Integração de multicamadas e óxidos para a formação de skyrmions magnéticos

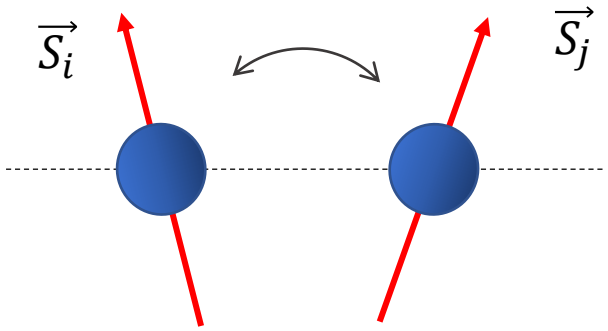
Juliana Zarpellon

2024

Domínios magnéticos

Domínios magnéticos

Dois spins localizados

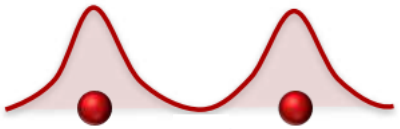


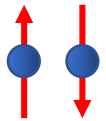
Férmions indistinguíveis

Autofunção total do sistema

ϕ

ANTI-SIMÉTRICA NA TROCA DAS COORDENADAS DAS PARTÍCULAS





singleto, E_s

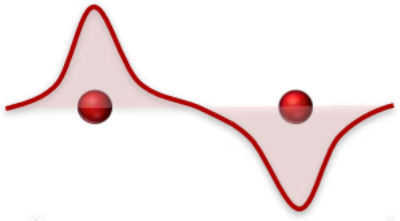
simétrica

anti-simétrica $\frac{1}{\sqrt{2}}(|\uparrow\downarrow> - |\downarrow\uparrow>)$

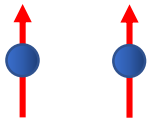
$\phi = \psi_{ESPACIAL} \cdot \varphi_{SPIN}$

anti-simétrica

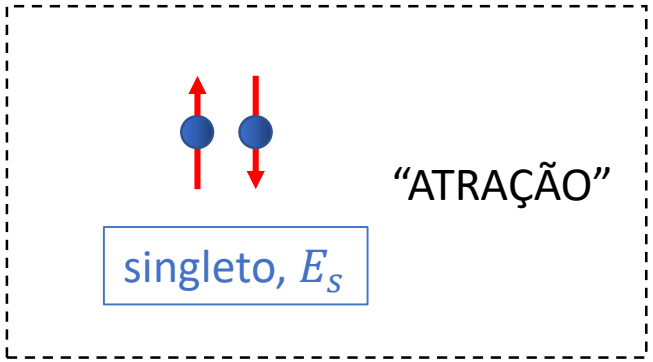
simétrica $\frac{1}{\sqrt{2}}(|\uparrow\downarrow> + |\downarrow\uparrow>); |\uparrow\uparrow>; |\downarrow\downarrow>$

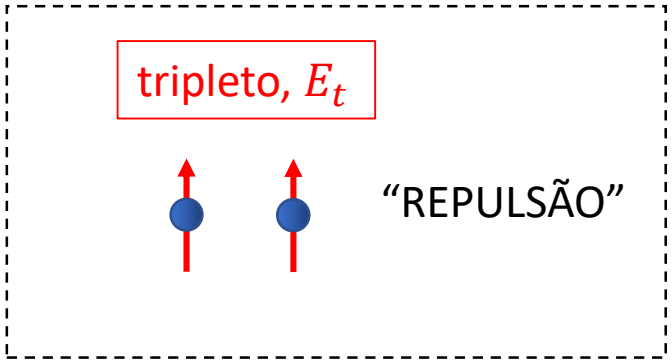


tripleto, E_t



Domínios magnéticos





$$E_s \neq E_t$$

$$(E_s - E_t) \propto \frac{e^2}{4\pi\varepsilon_0} \iint \psi_i(\vec{r_1})\psi_j(\vec{r_2}) \frac{1}{|r_2 - r_1|} \psi_j^*(\vec{r_1})\psi_i^*(\vec{r_2}) d\vec{r_1} d\vec{r_2}$$

Integral de troca J

conectada à orientação relativa dos spins

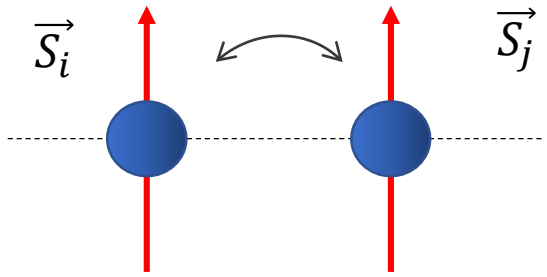
paridade da função de onda

INTERAÇÃO DE TROCA

Hamiltoniano de Heisenberg

$$H_H = -\sum_{i \neq j} J \vec{S_i} \cdot \vec{S_j}$$

spins paralelos

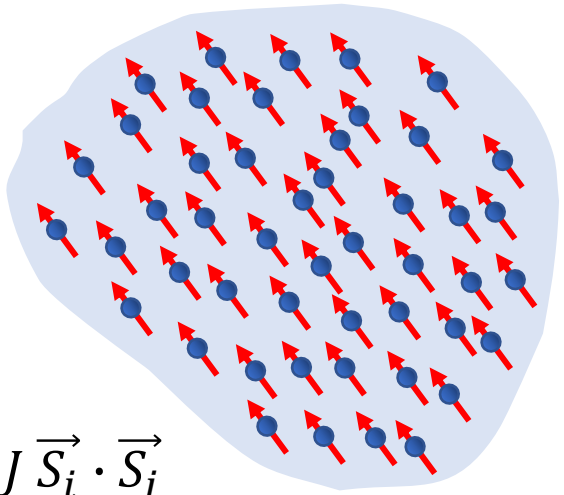


FERROMAGNETISMO

Domínios magnéticos

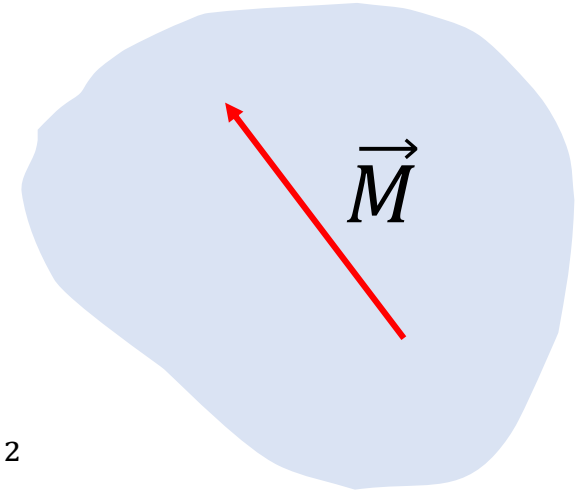
MATERIAL FERROMAGNÉTICO

milhares de spins, volume V



pequenos desvios em torno da direção

preferencial de alinhamento



$$\vec{M} = \frac{\mu_B}{V}\sum_i \vec{S_i}$$

$$|\vec{M}| = M_S$$

magnetização de saturação

$$H = -\sum_{i \neq j} J\,\vec{S_i}\cdot\vec{S_j}$$

$$\vec{S}_i \cdot \vec{S}_{i+1} = \vec{M}^2 - a^2\left(\partial_i \vec{M}\right)^2$$

Interação de troca micromagnética

$$W = -\sum_i \frac{a^2 J}{V}\left(\partial_i \vec{M}\right)^2 = -\sum_i A\left(\partial_i \vec{M}\right)^2$$

distância entre os átomos

exchange stiffness

grau de alinhamento dos momentos magnéticos atômicos

Domínios magnéticos

MATERIAL FERROMAGNÉTICO

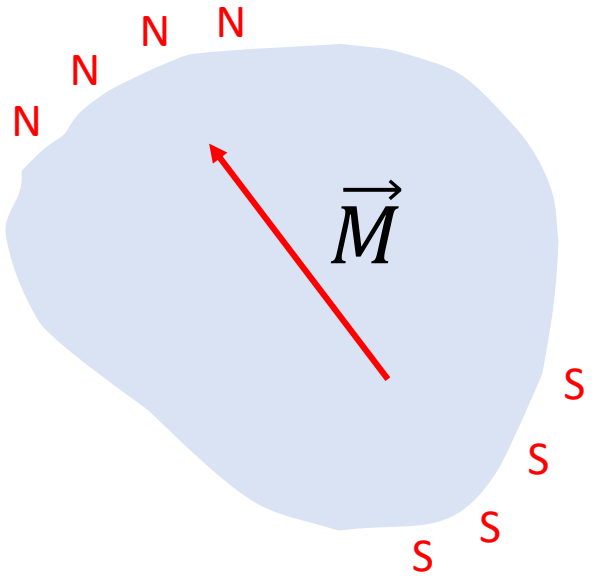
milhares de spins, volume V

pequenos desvios em torno da direção

preferencial de alinhamento

$$\hat{H} = -\sum_{i \neq j} J\, \vec{S}_i \cdot \vec{S}_j$$

Qual a consequência disso?



$$\vec{M} = \frac{\mu_B}{V} \sum_i \vec{S}_i$$

$$|\vec{M}| = M_S$$

magnetização de saturação

Distância entre os átomos

Interação de troca micromagnética

$$W = \sum_i \frac{a^2 J}{V} \left(\partial_i \vec{M}\right)^2$$

grau de alinhamento dos momentos magnéticos atômicos

$$\vec{S}_i \cdot \vec{S}_{i+1} = \vec{M}^2 - a^2 \left(\partial_i \vec{M}\right)^2$$

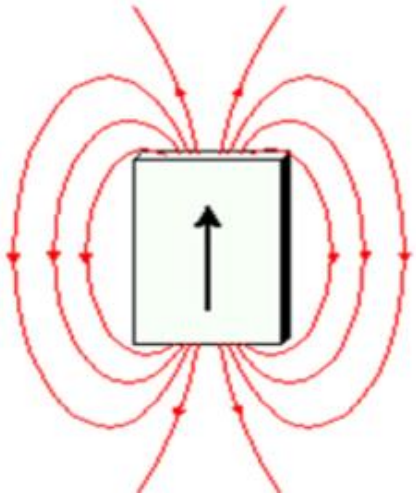
Domínios magnéticos

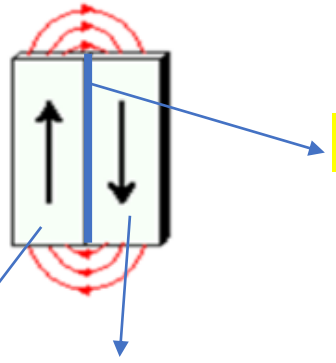
$E_{dipolar,inicial}$ → muito grande
$E_{troca,inicial}$ → mínima

$E_{dipolar} \rightarrow E_{dipolar,inicial}/2$
$E_{troca} > E_{troca,inicial}$

$E_{dipolar} \rightarrow E_{dipolar,inicial}/4$
$E_{troca} >> E_{troca,inicial}$

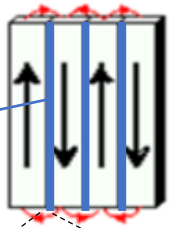
campo dipolar
ou
campo de fuga
$\vec{H}_{fuga}$



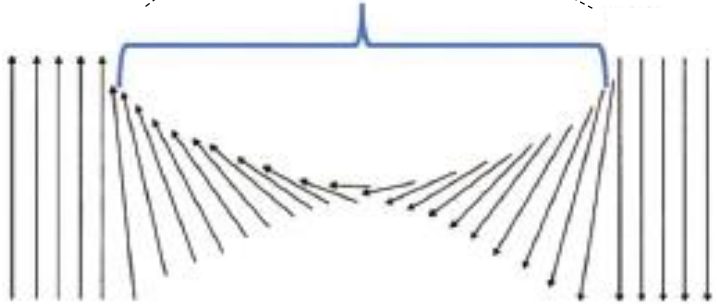


PAREDES DE DOMÍNIO

DOMÍNIOS MAGNÉTICOS



$\delta \propto \lambda$



$\downarrow E_{dipolar}$

$\uparrow E_{troca}$

Formação de domínios magnéticos

$$\lambda = \sqrt{\frac{A}{K_d}} = \sqrt{\frac{2A}{\mu_0 M_S^2}}$$

comprimento de troca

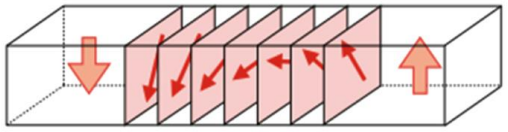
Interação dipolar X Interação de troca

Domínios magnéticos

Paredes de domínio

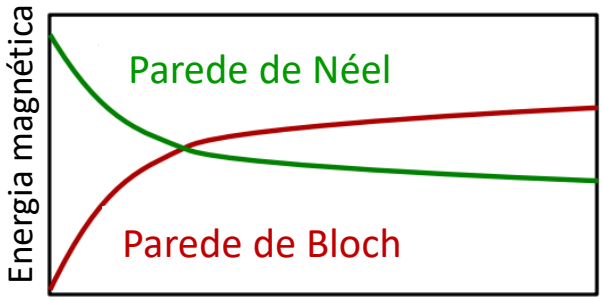
1D

Parede de Bloch



Parede de Néel

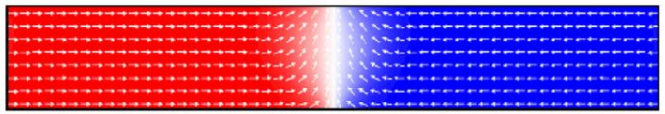




dimensão do sistema

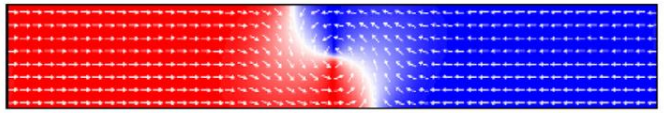
2D e 3D

Transverse Wall

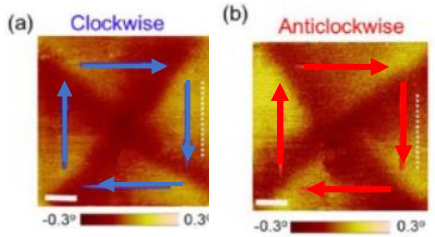


$d < \lambda$

Vortex Wall



$d > \lambda$



Zhang et al., Science Bulletin (2020)

Interação dipolar ***X*** *Interação de troca*

Manipulação das interações

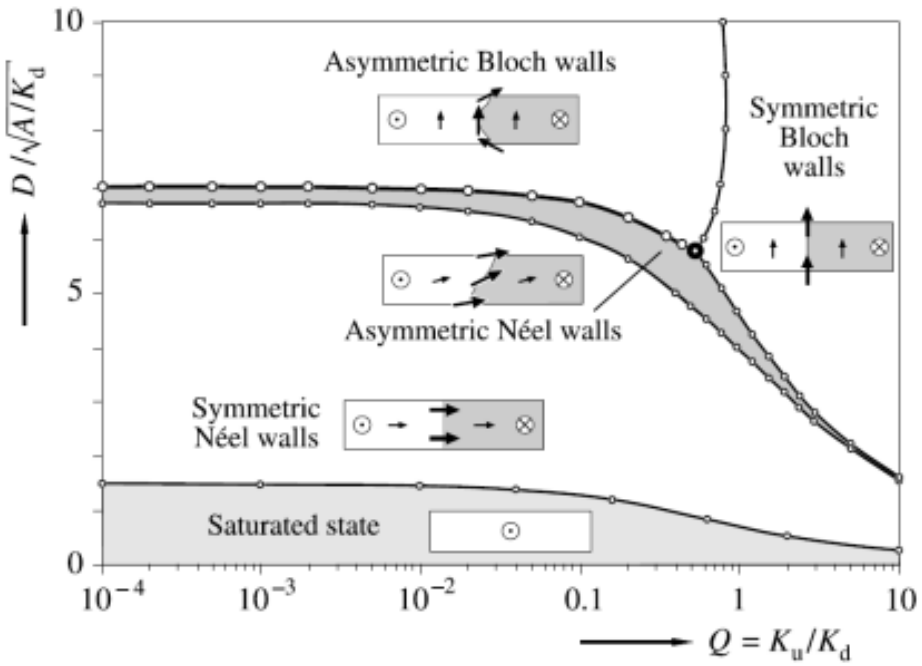


Diagrama de fase em um filme fino

Domínios magnéticos

Interação de troca ***X*** *Interação dipolar*

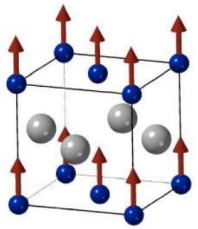
acoplamento spin-órbita E simetria cristalina

Eixos de fácil e de difícil magnetização

Bulk – 3D

Uniaxial anisotropy

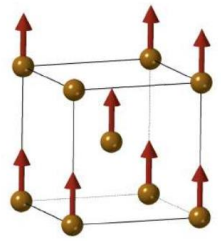
$W_u = K_0 + K_1 \sin^2\theta + K_2 \sin^4\theta + K_2' \sin^4\theta \cos 4\varphi \ldots$



Example: $L1_0$ phase (CoPt, FePt)

Cubic anisotropy

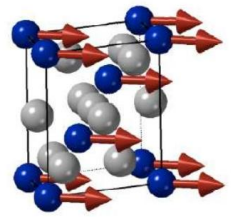
$W_c = K_0 + K_{c1}(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_{c2}\alpha_1^2\alpha_2^2\alpha_3^2$



Example: bcc, hcp, fcc (Fe, Co, Ni)

Hexagonal anisotropy

$W_t = K_0 + K_1 \sin^2\theta + K_2 \sin^4\theta + K_2' \sin^3\theta \cos\theta \sin 3\varphi$

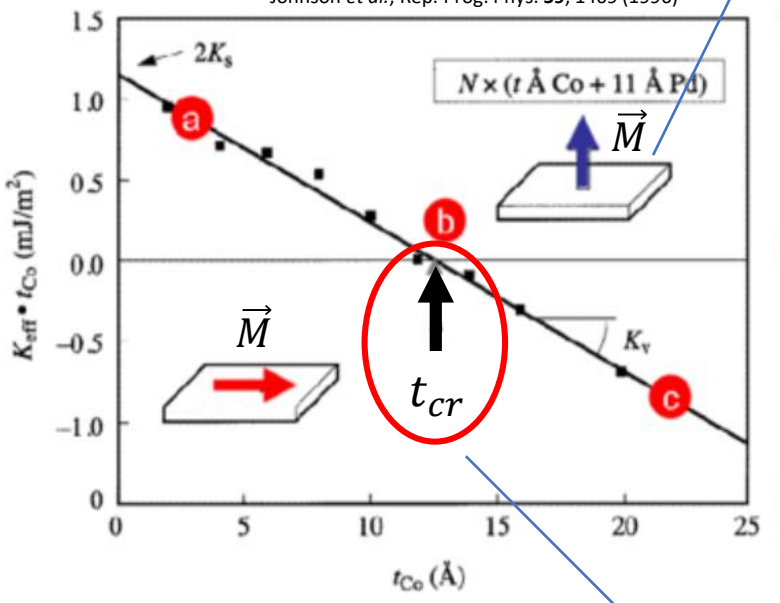


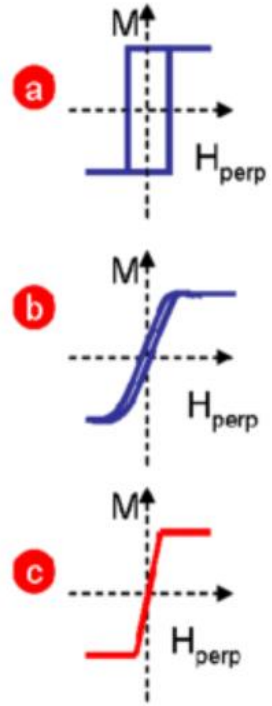
Example: $L1_1$ phase (CoPt, FePt)

$E_{MC} > E_{dipolar}$

Superfícies/interfaces – 2D

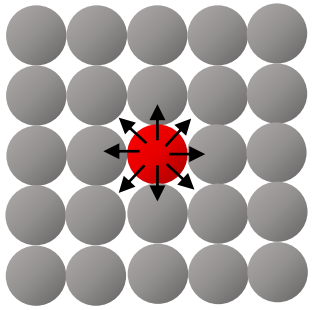
Johnson *et al.*, Rep. Prog. Phys. **59**, 1409 (1996)





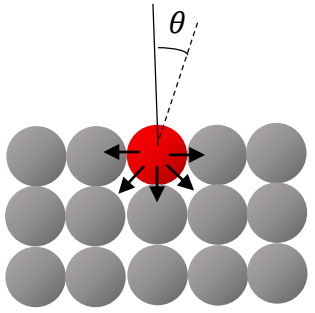
$E_{MC} < E_{dipolar}$

SIMETRIA DAS LIGAÇÕES



$$E_{MC} = \left(K_V + \frac{2K_s}{t}\right) sen^2\theta$$

dimensão



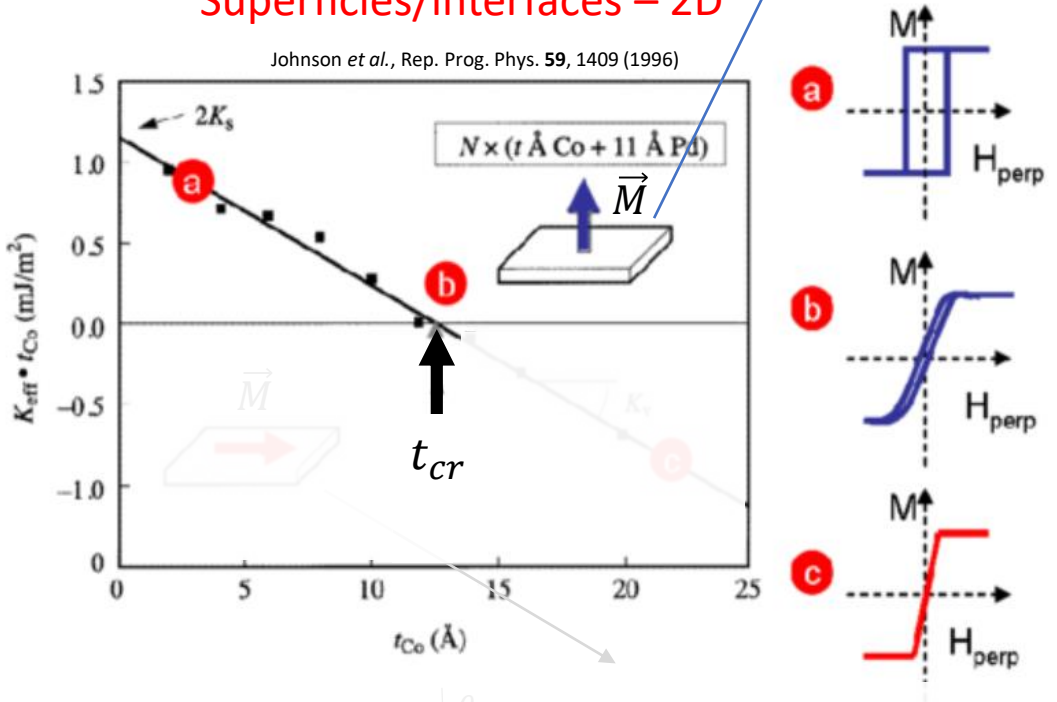
QUEBRA DE SIMETRIA DAS LIGAÇÕES

Domínios magnéticos

$E_{MC} > E_{dipolar}$

Superfícies/interfaces – 2D

Johnson *et al.*, Rep. Prog. Phys. **59**, 1409 (1996)



Anisotropia magnética perpendicular

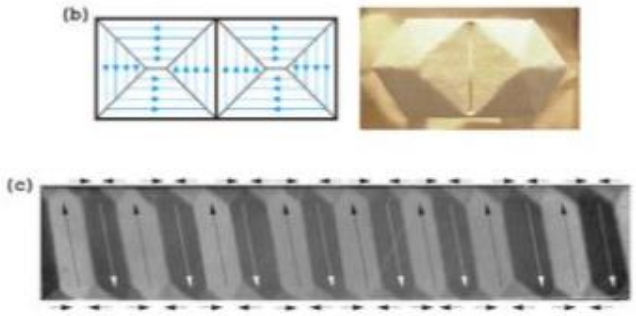
PMA

Domínios magnéticos

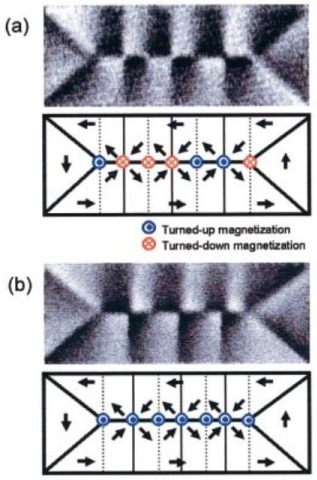
Interação de troca **X** *Interação dipolar* **X** *Anisotropia magnetocristalina*

Diferentes formatos e tamanhos

Fe



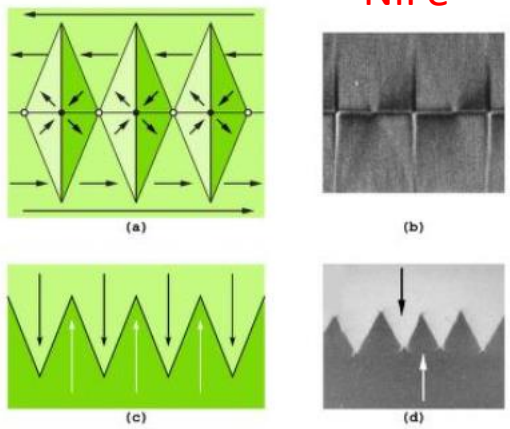
Fruchart, *Lecture on nanomagnetism*



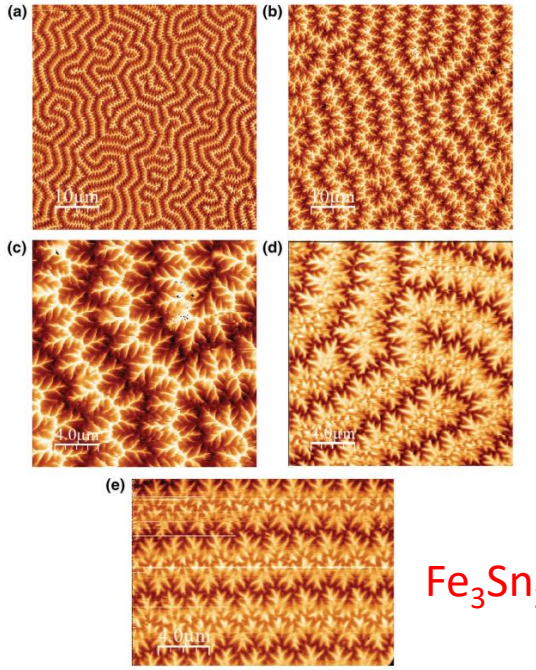
Moon *et al.*, *NPG Asia Materials*

CoFe

NiFe

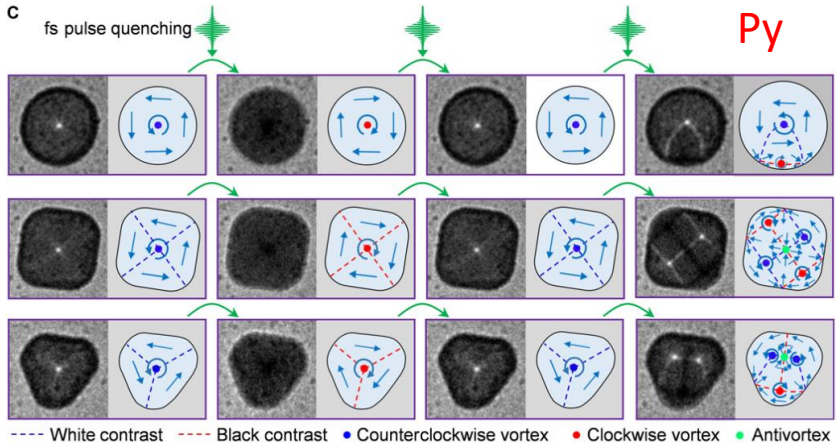


Joinsten *et al.*, JMMM **233**, 230 (2001)



Fe_3Sn_2

Heritage *et al.*, Adv. Funct. Mat. **30**, 1909163 (2020)

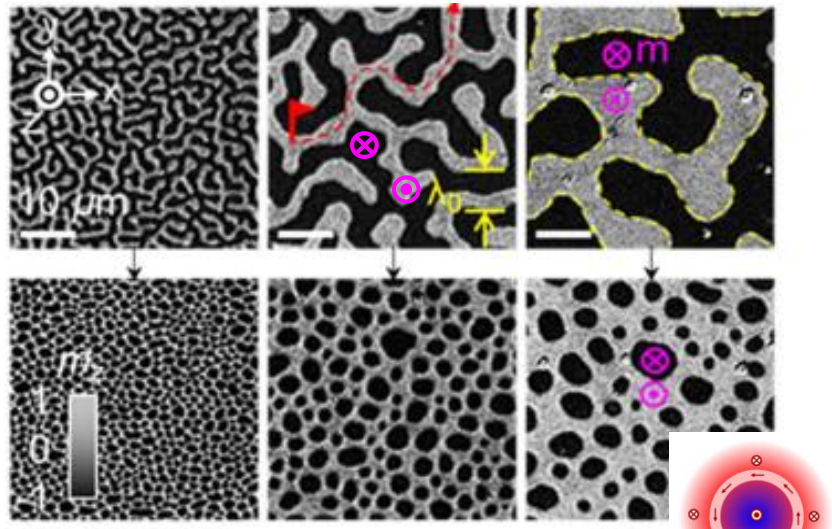


Py

Fu *et al.*, Science Adv. 4, 3077 (2018)

Maze domains

CoFeB/MgO



Moon *et al.*, NPG Asia Materials

Bubble domains

Domínios magnéticos

Interação de troca **X** *Interação dipolar* **X** *Anisotropia magnetocristalina*

Diferentes formatos e tamanhos

Fe

Fruchart, *Lecture on nanomagnetism*

NiFe

CoFe

Moon *et al.*, *NPG Asia Materials*

Joinsten *et al.*, JMMM **233**, 230 (2001)

Fe_3Sn_2

Heritage *et al.*, Adv. Funct. Mat. **30**, 1909163 (2020)

Py

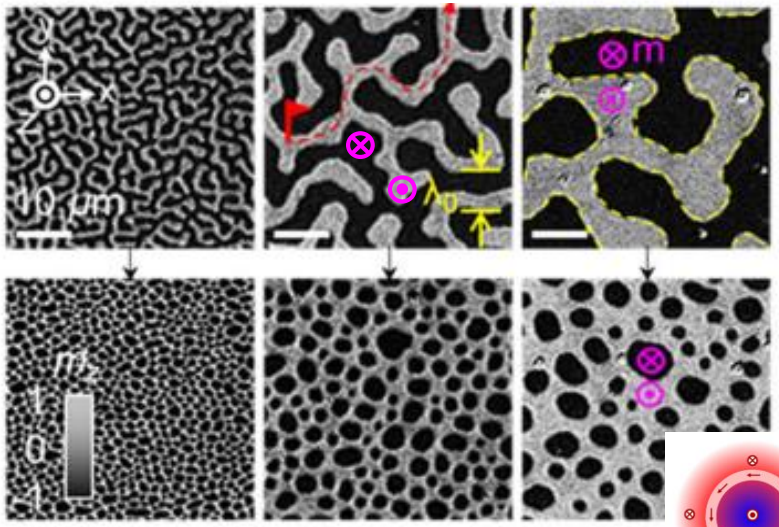
White contrast Black contrast Clockwise vortex Antivortex

ence Adv. 4, 3077 (2018)

PMA

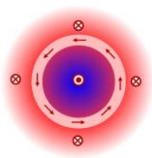
CoFeB/MgO

Maze domains



Moon *et al.*, NPG Asia Materials

Bubble domains

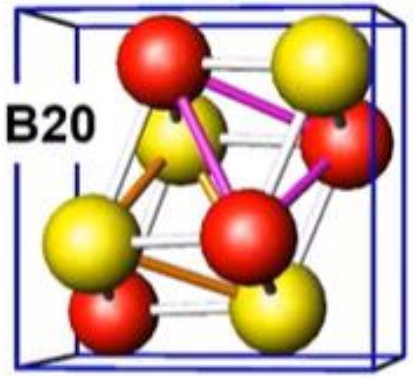


Skyrmions magnéticos

Skyrmions magnéticos

Sistemas sem ou com quebra de simetria de inversão → Interação de troca assimétrica

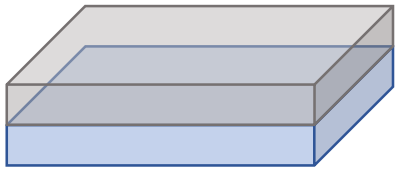
Estrutura cúbica B20
Bulk – 3D



Exemplos: MnSi, FeGe

Bicamada FM/HM
Interface – 2D

Material ferromagnético



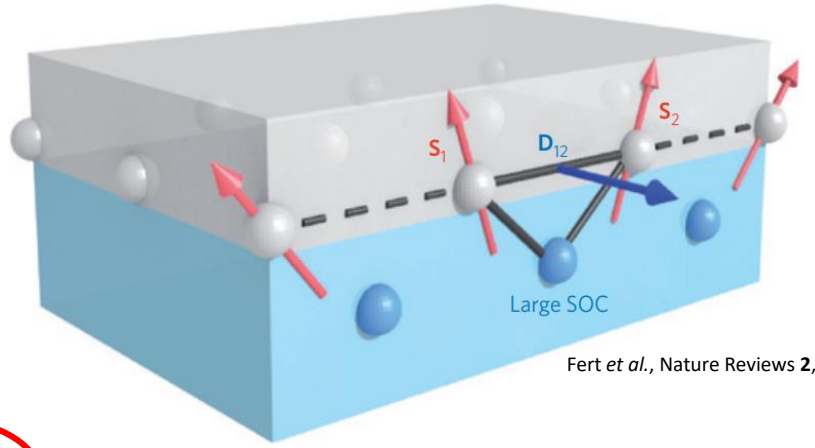
Metal pesado
→ forte acoplamento SO

Exemplos: CoFeB/MgO, Co/Ni

Interação Dzyaloshinskii-Moriya

$$H_{DM} = -\sum_{i \neq j} \vec{D} \cdot (\vec{S_i} \times \vec{S_j})$$

spins inclinados
E
perpendiculares à
interface



Fert *et al.*, Nature Reviews **2**, 17031 (2017)

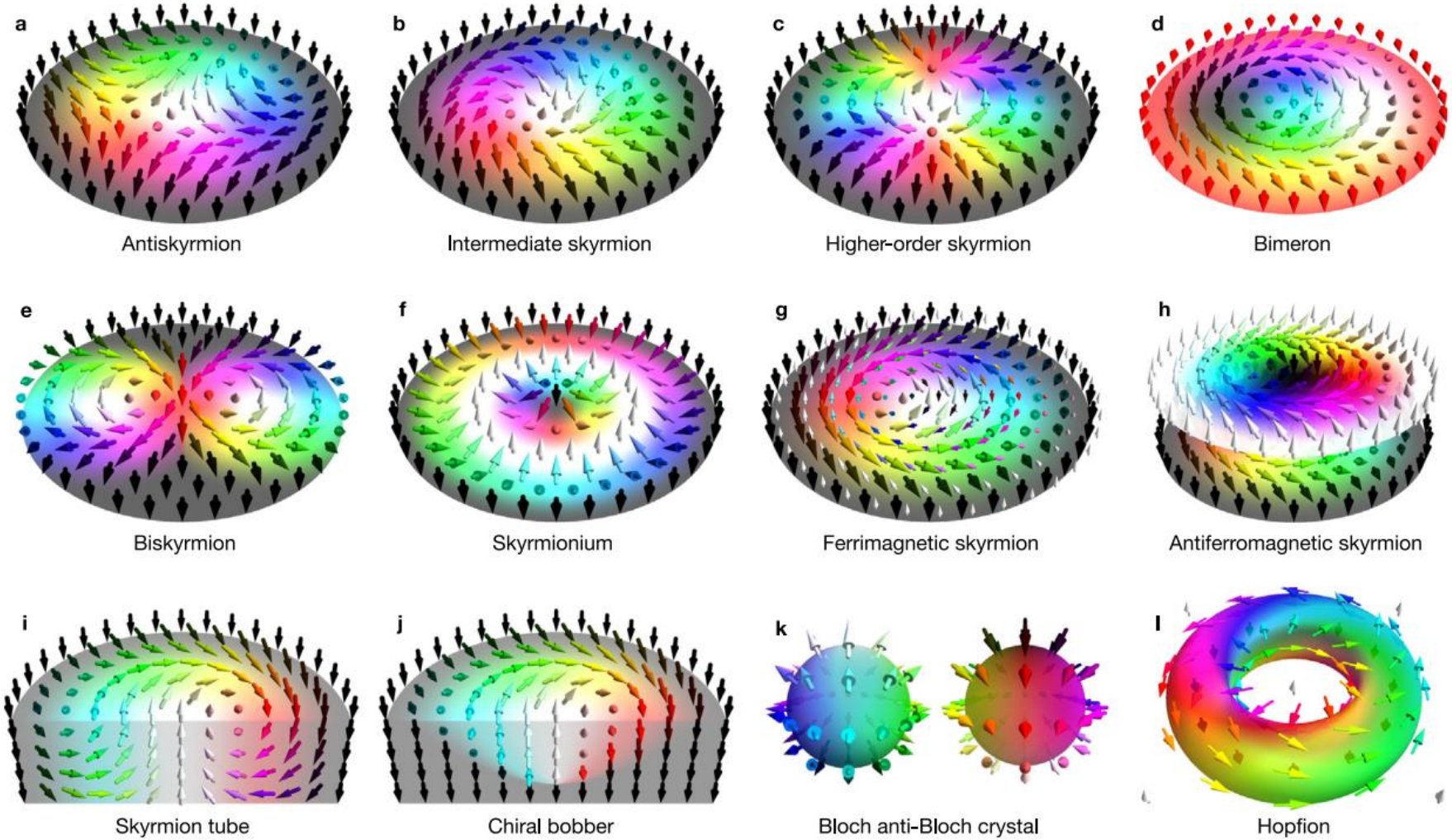
$$H_H = -\sum_{i \neq j} J (\vec{S_i} \cdot \vec{S_j}) \quad X \quad H_{DM} = -\sum_{i \neq j} \vec{D} \cdot (\vec{S_i} \times \vec{S_j})$$

além da interação dipolar e da anisotropia magnetocristalina...

Qual a consequência dessa competição?

Skyrmions magnéticos

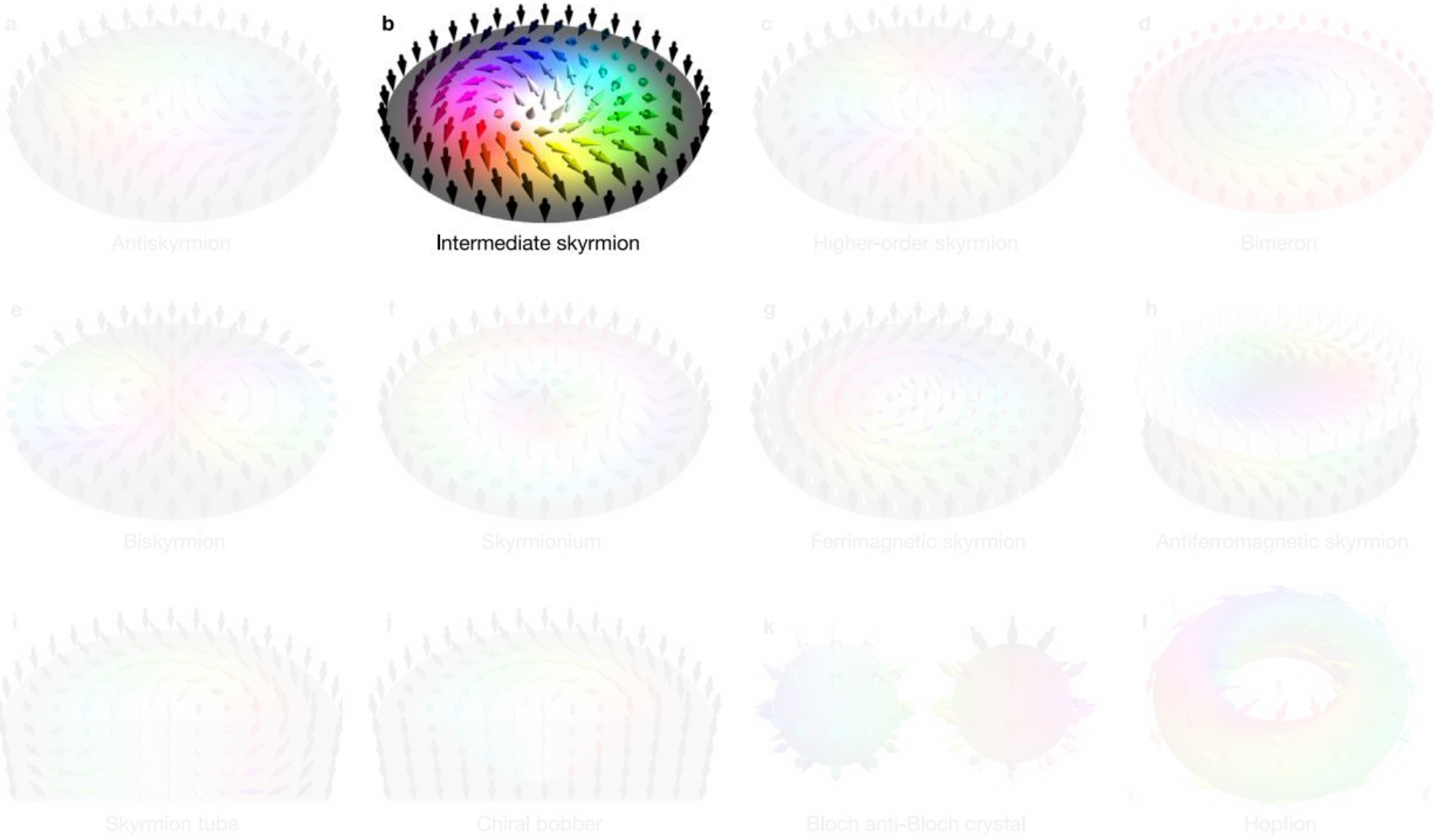
Domínios magnéticos topológicos → Texturas de spin topológicas



Göbel *et al.*, Phys. Rep. **895**, 1 (2021)

Skyrmions magnéticos

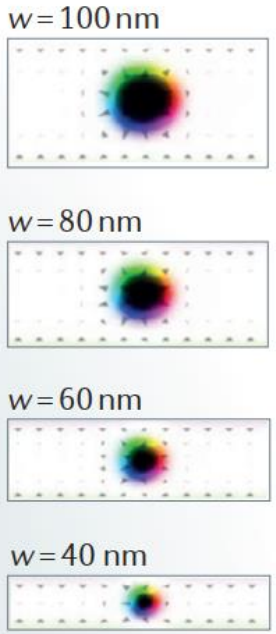
Domínios magnéticos topológicos → Texturas de spin topológicas



Göbel *et al.*, Phys. Rep. **895**, 1 (2021)

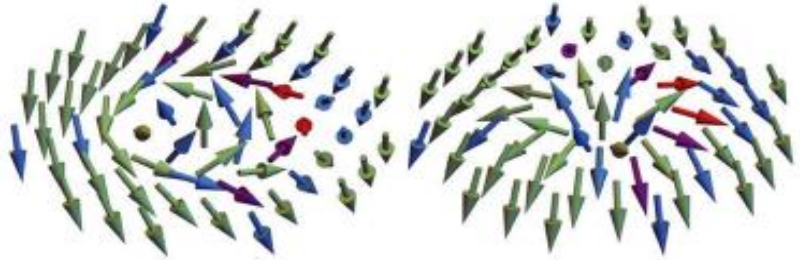
Skyrmions magnéticos

Diâmetro



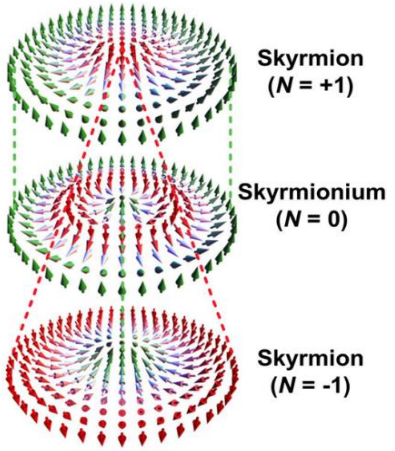
Fert *et al.*, Nature Reviews **2**, 17031 (2017)

Skyrmion tipo Bloch Skyrmion tipo Néel



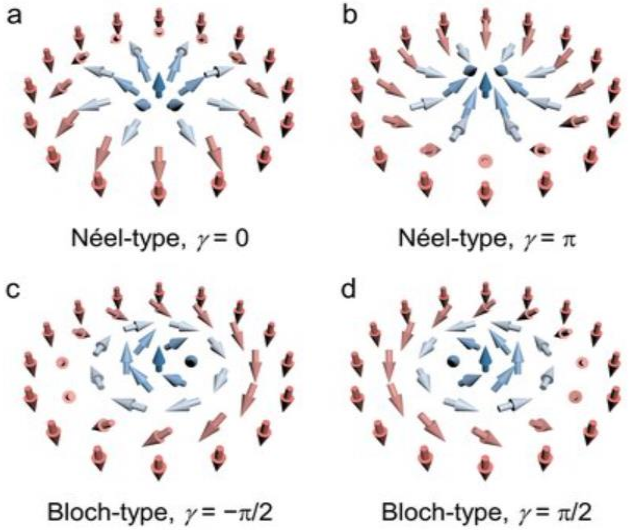
Carga topológica

$$N = \frac{1}{4\pi}\int \vec{m}\cdot\left(\partial_x\vec{m}\times\partial_y\vec{m}\right)dxdy = \pm 1$$



Li *et al.*, Interd. Mat. **2**, 175 (2023)

Número de helicidade, γ



Zhang *et al.*, Adv. Mat. **34**, 2204163 (2022)

Estruturas muito estáveis

Skyrmions são estruturas topologicamente protegidas

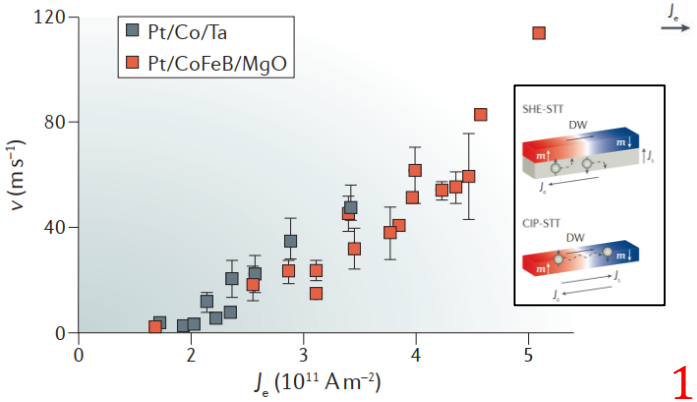
Comportamento uniforme e coerente

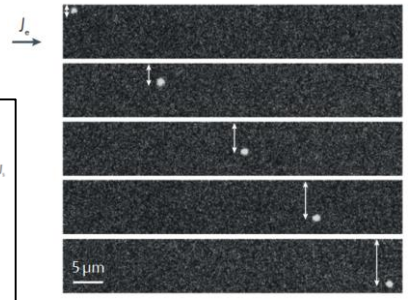
Skyrmions magnéticos

USO EM DISPOSITIVOS SPINTRÔNICOS

Processamento de dados

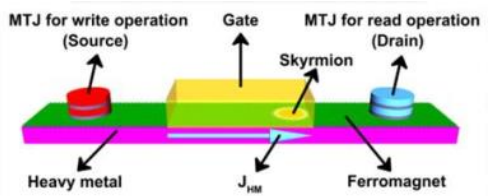
- Movimento e
- Detecção individuais

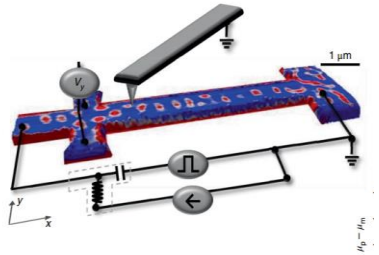




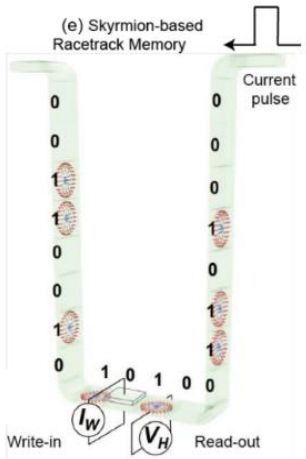
Fert *et al.*, Nature Reviews **2**, 17031 (2017)

$10^5\ j_{skyrmions} \sim j_{DW}$





Maccariello *et al.*, Nature Nanotech. **13**, 233 (2018)

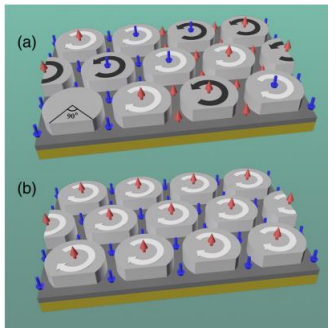


Jibiki *et al.*, APL **117**, 082402 (2020)

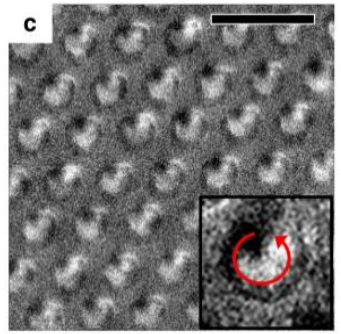
Armazenamento de dados

- Rede bem organizada
- Detecção individual

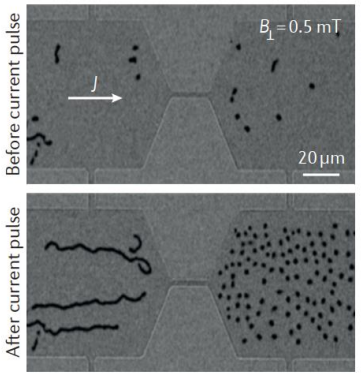
nucleação, aniquilação e inversão do estado magnético de forma reversível



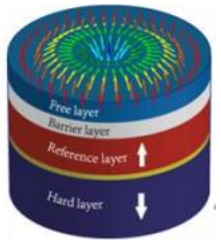
Sun *et al.*, PRL **110**, 167201 (2013)



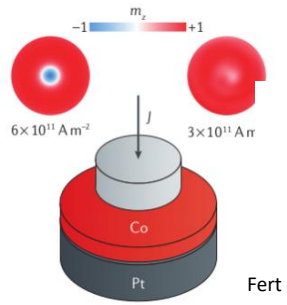
Gilbert *et al.*, Nat. Comm. **6**, 84621 (2015)

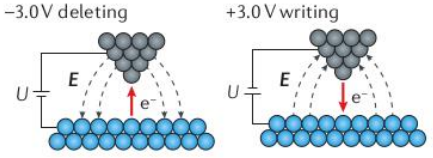


Jiang *et al.*, Science **349**, 283 (2015)

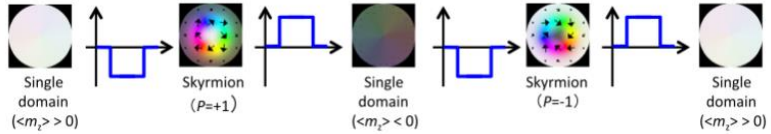


Zhang *et al.*, Appl. Mat. & Int. **10**, 16





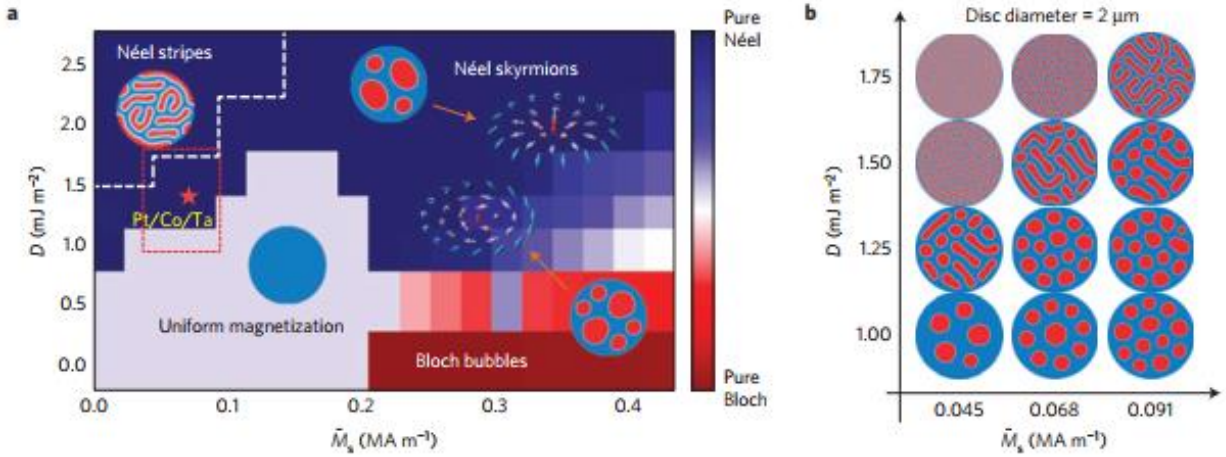
Fert *et al.*, Nature Reviews **2**, 17031 (2017)



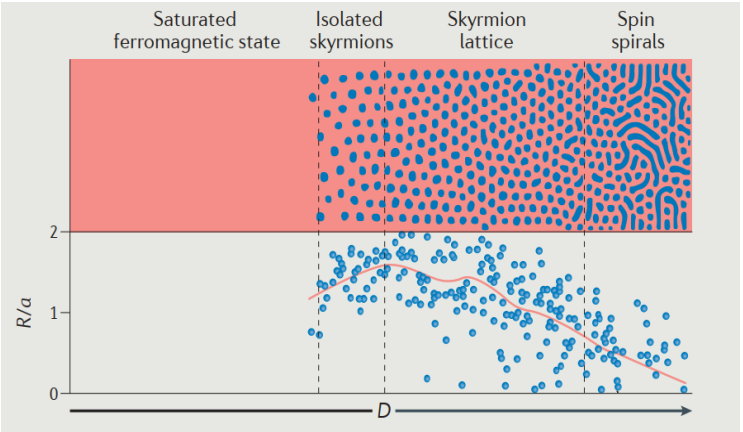
Skyrmions magnéticos

Diagrama de fase

Maze domains → bubble domains → skyrmions → Materiais com PMA



Xoo *et al.*, Nature Mat. **15**, 501 (2016)

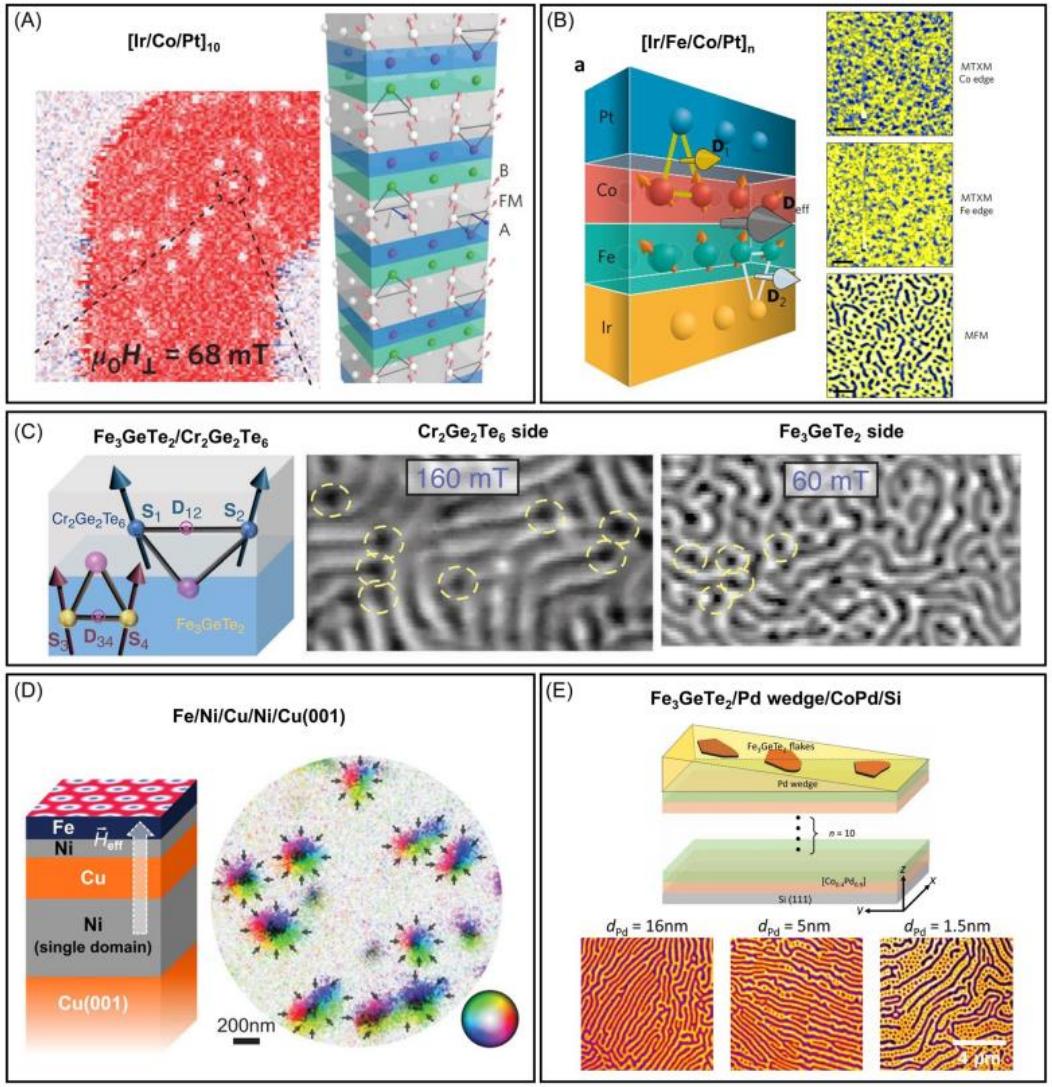


Fert *et al.*, Nature Reviews **2**, 17031 (2017)

PARA ESTABILIZAR SKYRMIONS À RT

- Materiais utilizados
- Espessura das camadas
- Geometria da amostra
- Campo magnético aplicado
- Campo elétrico aplicado

Manipulação da interação DM
Manipulação da PMA



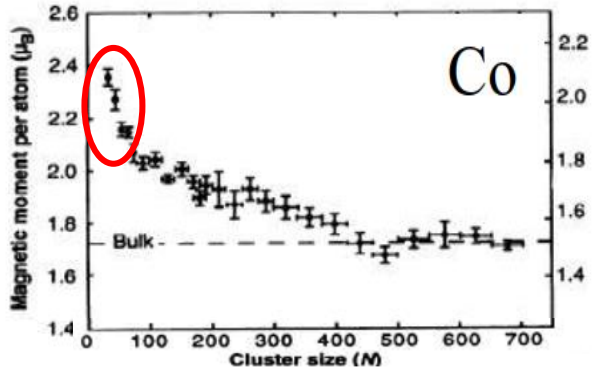
Li *et al.*, Interd. Mat. **2**, 175 (2023)

Multicamadas Co/Pt

Multicamadas Co/Pt

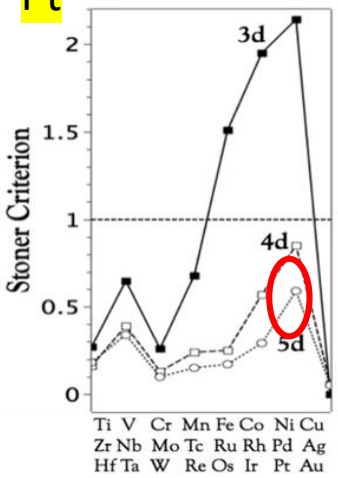
Co

2D – maior M_S



Billas *et al.*, Science **265**, 1682 (1994)

Pt



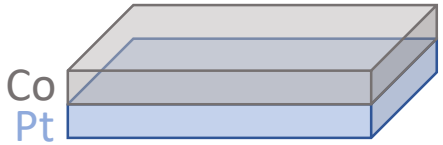
Blugel *et al.*(2007)

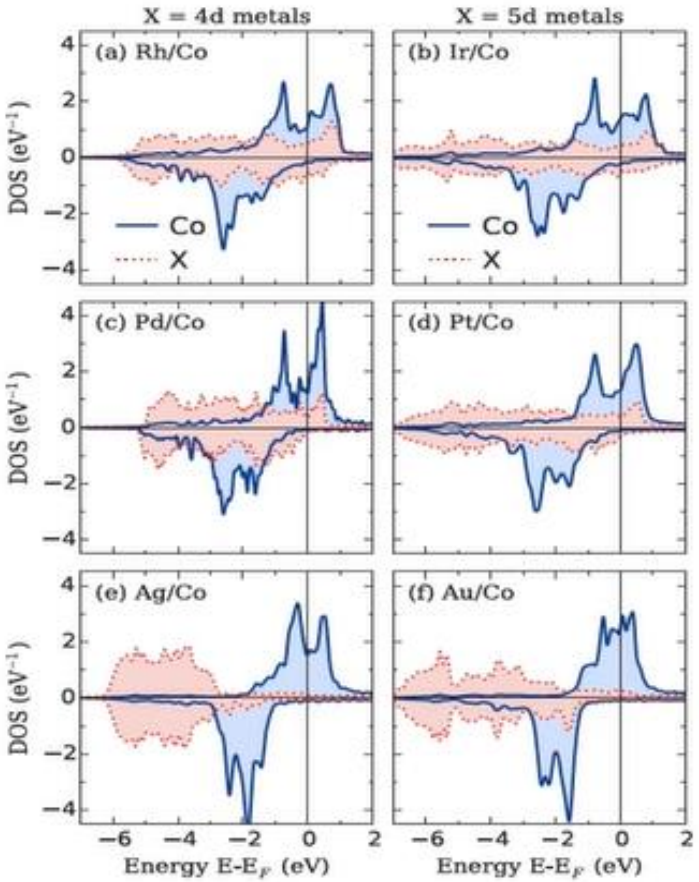
Critério de Stoner

$UN(E_F) > 1$

Diminuir a dimensionalidade

Monocamadas atômicas de Co e de Pt

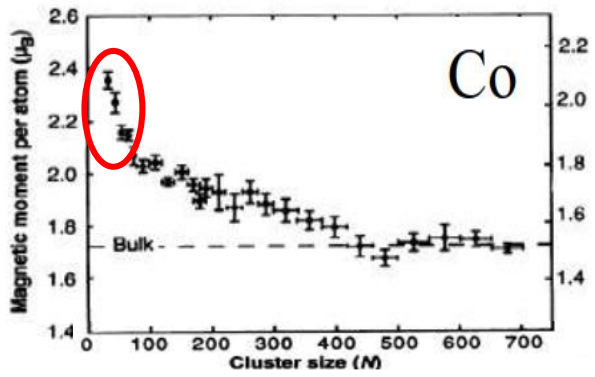




Grytsyuk *et al.*, PRB **93**, 174421 (2016)

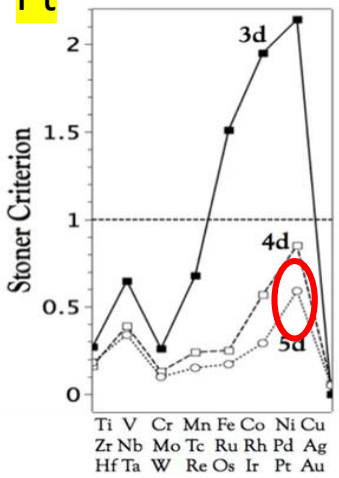
Multicamadas Co/Pt

Co



Billas *et al.*, Science **265**, 1682 (1994)

Pt



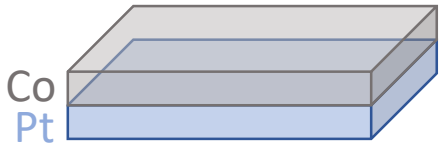
Blugel *et al.*(2007)

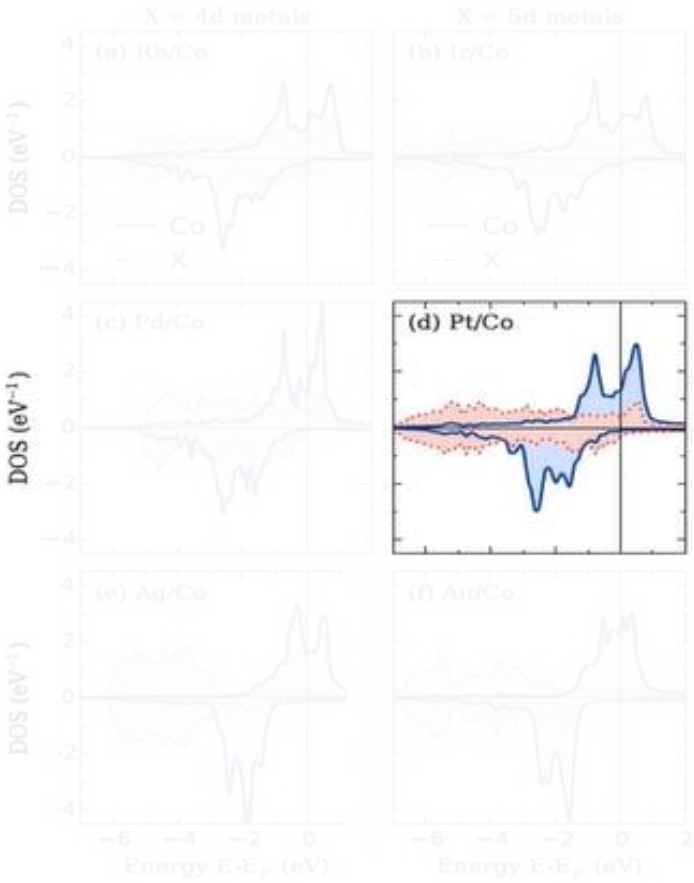
Critério de Stoner

$UN(E_F) > 1$

Diminuir a dimensionalidade

Monocamadas atômicas de Co e de Pt



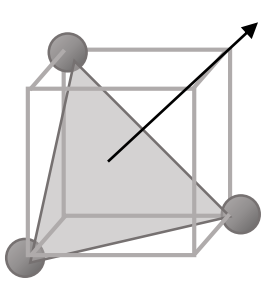


Grytsyuk *et al.*, PRB **93**, 174421 (2016)

Hibridização na interface dos orbitais 5d da Pt e 3d do Co

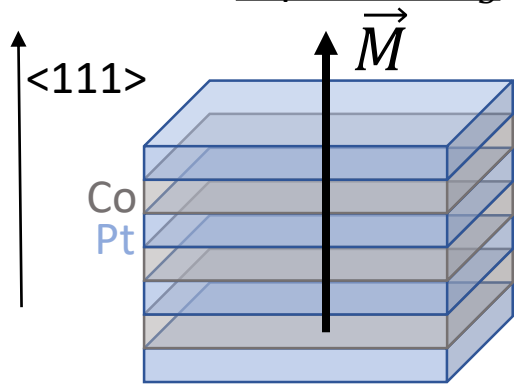
- A Pt adquire magnetismo
- O Co adquire momento orbital

Pt (111) // Co (111)



Eixo de fácil magnetização do Co

anisotropia magnecristalina de superfície, K_S



PMA

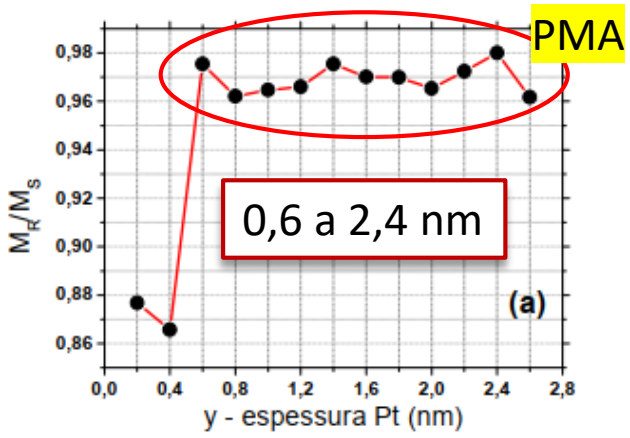
Muticamadas Co/Pt

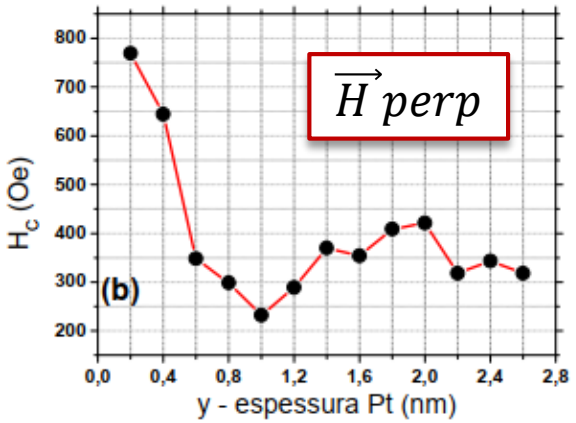
Multicamadas Co/Pt

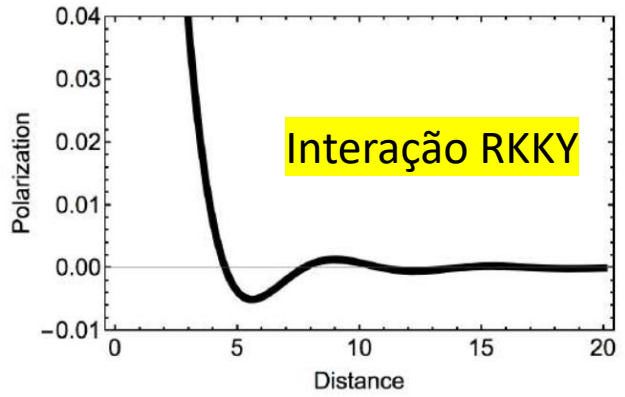
Si/SiO_2//Pt 20 nm/(Co 0,6 nm/Pt y nm)x5

Analisando o acoplamento magnético

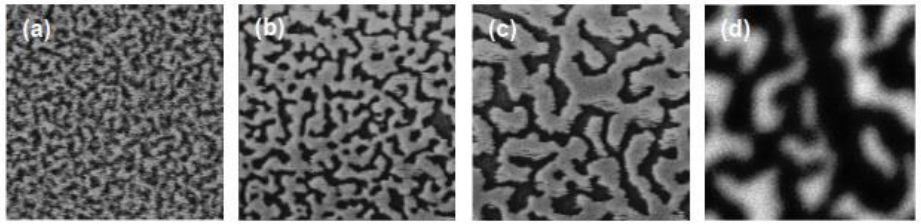
Mas a PMA é sensível à espessura da camada de Pt

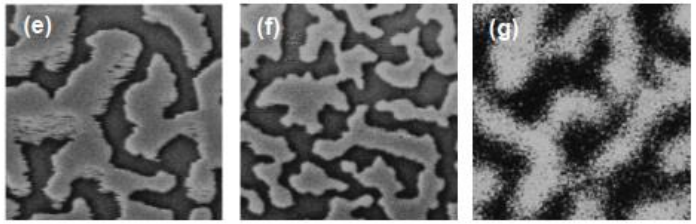




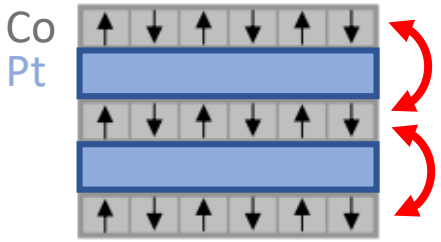


Maze domains





De 0,6 a 1,4 nm

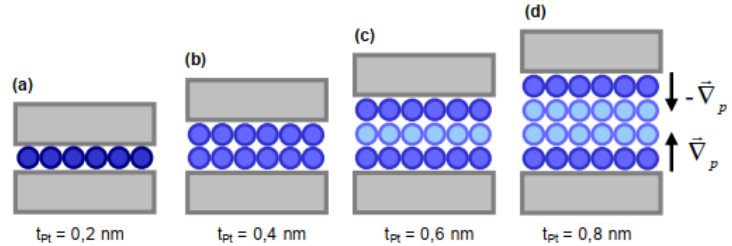


Acoplamento FM entre as camadas de Co

Interação de troca indireta

$\propto J(r)$

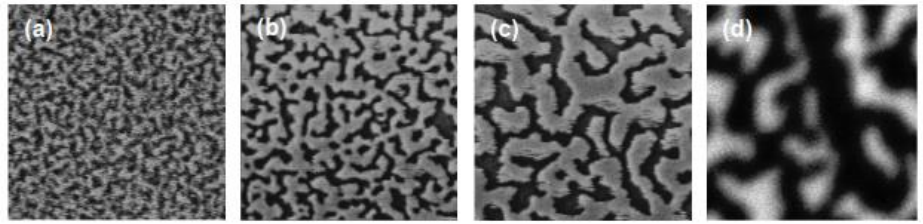
$J(r) \propto \sin(2k_F r)$



Gradiente de polarização magnética na Pt

Multicamadas Co/Pt

Maze domains

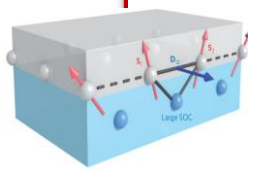


Maze domains → bubble domains → SKYRMIONS

Skyrmions podem ser formados em multicamadas Co/Pt?

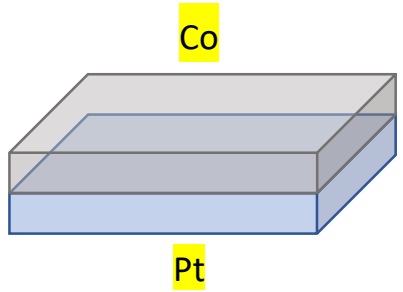
Falta apresentar interação DM...

Multicamadas Co/Pt



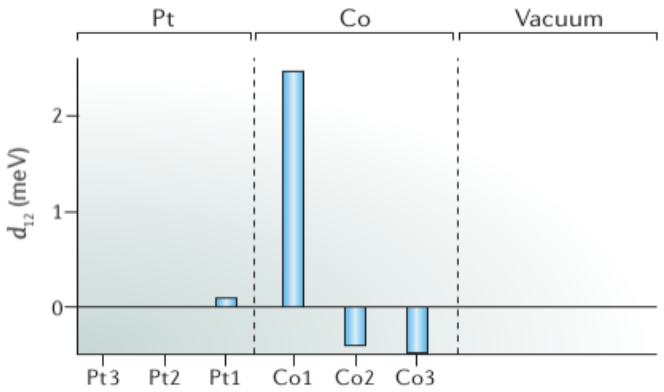
Bicamada HM/FM

Interface – 2D



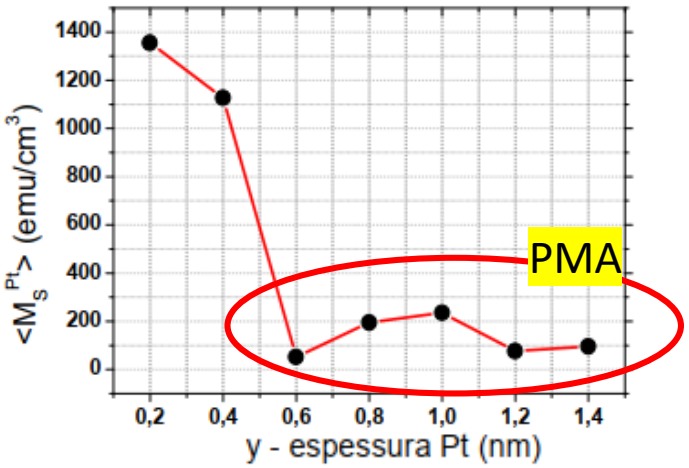
→ forte acoplamento SO

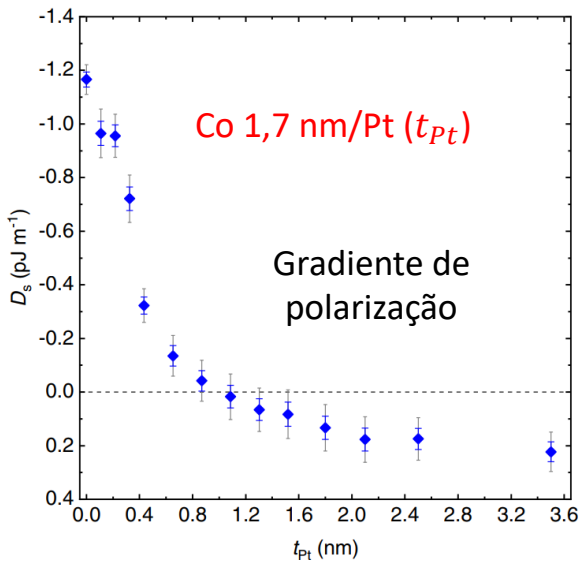
Exemplo: CoFeB/MgO, Co/Ni



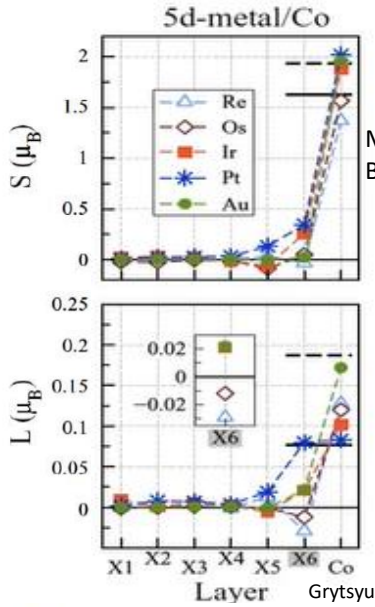
Fert *et al.*, Nature Reviews **2**, 17031 (2017)

A Pt não contribui com Ms, mas...





Legrand *et al.*, PR Mat. **6**, 024408 (2022)



Monocamada Co

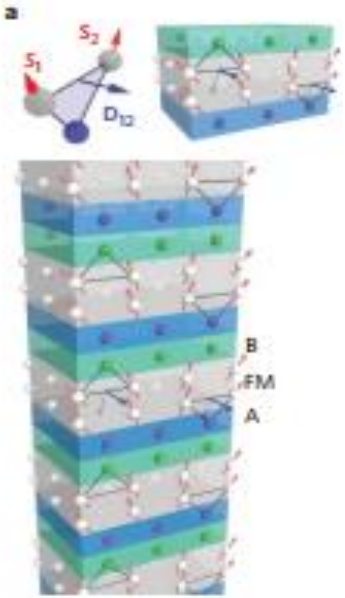
Bulk Co

Monocamada Co

Bulk Co

Grytsyuk *et al.*, PRB **93**, 174421 (2016)

Na hibridização, o acoplamento SO fica forte na interface



Moreau-Luchaire *et al.*, Nature Nanotech. **11**, 444 (2016)

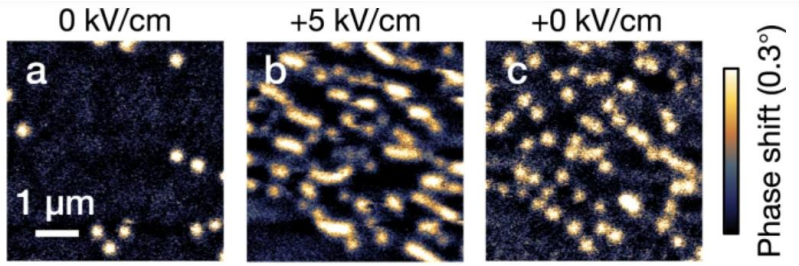
Cada interface → DM

Interação DM aditiva

Multicamadas Co/Pt

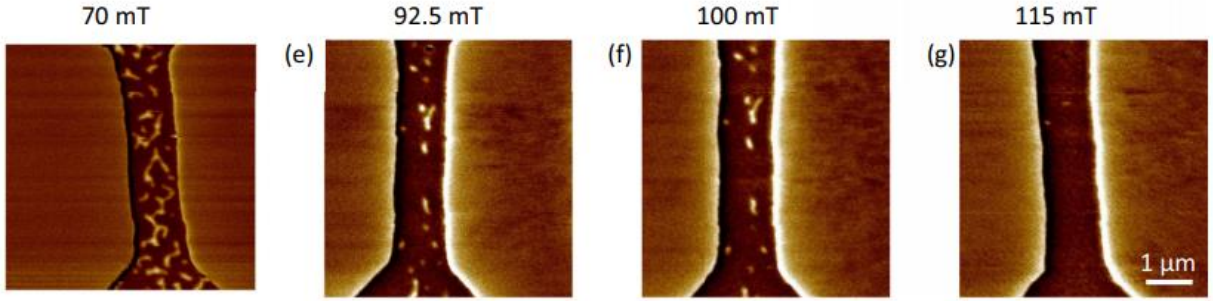
Multicamadas Co/Pt são ótimos sistemas para a obtenção e estabilização de skyrmions

Pt/Co/Gd



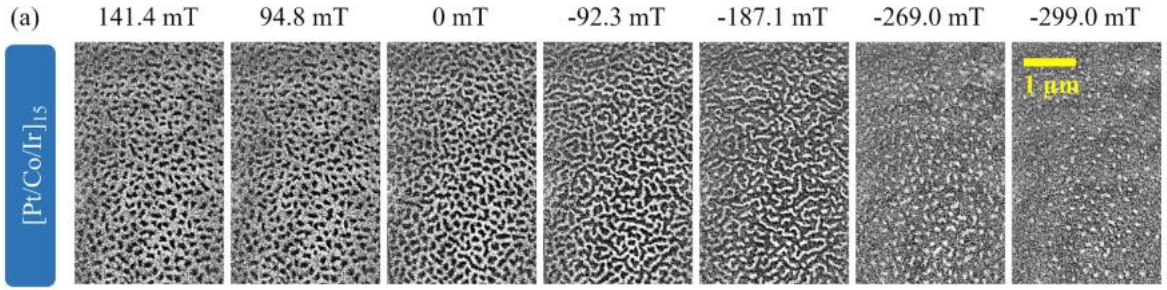
Sun *et al.*, Nature Comm. **14**, 3434 (2023)

Pt/Co/Cu



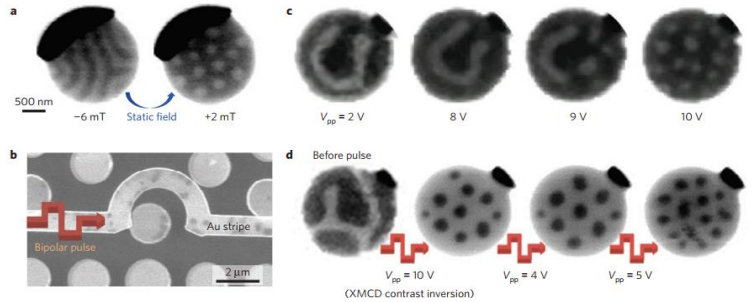
Cheng *et al.*, PRB **108**, 174433 (2023)

Pt/Co/Ir



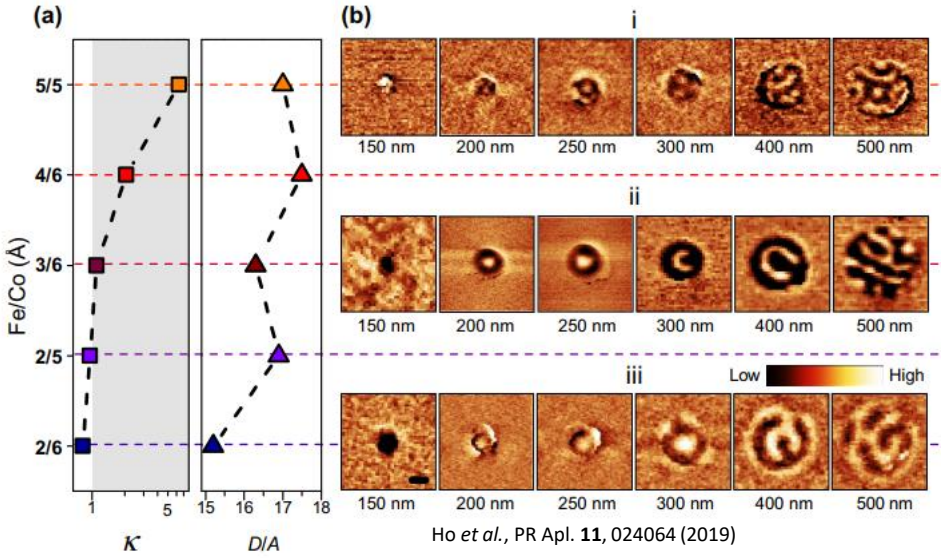
Tomasello *et al.*, PRB **107**, 184416 (2023)

Pt/Co/Ta



Xoo *et al.*, Nature Mat. **15**, 501 (2016)

Ir/Fe/Co/Pt



Ho *et al.*, PR Apl. **11**, 024064 (2019)

CeO_2

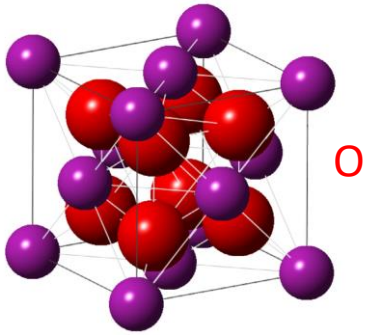
CeO_2

CeO_2 estequiométrico

Ce

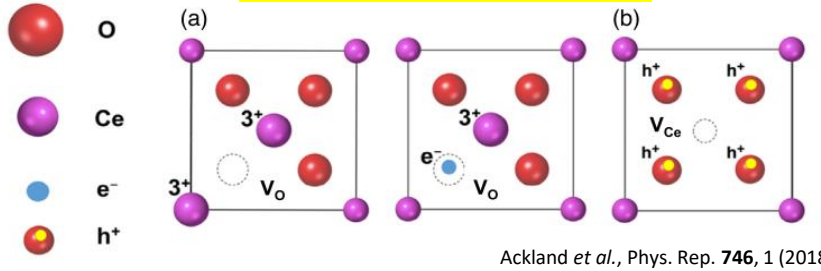
fluorita

O



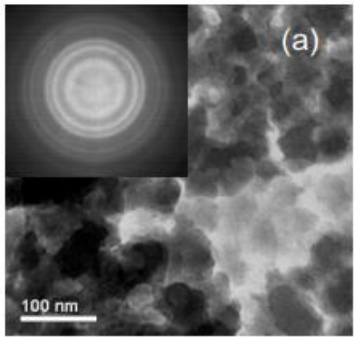
CeO_2 não-estequiométrico - $CeO_{2-\delta}$

Vacâncias de O de Ce



Ackland *et al.*, Phys. Rep. **746**, 1 (2018)

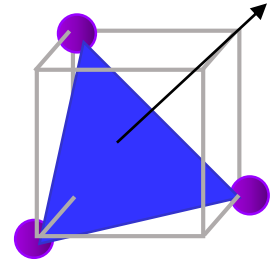
Eletroquímica



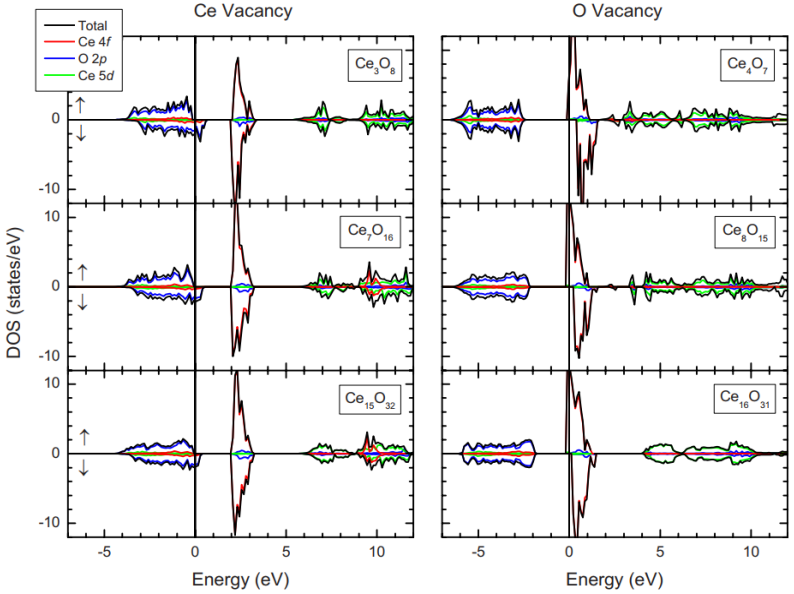
Fernandes *et al.*, PRB **80**, 035202 (2009)

Nano-grãos cristalinos

Si (111) //CeO_2 (111)

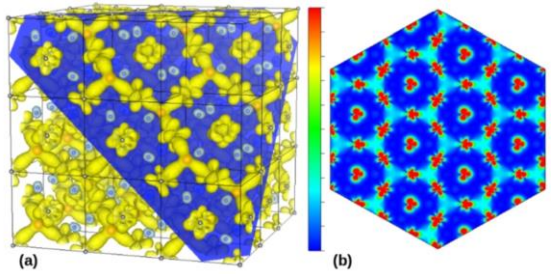


Normal ao plano



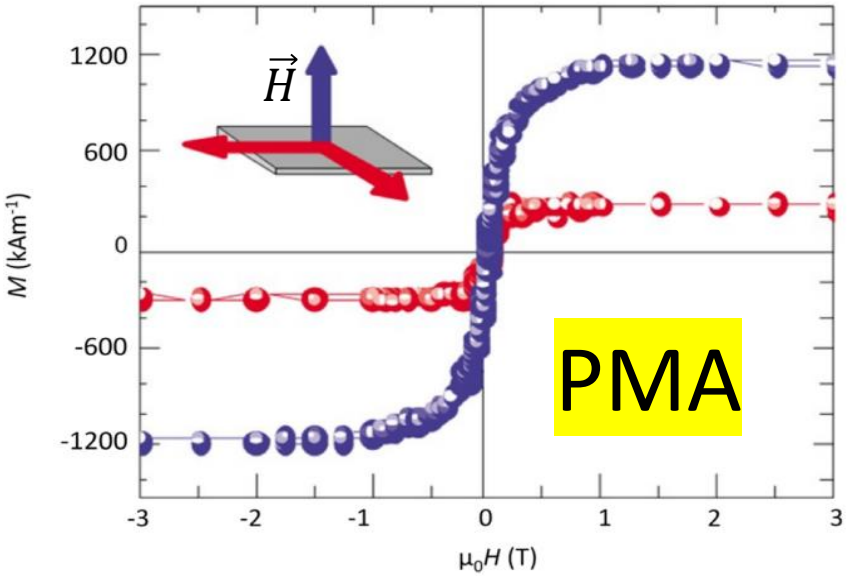
Fernandes *et al.*, PRB **80**, 035202 (2009)

Vacâncias de O
pares o longo de <111>



Varalda *et al.*, Sci. Rep. **9**, 4708 (2019)

Óxido transparente
e ferromagnético à RT

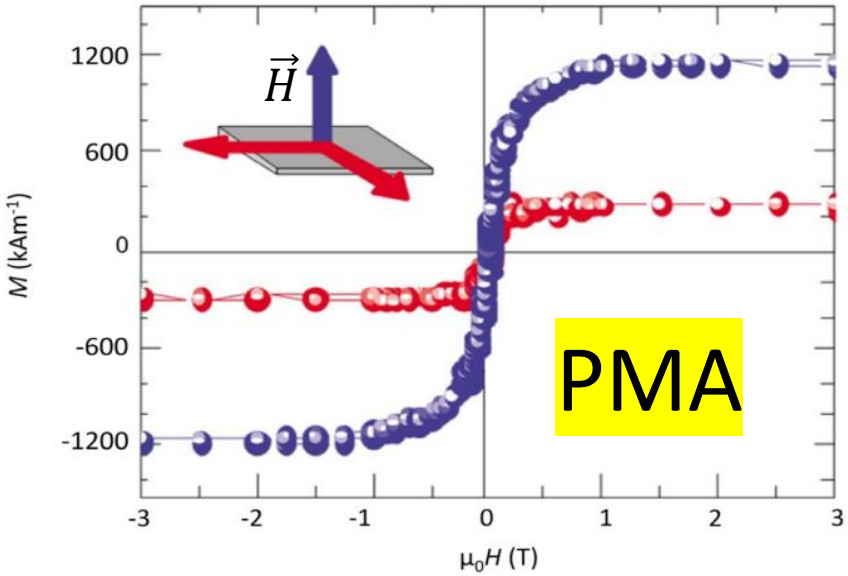


Ackland *et al.*, Phys. Rep. **746**, 1 (2018)

CeO_2

E se juntarmos Co/Pt com o CeO_2, para aliar propriedades magnéticas com propriedades óticas?

Skyrmions no CeO_2?



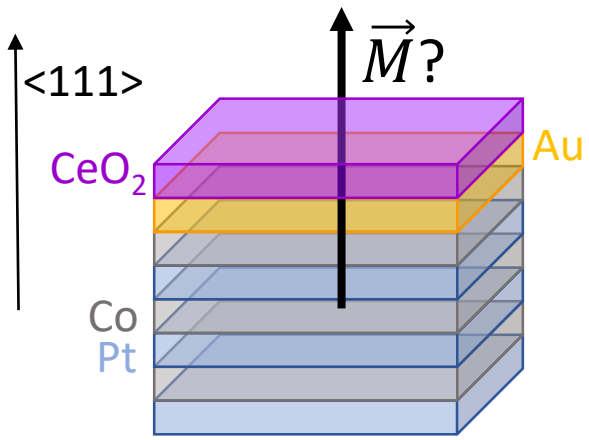
Óxido transparente
e ferromagnético à RT

Ackland *et al.*, Phys. Rep. **746**, 1 (2018)

Co/Pt e CeO_2

Co/Pt e CeO_2

Acoplamento Co/Pt - CeO_2

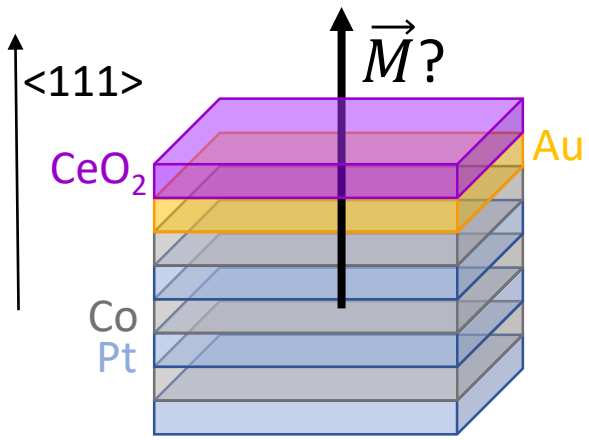


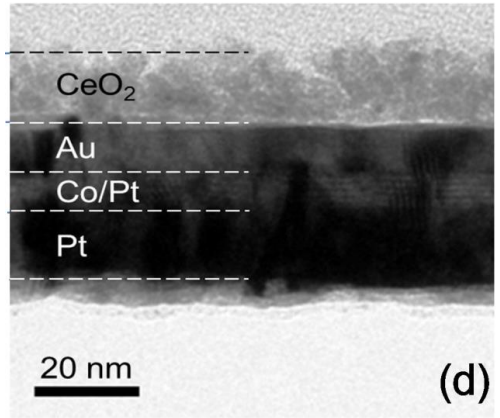
sputtering

SiO_2//Pt 20 nm/(Co 0,6 nm/Pt 0,8 nm)x5/Au 10 nm

Co/Pt e CeO_2

Acoplamento Co/Pt - CeO_2

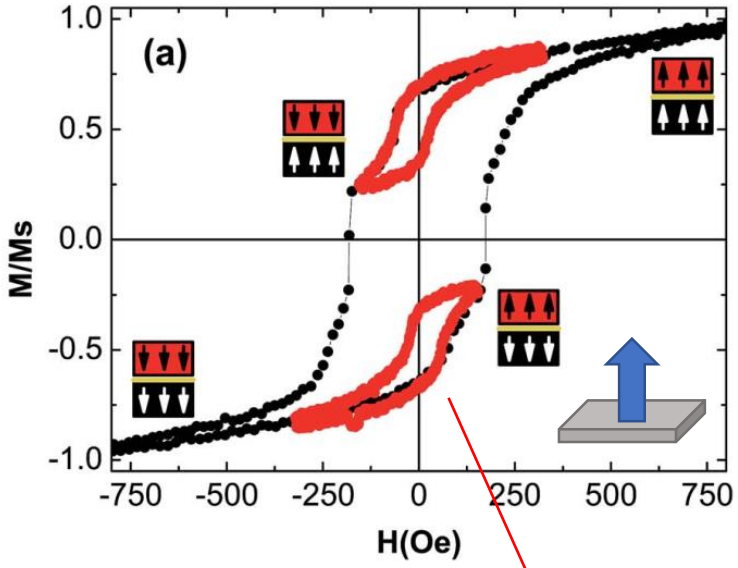


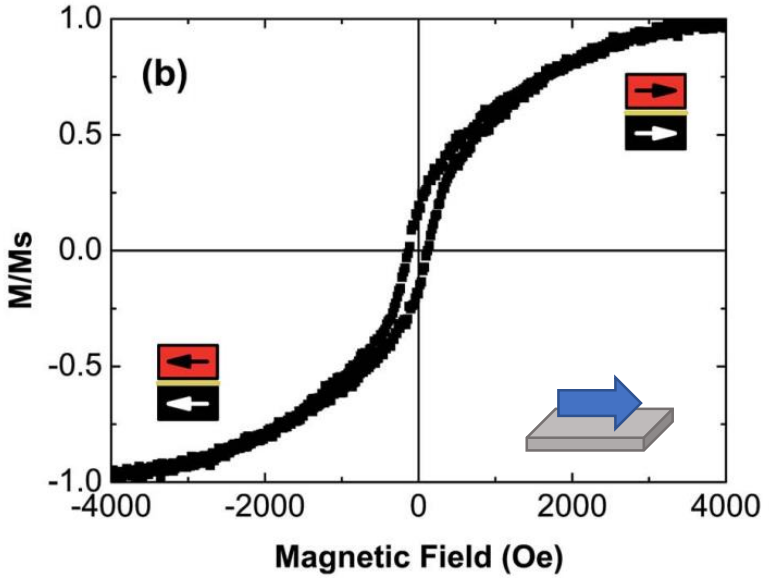


sputtering

eletroquímica

SiO_2//Pt 20 nm/(Co 0,6 nm/Pt 0,8 nm)x5/Au 10 nm/CeO_2 20 nm

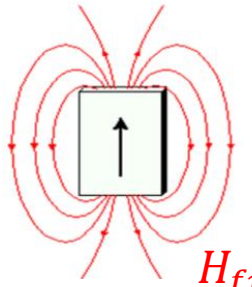




PMA

Reversão independente do CeO_2

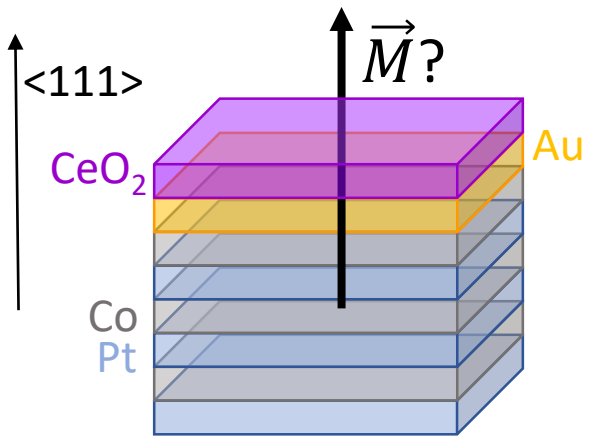
Acoplamento FM fraco



$H_{fuga} \sim 40\ Oe$

Co/Pt e CeO_2

Acoplamento Co/Pt - CeO_2



sputtering — eletroquímica

SiO_2//Pt 20 nm/(Co 0,6 nm/Pt 0,8 nm)x5/Au 10 nm/CeO_2 20 nm

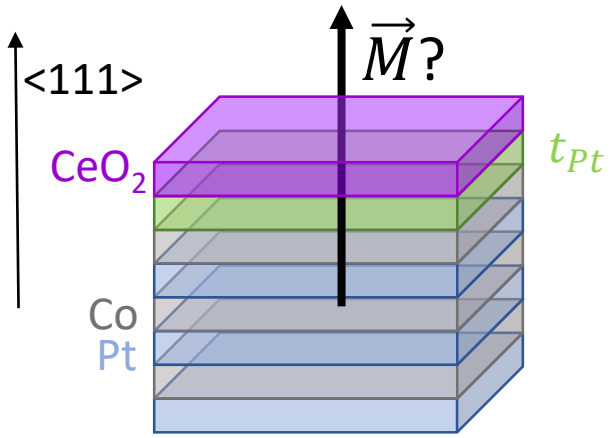
Co/Pt e CeO_2

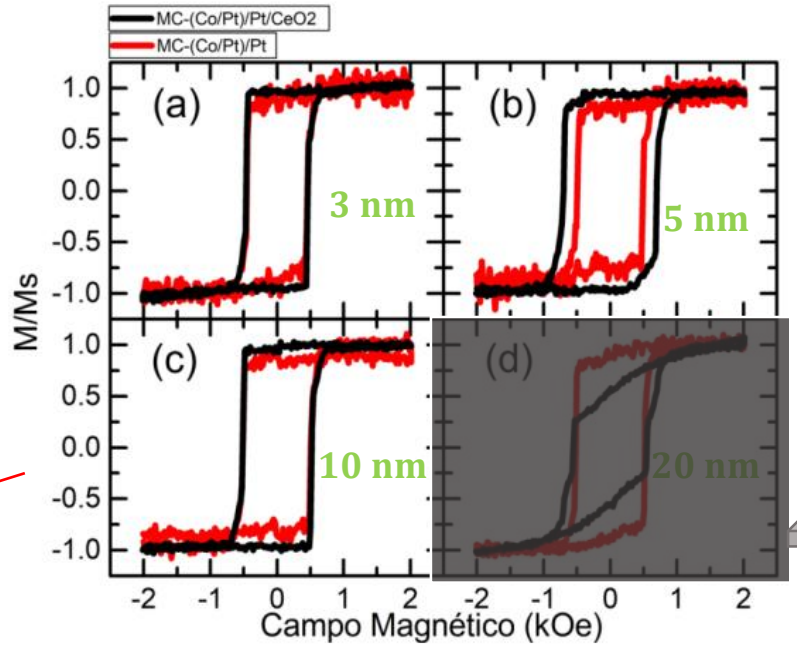
Acoplamento Co/Pt - CeO_2

sputtering

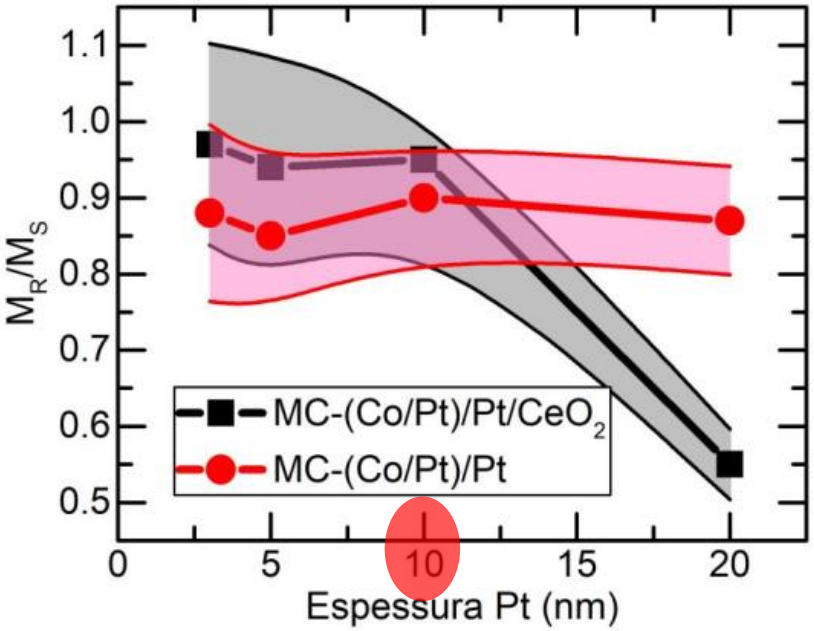
eletroquímica

SiO_2//Pt 20 nm/(Co 0,6 nm/Pt 0,8 nm)x5/Pt t_{Pt} nm/CeO_2 20 nm



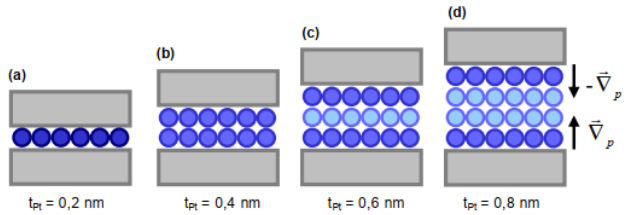


PMA



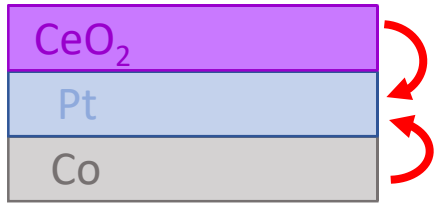
Acoplamento FM forte

Apesar de...



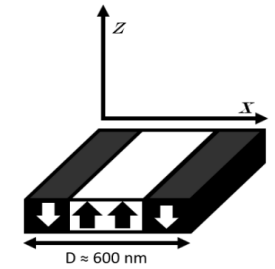
Poucas monocamadas de Pt

Hibridização das interfaces

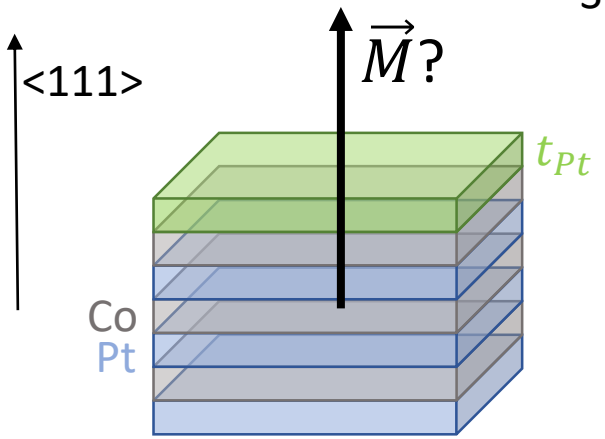


Estabilidade da PMA do sistema

Co/Pt e CeO_2



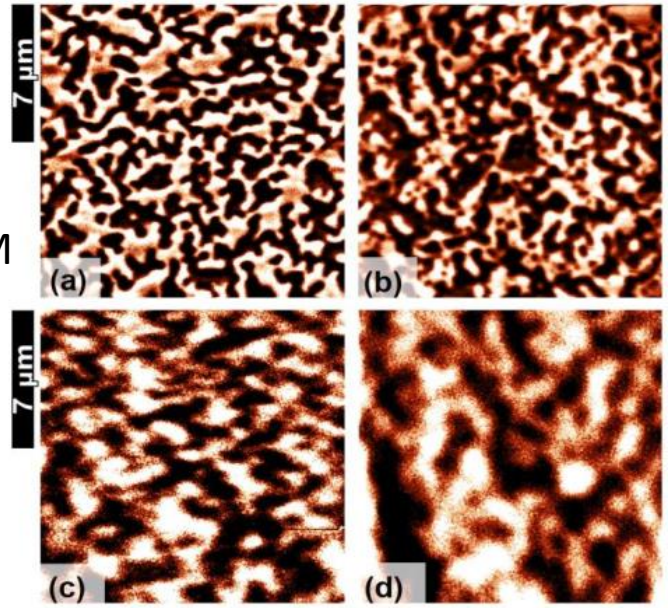
SiO_2//Pt 20 nm/(Co 0,6 nm/Pt 0,8 nm)x5/Pt t_{Pt} nm



Sem CeO_2

Co/Pt 3 nm Co/Pt 5 nm

MFM



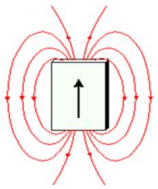
Co/Pt 10 nm Co/Pt 20 nm

↑ t_{Pt}

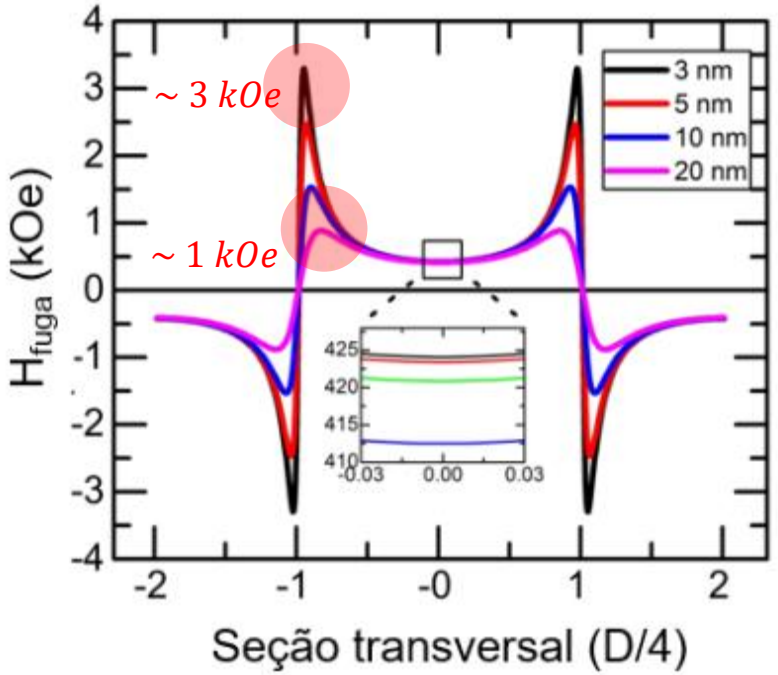
↑ tamanho dos domínios

Menor a definição das paredes de domínio

H_{fuga} =?



$$H_{z-fuga}(x,z) = 4M_S\left\{\arctan\left[\frac{\cos(2\pi x/D)}{\sinh(2\pi x/D)}\right] - \arctan\left[\frac{\cos(2\pi x/D)}{\sinh(2\pi(z+h)/D)}\right]\right\}$$



3 nm → acoplamento forte

20 nm → acoplamento intermediário

Linhas de campo mais "dispersas"

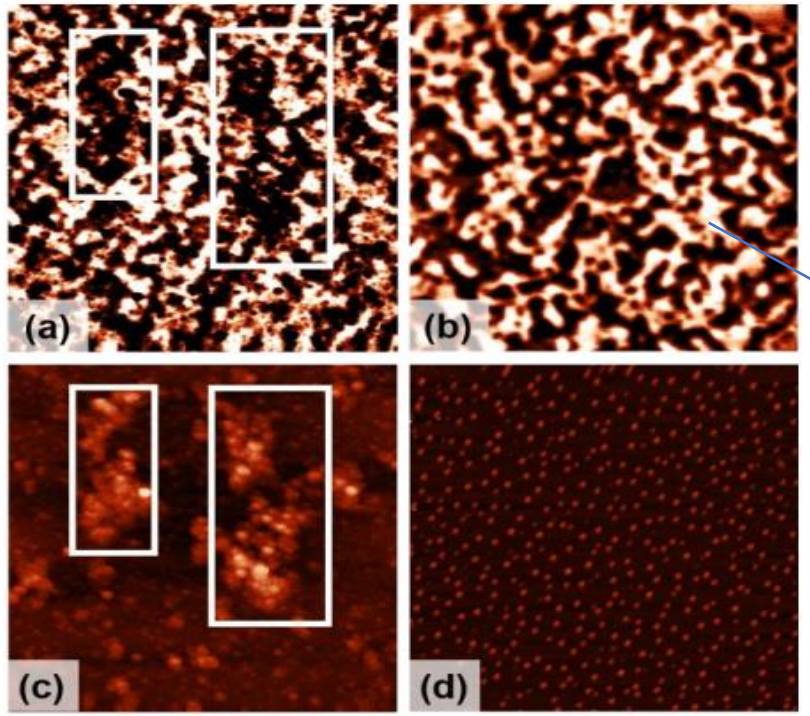
Co/Pt e CeO_2

Co/Pt 5 nm

Co/Pt 5 nm/CeO_2

MFM

AFM

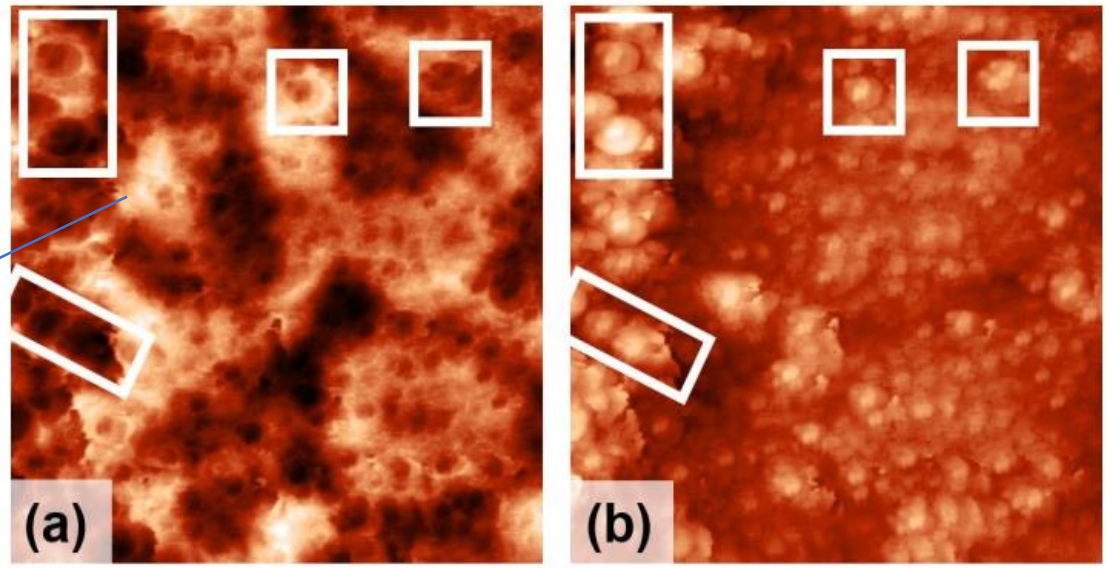


15 µm x 15 µm

Maze domains!

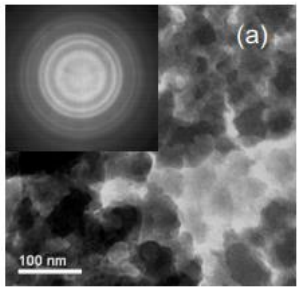
Co/Pt 5 nm/CeO_2

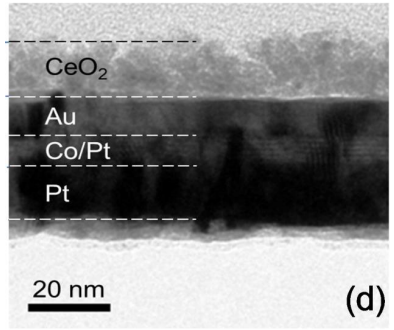
5 µm x 5 µm



MFM

AFM





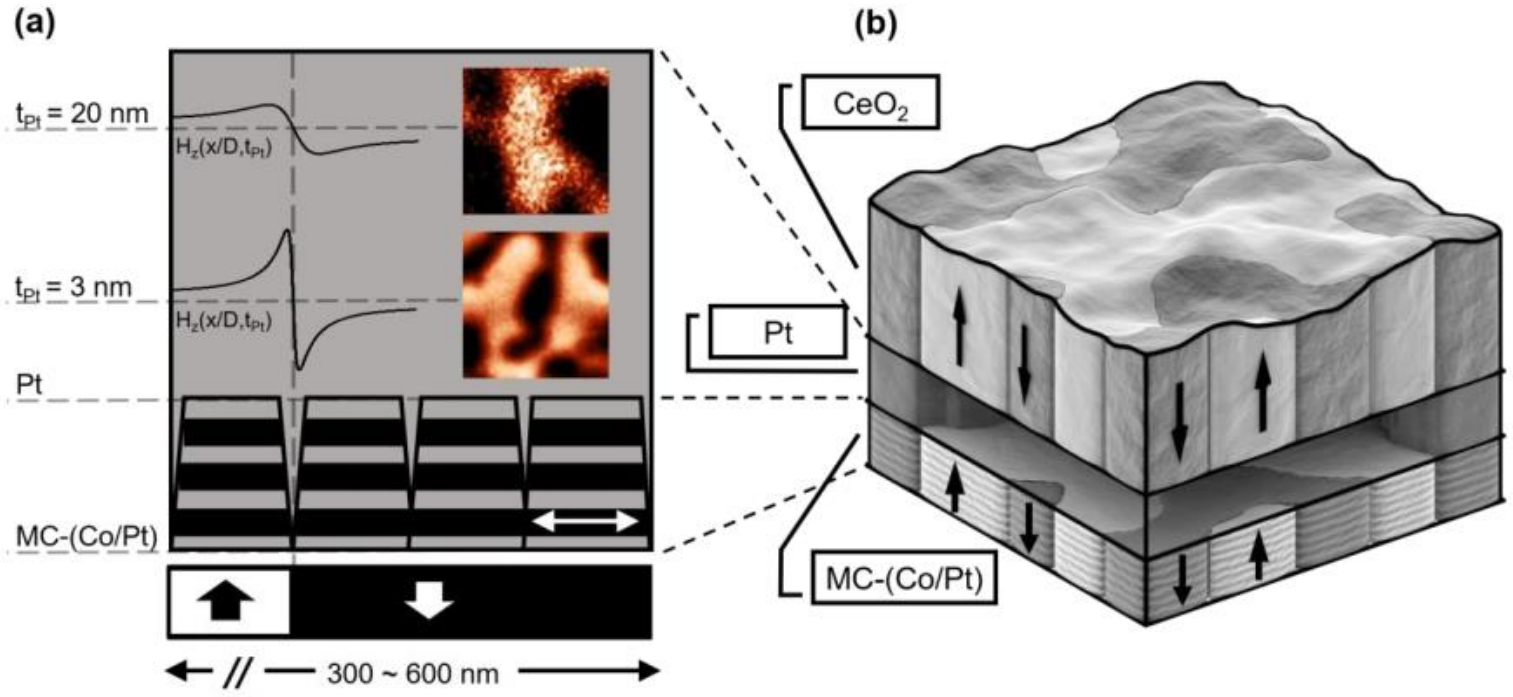
Fernandes *et al.*, PRB **80**, 035202 (2009)

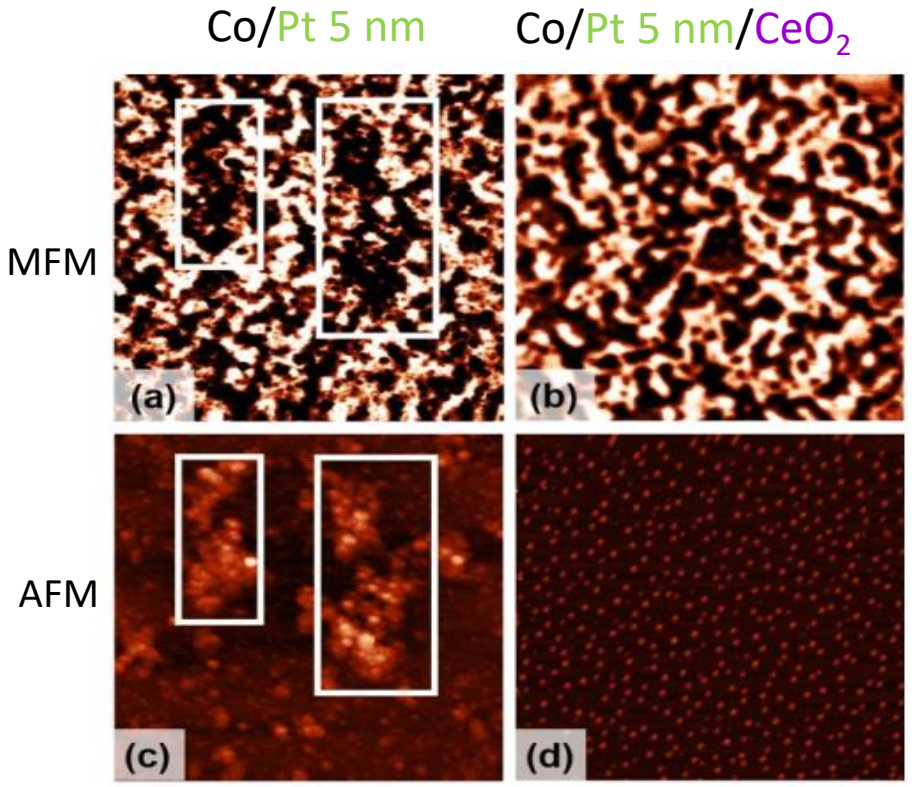
Efeitos da rugosidade do CeO_2

Efeitos de pinnagem

Co/Pt e CeO_2

Os domínios magnéticos são reproduzidos no CeO_2





15 µm x 15 µm

Pra termos skyrmions no CeO_2

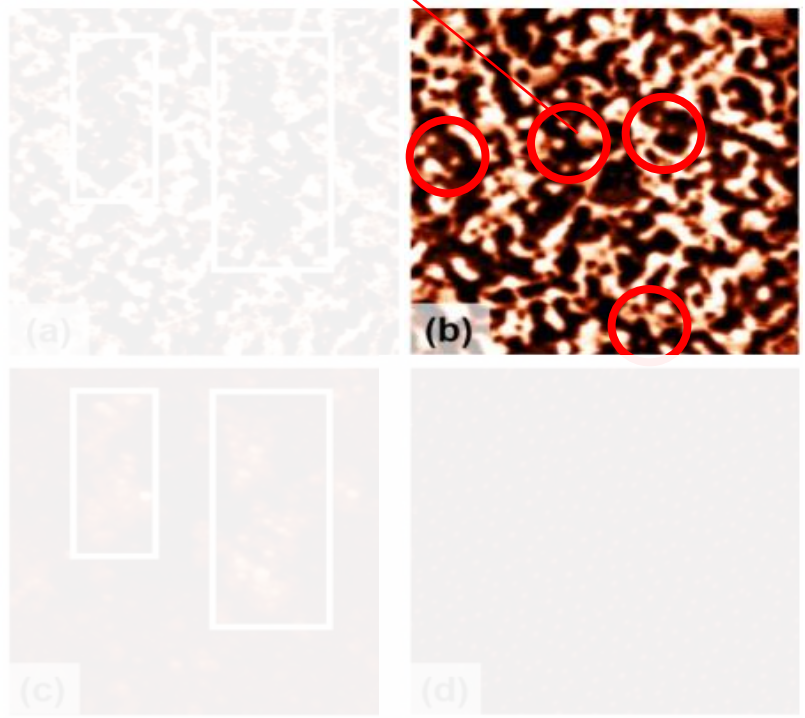
→ Interação DM na interface Pt/ CeO_2 → Será que tem?

Ainda não sabemos...

Co/Pt e CeO_2

Possíveis precursores de skyrmions?

Co/Pt 5 nm/CeO_2



Os domínios magnéticos são reproduzidos no CeO_2

Pra termos skyrmions no CeO_2

Interação DM na interface Pt/ CeO_2 —

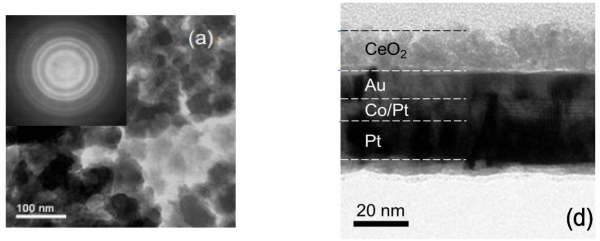
Será que tem?

Ainda não sabemos...

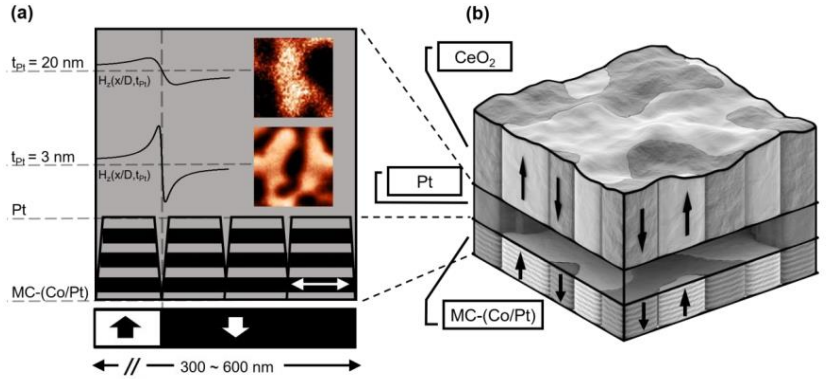
Co/Pt, CeO_2 e skyrmions – PRÓXIMOS PASSOS

Co/Pt, CeO_2 e skyrmions – PRÓXIMOS PASSOS

- Diminuir a rugosidade da camada de CeO_2, mantendo-o FM

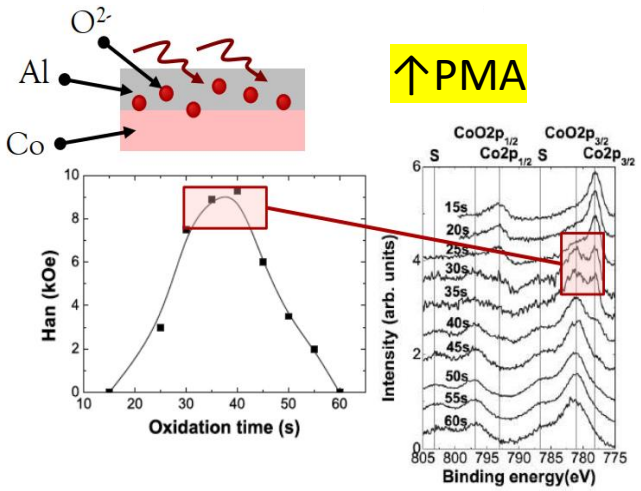


Fernandes *et al.*, PRB **80**, 035202 (2009)

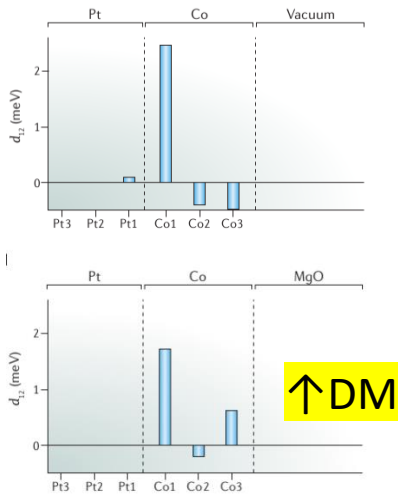


- Manipulação do estado skyrmiônico através da aplicação de campo magnético e campo elétrico
- Investigar a DM na interface Pt/CeO_2

- Inverter as camadas: ao invés de fazer $Co/Pt/CeO_2$ fazer $Pt/Co/CeO_2$



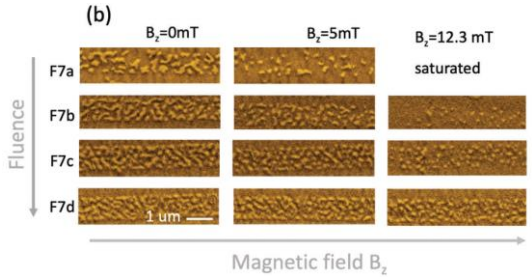
↑PMA



↑DM

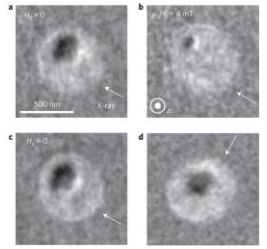
Fert *et al.*, Nature Reviews **2**, 17031 (2017)

- Outros óxidos por eletroquímica



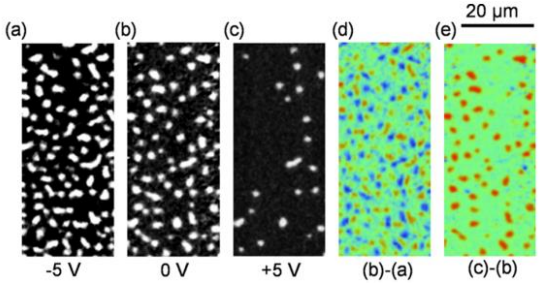
Balan *et al.*, Nano Micro Small **19**, 2302039 (2023)

com MgO



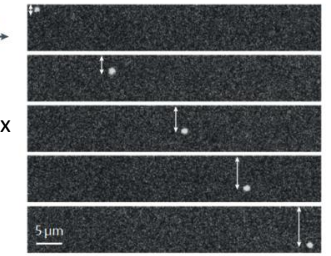
Boulle *et al.*, Nature Nanotech.**11**, 449 (2016)

com AlO_x



Schott *et al.*, Nano Letters **17**, 3006 (2017)

com TaO_x

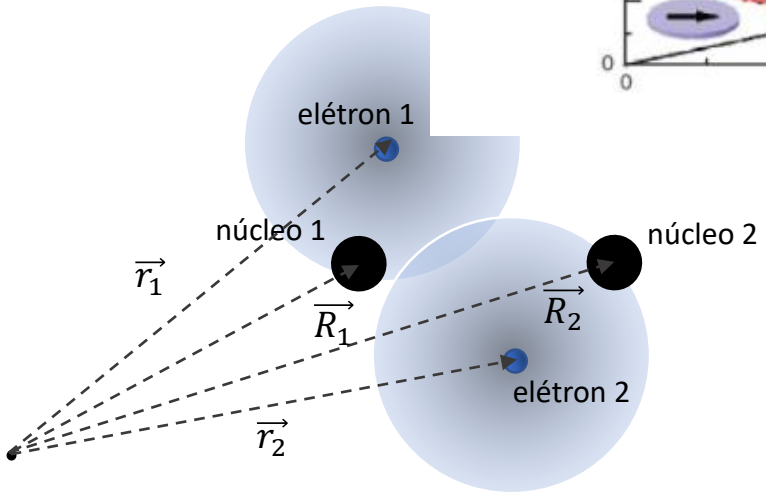


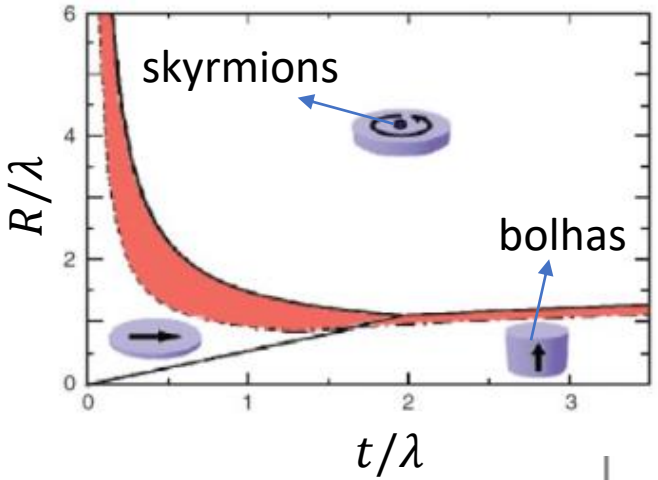
Jiang *et al.*, Nature Physics **13**, 162 (2017)

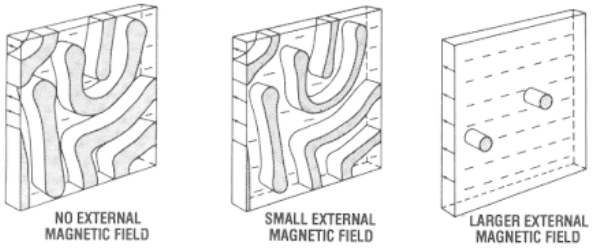
Muito obrigada!

Domínios magnéticos

Dois átomos de H





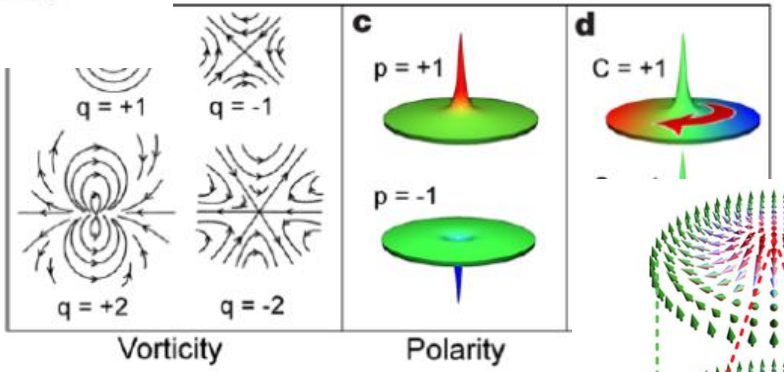


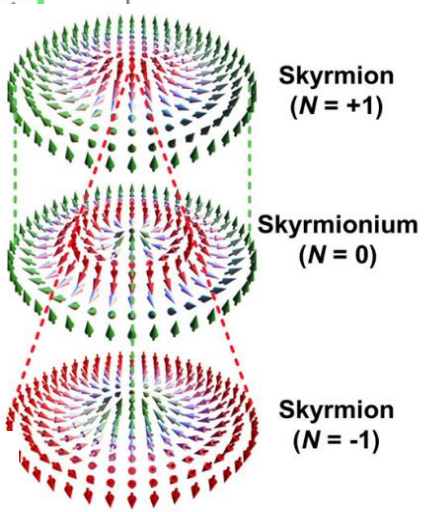
External magnetic field shrinks random serpentine domains of magnetically neutral crystal to cylindrical form.

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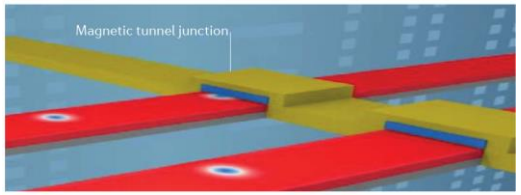
FIGURE 2–MAGNETIC-BUBBLE DOMAINS

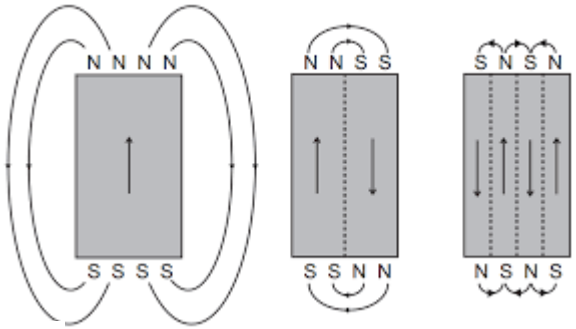
-função tot





Li *et al.*, Interd. Mat. **2**, 175 (2023)





Modelo Heitler-Lon

