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Epitaxial cobalt-based Heusler alloys for spintronic applications: Elaboration, structural and magnetic investigation

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Cobalt-based Heusler alloys for spintronic devices

Half-metallicity and ultra-low damping investigation

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BERTRAN, S. ANDRIEU*

Outline

I. Co_2MnX Heusler alloys & spintronics

II. *In situ* SR-PES on the Cassiopée beamline

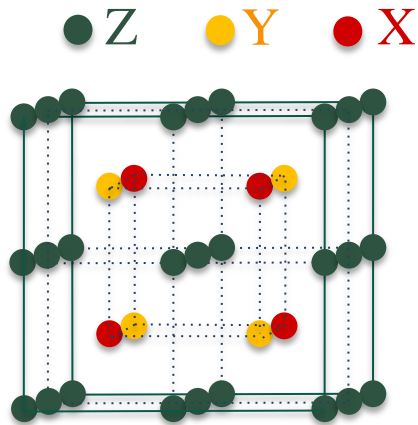
- Elaboration of Co_2MnX
- Spin-Resolved Photoemission Spectroscopy

III. Ferromagnetic resonance

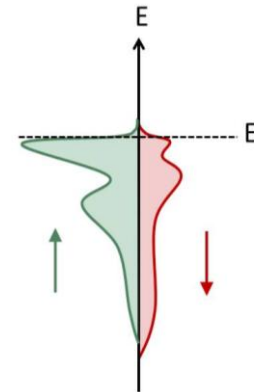
- Out-of-plane geometry
- Low magnetic damping results

IV. Summary

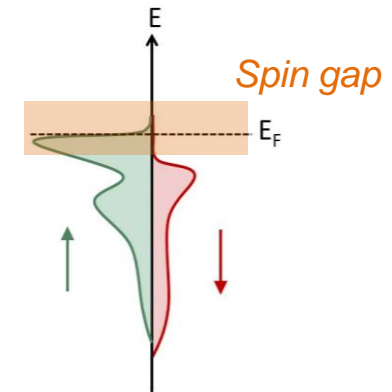
Heusler alloys



Some are predicted Half Metal Magnet [1]



Standard Ferromagnet



Half Metal Magnet (HMM)

Full Heusler Z_2YX :

Co_2MnSi , Pd_2PbU ...

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



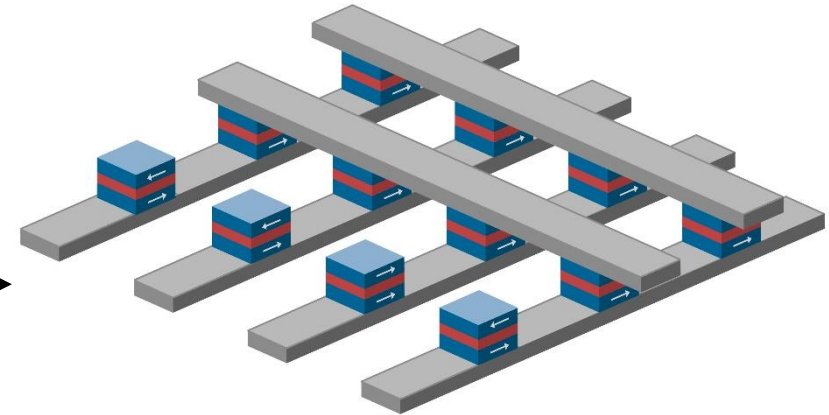
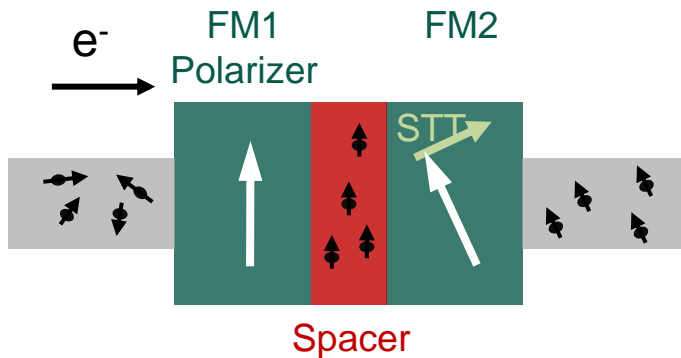
$$TMR = \frac{R_{ap} - R_p}{R_p} \rightarrow \infty$$

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

Exp. 1996 %
H. Liu *et al*, *App. Phys. Lett.* 101, 2012

Interest for spintronic devices :

Spin transfer torque (STT) and STT – MRAM :



Switching magnetization of the free layer using a spin polarized current.

[Slonczewski, JMMM, 1996]

$$J_c = \frac{2e\alpha M_S V}{\hbar\eta} (M_S + H_k)$$

α = magnetic damping
 η = spin polarization rate

Spin Transfer Torque - RAM

- ✓ High bit density
- ✓ Fast switching
- ✓ Non-volatile memory

The switching current density is very high ($\sim 7 \cdot 10^8$ A/m²)

[S. Mangin et al, App. Phys. Lett. 94, 2009]

Motivations

Co₂MnX Heuslers good candidates for STT-MRAM :

- ✓ Predicted HMM (*ab initio* calc.)
- ✓ Ultra-low damping materials (down to 10⁻⁵)
- ✓ Appreciable T_C & M_S
- ✓ Lattice parameter close to MgO (tunnel barrier)
- ✓ (Perpendicular magnetic anisotropy ??)

$$J_c = \frac{2e\alpha M_S V}{\hbar\eta} (M_S + H_k)$$

Our strategy :

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

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The Cassiopée Beamline

Mott detection SR-PES



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

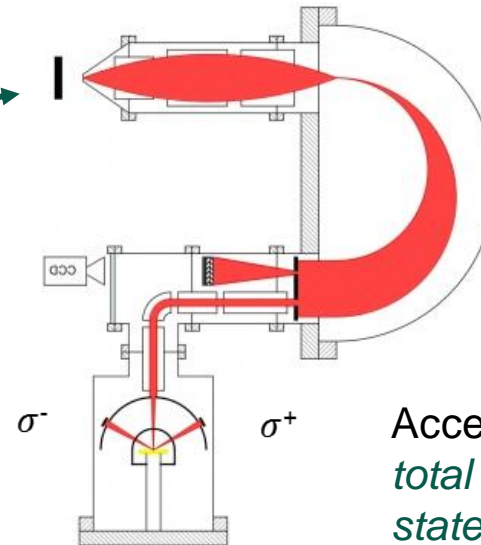
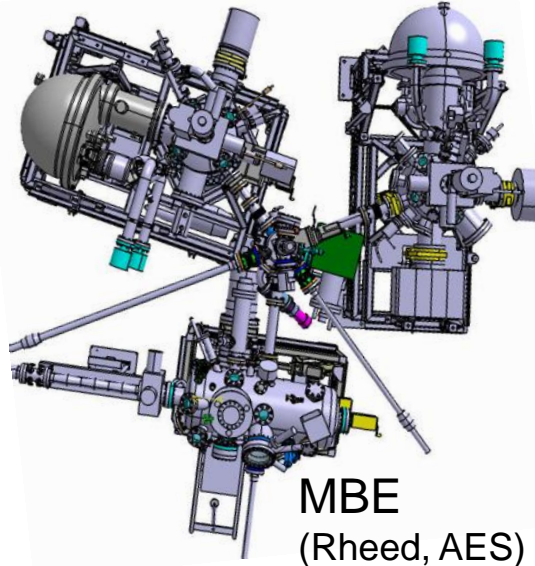
$h\nu$

AR-PES

SR-PES

Angular aperture of $\pm 8^\circ$

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

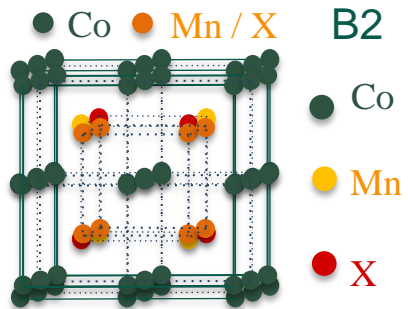
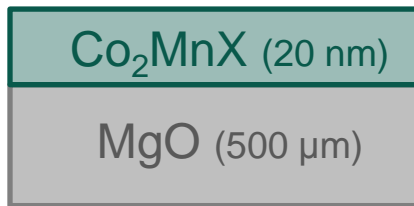


Access to the *total density of states resolved in spin*

MBE growth

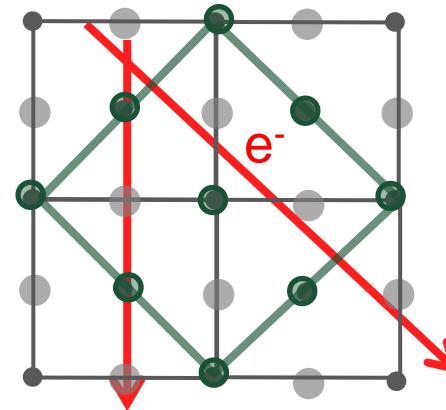
MgO(001) [100] // Co₂MnX(001) [110]

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

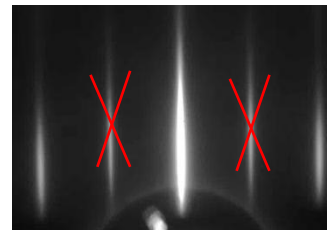


Same space group as MgO
L2₁

$Fm\bar{3}m$

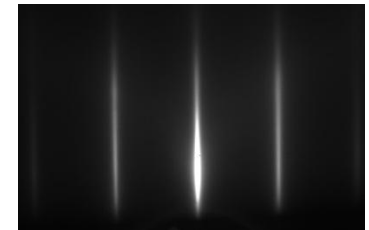


[110]_{Co₂MnX}



Typical RHEED patterns

[100]_{Co₂MnX}

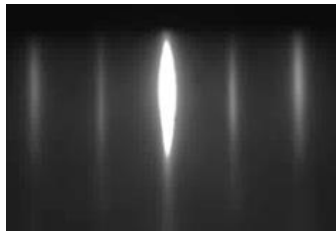


MBE growth

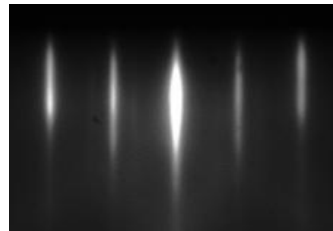
The [110] RHEED patterns

Co₂MnX with X =

Si



Sn

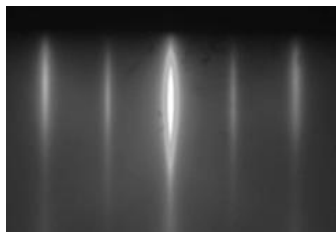


Al

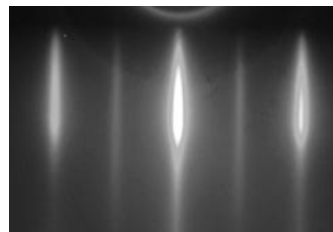


Low chemical order

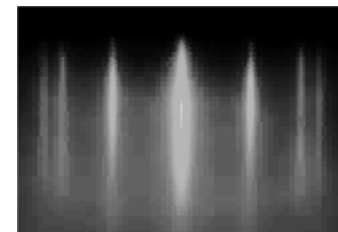
Ge



Ga



Sb



Growth along (111)
2 Hex. domains

MBE growth

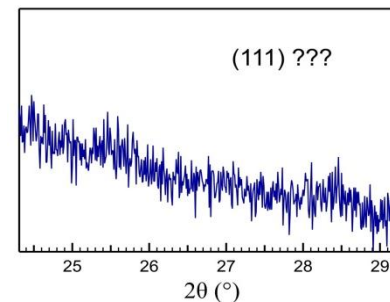
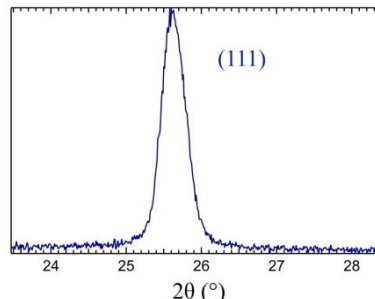
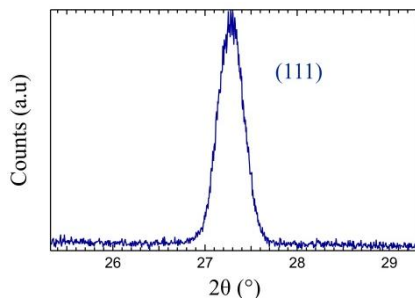
XRD : the (111) asymmetric peak

Co₂MnX with X =

Si

Sn

Al



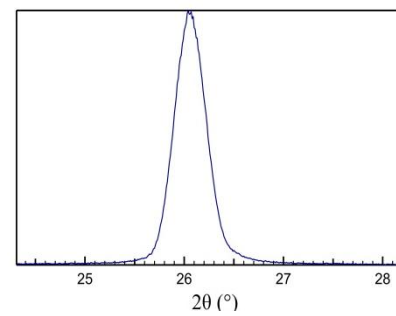
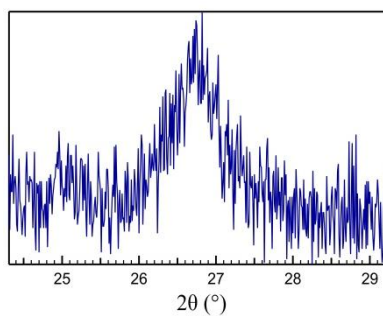
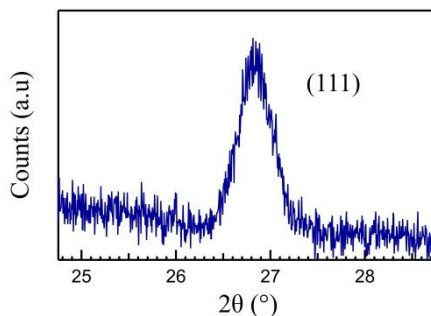
Low chemical order

θ-2θ configuration

Ge

Ga

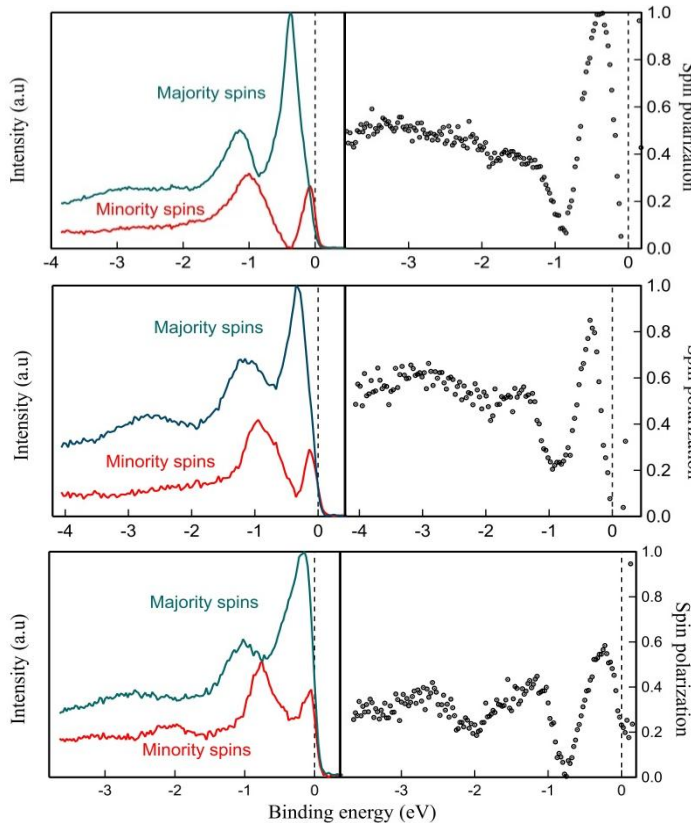
Sb



Growth along (111)
2 Hex. domains

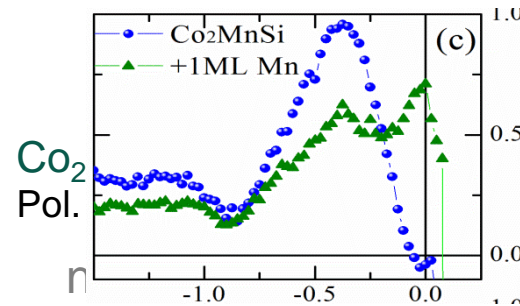
Spin Resolved Photoemission

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



Co_2MnSi
 Pol. = 100% just below E_F
 (*S. Andrieu et al. Phys. Rev. B, 2016*)

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



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

Co_2MnSn
 Pol. = 60% just below E_F
 not yet published

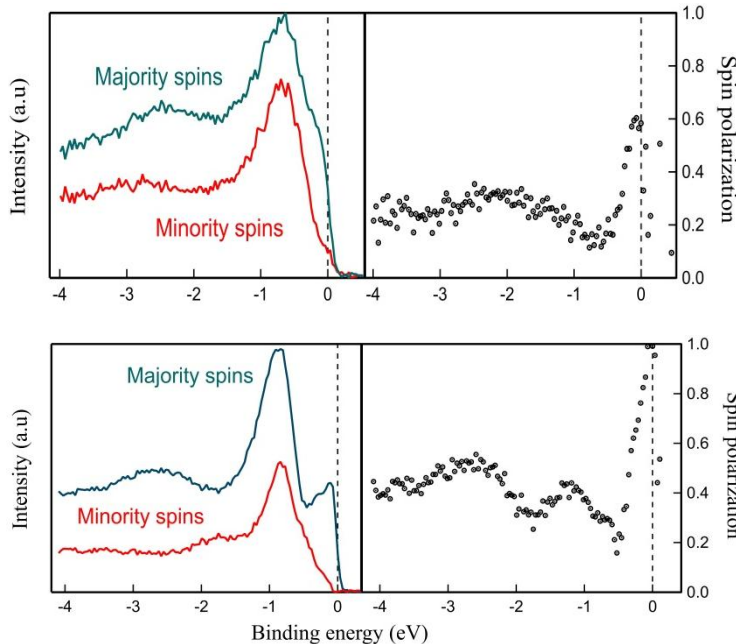
$h\nu = 27 \text{ eV}$

High spin polarization for $\text{Co}_2\text{MnX}_{\text{IV}}$
 Polarization at E_F decreases because of a surface resonant state which disappears with Mn on top

But there is a spin gap below E_F

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^-

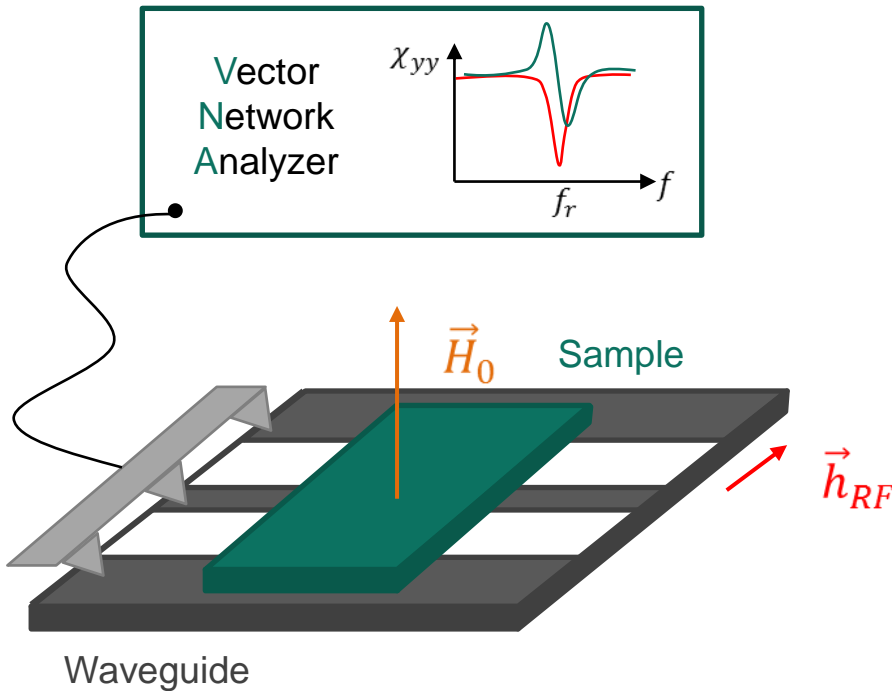
Spin gap at E_F for Co_2MnGa

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Ferromagnetic resonance

Perpendicular magnetic field VNA-FMR



H_0 from 0 to 2,5 T

In the perpendicular geometry, Kittel law is linear :

$$f_r = \gamma_0(H_0 - M_S)$$

Gilbert damping given by HWHM vs f_r

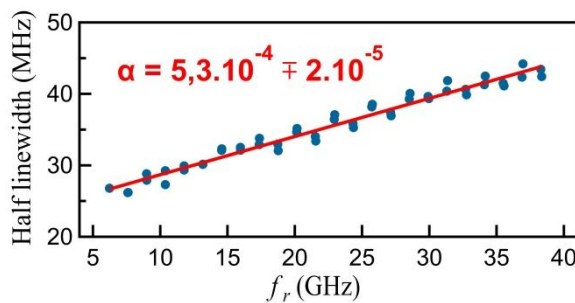
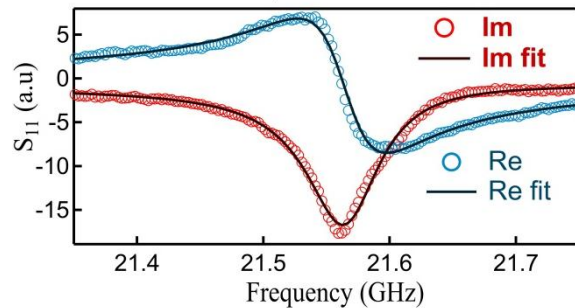
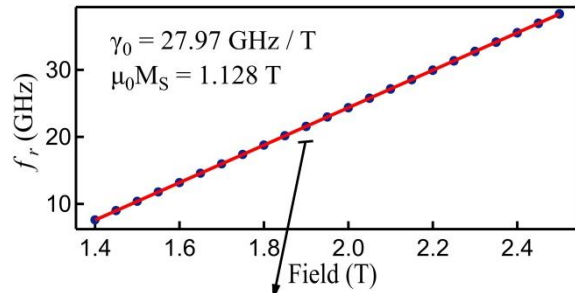
$$\Delta f = 2\alpha f_r$$

\vec{H}_0 : out-of-plane static magnetic field

\vec{h}_{RF} : in-plane RF magnetic field

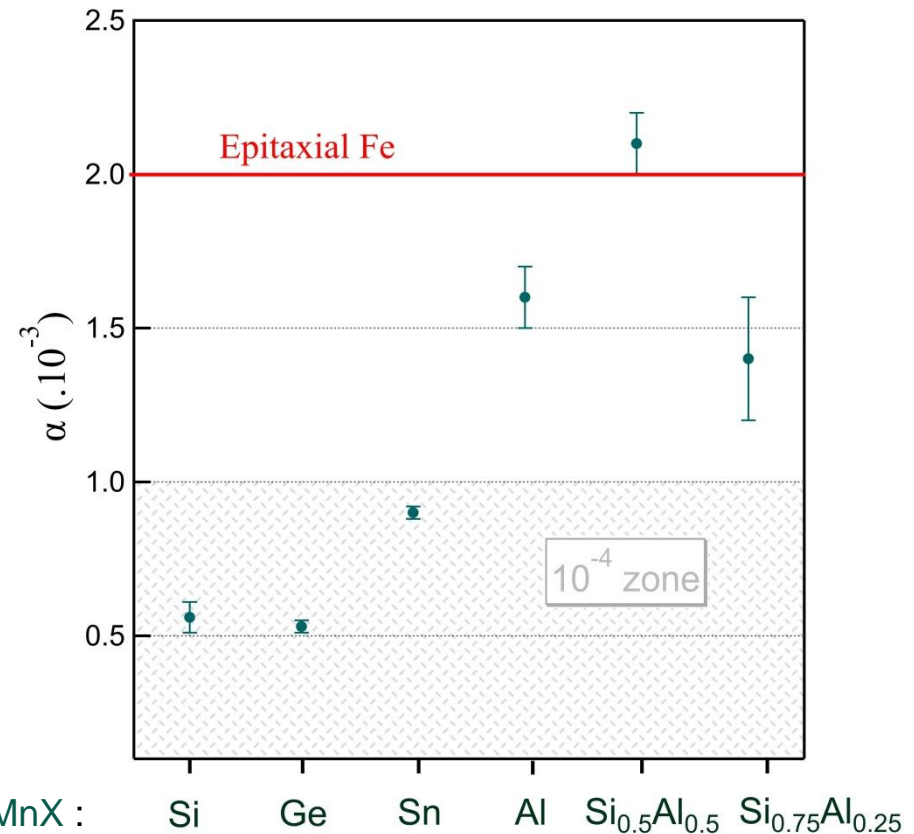
Ferromagnetic resonance

Low magnetic damping on Heuslers



Co₂MnGe

not yet published



→ Ga and Sb measurement in progress

Summary

- Epitaxial Co_2MnX thin films can be grown by MBE
 - Why low chemical order for Co_2MnAl or (111) growth for Co_2MnSb ?
- High spin polarization for almost all of them
 - HMM confirmed for Co_2MnSi and Co_2MnGa !
- Ultra-low magnetic damping also confirmed
 - In the 10^{-4} range for $\text{Co}_2\text{MnX}_{\text{IV}}$
- 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)

Thank you for your attention !



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