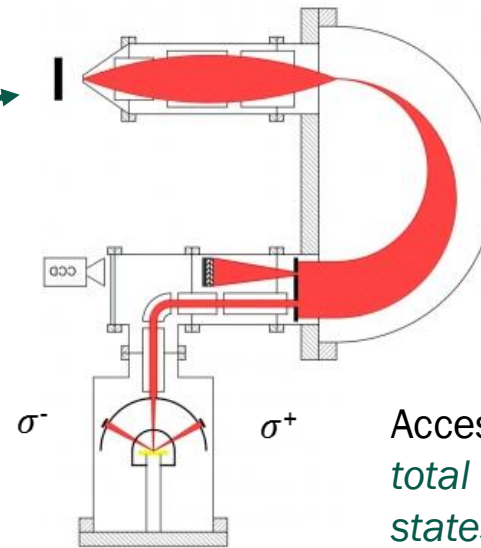
$h\nu$

AR-PES

2 e-guns (5 pockets)
4 effusion cells
=
14 materials in the MBE



Angular aperture of $\pm 8^\circ$

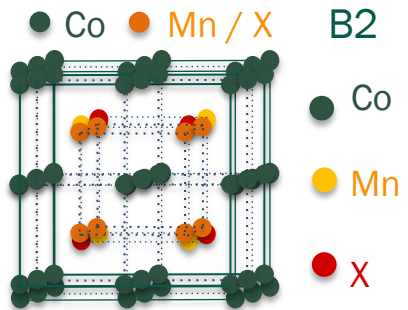
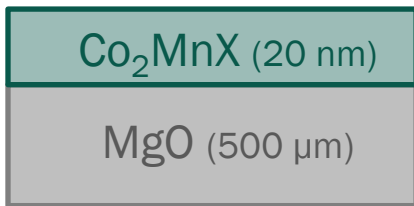


Access to the *total density of states resolved in spin*

MBE growth

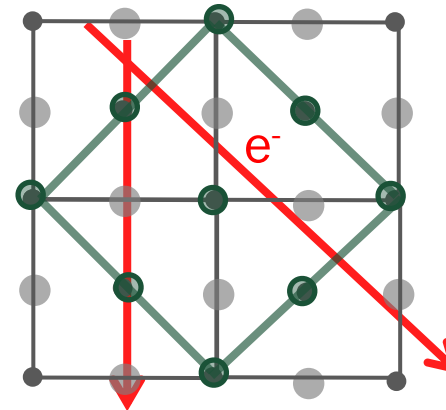
MgO(001) [100] // Co₂MnX(001) [110]

Growth by co-evap.
Controlled by QCM (error : 5%)

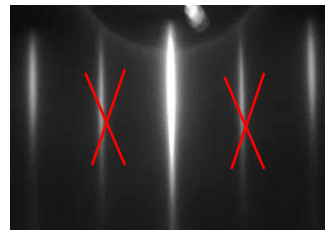


Same space group as MgO
L2₁

$Fm\bar{3}m$

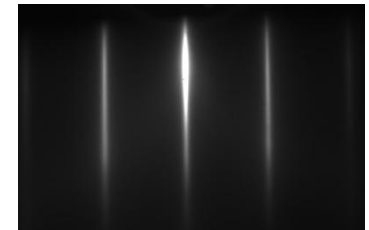


$[110]_{Co_2MnX}$



Typical RHEED patterns

$[100]_{Co_2MnX}$



MBE growth

[110] RHEED patterns

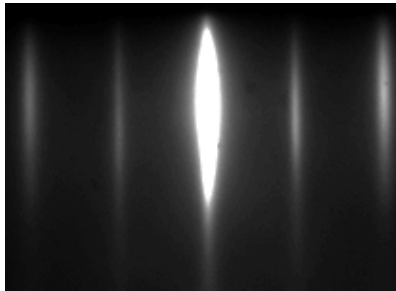
Co_2MnX with $X =$

Al

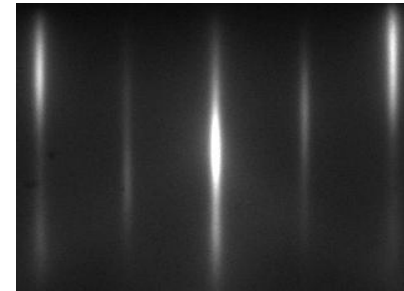


No half streaks :
Chemical disorder

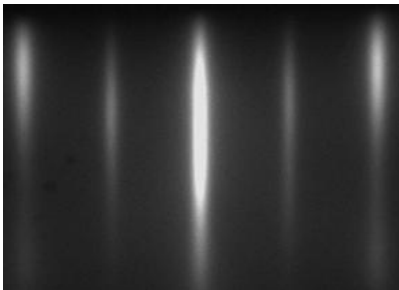
Si



Ga



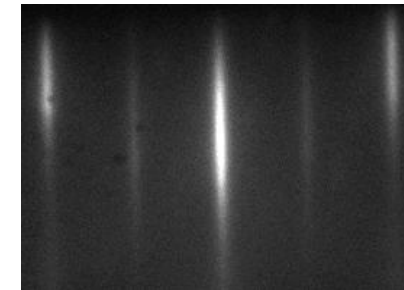
Ge



Sn



Sb

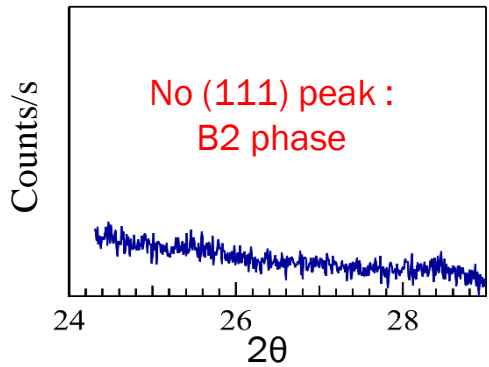


MBE growth

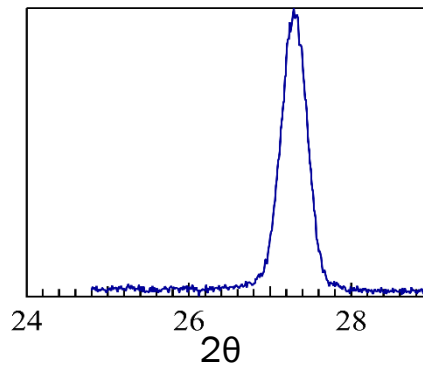
XRD: (111) reflection

$$I_{111} \propto |(f_X - f_{Mn})|^2$$

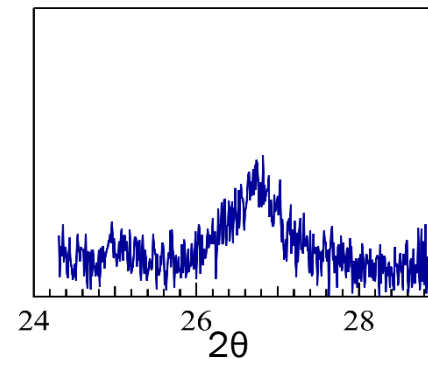
Co₂MnX with X = Al



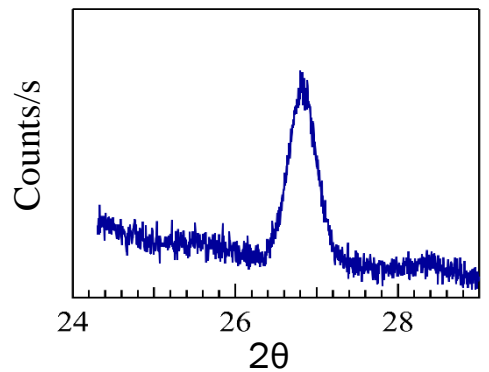
Si ✓



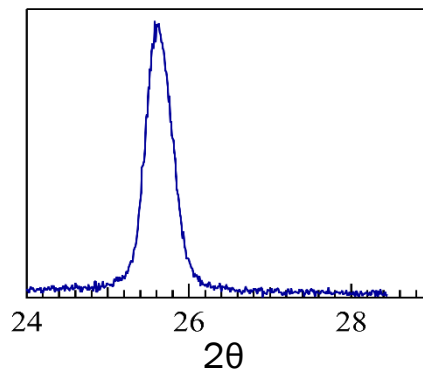
Ga ✓



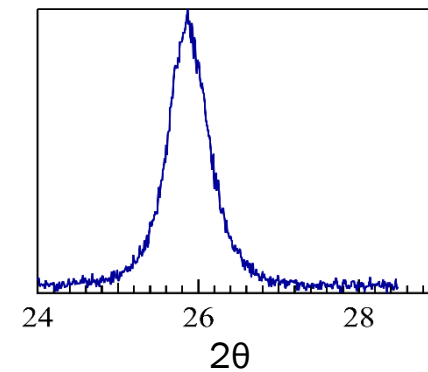
Ge ✓



Sn ✓

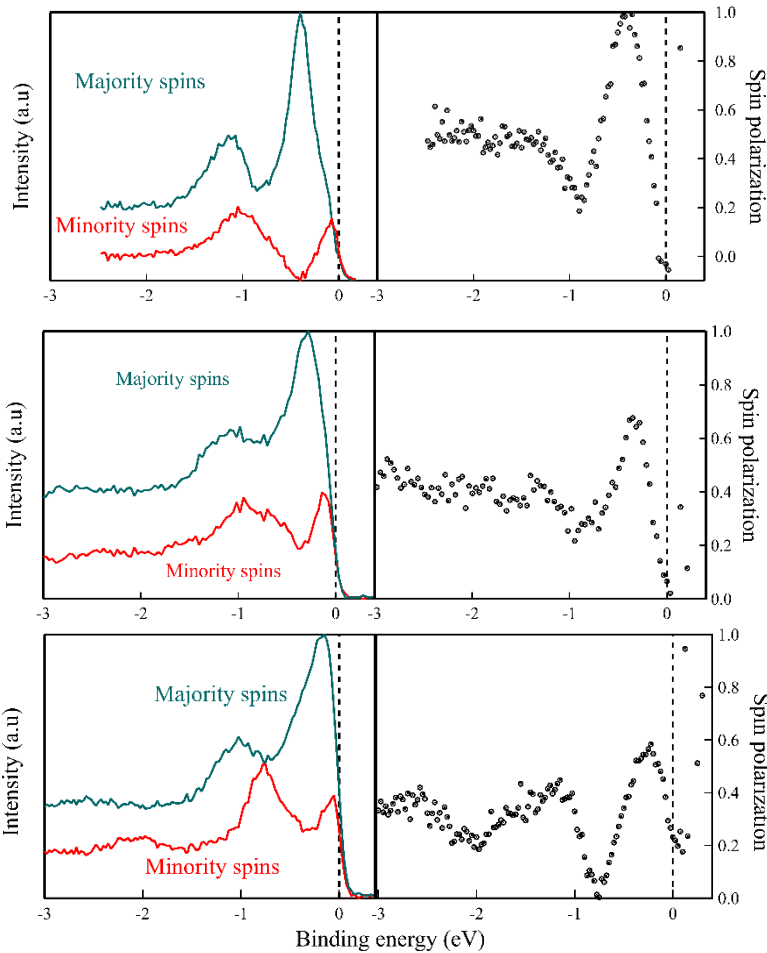


Sb ✓



Spin Resolved Photoemission

Results on $\text{Co}_2\text{MnX}_{\text{IV}}$ ($\text{X}_{\text{IV}} = \text{Si, Ge, Sn}$)



Co_2MnSi

Pol. = 100% below E_F

(S. Andrieu et al. *Phys. Rev. B*, 2016)

$h\nu = 37 \text{ eV}$

Co_2MnGe

Pol. > 70% below E_F

not yet published

$h\nu = 30 \text{ eV}$

Co_2MnSn

Pol. > 60% below E_F

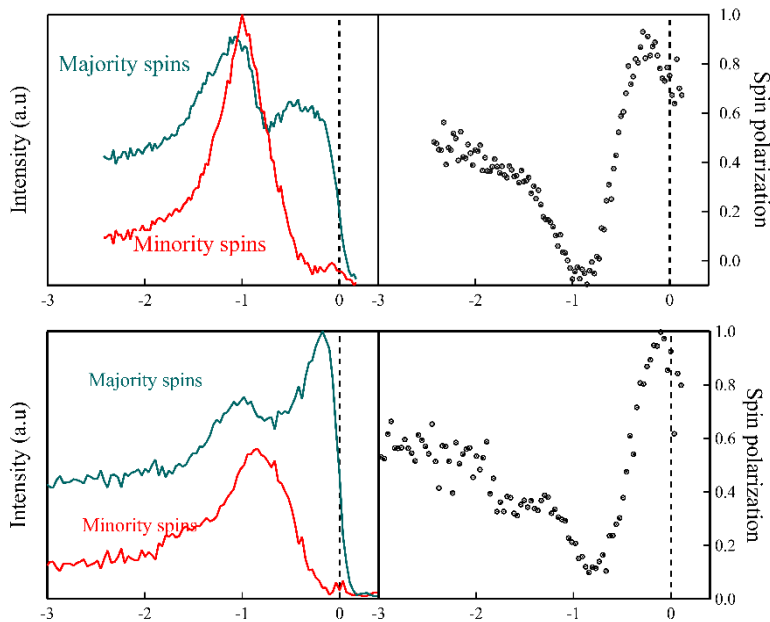
not yet published

$h\nu = 27 \text{ eV}$

- High spin polarization
- Surface states kill the polarization at E_F

Spin Resolved Photoemission

Results on $\text{Co}_2\text{MnX}_{\text{IV}}$ ($\text{X}_{\text{IV}} = \text{Si, Ge, Sn}$)



Co_2MnSi
Spin gap
 (S. Andrieu et al. Phys. Rev. B, 2016)

$h\nu = 37 \text{ eV}$
 Pol. s

Co_2MnGe
Spin gap
 not yet published

$h\nu = 30 \text{ eV}$
 Pol. s

Measurement next week !

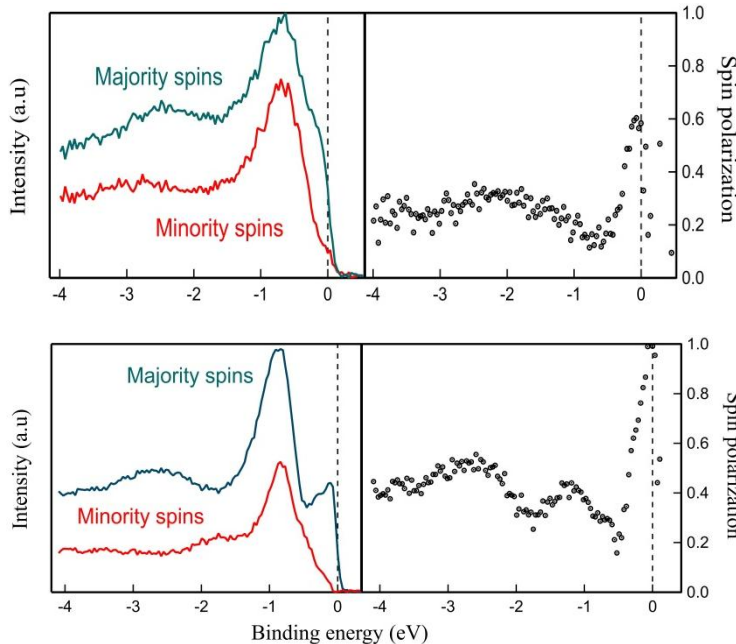
Co_2MnSn

$h\nu = 27 \text{ eV}$
 Pol. s

Spin gap for Co_2MnGe and Co_2MnSi with pol. s

Spin Resolved Photoemission

Results on $\text{Co}_2\text{MnX}_{\text{III}}$ ($\text{X}_{\text{III}} = \text{Al, Ga}$)



Co_2MnAl

60% spin polarization at E_F

$h\nu = 37 \text{ eV}$

Co_2MnGa

100% spin polarization at E_F

$h\nu = 37 \text{ eV}$

not yet published

For the $\text{Co}_2\text{MnX}_{\text{III}}$, the Fermi level slides down since there is one less valence e^-

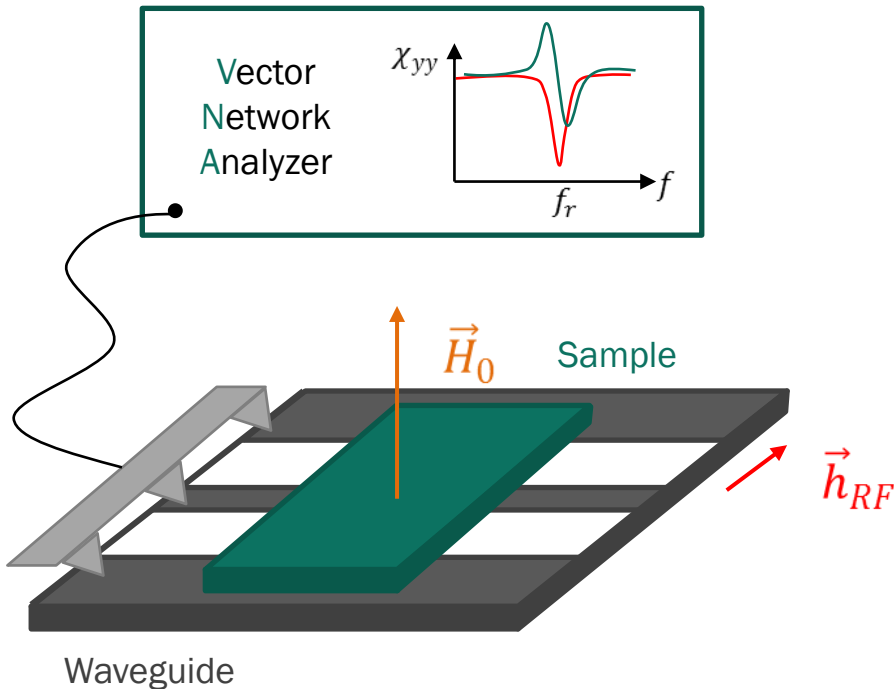
Spin gap at E_F for Co_2MnGa

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Ferromagnetic resonance

Perpendicular magnetic field VNA-FMR



H_0 from 0 to 2.5 T

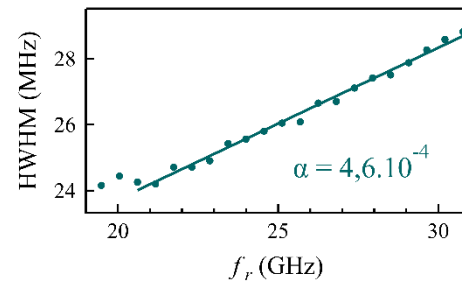
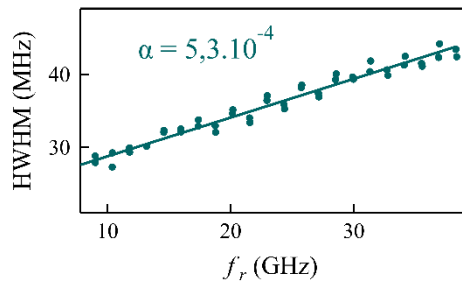
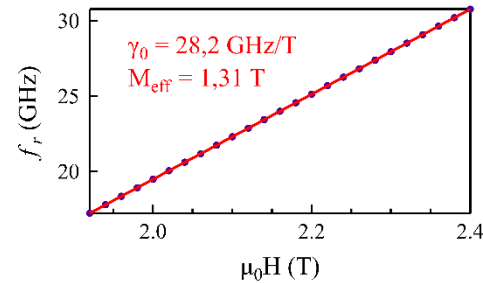
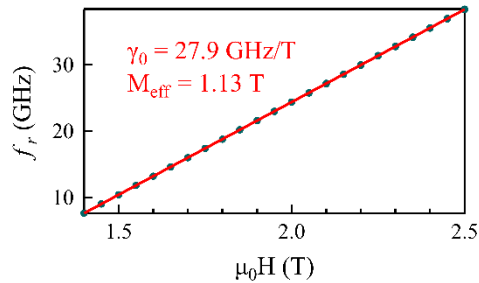
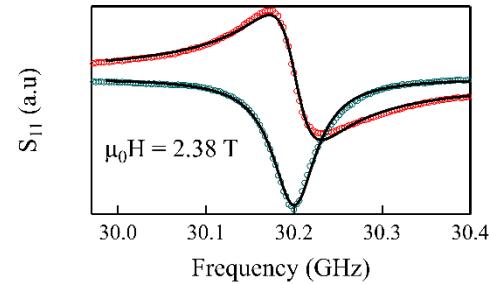
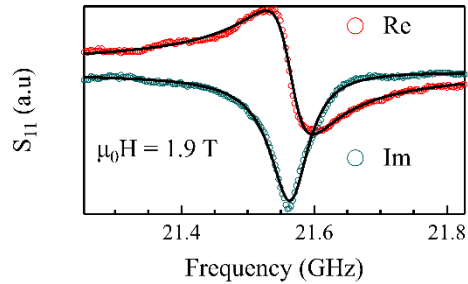
- Kittel law :

$$f_r = \gamma_0 (H_0 - M_{eff})$$
- Gilbert damping given by HWHM

$$\Delta f = 2\alpha f_r$$
- 2-magnons scattering avoided
- No corrections (raw effective values)

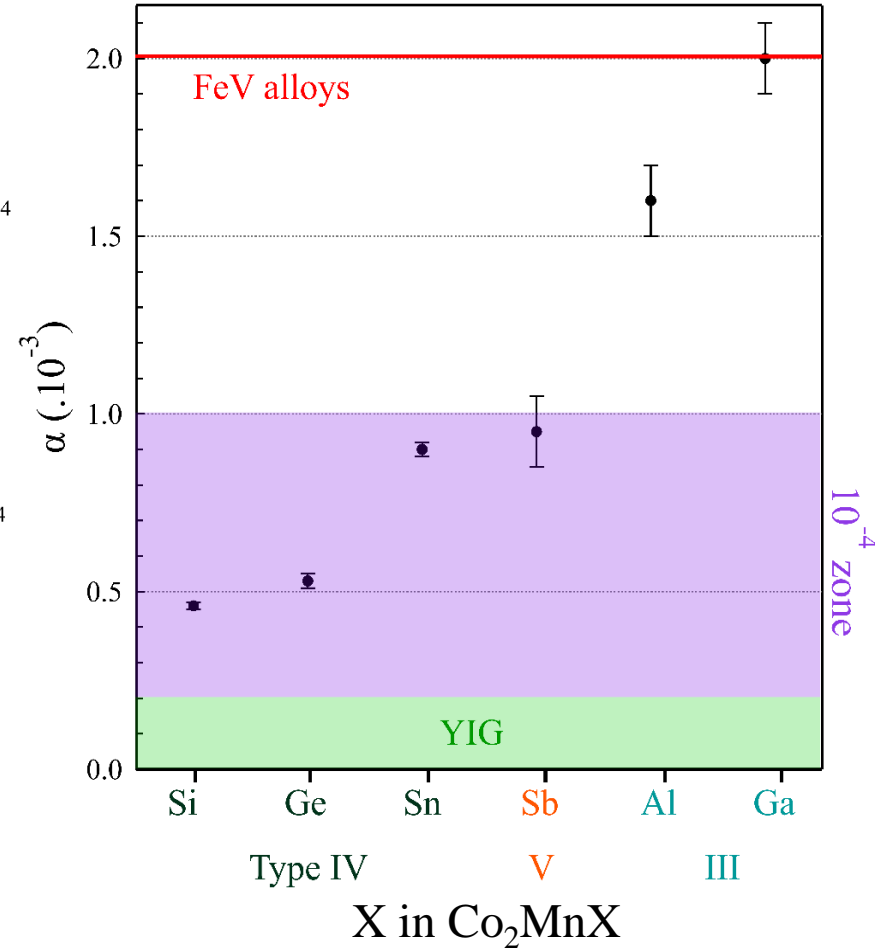
Ferromagnetic resonance

Low magnetic damping on Heuslers



Co2MnGe

Co2MnSi



Summary

- Epitaxial Co_2MnX thin films grown by MBE
 - Low chemical order for Co_2MnAl
- High spin polarization for almost all of them
 - HMM confirmed for Co_2MnSi , Ge and Ga!
- Ultra-low magnetic damping also confirmed
 - 4 out of 6 in the 10^{-4} range
- How does the chemical disorder impact the physical properties?
- Link the SR-DOS with the calculated band structures
- Find connections between the magnetic damping and the spin polarization (and the electric conductivity)
- Insertion in devices (MTJ)

Thank you for your attention !



Institut Jean Lamour
101 team

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Cassiopee beamline

F. Bertran †
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