The European Magnetism Association

2025 European School on Magnetism

Surface and Interface Magnetism:

An Introduction for thin-films and multilayers

Del Atkinson

Department of Physics

Durham University, UK

www.durham.ac.uk/cmp

Surface and Interface Magnetism: An Introduction

Learning Objectives

To introduce some relevant physics related to functional behaviour of surface and interfacial effects in magnetic thin-films and multilayers

Outline of physical principles and examples

- The emergence of magnetism with thickness
- Surface effects on magnetism
- Interfacial effects on magnetic & spin-transport phenomena

Common theme: The importance of physical structure!

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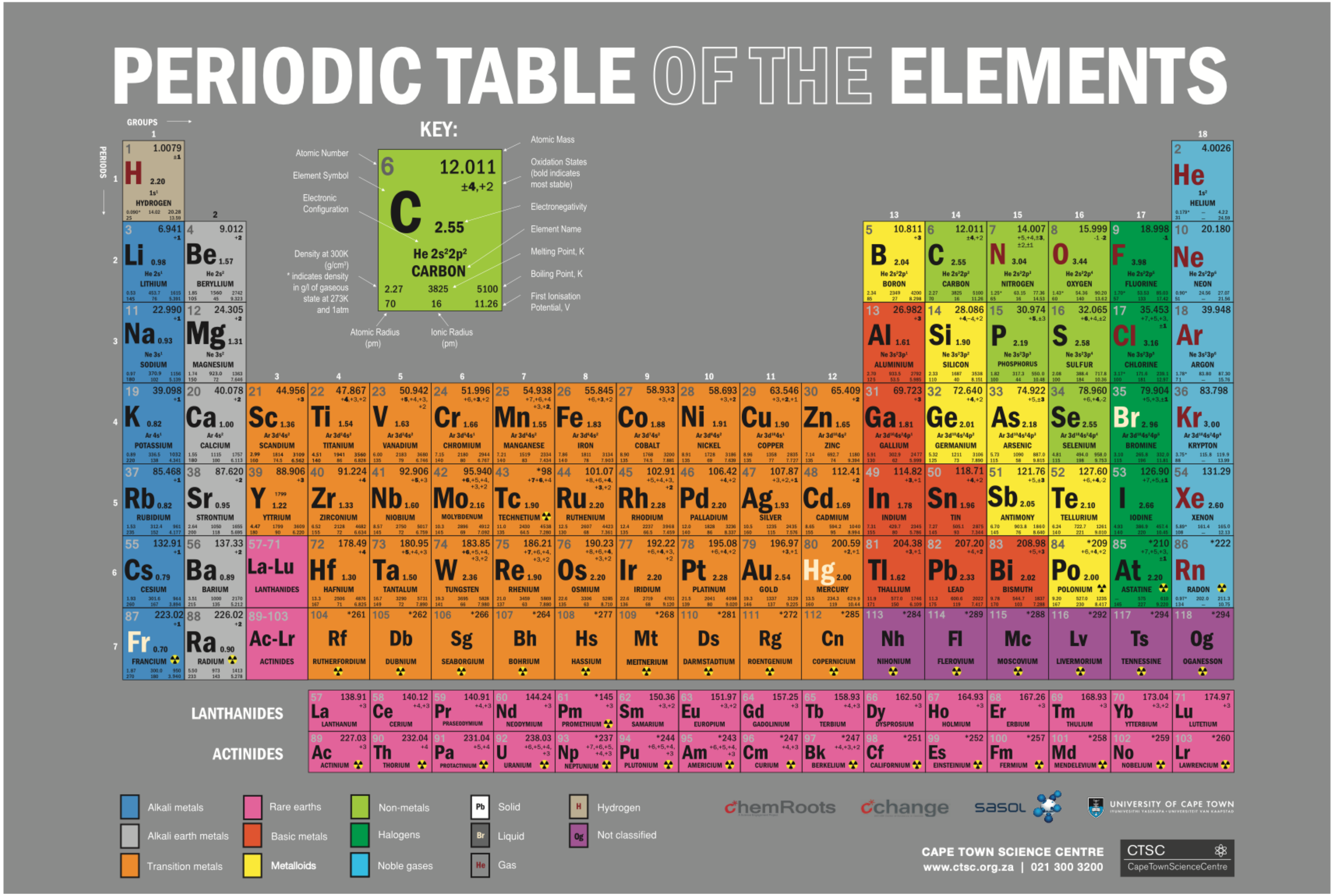
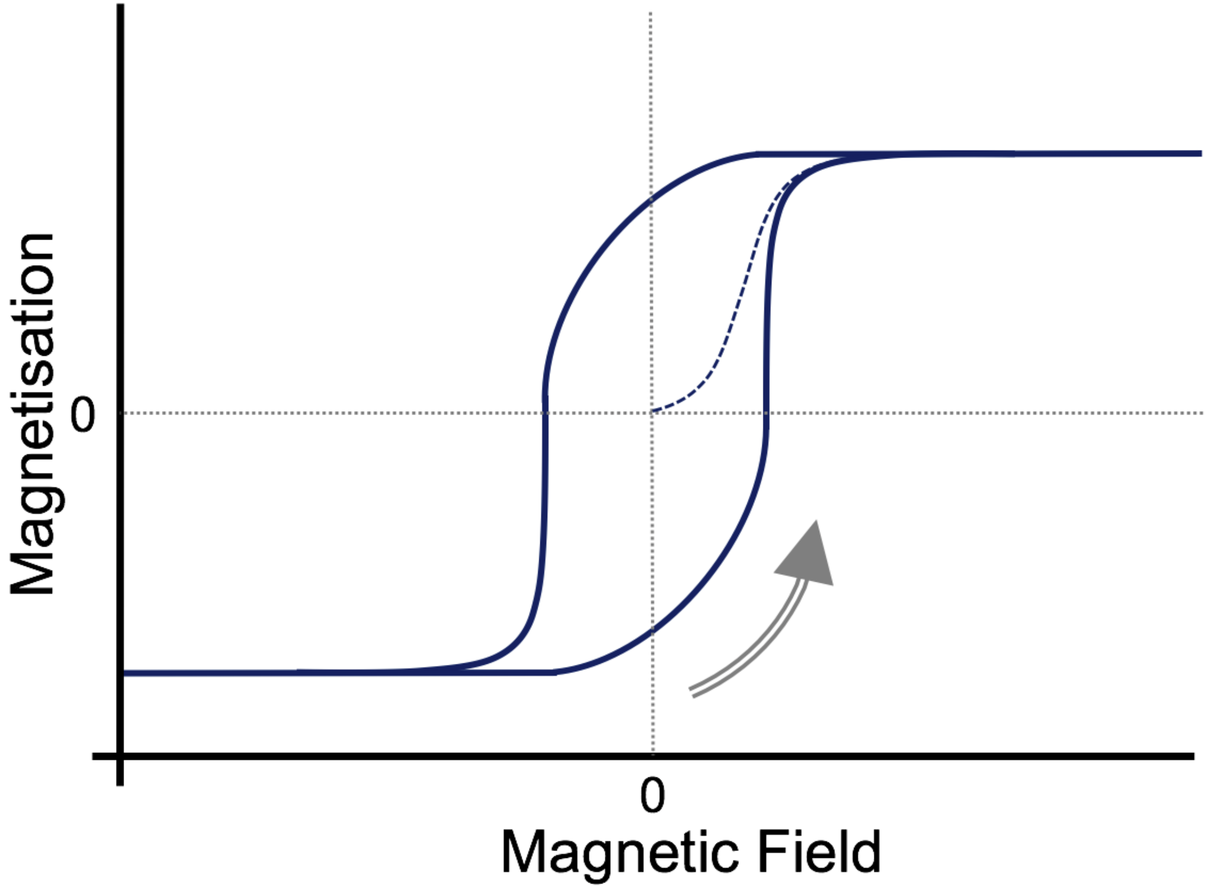
Surface and Interface Magnetism: An Introduction

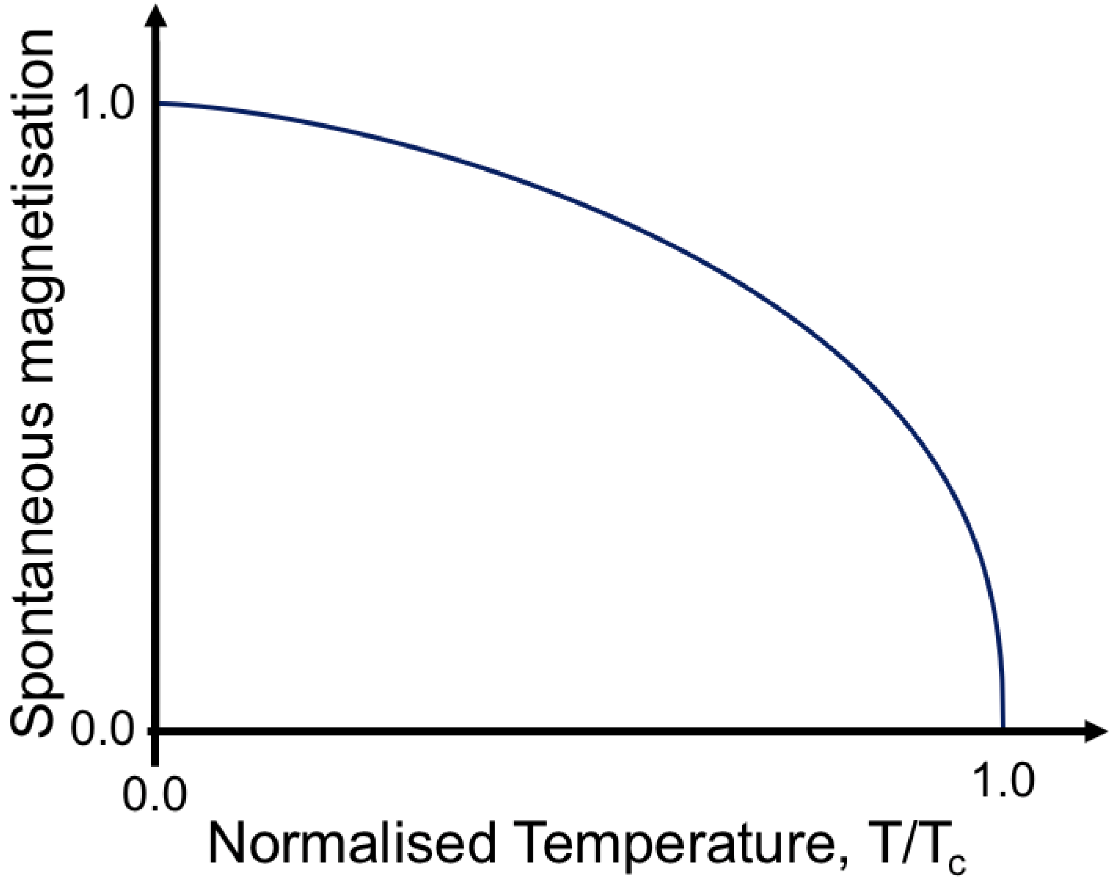


Introduction to some critical magnetic phenomena and parameters

Susceptibility $\chi = M/H$

$$\frac{M(T)}{M(0)} \propto (T - T_c)^{\beta}$$





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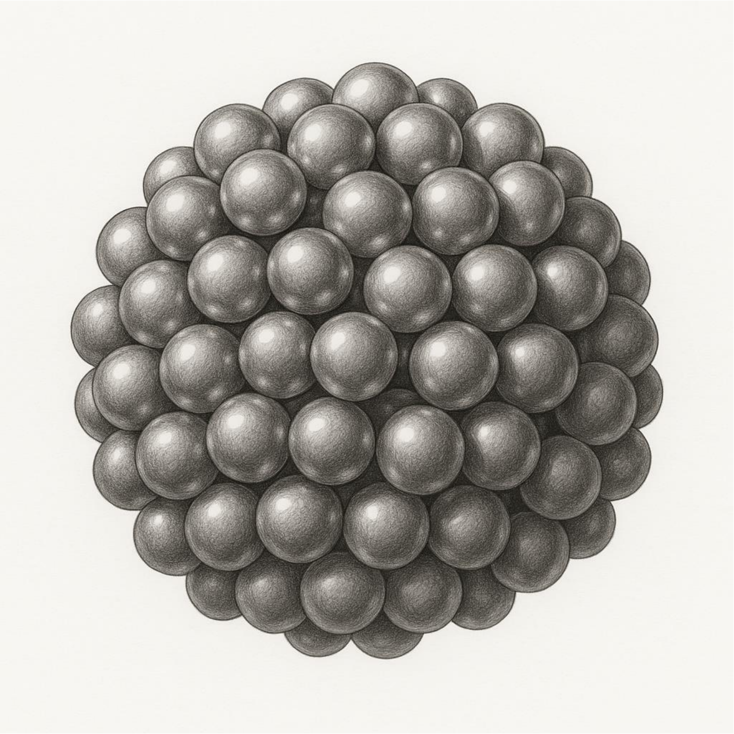
Magnetization on the nanoscale - Magnetic nanoclusters

25 atoms

100 atoms



400 atoms

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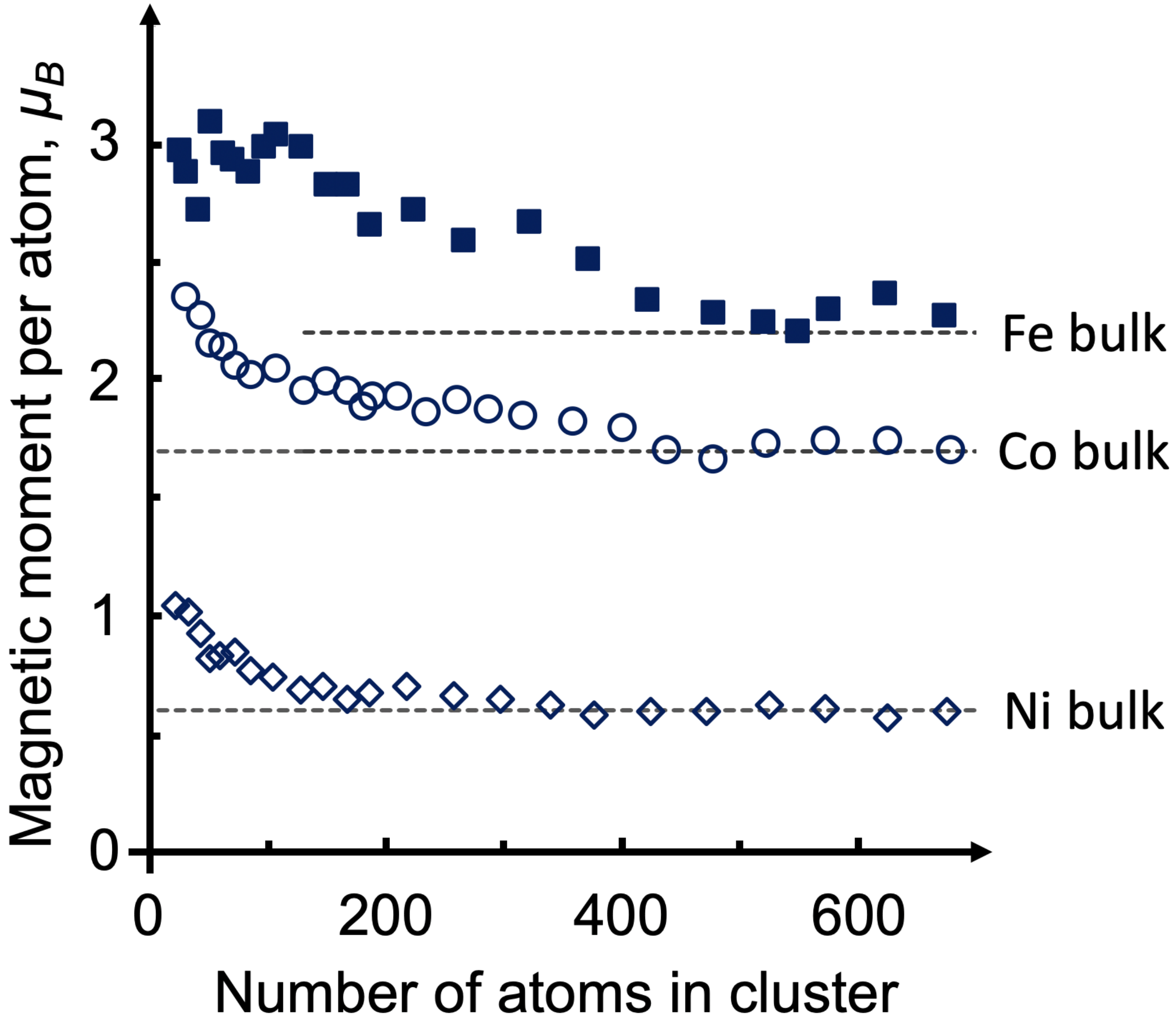
Magnetization on the nanoscale - Magnetic nanoclusters



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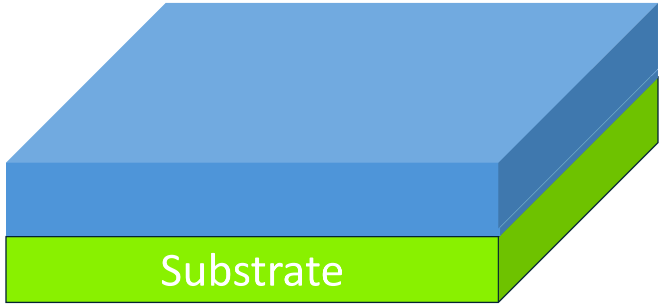
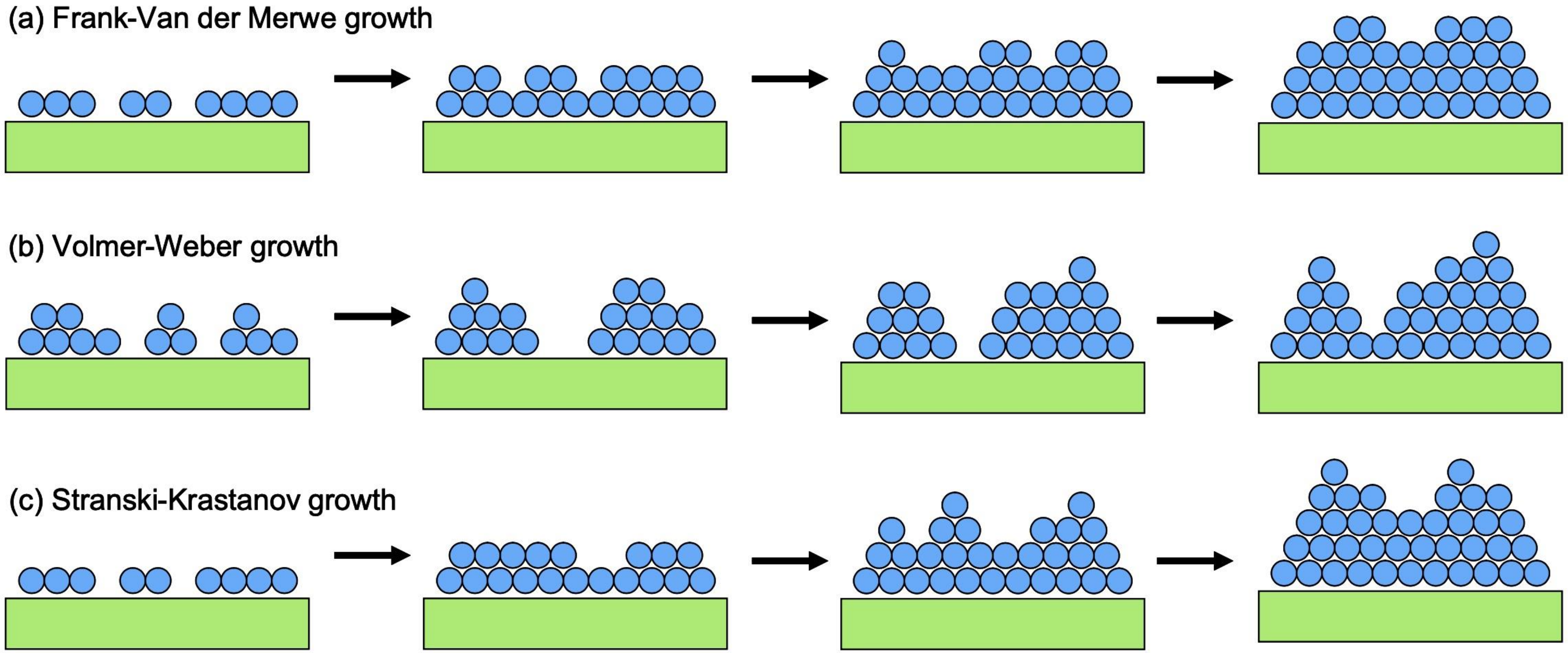
IML Billas, A Chatelain, WA de Heer. ***Science***, 1994

Magnetization on the nanoscale - Thin-film geometry and growth

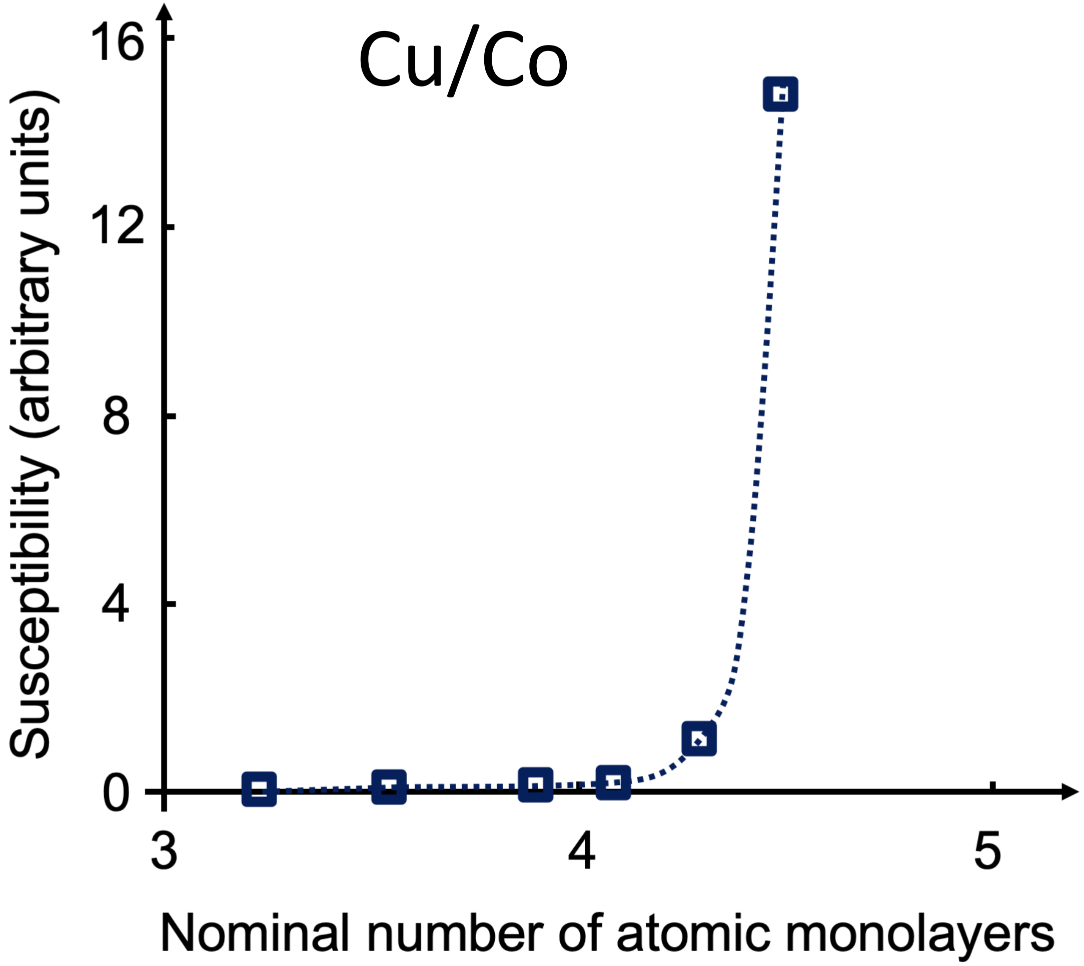




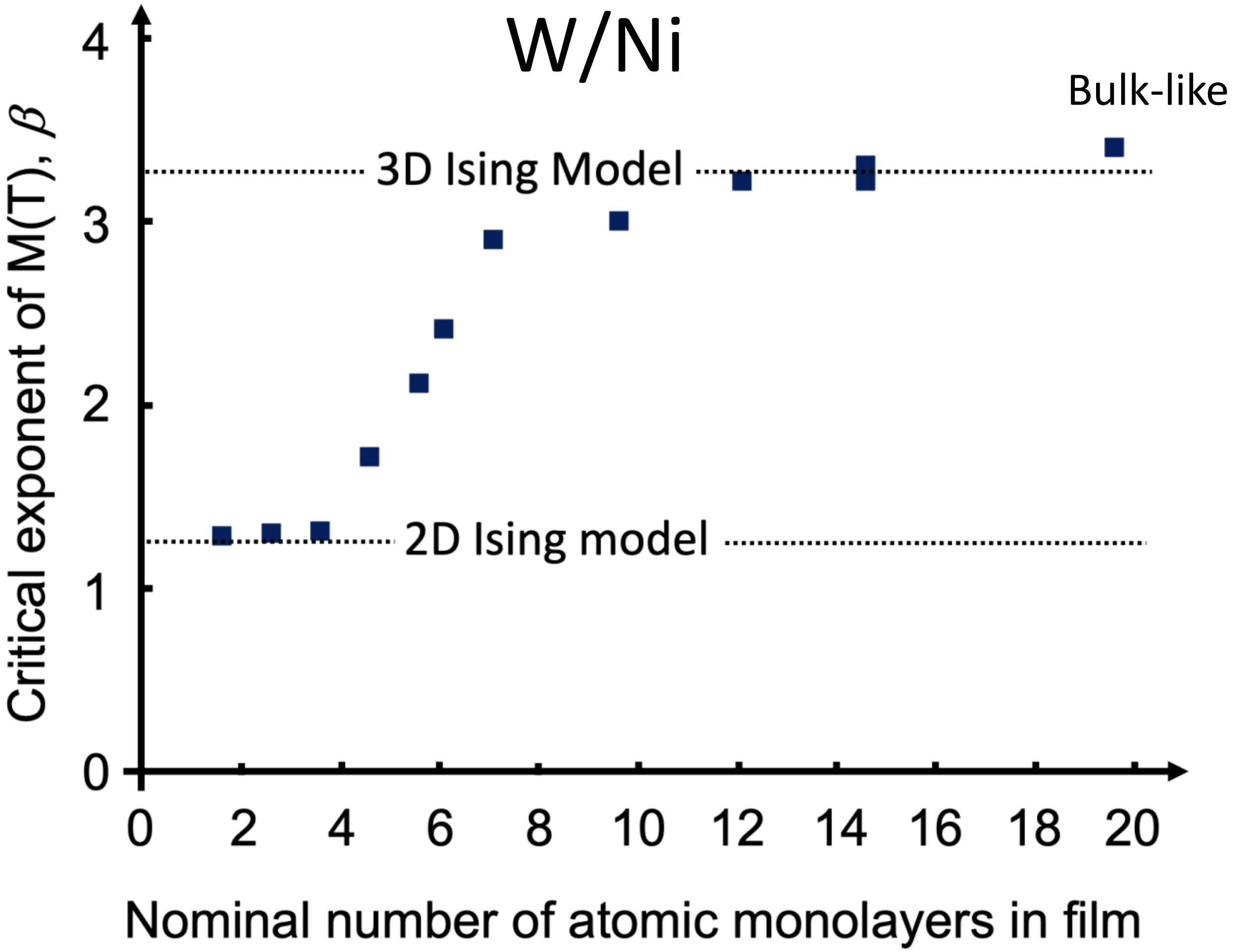
Growth mechanism depends on relative strength between adatom-adatom and adatom-surface binding energies

D Burn ethesis, Durham University 2013

Magnetization on the nanoscale - The onset of magnetism in thin-films



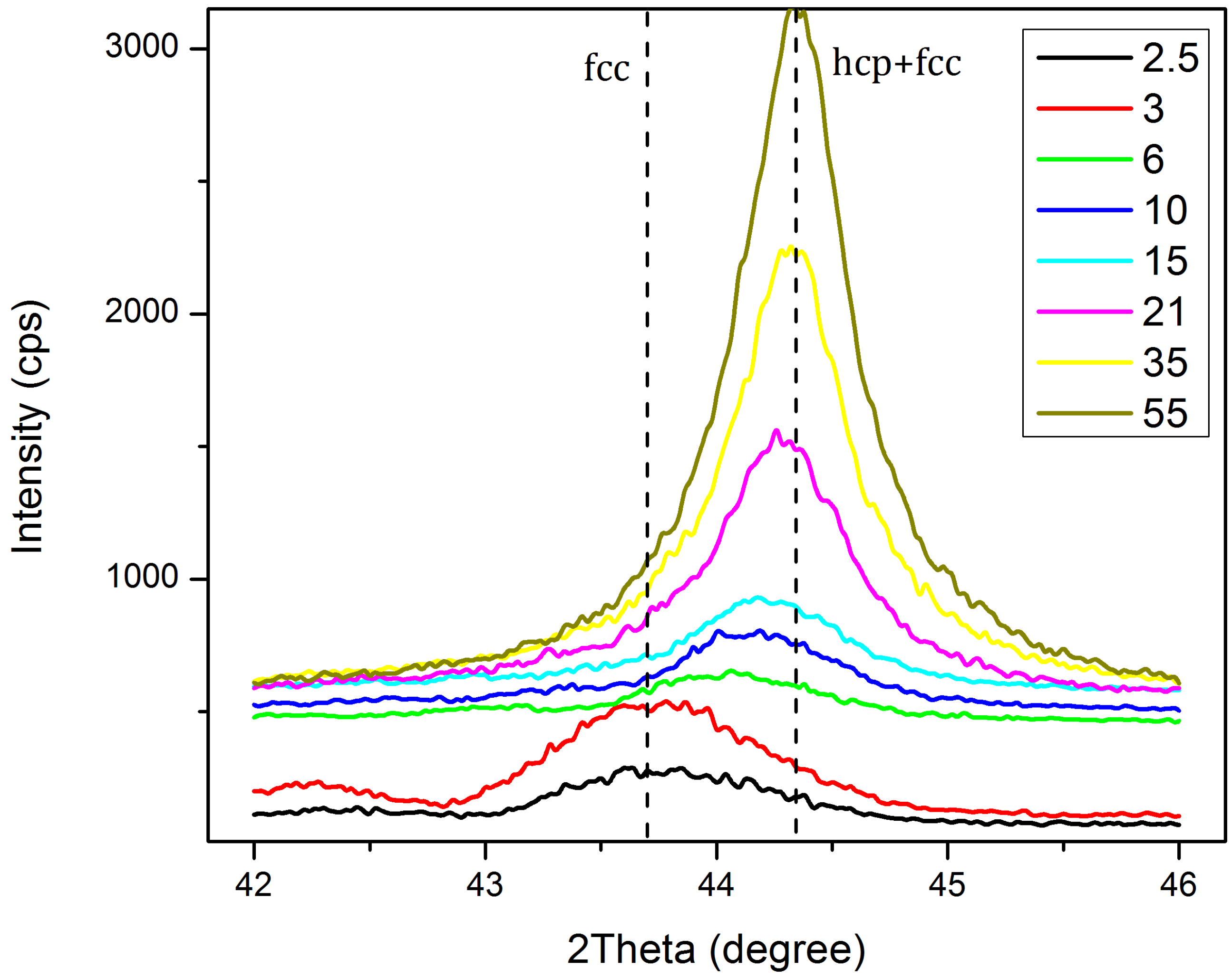
S. Hope et al. J. Appl. Phys. 85 (1999)



Li and Baberschke 1992 PRL

Magnetization on the nanoscale – Thickness dependent crystal structure

Thickness dependence of Co crystal structure



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M. Tokaç *et al.* Phys. Rev. Letts. (2015)

Surface and Interface Magnetism: An Introduction

Topics

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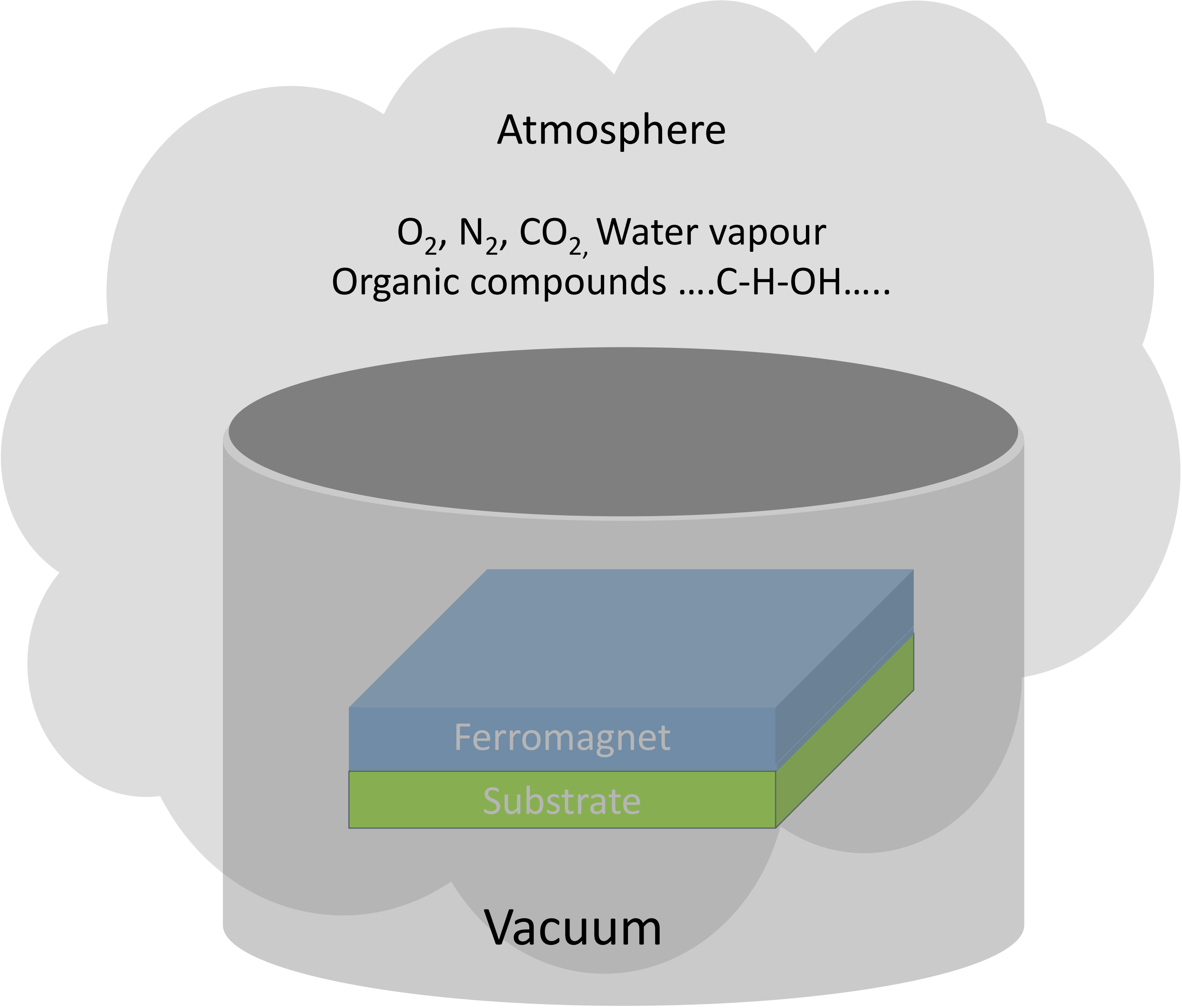
Surface and Interface Magnetism: An Introduction

Topic Surface effects on magnetism

Surface oxidation

Magnetic Dead Layer

Magnetization on the nanoscale – Surface Oxidation



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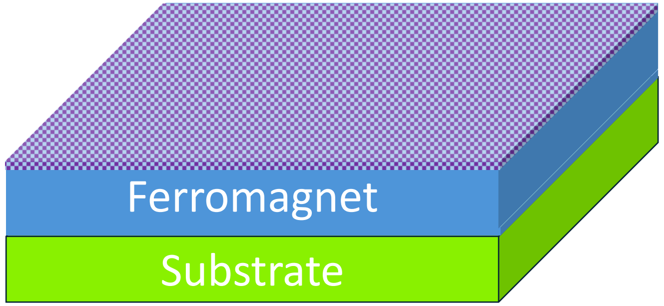
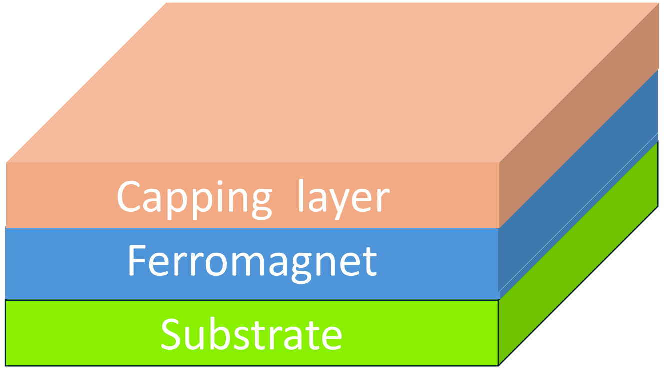
Magnetization on the nanoscale – Surface Oxidation



Magnetization on the nanoscale – Surface Oxidation

Capping layer – choose wisely!



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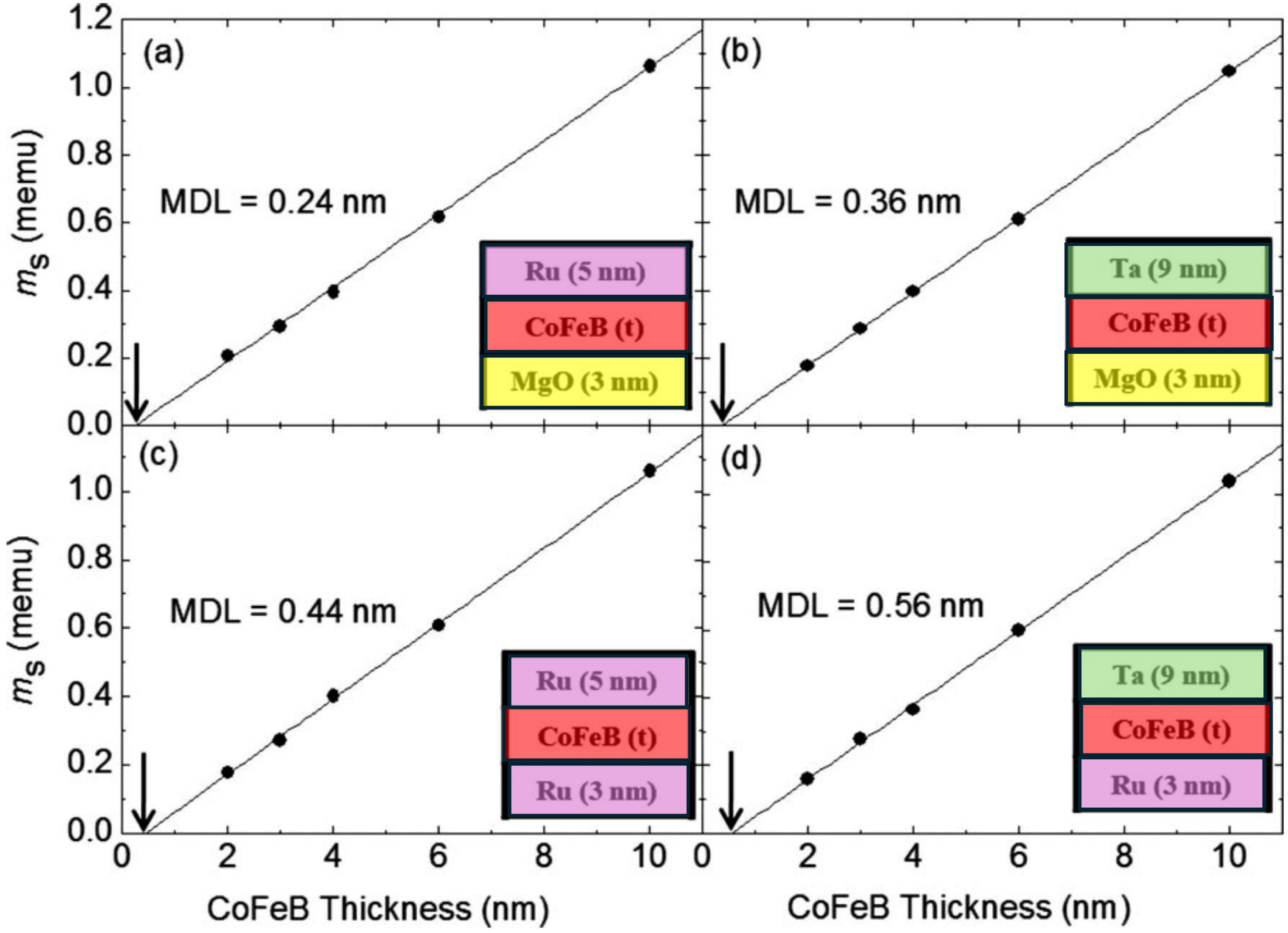
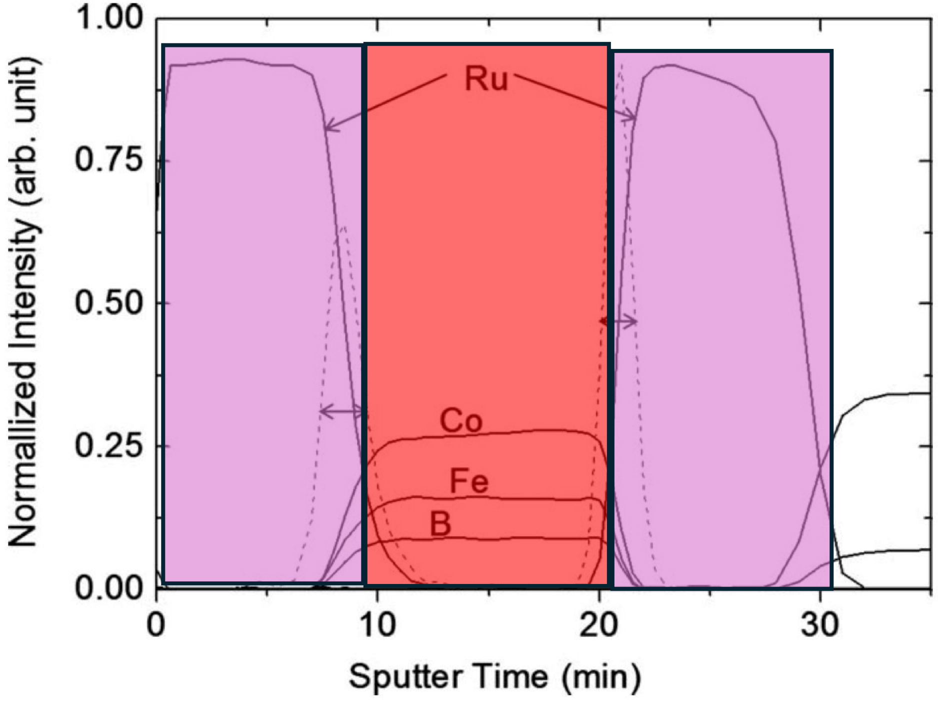
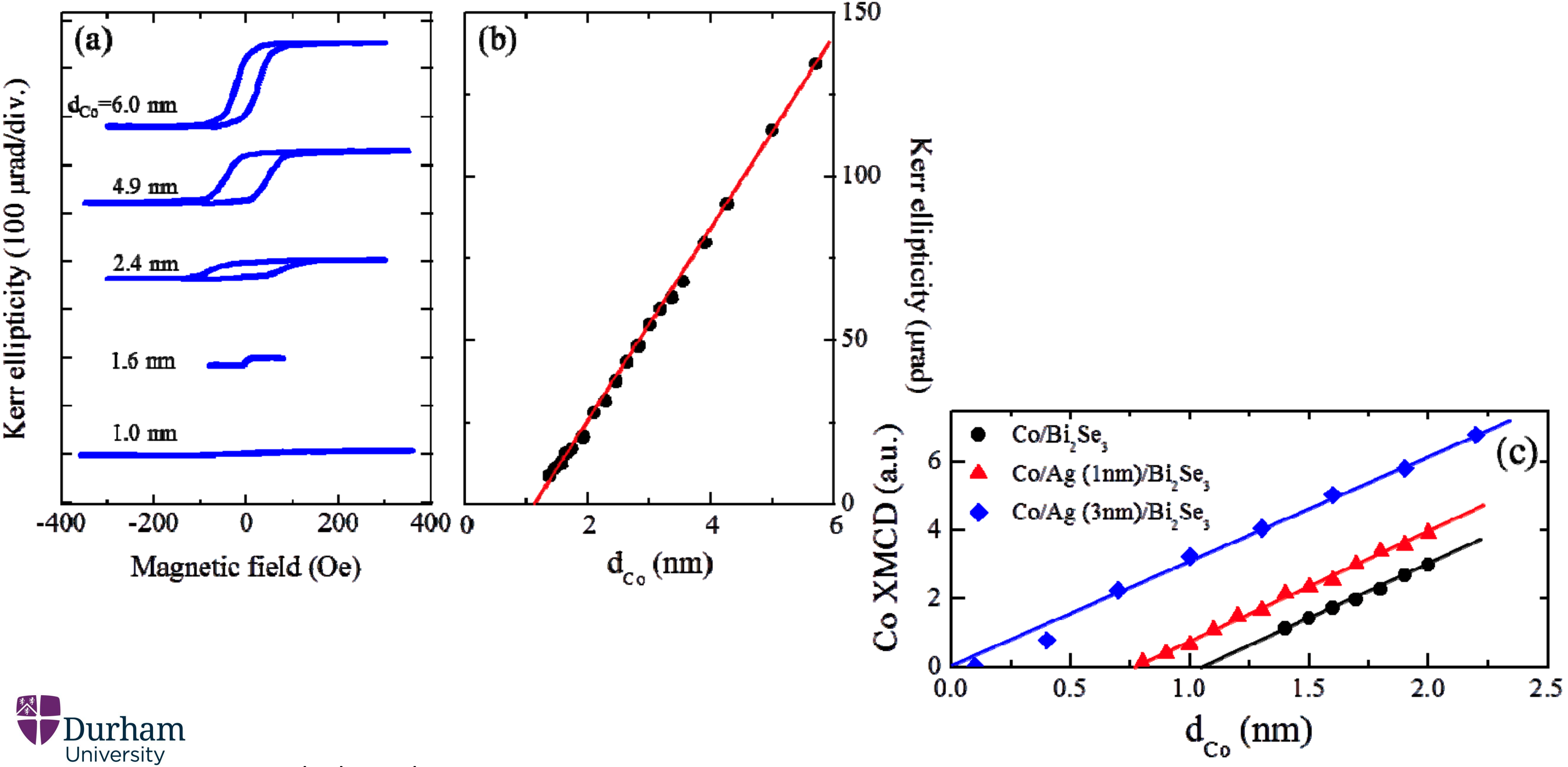
Magnetization on the nanoscale – Magnetic dead layer: CoFeB





SY Jang, SH Lim, SR Lee - Journal of Applied Physics, 2010

Magnetic dead layer Co on topological insulator Bi_2Se_3



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J Li et al. Physical Review B 2012

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Let's begin with some context…

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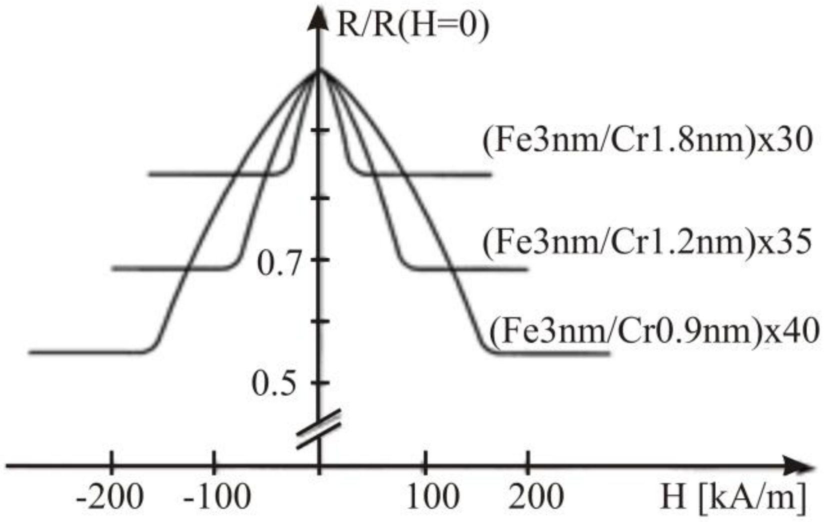
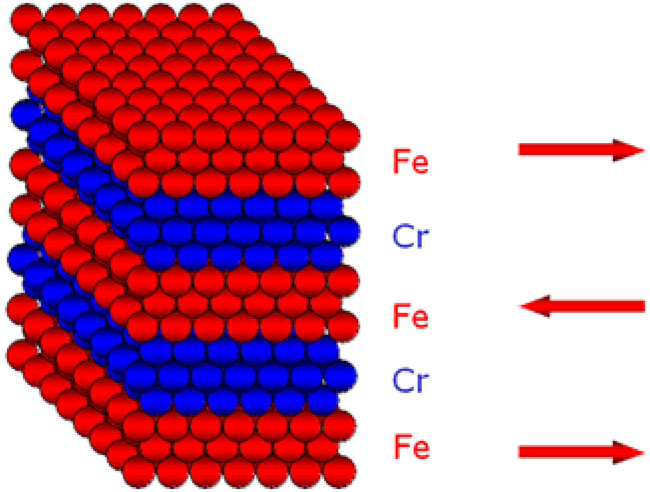
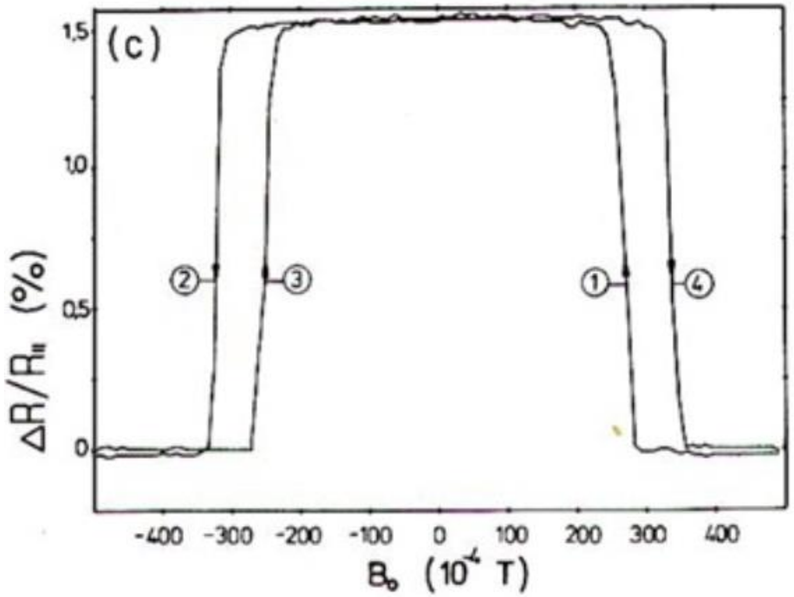
Physics at the Interface… in magnetism → Spintronics

Albert Fert Peter Grünberg







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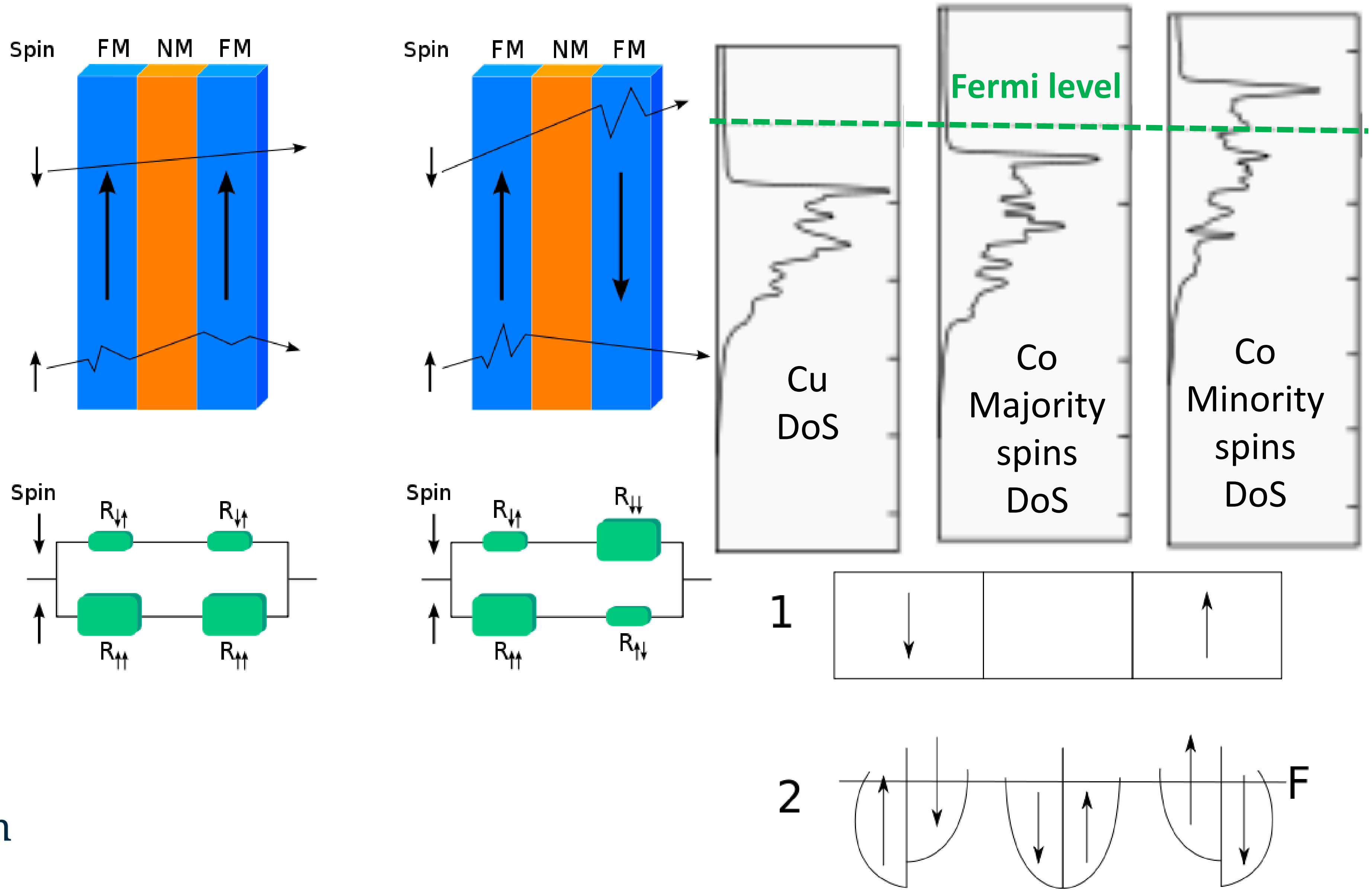
Interface Spintronics - Giant Magnetoresistance GMR



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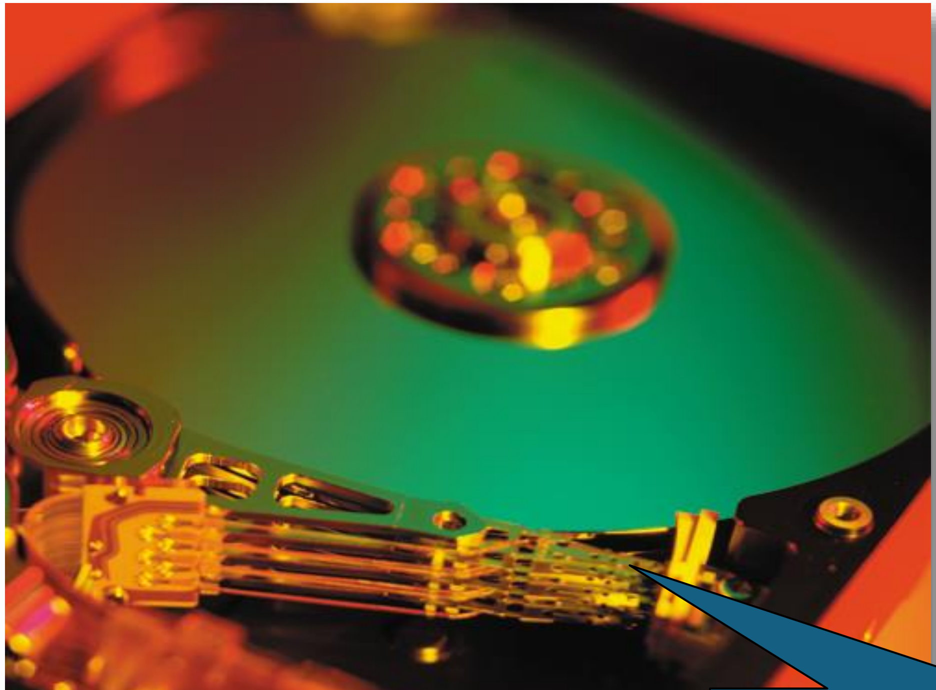
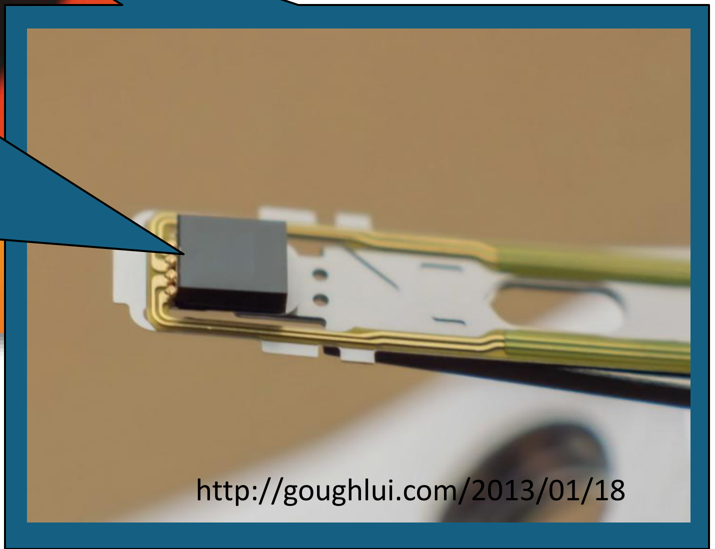
Magnetic HDD – Recording media and recording heads

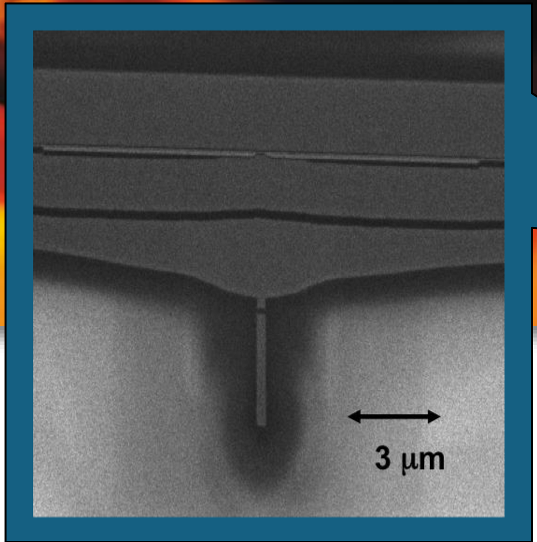


Hard disk drive

Read-write head -



Read-Write head



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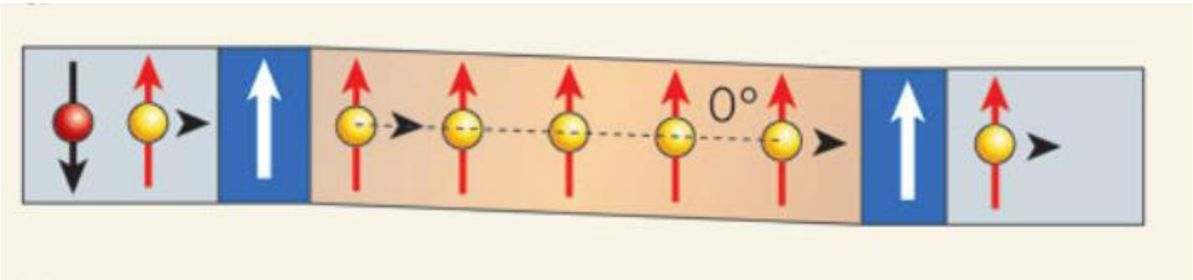
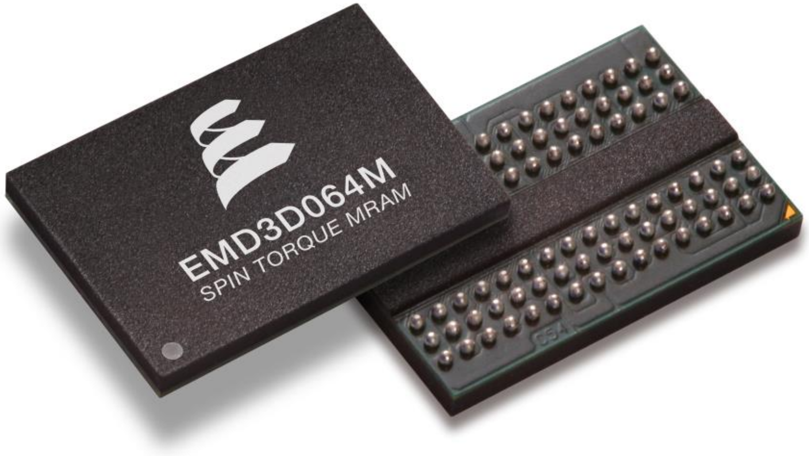
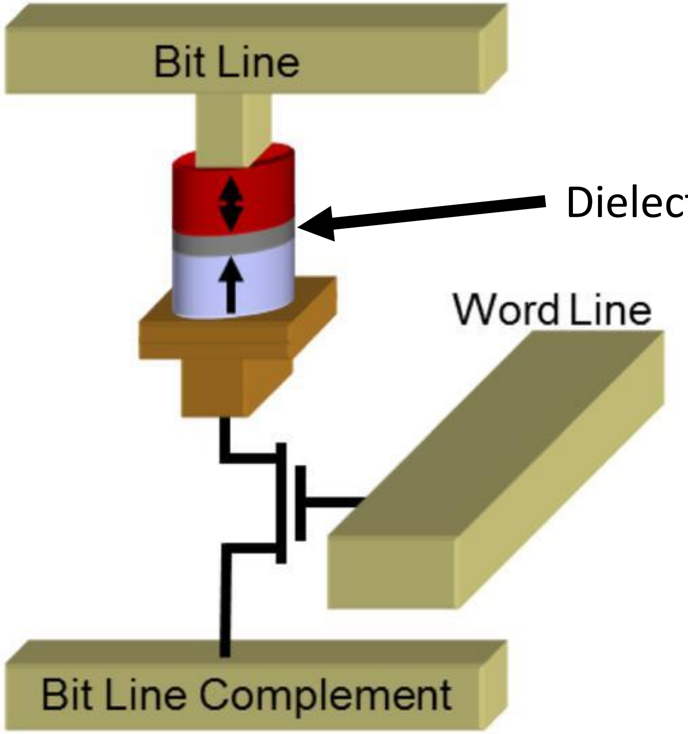
Spintronics – Spin Transfer Torque (STT) switching

John Slonczewski, IBM

Spin-polarised current







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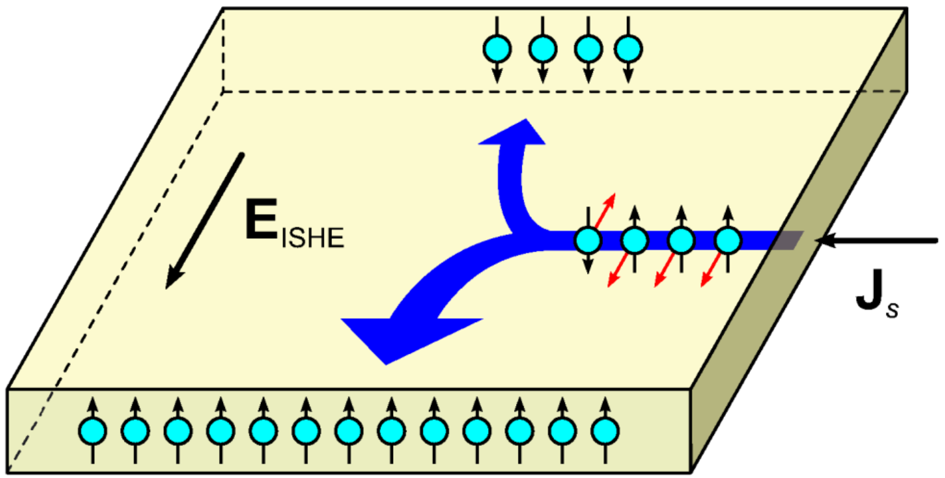
Spin Hall Effect and Spin-Orbit Torques

Spin Hall Effect - SHE

MI D’yakanov and VI Perel



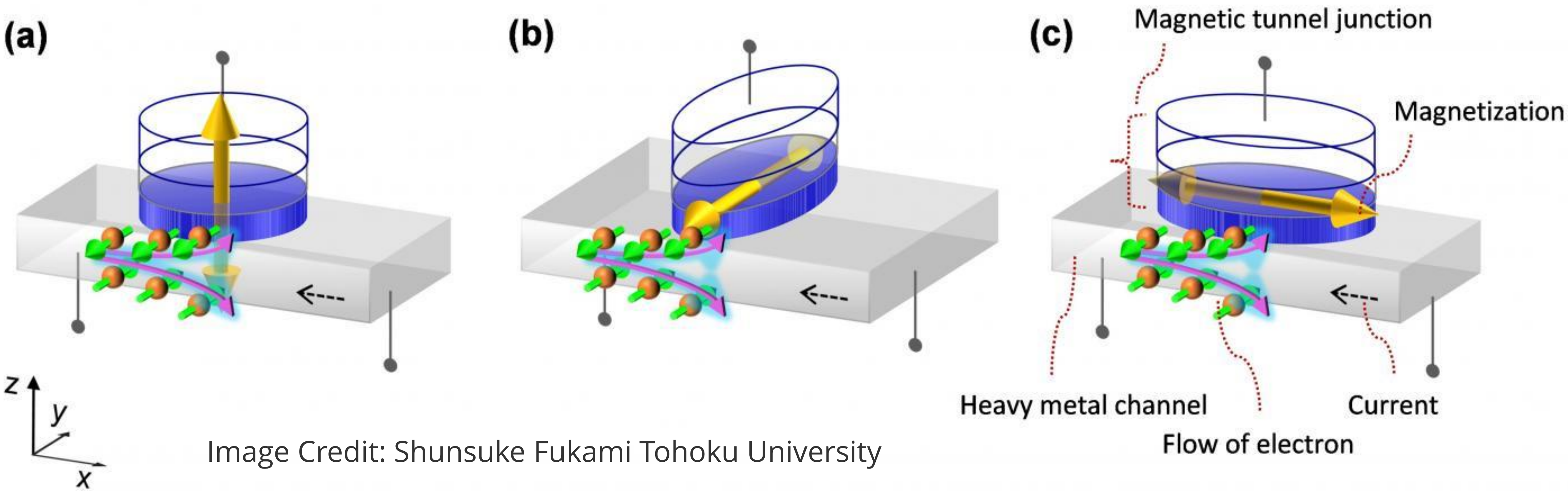
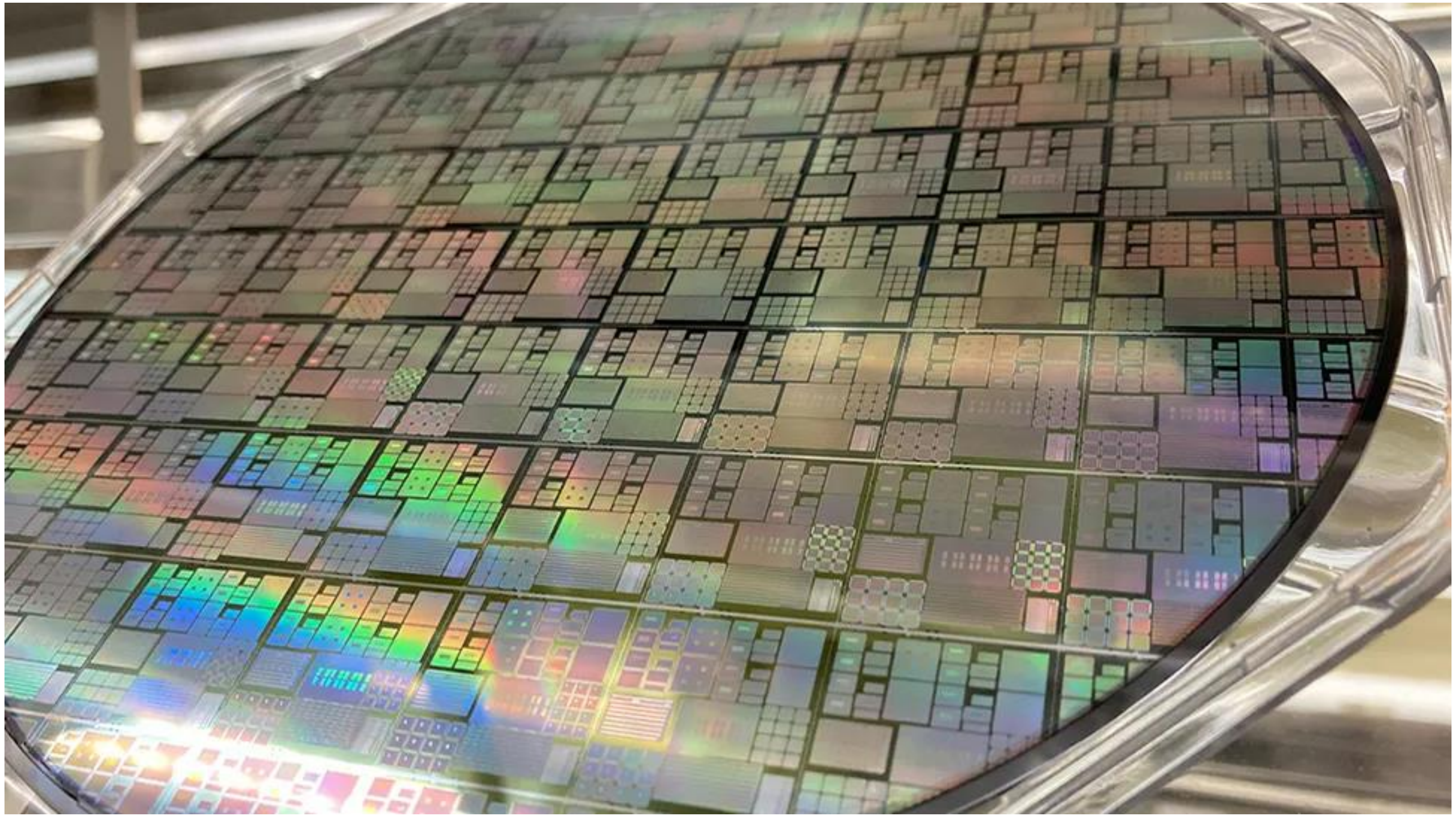


Image Credit: Shunsuke Fukami Tohoku University

Spintronics –Energy Efficient Spin-Orbit Torques – MRAM soon…



(Image credit: ITRI)

Industrial Technology Research Institute (ITRI) and Taiwan Semiconductor Manufacturing Company (TSMC) have announced a SOT-MRAM (spin-orbit torque magnetic random-access memory) array chip

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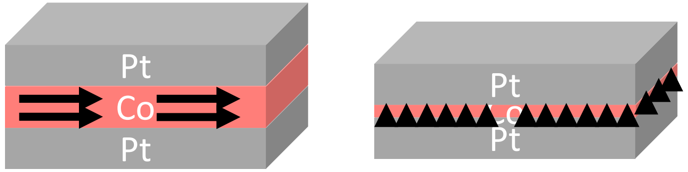
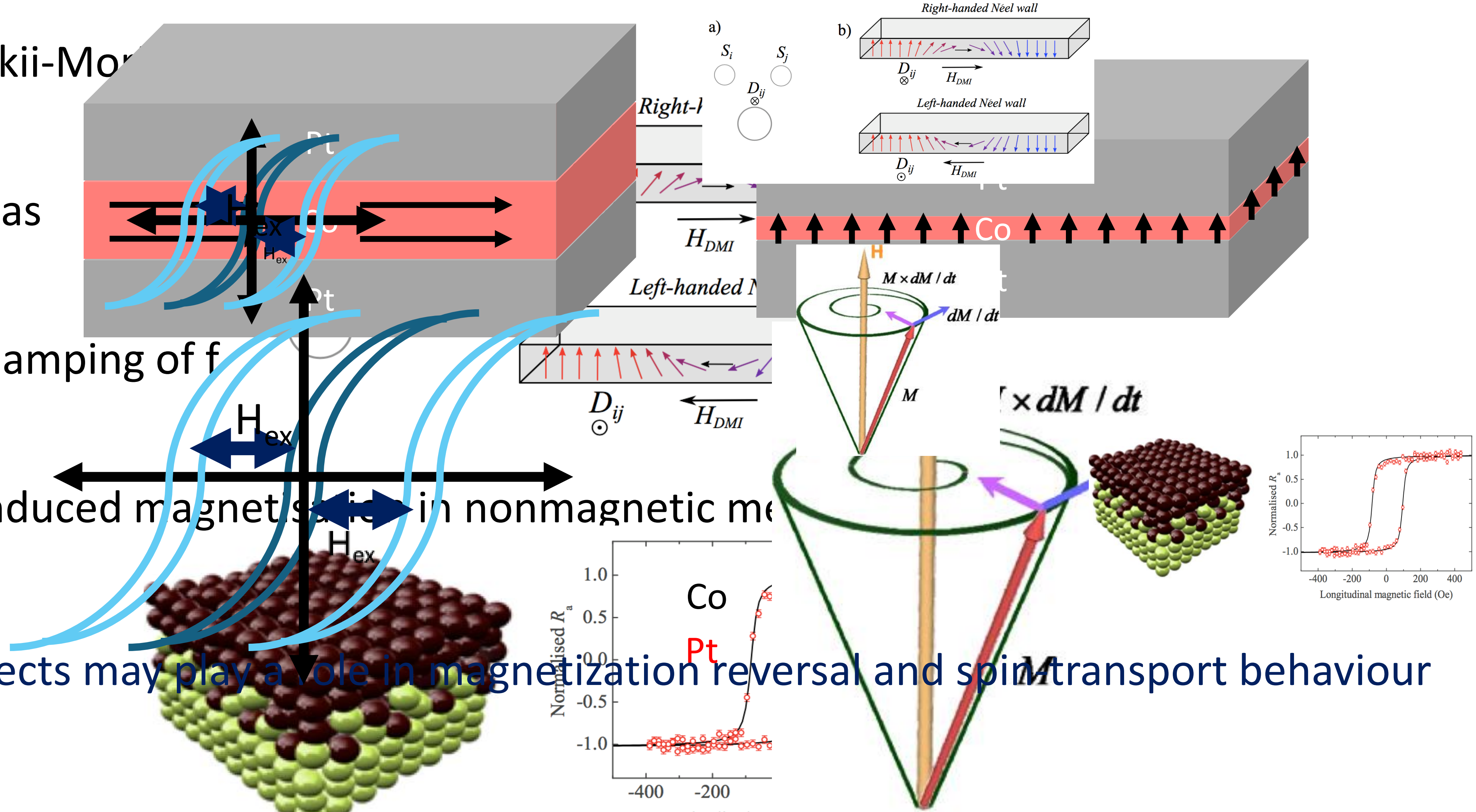
Magnetic phenomena across the Interface

- Perpendicular Magnetic Anisotropy



- Dzyaloshinskii-Mor
- Exchange Bias
- Enhanced Damping of f
- Proximity-induced magnetis in nonmagnetic me



Interfacial effects may play a role in magnetization reversal and spin transport behaviour

Magnetic phenomena across the Interface

Topics

- Thin-film and interfacial anisotropies
- Interfacial Dzyaloshinskii-Moriya Interatcions – iDMI
- Exchange bias
- Interface enhanced Ferromagnetic Damping and Spin Transport – Spin Pumping
- Interfacial Proximity-Induced-Magnetism in Heavy Metals - PIM
- Examples of Interface effects on Magnetization and Spin Transport

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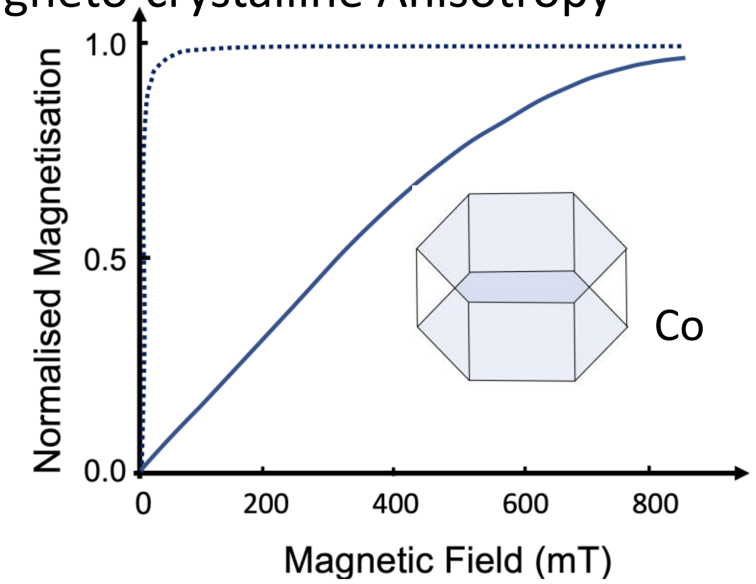
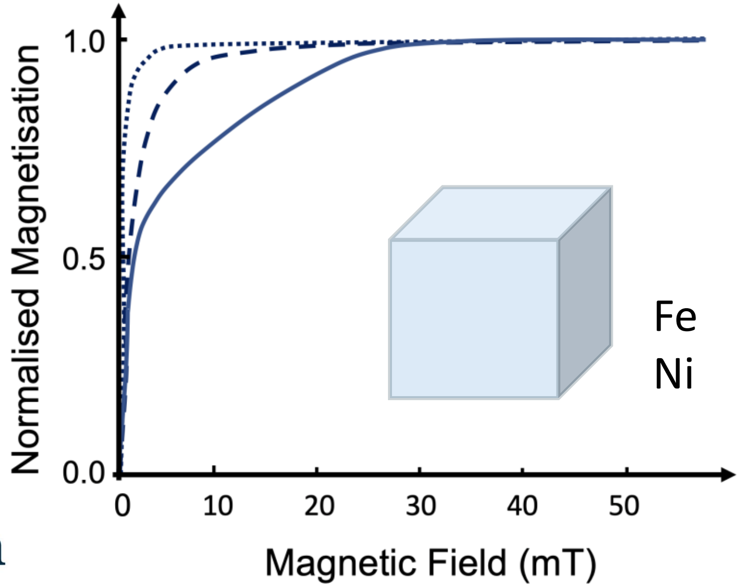
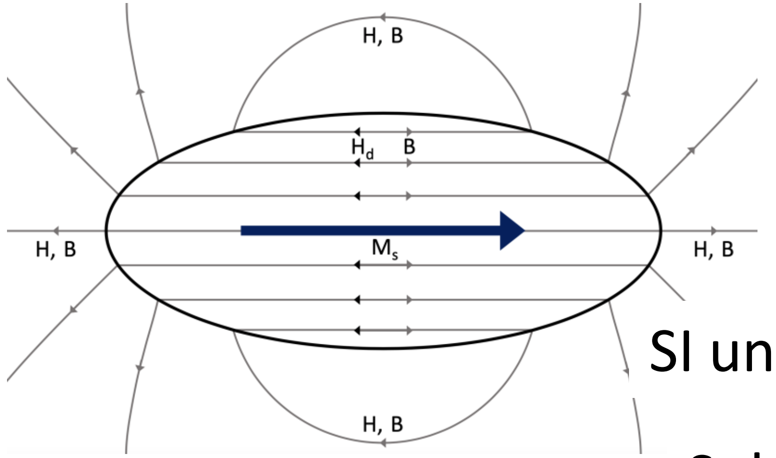
Interfacial Effects in Magnetic Thin-films: Magnetic Anisotropy - Introduction

Magneto-crystalline Anisotropy





Shape Anisotropy

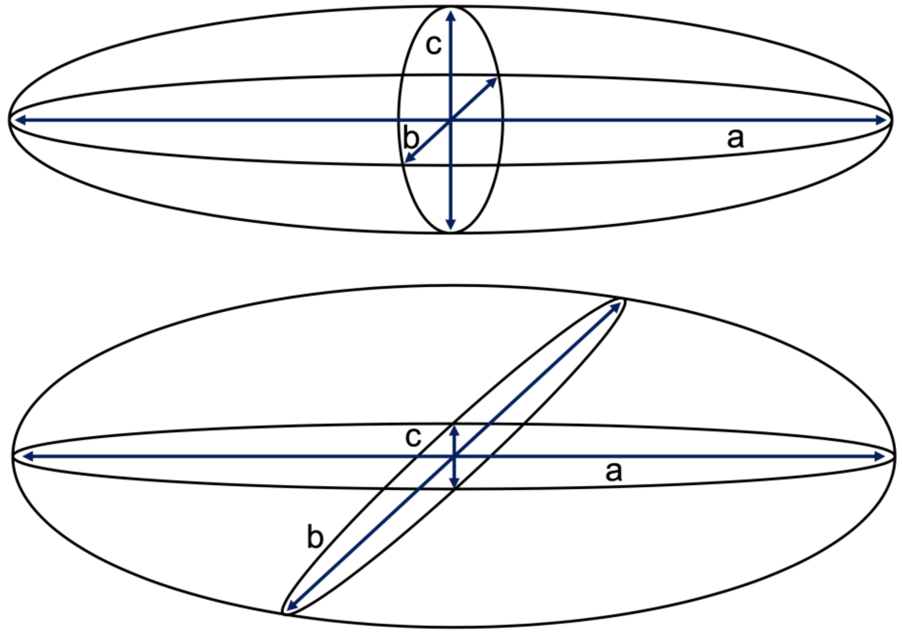


$$H_d = -N_d M$$

N_d is demagnetizing factor

SI units $N_a+N_b+N_c= 1.0$

Sphere $N_a=N_b=N_c= 1/3$



$N_b=N_c$

$N_a<N_{b,c}$

$N_a=N_b$

$Nc>Nb_{a,b}$

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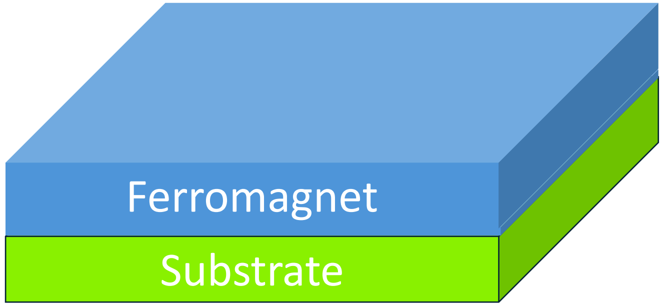
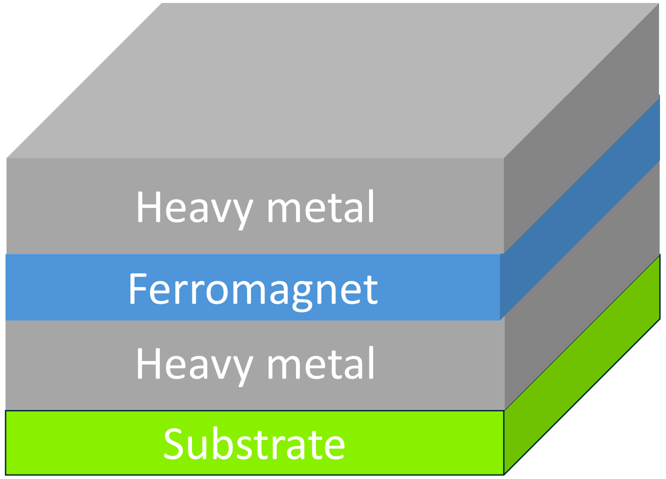
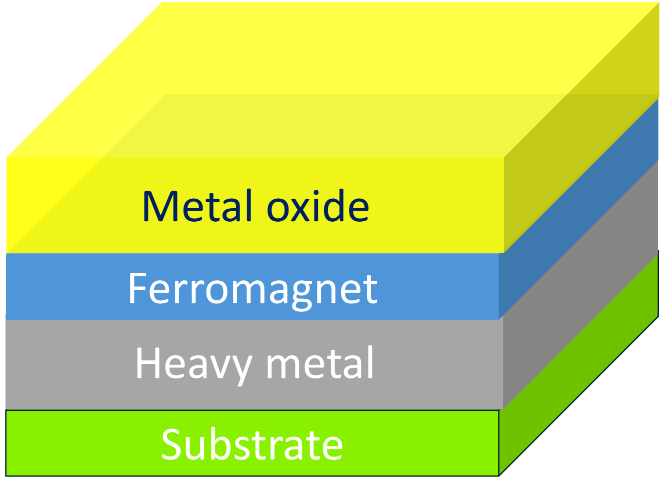
Surface/Interfacial Magnetic Anisotropy: Thickness dependence







Heavy metal
Ru Pd
Ir Pt Au

Ferromagnet
Co

Metal oxide
MgO

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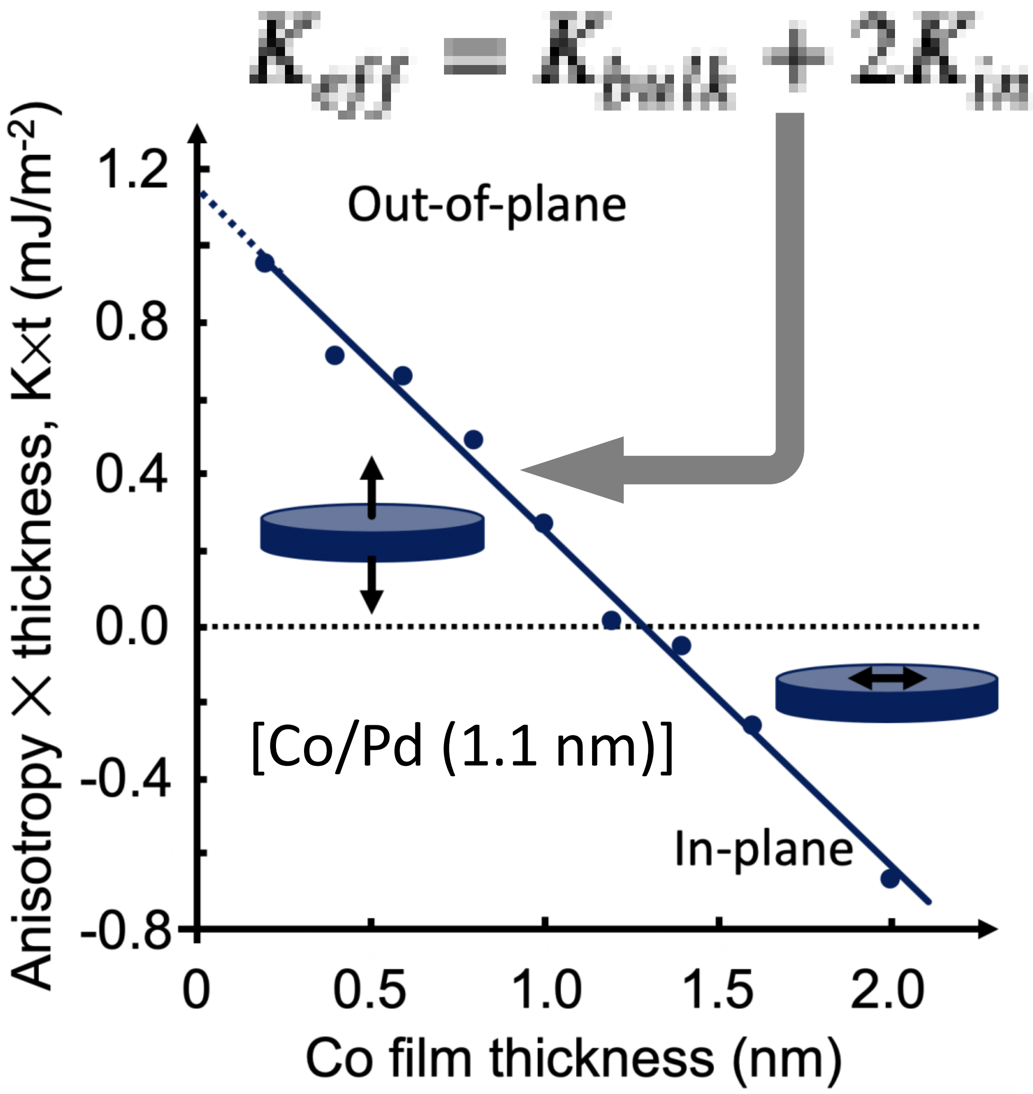
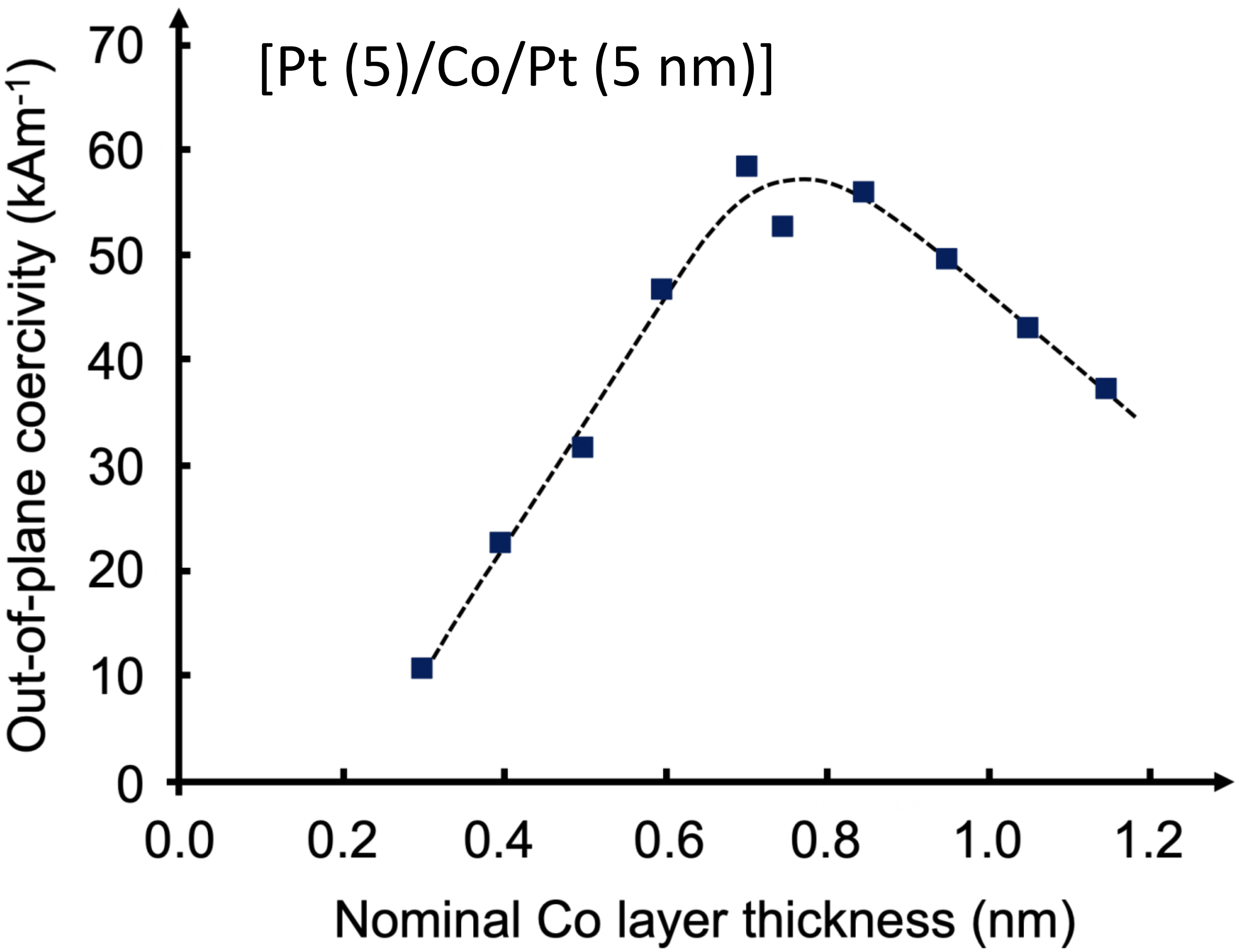
Thin-films: In-plane (IP) and out-of-plane (PMA) Magnetic Anisotropies





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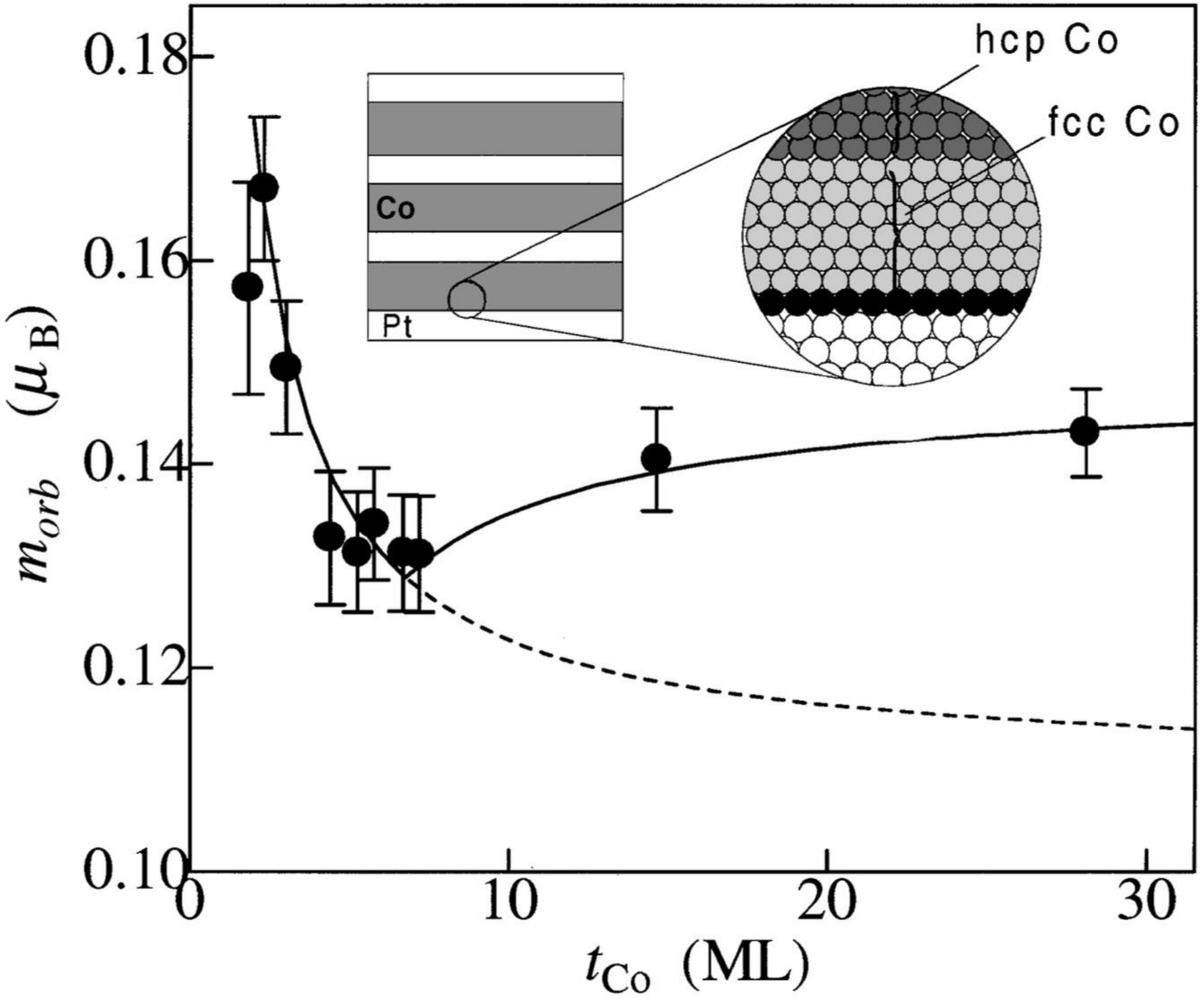
Data -- FJA den Broeder et al. J. Magn. Magn. Mater. 1991.

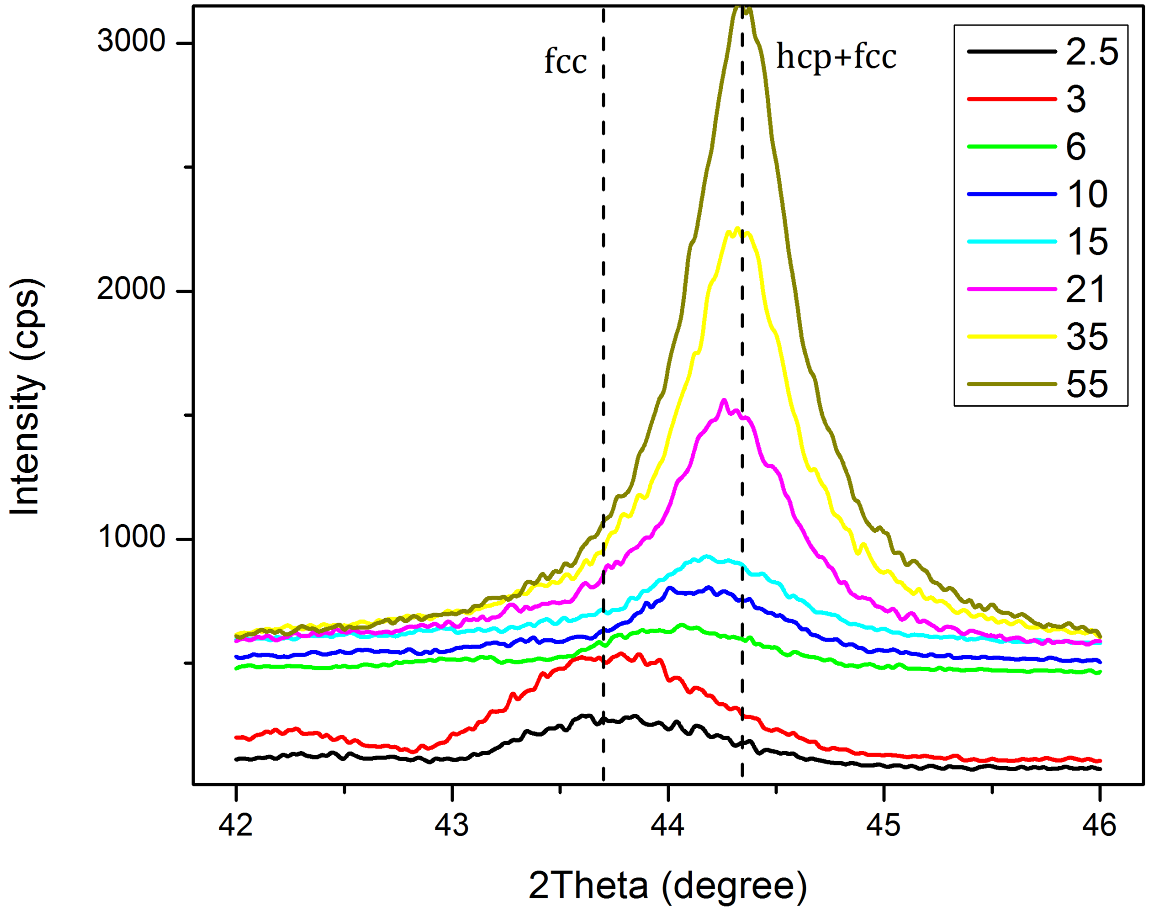
A Bahaaldin ethesis Durham, 2018

Interfacial Perpendicular Magnetic Anisotropy – Origin of PMA



N Nakajima et al . 81, 23 Phys Rev Letts 1998

Thickness dependence of Co crystal structure



M. Tokaç *et al.* Phys. Rev. Letts. (2015)

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Magnetic phenomena across the Interface

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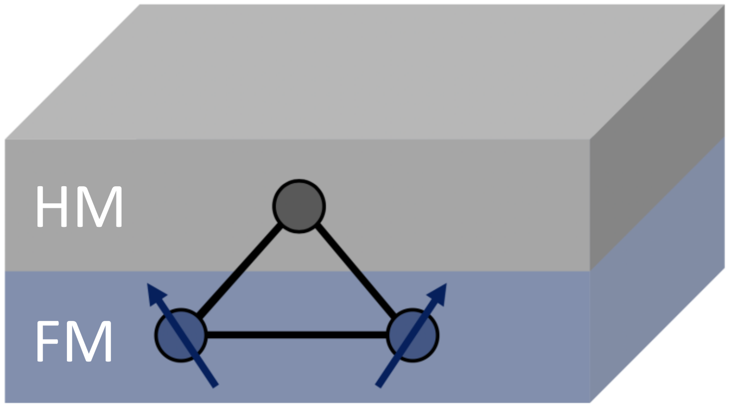
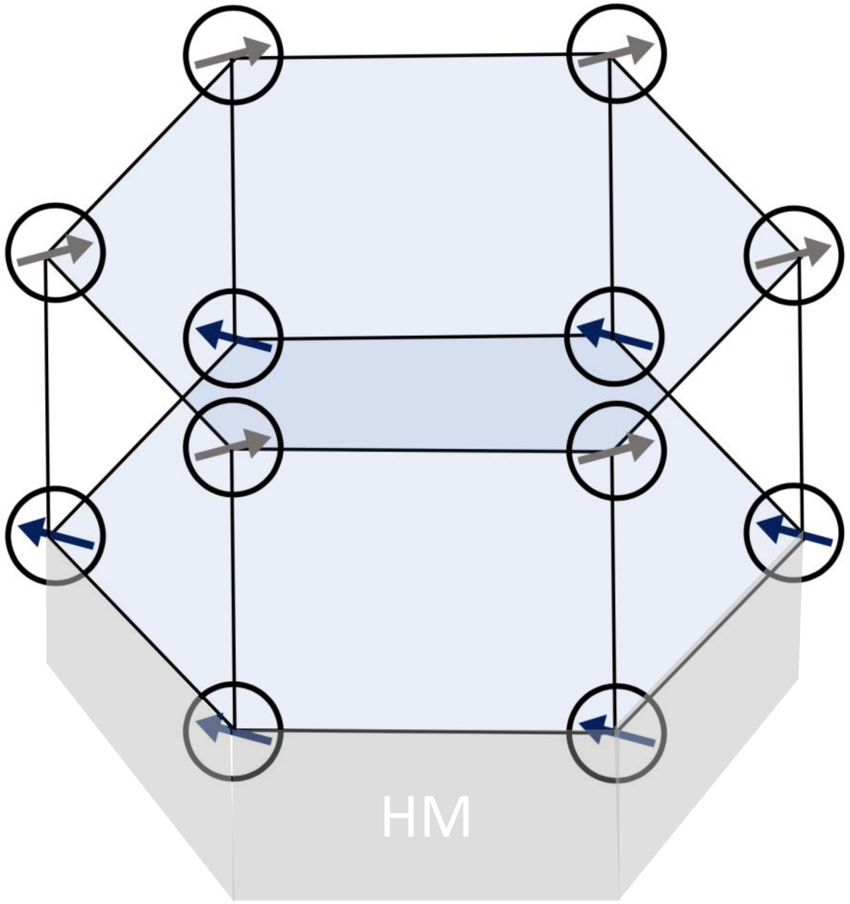
Interfacial Effects in Magnetic Thin-films: Dzyaloshinskii – Moriya Interaction





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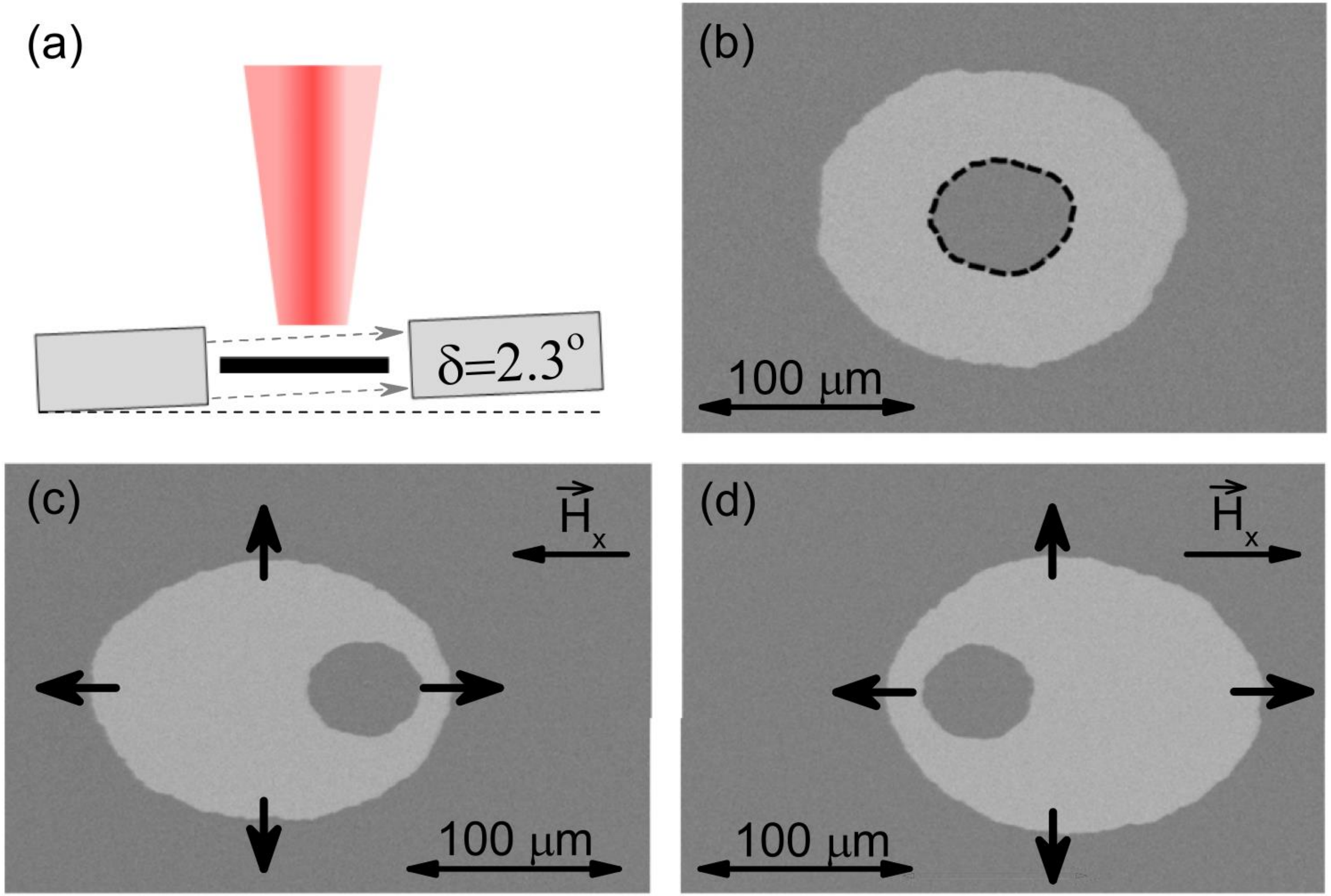
DMI – Measurement: Polar MOKE + In-plane field



Pt/Co/Pt and Pt/Co/Ir/Pt

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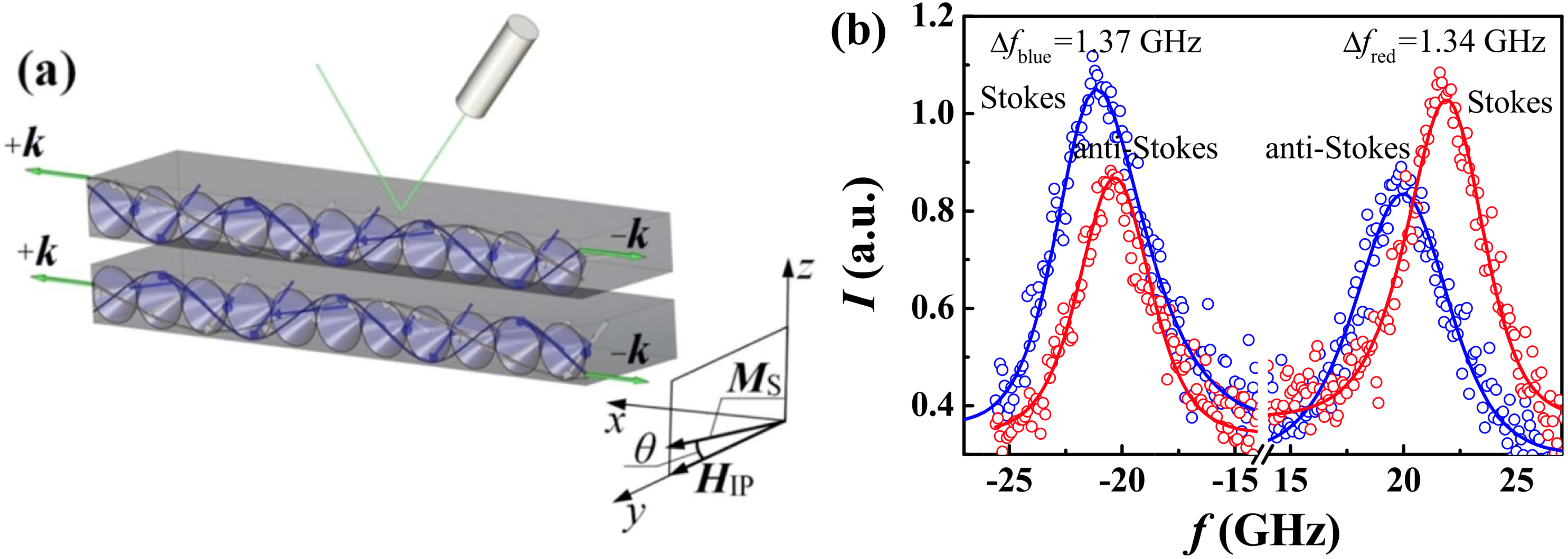
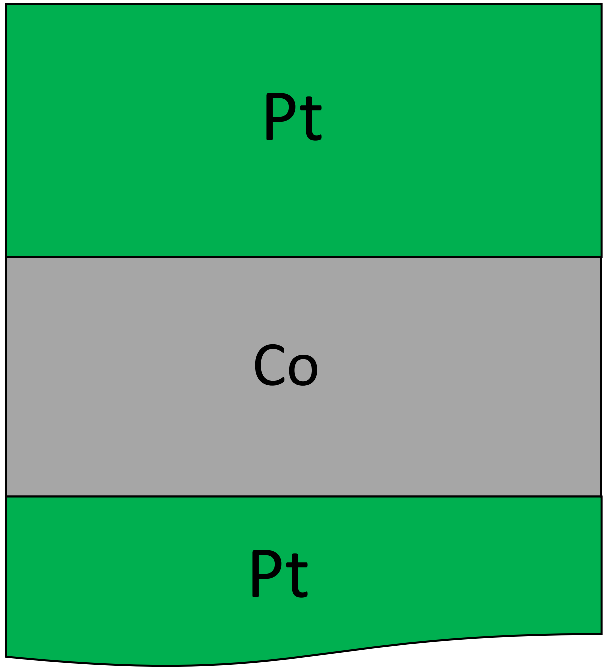
Hrabec *et al*. PHYSICAL REVIEW B 90, 020402(R) (2014)

DMI – Measurement: Brillouin Light Scattering BLS



Oksana Koplak et al. J. Phys.: Condens. Matter 34 085803, 2022

Dzyaloshinskii-Moriya Interaction: Example Pt/Co/sl/Pt



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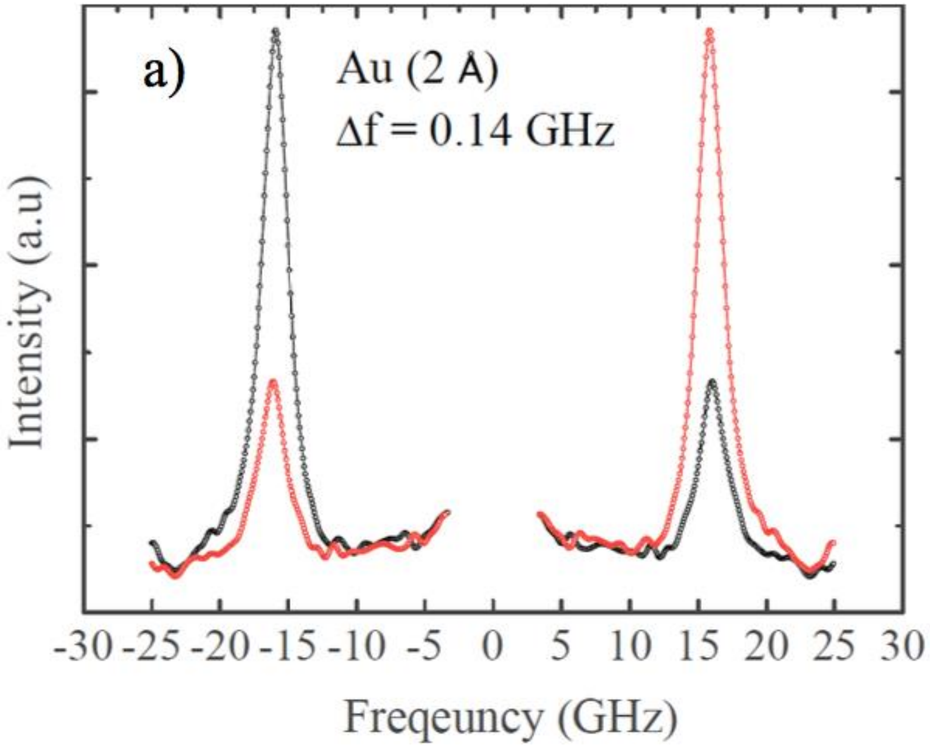
R Rowan-Robinson *et al.* *Scientific Reports* 2017

The interfacial Dzyaloshinskii-Moriya Interaction: Example Pt/Co/sl/Pt

Brillouin Light Scattering – BLS measurements



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R Rowan-Robinson *et al.* *Scientific Reports* 2017

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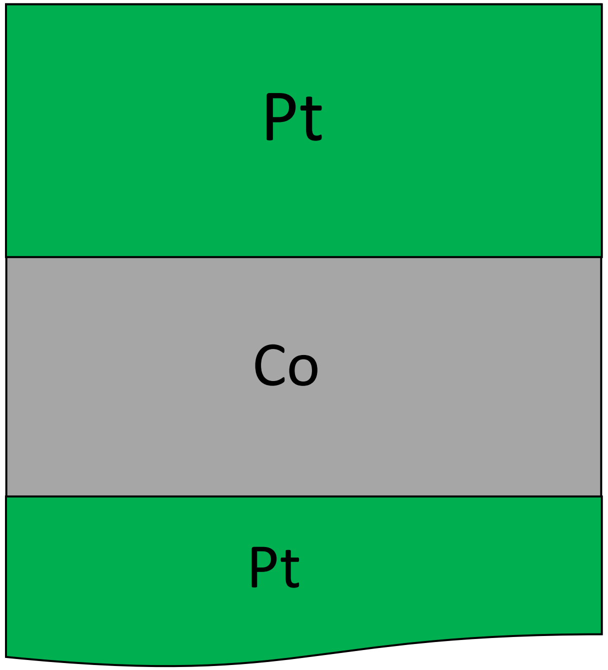
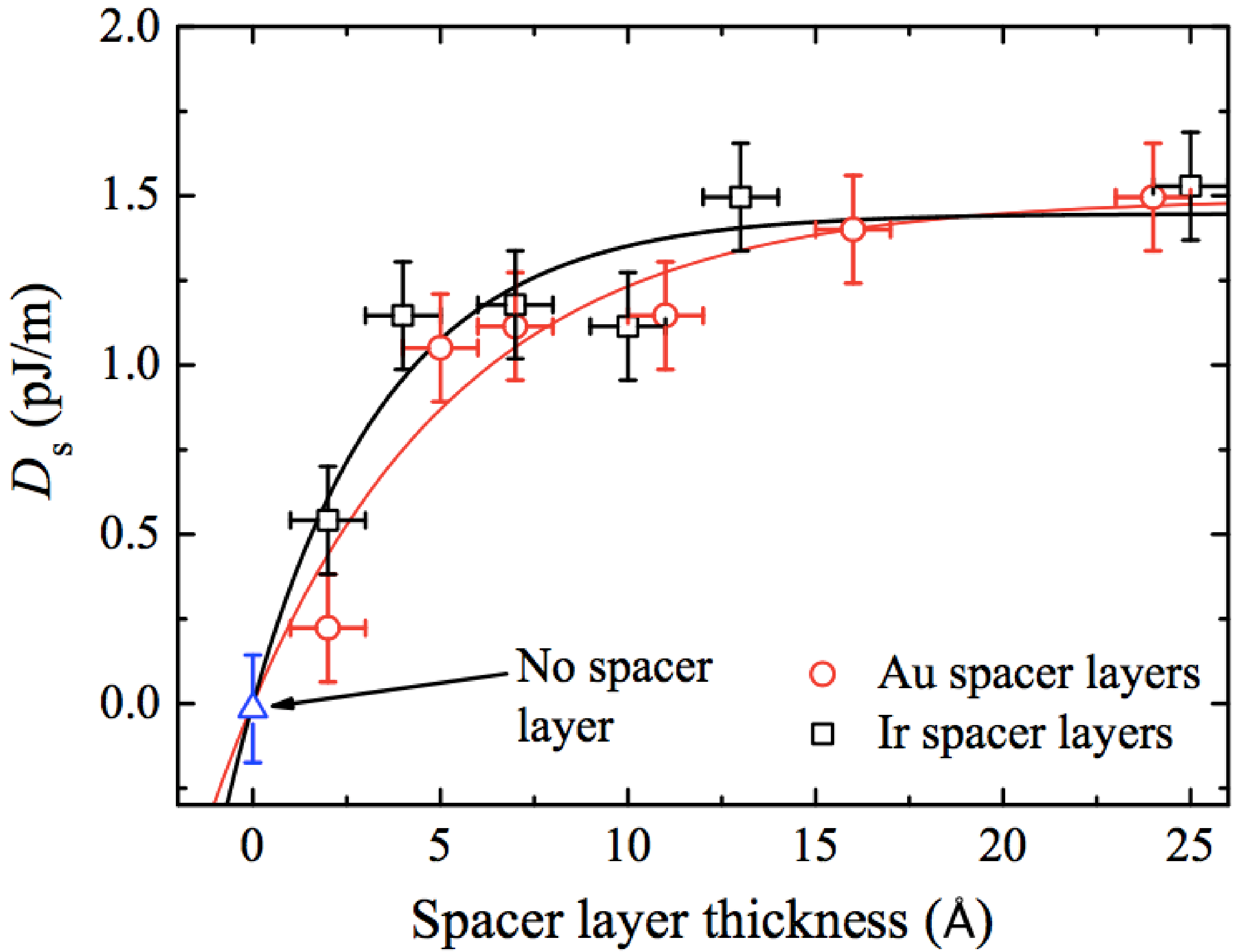
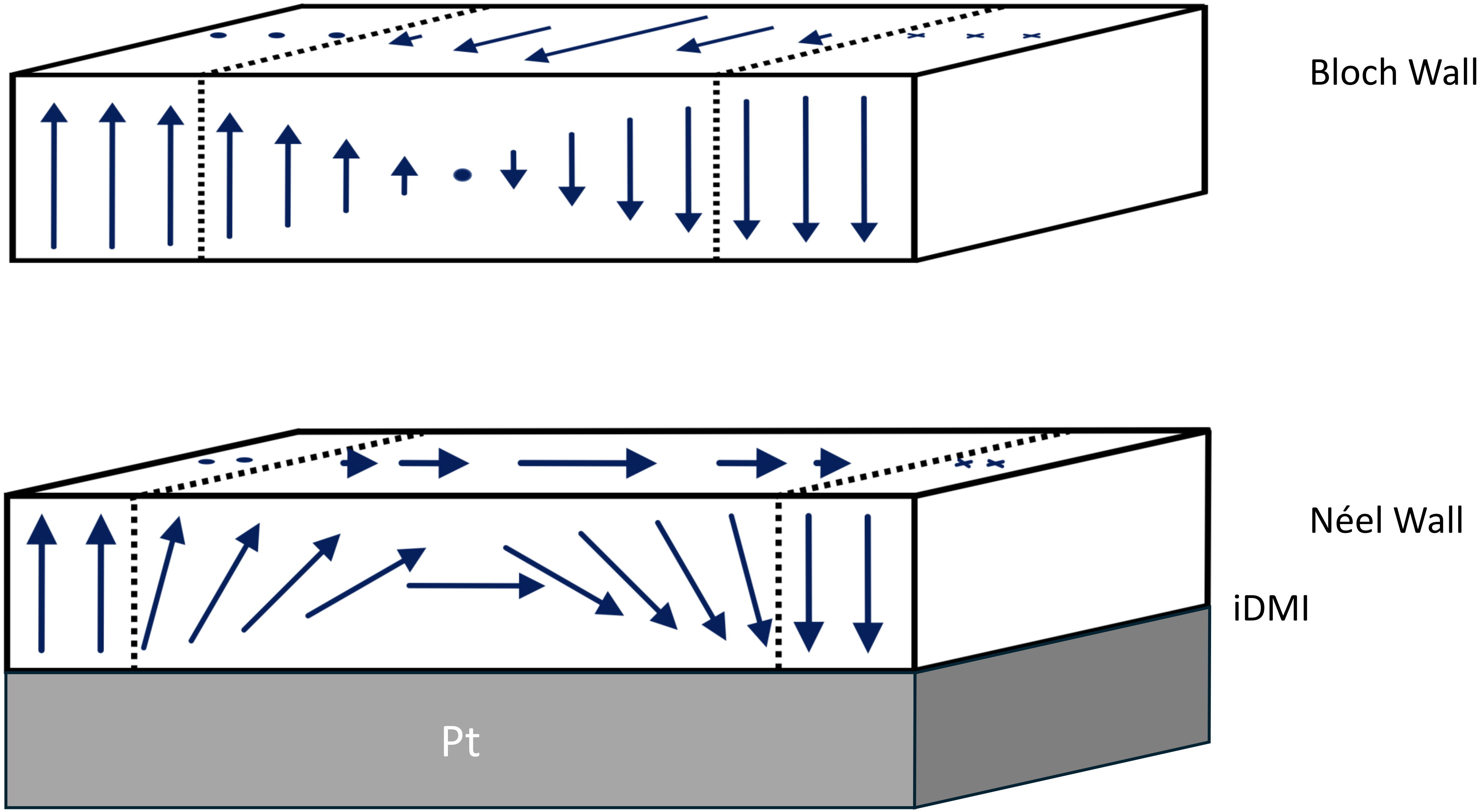


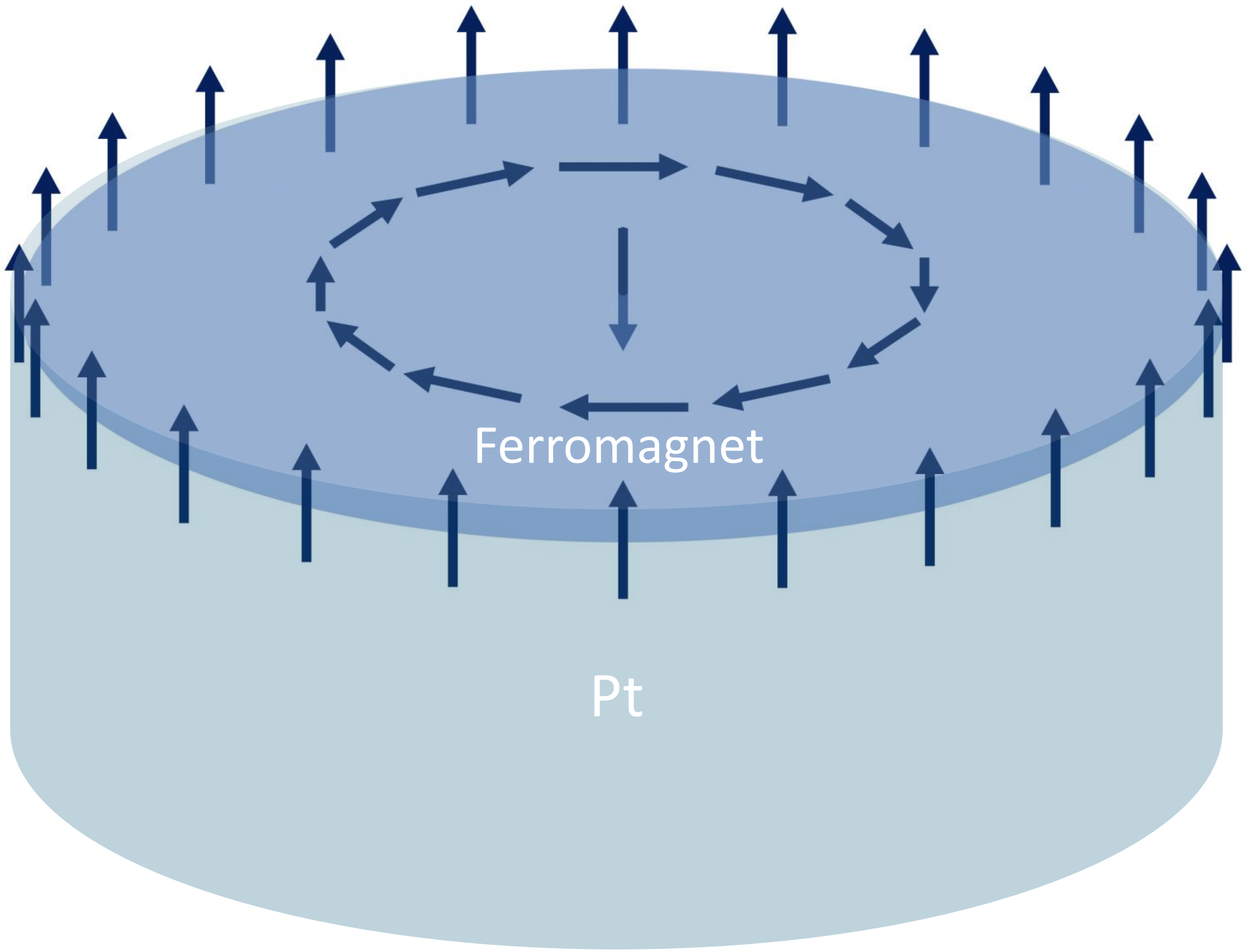


R Rowan-Robinson *et al.* *Scientific Reports* 2017

Interfacial Effects - iDMI Spin textures - Chiral Domain Walls



Interfacial Effects - iDMI Spin textures - Chiral Domain Walls



Bloch Skyrmion

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Magnetic phenomena across the Interface

Topics

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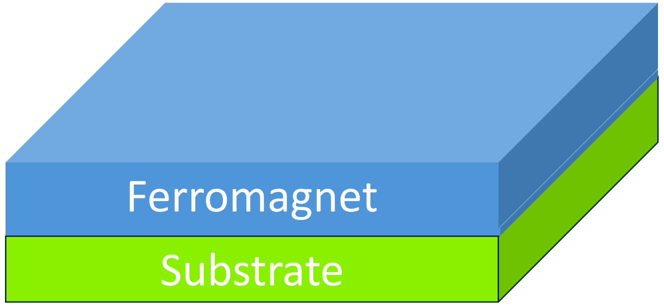
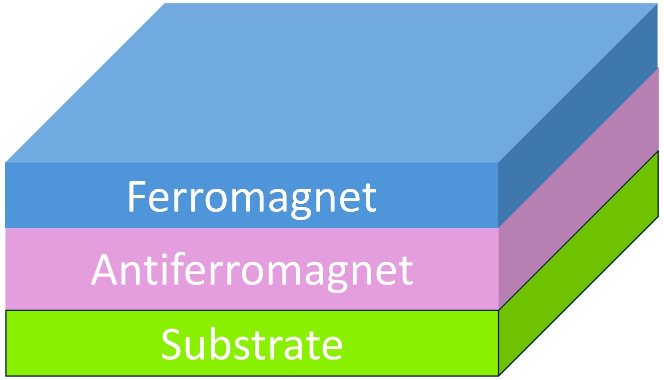
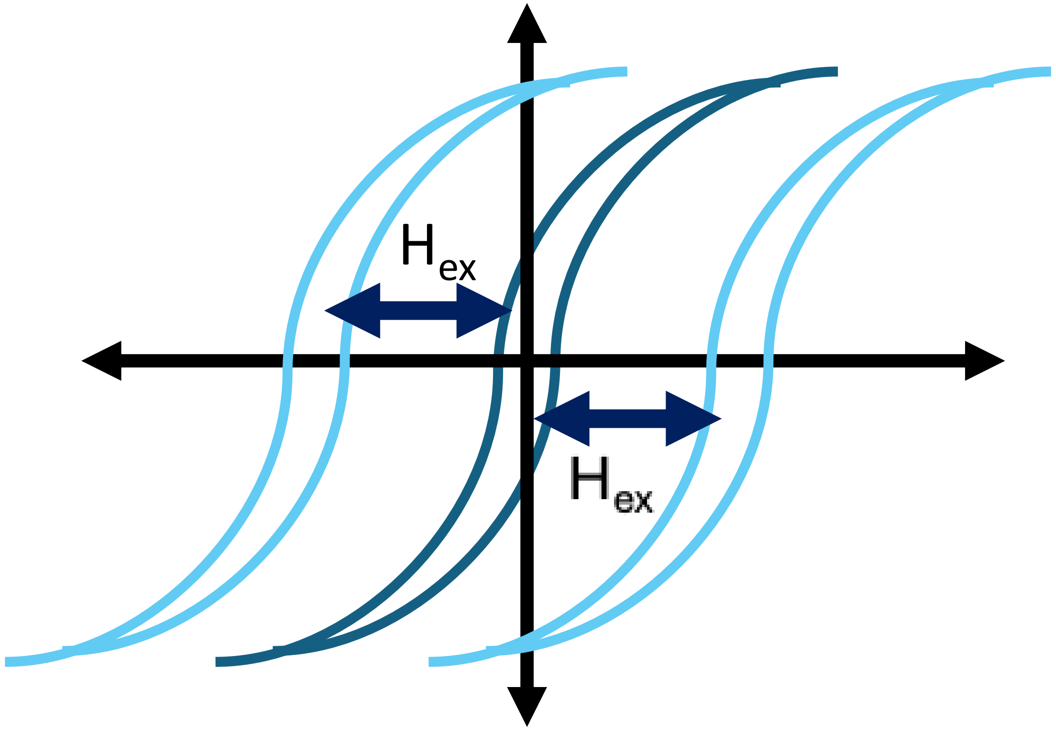
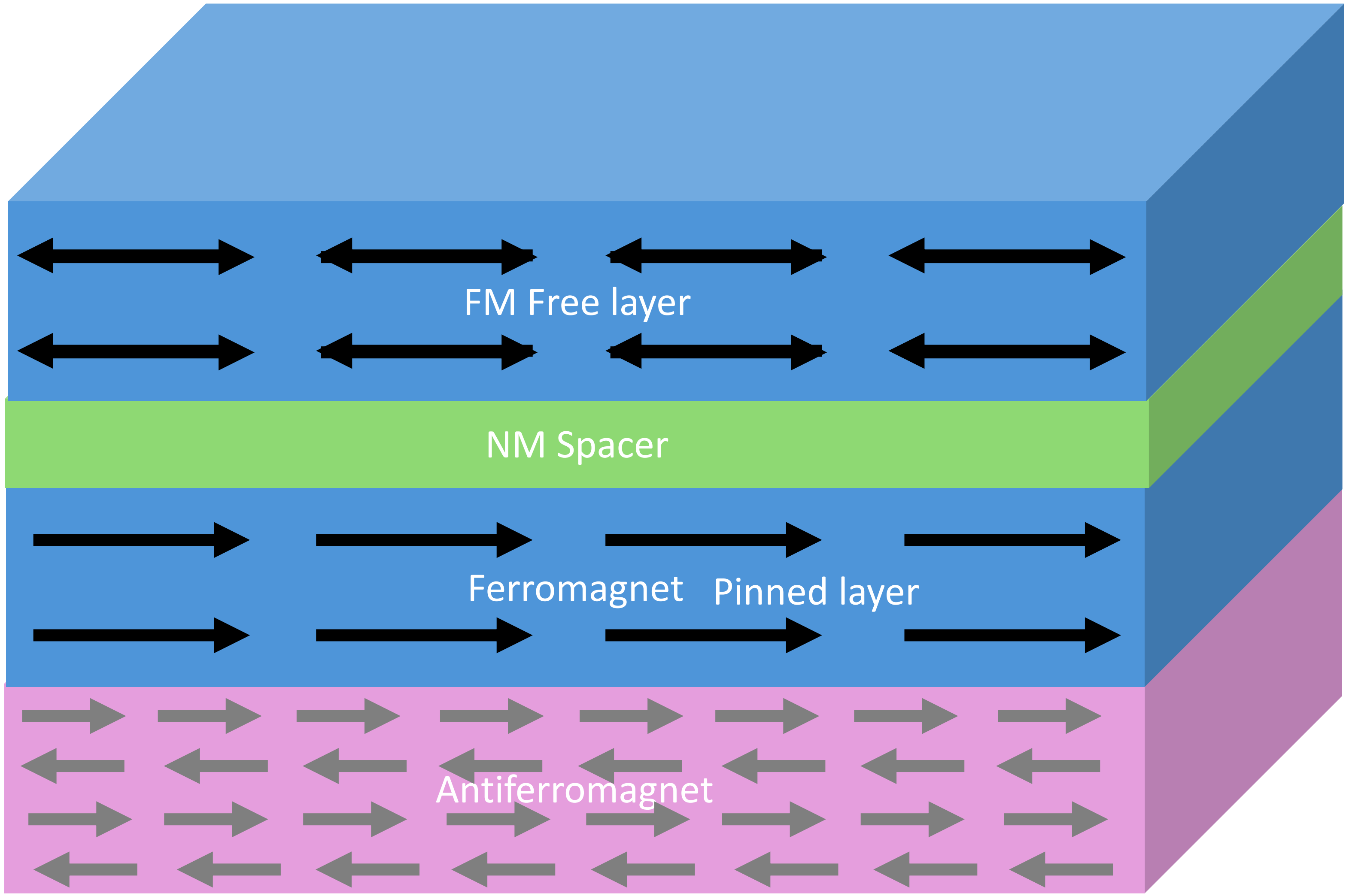
Magnetic phenomena across the Interface – Exchange bias

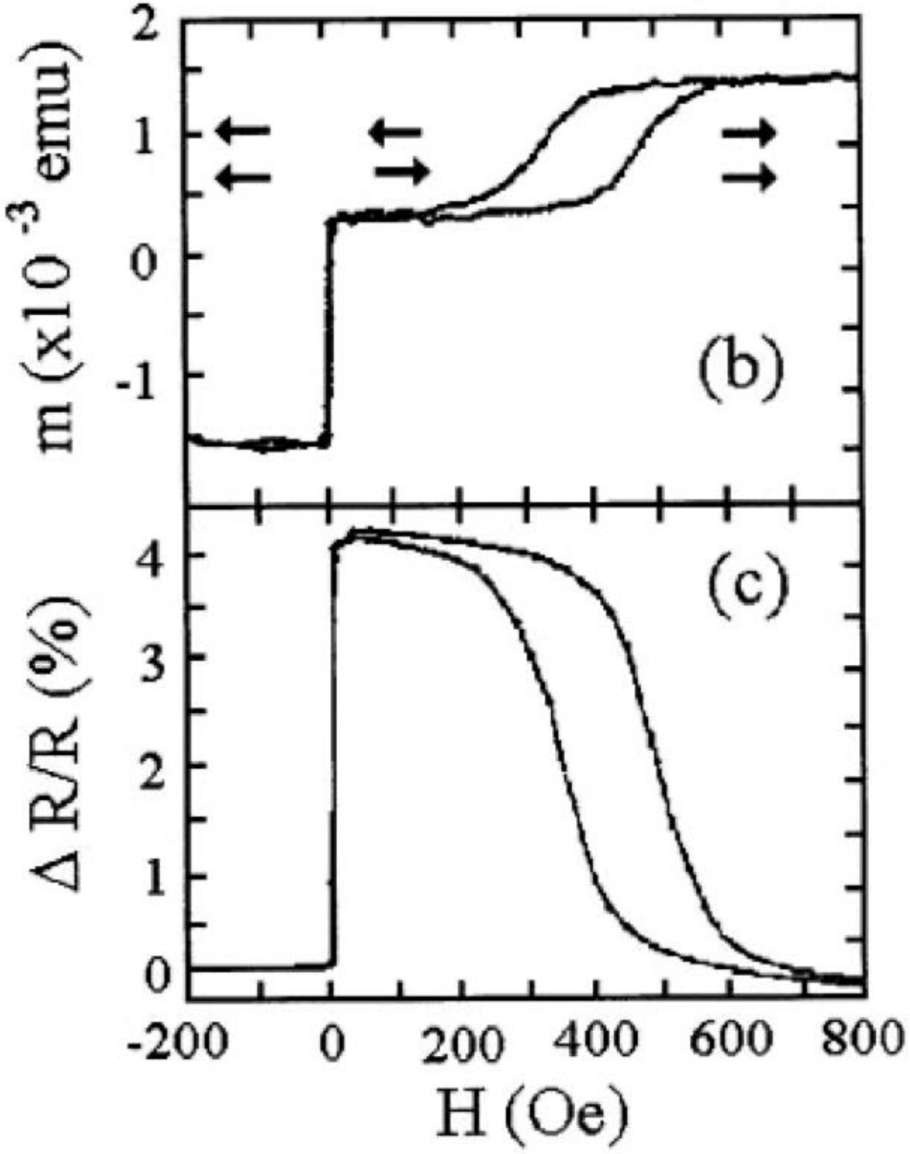






Magnetic phenomena across the Interface – Exchange bias





Setting exchange bias:

Field cool through antiferrromagnetic Néel temperature, T_N

B. Dieny et al. Phys. Rev. B 43 (1991)

Magnetic phenomena across the Interface

Topics

- Thin-film and interfacial anisotropies
- Interfacial Dzyaloshinskii-Moriya Interactions – iDMI
- Exchange bias
- Interface enhanced Ferromagnetic Damping and Spin Transport – Spin Pumping
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- Examples of Interface effects on Magnetization and Spin Transport

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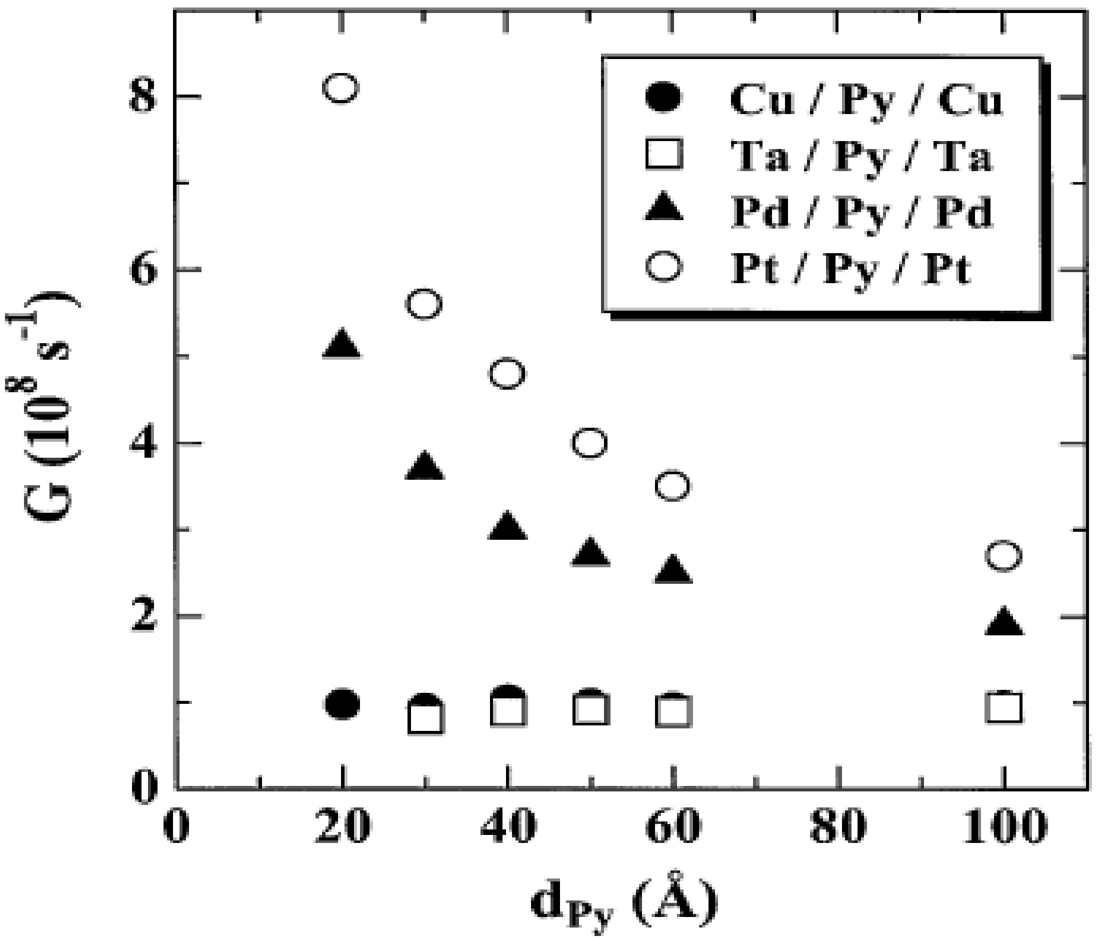
Ferromagnetic Damping in NM/FM Multilayers

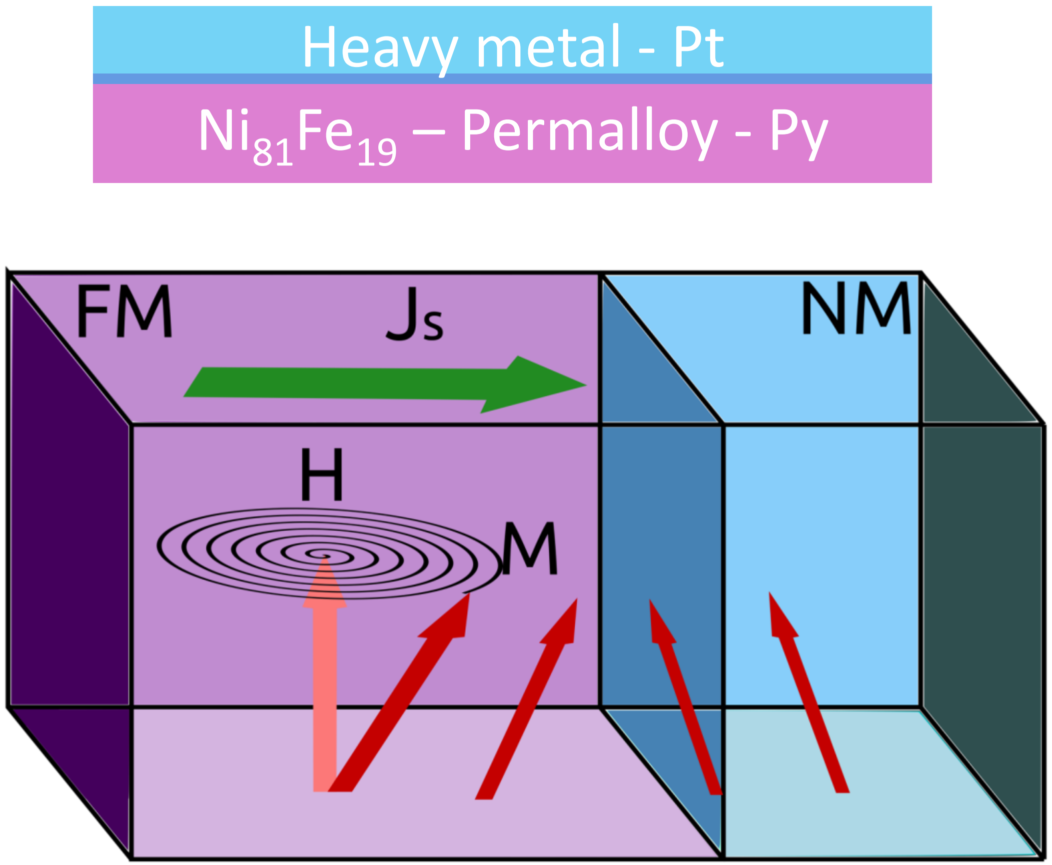
Thickness dependence of damping in ferromagnetic/non-magnetic layers

Ferromagnetic layer thickness



Mizukami et al., JMMM, 226-230, 2001

Ferromagnetic Damping and spin-pumping in NM/FM Multilayers



$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}$$

$$\mathbf{I}_{pump} \propto g_{\text{eff}}^{\uparrow\downarrow} \frac{1}{M^2} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}$$

$$\alpha = \alpha_0 + \frac{g \mu_B}{4\pi M d_{FM}} g_{\text{eff}}^{\uparrow\downarrow}$$

Effective spin-mixing conductance

Ganguly et al. Scientific Reports 2015

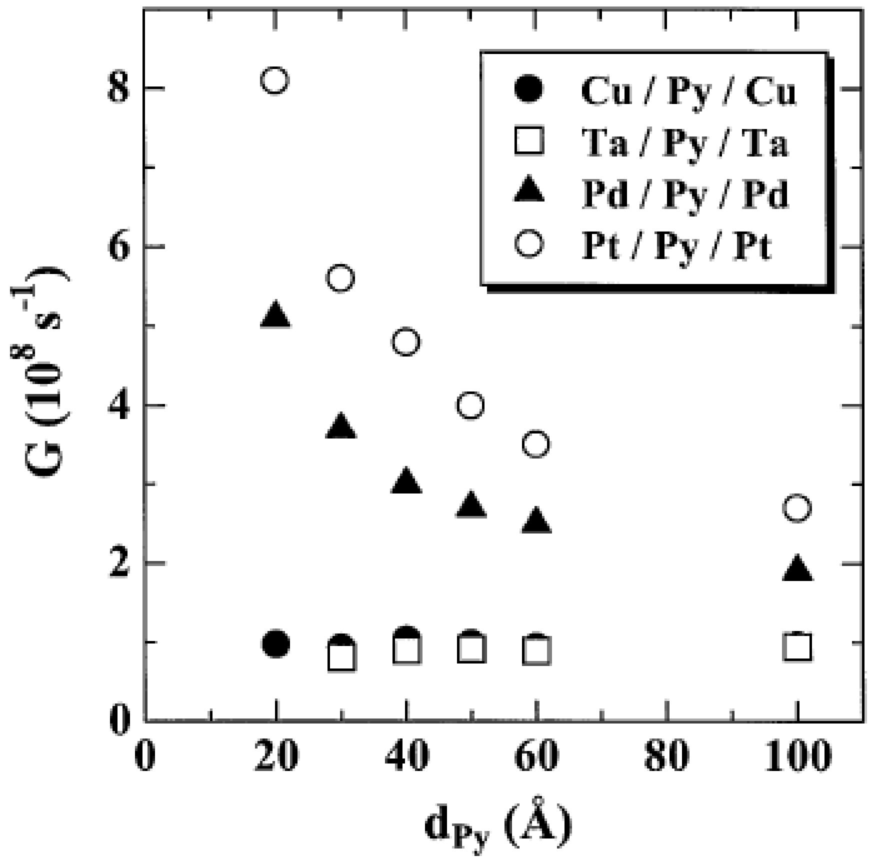
Durham University

Tserkovnyak *et al.*, Rev. Mod. Phys. 2005, Liu et al., PRL 2014

Damping in NM/FM Multilayers

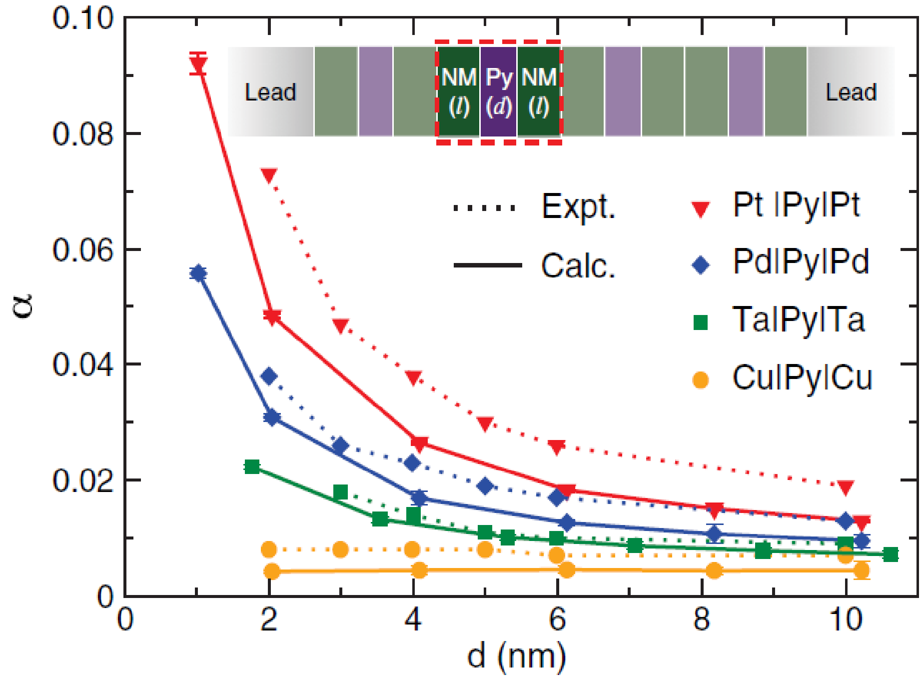
Thickness dependence of damping in ferromagnetic/non-magnetic layers

Ferromagnetic layer thickness



Mizukami et al., JMMM, 226-230, 2001

Theoretical analysis



Tserkovnyak et al., Rev. Mod. Phys. 2005

Liu et al., PRL 2014

Effect of NM Layer on Damping and spin transport

$$\alpha = \alpha_0 + \frac{g\mu_B}{4\pi M d_{FM}} g_{\text{eff}}^{\uparrow\downarrow}$$

$$g^{\uparrow\downarrow}(t_{NM}) = \frac{g_{\infty}^{\uparrow\downarrow}\sqrt{\epsilon}}{\sqrt{\epsilon} + coth\left(\frac{t_{NM}}{\lambda_{sf}}\right)}$$

Interfacial spin-flip probability

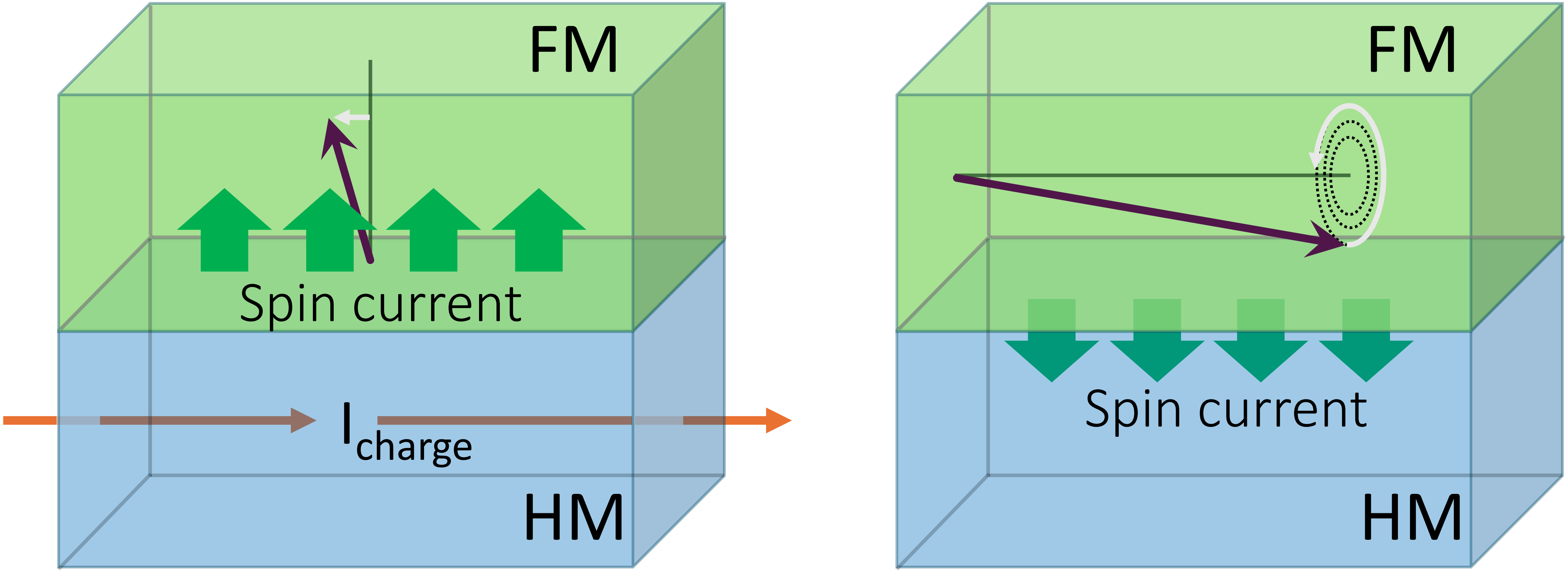
Spin diffusion length

Durham University

Y. Tserkovnyak, A. Brataas, and G. E. Bauer, Phys. Rev. B -. 66, 1 (2002)

Spin current in Ferromagnetic/heavy metal systems

Spin-orbit torque   Spin pumping - Enhanced damping

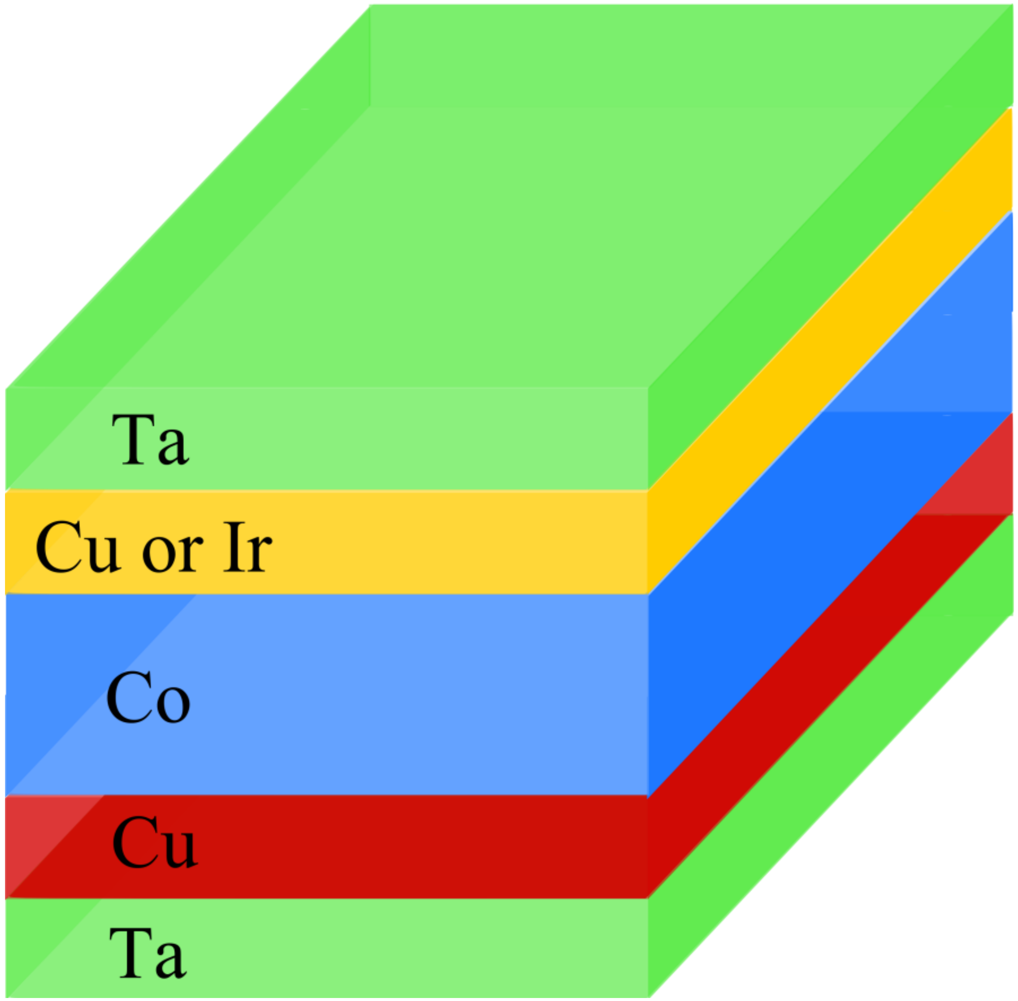


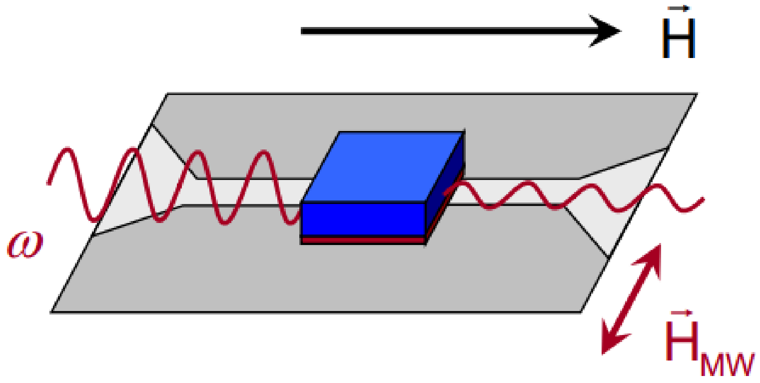
Onsager Reciprocity
Equivalence dynamical processes

Durham University

A. Brataas, Y. Tserkovnyak, G. Bauer, and P. J. Kelly, “Spin pumping and spin transfer,” Spin current 17 (2012)

Effect of Crystallographic Structure at the Interface on Damping - Co/HM





Damping measurement VNA-FMR

- Ta/Cu seed layer
- Co thicknesses 2 – 55 nm
  fcc → hcp
- Overlayers of Cu and Ir
- Top Ta prevents oxidation

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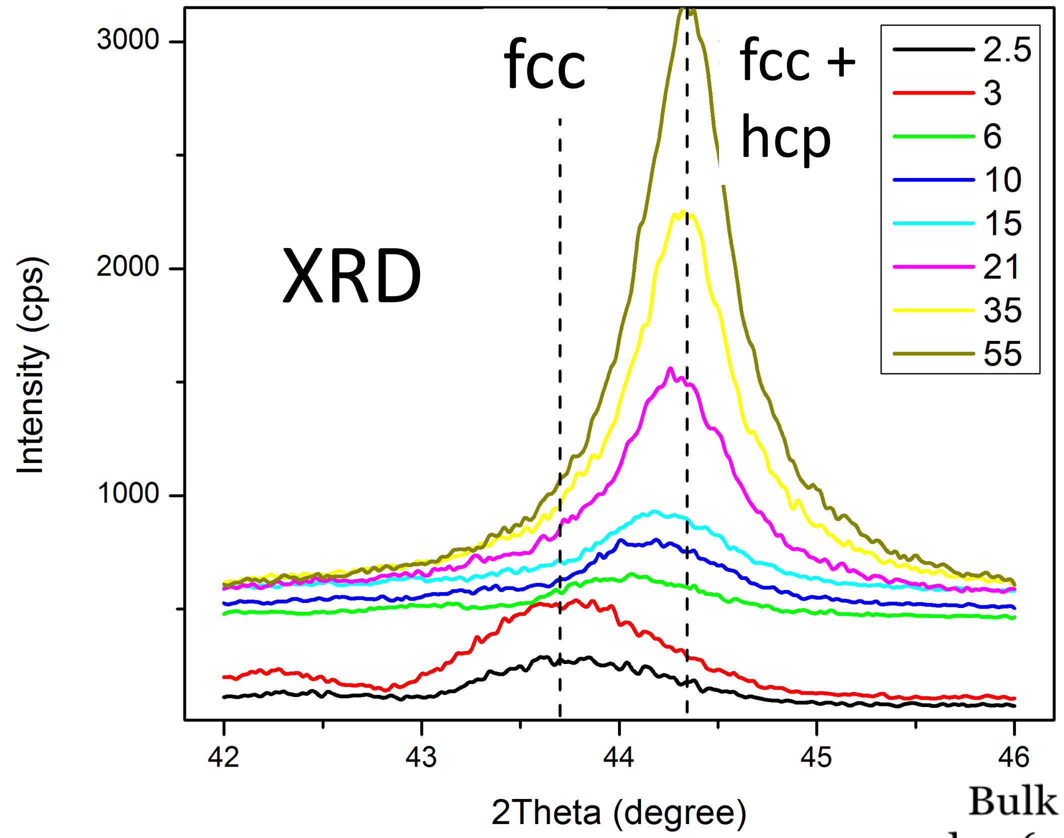
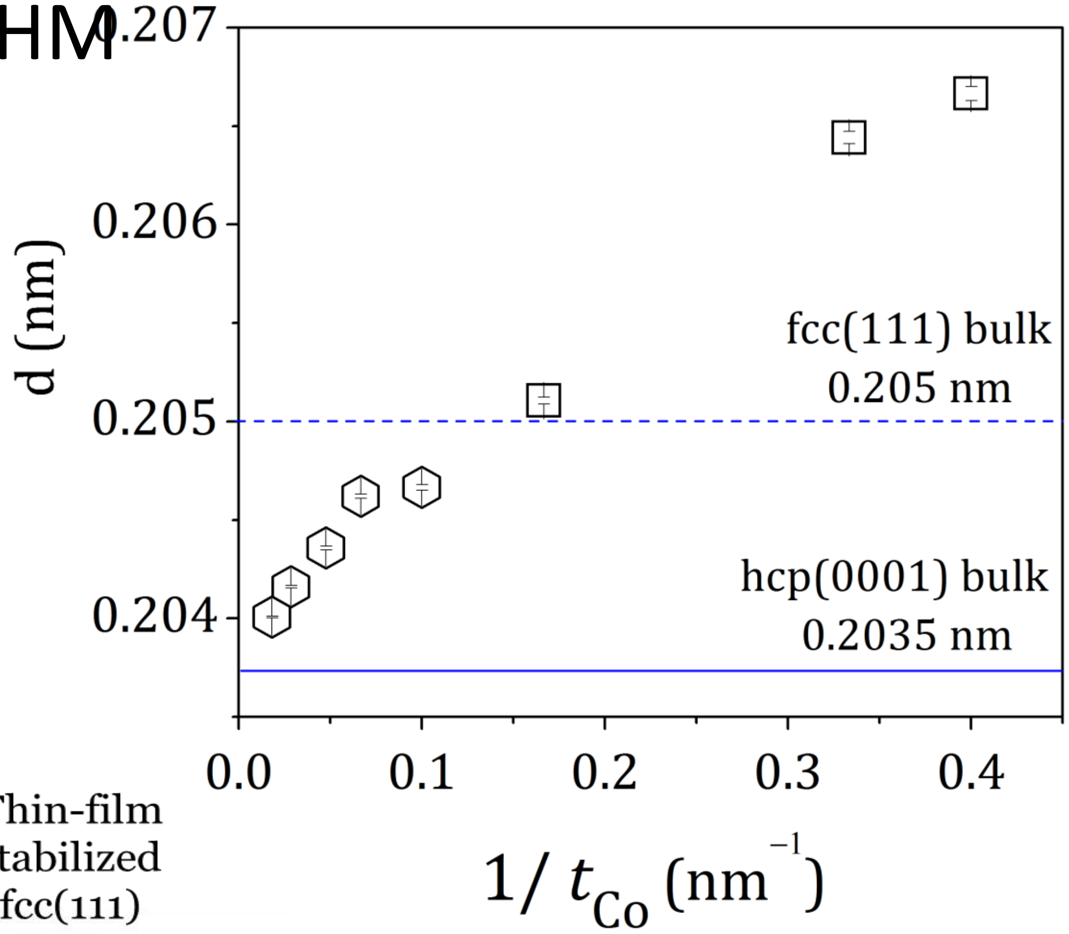
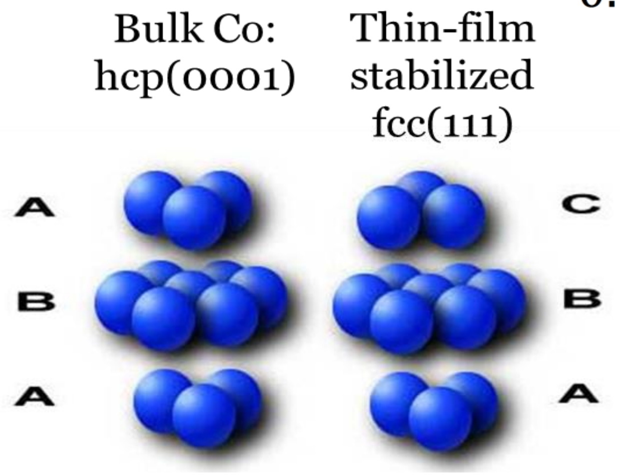
Tokaç *et al* ***Phys. Rev. Letts.*** (2015)

Effect of Crystallographic Structure at the Interface on Damping - Co/HM





Note: fcc Co is not stable in bulk!



Strain relaxes and hcp stacking-faults develop as cobalt thickness increases

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Effect of Crystallographic Structure at the Interface on Damping - Co/HM

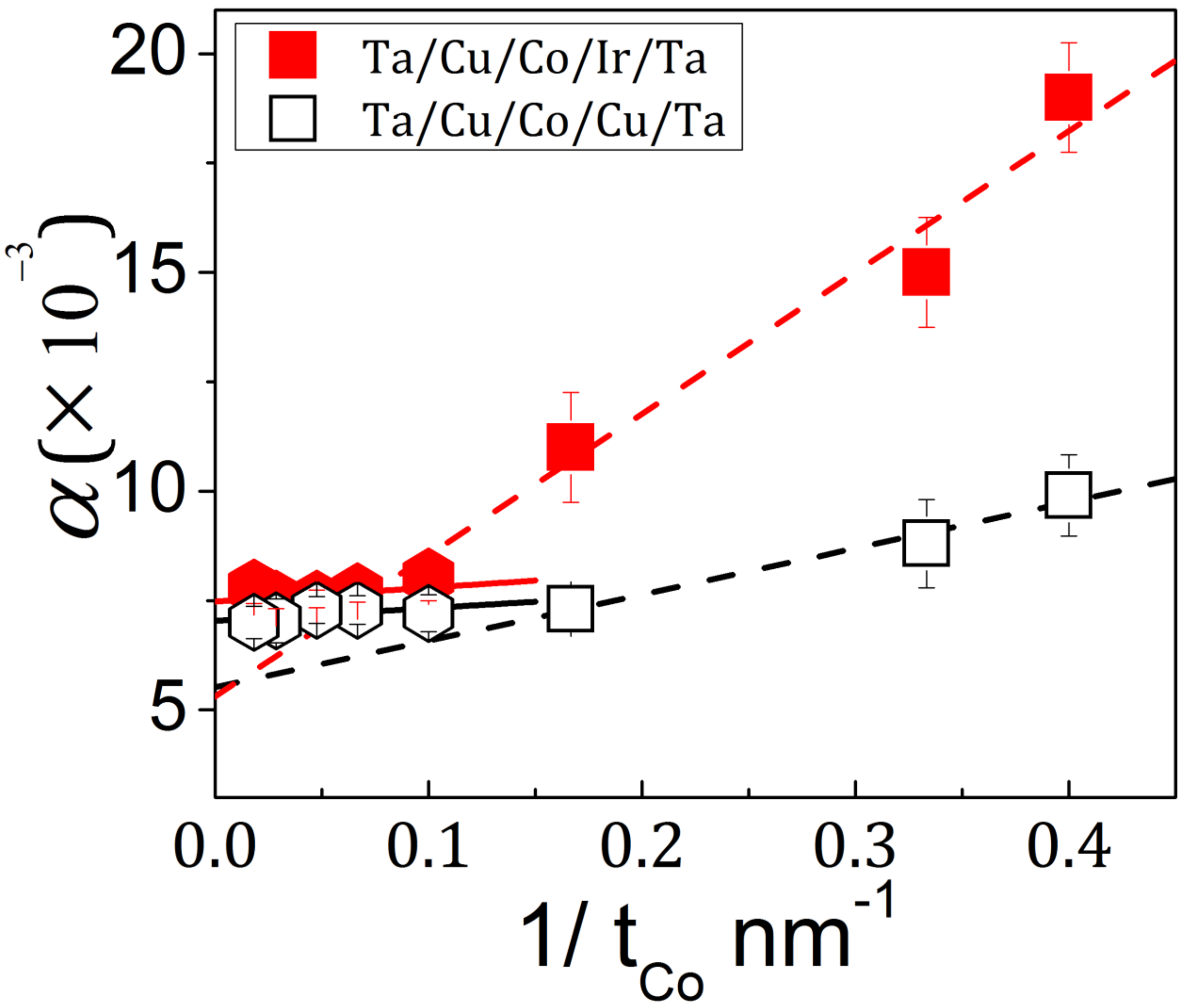
$$\alpha = \alpha_0 + \frac{g\mu_B}{4\pi M d_{FM}} g_{\mathrm{eff}}^{\uparrow\downarrow}$$

Spin-mixing conductance

Bulk damping α_0

hcp Co ~ (7.3±0.2) x10^{-3}

fcc Co ~ (5.3±0.3) x10^{-3}



Tokaç et al. Phys. Rev. Letts. (2015)

Durham University

Pelzl et al, JPCM 2003
Barati et al, PRB 2014

Spin mixing conductance for different interfaces

Spin-pumped interface(s)	$\alpha_0 (\times 10^{-3})$	$g_{\uparrow\downarrow}^{\text{eff}}$ $(\times 10^{18}\ \text{m}^{-2})$
hcp(0001)-Co/Cu	7.1 ± 0.2	0.4 ± 0.1
fcc(111)-Co/Cu	5.5 ± 0.3	1.8 ± 0.1
hcp(0001)-Co/Ir	7.5 ± 0.2	0.6 ± 0.1
fcc(111)-Co/Ir	5.2 ± 0.3	9.1 ± 0.5

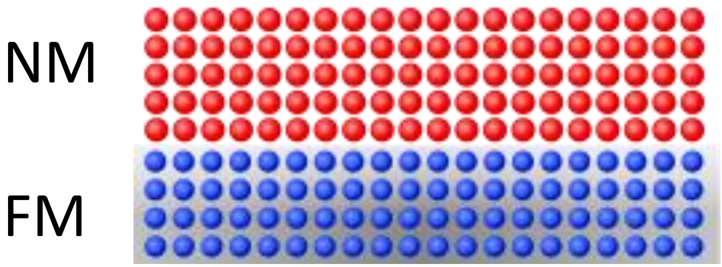
Enhancement of spin-mixing conductance for fcc Co interfaced structure

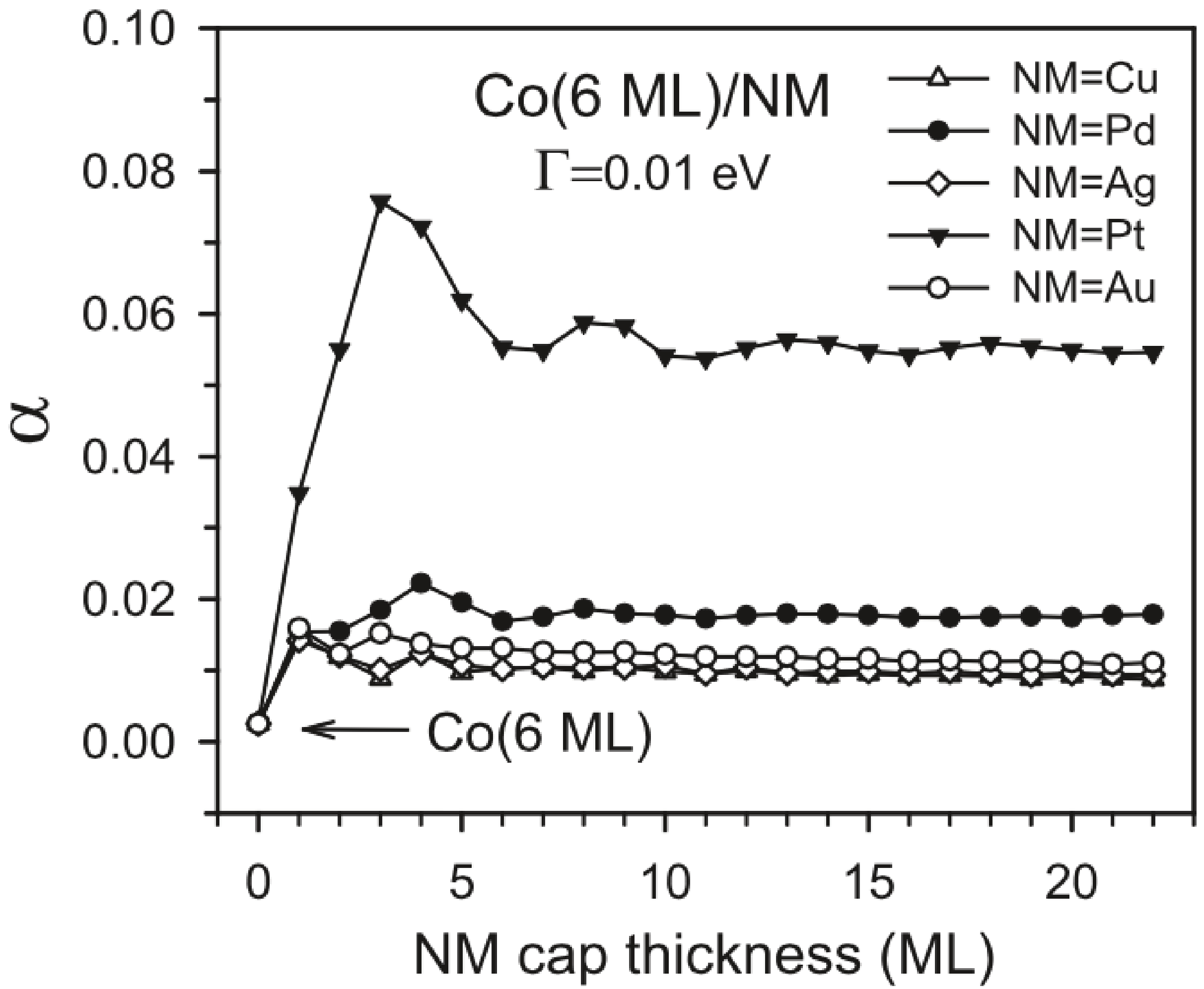
Durham University

M. Tokaç *et al.* Phys. Rev. Letts. (2015)

Interface enhanced damping in ferromagnetic thin-films

Enhancing SOC at the interface - damping in ferromagnetic/non-magnetic layers





Realistic nine-orbital tight-binding model

Including spin-orbit coupling

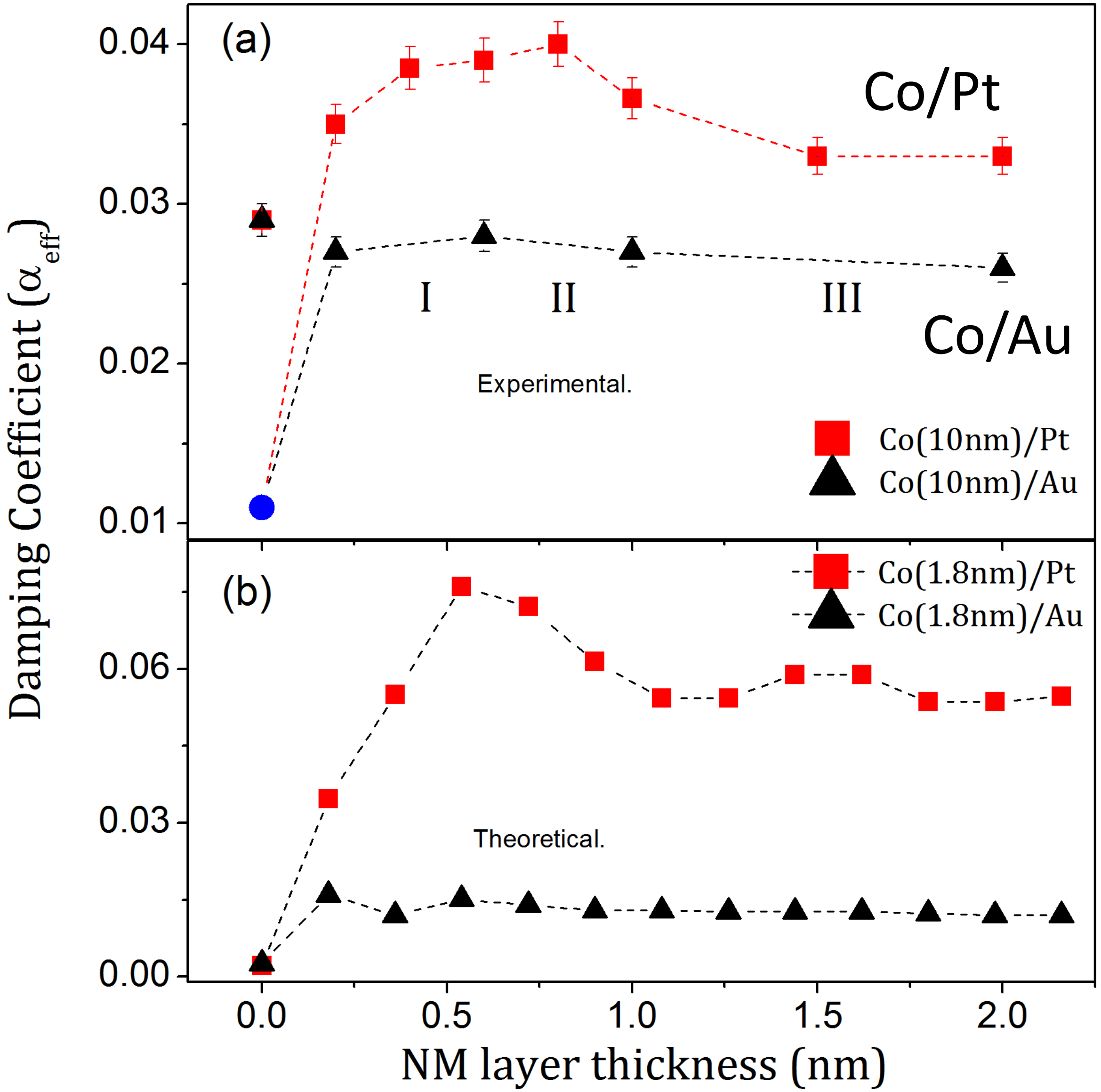
Finite temperature in the electronic occupation factors and subsequent summation over the Matsubara frequencies

Durham University

E. Barati, M. Cinal, D. M. Edwards and A. Umerski Phys Rev B (2014)

Damping Mechanism with NM Layer thickness

S. Azzawi et al. Phys. Rev. B (2016)



Experimental

Theoretical

Barati … Umerski

2014

Magnetic phenomena across the Interface

Topics

- Thin-film and interfacial anisotropies
- Interfacial Dzyaloshinskii-Moriya Interactions – iDMI
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- Interfacial Proximity-Induced-Magnetism in Heavy Metals - PIM
- Examples of Interface effects on Magnetization and Spin Transport

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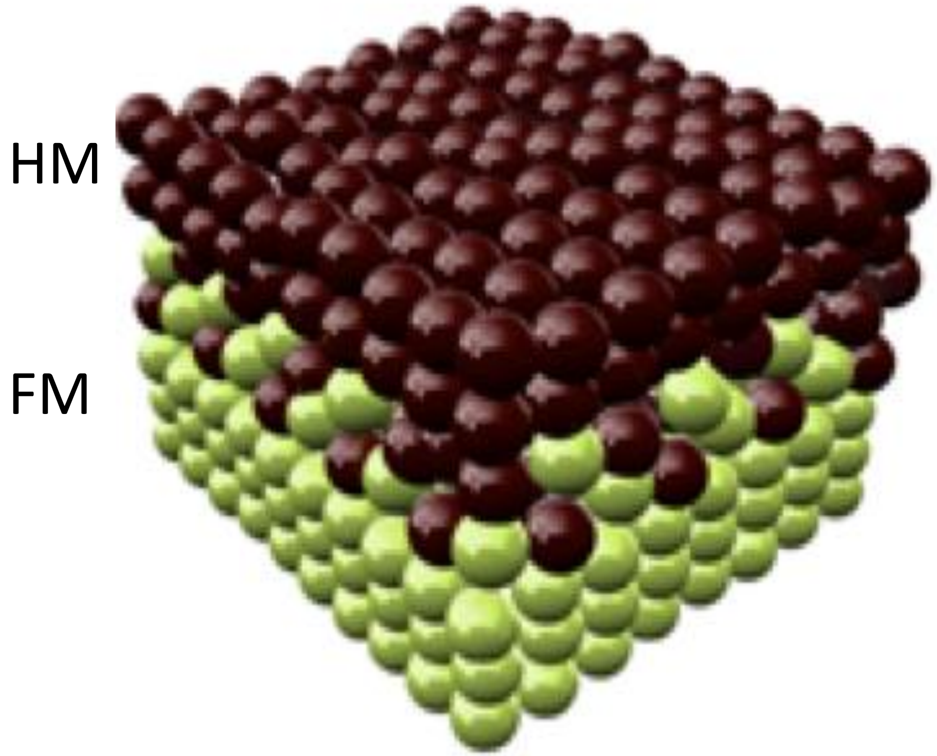
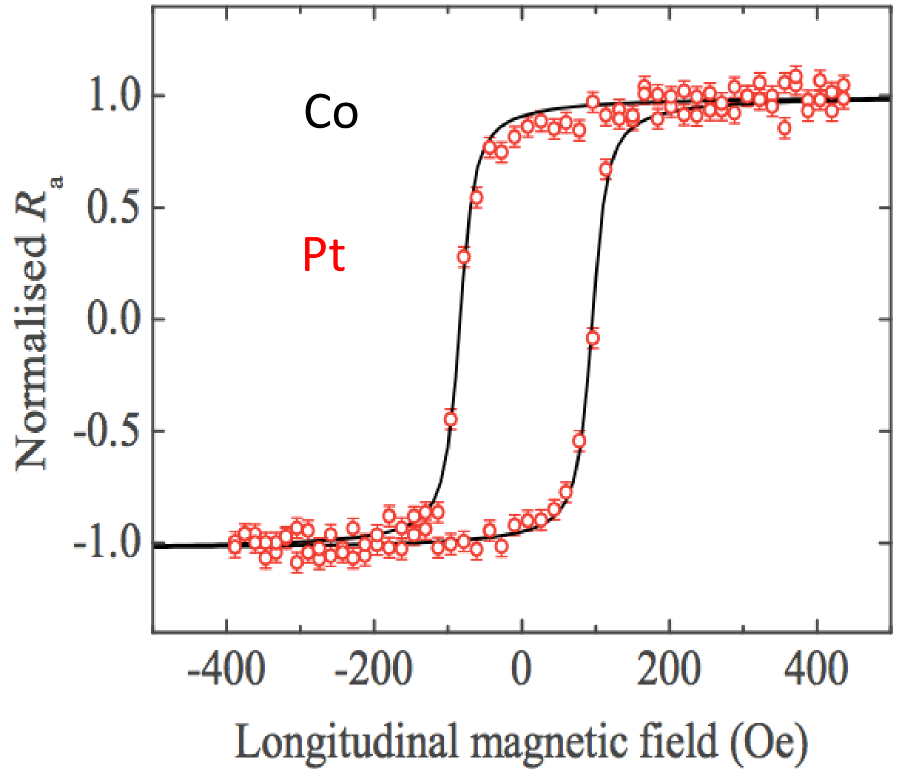
Interfacial Proximity-Induced-Magnetism in Heavy Metals - PIM

Magnetic Proximity Effect (MPE) or Proximity- induced magnetization (PIM)





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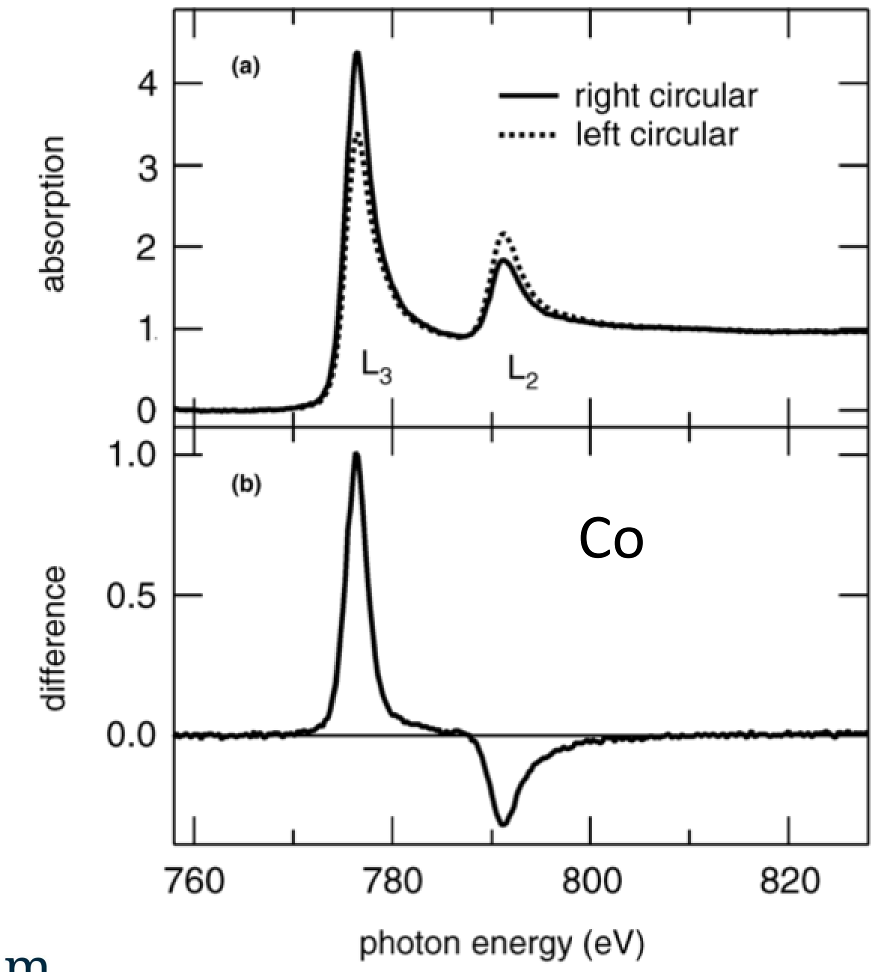
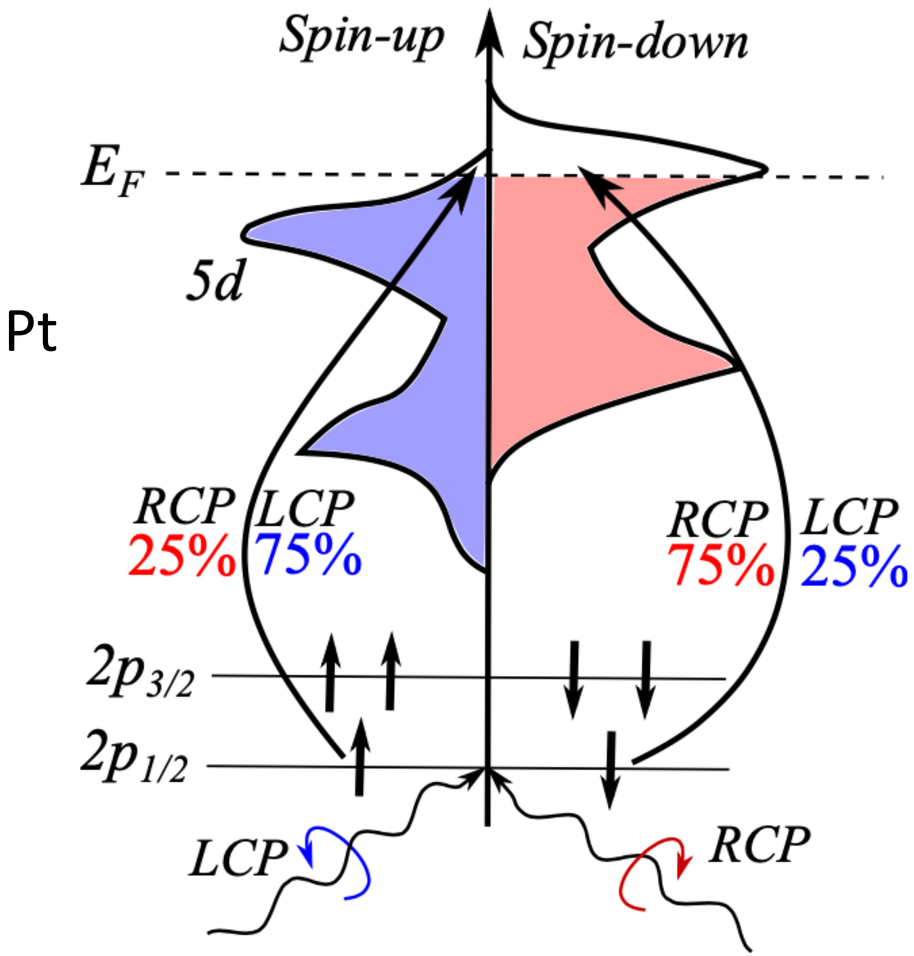
Proximity-Induced Magnetism – Physics & Measurement

Element specific X-ray Resonant Magnetic Reflectivity XRMR – Reflectivity at X-ray resonant energy edge

- Same physics as X-ray magnetic circular dichroism - XMCD





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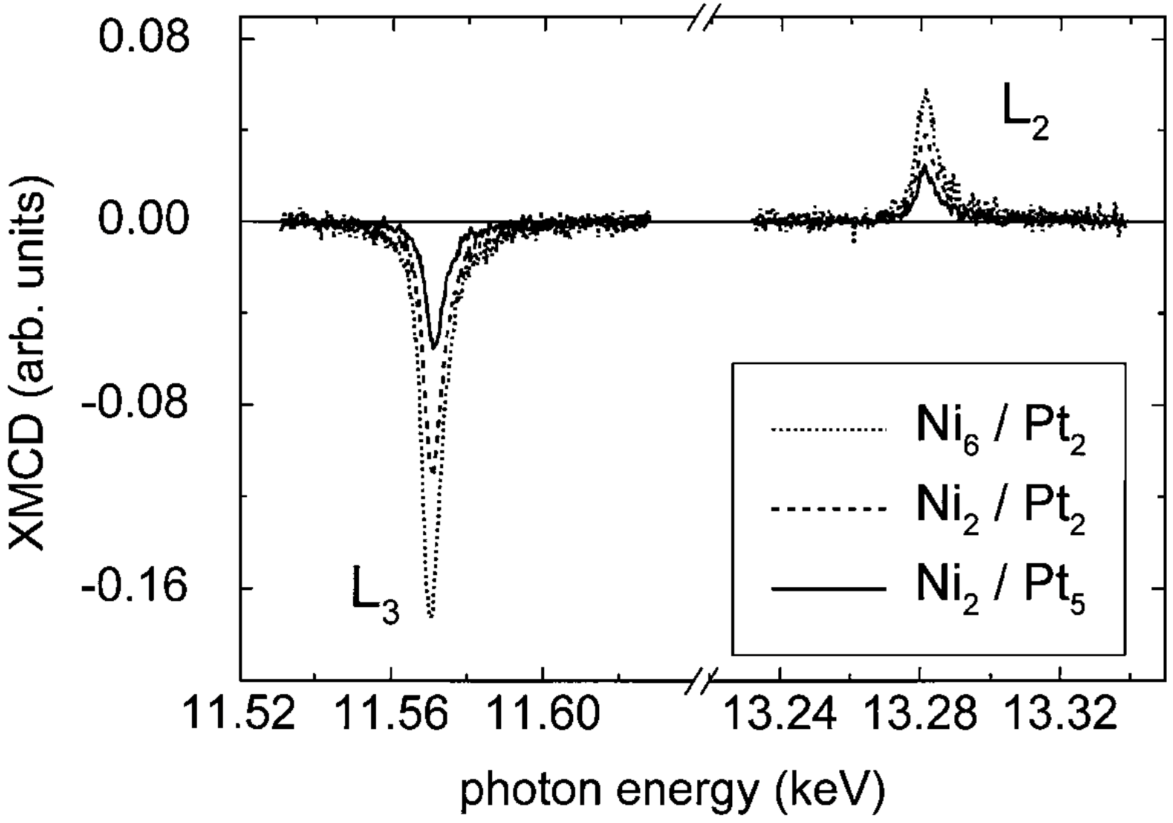
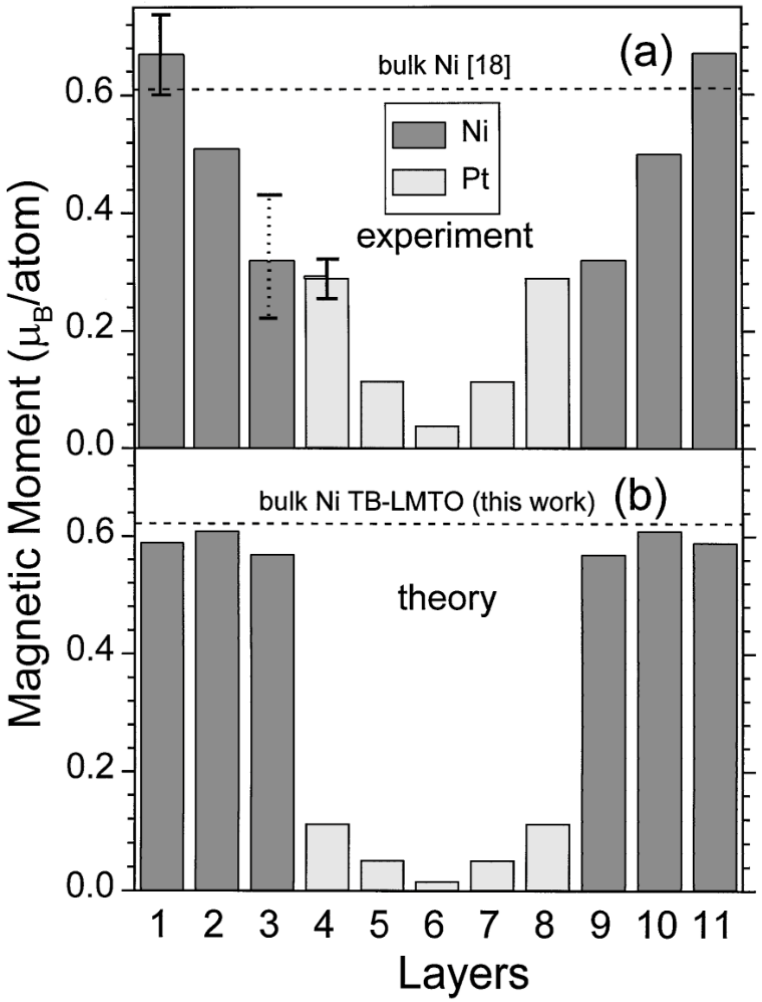
Kuch ***Physica Scripta***. T109, 89–95, (2004)

Interfacial Proximity-Induced-Magnetism in Heavy Metals - PIM

Magnetic Proximity Effect (MPE) or Proximity- induced magnetisation (PIM)





F. Wilhelm et al. Phys. Rev. Letts. (2000)

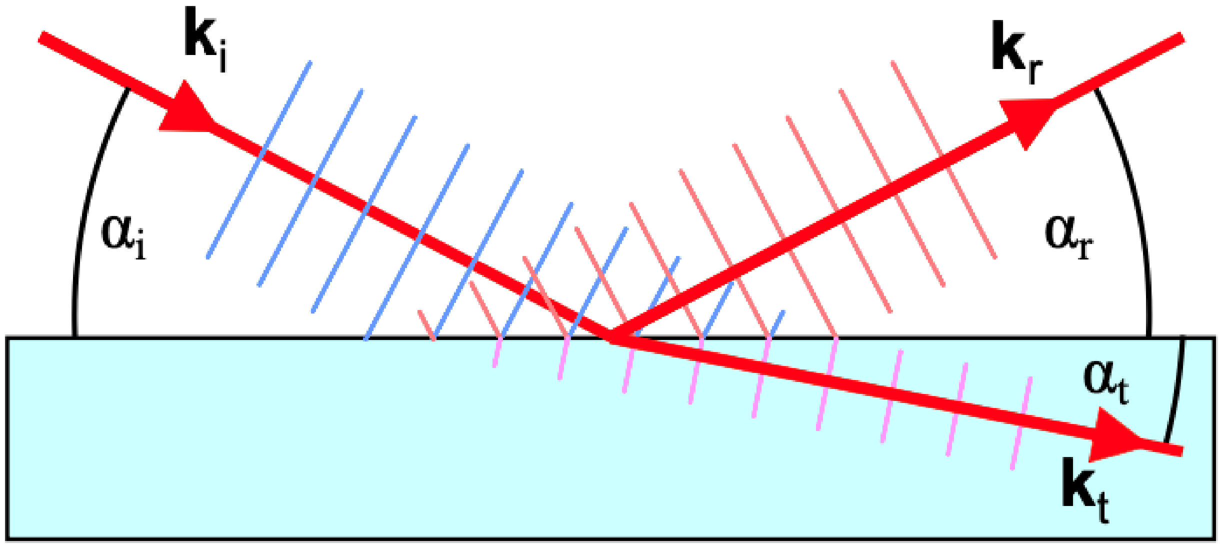
Mapping thin-film structure and magnetism:Resonant X-ray reflectivity

- X-ray Reflectivity (XRR, GIXR) + XMCD physics

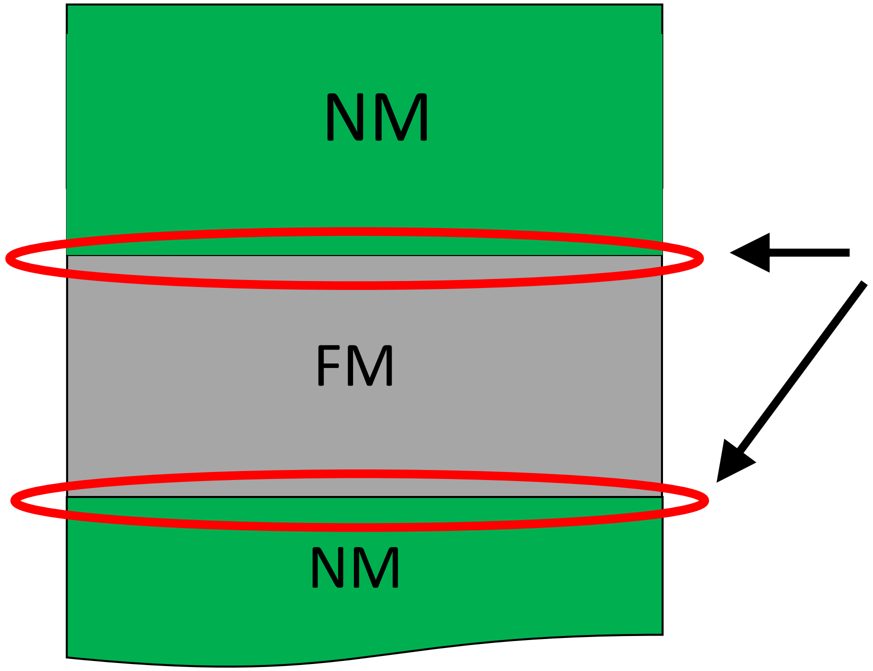
Refractive index n=c/v

$n_0 = 1$

$n_1 = 1 - \delta + i\beta$

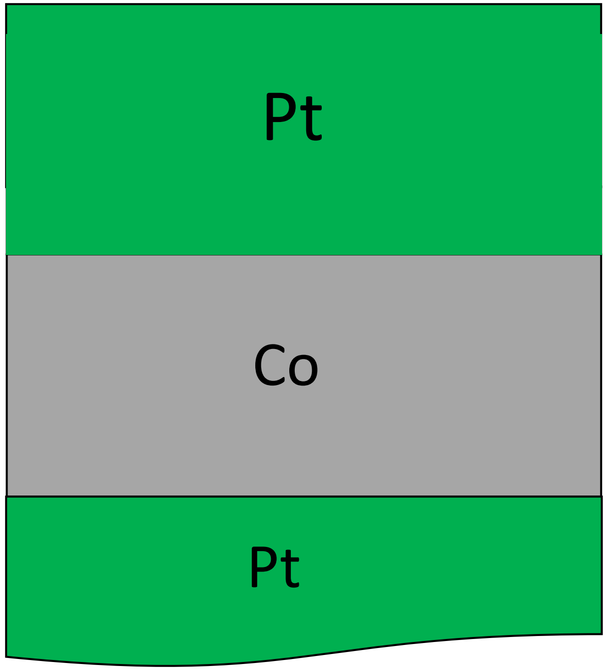


Magnetic Proximity Effect (MPE) or Proximity- induced magnetisation (PIM)

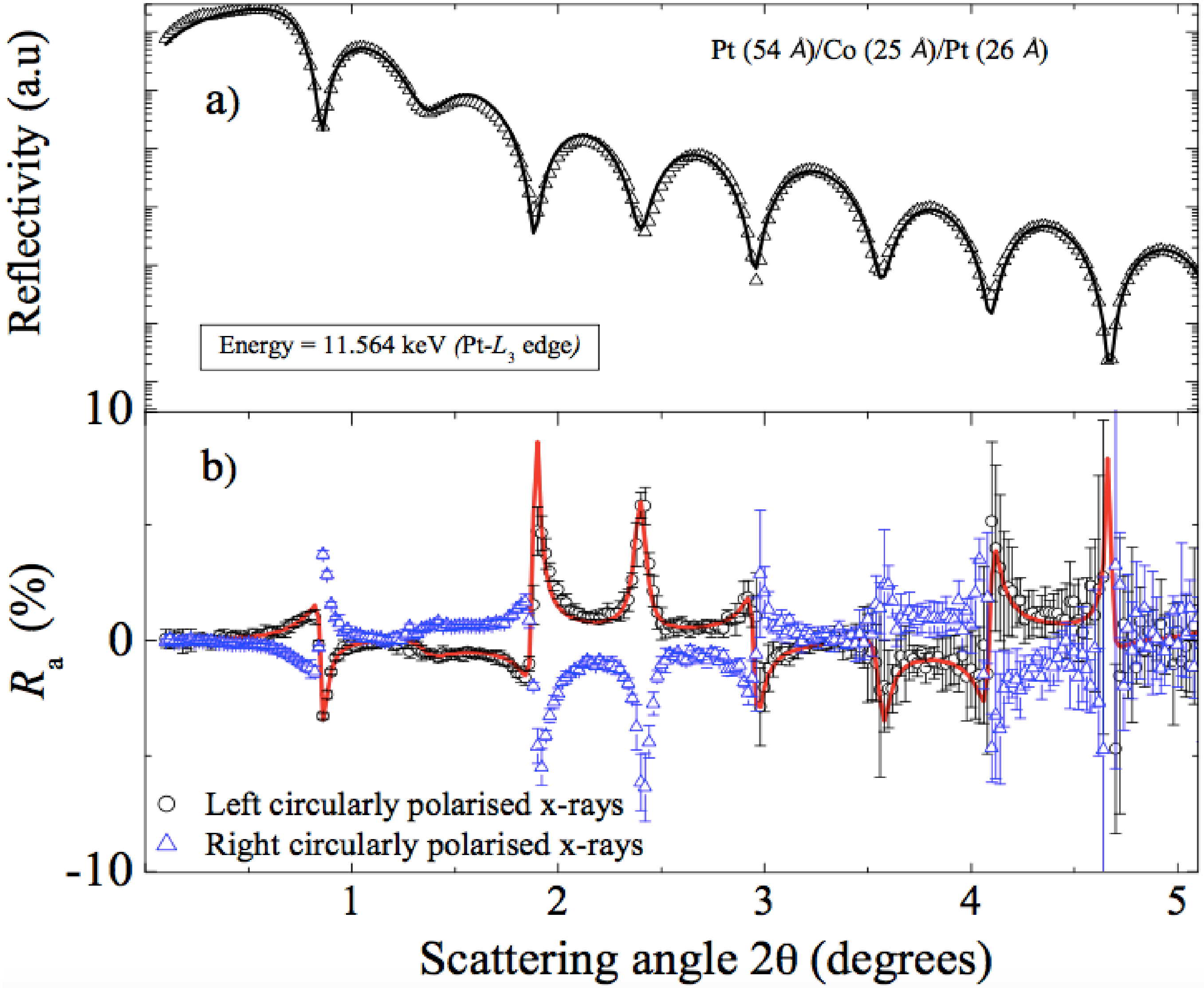


Non-magnetic material becomes magnetically polarized by proximity to ferromagnet

Proximity-induced magnetisation (PIM) in Pt



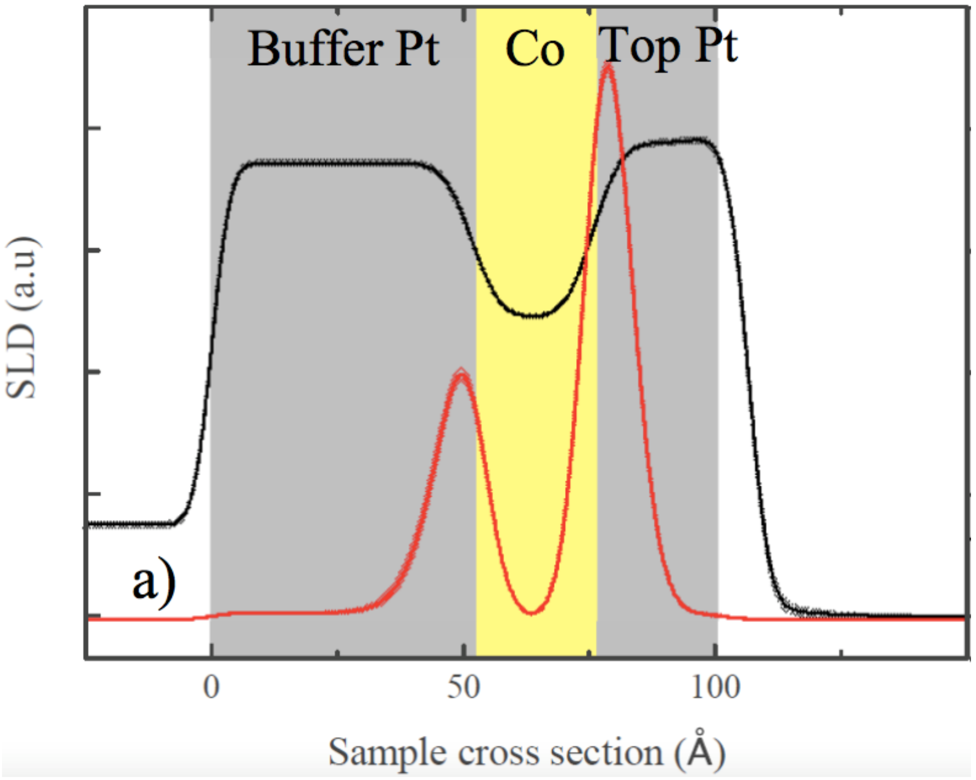
X-ray Resonant Magnetic Reflectivity XRMR



Rowan-Robinson et al. Scientific Reports December 2017

Proximity-induced magnetisation in Pt/Co/Pt

Structural and Magnetic Scattering Length densities (SLDs)



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Rowan-Robinson et al. Scientific Reports December 2017

Magnetic phenomena across the Interface

Topics

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- Exchange bias
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- Interfacial Proximity-Induced-Magnetism in Heavy Metals - PIM

Further Information

"Magnetism of surfaces and interfaces"
U Gradmann ***J. Magn. Magn. Mater. 6*** (1977) 173-182

"Magnetism from the Atom to the Bulk in Iron, Cobalt, and Nickel Clusters"
Isabelle M. L. Billas, A. Chatelain, Walt A. de Heer, ***SCIENCE*** *265* 1994

"*Theoretical Approaches of magnetism of transition-metal thin-films and nanostructures on semi-infinite substrate*" H Dreyssé & C. Demangeat ***Surface Science Reports 28, 65-122*** (1997)

"*Magnetic anisotropy in metallic multilayers"*
MT Johnson, PJH Bloemen, FJA den Broeder and JJ de Vries, ***Rep. Prog. Phys***. 59, 1409-1456 (1996)

"*Interface-induced phenomena in magnetism"*
F Hellman et al. ***Rev. Mod. Phys.*** *89, 0250066 (2017*

"*Exchange bias*"
J. Nogues , Ivan K. Schuller, ***J. Magn. Magn. Mater.*** 192 (1999) 203—232

"*Nonlocal magnetization dynamics in ferromagnetic heterostructures*"
Tserkovnyak et al., ***Rev. Mod. Phys.*** *(2005)*

"Magnetic damping phenomena in ferromagnetic thin-films and multilayers"
S Azzawi At Hindmarch & D Atkinson 2017 ***J. Phys. D: Appl. Phys****. 50 473001 (2017)*

Magnetic phenomena across the Interface

Topics

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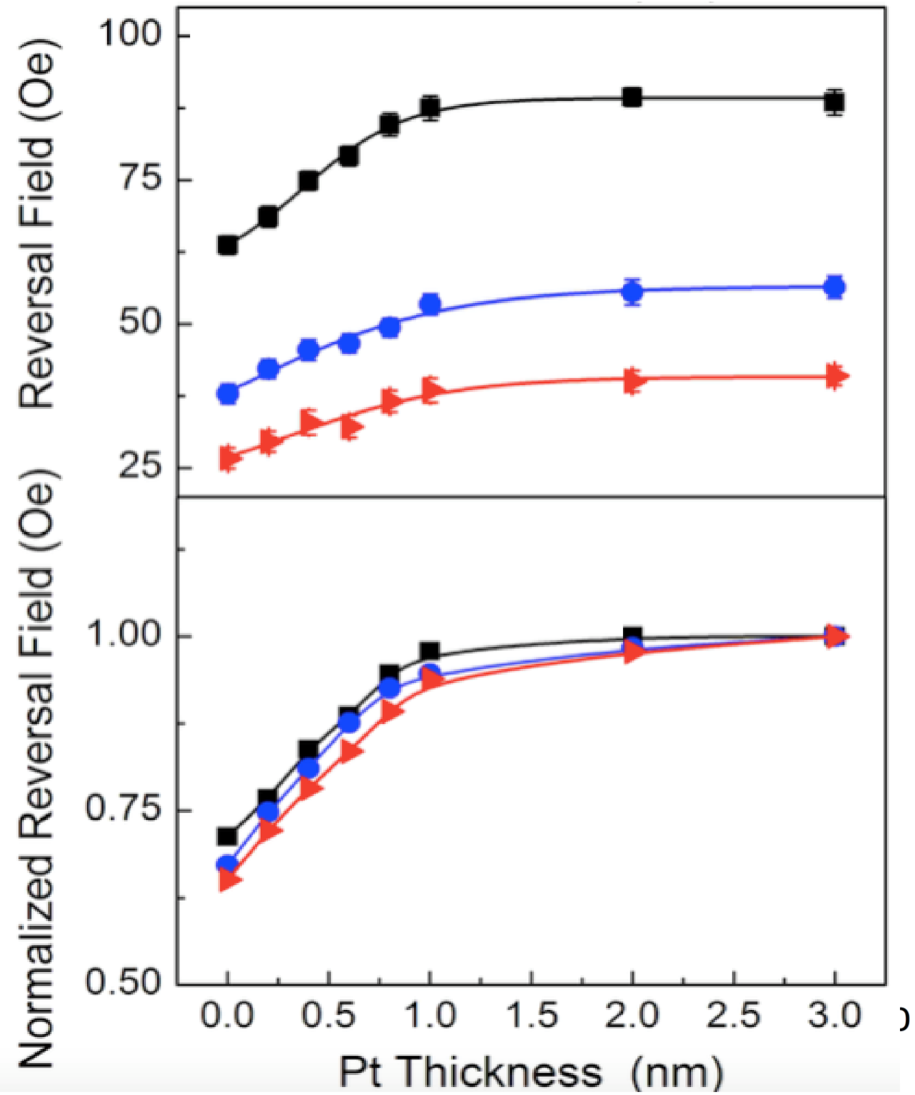
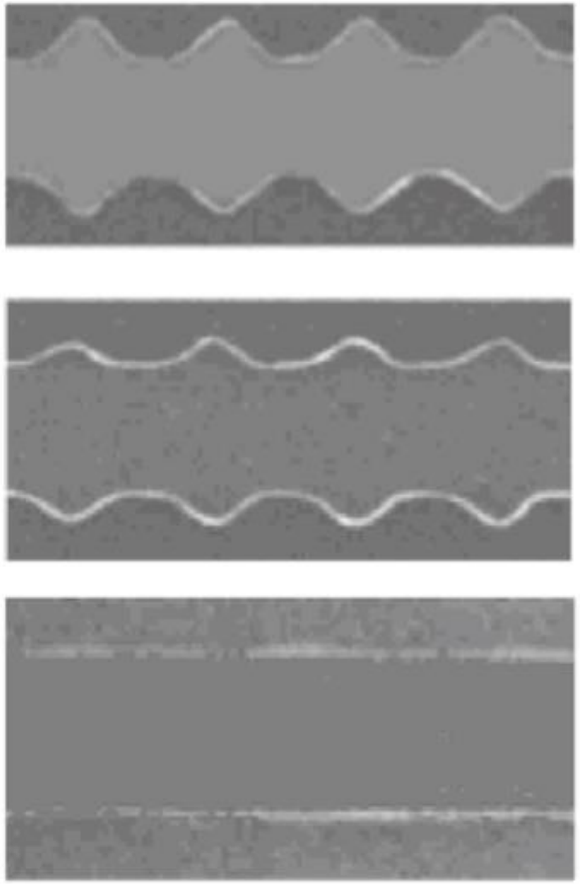
Example 1 - Domain Wall reversal in NiFe nanowires with Pt layer

MOKE



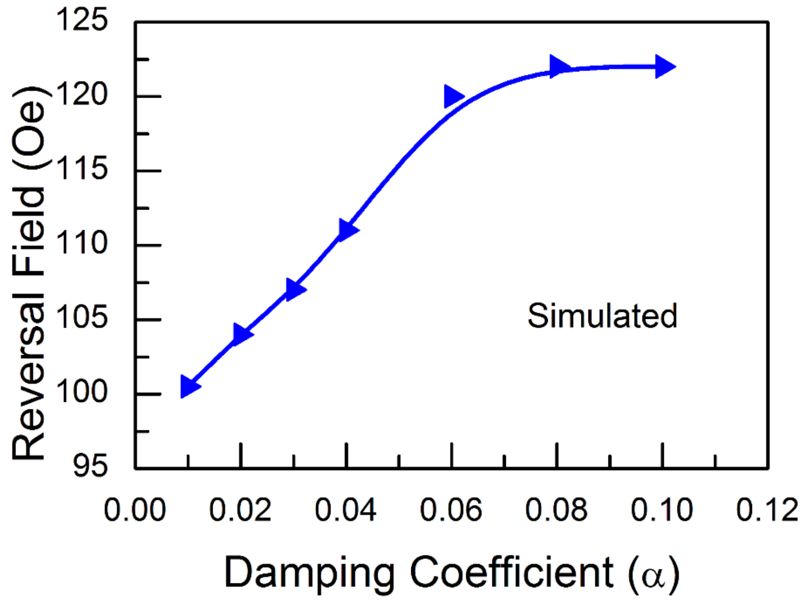
J Brandão et al. Scientific Reports 2017

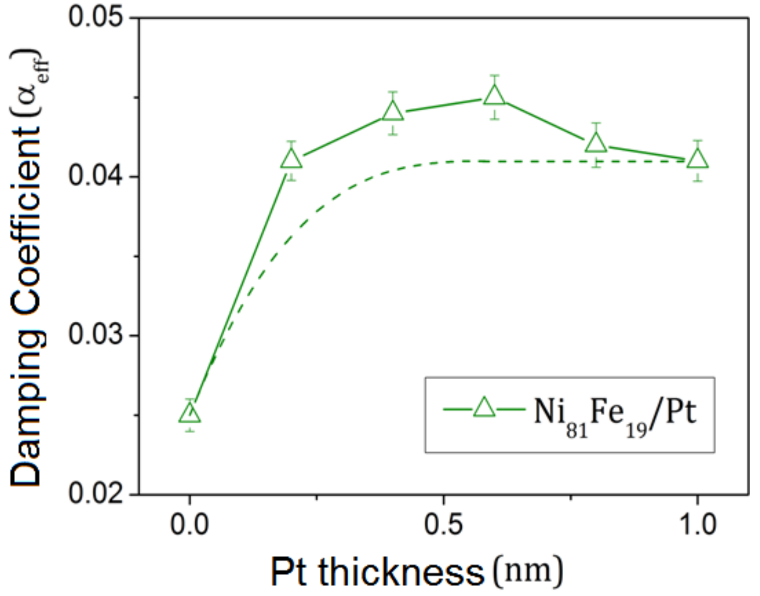
$Ni_{80}Fe_{20}$ Planar Nanowires
10 nm thick

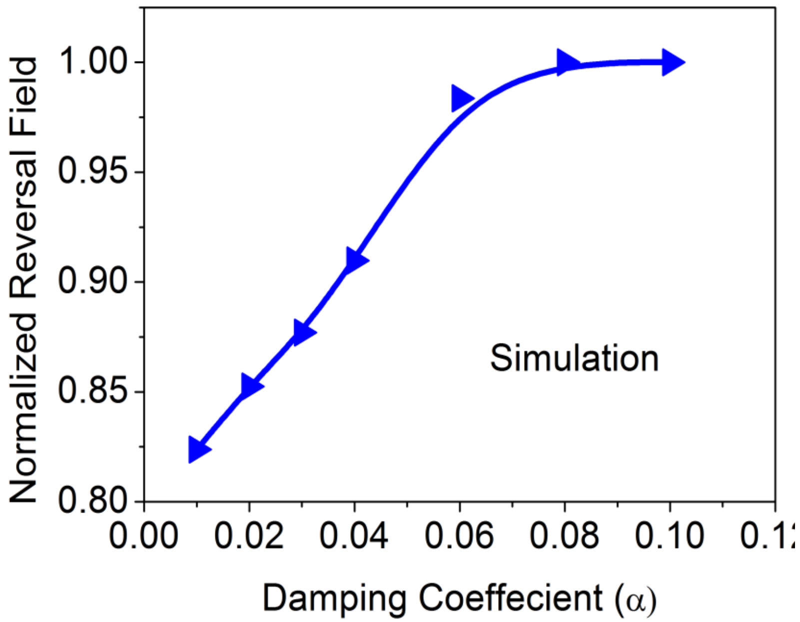


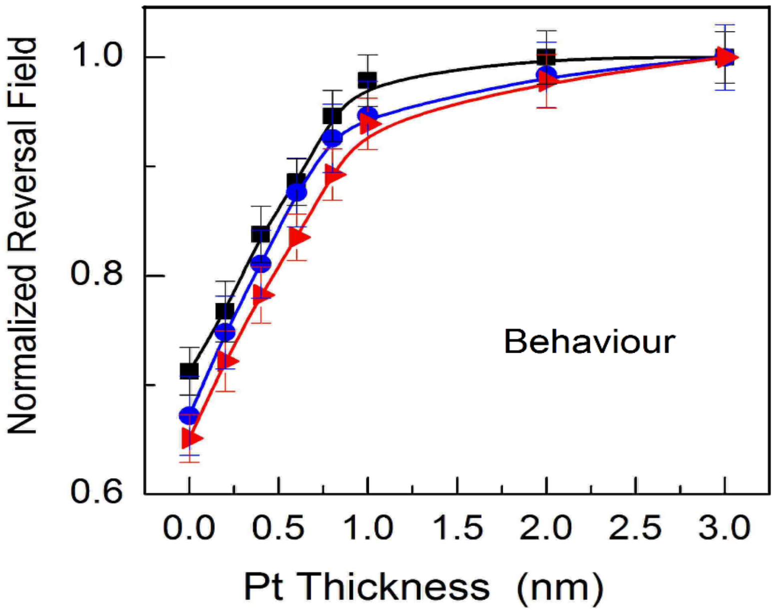
J Brandão et al. APL 2016

DW reversal field NiFe/Pt – Ferromagnetic Damping

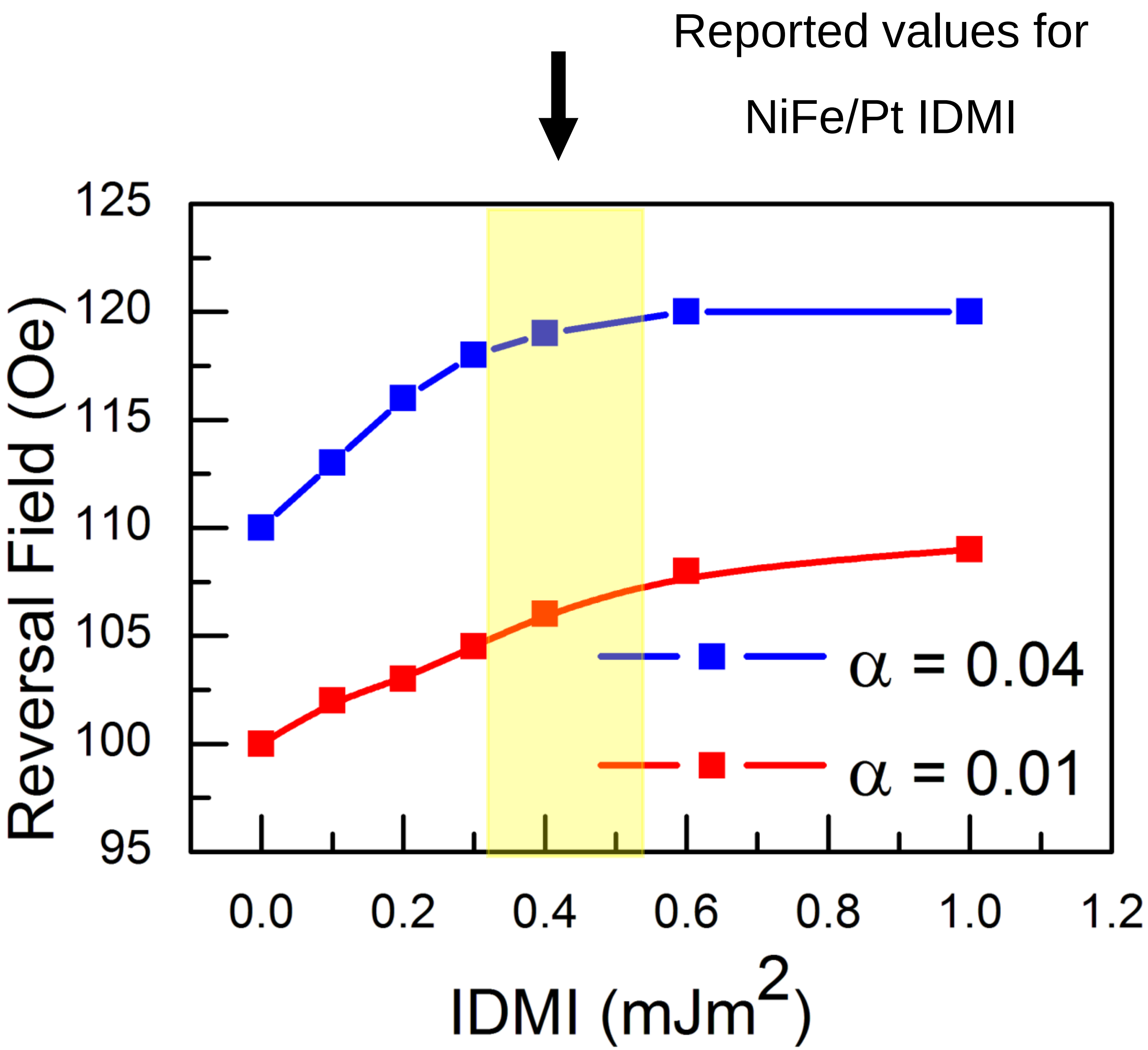








DW reversal field in NiFe/Pt – interfacial DMI



Micromagnetic simulations

J Brandão et al. Scientific Reports 2017

Example 2 - Is there a relation between PIM & damping/spin current flow?

Some debate …some of the key papers…

M. Caminale, A. Ghosh, S. Auffret, U. Ebels, *et al.*, ***Phys. Rev. B*** 94, 014414 (2016)

L. Zhu, D. Ralph, and R. Buhrman, ***Phys. Rev. B*** 98, 134406 (2018)

A. Conca, B. Heinz, M. Schweizer, S. Keller, E. Papaioannou, and B. Hillebrands, ***Phys. Rev. B*** 95, 174426 (2017)

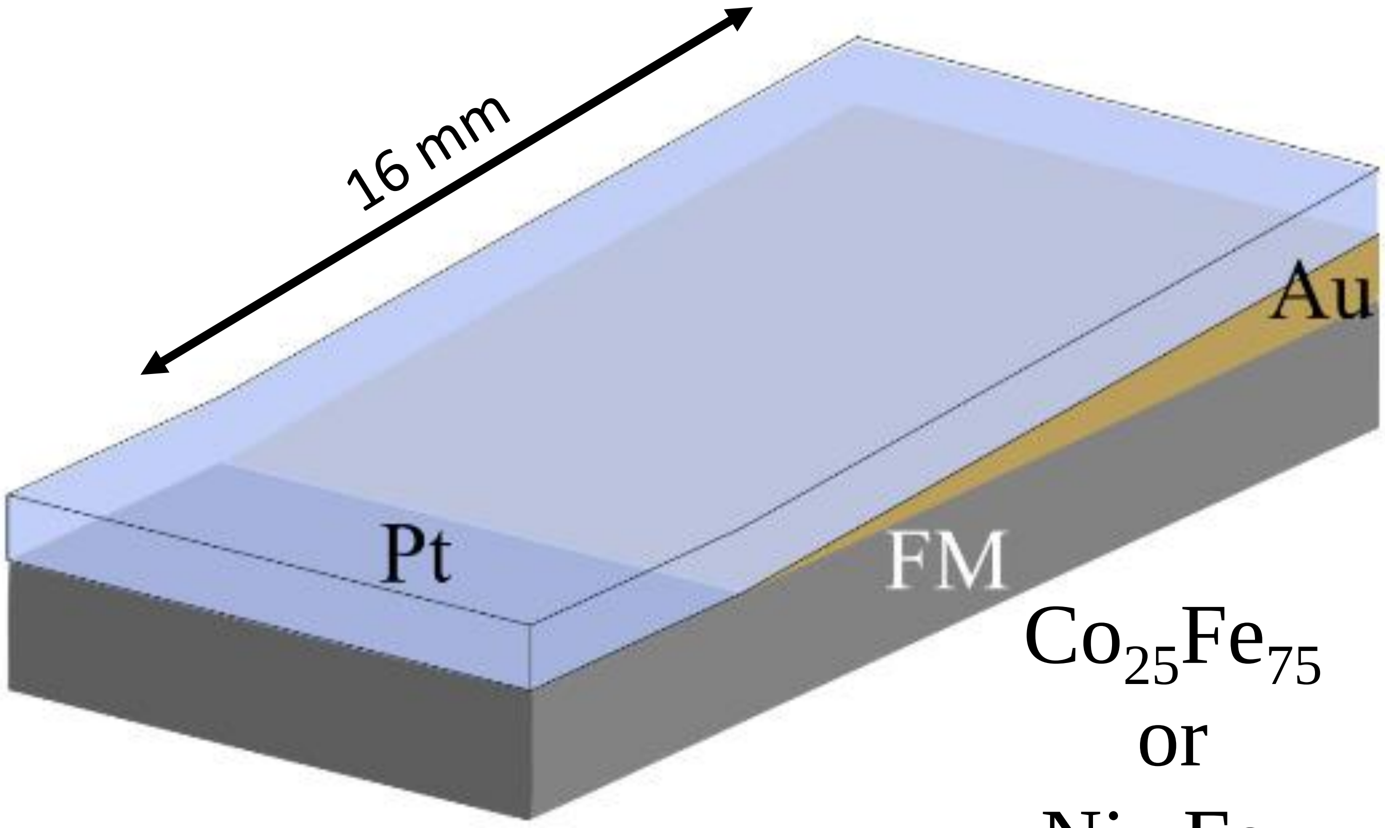
W. Amamou, I. V. Pinchuk, A. H. Trout, R. E. Williams, N. Antolin, A. Goad, D. J. O'Hara, A. S. Ahmed, W. Windl, D. W. McComb, et al., ***Phys. Rev. Mater.*** 2, 011401 (2018).

M. Collet, R. Mattana, J.-B. Moussy, K. Ollefs, S. Collin, C. Deranlot, A. Anane, V. Cros, F. Petroff, F. Wilhelm, et al., ***Appl. Phys. Lett.*** 111, 202401 (2017)

X. Liang, G. Shi, L. Deng, F. Huang, J. Qin, T. Tang, C. Wang, B. Peng, C. Song, and L. Bi, ***Physical Review Applied*** 10, 024051 (2018)

M. Valvidares, N. Dix, M. Isasa, K. Ollefs, F. Wilhelm,A. Rogalev, F. Sanchez, E. Pellegrin, A. Bedoya-Pinto, P. Gargiani, et al., ***Phys. Rev. B*** 93, 214415 (2016)

Testing the relation between Pt PIM and spin pumping



Au or Cu Spacer Layer

0 - 3 nm Au

0 – 6 nm Cu

$Co_{25}Fe_{75}$
or
$Ni_{80}Fe_{20}$

Measured PIM in Pt and damping in the SAME samples varying Spacer Layer thickness

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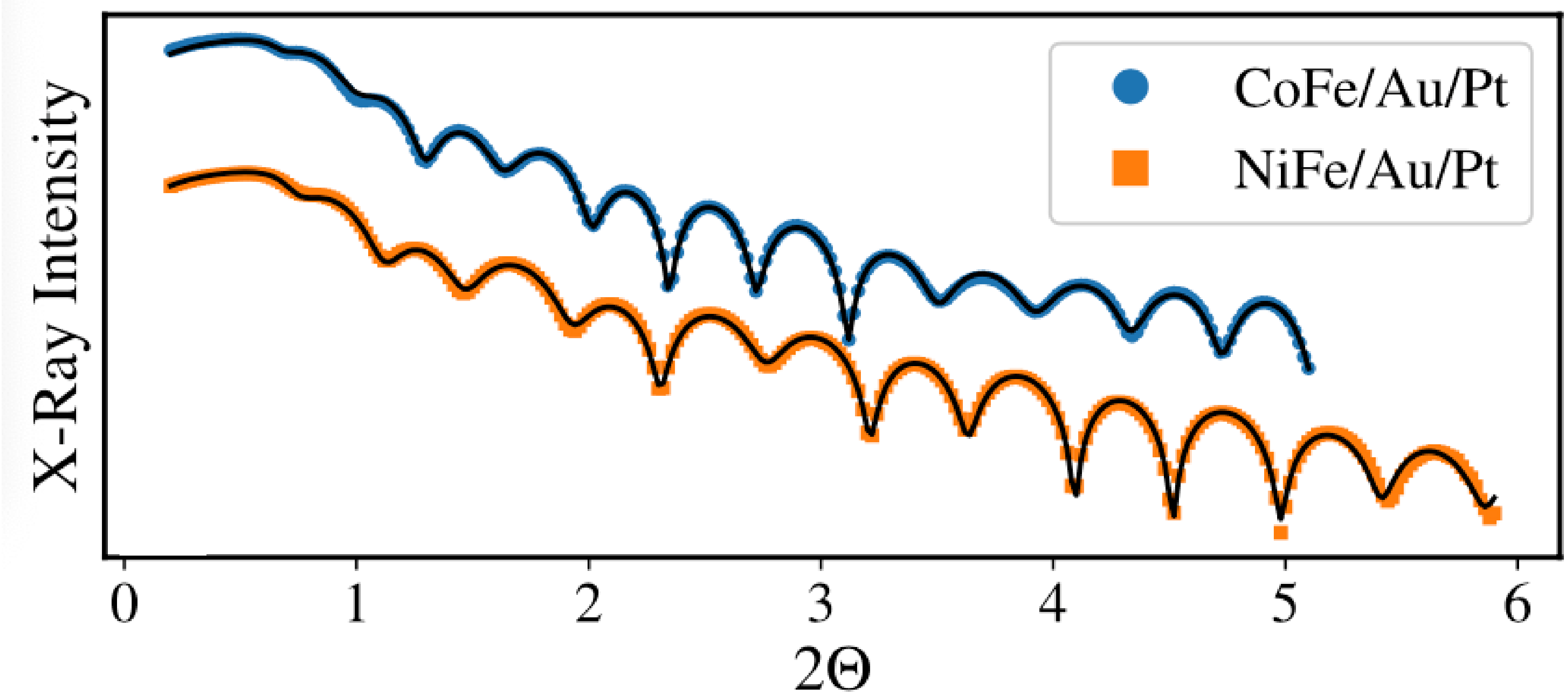
Sample structure from GIXR with Au thickness



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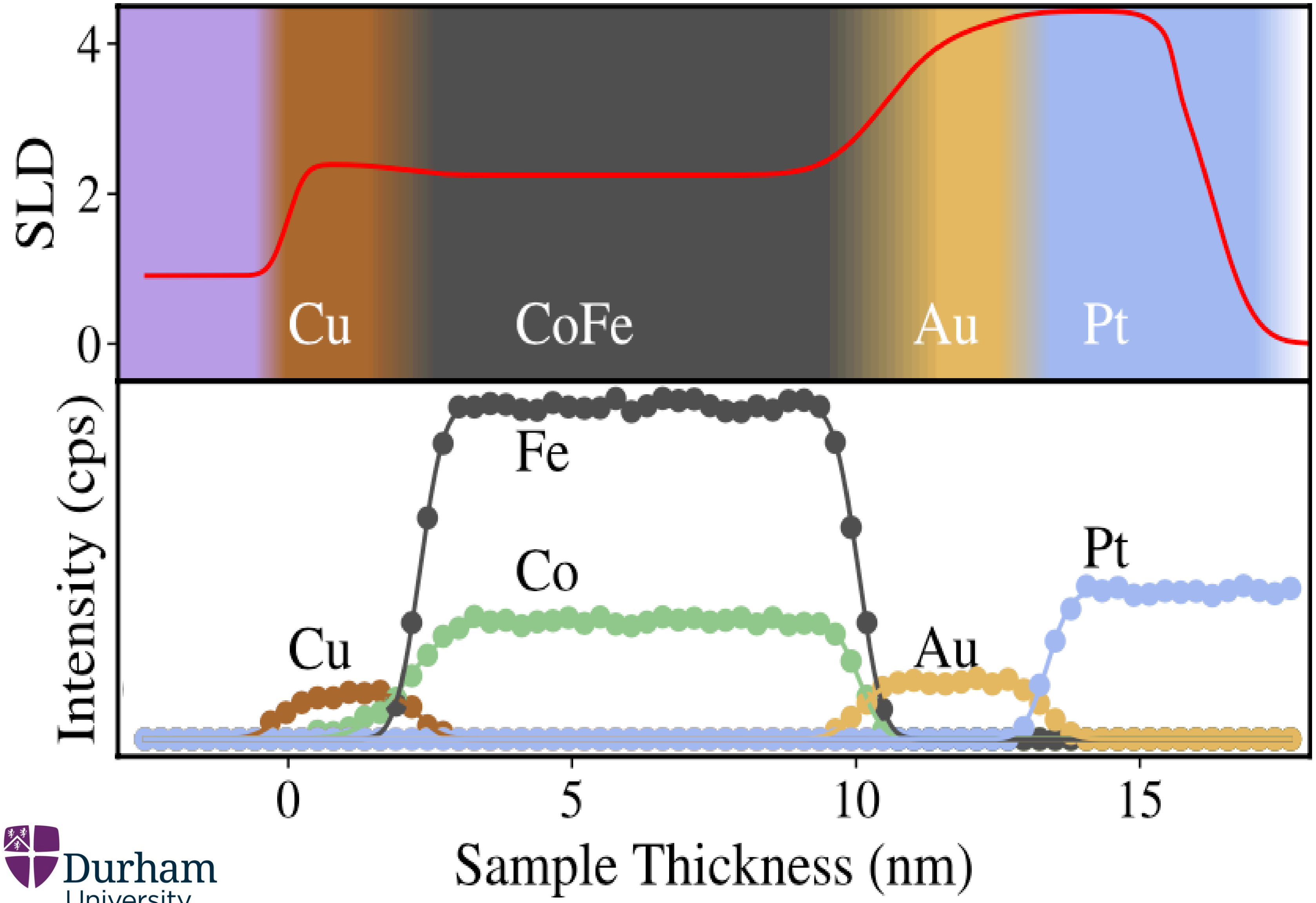
Sample structure from XRR and SIMS



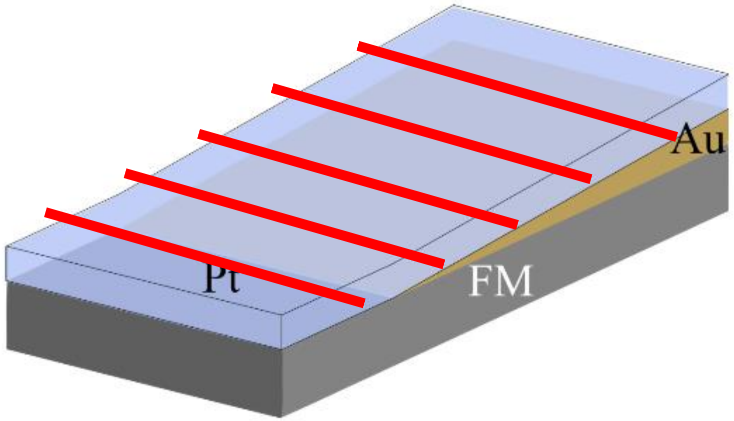
XRR
X-ray reflectivity

SLD
Scattering length density

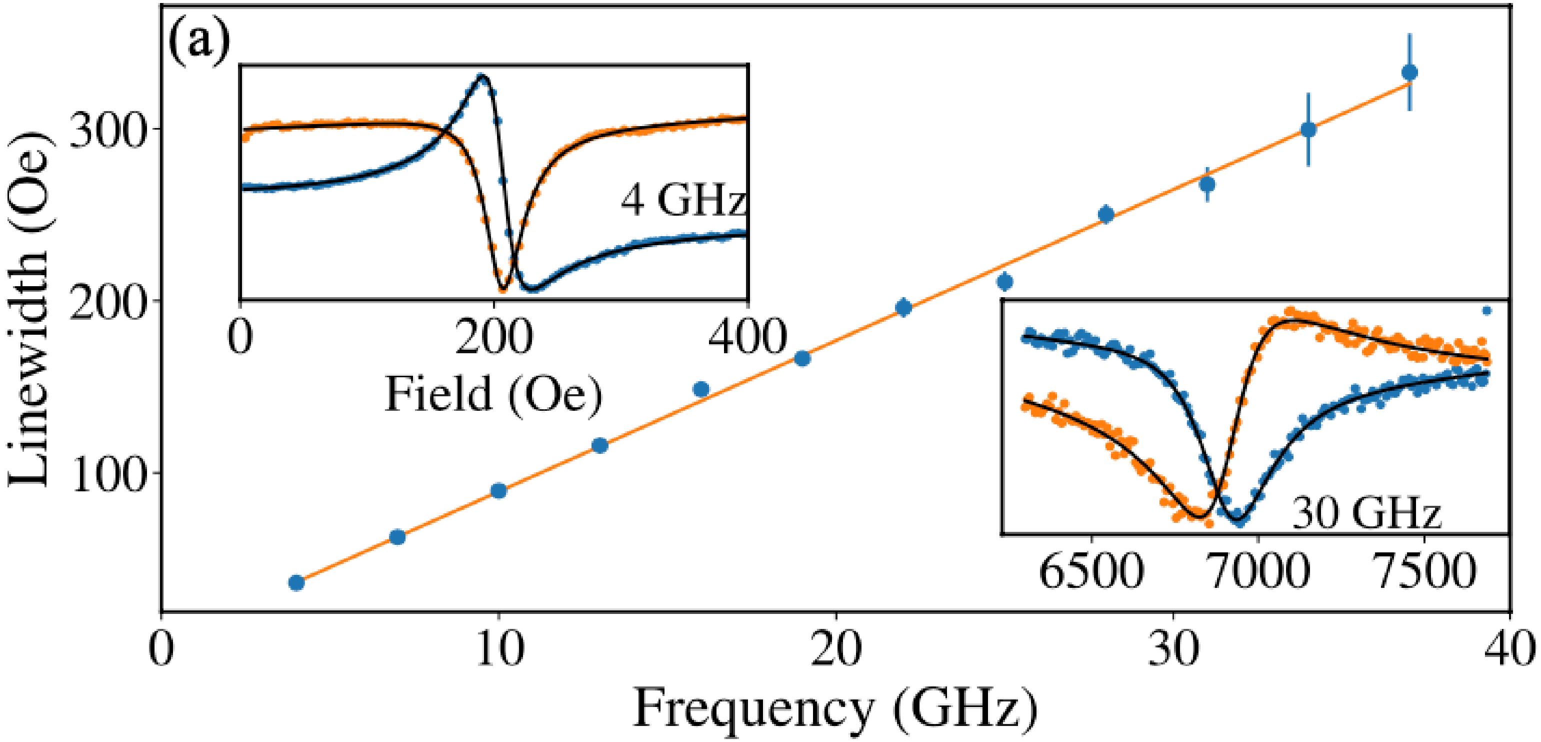
SIMS
Secondary ion mass spectrometry

Durham University

Measuring the Damping with increasing Au spacer layer



VNA FMR measurements
At different Spacer layer thicknesses



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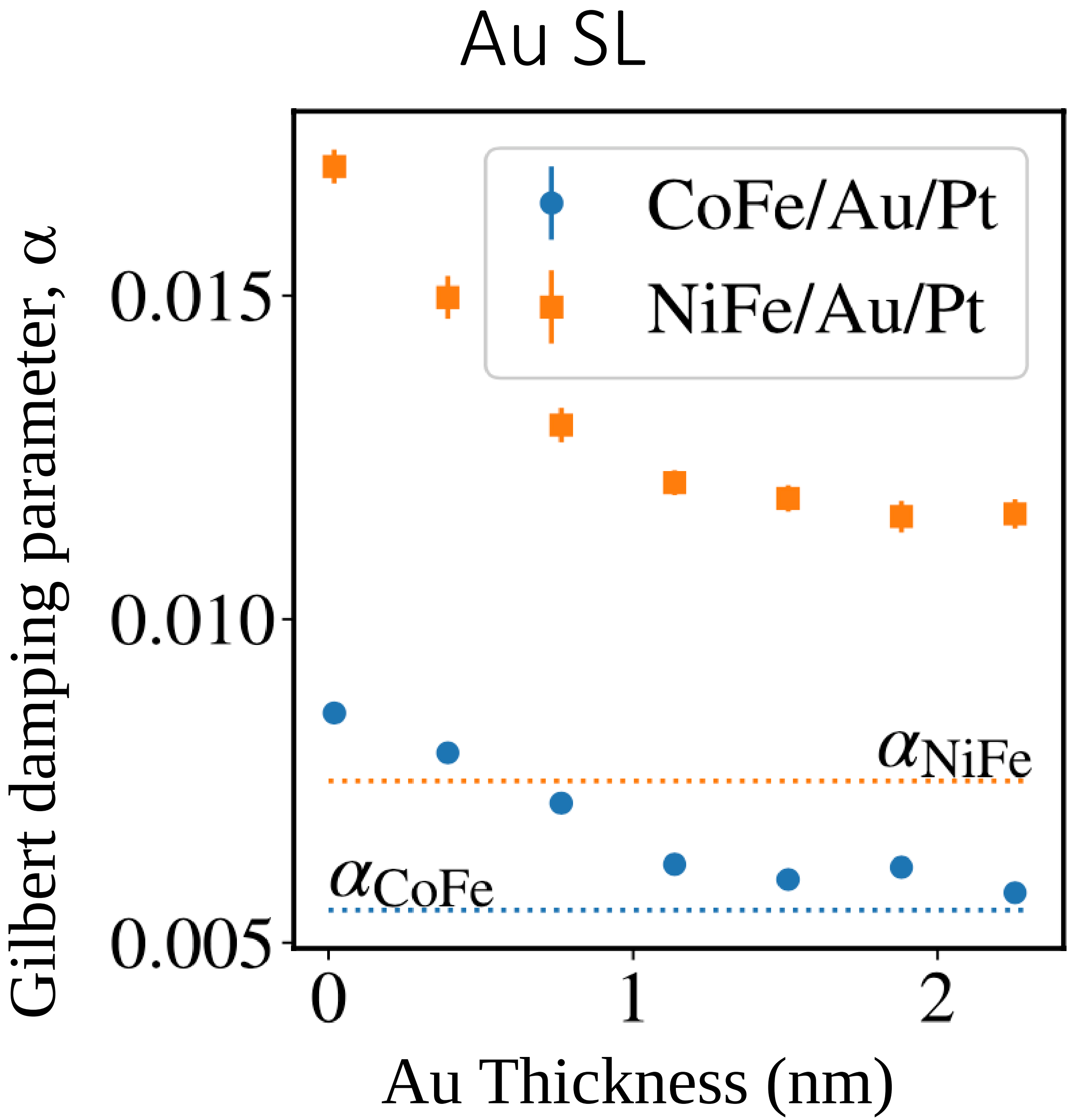
Damping with increasing Au Spacer Layer thickness



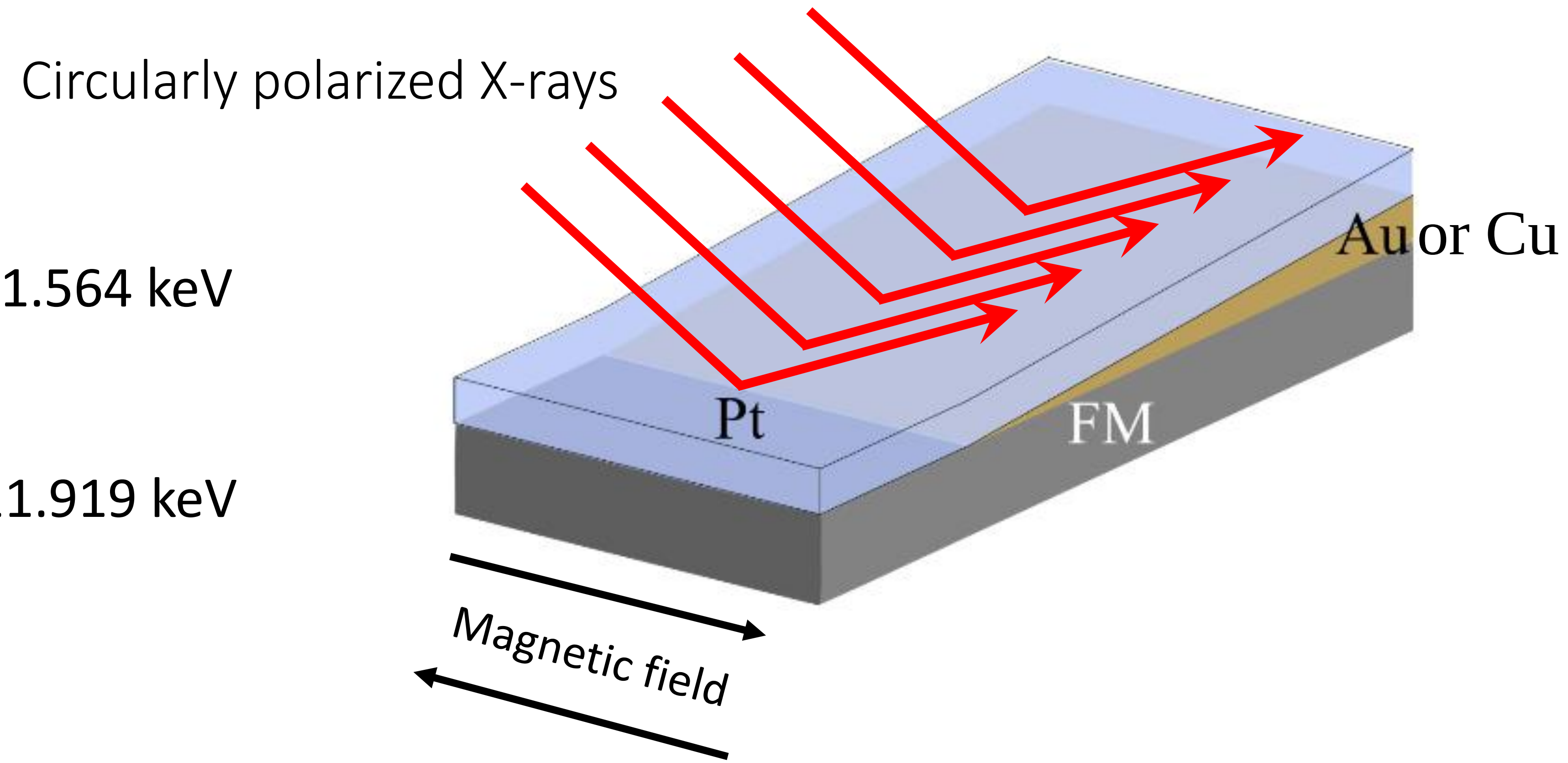
Durham University

Measuring the PIM with increasing Spacer Thickness

XMCD and XRMR measurements at different Au or Cu thicknesses

Pt
L_3 11.564 keV

Au
L_3 11.919 keV



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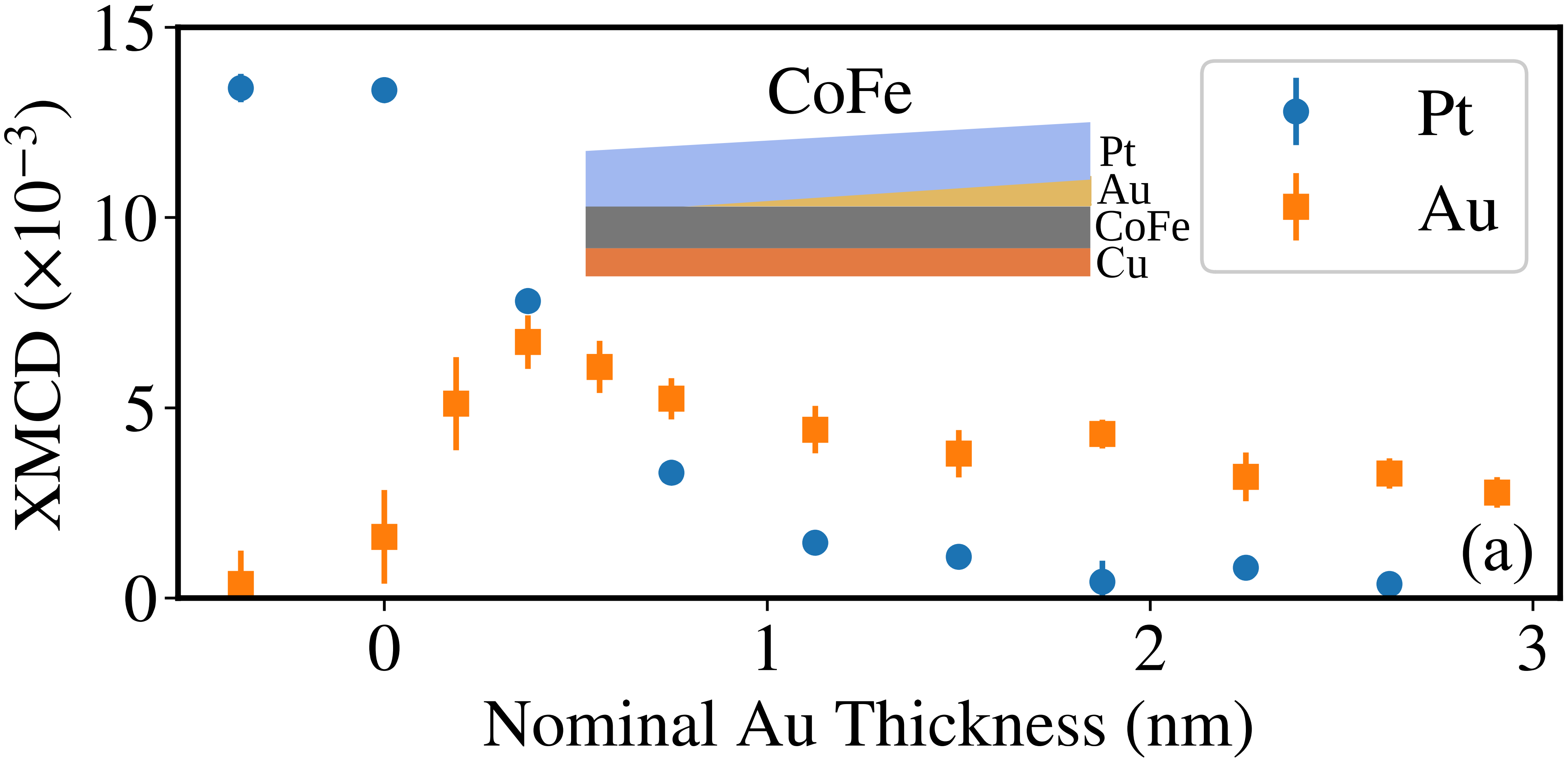
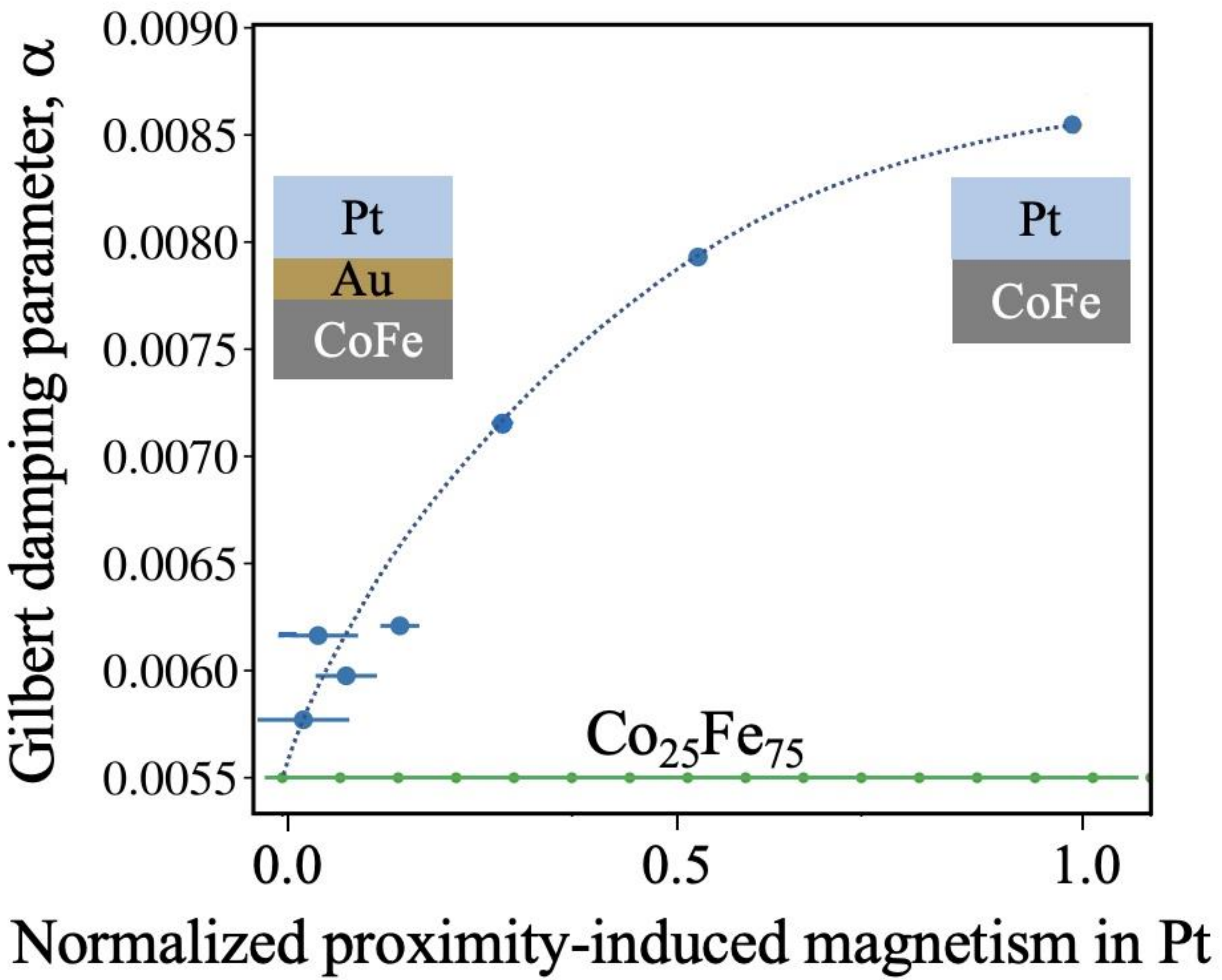
XMCD Measurement of the PIM with increasing Au spacer thickness



The relation between Pt PIM and spin pumping

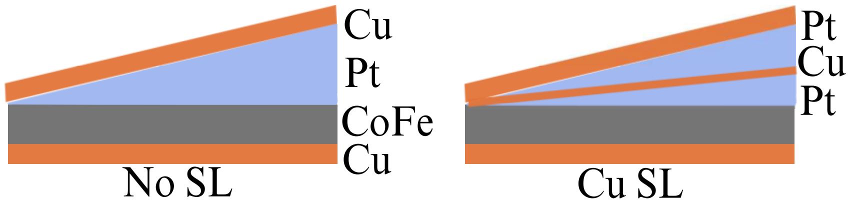
C. Swindells *et al.* ***Phys Rev B*** 105, 094433 (2022)



Au SL

CoFe/Au(t)/Pt

Is it Pt PIM or just an additional interface?



Cu SL

CoFe/Pt(t)

CoFe/Pt(t)/ Cu/Pt

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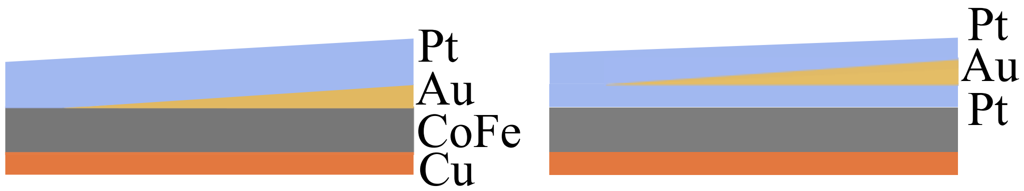
Is it Pt PIM or just an additional interface?

C. Swindells *et al.* ***Phys Rev B*** 105, 094433 (2022)



Au SL

CoFe/Pt/Au(t)/Pt

CoFe/Au(t)/Pt

Surface and Interface Magnetism: An Introduction

Summary

To introduce some relevant physics related to functional behaviour of surface and interfacial effects in magnetic thin-films and multilayers

Outline of physical principles and examples

- The emergence of magnetism with thickness
- Surface effects on magnetism
- Interfacial effects on magnetic & spin-transport phenomena

Common theme: The importance of physical structure!

Durham University

Further Information

"Magnetism of surfaces and interfaces"
U Gradmann ***J. Magn. Magn. Mater. 6*** (1977) 173-182

"Magnetism from the Atom to the Bulk in Iron, Cobalt, and Nickel Clusters"
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Further Information

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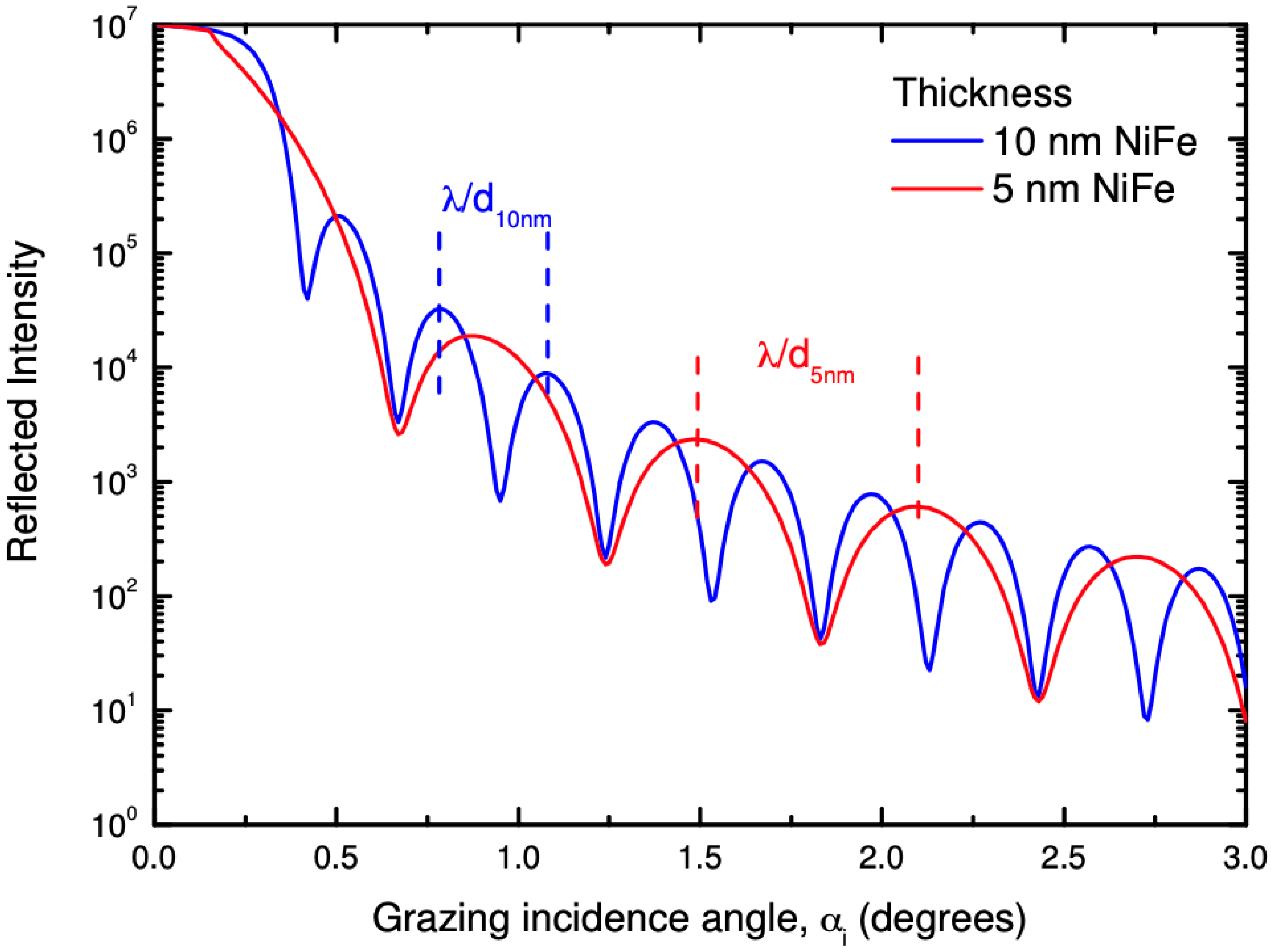
X-ray reflectivity from thin films – scattering from thin films

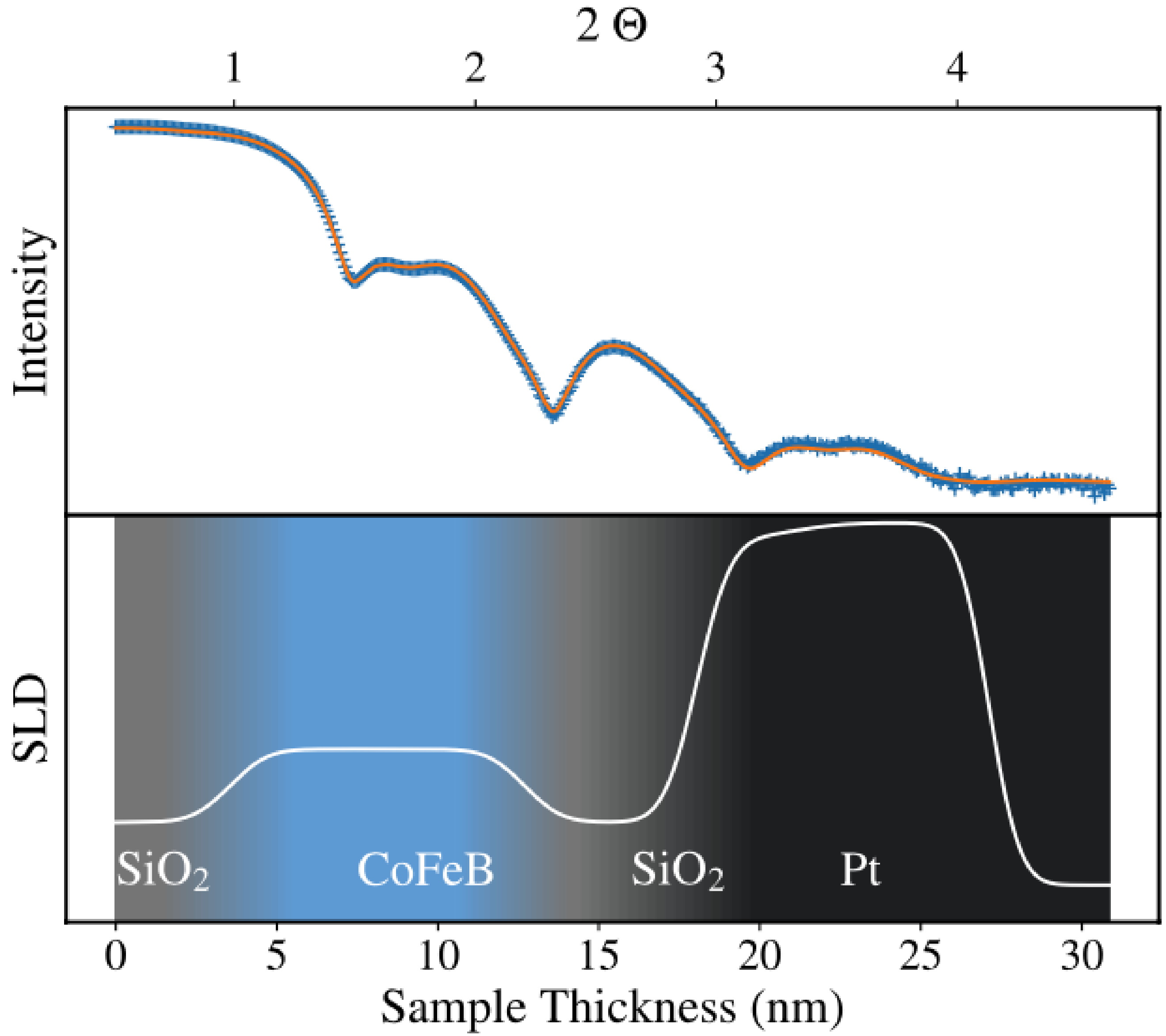
$$\alpha_{m+1} - \alpha_m = \frac{\lambda}{d}$$

d is layer thicknesss



FM/NM Interface: The importance of interfacial structure

- X-ray Reflectivity (XRR, GIXR) – Scattering Length Density - SLD



GIXR Quantification:

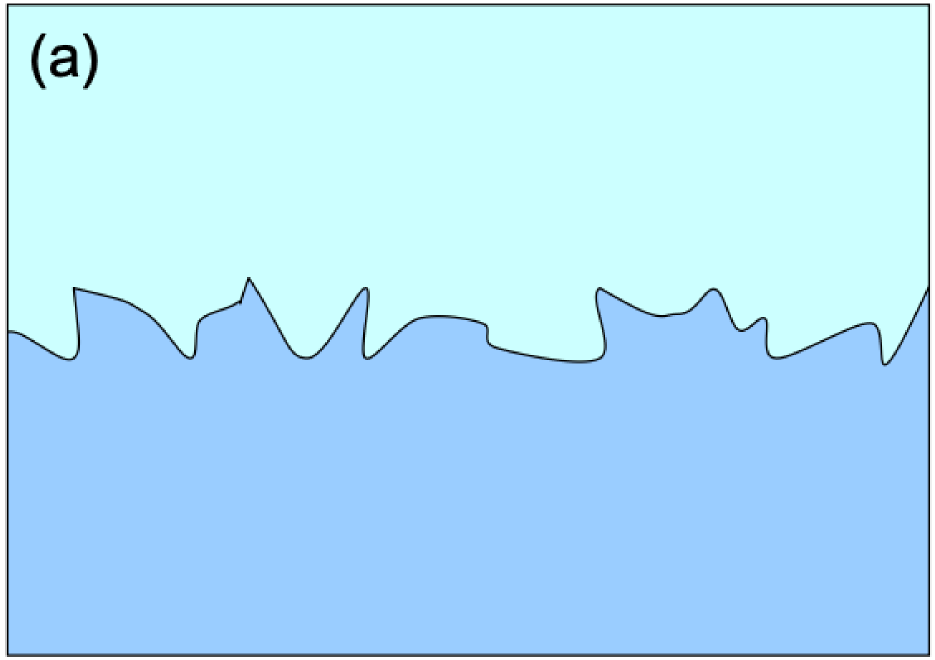
- Film thickness
- Surface roughness
- Interface width
- between layers

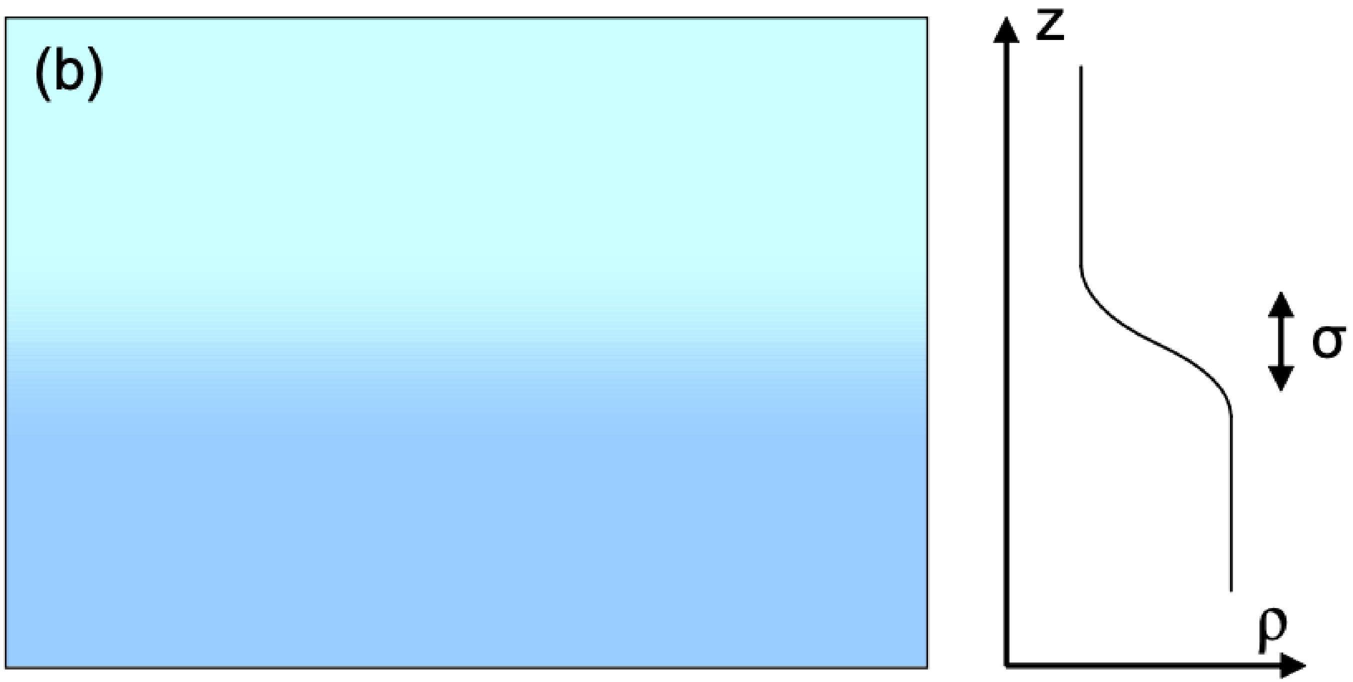
FM/NM Interface: Interface Width

GIXR Quantification:

Topographical roughness

Compositional intermixing





Cannot simply attribute to ‘roughness’ – can be roughness or intermixing or a combination