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

C. Guillemard, F. Bertran, A. Bataille, P. Le Fevre, S. Petit-Watelot, J.-C. Rojas-Sánchez, Stéphane Andrieu

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# Cobalt-based Heusler alloys for spintronic devices

Half-metallicity and ultra-low damping investigation

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

# Outline

## I. $\text{Co}_2\text{MnX}$ Heusler alloys & spintronics

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

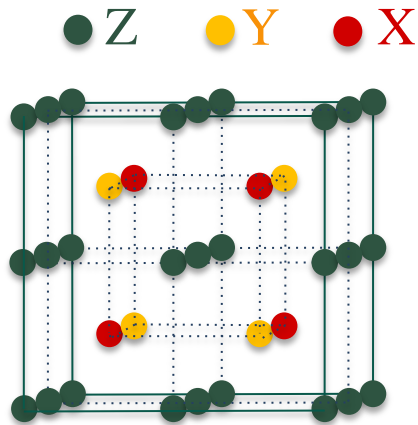
- Elaboration of  $\text{Co}_2\text{MnX}$
- Spin-Resolved Photoemission Spectroscopy

## III. Ferromagnetic resonance

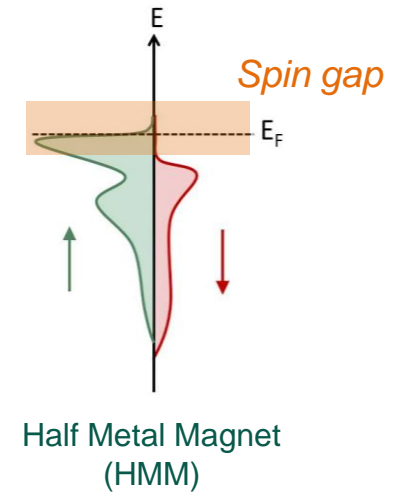
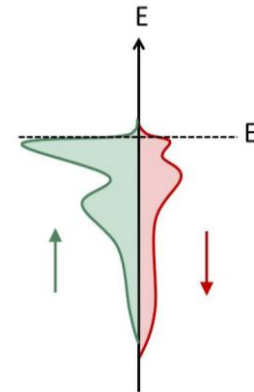
- Out-of-plane geometry
- Low magnetic damping results

## IV. Summary

# Heusler alloys



Some are predicted Half Metal Magnet [1]



Full Heusler  $Z_2YX$  :

$Co_2MnSi$ ,  $Pd_2PbU$ ...

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



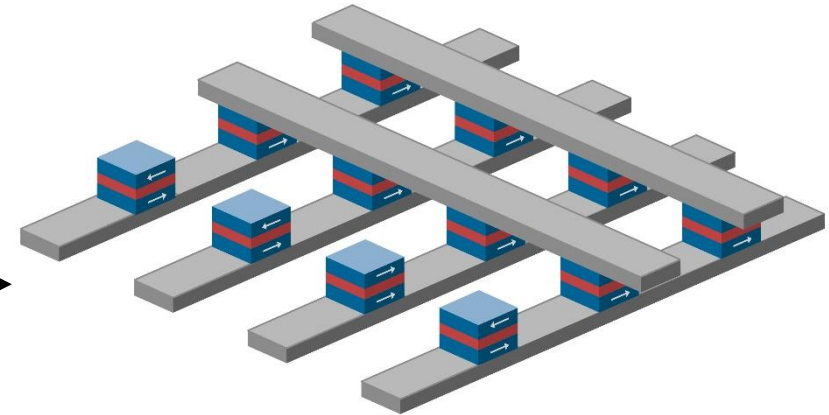
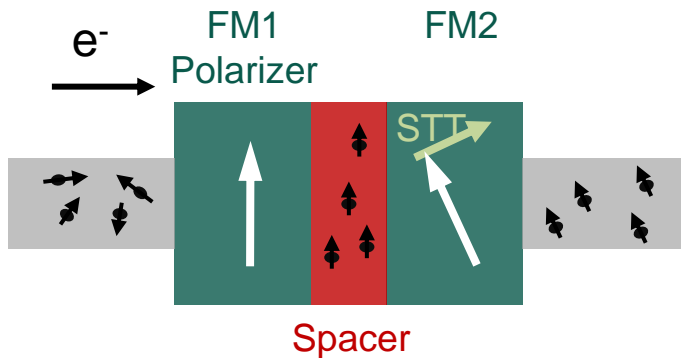
$$TMR = \frac{R_{ap} - R_p}{R_p} \rightarrow \infty$$

[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]

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

$\alpha$  = magnetic damping  
 $\eta$  = 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/m<sup>2</sup>)

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

# Motivations

Co<sub>2</sub>MnX Heuslers good candidates for STT-MRAM :

- ✓ Predicted HMM (*ab initio* calc.)
- ✓ Ultra-low damping materials (down to 10<sup>-5</sup>)
- ✓ Appreciable T<sub>C</sub> & M<sub>S</sub>
- ✓ 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 Co<sub>2</sub>MnX 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<sub>IV</sub> by X<sub>III</sub>, X<sub>V</sub> 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.

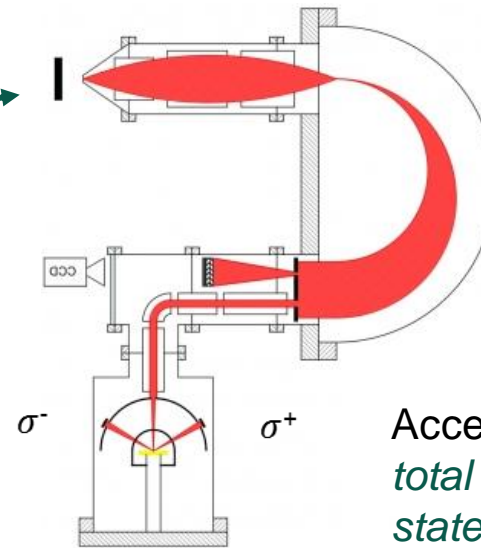
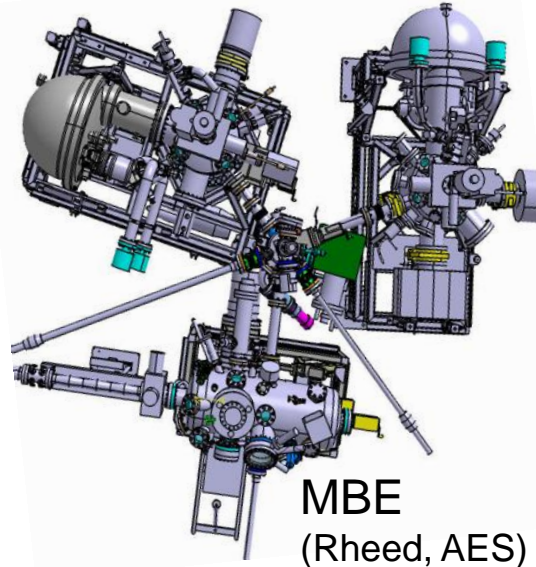
$h\nu$

AR-PES

SR-PES

Angular aperture of  $\pm 8^\circ$

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



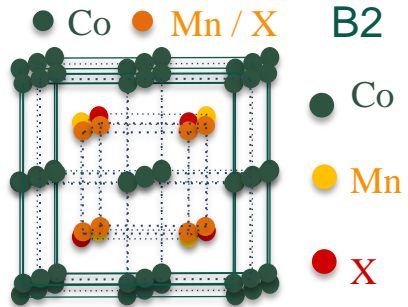
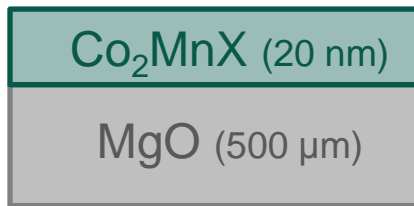
Access to the *total density of states resolved in spin*



# MBE growth

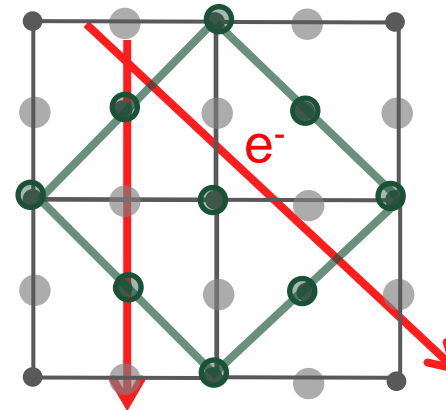
MgO(001) [100] // Co<sub>2</sub>MnX(001) [110]

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

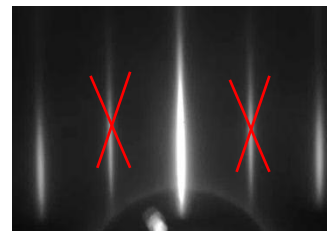


Same space group as MgO  
L2<sub>1</sub>

$Fm\bar{3}m$

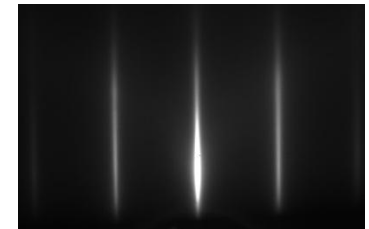


[110]<sub>Co<sub>2</sub>MnX</sub>



Typical RHEED patterns

[100]<sub>Co<sub>2</sub>MnX</sub>

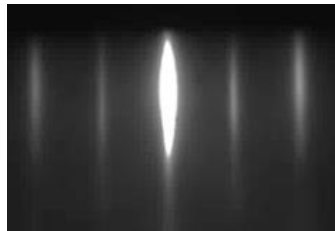


# MBE growth

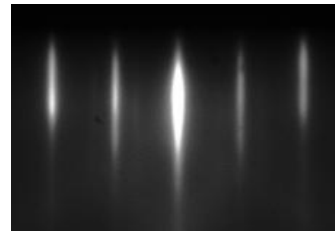
The [110] RHEED patterns

Co<sub>2</sub>MnX with X =

Si



Sn

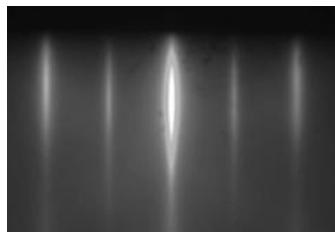


Al

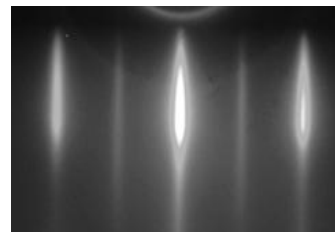


Low chemical order

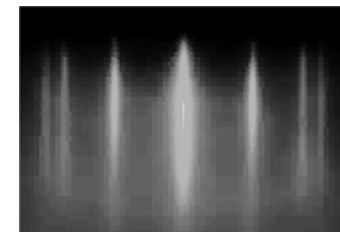
Ge



Ga



Sb



Growth along (111)  
2 Hex. domains

# MBE growth

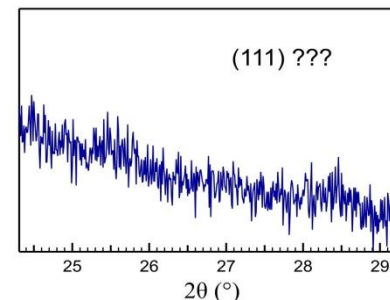
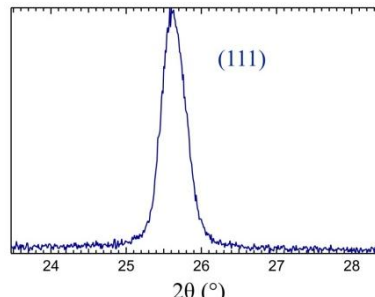
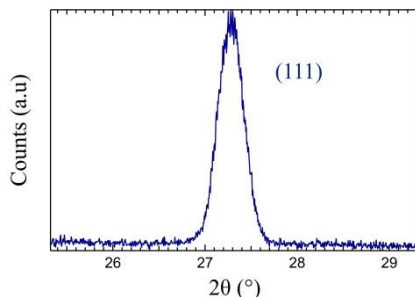
XRD : the (111) asymmetric peak

Co<sub>2</sub>MnX with X =

Si

Sn

Al



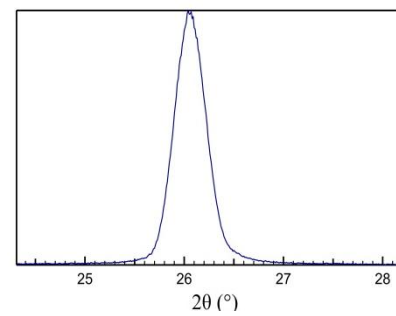
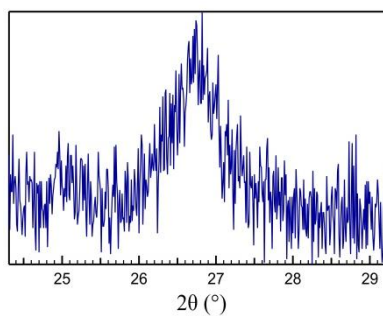
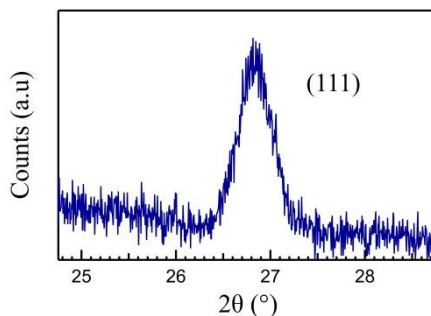
Low chemical order

θ-2θ configuration

Ge

Ga

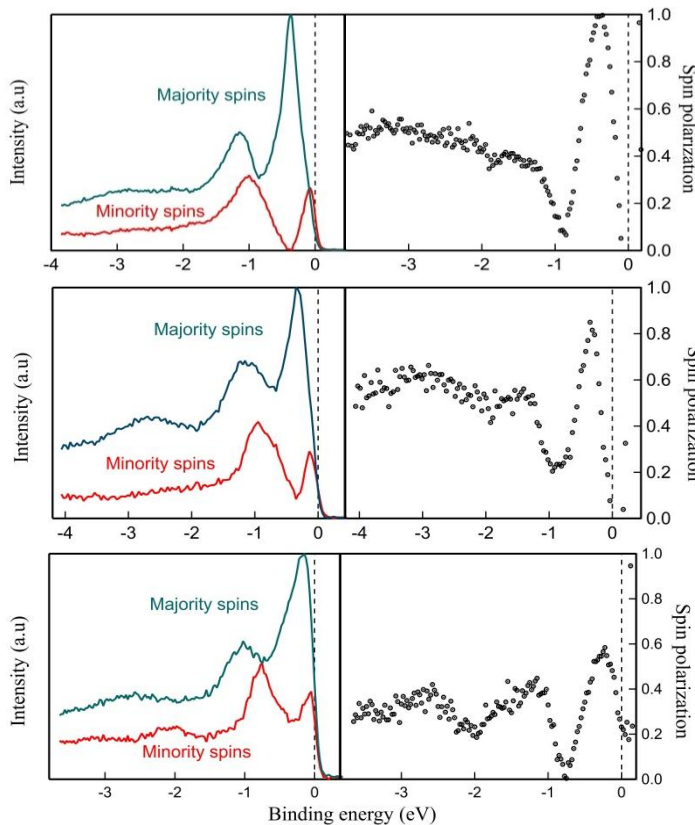
Sb



Growth along (111)  
2 Hex. domains

# Spin Resolved Photoemission

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

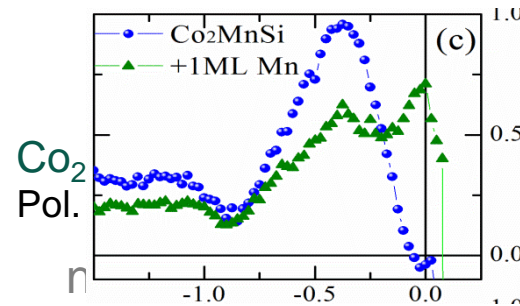


$\text{Co}_2\text{MnSi}$

Pol. = 100% just below  $E_F$

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

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



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

$\text{Co}_2\text{MnSn}$

Pol. = 60% just below  $E_F$

not yet published

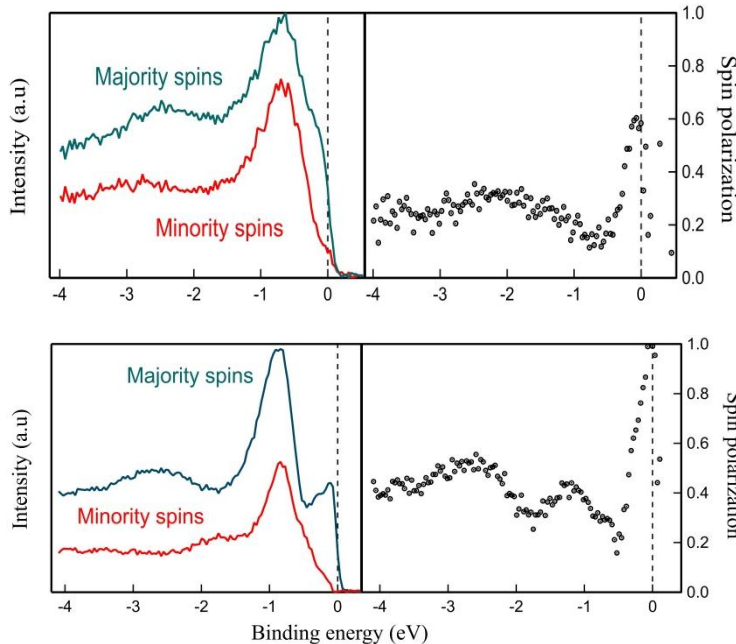
$h\nu = 27 \text{ eV}$

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



$\text{Co}_2\text{MnAl}$

60% spin polarization at  $E_F$

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

$\text{Co}_2\text{MnGa}$

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  $e^-$

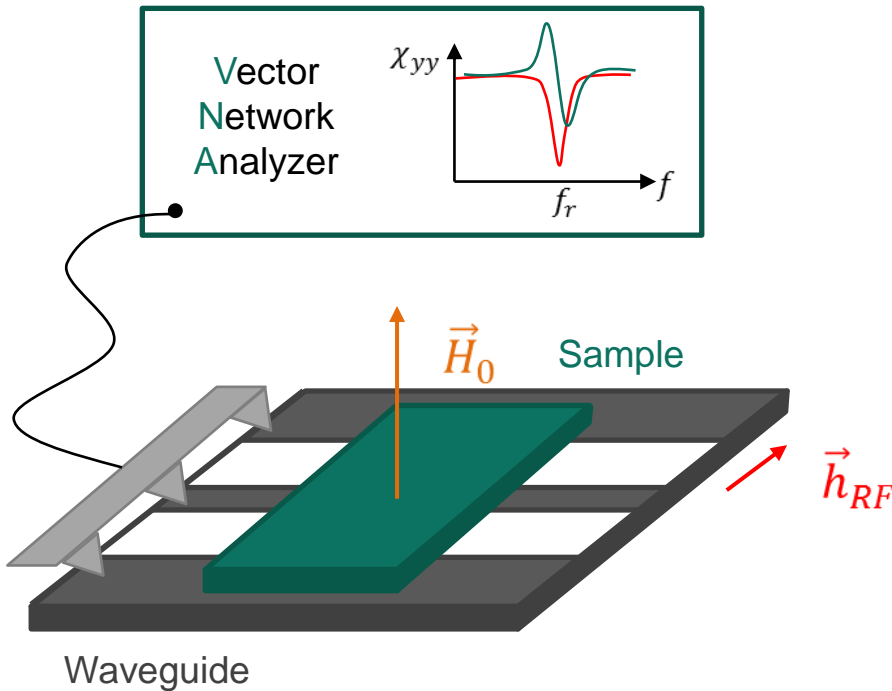
**Spin gap at  $E_F$  for  $\text{Co}_2\text{MnGa}$**

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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  $f_r$

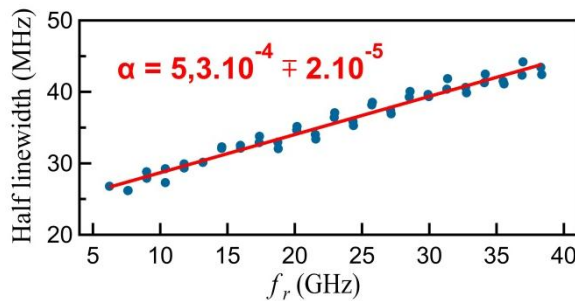
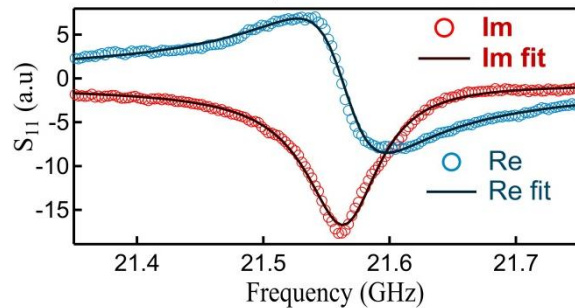
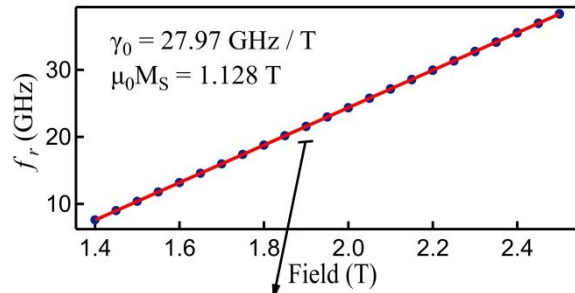
$$\Delta f = 2\alpha f_r$$

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

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

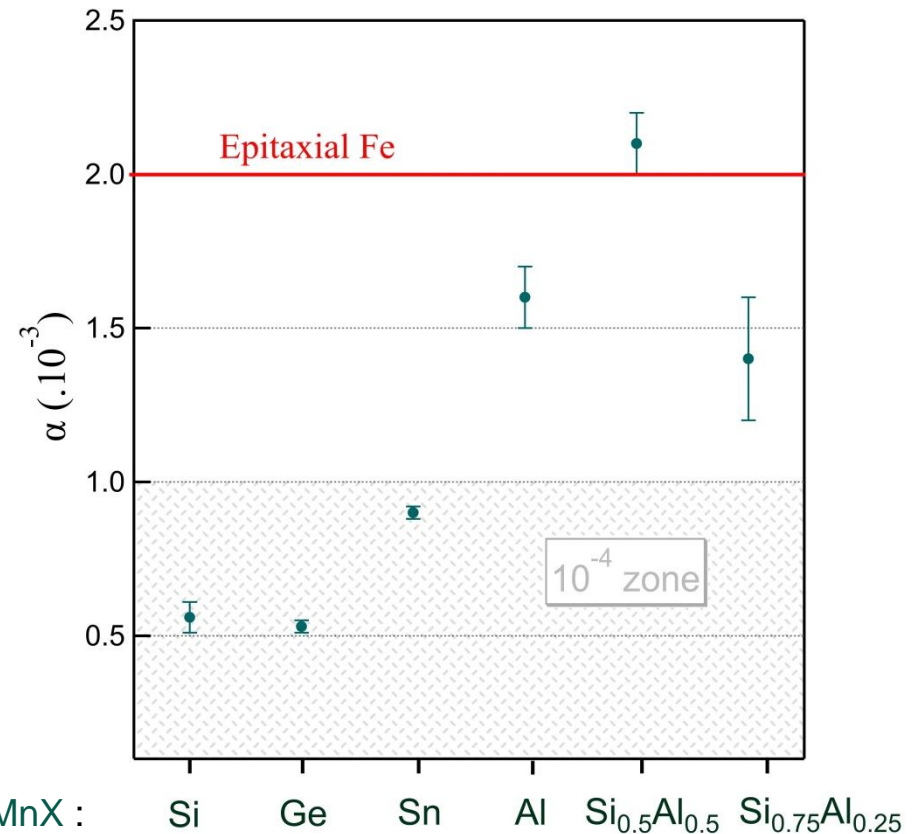
# Ferromagnetic resonance

Low magnetic damping on Heuslers



Co<sub>2</sub>MnGe

not yet published



→ Ga and Sb measurement in progress



# Summary

- Epitaxial  $\text{Co}_2\text{MnX}$  thin films can be grown by MBE
  - Why low chemical order for  $\text{Co}_2\text{MnAl}$  or (111) growth for  $\text{Co}_2\text{MnSb}$  ?
- High spin polarization for almost all of them
  - HMM confirmed for  $\text{Co}_2\text{MnSi}$  and  $\text{Co}_2\text{MnGa}$  !
- 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 !



Institut Jean Lamour

Institut Jean Lamour  
101 team

S. Andrieu †  
C. Rojas-Sanchez  
S. Petit-Watelot



Soleil Synchrotron  
Cassiopee beamline

F. Bertran †  
P. Le Fèvre



Laboratoire Léon  
Brillouin

A. M. Bataille †