Bottom-up magnetic systems

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Modern applications of magnetism

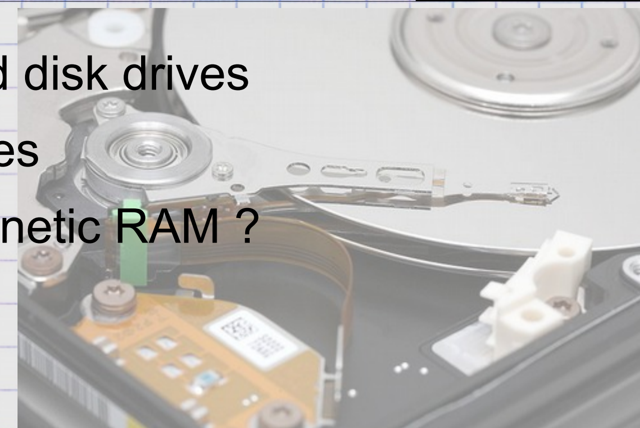
Where can 'nano' contribute ?

Materials

- Magnets (→ motors and generators)
- Transformers
- Magnetocaloric

Data storage

- Hard disk drives
- Tapes
- Magnetic RAM ?

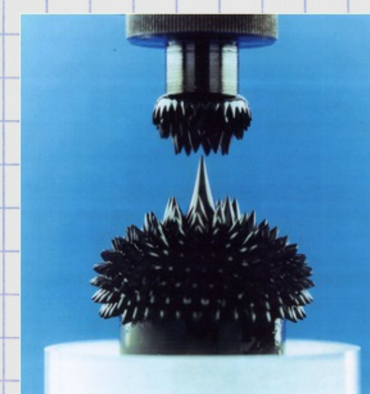


Sensors

- Compass
- Field mapping
- HDD Read heads

Nanoparticles

- Ferrofluids
- IRM contrast
- Hyperthermia
- Sorting & tagging



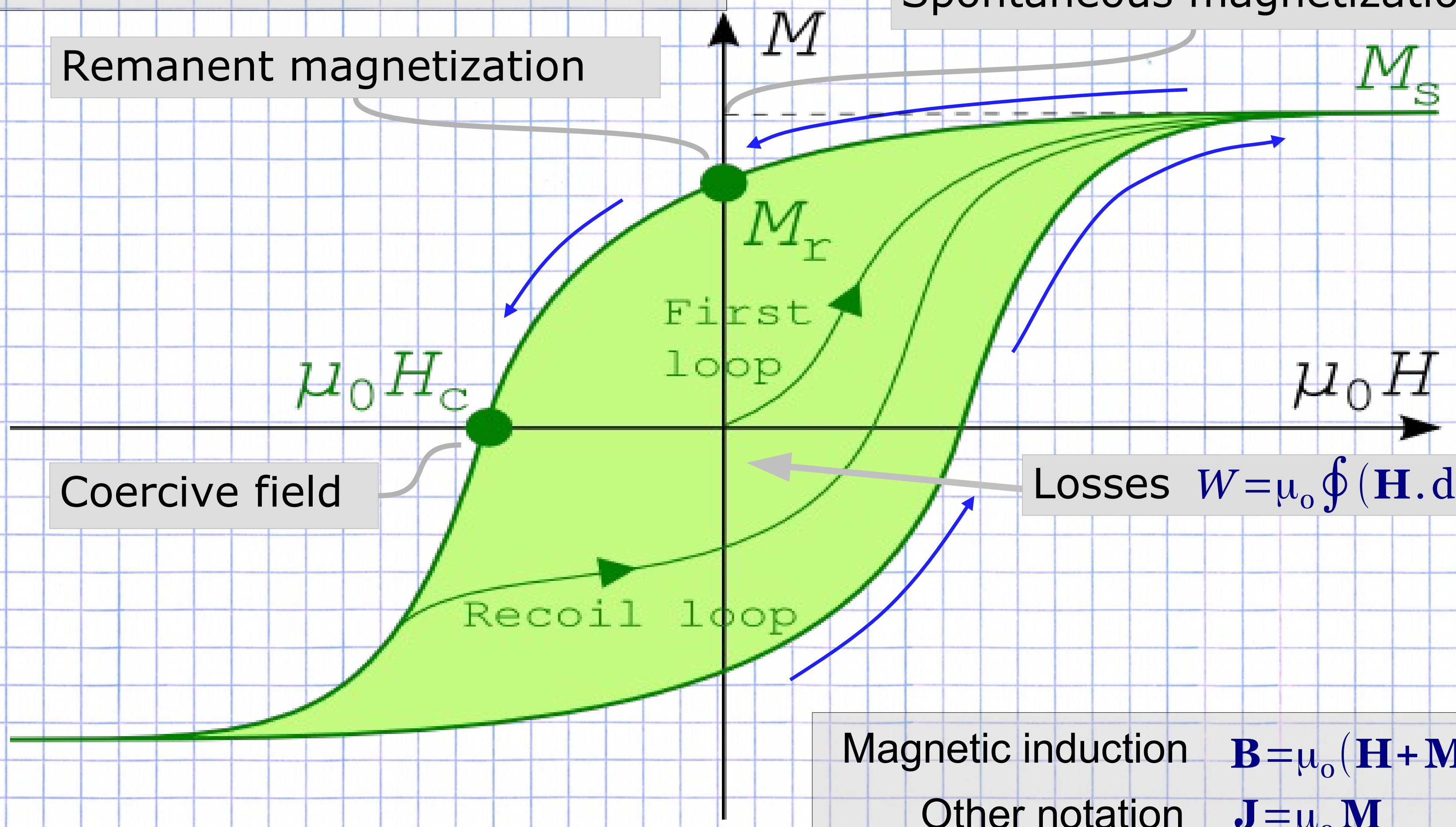
Where can 'bottom-up' contribute ?

Personal views

- Lowest size
- Highest quality
- Low-cost and/or mass production
- 3D self-assembly

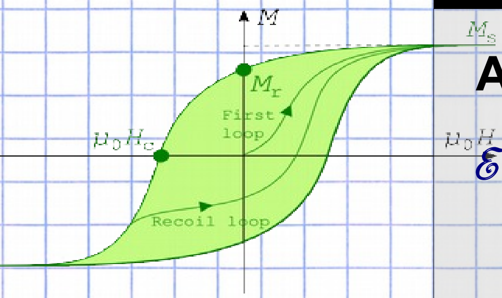
Manipulation of magnetic materials:
↳ Application of a magnetic field

Zeeman energy: $E_Z = -\mu_0 \mathbf{H}.\mathbf{M}$



Magnetic induction $\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$

Other notation $\mathbf{J} = \mu_0 \mathbf{M}$



Framework

Approximation: $\partial_{\mathbf{r}} \mathbf{m} = \mathbf{0}$ (uniform magnetization)

$$\mathcal{E} = EV = V\left[K_{\text{eff}} \sin^2\theta - \mu_0 M_S H \cos(\theta - \theta_H)\right]$$

$$K_{\text{eff}} = K_{\text{mc}} + K_{\text{d}}$$ Magnetic anisotropy

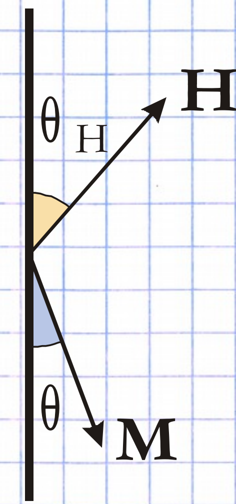
Dimension-less units:

$$e = \sin^2\theta - 2h\cos(\theta - \theta_H)$$

$$e = \mathcal{E}/KV$$

$$h = H/H_a$$

$$H_a = 2K/\mu_0 M_S$$



L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)

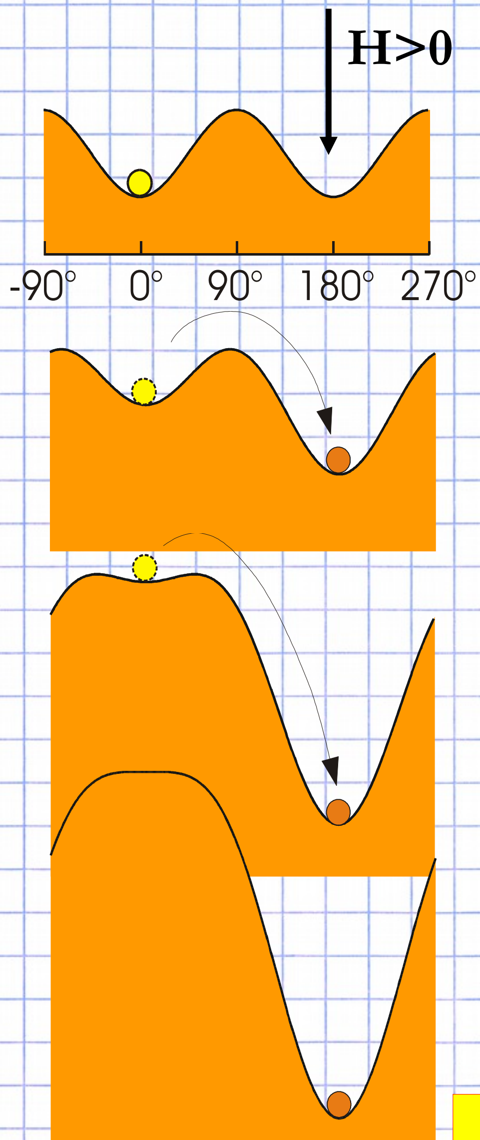
E. C. Stoner and E. P. Wohlfarth, Phil. Trans. Royal. Soc. London A240, 599 (1948)

IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

- Uniform rotation / magnetization reversal
- Coherent rotation / magnetization reversal
- Macrospin etc.

Example for $\theta_H = 180°$ → $e = \sin^2\theta + 2h\cos\theta$



Switching field

Switching field ~ coercive field

$$h_c \approx 1$$

$$H_c \approx 2K/\mu_0 M_s$$

Energy barrier

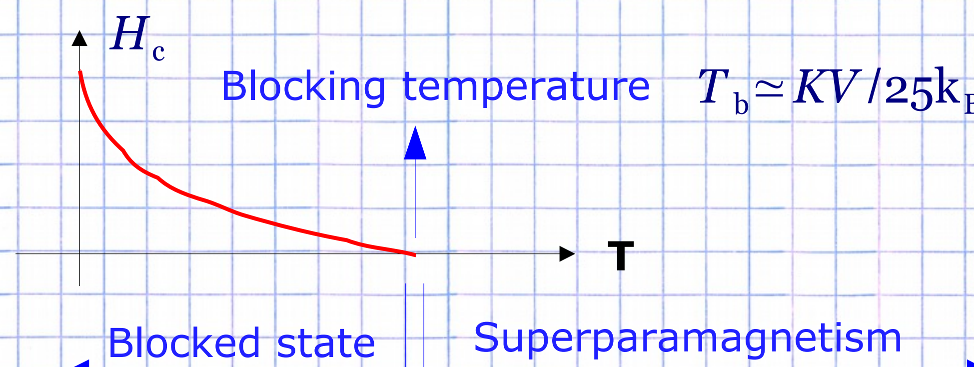
$$\Delta e = e(\theta_{max}) - e(0) = (1-h)^2$$

$$\Delta\mathcal{E} = KV(1 - H/H_a)^2$$

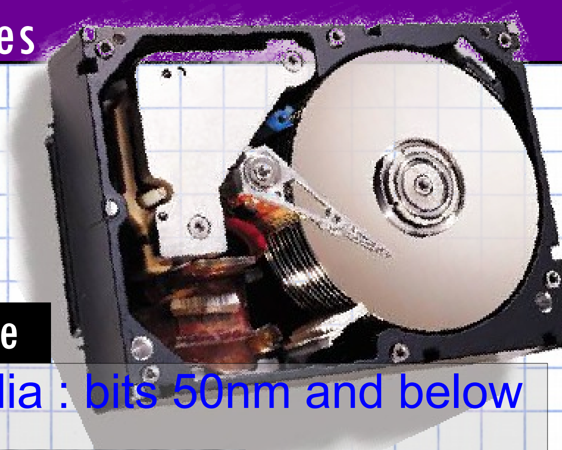
$$\Rightarrow H_c(T) = \frac{2K}{\mu_0 M_s}\left(1 - \sqrt{\frac{\ln(\tau/\tau_0) k_B T}{KV}}\right)$$

$\tau_0 \approx 10^{-10}$ s

M. P. Sharrock, J. Appl. Phys. 76, 6413 (1994)

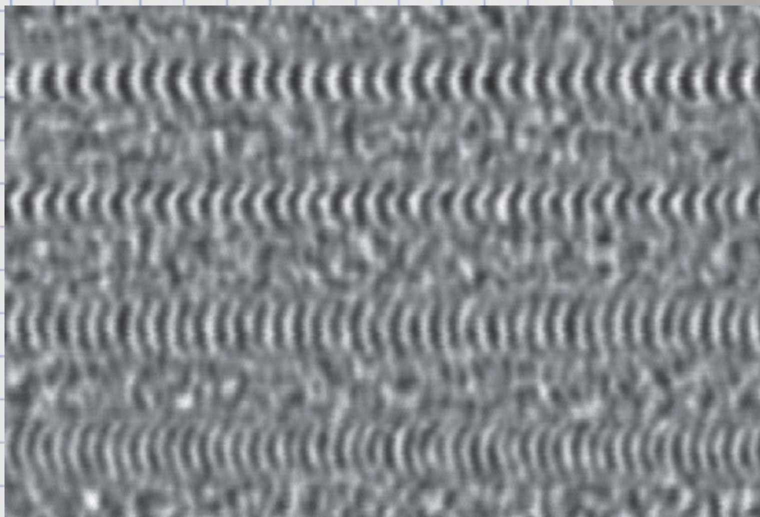


Magnetic anisotropy and volume crucial for thermal stability



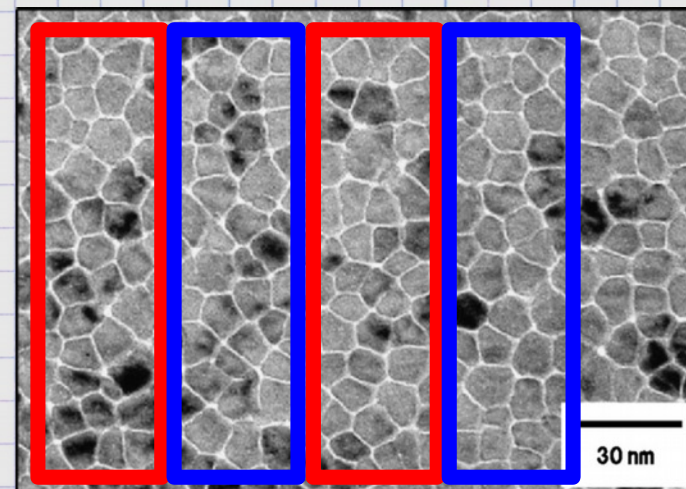
Magnetic bits on hard disk drive

Co-based Hard disk media : bits 50nm and below



B. C. Stipe, Nature Photon. 4, 484 (2010)

Underlying microstructure



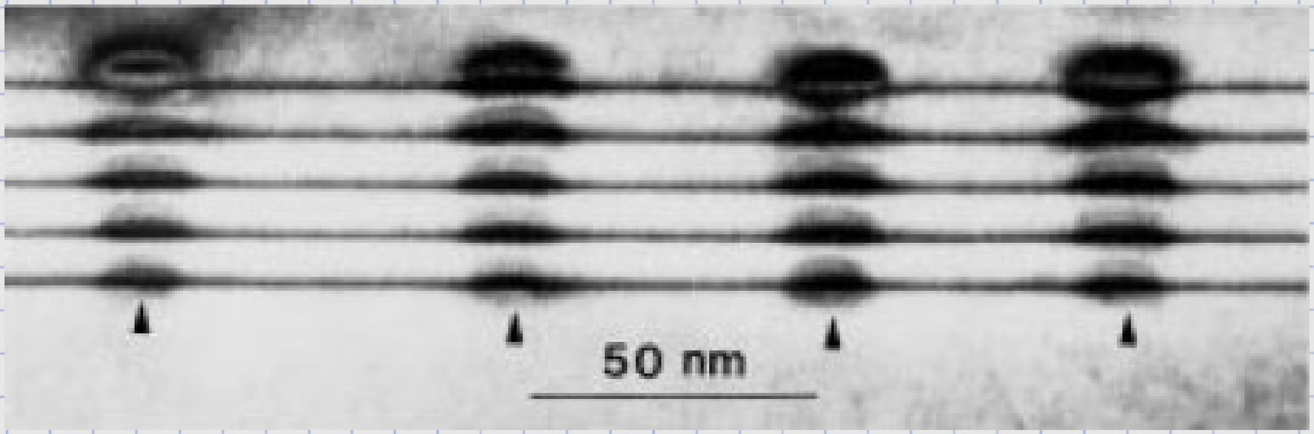
S. Takenoiri, J. Magn. Magn. Mater. 321, 562 (2009)

Questions and dreams

- Engineer (increase) magnetic anisotropy in nano-objects
- Self-organize grains for one-grain-per-bit concept

Example – Go from 2D to 3D through physical routes

Litterature – Stacking dots



InAs

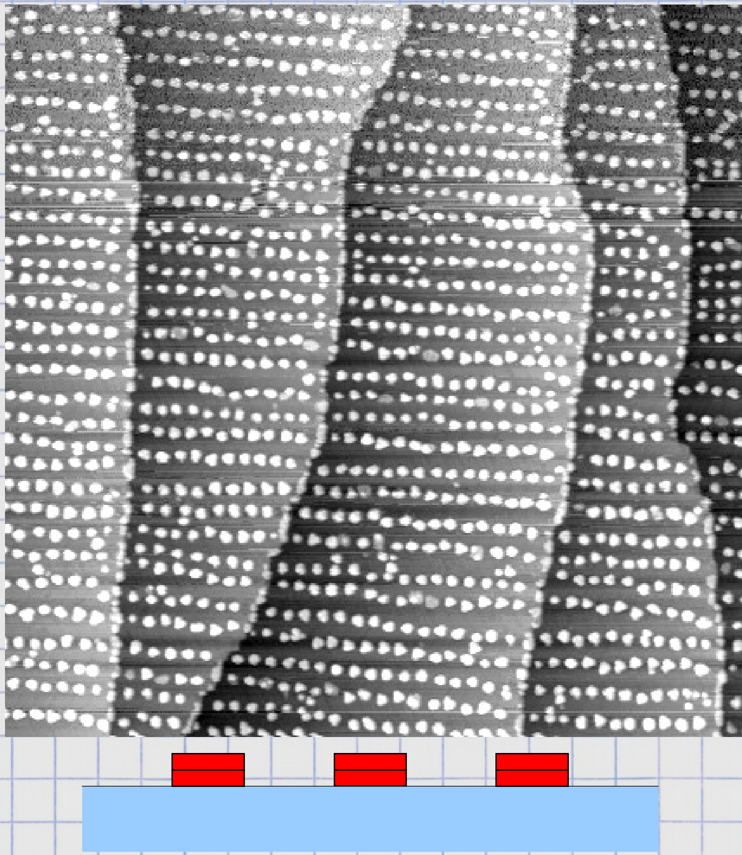
Q.Xie, Phys.Rev.Lett.75(13), 2542 (1995)

Driving forces

- Strain
- Surface / Interface energy
- Thermodynamics and kinetics

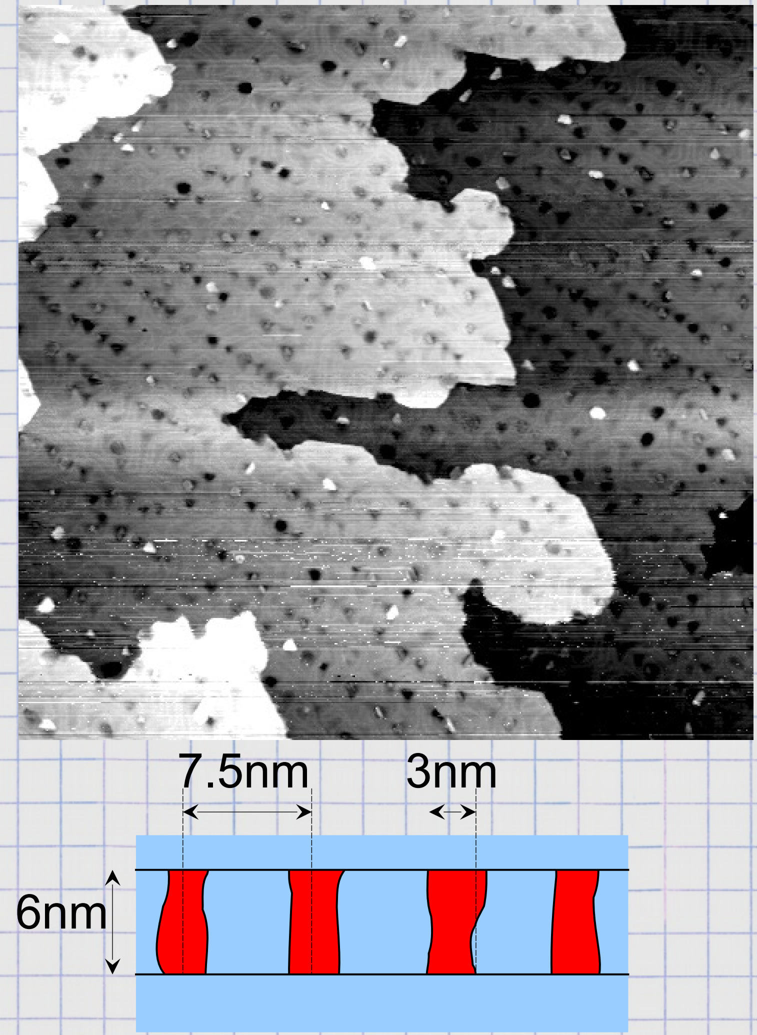
Step 1 – The 2D seed

Co/Au(111) dots – 300nm FoV

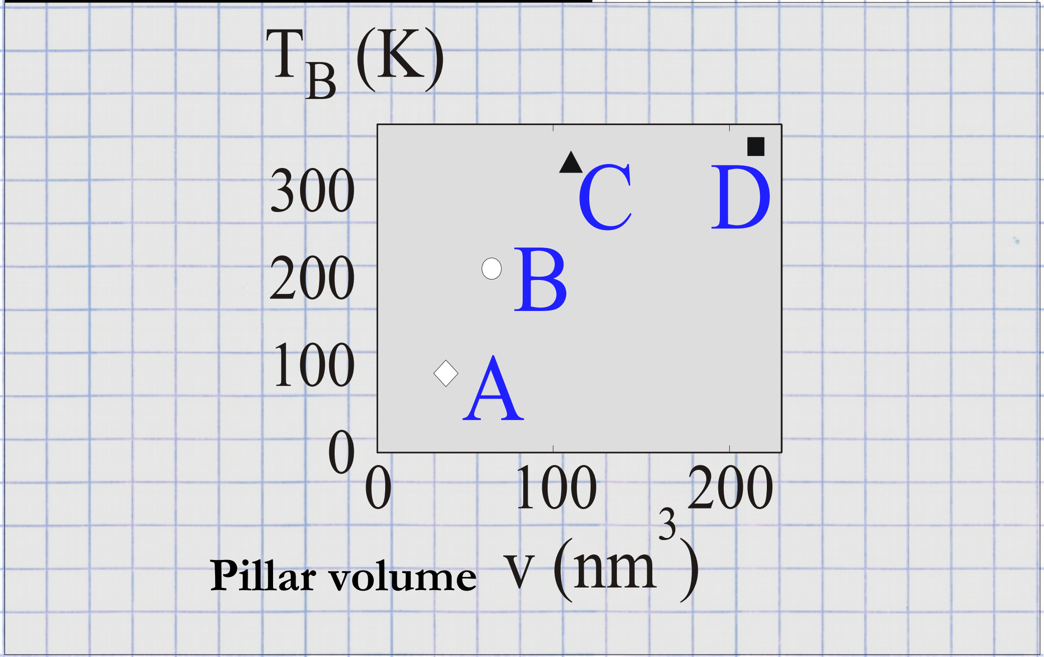


Step 2 etc. – Vertical replication

+ Au + Co etc. – 300nm FoV



Increase blocking temperature



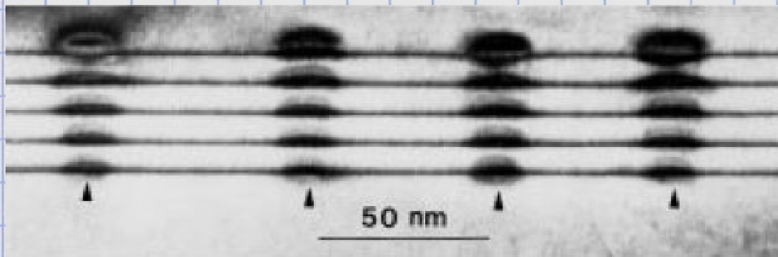
O. Fruchart et al., Phys. Rev. Lett. 23 (14), 2769 (1999)

O. Fruchart et al., J. Cryst. Growth 237-239, 2035 (2002)

O. Fruchart et al., J. Magn. Magn. Mater. 239, 224 (2002)

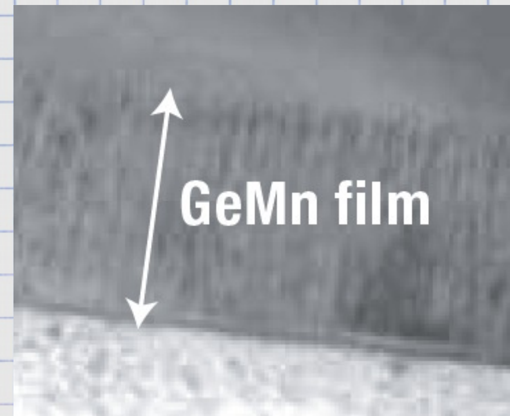
Other examples of 3D/columnar growth

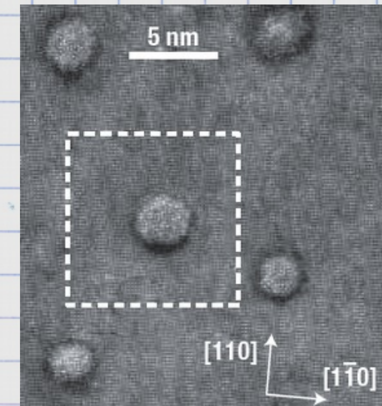
Stacked dots



Q.Xie, Phys.Rev.Lett.75(13), 2542 (1995)

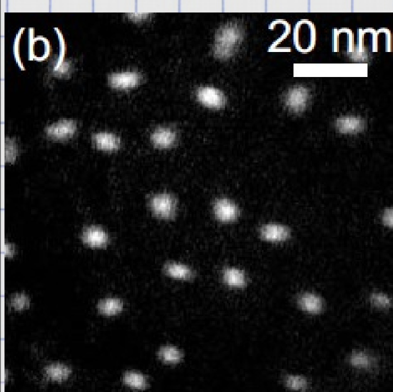
GeMn2 columns inside a Ge matrix

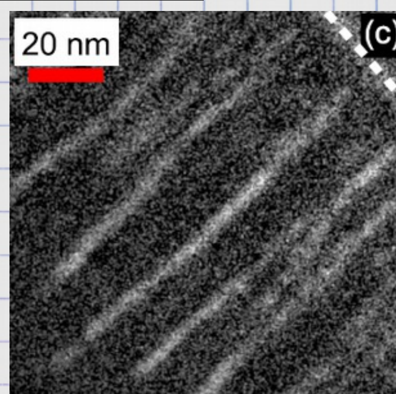




M. Jamet et al., Nature Mater. 5, 653 (2006)

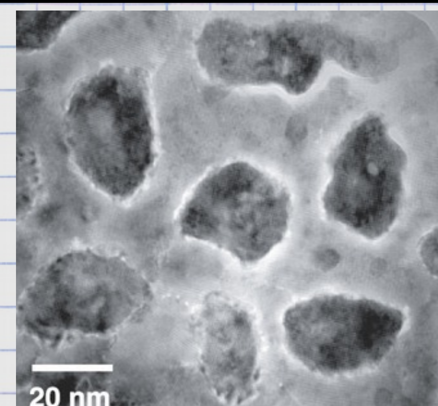
Co columns inside a CoO_2 matrix





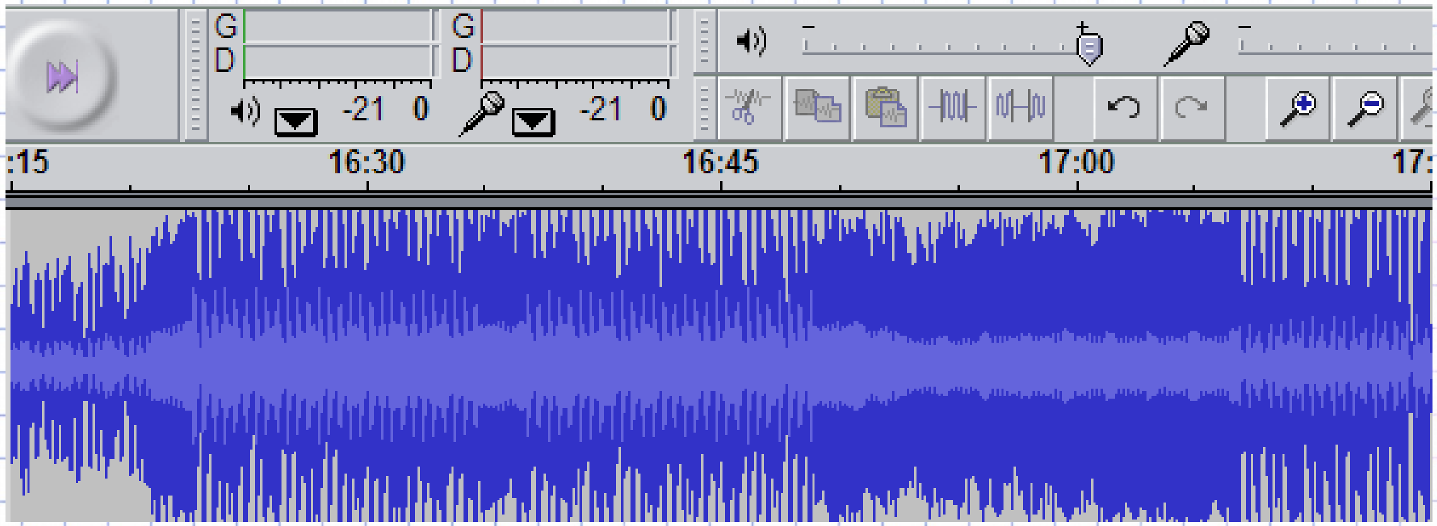
F. Vidal et al., Appl. Phys. Lett. 95, 152510 (2009)
F. Vidal et al., Phys. Rev. Lett. 109, 117205 (2012)

Multifunctional → metamaterials



$CoFe_2O_4$ columns
$BaTiO_3$ matrix

H. Zheng et al., Science 303, 661 (2004)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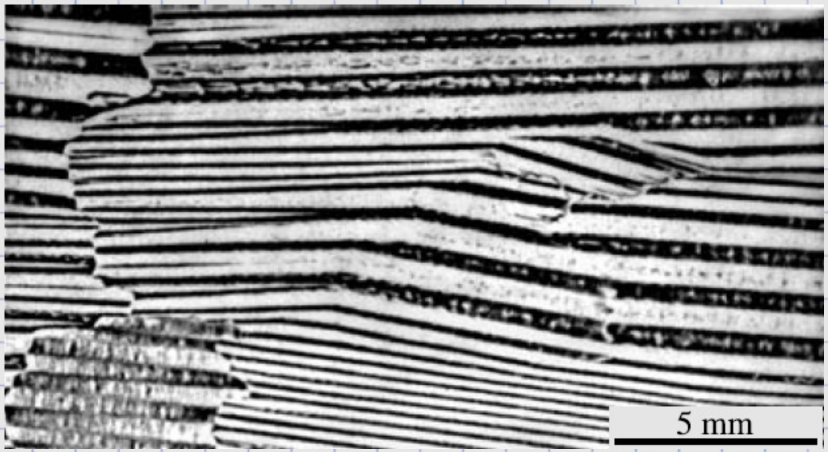
17:

Magnetic domains

Numerous and complex magnetic domains



(History : Weiss domains)

➥ Nanomagnetism ~ Mesomagnetism
➥ Need to adapt size of nanostructure to seek new effects

Length scales (eg domain wall width)

$$E = A\left(\partial_{x_i} m_j\right)^2 + K\sin^2\theta$$

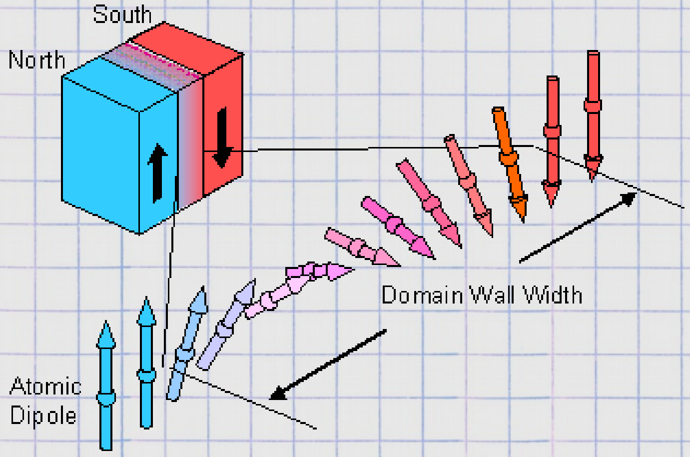
Exchange $\rightarrow$ J/m

Anisotropy $\rightarrow$ J/m^3

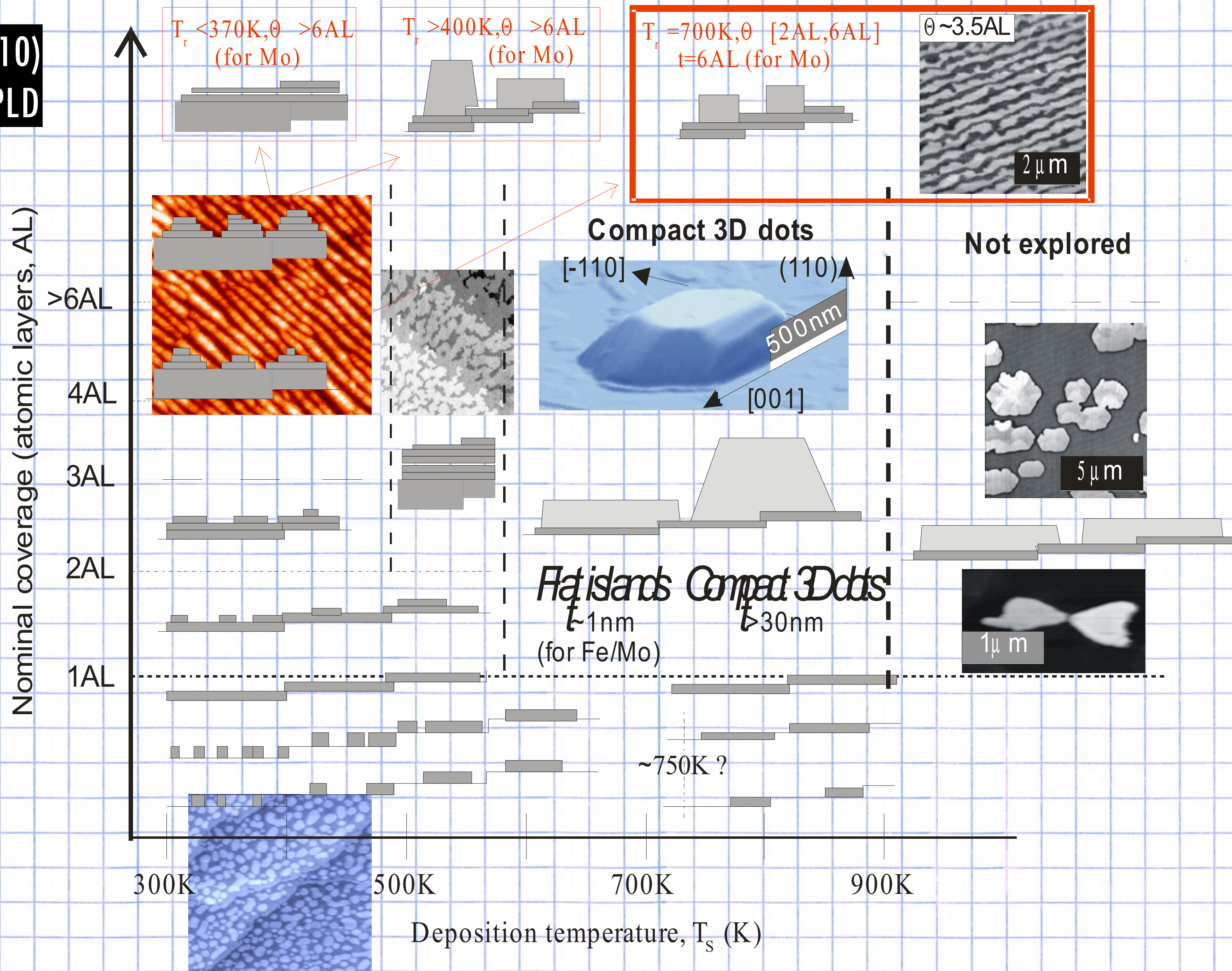
Anisotropy exchange length: $\Delta_u = \sqrt{A/K}$

$\Delta_u \approx 1$ nm $\rightarrow$ $\Delta_u \geq 100$ nm

Hard → Soft

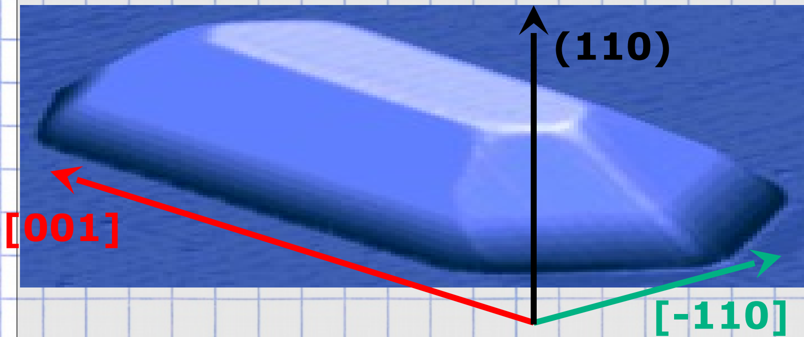


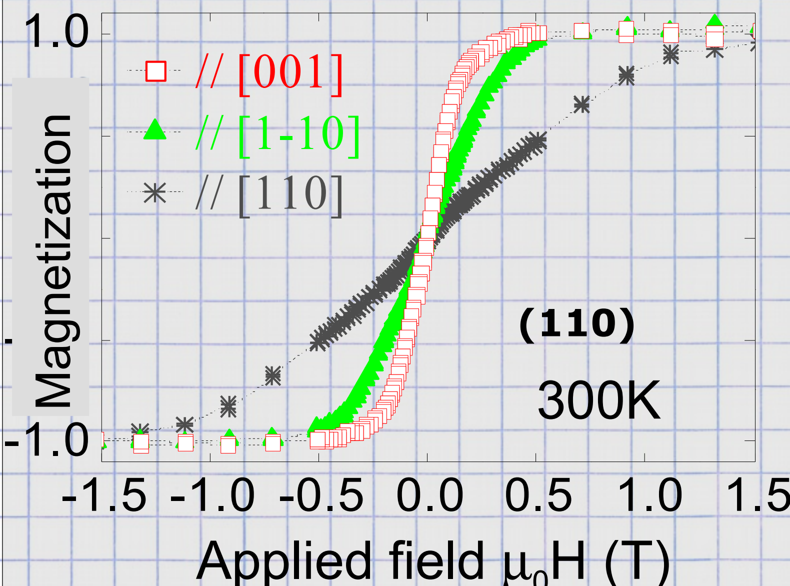
Overview of Fe(110) growth by PLD



O. Fruchart et al., J. Phys.: Condens. Matter 19, 053001, Topical Review (2007).

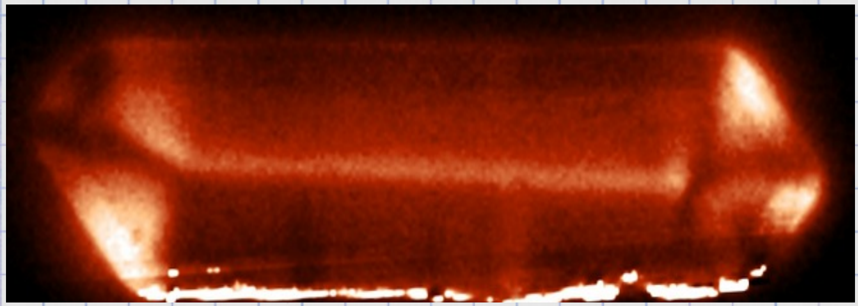
Hysteresis loops



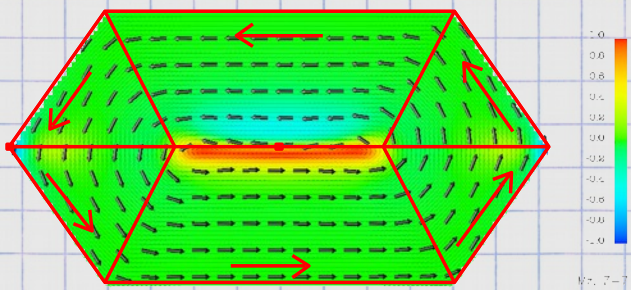


Magnetization states

Landau states: two antiparallel domains

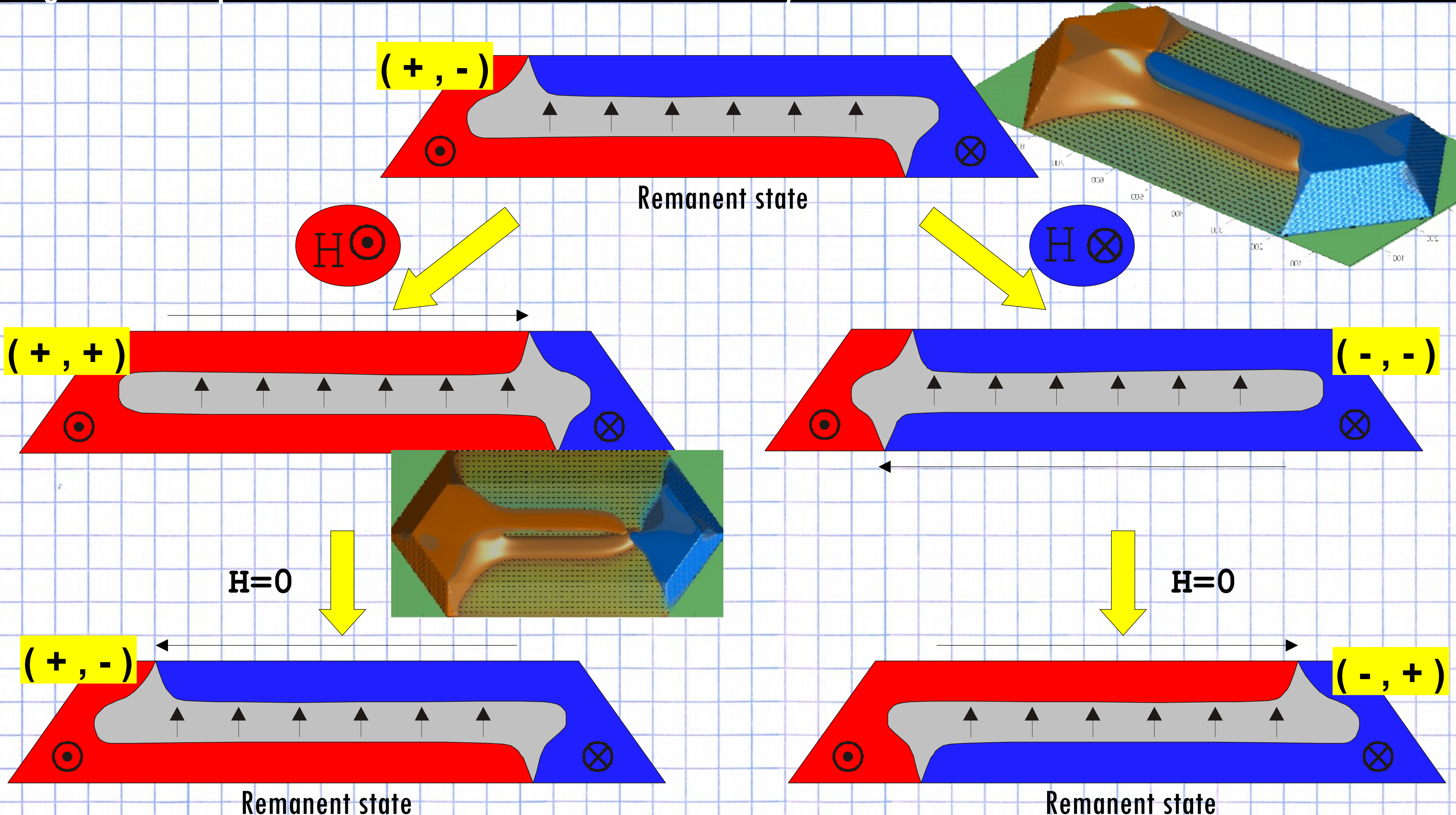


Typical length: 1 micron



P.-O. Jubert et al., Phys. Rev. B64, 115419 (2002)
P.-O. Jubert et al., Europhys. Lett. 63, 135 (2003)

- Flux-closure domains
- Domain wall in a box



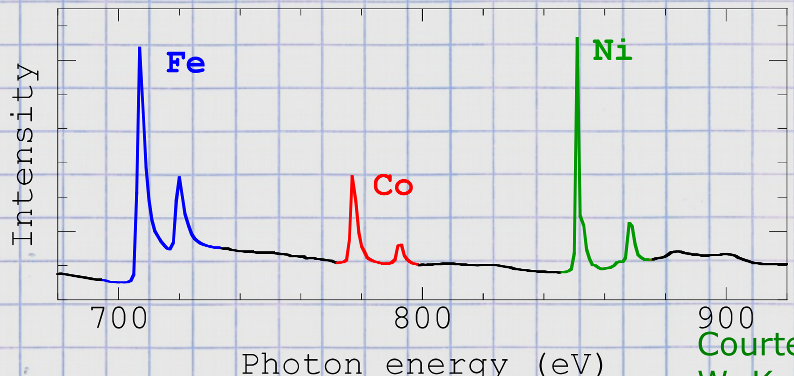
- Remanent state can be switched: makes one more controlable ‘bit’
- Remanence of Néel cap is opposite to applied field

F. Cheynis et al., Phys. Rev. Lett. 102, 107201 (2009)

XMCD

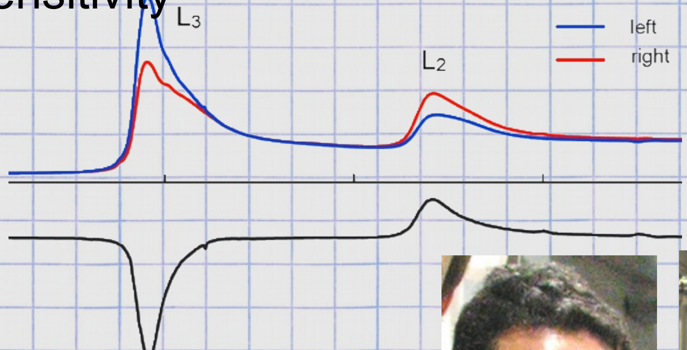
X-ray Magnetic Circular Dichroism

⇨ Element selectivity



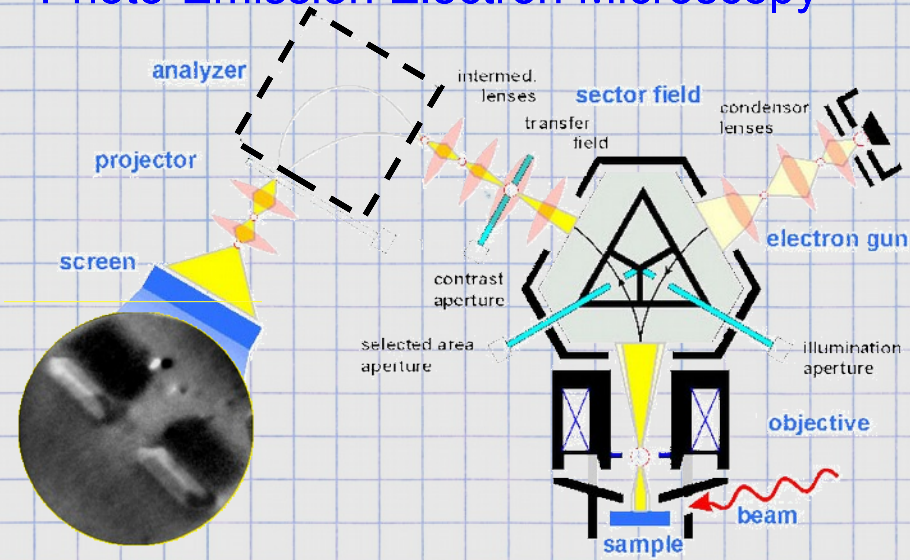
Courtesy: W. Kuch

⇨ Magnetic sensitivity



PEEM

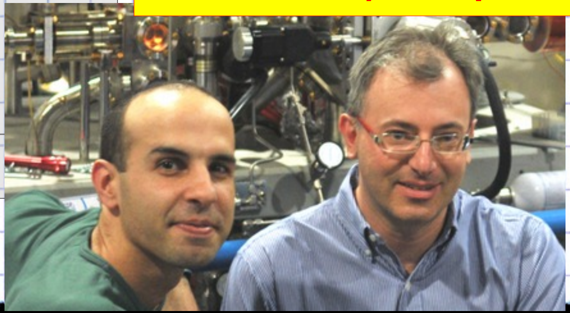
Photo-Emission Electron Microscopy



Features

- Collection of electrons → surface sensitive
- Spatial resolution : 20-25nm
- Hardly compatible with applied field

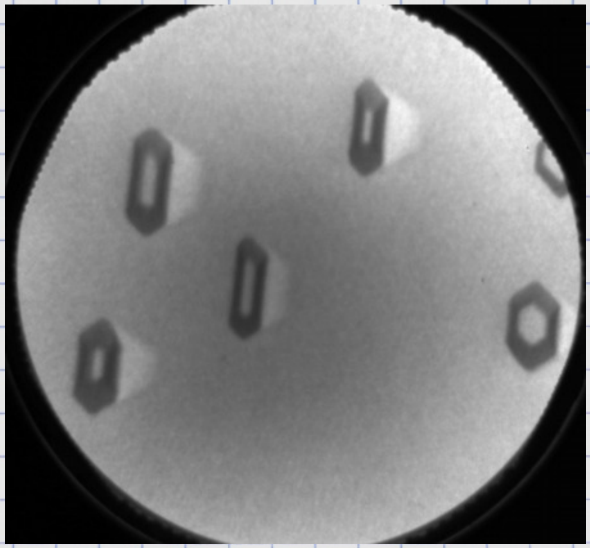
SOLEIL



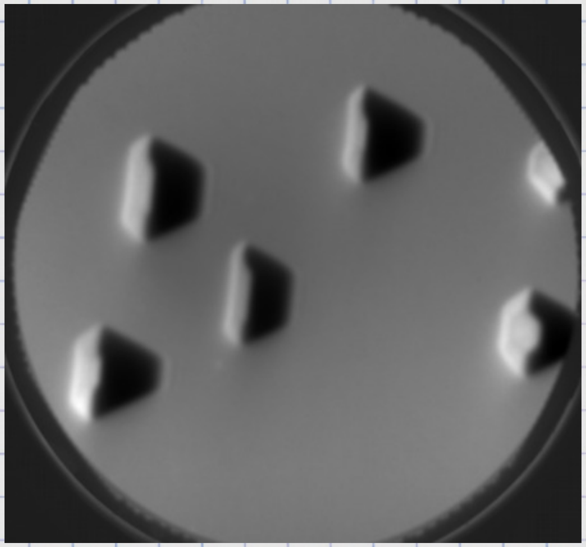
ELETTRA

Topography

Field of view: 5µm

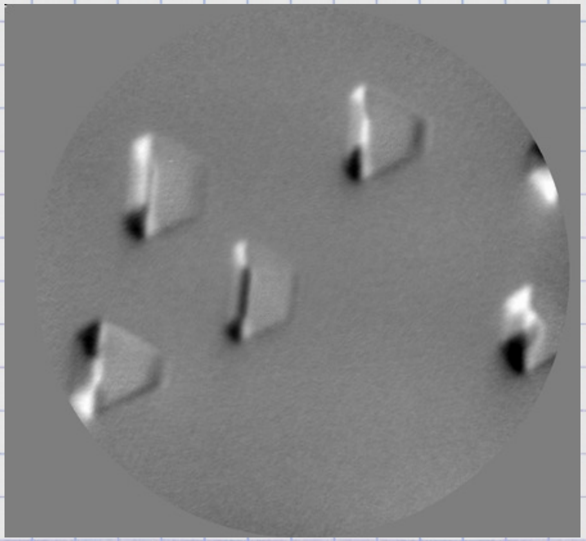


LEEM

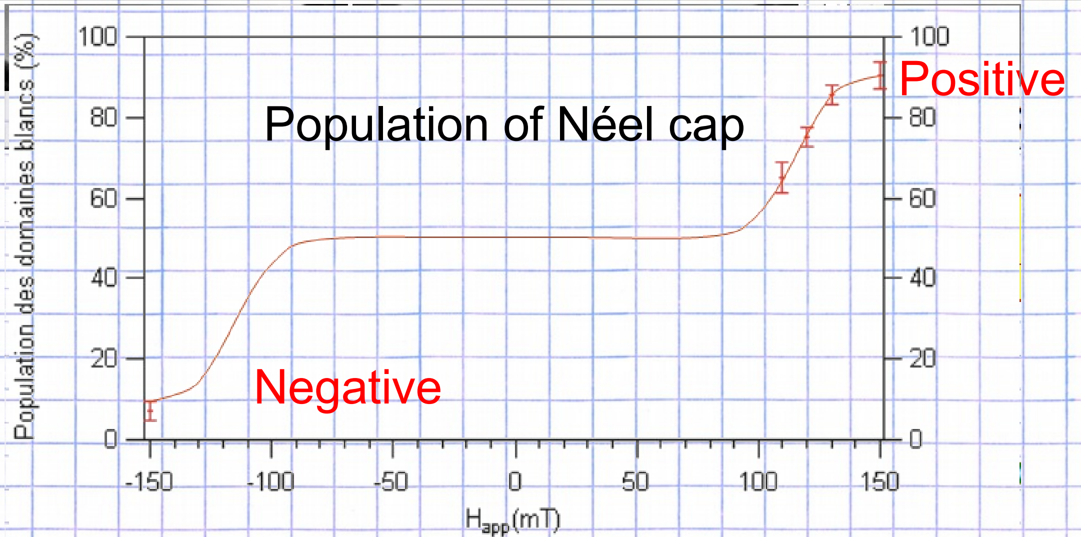


PEEM

Magnetic contrast



XMCD-PEEM

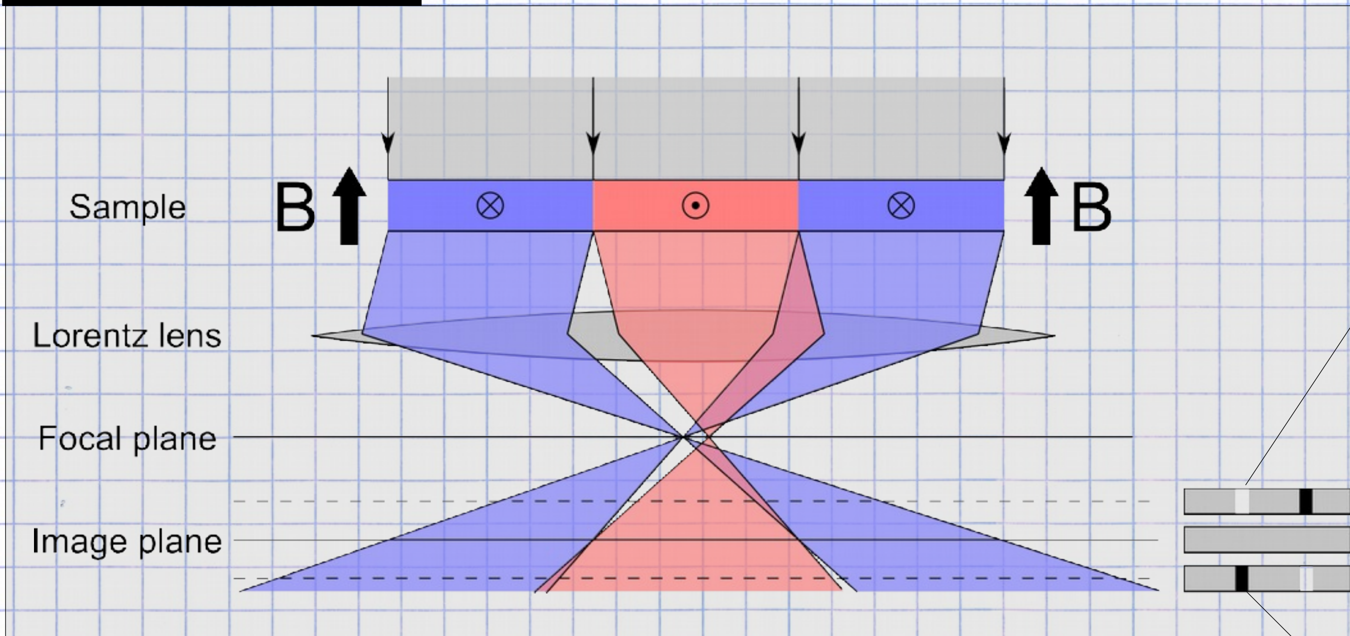


Experiments: 90% switching.

F. Cheynis et al.,
JAP103, 07D915 (2008)

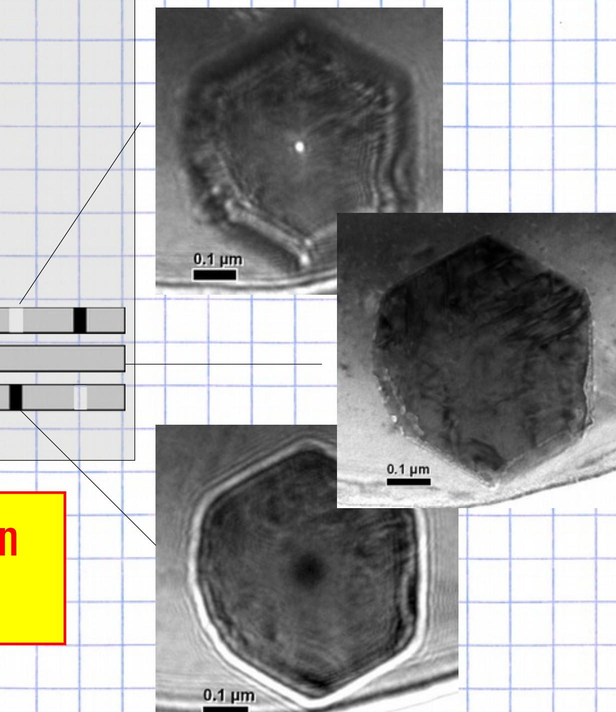
F. Cheynis et al.,
Phys. Rev. Lett. 102, 107201 (2009)

Fresnel imaging mode



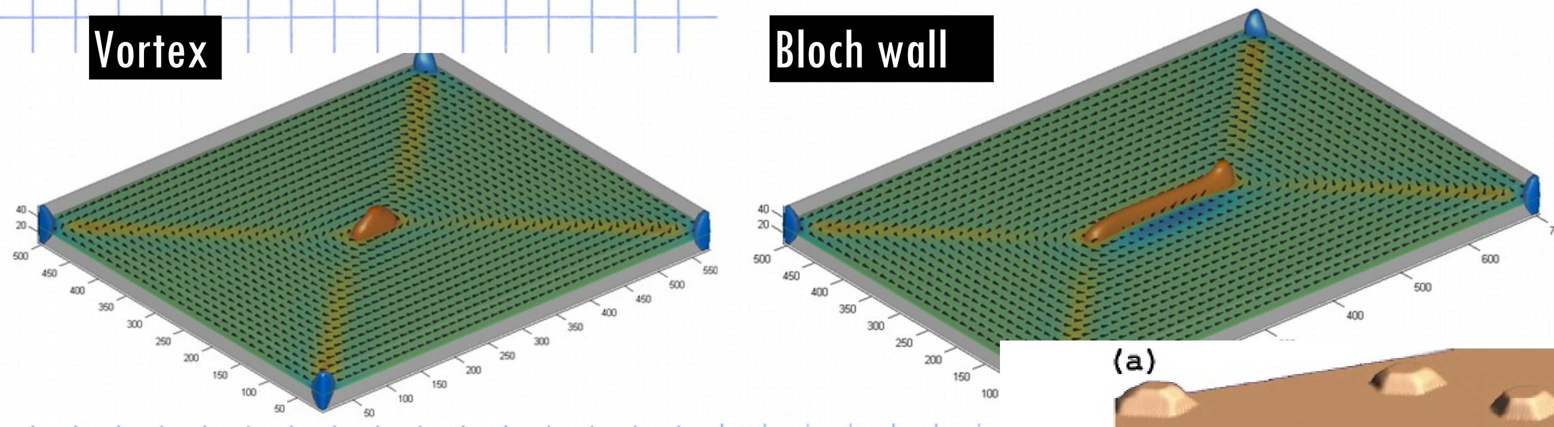
Self-assembled fcc Co dots

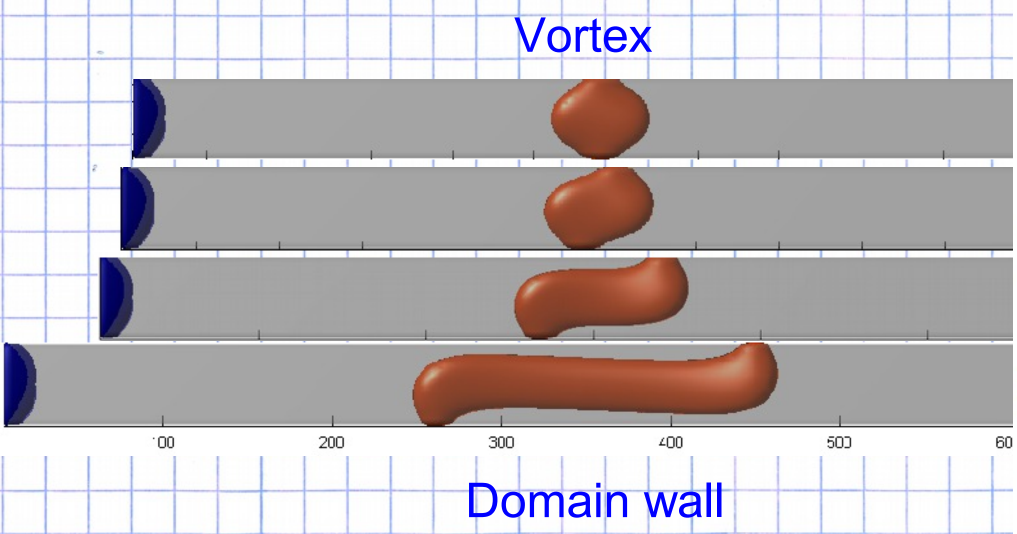
(vortex state)

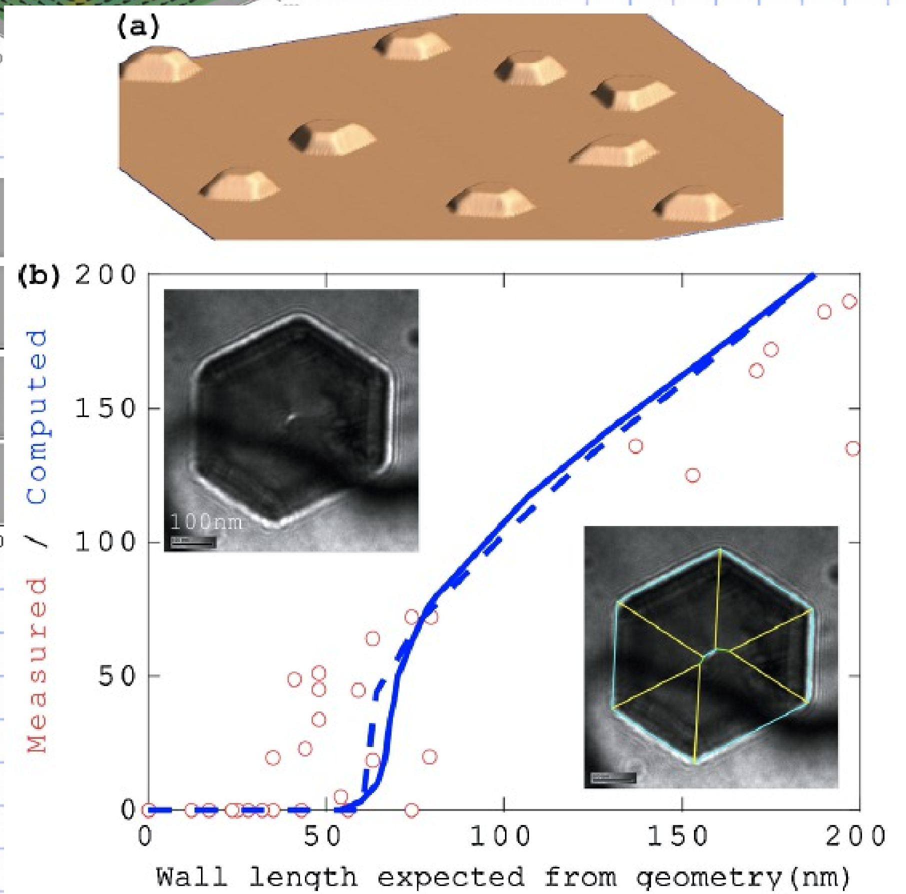


↳ Sensitive mainly to in-plane components of magnetization integrated over the sample's thickness


Pascale Bayle-Guillemaud (INAC)
Aurélien Masseboeuf et al. (INAC → CEMES)



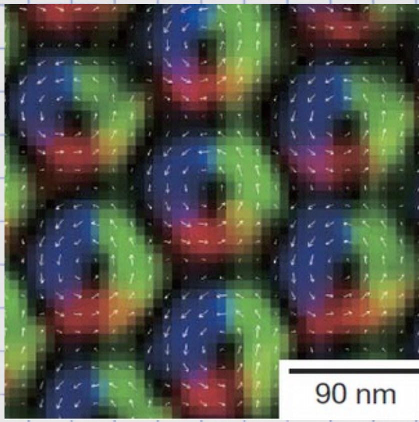




A. Masseboeuf et al., Phys. Rev. Lett. 104, 127204 (2010)

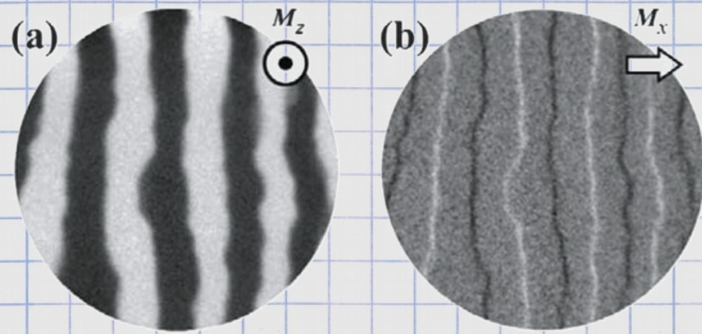
Spin textures : 2D/3D

Skyrmions and helix



$Fe_{0.5}Co_{0.5}Si$, bulk

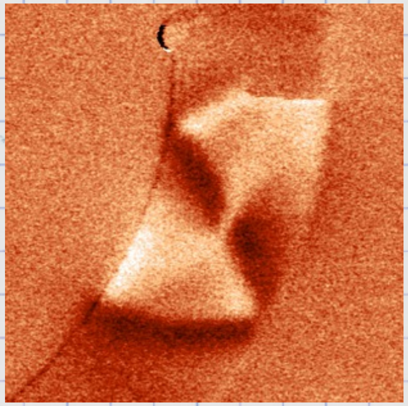
X. Z. Yu et al., Nature 465, 901 (2010)



Cu\Fe\Ni stackings, interfacial

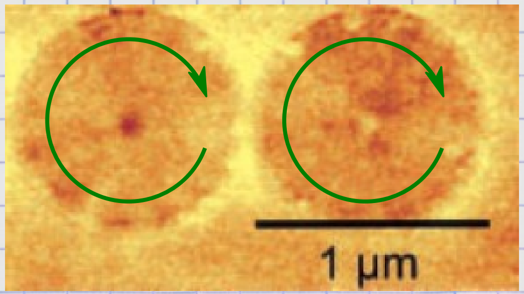
G. Chen et al., Phys. Rev. Lett. 110, 177204 (2013)

Constrained walls (eg : in stripes) : 1D/2D



Permalloy (15nm) - Stripe 500nm

Magnetic vortices (1D/0D)



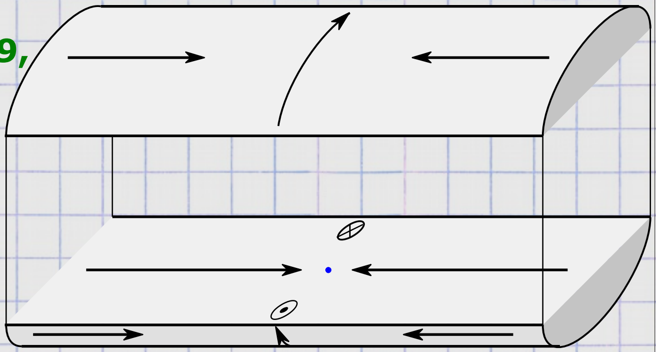
Diameter ~ 10nm

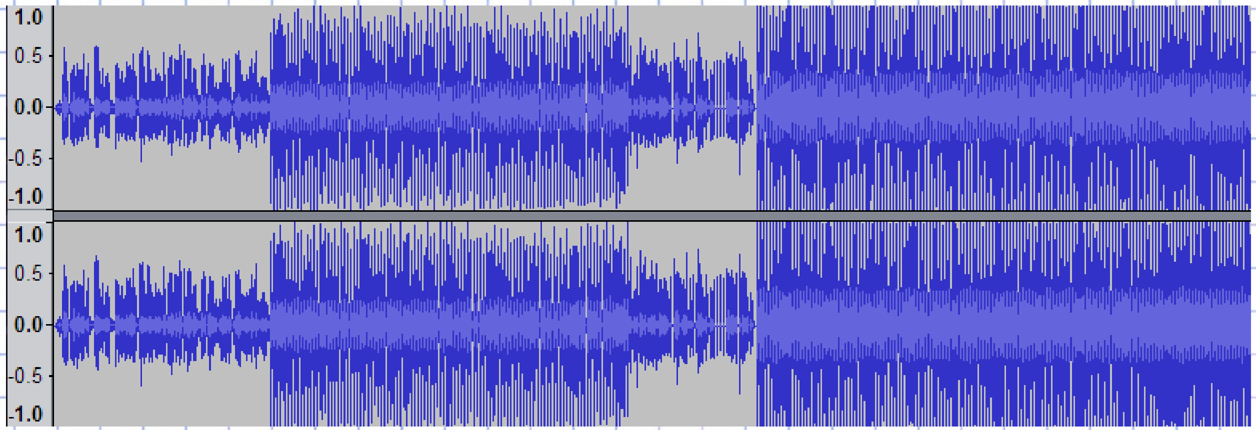
T. Shinjo et al., Science 289, 930 (2000)

Bloch point (0D)

⇨ Point with vanishing magnetization

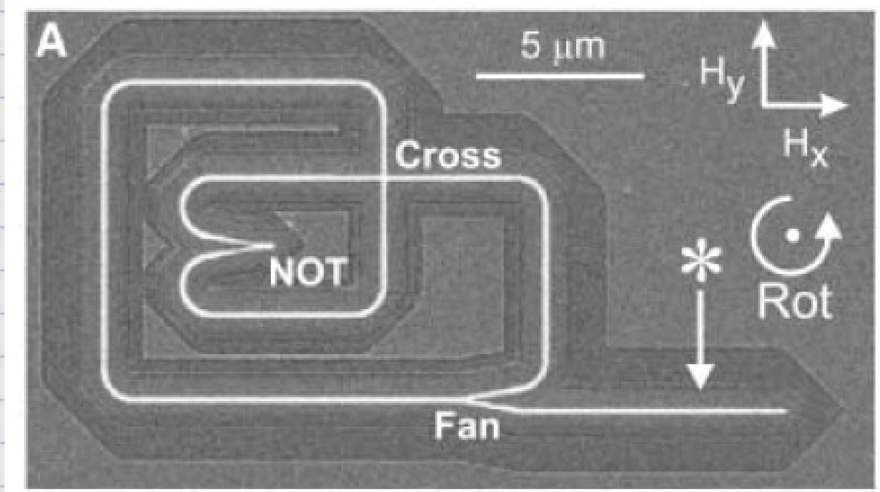
W. Döring, J. Appl. Phys. 39, 1006 (1968)




1.0
0.5
0.0
-0.5
-1.0
1.0
0.5
0.0
-0.5
-1.0

~~Prospects~~ *Dreams* for domain-wall devices

Magnetic logic with domain walls (Field driven)

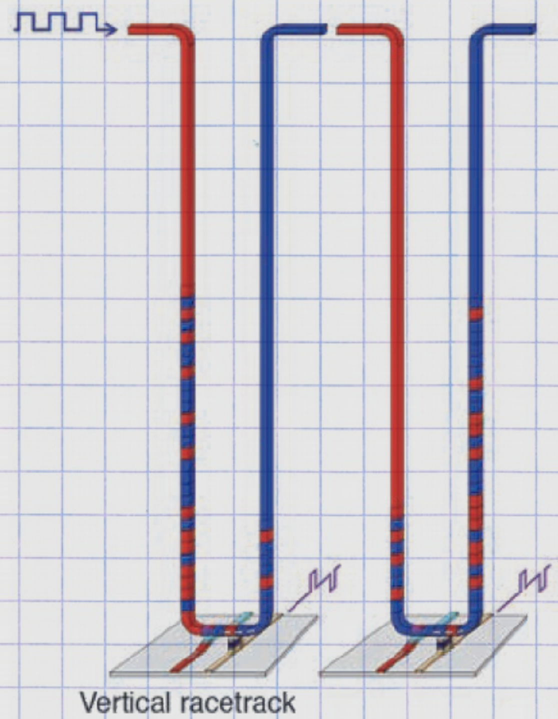


D. A. Allwood et al., Science 309, 1688 (2005)

Limitation:

Requires homogeneous rotating field

Magnetic memories with domain walls (Current driven)

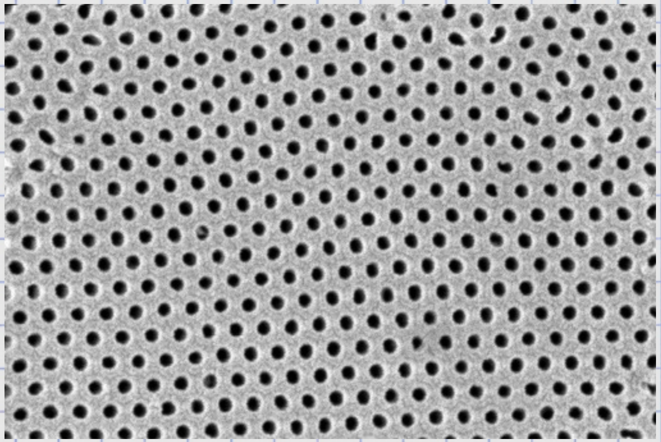


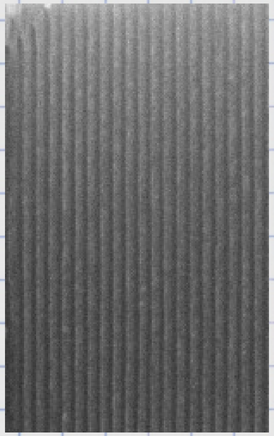
S. S. P. Parkin, Science 320, 190 (2008)
+ patents

- Makes use of spin transfer effect
- Potentially 3D storage, however technologically challenging

The basics

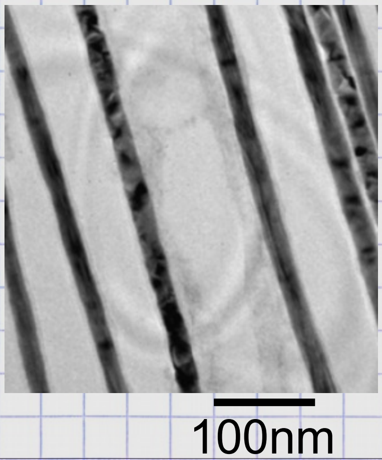
Anodization of aluminum → template





H. Masuda, Science 268, 1466-1468 (1995)

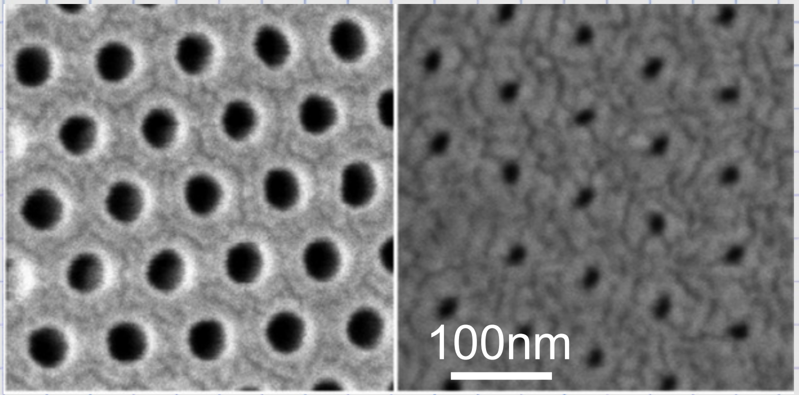
Electroplating → magnetic nanowires



⇨ Simple metals and alloys : Co, Ni, FeNi

Specific aspects

ALD to reduce pore diameter

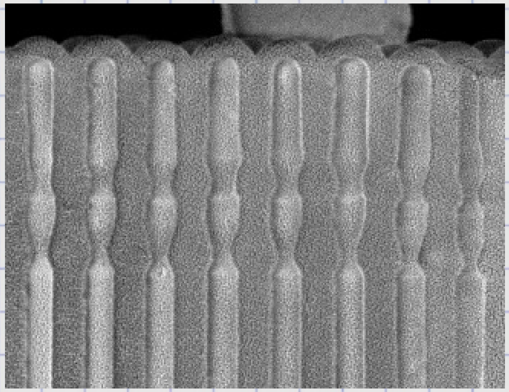


S. Da Col et al., Appl. Phys. Lett. 98, 112501 (2011)

⇨ Decrease dipolar interactions

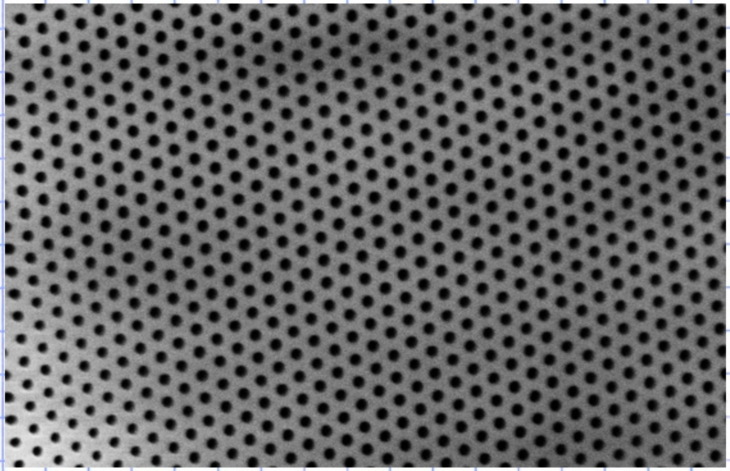
Modulation of pore diameter

S. Allende et al., Phys. Rev. B 80, 174402 (2009)

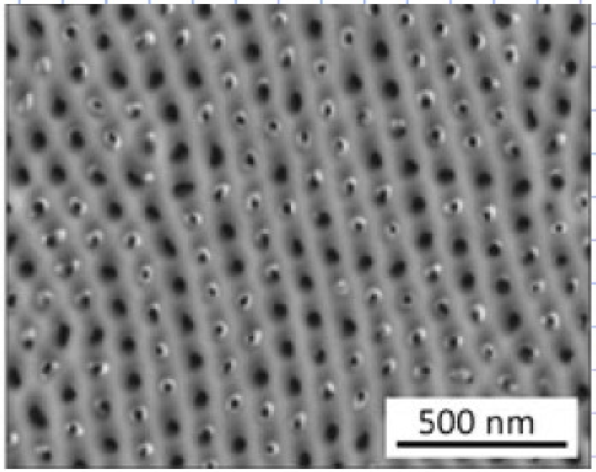


⇨ Landscape for domain walls

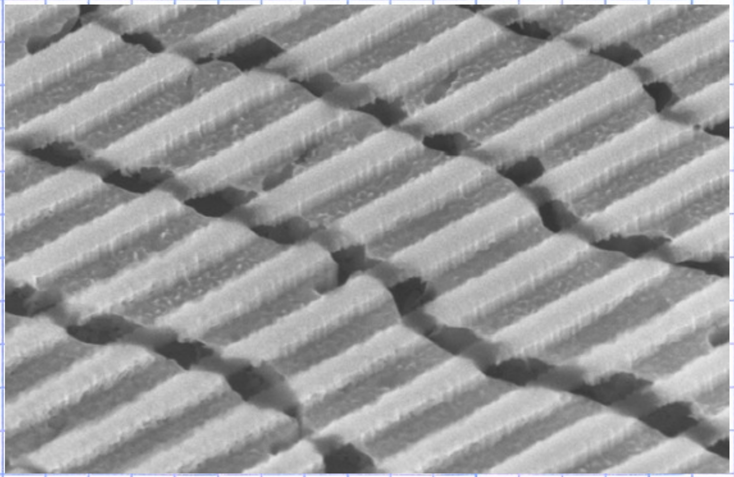
Long-range ordered templates



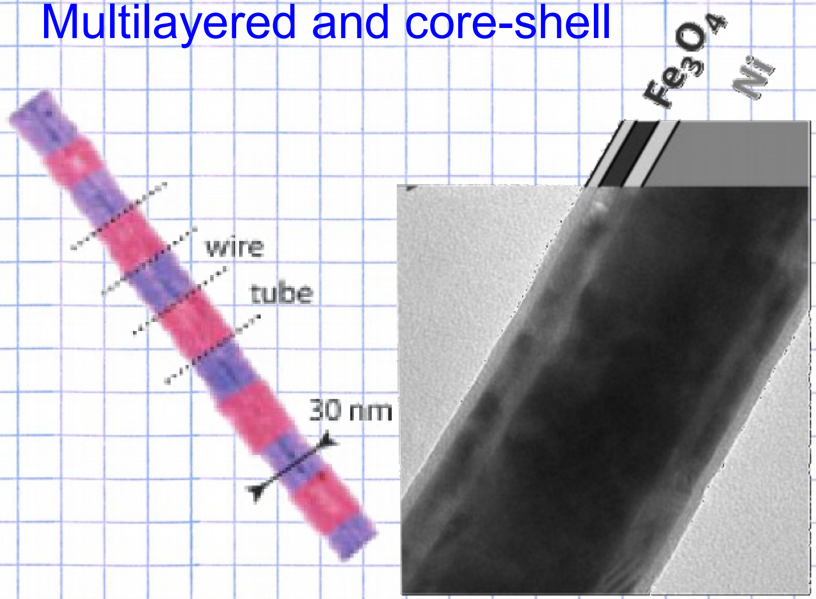
Nanotubes



Planar structures



Multilayered and core-shell

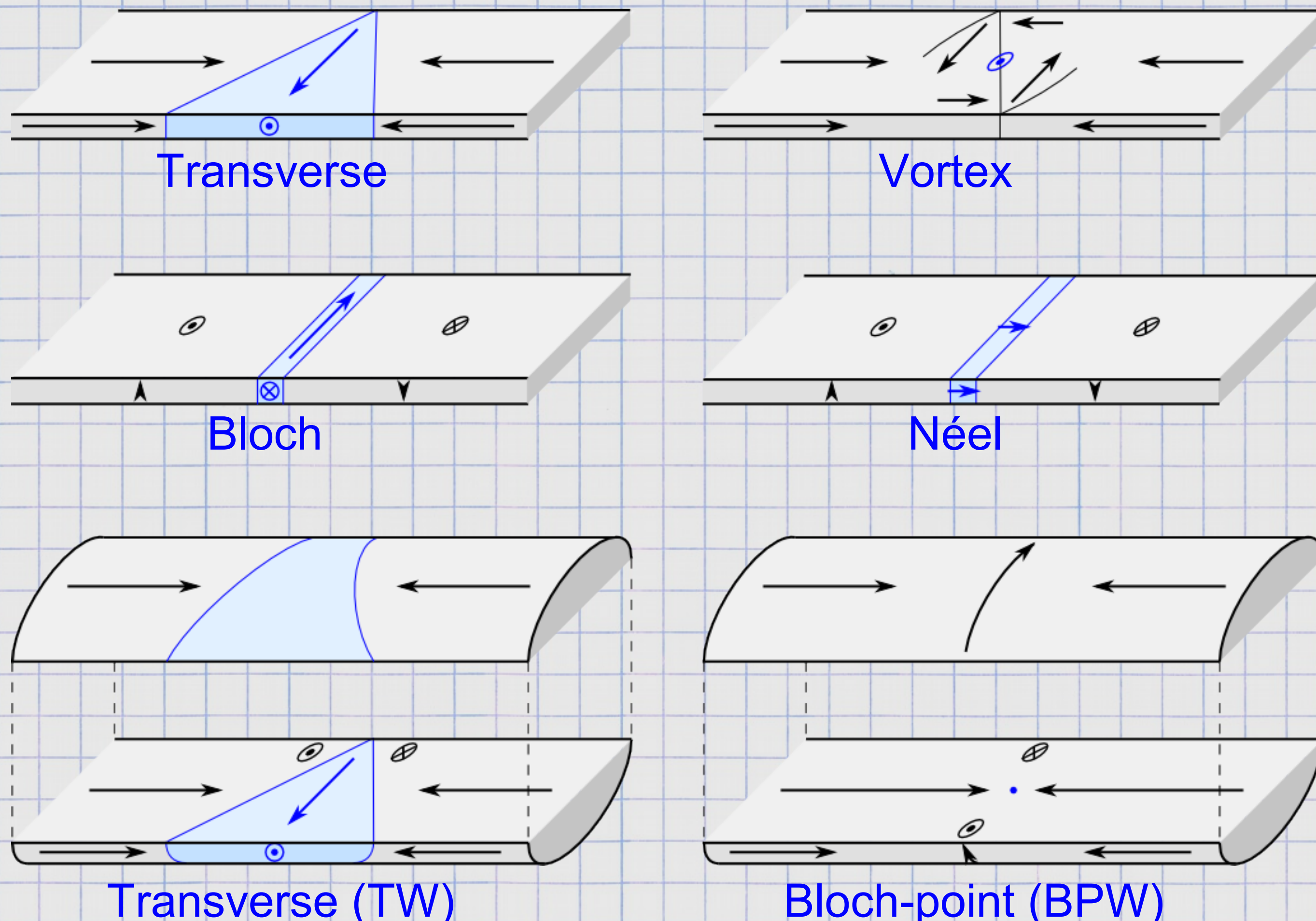


K. Nielsch et al., Univ. Hamburg
J. Bachmann et al., Univ. Erlangen
J. P. Araujo, Univ. Porto
Smartmembrane GmbH, Halle

Stripes, in-plane magnetization

Stripes, out-of-plane magnetization

Wires, longitudinal magnetization



Stripes

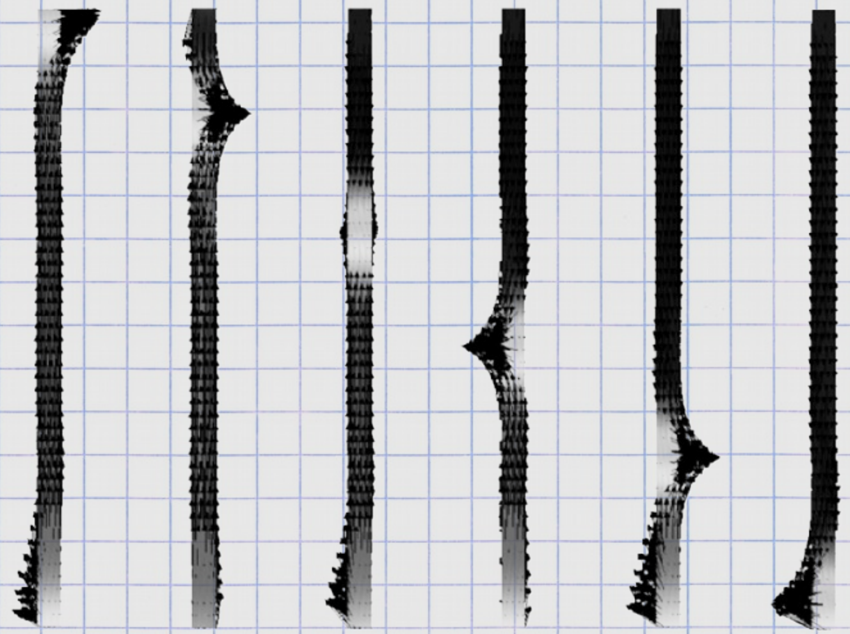
- ⇨ Domain-wall transformation
- ⇨ Walker limit, low speed (~100m/s)
- ⇨ Experiments and theory

BPW in wires

- ⇨ Theory predictions ; no experiments
- ⇨ No domain-wall transformation
- ⇨ High speed (>1000m/s)

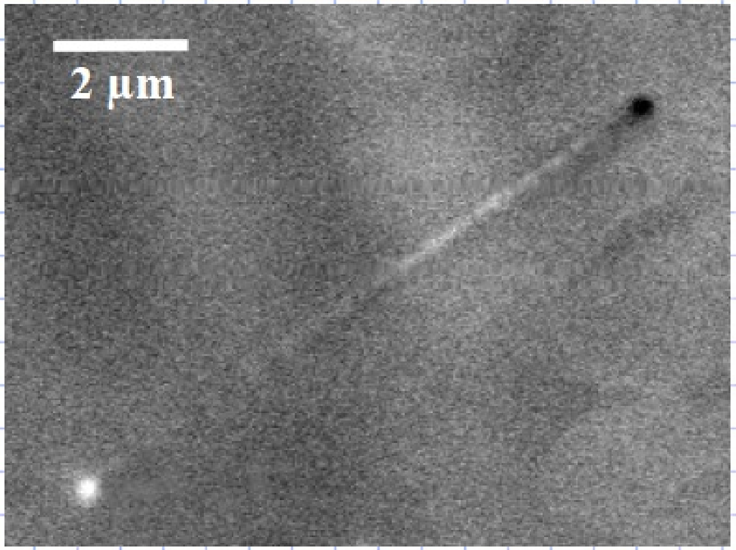
Nucleation – Propagation mechanism

Sequence of magnetization reversal



R. Hertel et al., J. Magn. Magn. Mater. 249, 251 (2002)

Single-domain wire (MFM)



Y. Henry et al., Eur. Phys. J. B 20, 35 (2001)

⇨ Explains why domain walls hardly reported in cylindrical nanowires

Collaborative work !

Domain wall nucleation and propagation in cylindrical nanowires

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