

NGUYEN THANH NAM

**Fabrication and Study of Magnetic and Transport
Properties of GdCo Thin Films, GdCo-Based
Multilayers, and Fe/Cr Multilayers**

Joint thesis VNU. Hanoi – UJF. Grenoble

Supervisors:

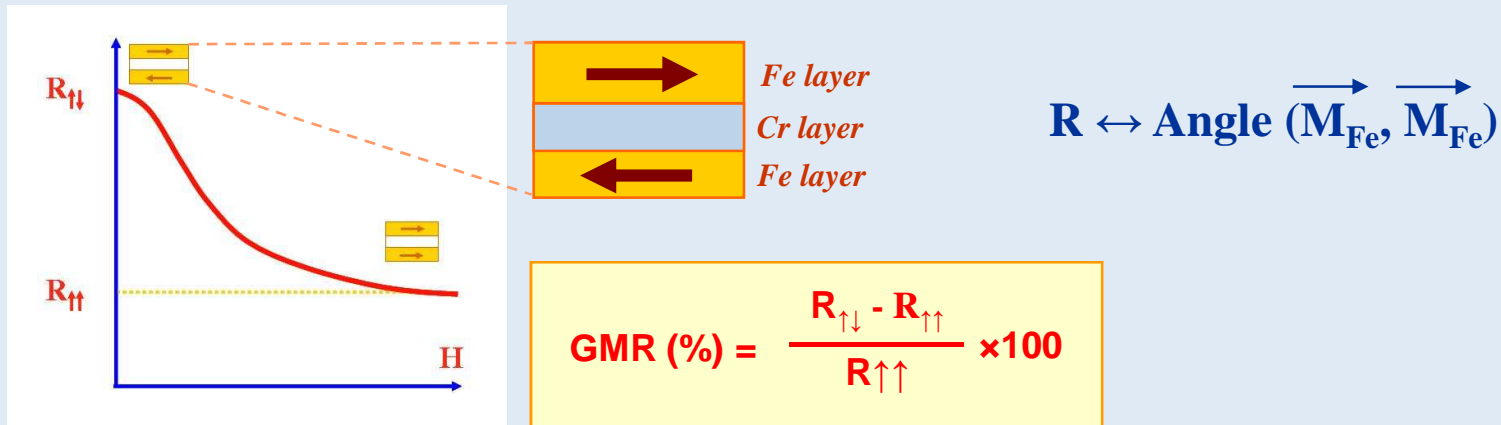
Dr. Laurent Ranno (UJF), Prof. Nguyen Huu Duc (VNUH), Dr. Claire Meyer (CNRS)

Outline

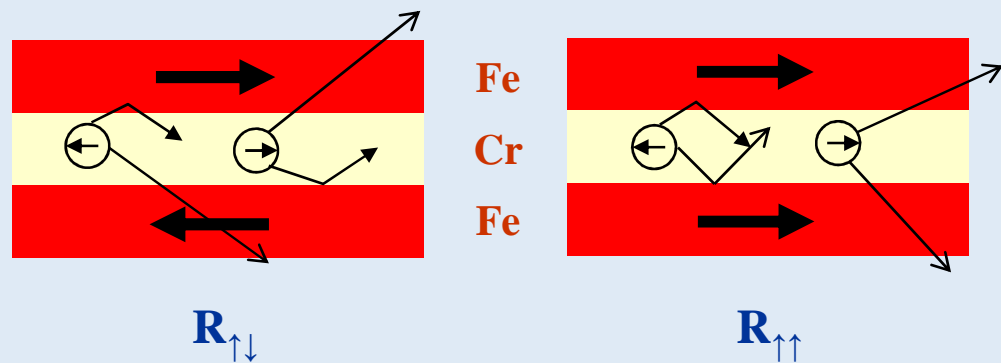
- 1. Introduction of spin-transport effects*
- 2. Compensation domain wall (CW) of GdCo thin films*
- 3. Extraordinary Hall effect (EHE) and magnetic properties of GdCo thin films*
- 4. GMR of Fe/Cr multilayers*
- 5. GMR of GdCo/Cu/FeNi multilayers*
- 6. Conclusion*

An "old " spin transport effect: Giant MagnetoResistance (GMR)

Invented in 1988 by **A. Fert** and **P. Grünberg** (Nobel 2007).

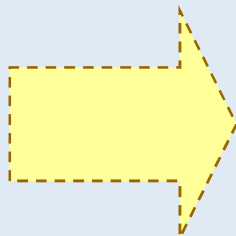


Spin-dependent scattering mechanism:



An "old " spin transport effect: Giant MagnetoResistance (GMR)

1. Where is the main location of spin dependent scattering centers in Fe/Cr multilayer (*in Fe-layer cores or Fe/Cr interfaces*)?
2. Is it possible to make a GMR junction with zero magnetisation?



1. Studying Fe/Cr multilayer with the variation of Fe layer thickness.
2. Using a compensated ferrimagnetic electrode: GdCo.

An "new " spin transport effect : Spin Torque Effect

GMR :

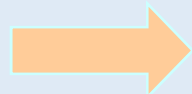
magnetisation configuration

\Rightarrow *magneto-resistance*

Spin Torque :

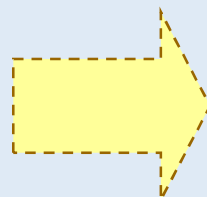
spin polarised current

\Rightarrow *magnetisation configuration*

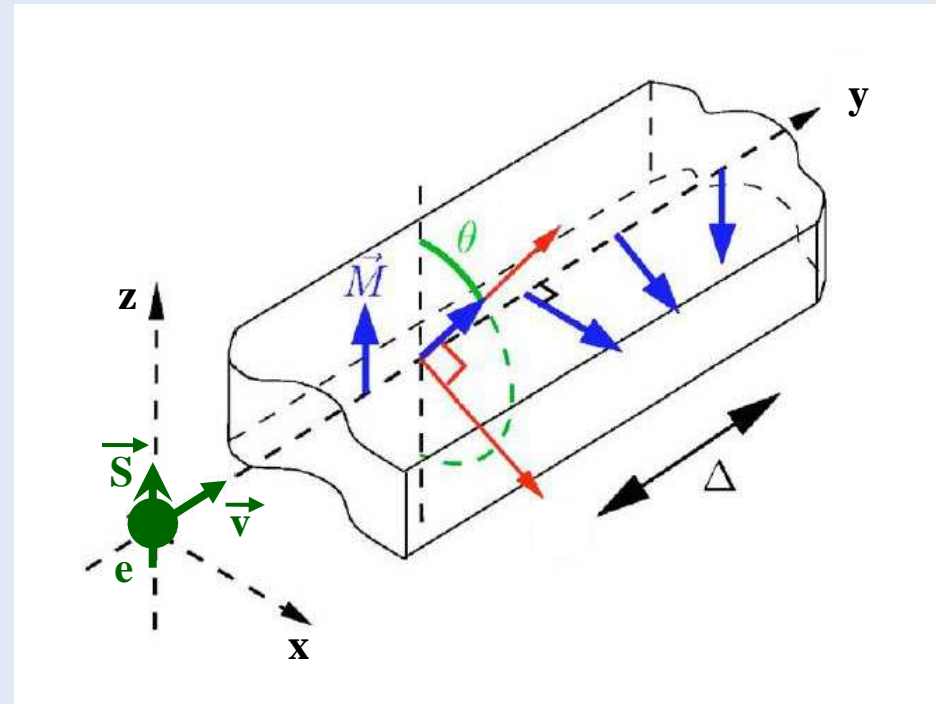


**Domain wall is moved
by a spin-polarised
current.**

**What if the domain wall has
no magnetic moment?**



**Using GdCo thin film to create
Compensation domain wall (CW)**



Extraordinary Hall Effect (EHE)

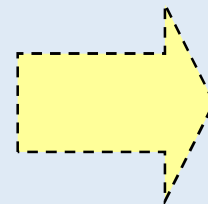
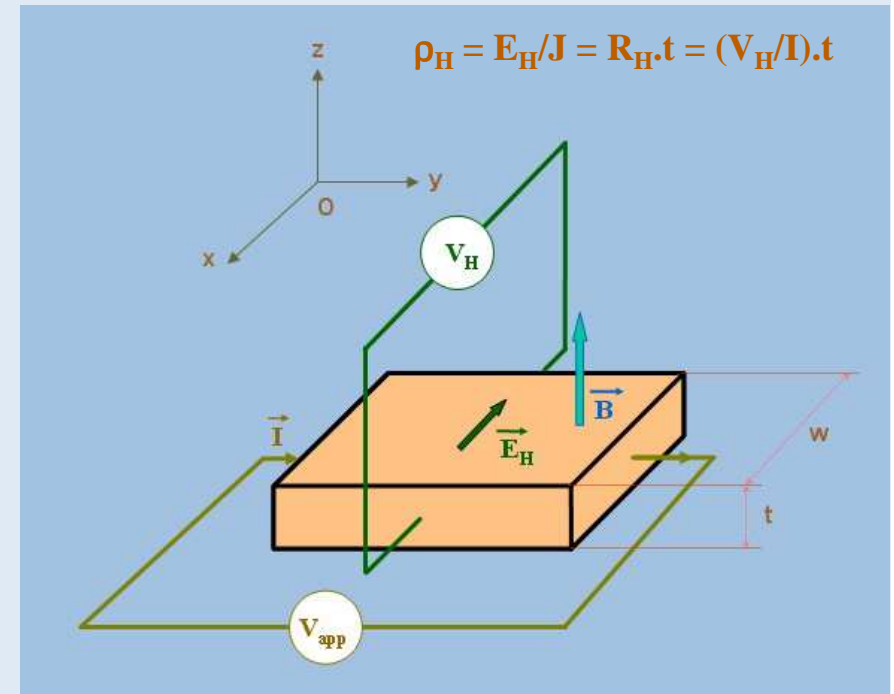
Ferromagnetic metals:

$$\rho_H = R_o \mu_o H + R_S \mu_o M_z = R_S \mu_o M_z \\ = \alpha \rho^n \mu_o M_z$$

+ R_o ($\sim 1/n$) is negligible

+ $R_S \sim \rho^n$ (skew scattering, side-jump)

1. What if the material has two magnetic sublattices?
2. What if non colinear configuration can be achieved ?

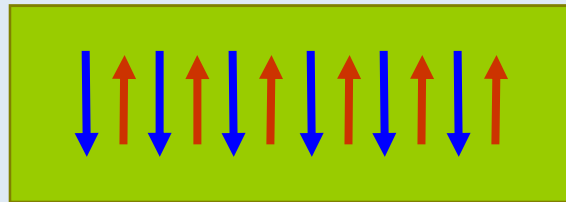


1. Using GdCo ferrimagnet.
2. Spin flop configuration

Introduction of GdCo alloy



Co is a ferromagnetic material



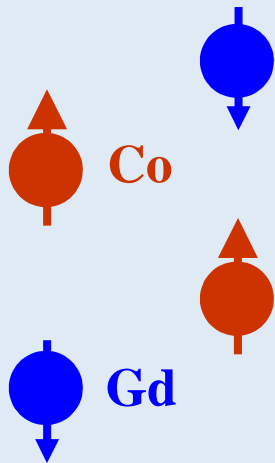
GdCo alloy is a ferrimagnetic material

Co-Co exchange : ferromagnetic

Gd-Co exchange : antiferromagnetic

→ $M_{\text{GdCo}} = |M_{\text{Co}} - M_{\text{Gd}}|$

Mean-field theory for $\text{Gd}_{1-x}\text{Co}_x$



The internal magnetic field:

$$\mathbf{H}_{\text{Co}} = \lambda_{\text{CoCo}} \mathbf{M}_{\text{Co}} + \lambda \mathbf{M}_{\text{Gd}}$$

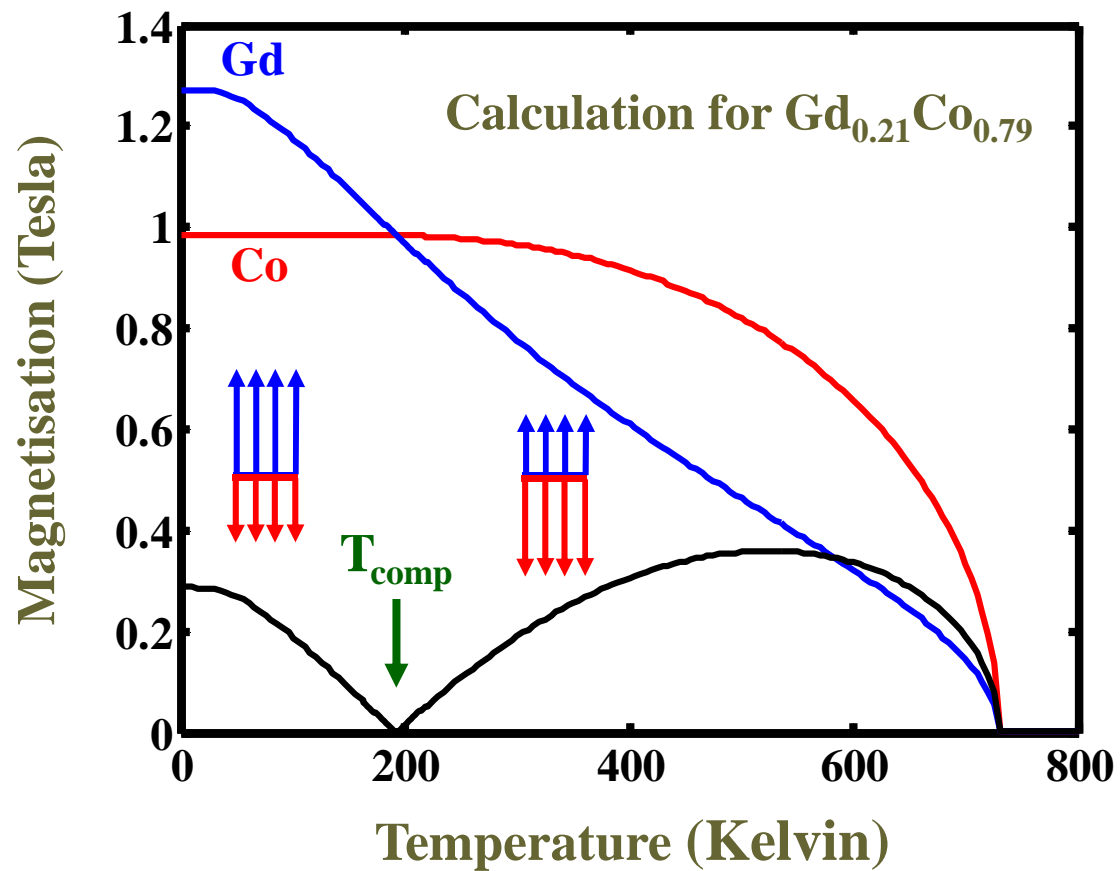
$$\mathbf{H}_{\text{Gd}} = \lambda \mathbf{M}_{\text{Co}}$$

Where λ_{CoCo} and λ are molecular field constants.

$$\mathbf{M}_{\text{Co}} = xN\mu_{\text{Co}} \mathbf{B}_{\text{J}_{\text{Co}}} \left(\frac{\mu_0 \overrightarrow{\mu}_{\text{Co}} \cdot (\overrightarrow{\mathbf{H}} + \lambda_{\text{CoCo}} \overrightarrow{\mathbf{M}}_{\text{Co}} + \lambda \overrightarrow{\mathbf{M}}_{\text{Gd}})}{k_B T} \right)$$

$$\mathbf{M}_{\text{Gd}} = (1-x)N\mu_{\text{Gd}} \mathbf{B}_{\text{J}_{\text{Gd}}} \left(\frac{\mu_0 \overrightarrow{\mu}_{\text{Gd}} \cdot (\overrightarrow{\mathbf{H}} + \lambda \overrightarrow{\mathbf{M}}_{\text{Co}})}{k_B T} \right)$$

Compensation temperature (T_{comp}) of GdCo



⇒ Tunable
Magnetisation
(including $M_S = 0$ at
compensation)

Spin electronics and $\text{Gd}_{1-x}\text{Co}_x$

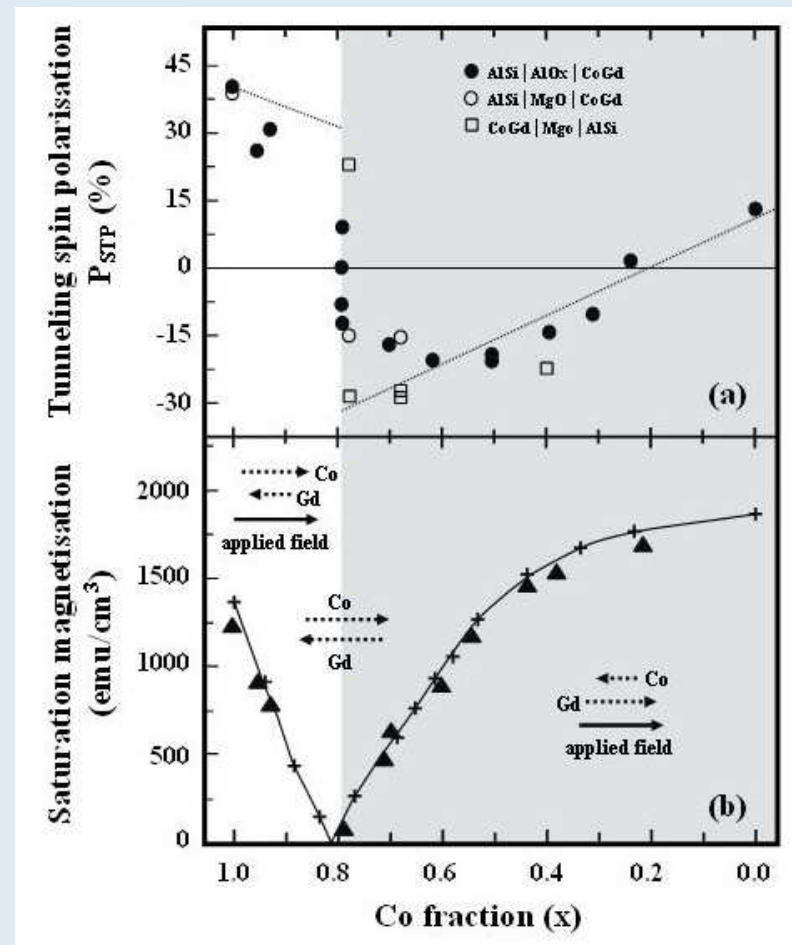
+ At 300 K deposition leads to amorphous GdCo alloys \rightarrow Large resistivity ($200 \mu\Omega\cdot\text{cm}$)

During my thesis, TMR results were published:

+ Tunnelling Spin Polarisation: $> 30\%$

+ By changing temperature across T_{comp} : TSP is changed and The sign is reversed at T_{comp} .

\Rightarrow is GdCo interesting for spin electronics ?



Stuart S. P. Parkin *et al* PRL 95 (2005)

Summary for GdCo alloys:

Old material :

- + *Developped for bubble memories in the 1970s (perpendicular anisotropy and bubble domains at room temperature).*
- + *EHE of GdCo film was studied alot at low fields (below spin-flop field).*

This material must be revisited:

- + *Tunable M --> possibility to cancel demagnetising field keeping ferromagnetic order unique as a micromagnetic model system → zero moment material for spin torque studies.*
- + *Perpendicular anisotropy and Large spin polarisation → GdCo (conductor) is possible to insert in spintronics devices*
- + *The Gd and Co sublattice contributions to EHE are still open question.*

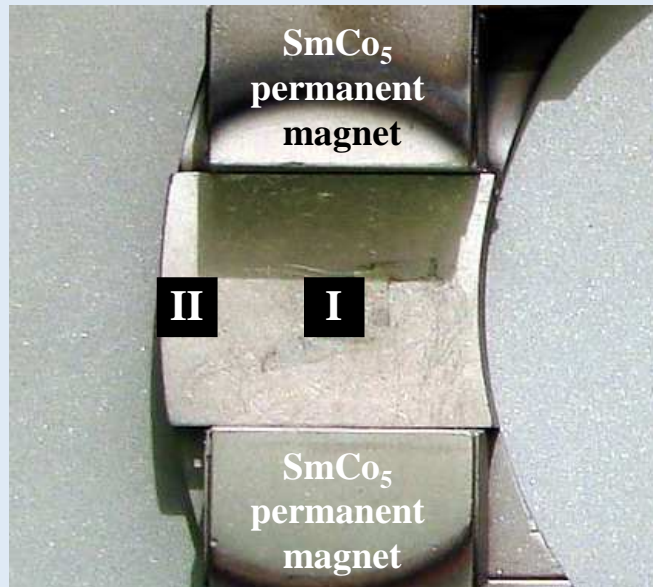
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The purpose of this study

*To create and manipulate a 180° domain
wall without magnetic moment.*

Ms=0 sample : composition gradient film



- + Target: Gd₁₄Co₈₆
- + The substrate: *off-center position (II)*
- + The film: **100 nm thick**

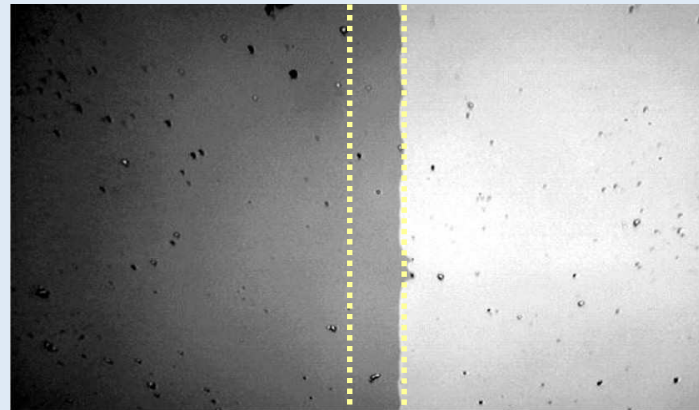
CW observation

Polar Kerr images

$T = 300 \text{ K}$

$H \perp \text{film}$

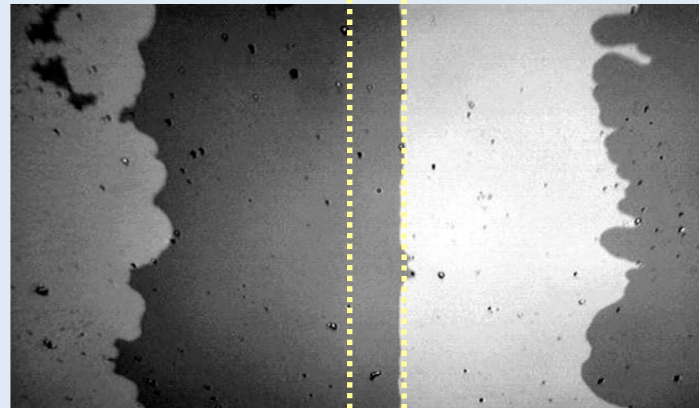
$\mu_0 H_{\text{max}} = 60 \text{ mT}$



$200 \mu\text{m}$
↔

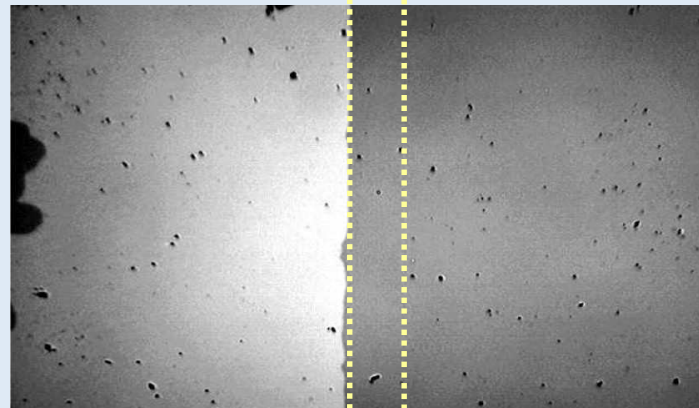
**Saturated
state**

$H = H_{\text{max}}$



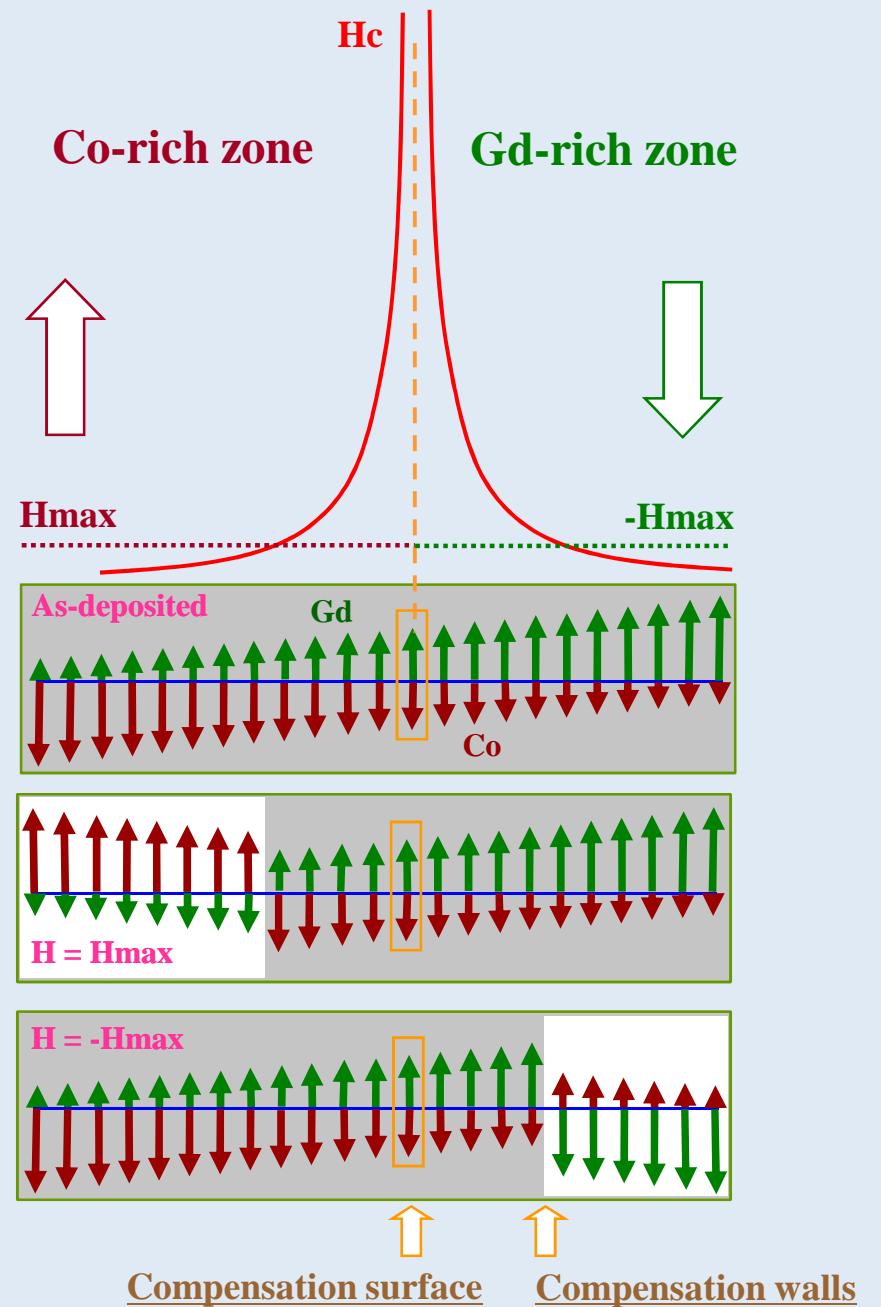
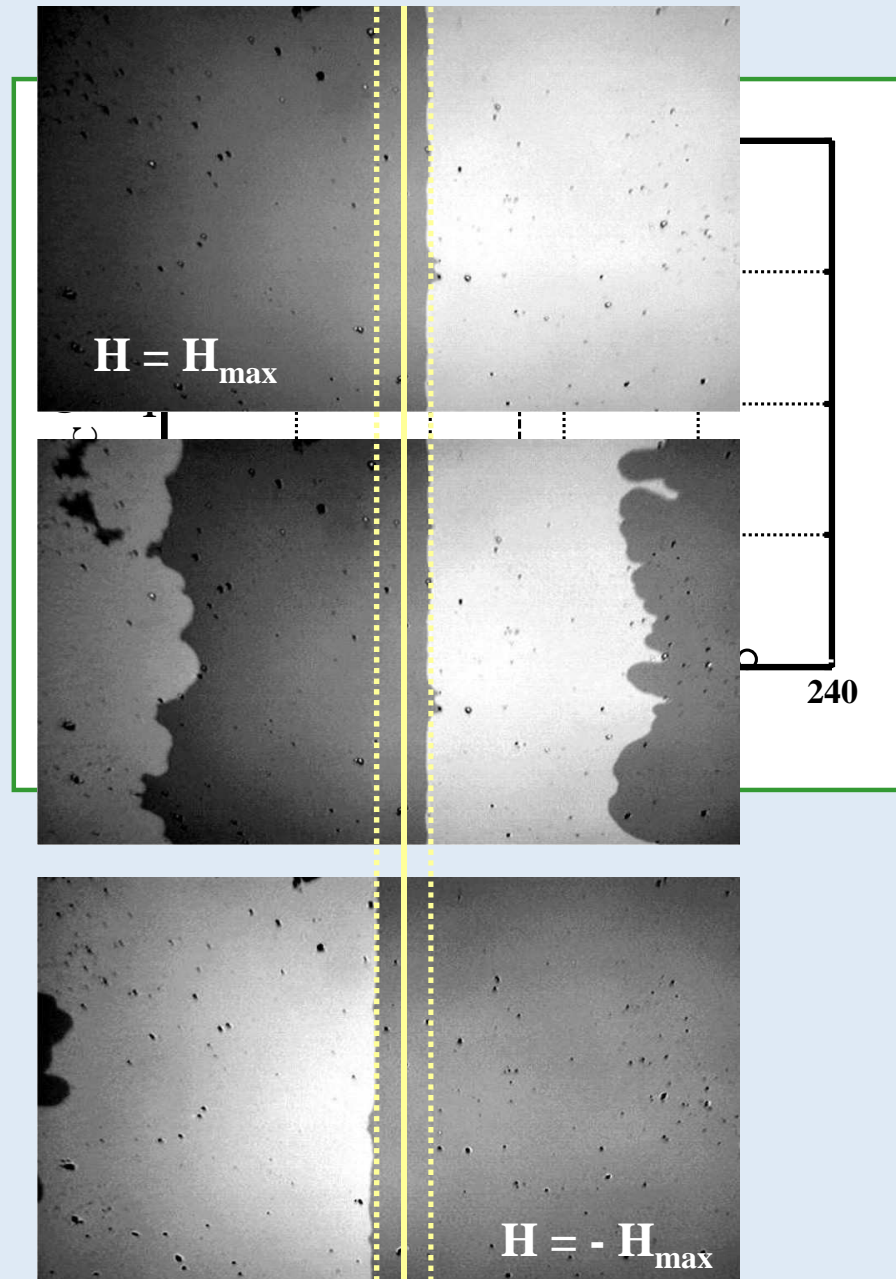
$H < H_{\text{max}}$

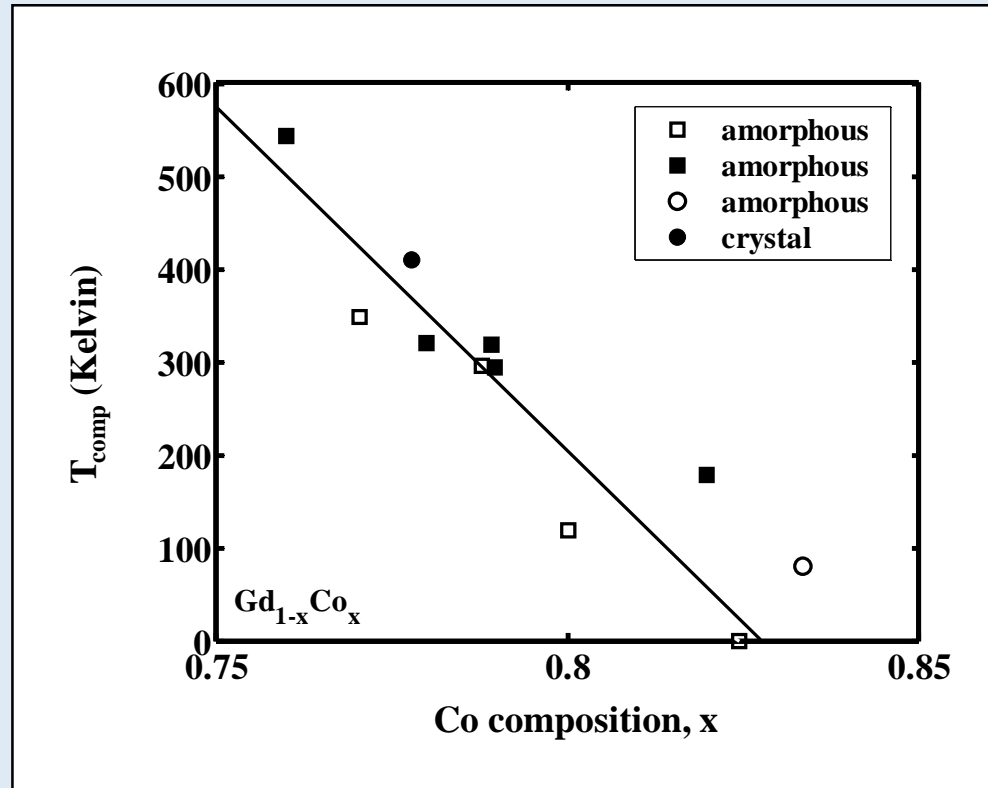
$H > -H_{\text{max}}$



**Saturated
state**

$H = -H_{\text{max}}$

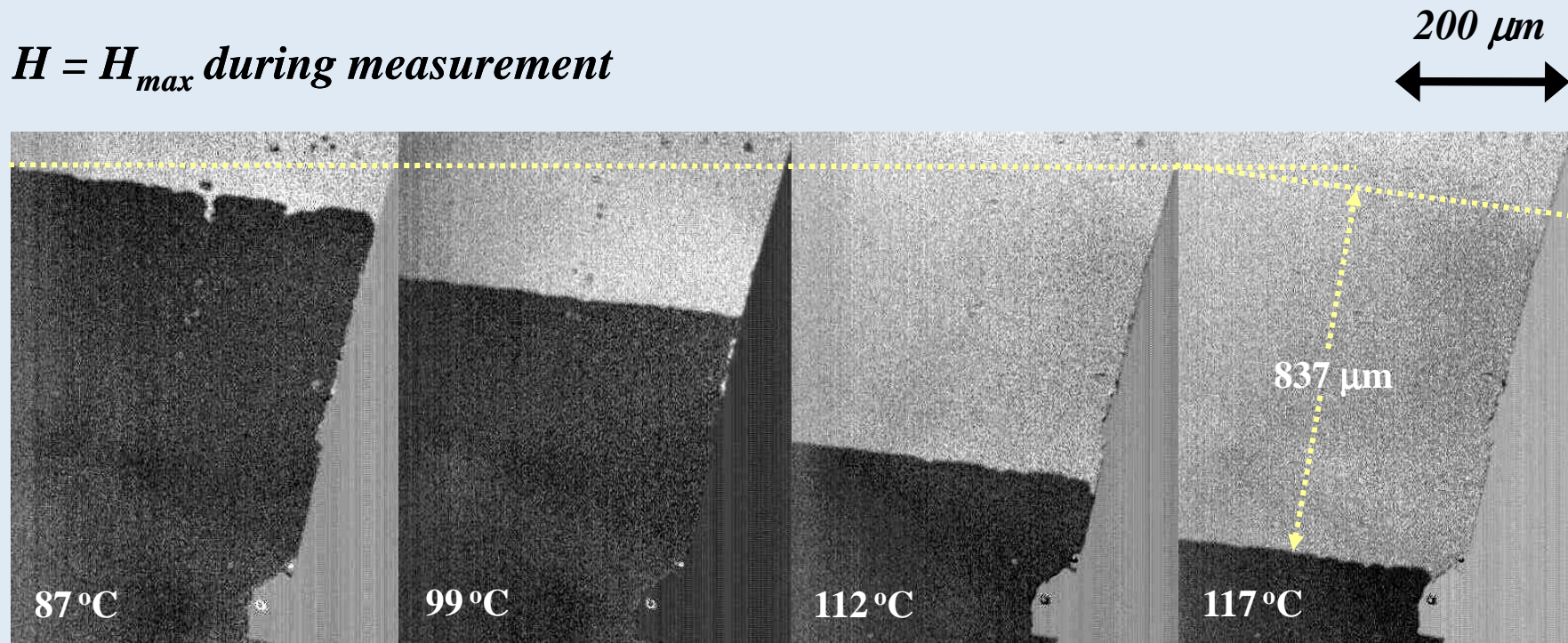




*Near 300 K, 1% change of composition makes about
40 K change of T_{comp}*

Measurement of the composition gradient

$H = H_{max}$ during measurement



Heating up the sample : the compensation wall moves 837 μm with $\Delta T = 30 \text{ K}$

Displacement 28 $\mu\text{m}/\text{K}$ (better than 0.1 K sensitivity).

Comparing to 40 K/% shift of T_{comp} \rightarrow Gradient 0.9 % / mm

Summary

We have succeeded in designing, in a reproducible way, samples with in-plane composition gradient. It allows to introduce a compensation surface and to manipulate it (by changing temperature in constant applied field) .

The compensation domain wall is a new micromagnetic object:

- perfect 180° Bloch domain wall (no demagnetising energy)**
- no magnetic moment for spin torque experiments**

(domain wall displacement, polariser for RF oscillations).

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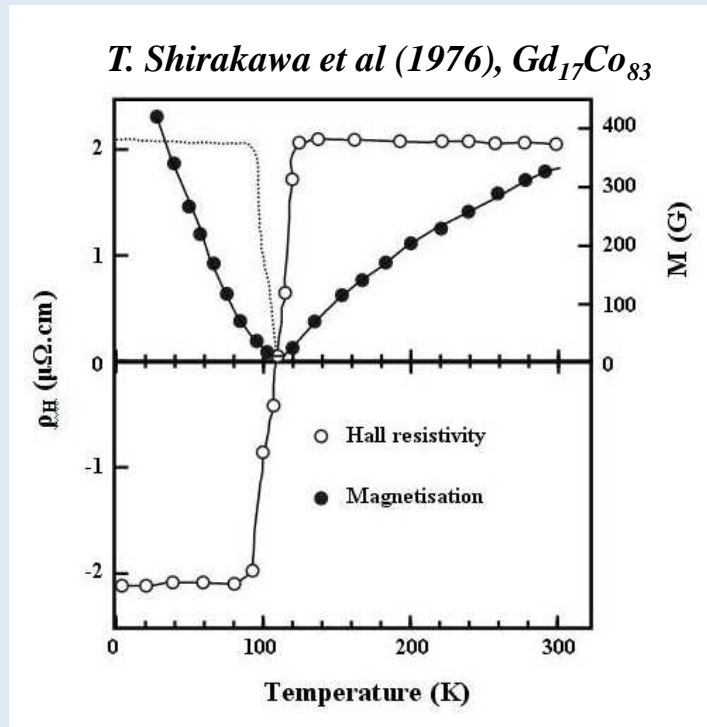
The aim of this study

To find the answers for two questions:

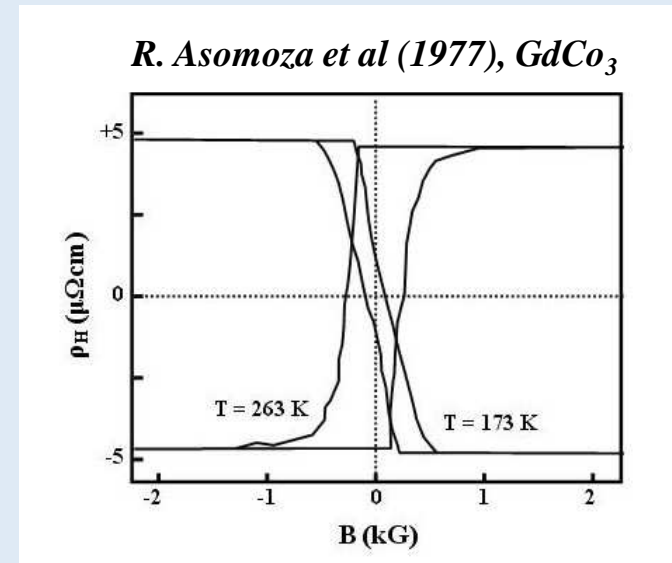
- + What are the contributions of Gd and Co sublattices to EHE of GdCo thin film?**
- + What happens to EHE of GdCo above the spin-flop transition?**

EHE of GdCo ferrimagnet:

$$\rho_H = R_{Co}\mu_0 M_{z-Co} + R_{Gd}\mu_0 M_{z-Gd} = \alpha_{Co}\rho^n\mu_0 M_{z-Co} + \alpha_{Gd}\rho^m\mu_0 M_{z-Gd}$$



EHE reverses at T_{comp}



$T > T_{\text{comp}}, \text{EHE} > 0, T < T_{\text{comp}}, \text{EHE} < 0$

In literature, the magnitude of both terms is still unclear

$$\rho_H = \alpha_{Gd} \rho^m M_{Gd} + \alpha_{Co} \rho^n M_{Co}$$

In our study:

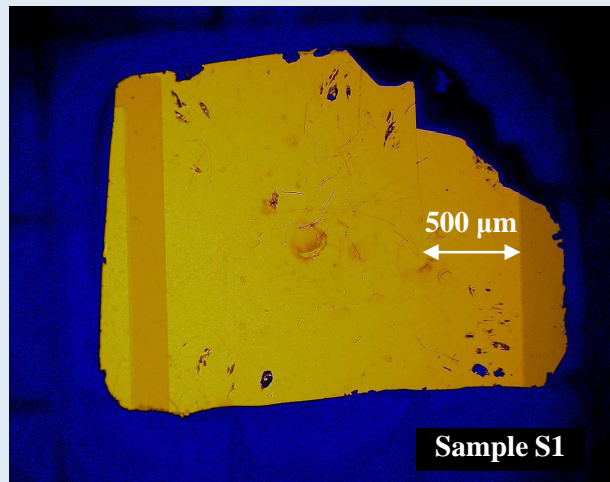
One film as a function of T

+ Measure ρ , ρ_H .

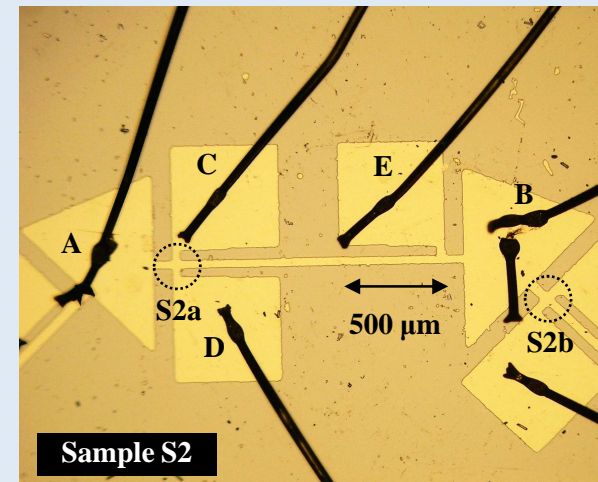
+ Get M_{Co} and M_{Gd} using mean field modelling

Sputtered GdCo thin films

2 films: 100 nm thick + Amorphous state + Perpendicular anisotropy

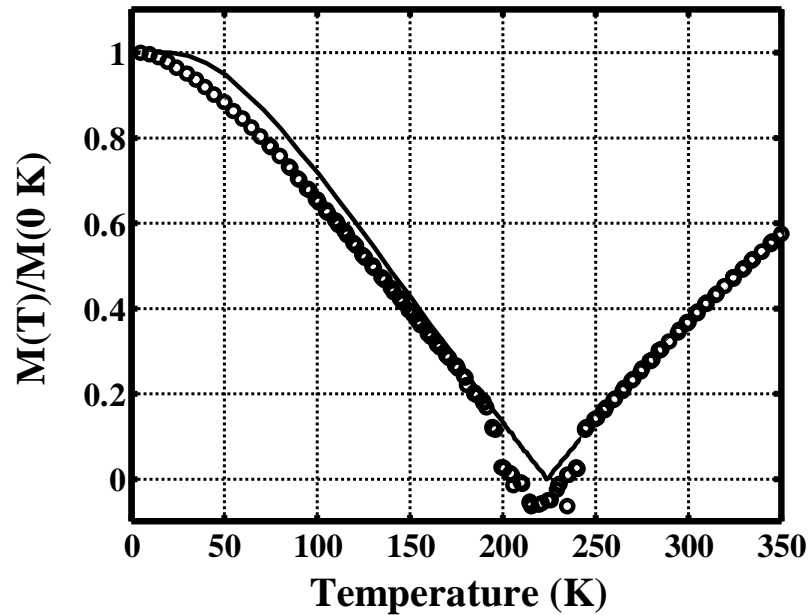


Film 1: Unpatterned sample S1
for **SQUID** measurement



Film 2: Patterned sample S2
for **EHE** and **R** measurement

Experimental and calculated magnetisation



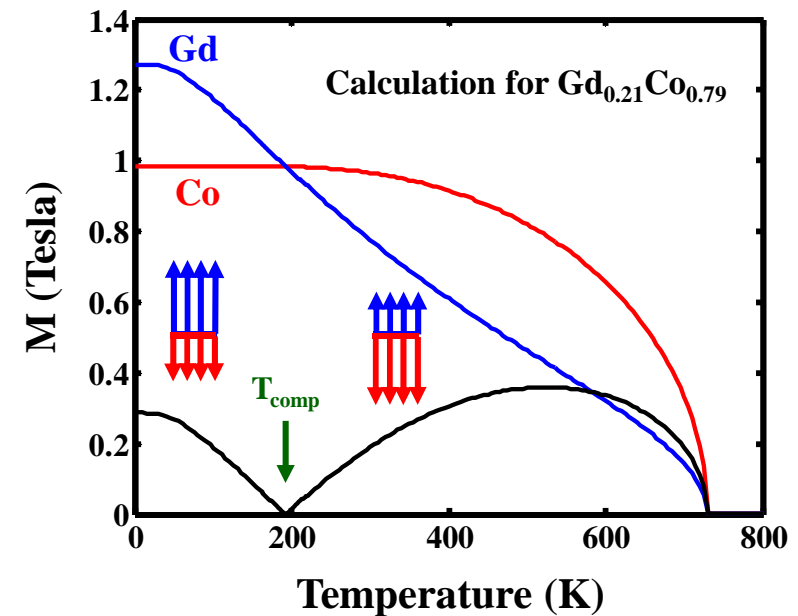
Sample S1 ($T_{\text{comp}} = 225\text{ K}$):

Open circles: SQUID data (normalised)

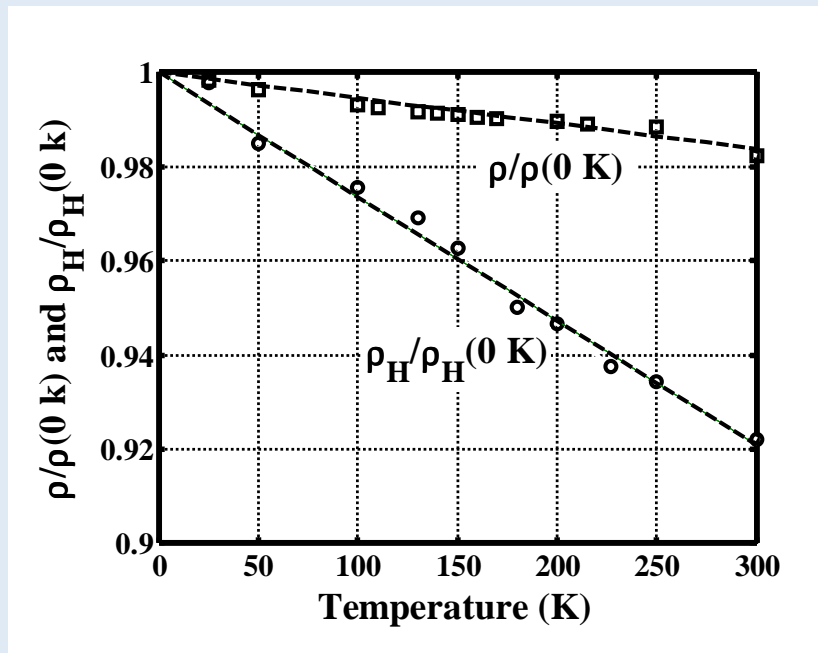
Solid curves: Calculated data (normalised)

Sample S2a ($T_{\text{comp}} = 193\text{ K}$):

Mean field calculation



Experimental T-dependences of ρ_H and ρ

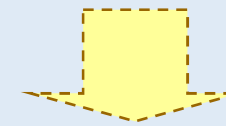


Sample S2a with $T_{\text{comp}} = 193\text{ K}$

Assuming that $n = m \in [1, 2]$,

we find:

$$\rho_H = \rho^n (\alpha_{\text{Gd}} M_{\text{Gd}} + \alpha_{\text{Co}} M_{\text{Co}})$$



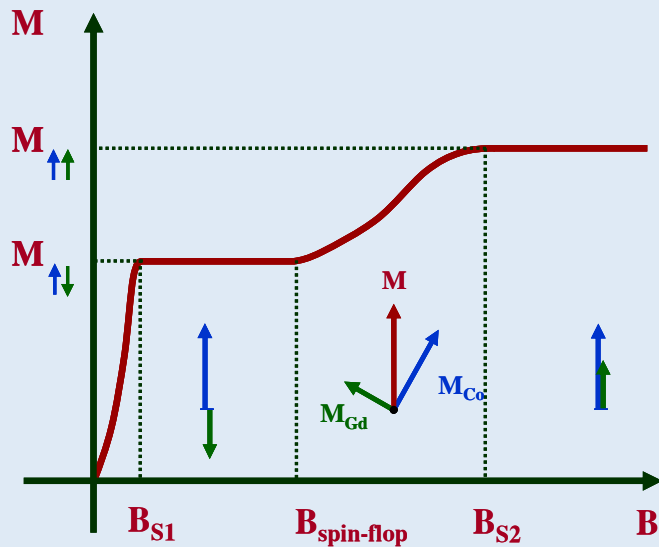
$$R_{\text{Gd}} = \alpha_{\text{Gd}} \rho^n \text{ and } R_{\text{Co}} = \alpha_{\text{Co}} \rho^n$$

Sublattice Hall coefficients R_{Gd} and R_{Co}

n	$R_{Co}(0\text{ K}) (\Omega\text{m}^2/\text{A})$	$R_{Gd}(0\text{ K}) (\Omega\text{m}^2/\text{A})$	$ R_{Gd}/R_{Co} $
1	28.6×10^{-9}	-2.99×10^{-9}	10.5%
2	29.9×10^{-9}	-1.94×10^{-9}	6.5%

*Co make positive sense ($\rho_{Co} > 0$) and Gd makes
negative sense to EHE ($\rho_{Gd} < 0$)*

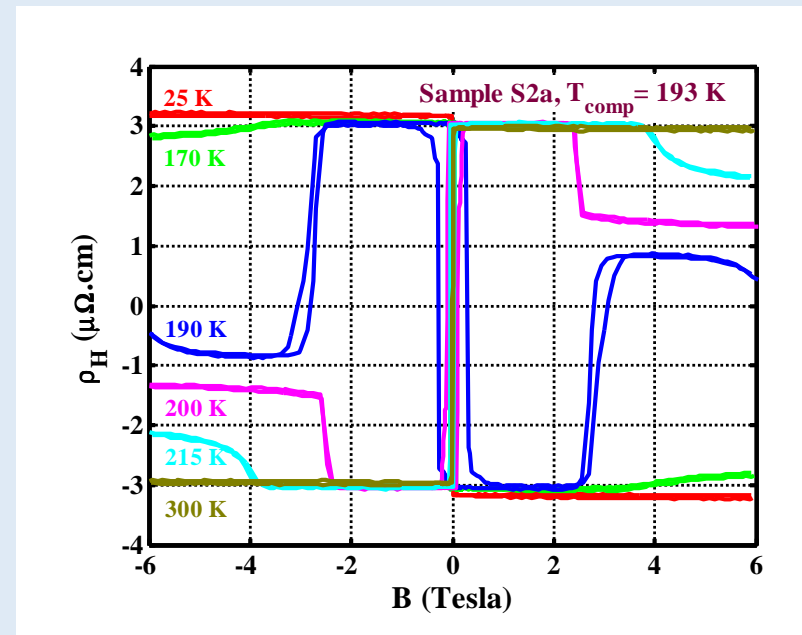
Observation of spin-flop by means of EHE



When $K_{Co} = 0$:

$$B_{spin-flop} = \lambda |M_{Gd} - M_{Co}| = \lambda M$$

EHE curves of patterned sample S2a



EHE to study spin-flop. Semi quantitative understanding of EHE above spin-flop

Summary

- + **We have succeeded in preparing GdCo film with T_{comp} is between 300 K and 0 K. The films always have perpendicular spontaneous magnetisation below 300 K.**
- + **The contributions of Gd and Co sublattices to EHE have been estimated. Co moments make positive sense and Gd moments make negative sense to EHE. However, EHE mainly originates from Co moments (~90%).**
- + **EHE has been applied to observe spin-flop phenomena even when the total magnetisation is vanishingly small. The T-dependence of spin-flop field has been experimentally studied for the first time.**

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- 6. Conclusion*

The purpose of this study

To find the answer for question:

Where is the main location of the spin-dependent scattering centers in Fe/Cr multilayers

(in the core of Fe layers or in the Fe/Cr interfaces)?

Study GMR vs the interface/Volume fraction ratio

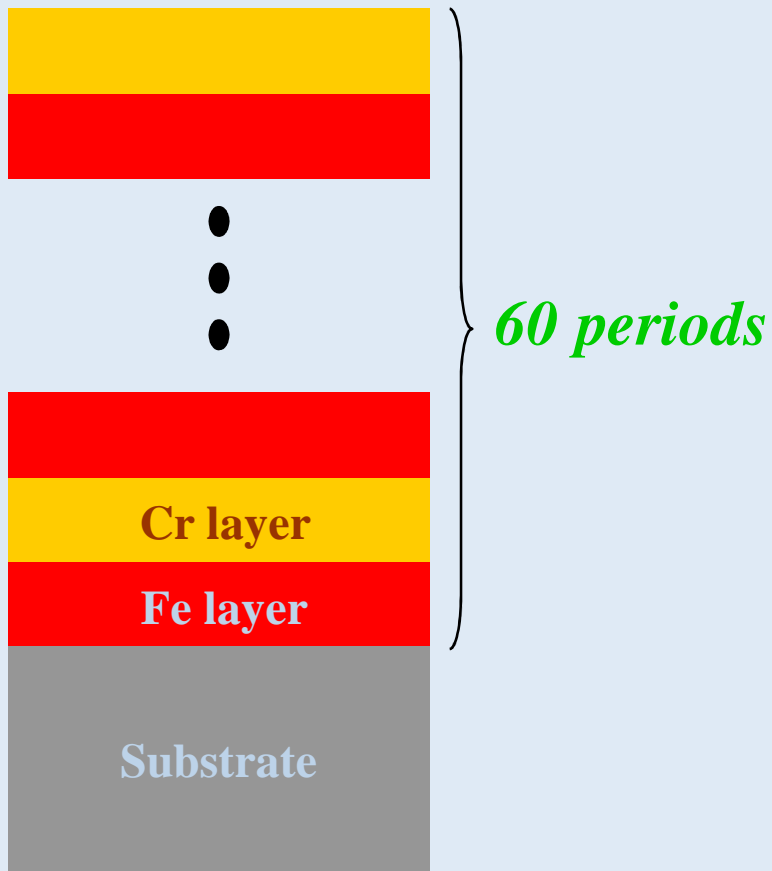
$$(V_{\text{int}}/V_{\text{Fe}})$$

This ratio can be varied by:

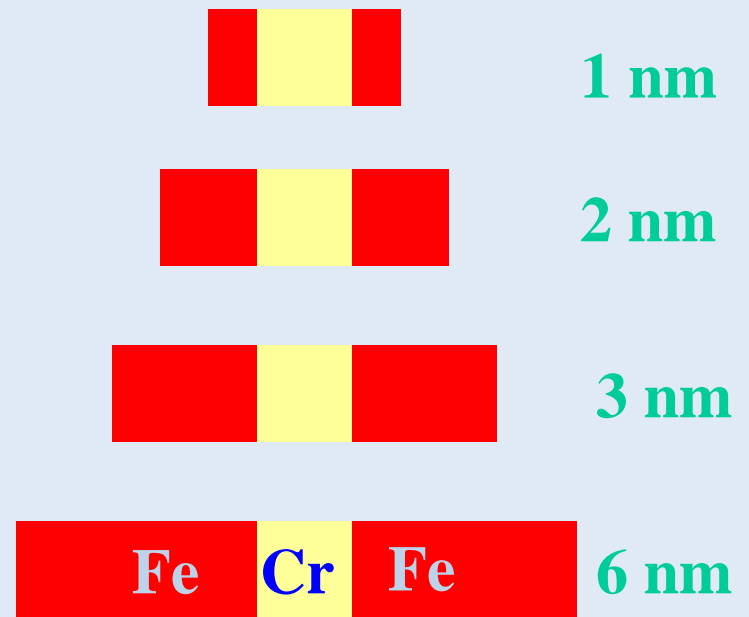
1. *Changing the thickness of Fe layer (t_{Fe}).*
2. *Changing the annealing temperature (T_A).*

I

Changing t_{Fe}



Variation of t_{Fe}



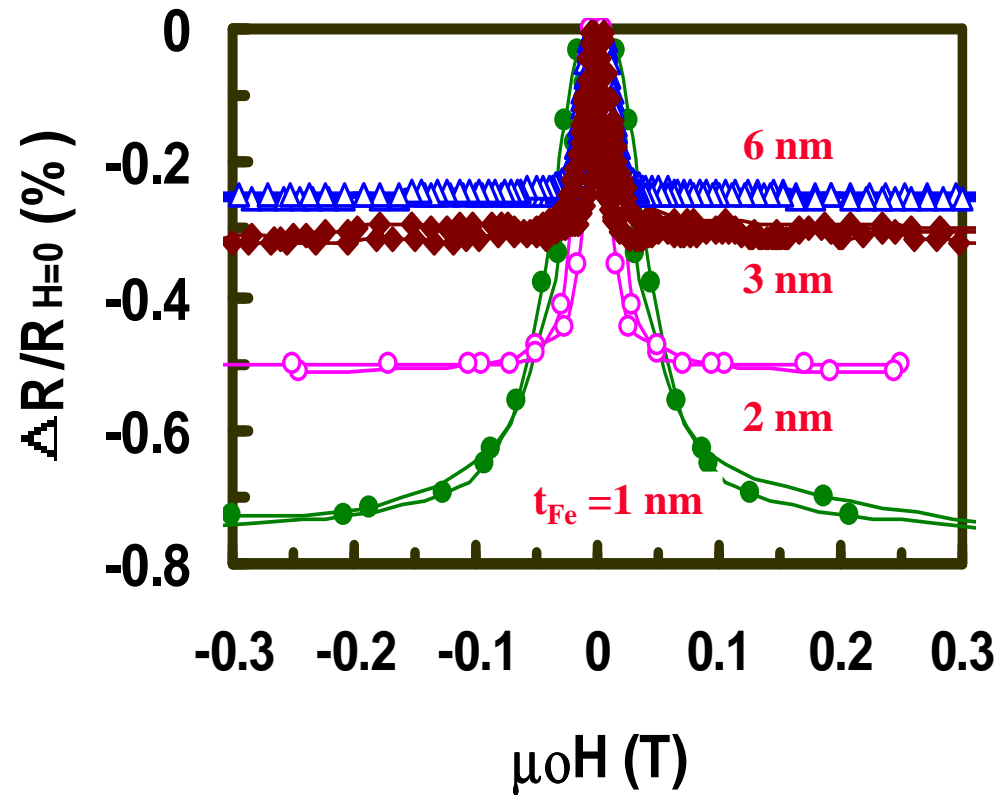
$t_{\text{Cr}} = 2 \text{ nm}$ (fixed)

GMR data for as-deposited films at 30 °C

t_{Fe} decreases

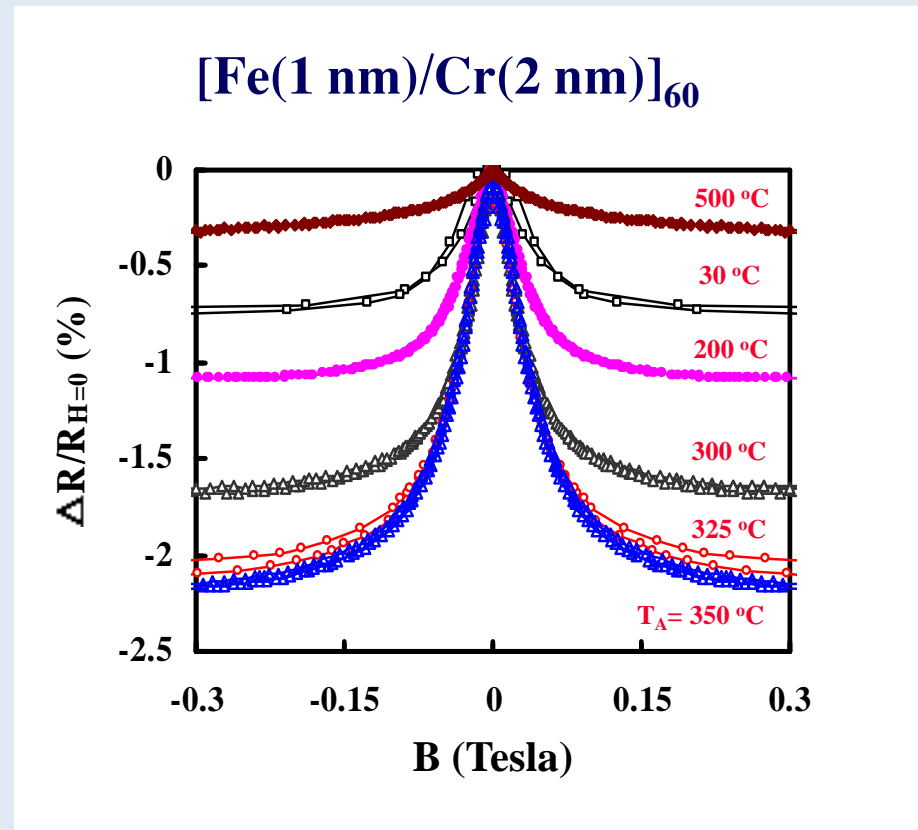
→ V_{int}/V_{Fe} increases

→ the GMR increases.



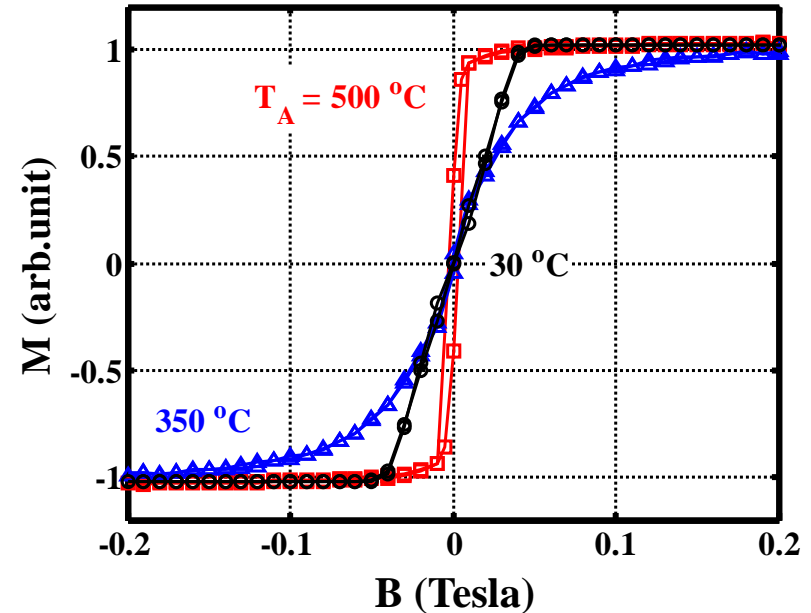
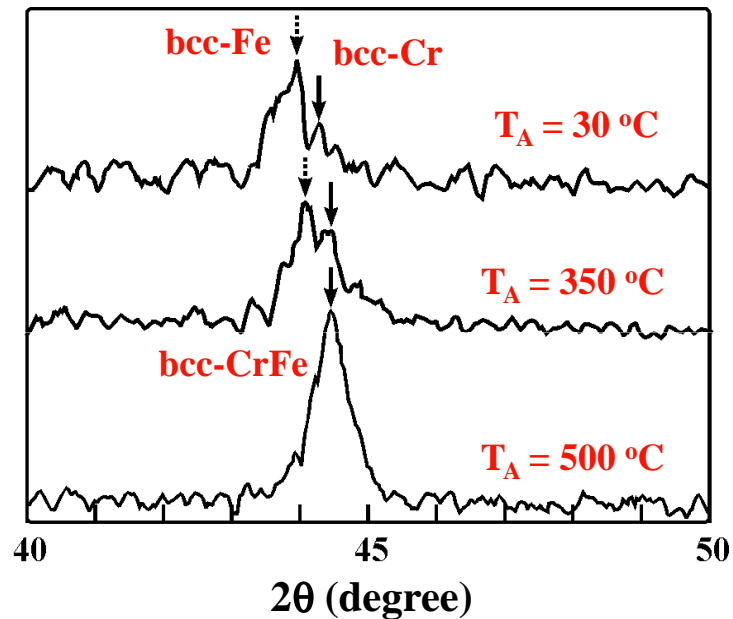
II

Changing T_A

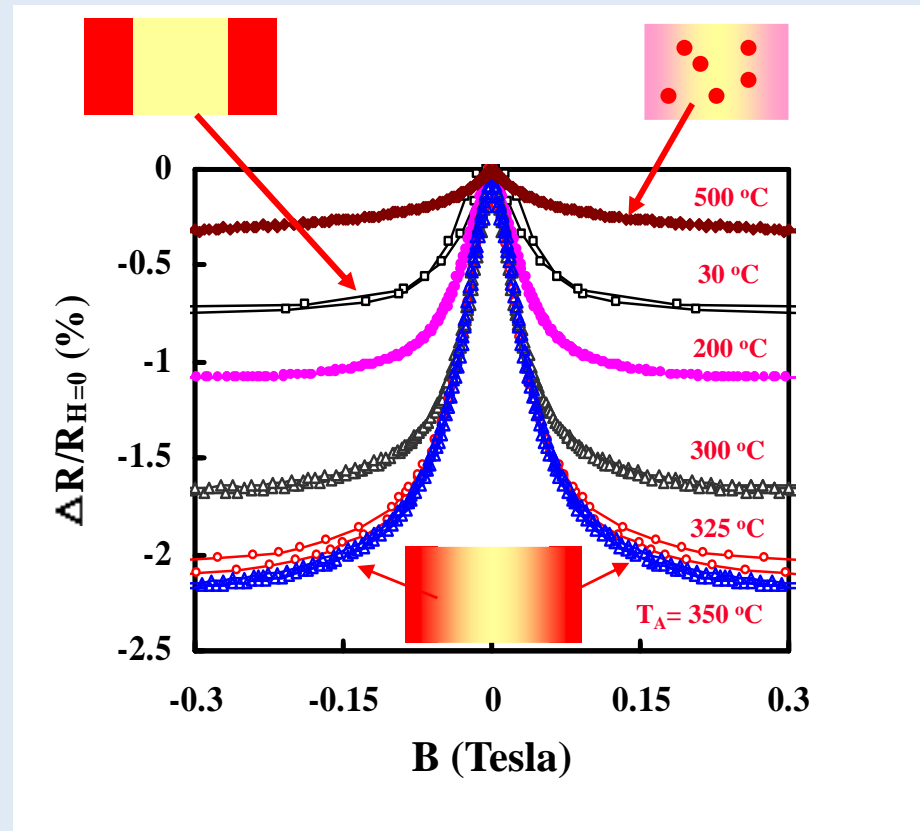


Annealing duration is 1 hour, $P_{Ar} = 5 \times 10^{-5}$ mbar

The film: $[\text{Fe}(1 \text{ nm})/\text{Cr}(2 \text{ nm})]_{60}$



When T_A increases over 350°C , the layer structure breaks down, so the GMR is reduced.



T_A increases to 350 °C $\rightarrow V_{int}/V_{Fe}$ increases \rightarrow GMR increases.



t_{Fe} decreases

→ V_{int}/V_{Fe} increases

→ the GMR increases.



T_A increases to 350 °C

→ V_{int}/V_{Fe} increases

→ GMR increases.

The spin dependent scattering centers mainly located at the Fe/Cr interfaces.

Summary

+ **Our investigations reveal the dominant role of the scattering centers located at the Fe/Cr interfaces with respect to the GMR of Fe/Cr multilayers.**

+ **The layer structure of sputtered Fe/Cr multilayers remains stable during annealing up to 350 °C. At higher temperature anneals, the multilayer structure is modified and the onset of ferromagnetic coupling is found, leading to the reduction of the GMR signal.**

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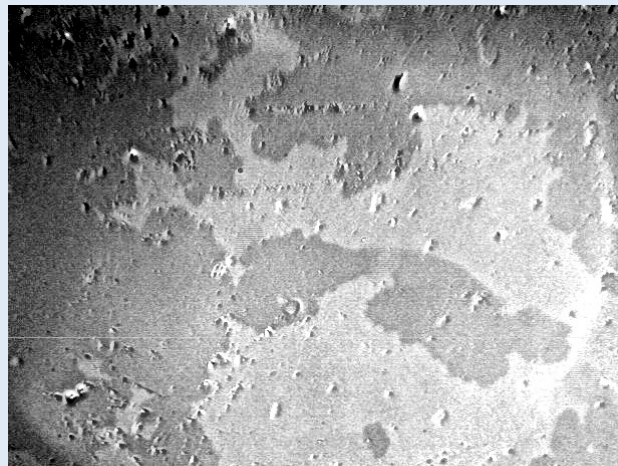
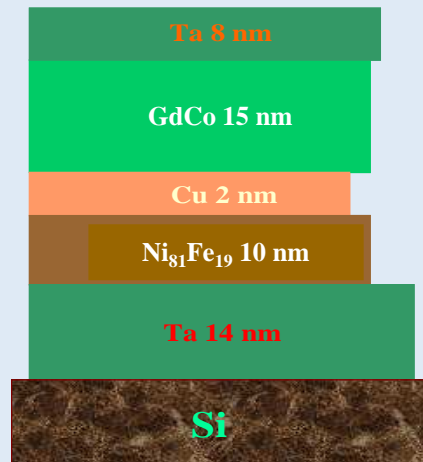
Is amorphous GdCo compatible with GMR ?

+ GMR with zero-M ?

+ Perpendicular anisotropy electrode?

GMR sample

Si/Ta (14 nm)/FeNi (10nm)/Cu (2 nm)/Gd_{1-x}Co_x (15 nm)/Ta (8 nm)



50 μm
↔

*Polar Kerr image of
as-deposited film*

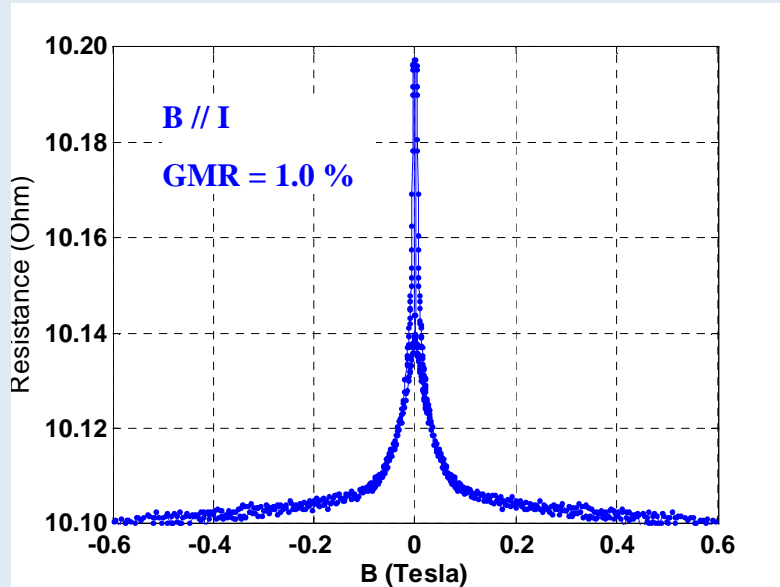
GdCo layer:

- + *Perpendicular anisotropy (PKE)*
- + *Tunable magnetisation M_s (including $M_s=0$)*
- + *Tunable spin polarisation*

NiFe layer:

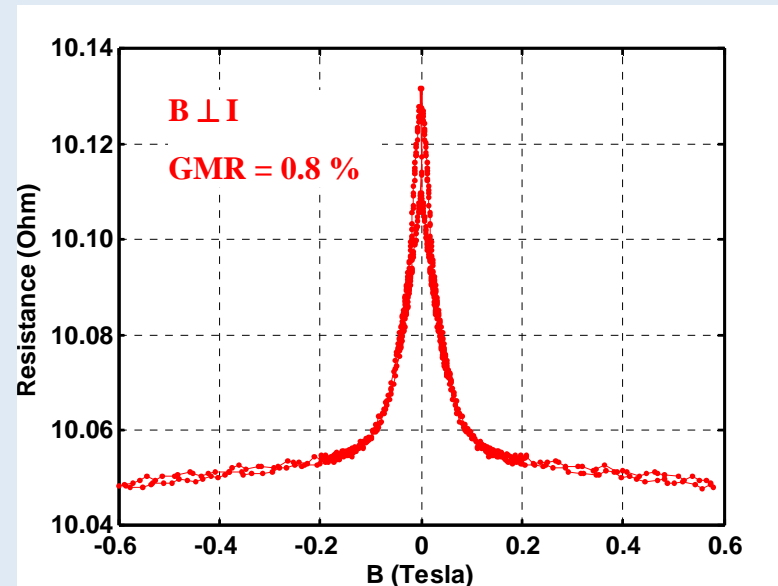
- + *In-plane anisotropy (VSM)*
- + *In-plane easy axis (VSM)*

AMR or GMR at 300K ?

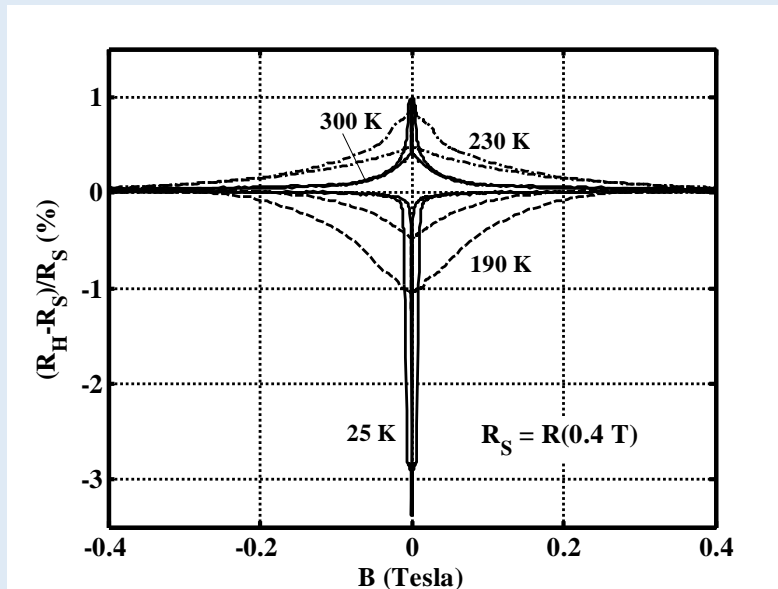


I// easy axis of Py (EAPy)

It does not depend on the direction of current with respect to applied field, so it is GMR

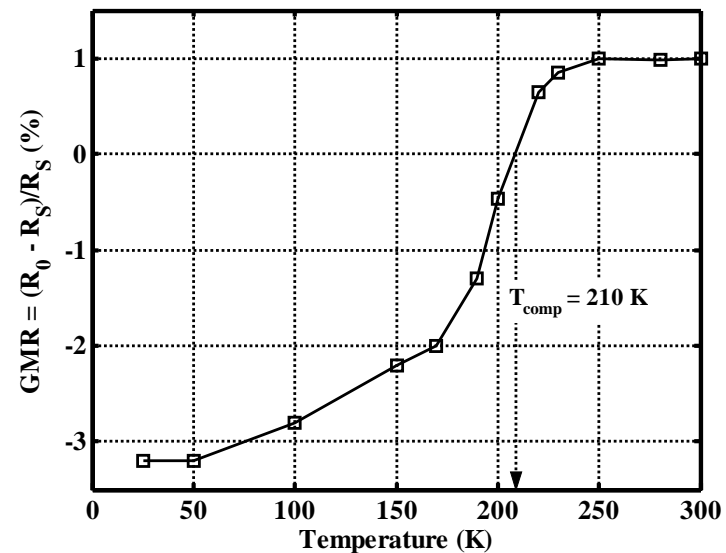


The change of GMR sign at low temperature

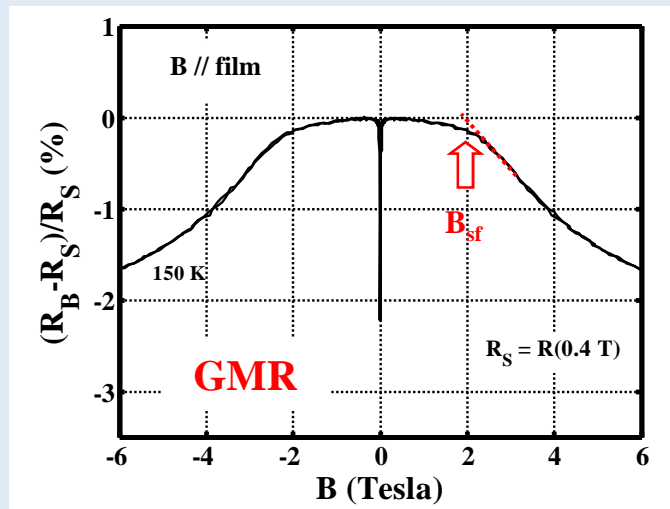


GMR(25 K) = -3.5 %
GMR(300 K) = +1.0 %

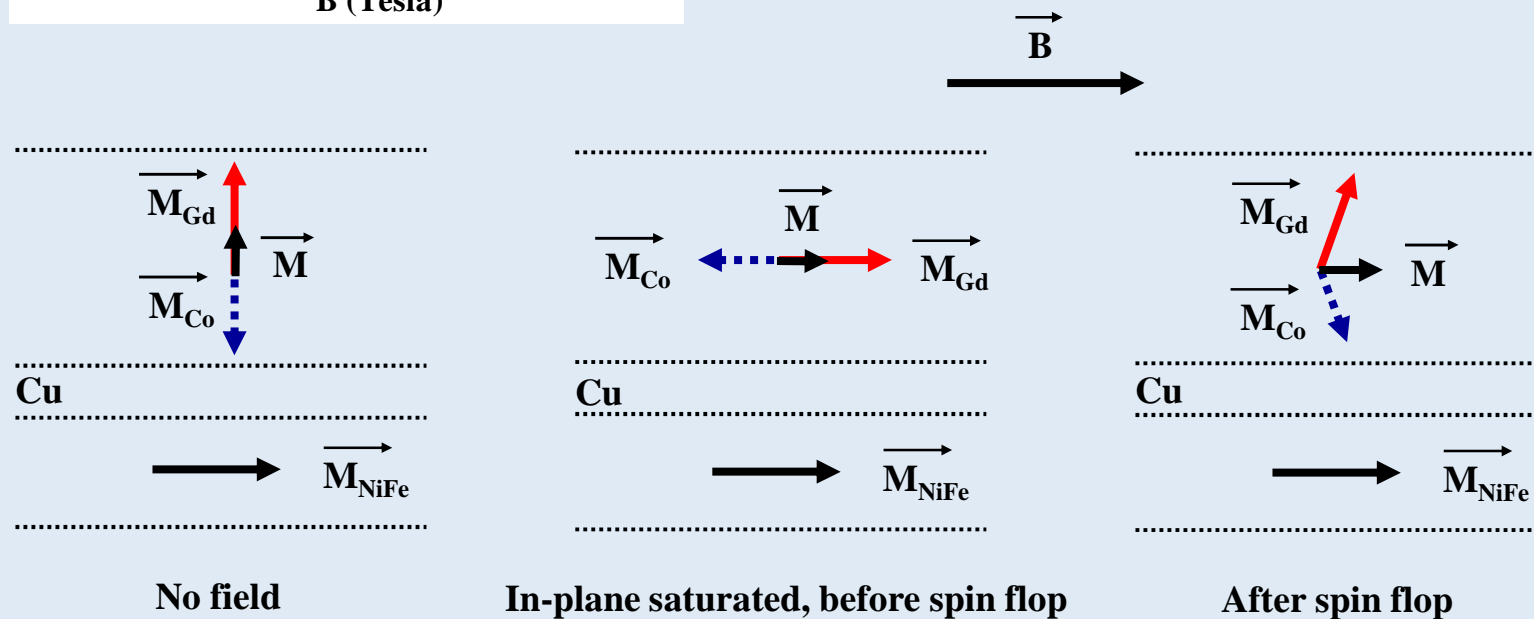
The sign of GMR reverses at
 $T_{\text{comp}} = 210 \text{ K}$ (specified by
EHE measurement)



The high field behaviour of GMR:



GMR does not depend on the angle (M_{Py} , M_{GdCo}) but depend on angles (M_{Py} , M_{Co}) and (M_{Py} , M_{Gd})



Summary

- + **New configuration of GMR: \perp layer (GdCo) - // layer (Py).**
- + **Low temperature: $\text{GMR} < 0$, Gd dominates.**
 - \Rightarrow **GdCo spin polarisation is the same as Co sublattice.**
- + **The impact of spin-flop of GdCo layer on GMR has been studied for the first time:**
 - \Rightarrow **GMR does not depend on the angle (M_{GdCo} , M_{Py}) but depend on the angles (M_{Co} , M_{Py}) and/or (M_{Gd} , M_{Py})**

Conclusion /Perspectives

- 1. GdCo is really an interesting model for micromagnetism and for spintronics.**
- 2. New micromagnetic object : the compensation wall. \Rightarrow Will be applied to study Spin Torque.**
- 3. Insight on the microscopic mechanism for EHE in a ferrimagnet**
- 4. Detail study of spin flop near $M=0$ has been done**
- 5. The important role of scattering centers located at Fe/Cr interfaces has been discovered**
- 6. New GMR structure: Perpendicular anisotropy + Sign reversal of GMR.**

I greatly appreciate :

Louis Néel Laboratoire (CNRS).

Cryogenic Laboratory (VNUH).

Nanofab (CNRS).

Center of Material Science (VNUH).

David Barral and Philippe David: *Thin film deposition.*

Richard Haettel: *Targets fabrication.*

Annick Liénard: *AFM, EDX measurements.*

Helge Haas: *Dektak, Lithography, Etching experiments.*

Didier Dufeu: *VSM measurements.*