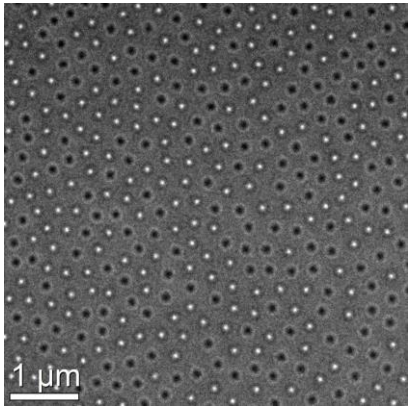
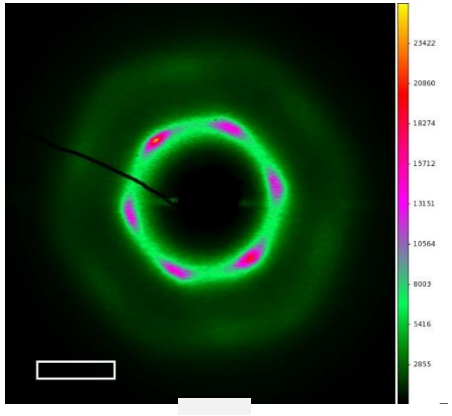
Materials optimization to form skyrmions and skyrmion lattices

S. Montoya, R. Tolley, V. Uhlíř, S. Couture, J. Chess, J. Lee, N. Kent, M.-Y. Im, X. Shi, S. Mishra, S. Sinha, P. Fischer, V. Lomakin, B. McMorran, V. Lomakin, S. Roy & E. Fullerton

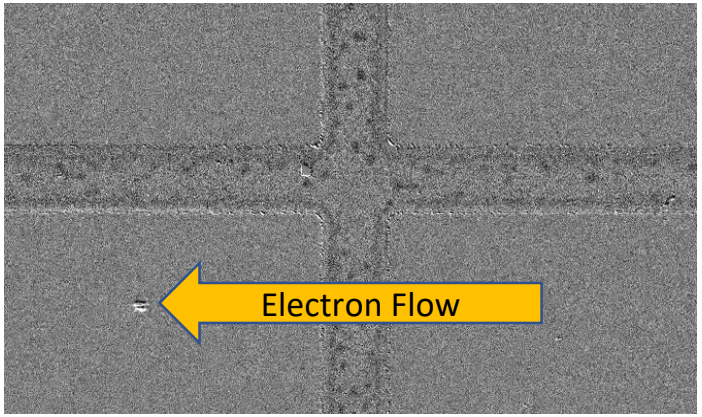
Fe/Gd multilayers





No DMI

Pt/Co/Os/Pt



DMI

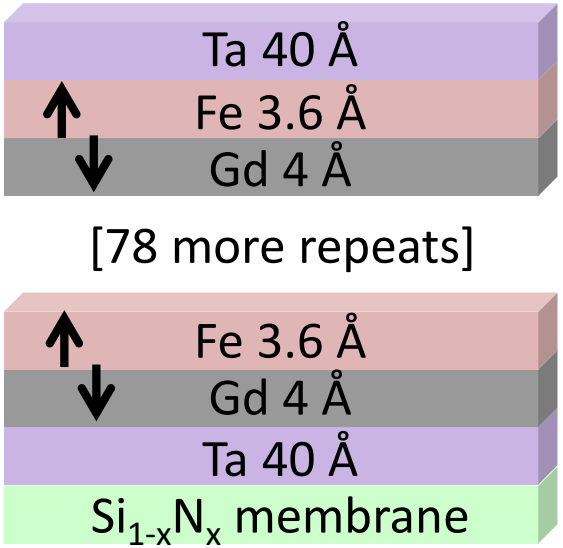
UC San Diego

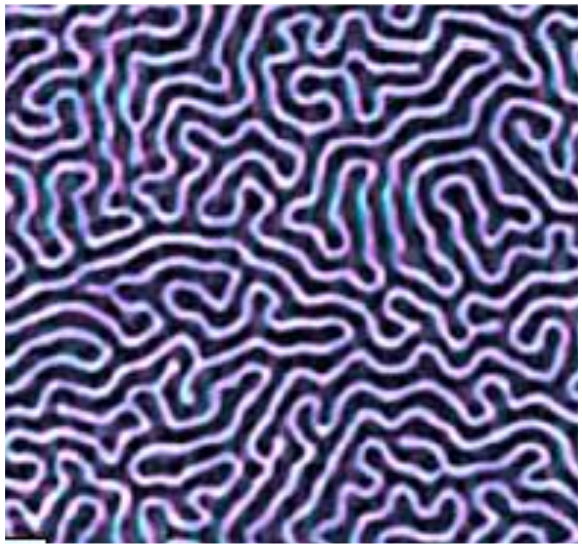
UCSC

UNIVERSITY OF OREGON

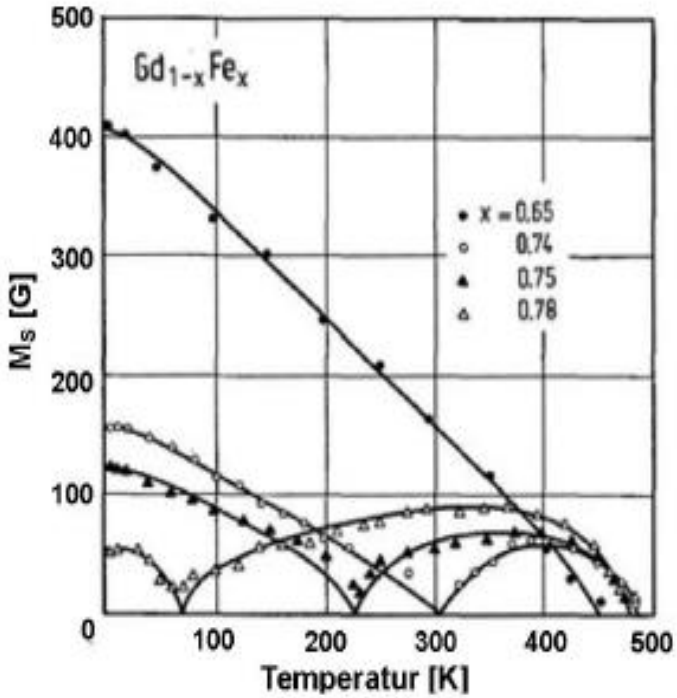
BERKELEY LAB
Lawrence Berkeley National Laboratory

Fe/Gd multilayers as a model AF

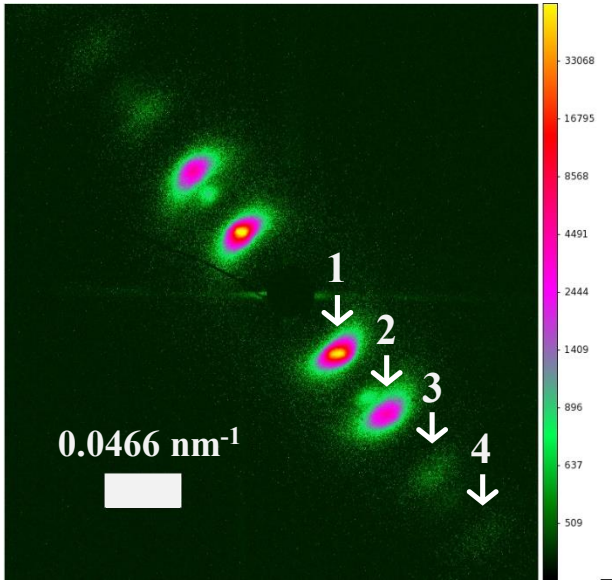




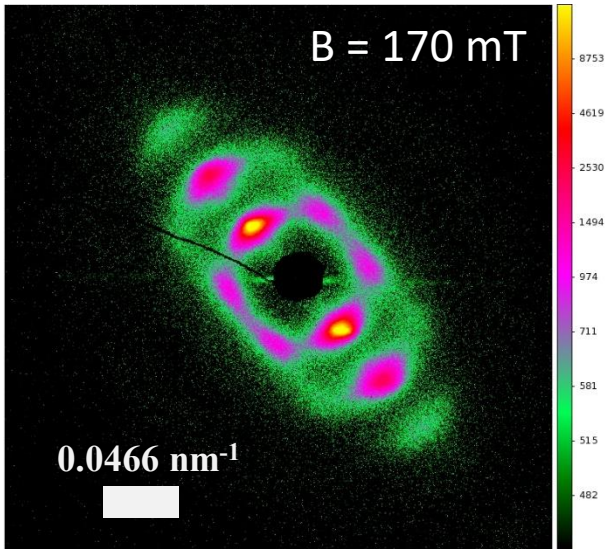
Ferrimagnet
Fe-Gd antiferromagnetically coupled
Perpendicular magnetic anisotropy
M_S tunable
T_C and $T_{compensation}$ tunable
No DMI



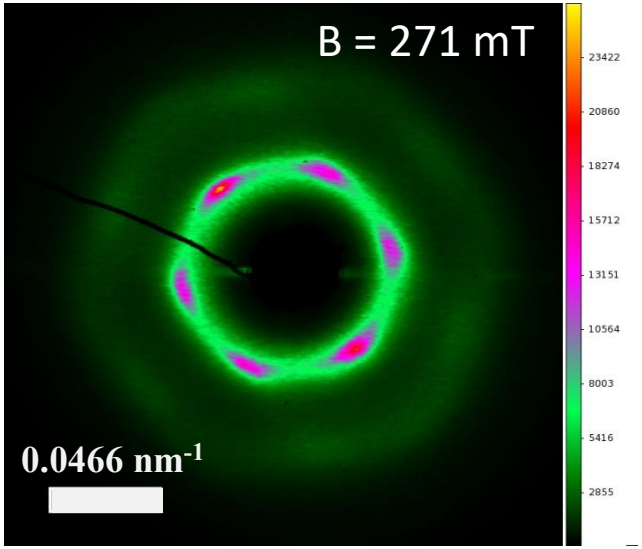
Fe/Gd multilayers as a model AF



Very well aligned stripe domain at B=0



Intermediate state

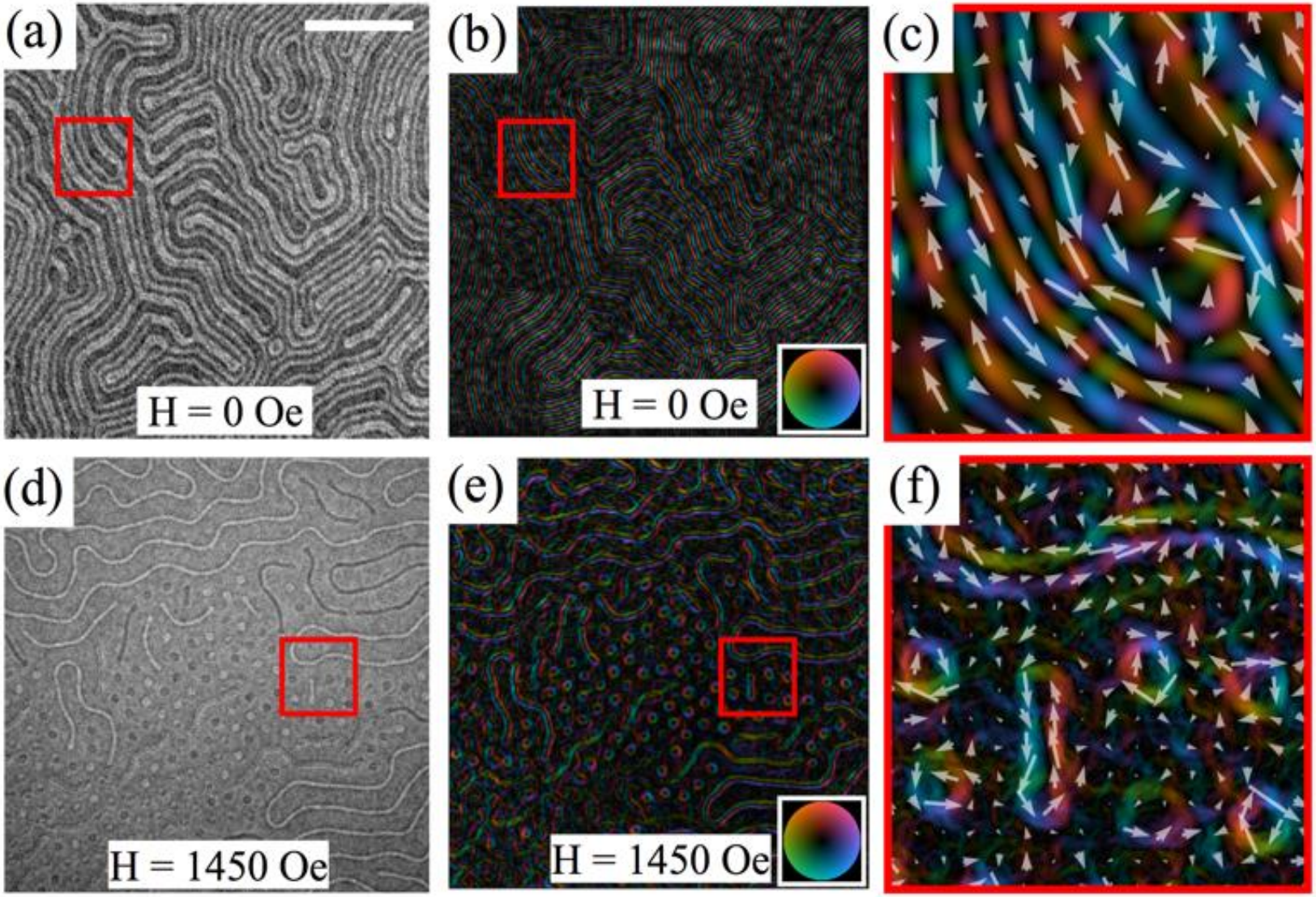


Hexagonal lattice !!

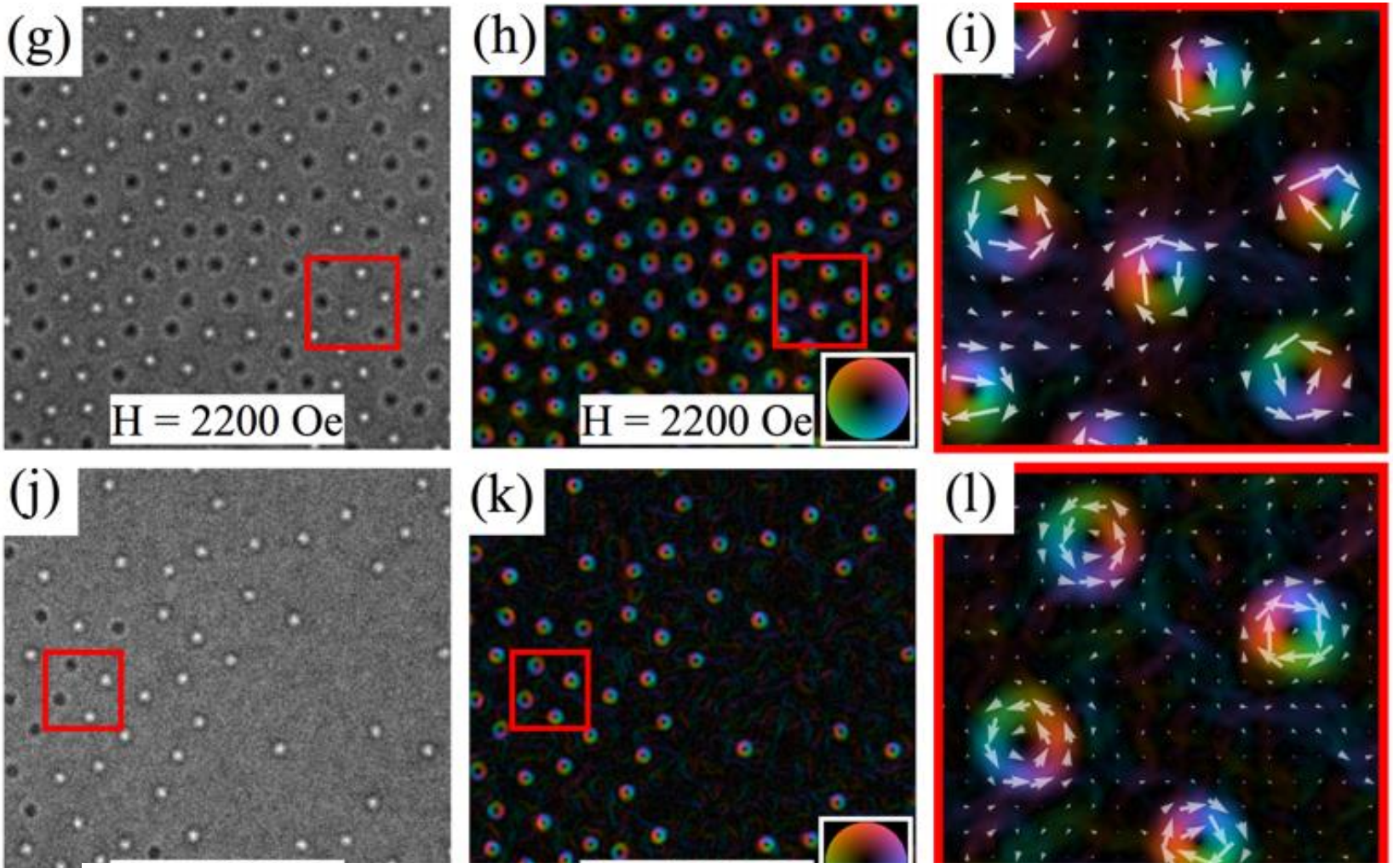
- Aligned stripe domains at low temperature, almost like a grating.
- Continuous deformation from stripe to hexagonal lattice.

Jordan Chess, Ben McMorran, U Oregon

Fe/Gd Lorentz TEM



Fe/Gd Lorentz TEM



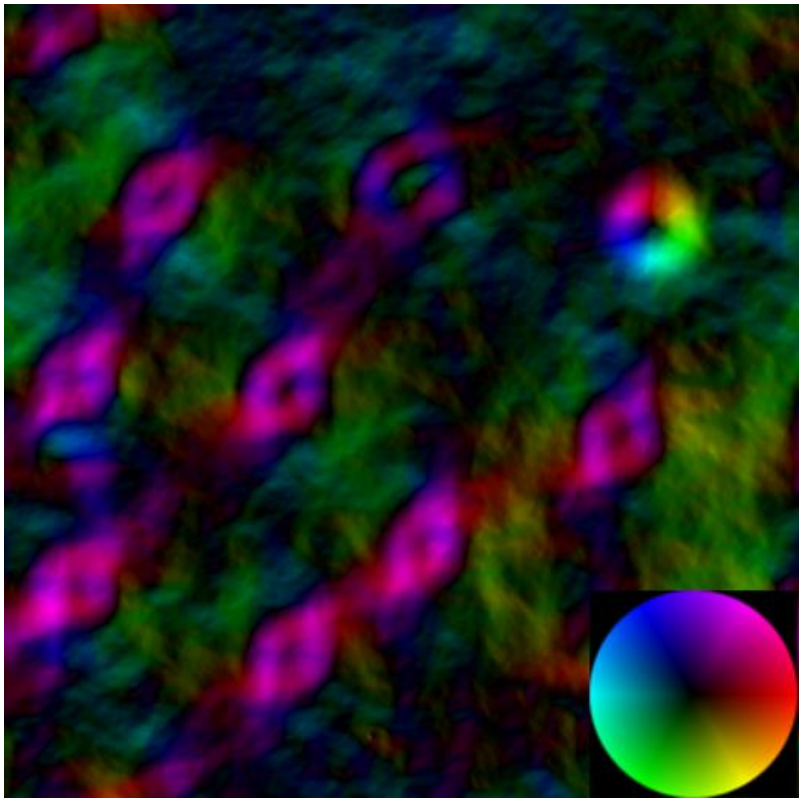
*Sc doped Barium Hexaferrite X. Yu et al, PNAS **109**, 8856 (2012)*

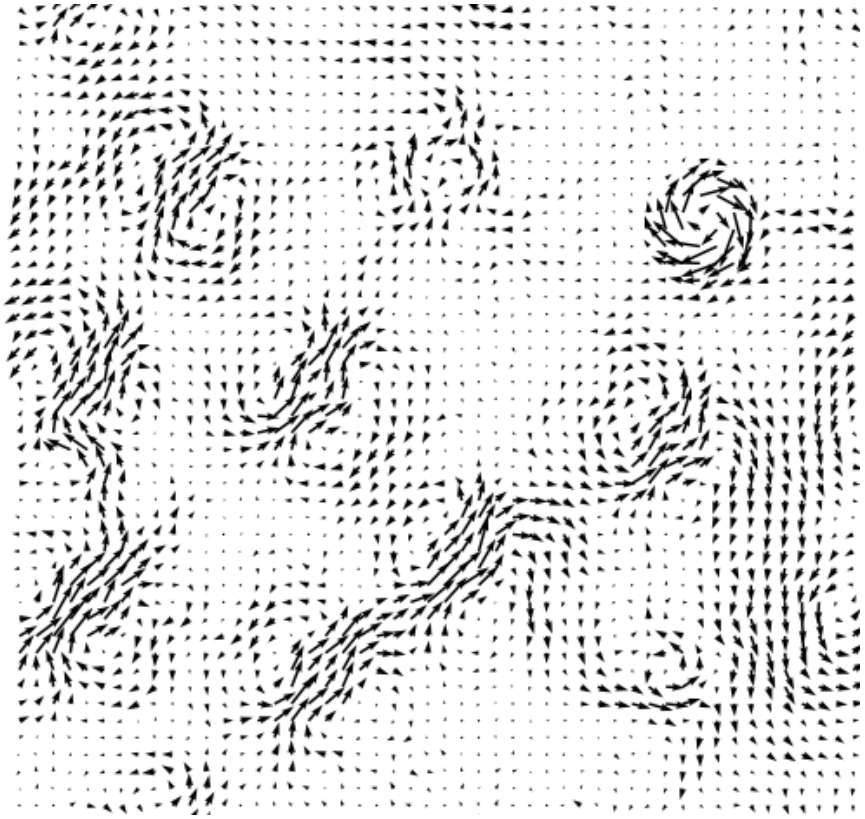
Fe/Gd

Lack of DMI allows other chiral structures to form

Fe/Gd LTEM

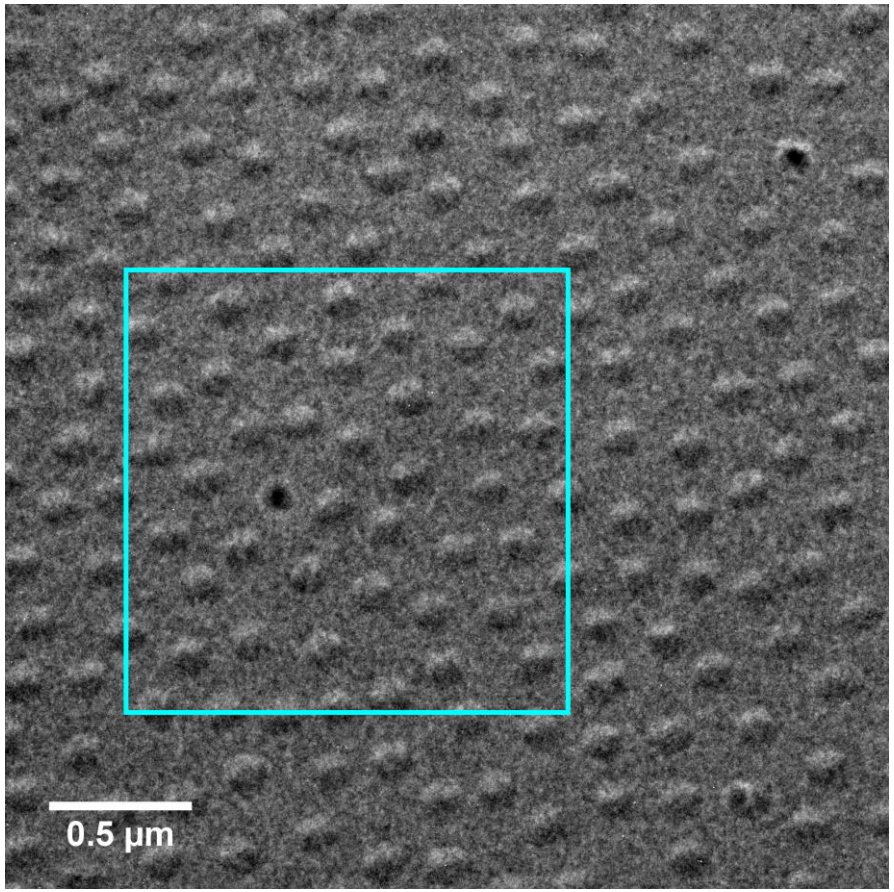
Lack of DMI allows other chiral structures to form

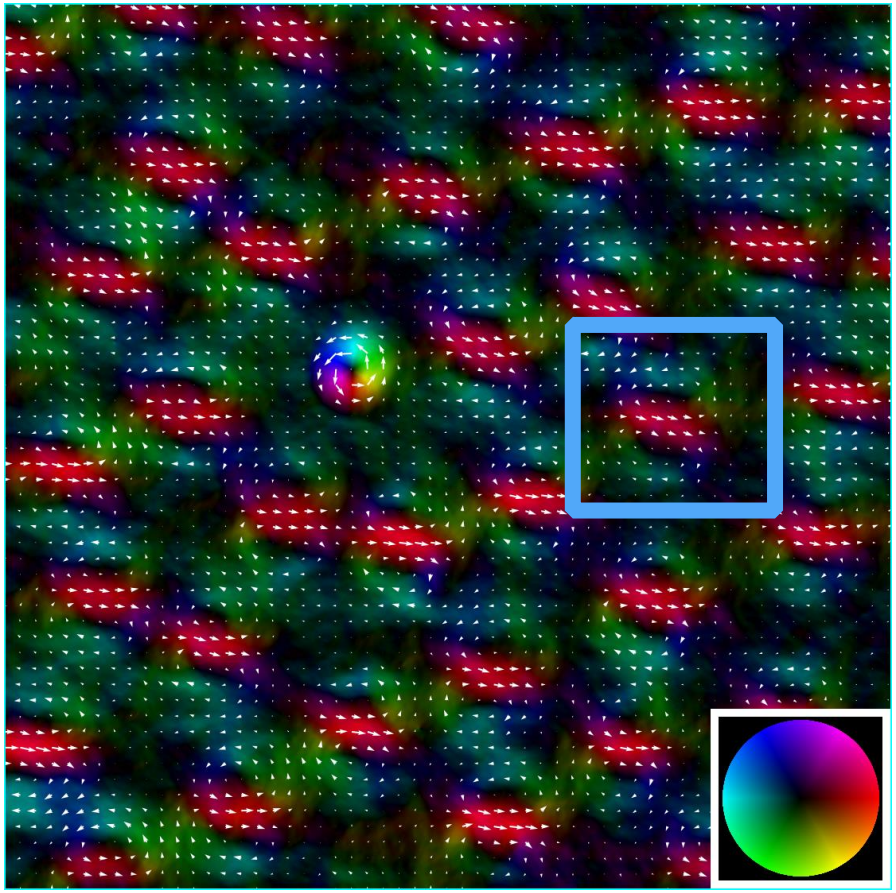




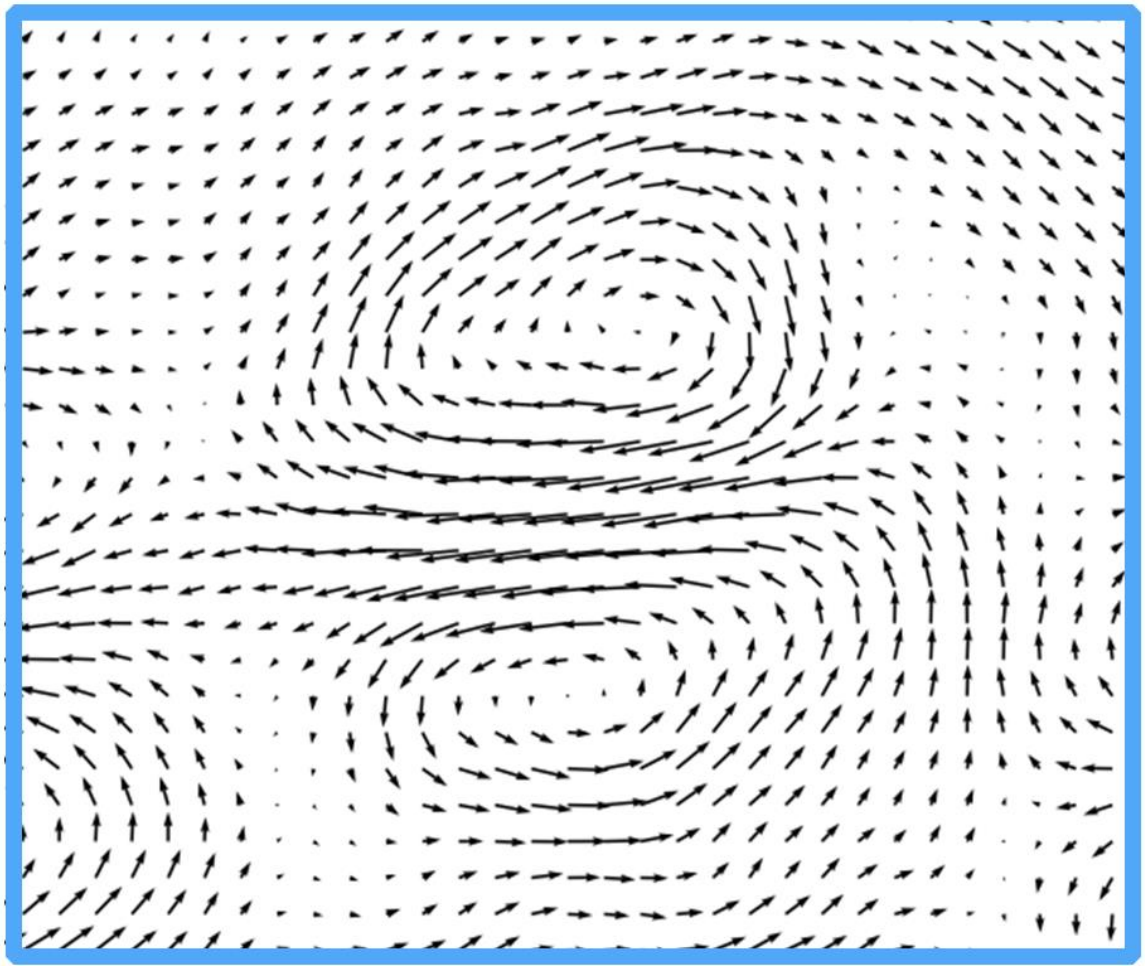
Winding number is zero

Fe/Gd LTEM





Fe/Gd LTEM



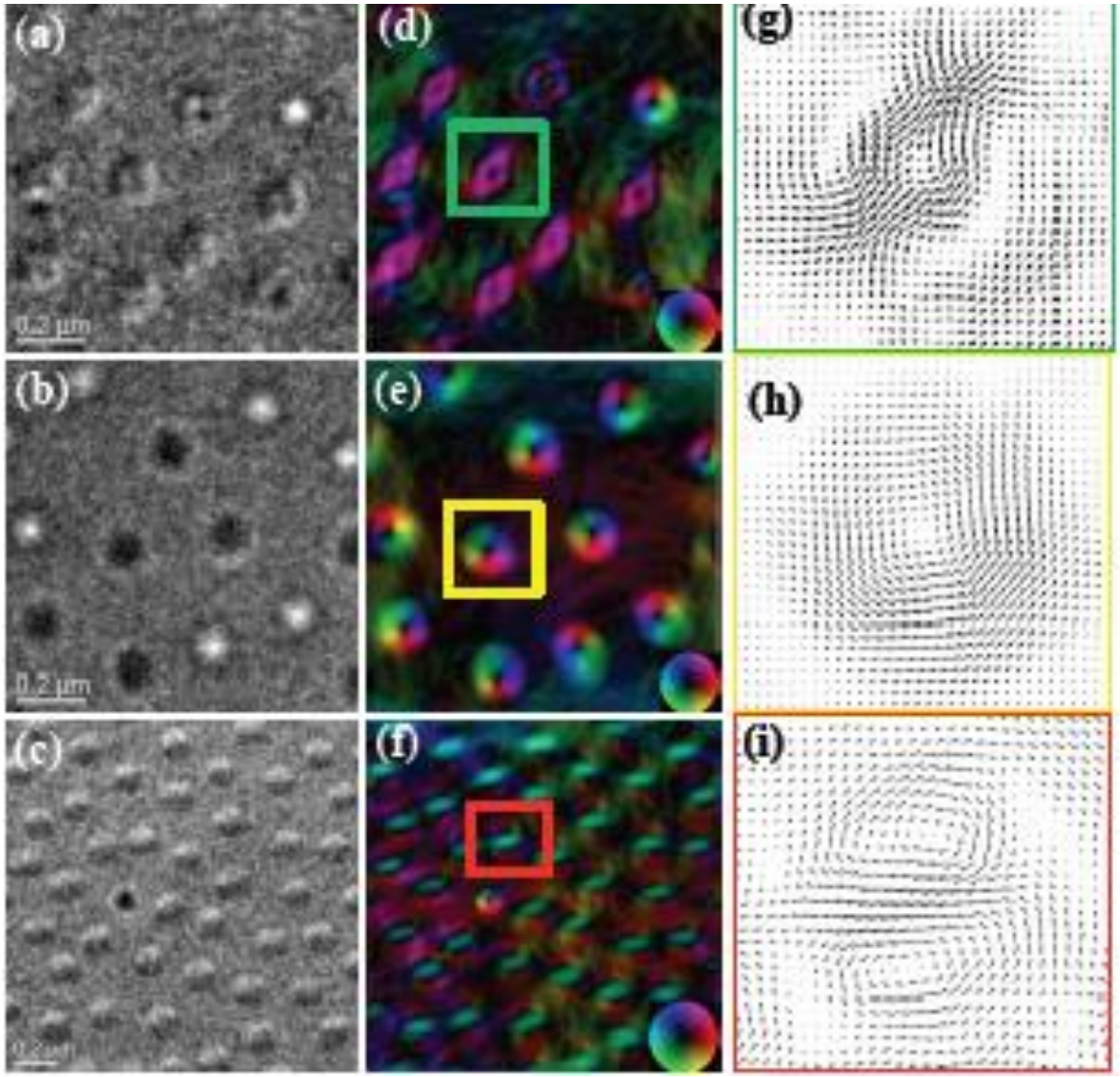
APPLIED PHYSICS LETTERS **109**, 022402 (2016)

Synthesizing skyrmion bound pairs in Fe-Gd thin films

J. C. T Lee,[1,2,3,a)] J. J. Chess,[1,a)] S. A. Montoya,[4,a)] X. Shi,[1] N. Tamura,[2] S. K. Mishra,[2] P. Fischer,[3,5] B. J. McMorran,[1] S. K. Sinha,[6] E. E. Fullerton,[4] S. D. Kevan,[1,2,3] and S. Roy

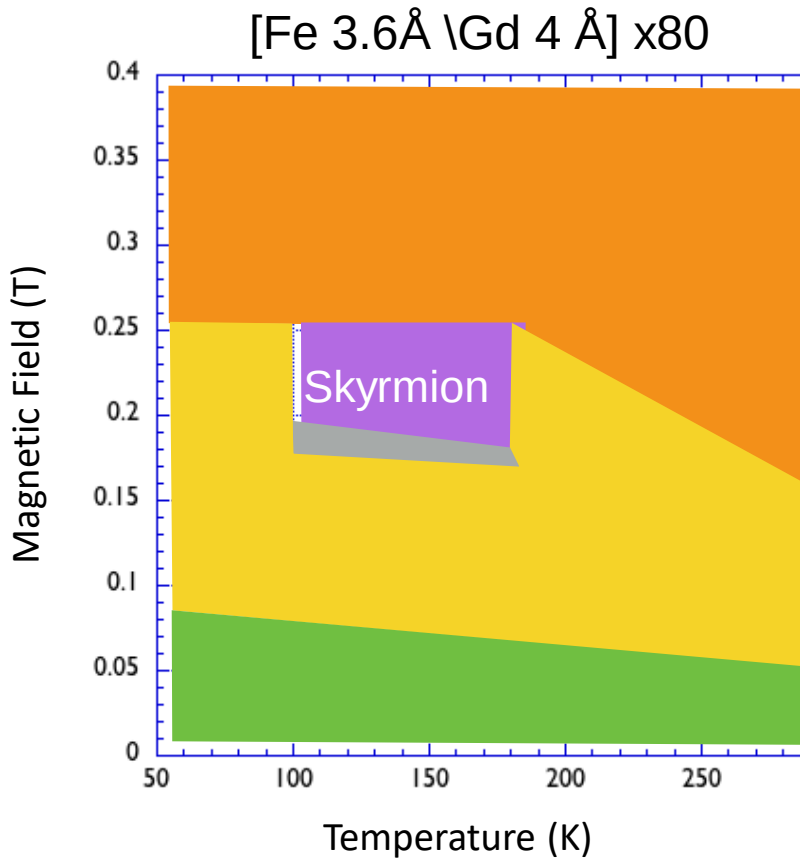
Wang et al., Advanced Materials, 28 (2016) 6887-6893.

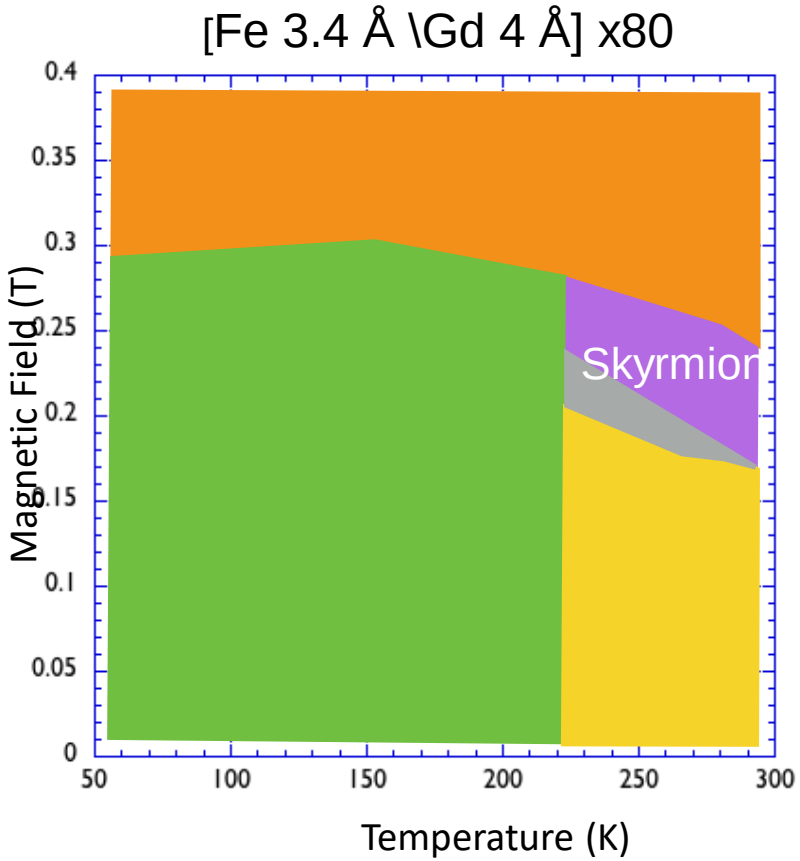
Fe/Gd films



What materials properties give rise to these specific spin structures?

Fe/Gd films





Saturation

Hexagonal Lattice

Stripe-Bubble Transition

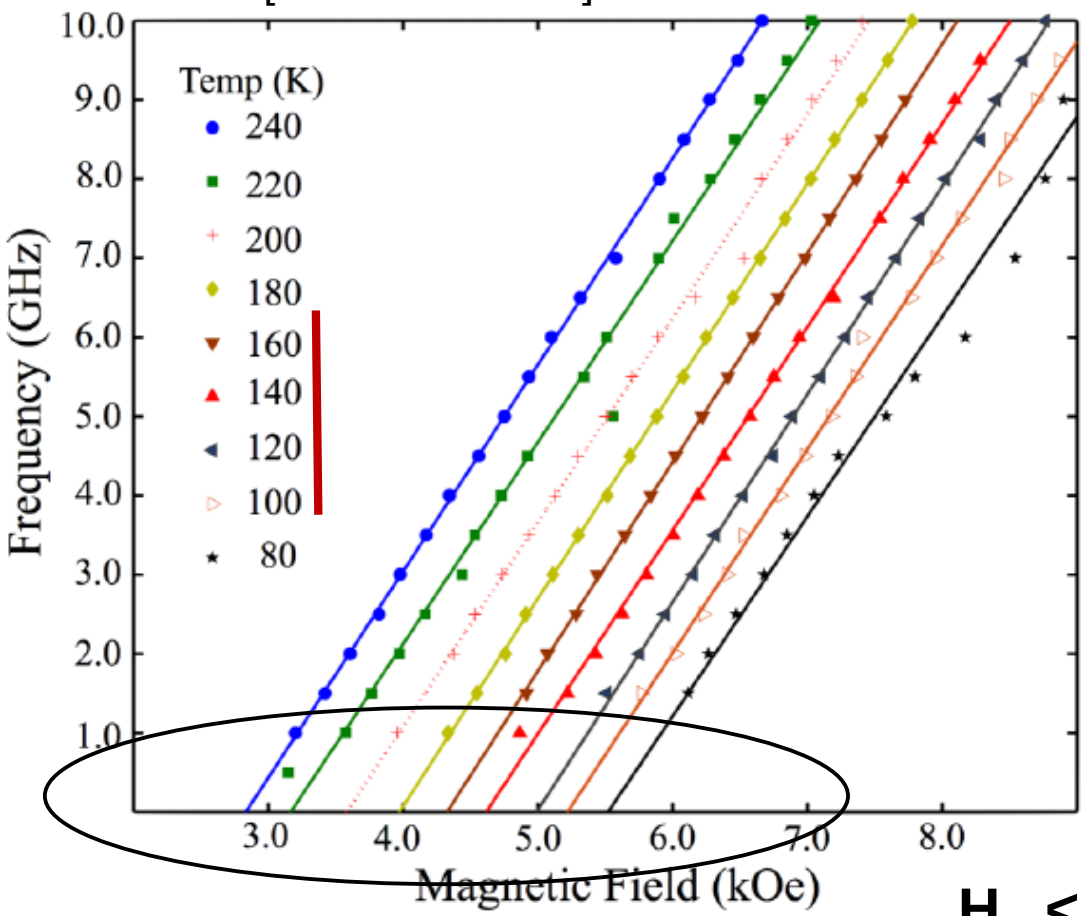
Stripes (aligned)

Labyrinth Domains

*Constructed using XMCD data

FMR

[Fe 3.6Å \Gd 4 Å] x80



$H_K < 4\pi M_S$

$Q = K_U/2\pi M_S^2 < 1$

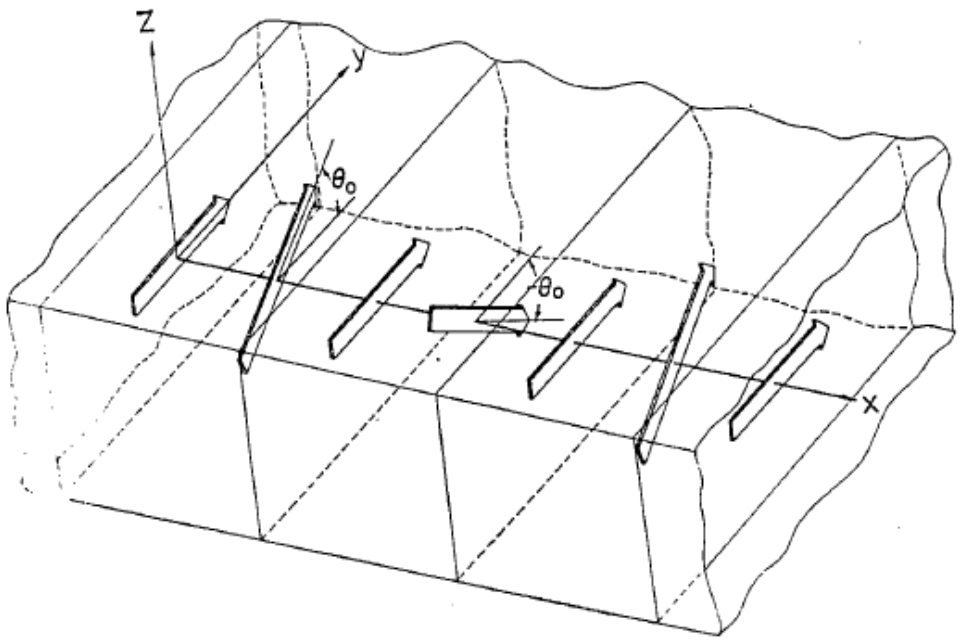
Kittel Formula: $\omega = \gamma(H + H_K - 4\pi M_S)$

Magnetic propeties

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 19, No. 7, JULY, 1964

A New Type of Magnetic Domain Structure in Negative Magnetostriction Ni-Fe Films

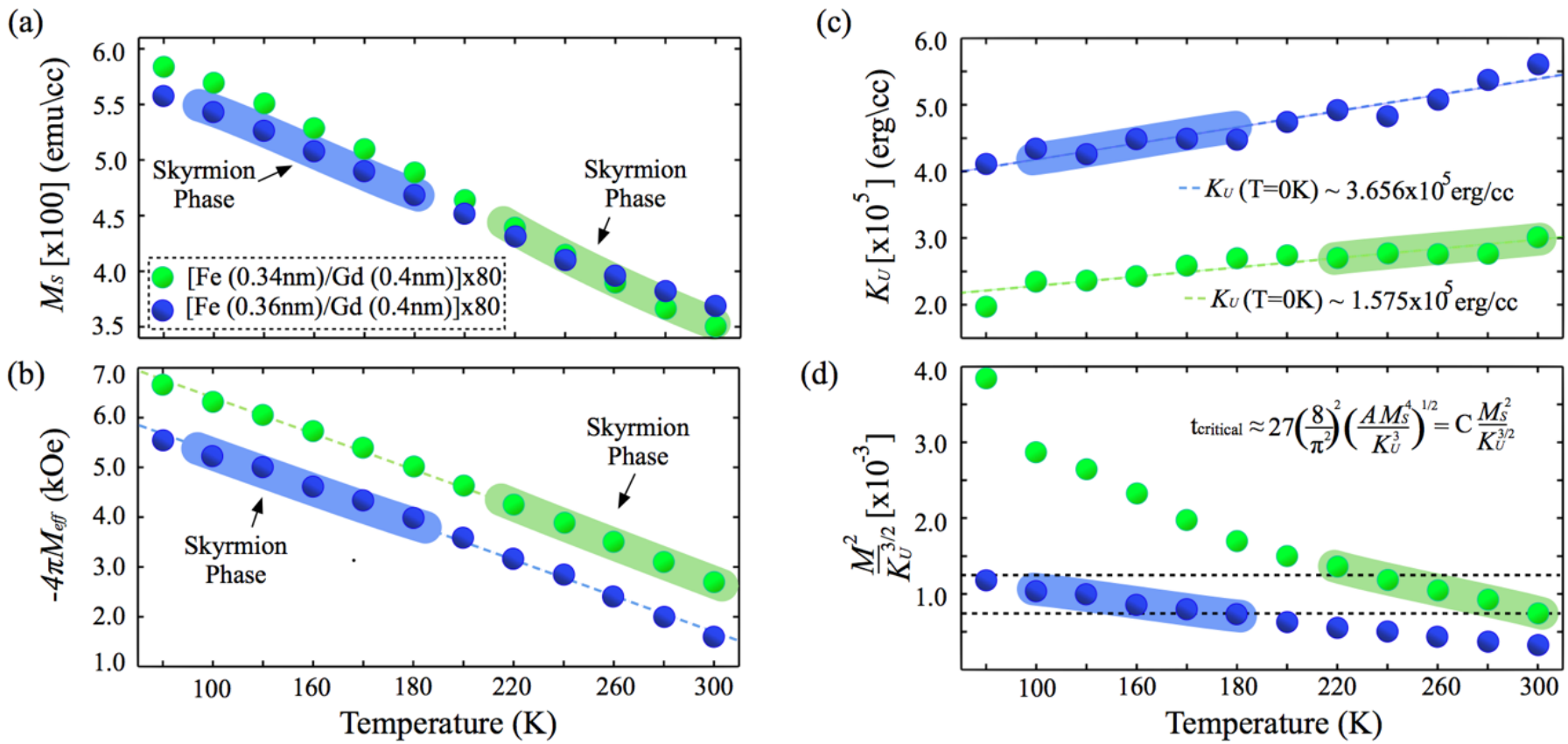
Nobuo SAITO, Hideo FUJIWARA and Yutaka SUGITA



Critical thickness

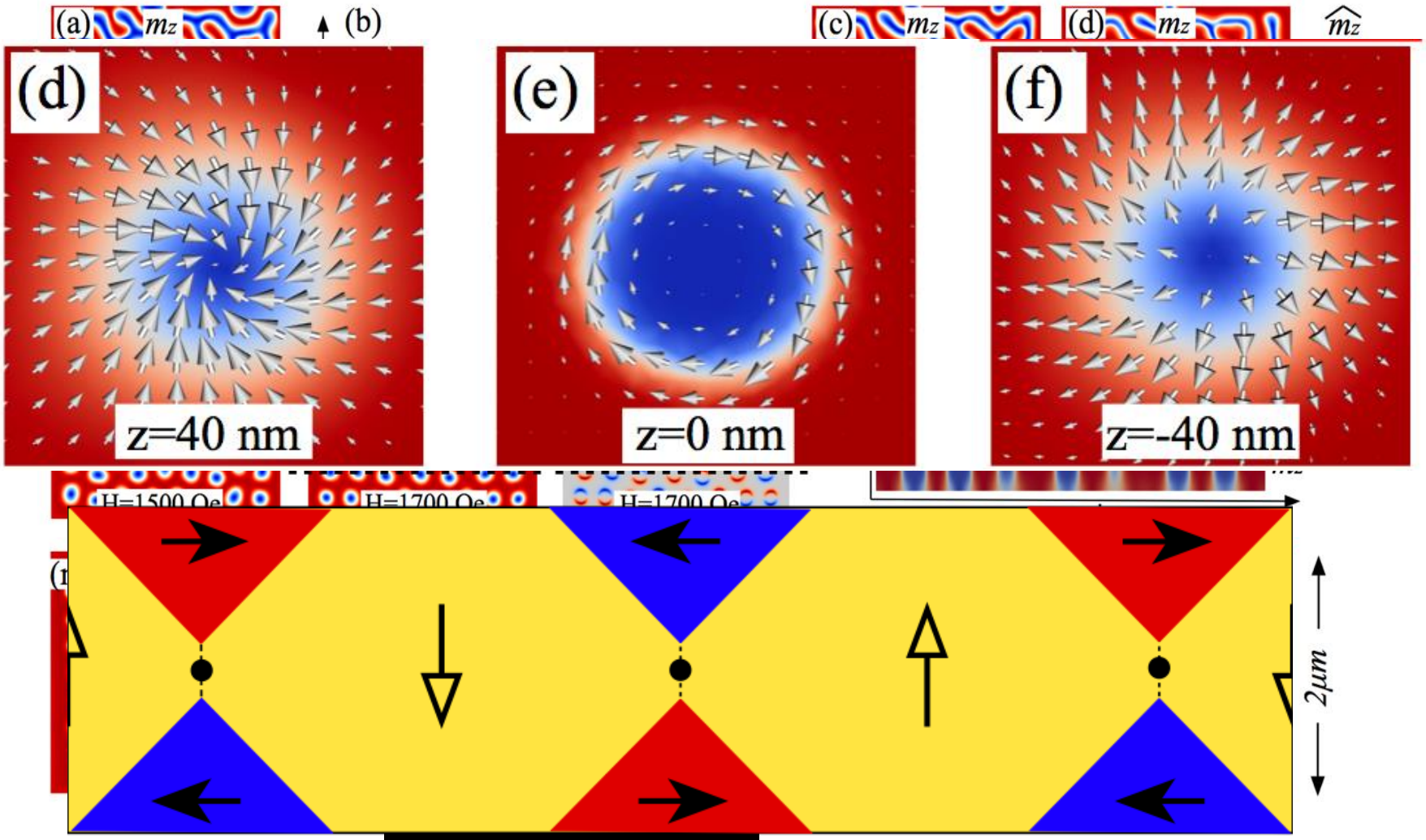
$$t_1 \sim 17.7\sqrt{A}\, M_S^2 / K_U^{3/2}$$

Magnetic properties



Fe/Gd modeling

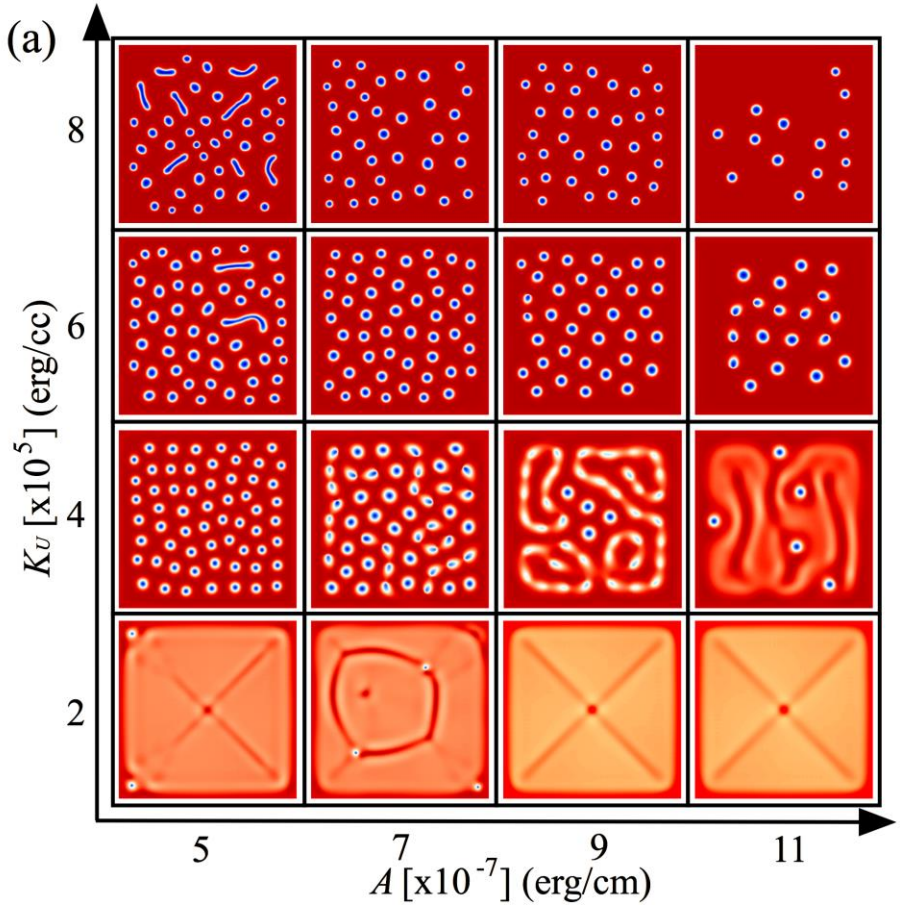
t = 80 nm, M_S = 400 emu/cc
K_U = 4x10^5 erg/cc, A= 5x10^{-7} erg/cm

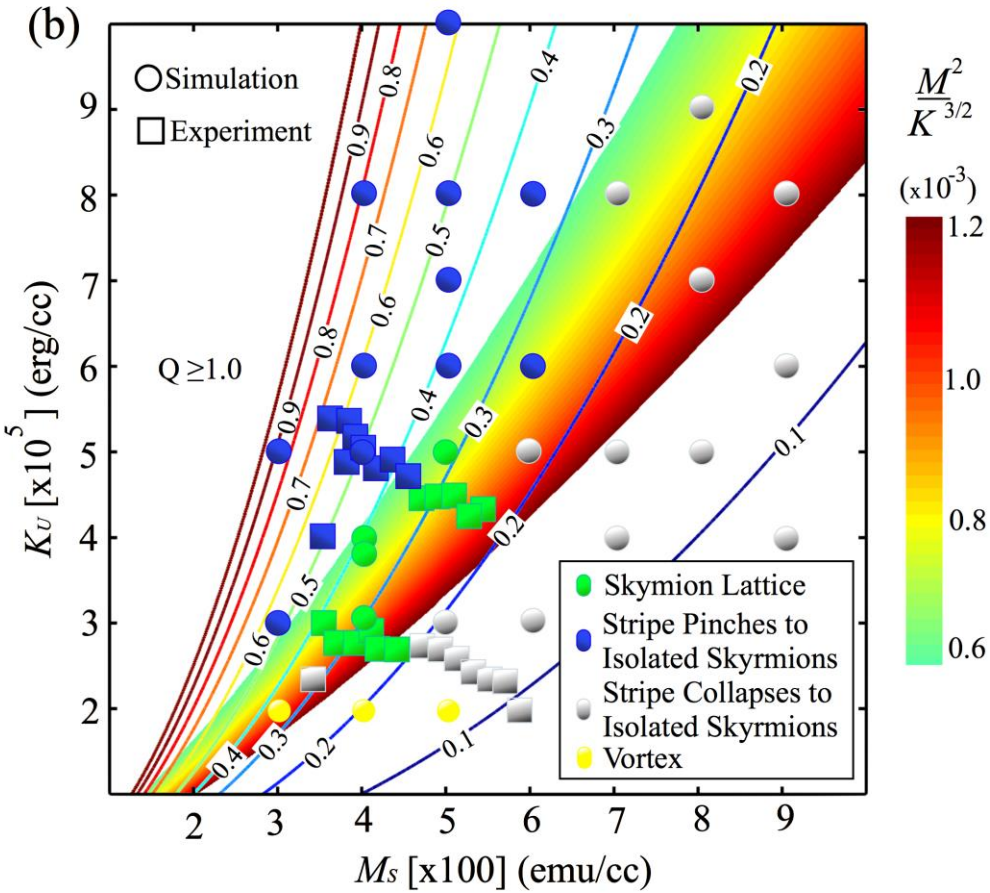


FASTMag

Vitaliy Lomakin

Fe/Gd modeling

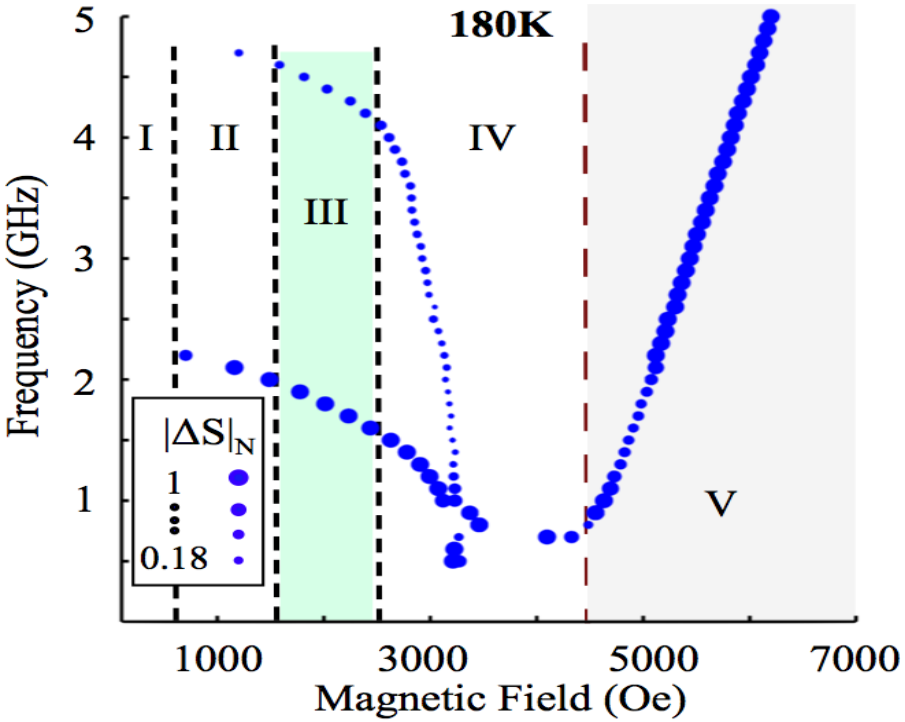




Fe/Gd magnetism

- Sub-100 nm dipolar field driven non-trivial spin textures
  - Bubbles, skyrmions, and bi-skyrmion states and lattices
- Ingredients: low M, low K, low A, thick films (above t_{crit})

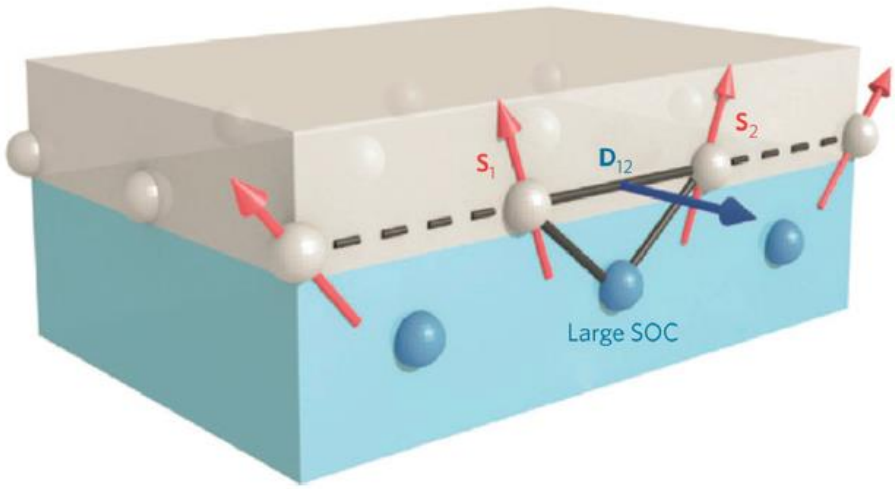
S. A. Montoya, *et al*., Phys. Rev. B **95**, 024415 (2017)

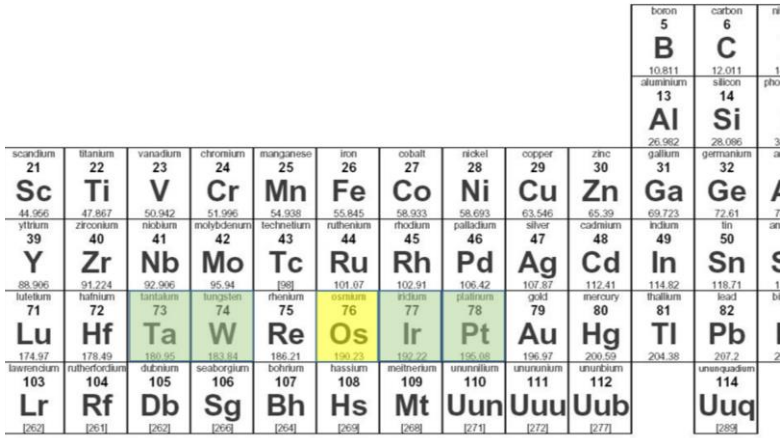


S. A. Montoya, *et al*., Phys. Rev. B **95**, 224405 (2017)

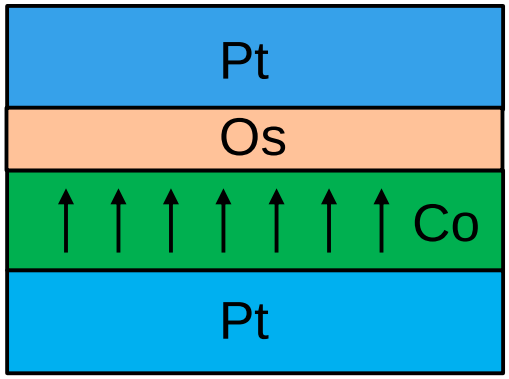
M. H. Seaberg, *et al*., Phys. Rev. Lett. In press
Sub-ns x-ray photon correlation spectroscopy

Co/Pt/Os/Pt Layers

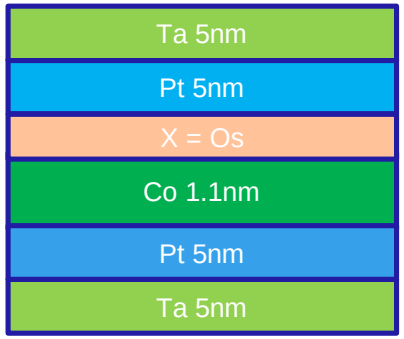


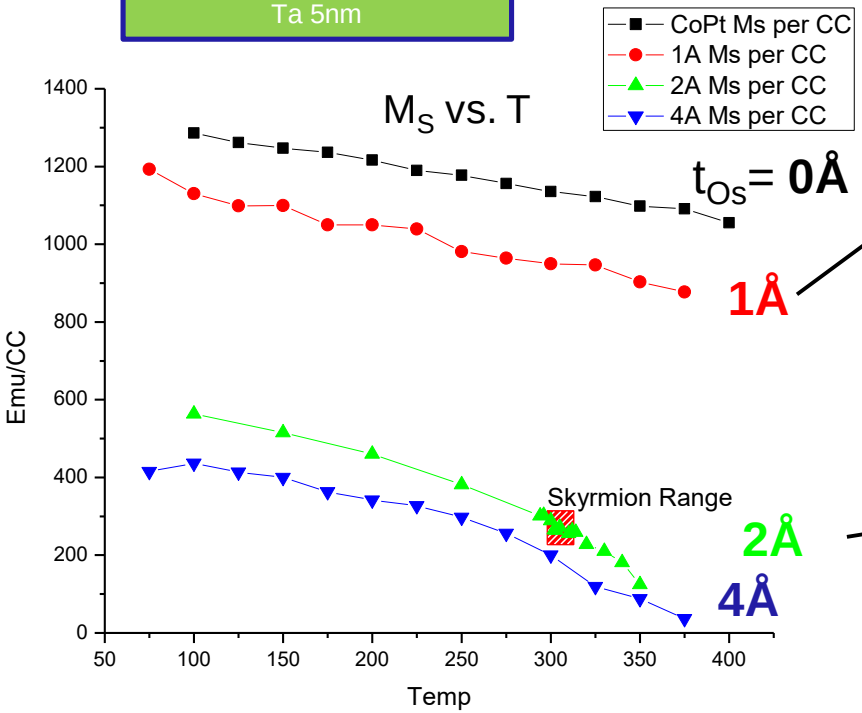


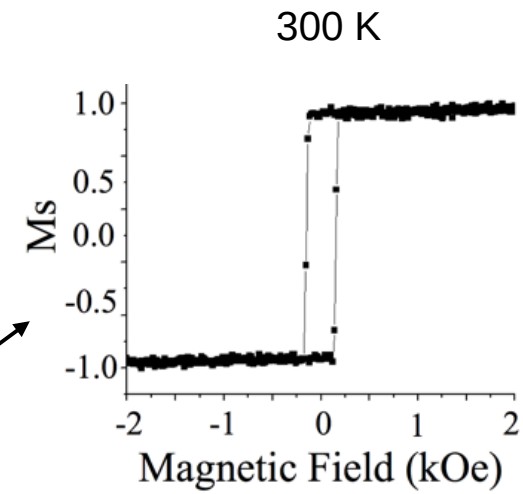
From Fert, Cros, and Sampaio, 2013

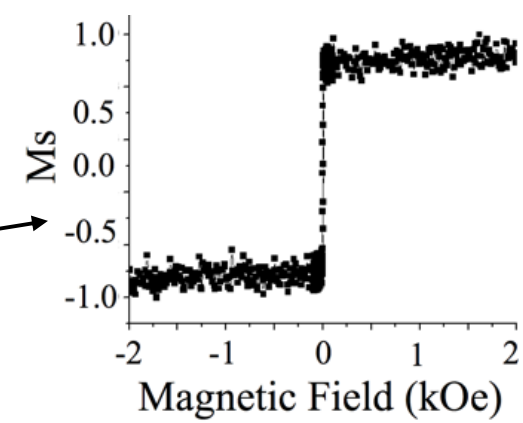


Co/Pt/Os/Pt Layers

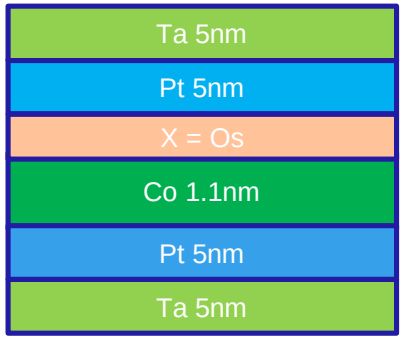


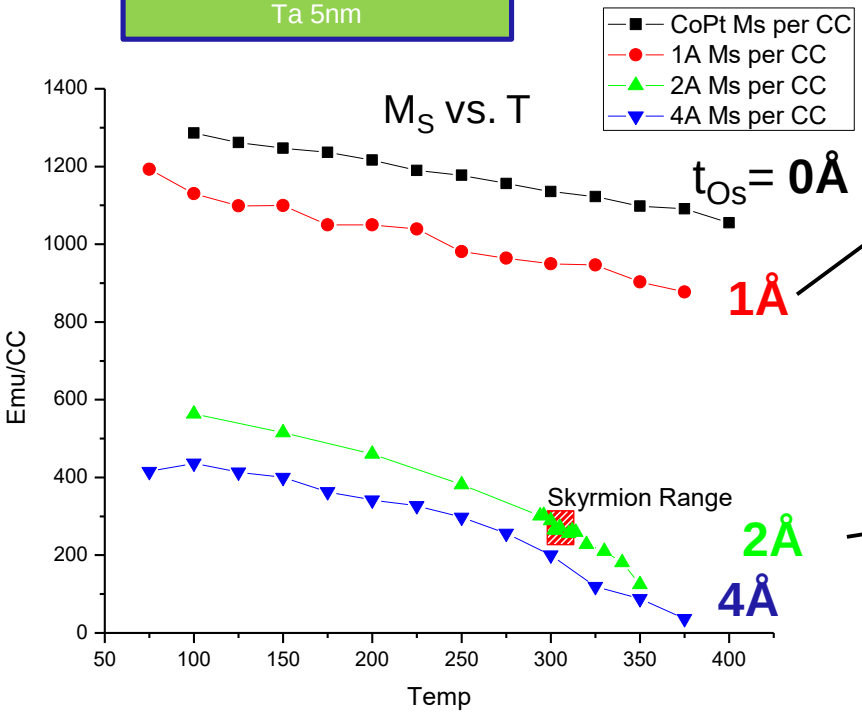


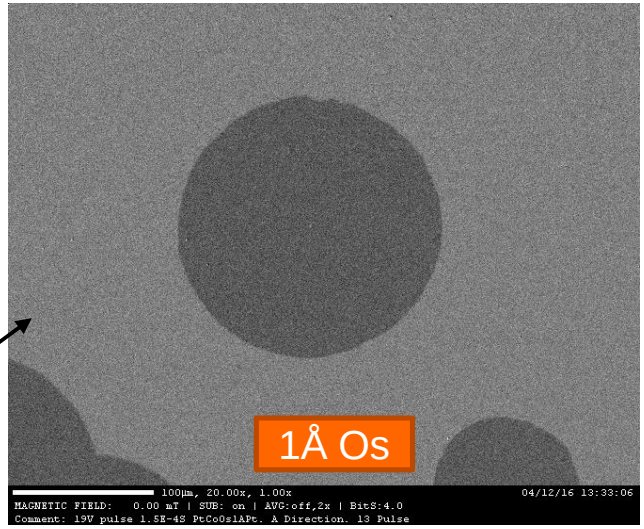


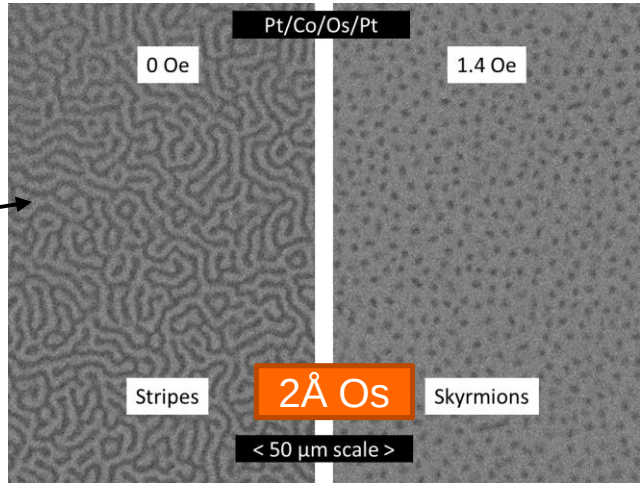


Co/Pt/Os/Pt Layers

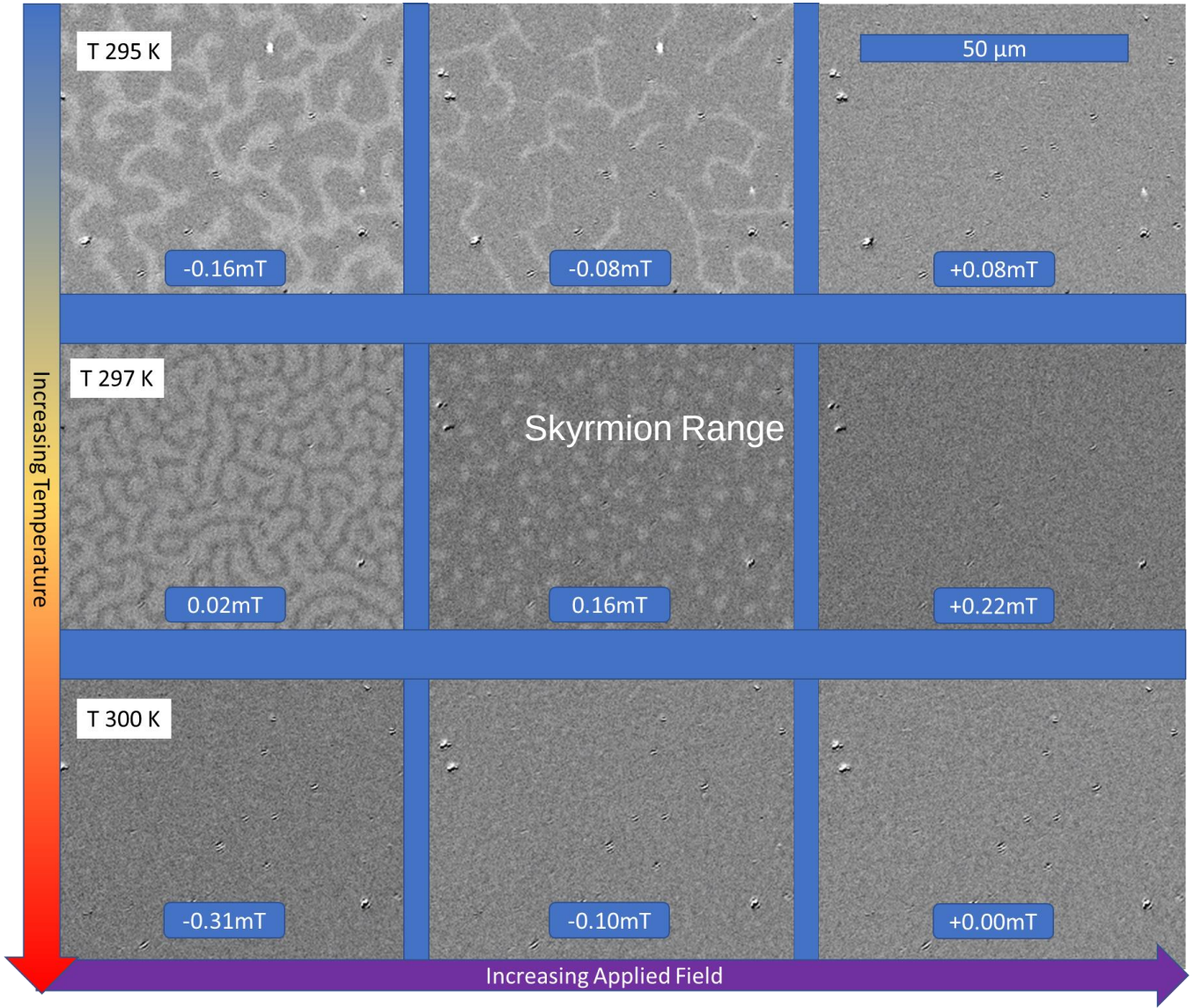




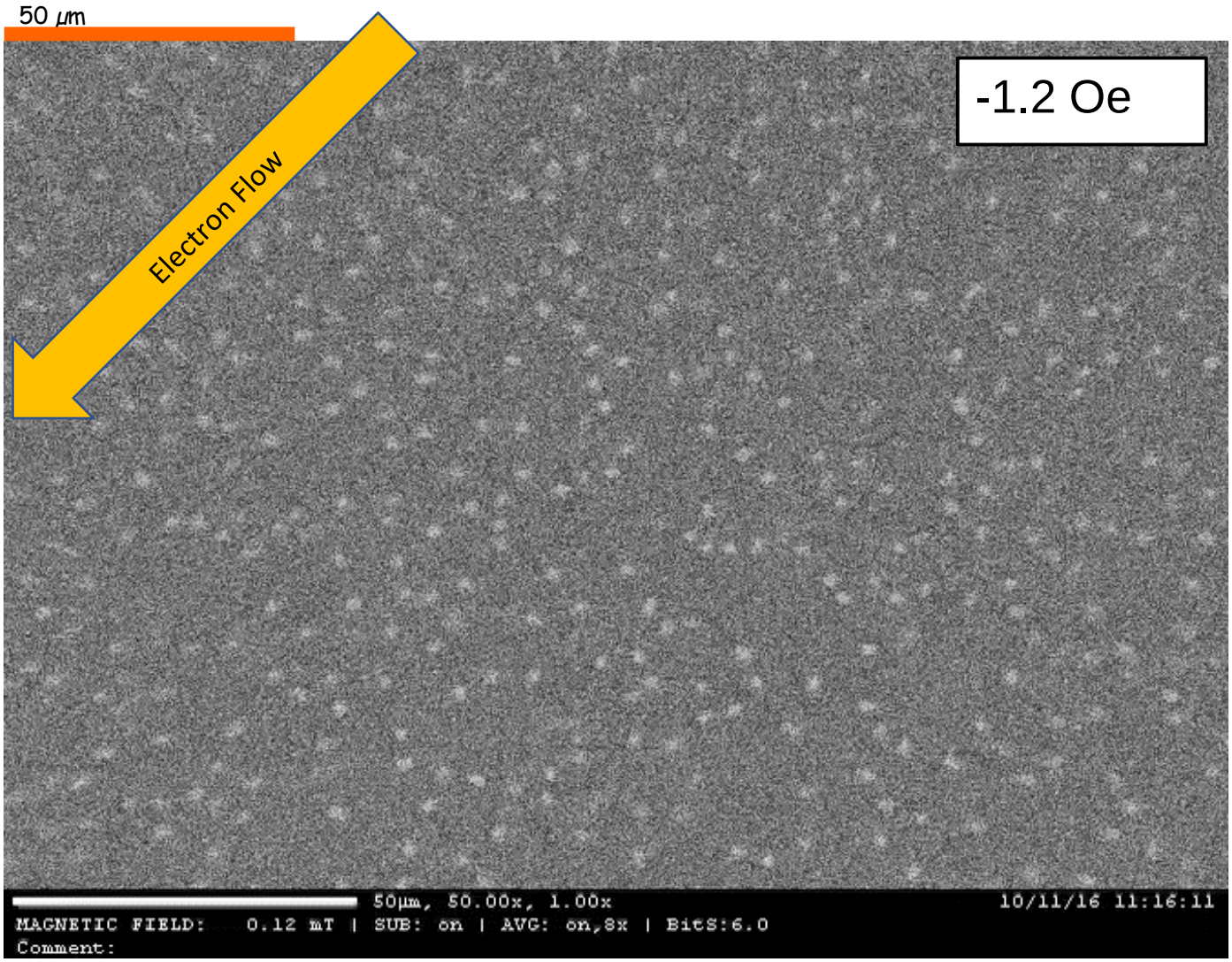




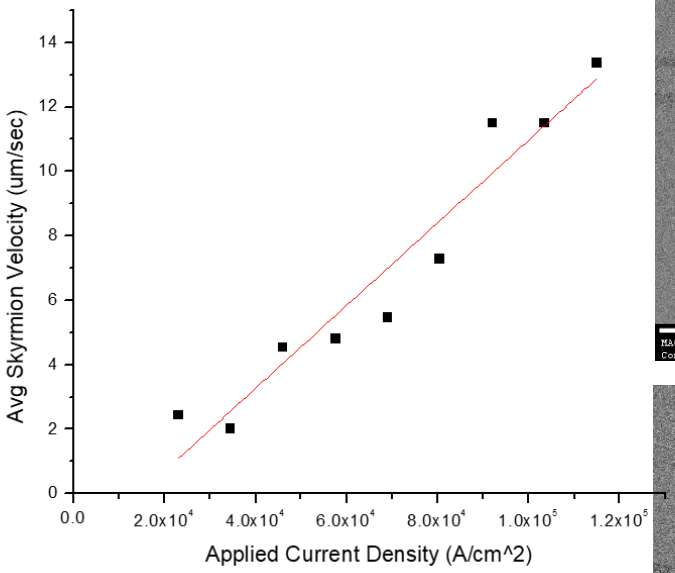
Temperature Dependence

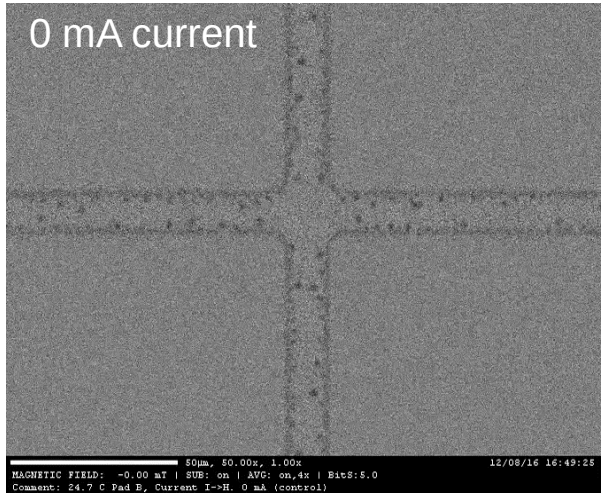


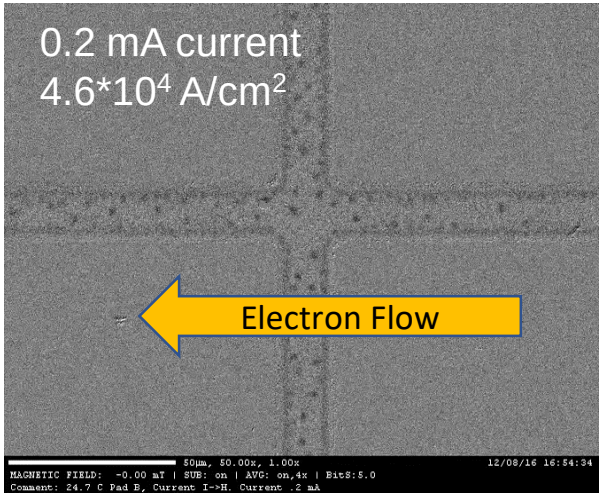
Current Driven Skyrmions

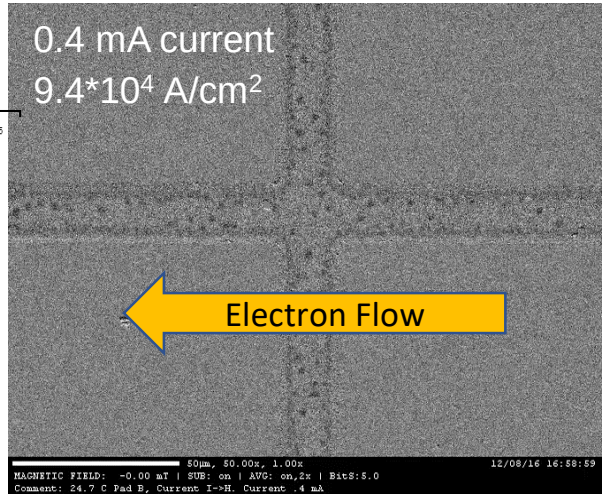


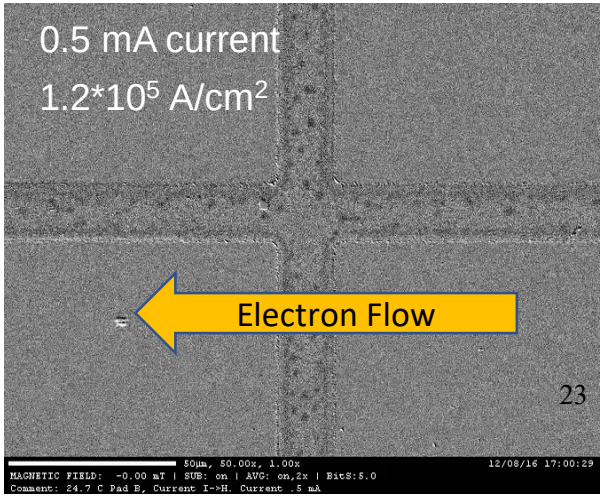
Moving Skyrmions





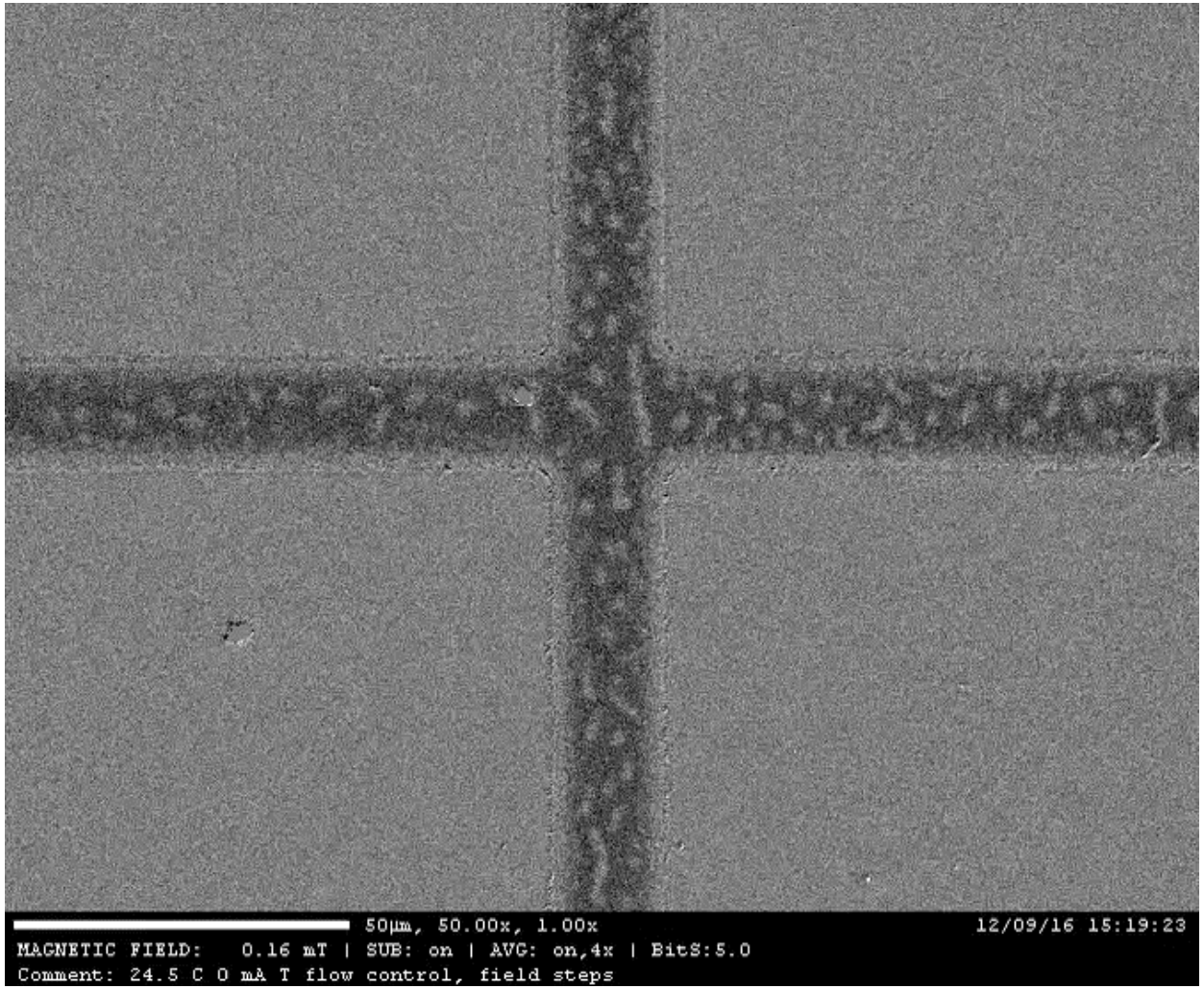




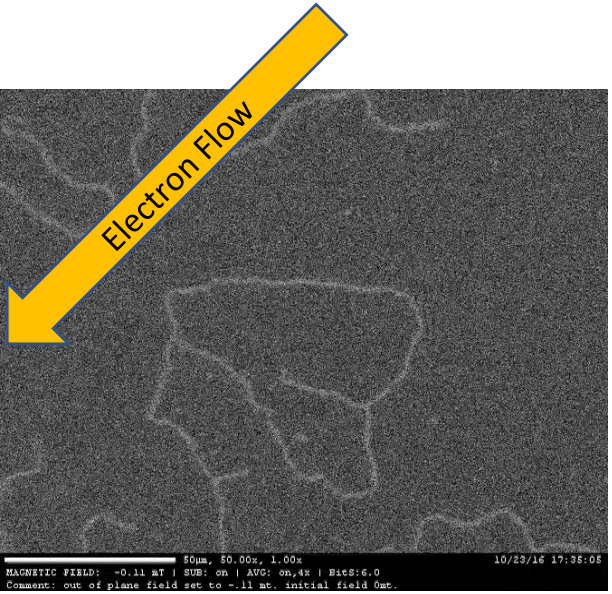


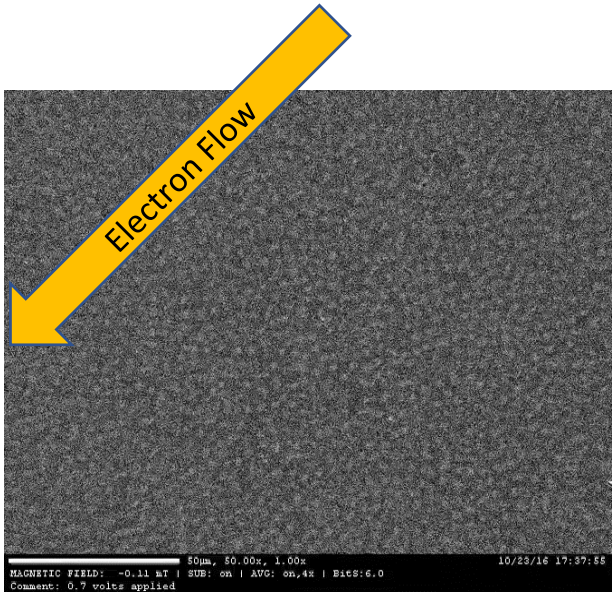
W. Jiang, *et al*. Science **349** (2015) 283-286

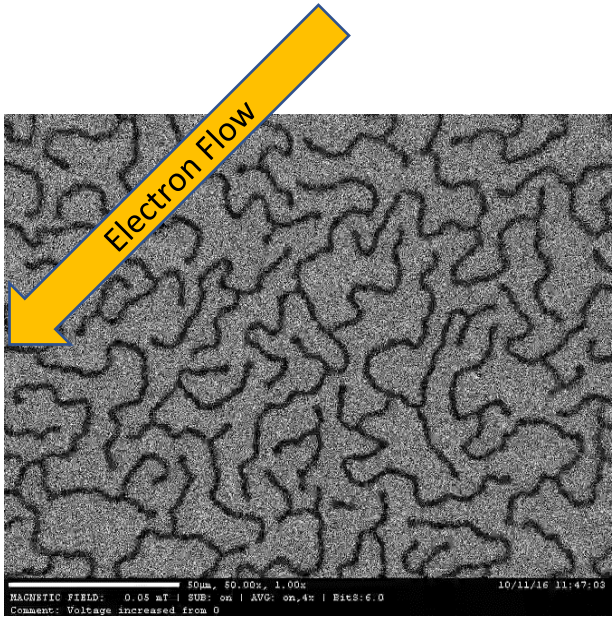
Moving Skyrmions



Formation with Current



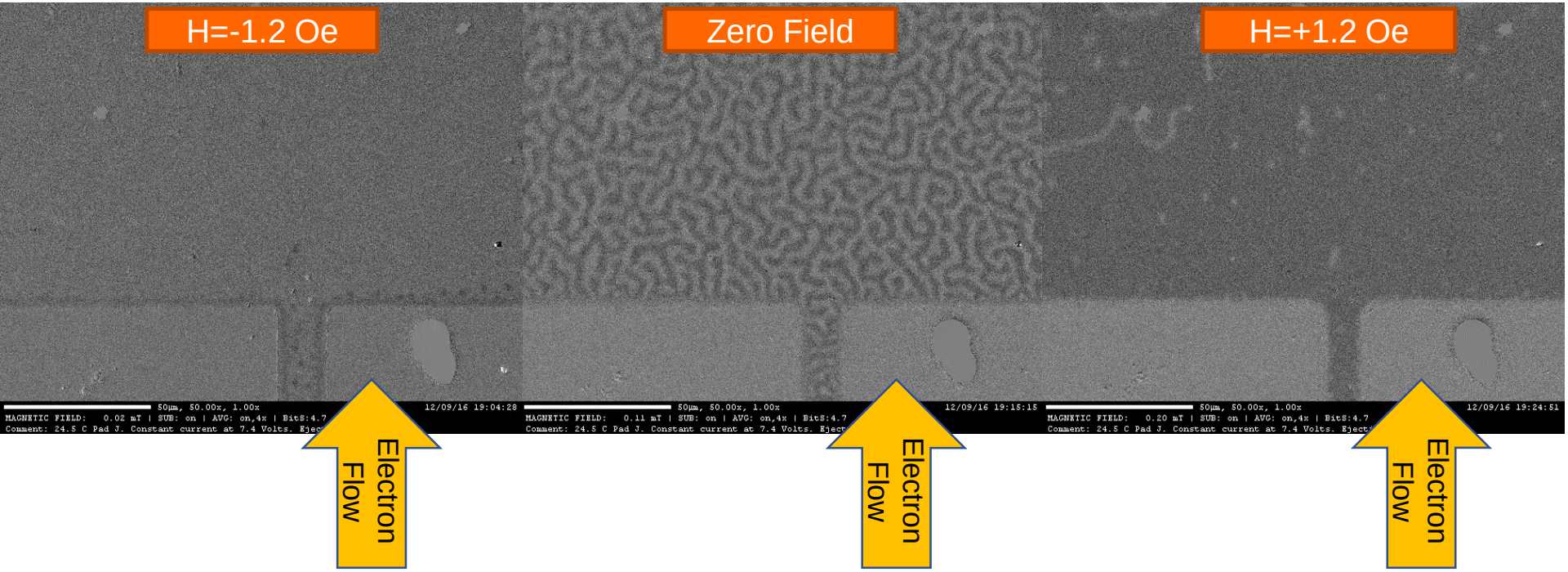




2.5 mA is sufficient to move skyrmions and stripes

3.5mA forces additional skyrmions to form. Within 10^4~10^5 A/cm2 causes stripes to break to skyrmions.

Skyrmion Hall effect

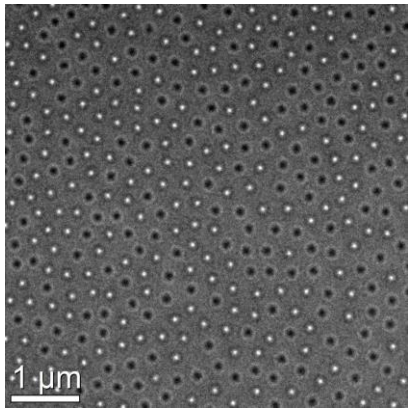


W. Jiang et al. *Nature Physics* **13** (2017) 162-169

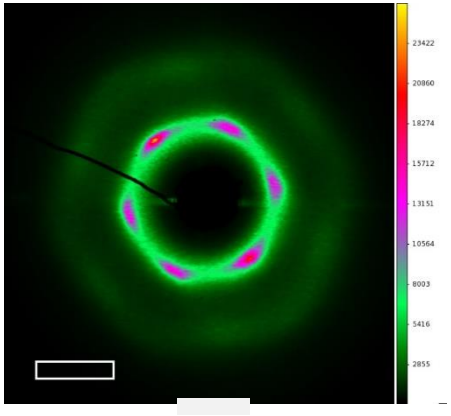
Materials optimization to form skyrmions and skyrmion lattices

Fe/Gd multilayers

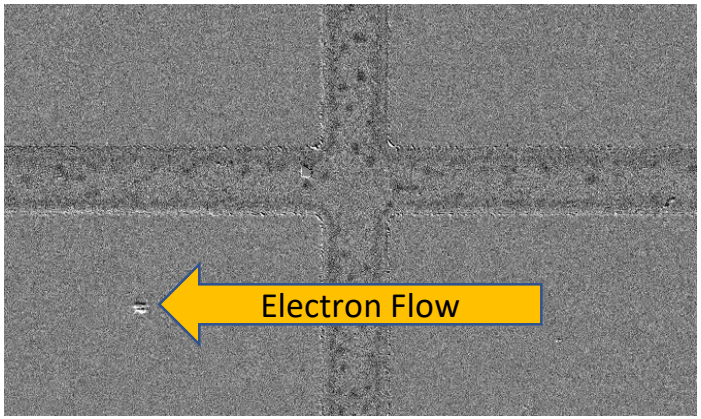
Pt/Co/Os/Pt



Lorentz-TEM



X-ray scattering



- Two very different systems: Fe/Gd dipole skyrmions w/o DMI
  Pt/Co/Os/Pt with DMI

- Common ingredients: low M, low K, and low A
  Near a spin reorientation transition