The challenge of three-dimensional spin textures

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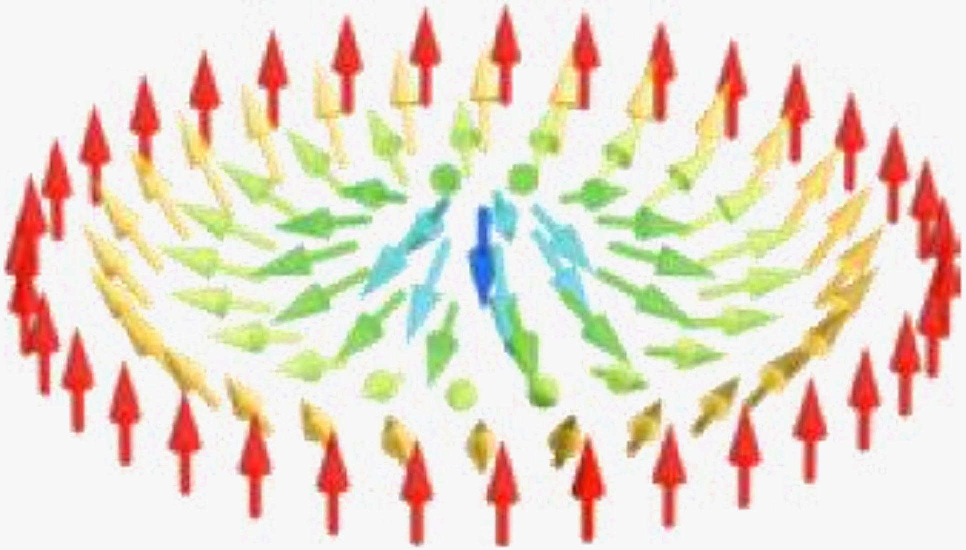
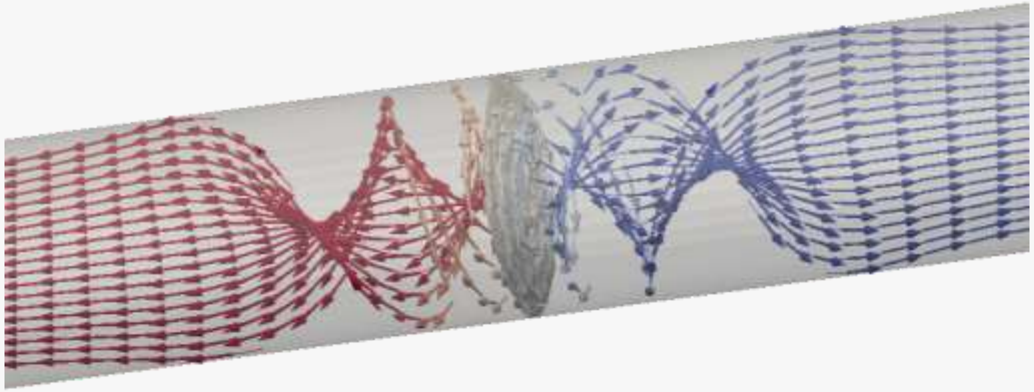
Dimensionality

Dimension of the vector order parameter *n*



- *n*=1 (Ising) to *n*=3 (Heisenberg)
- Not exactly the topic here

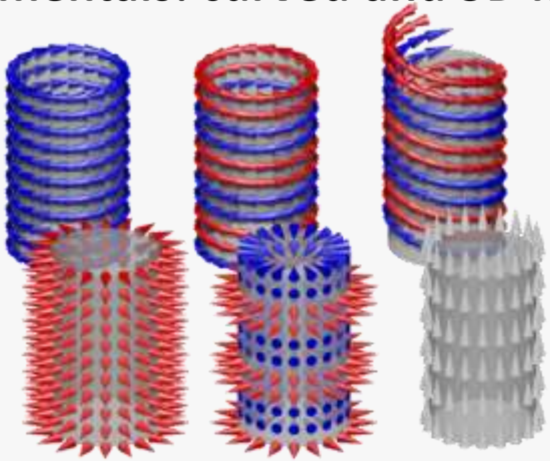
Dimension of space *d*



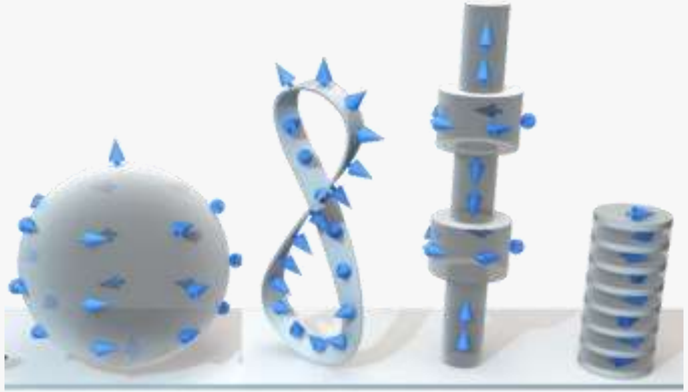
- *d*=1 (line) to *d*=3 (volume)
- Three-dimensional textures, often allowing for *n*=3

Motivation for three-dimensional magnetization textures

Fundamentals: curved and 3D magnetism

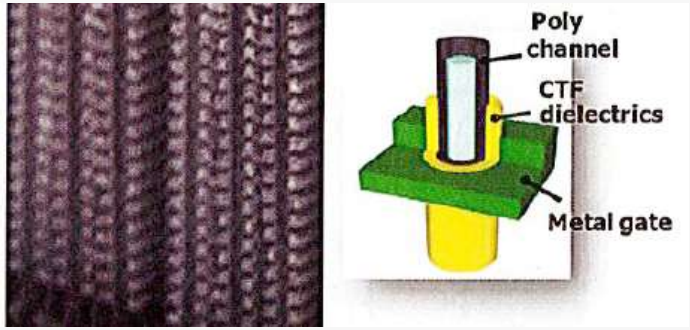


R. Streubel, J.Phys.D: Appl.Phys. 49, 363001 (2016)



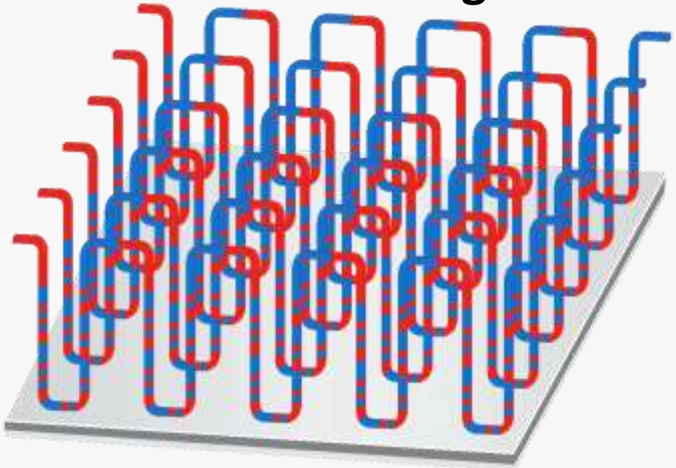
A. Fernandez-Pacheco, Nat. Comm. 8, 15756 (2017)

Note: 3D devices make the decision!



K. T. Park et al., IEEE J. Sol. State Circuits 50 (1), 204 (2015)

Dreams for a 3D storage device



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

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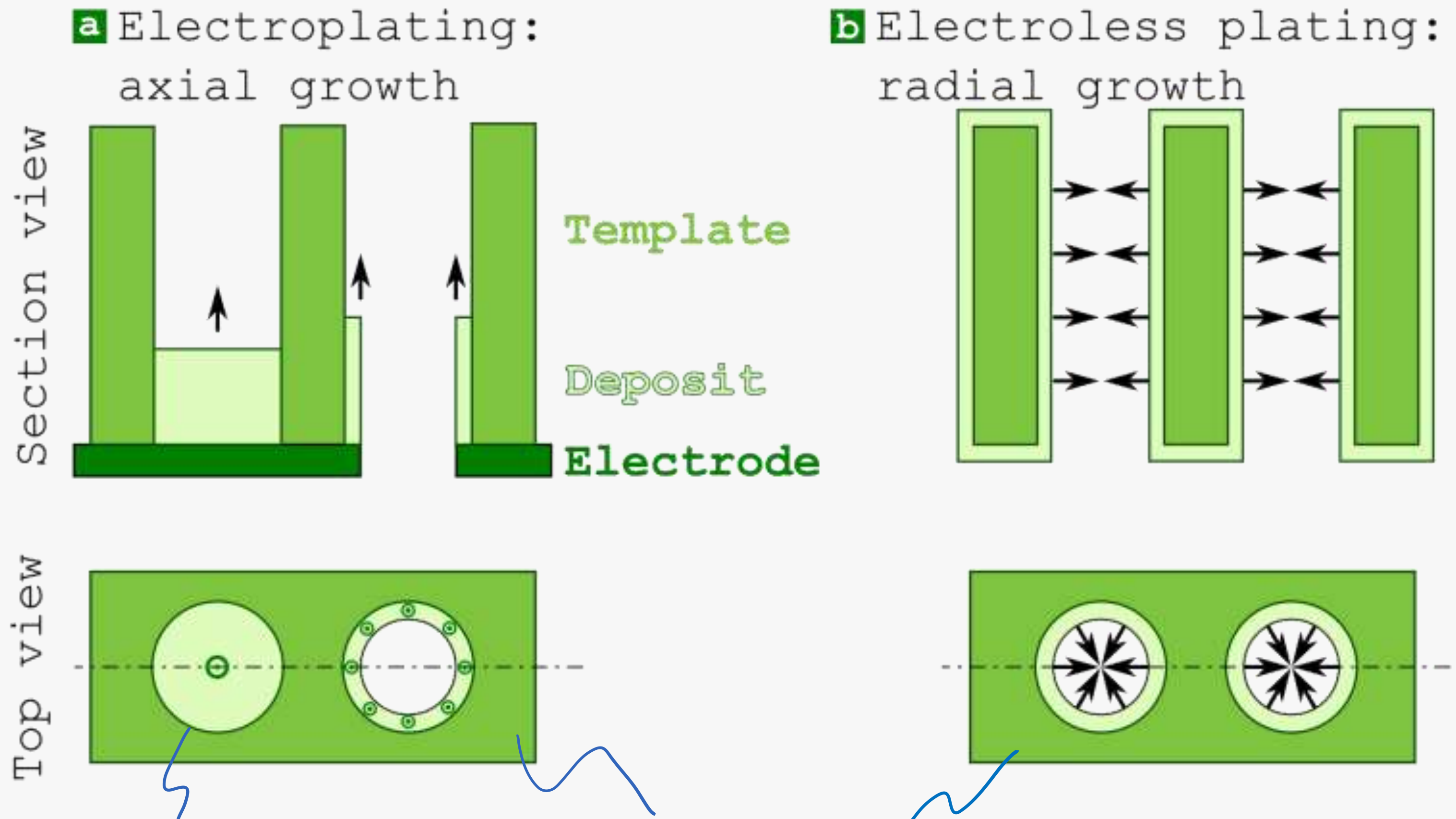
One-step filling techniques



Filled 3D

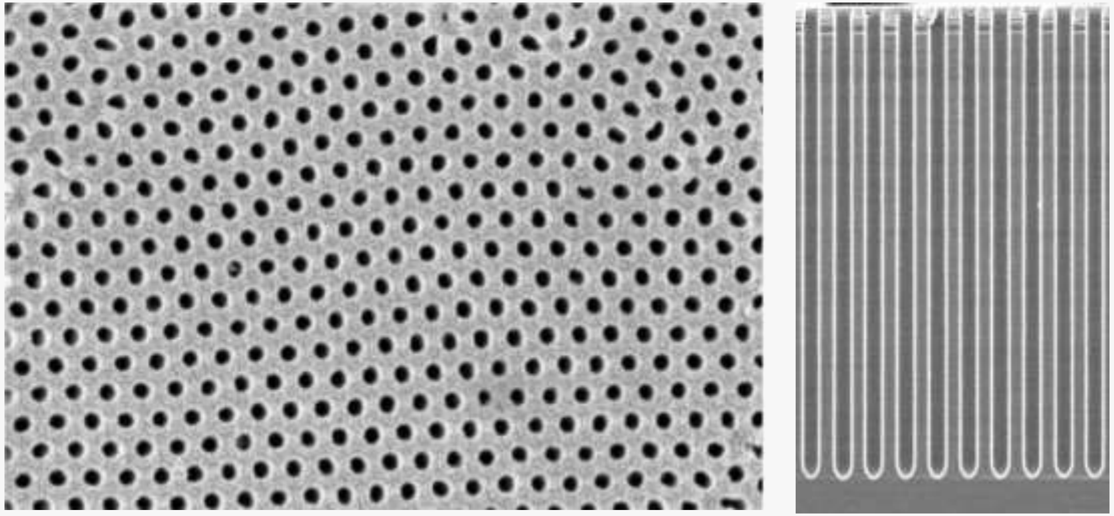
Hollow, curved surface

- Requires scaffolds

Synthesis for three-dimensional magnetization textures

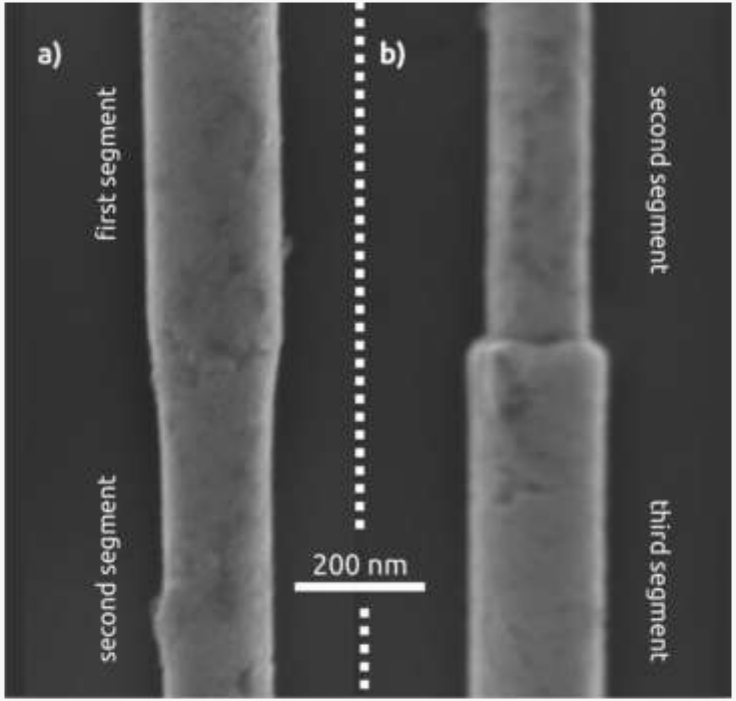
One-step templates

- Anodization of aluminum -> cylindrical pores



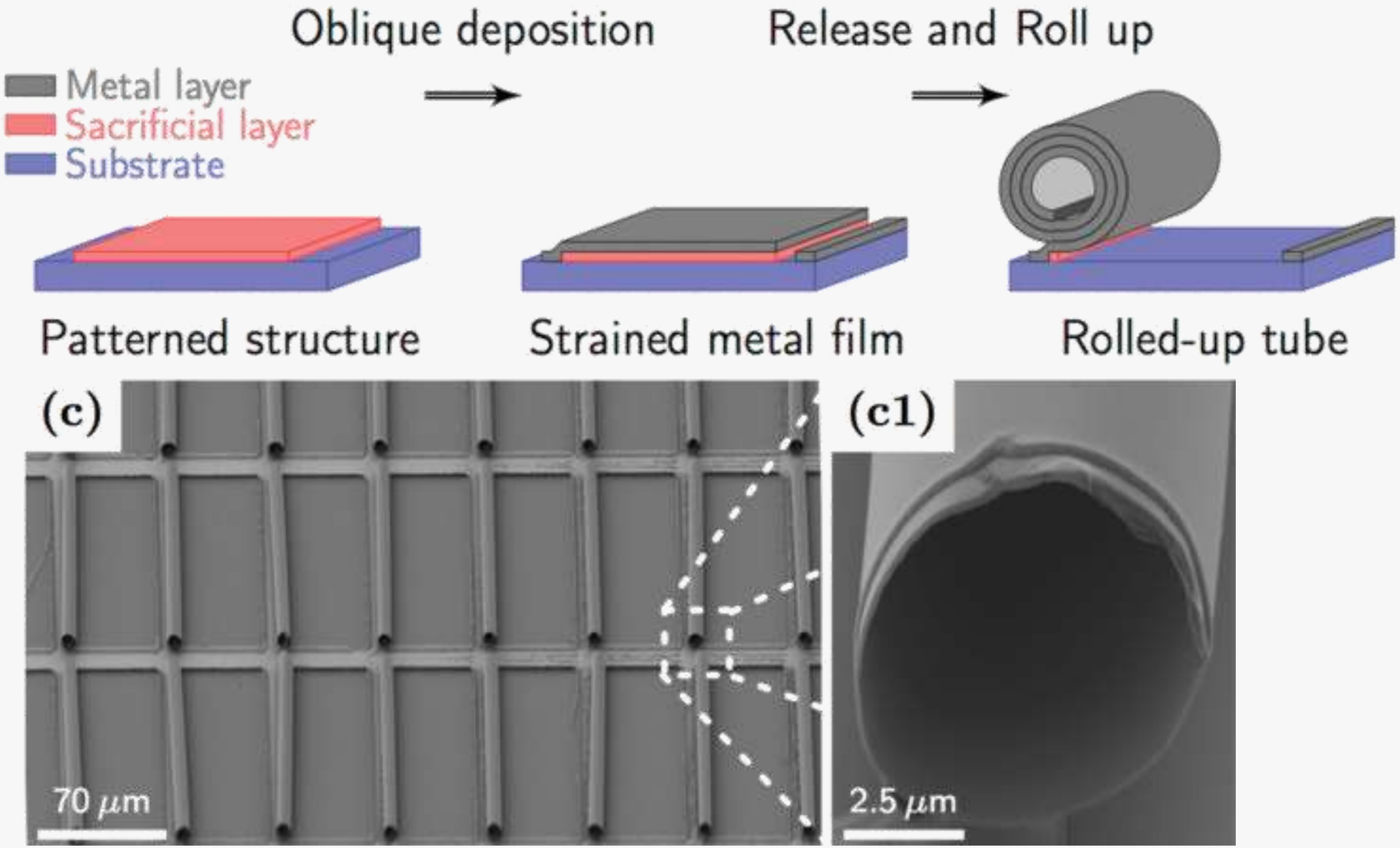
H. Masuda, Science 268, 1466-1468 (1995)

Modulations: geometrical or chemical



S. Bochmann et al., J. Appl. Phys. 124, 16 (2018)

Wafer-scale rolled structures

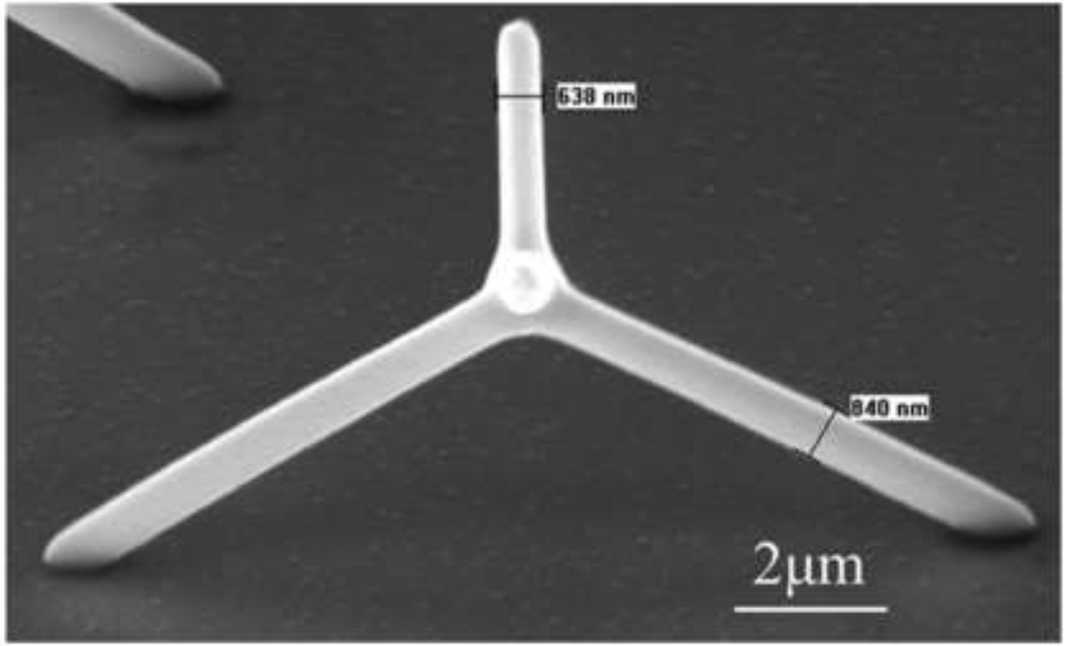


R. Streubel et al., Adv. Mater. 26, 316 (2014)

- New physics
- Devices: sensors, low foot-print electronics

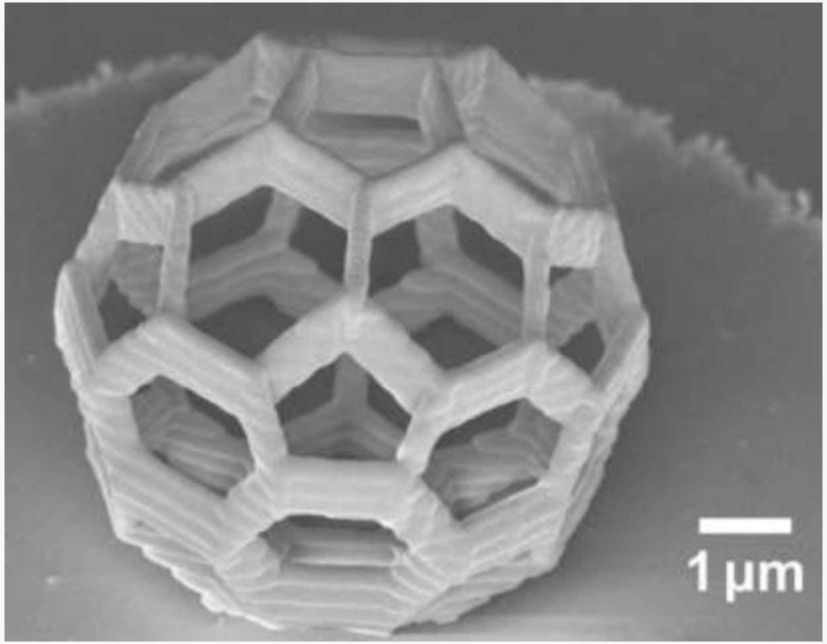
Direct writing

- Two-photo-lithography with positive resist + filling



G. Williams et al., Nano Res. (2017)

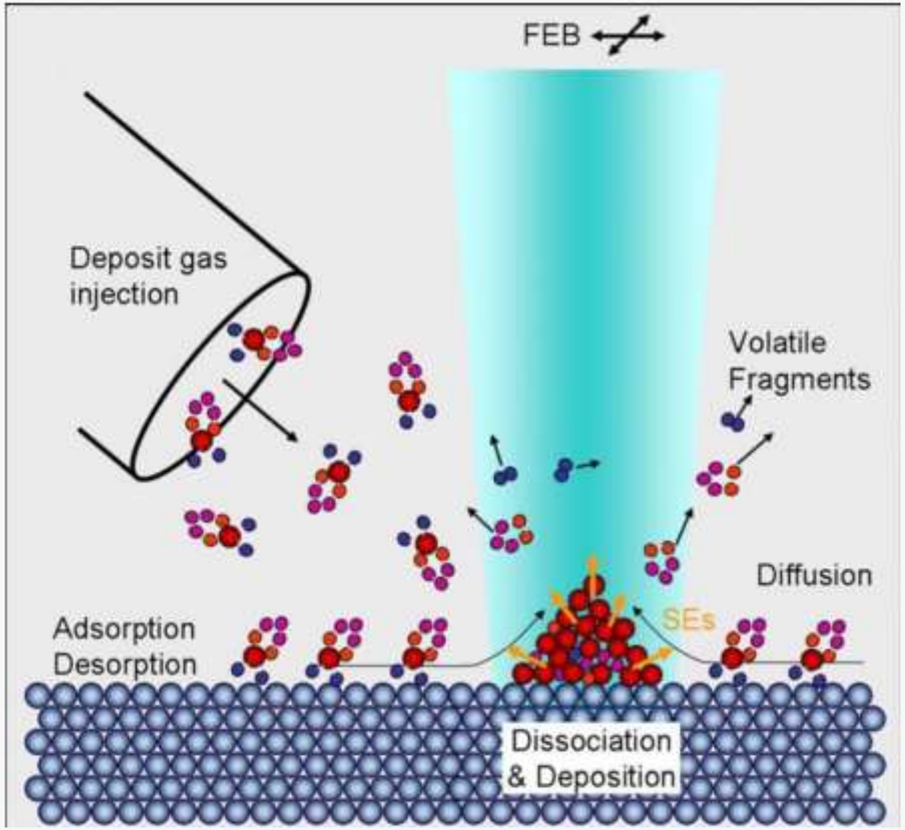
- TPL with negative resist + coating



C. Donnelly et al., PRL114, 115501 (2015)

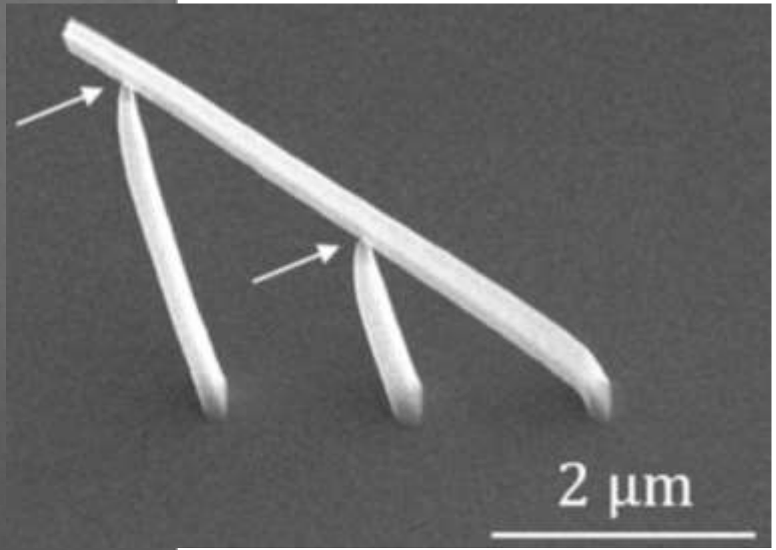
Synthesis for three-dimensional magnetization textures

Direct deposition technique: FEBID



Utke et al., J. Vac. Sci. Technol., B 26 (4), 1197 (2008)

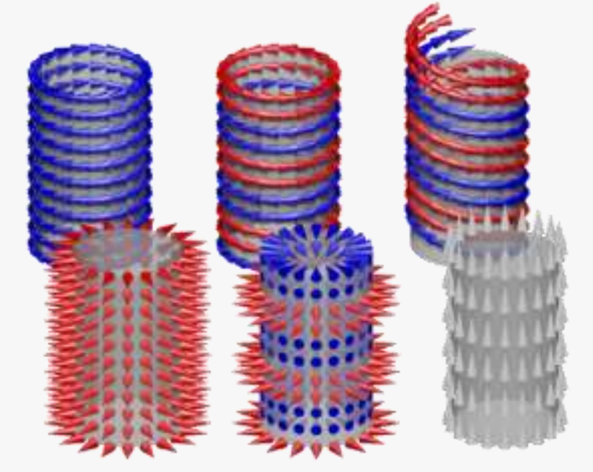
A. Fernandez-Pacheco et al., Sci. Rep. 3, 1492 (2013)

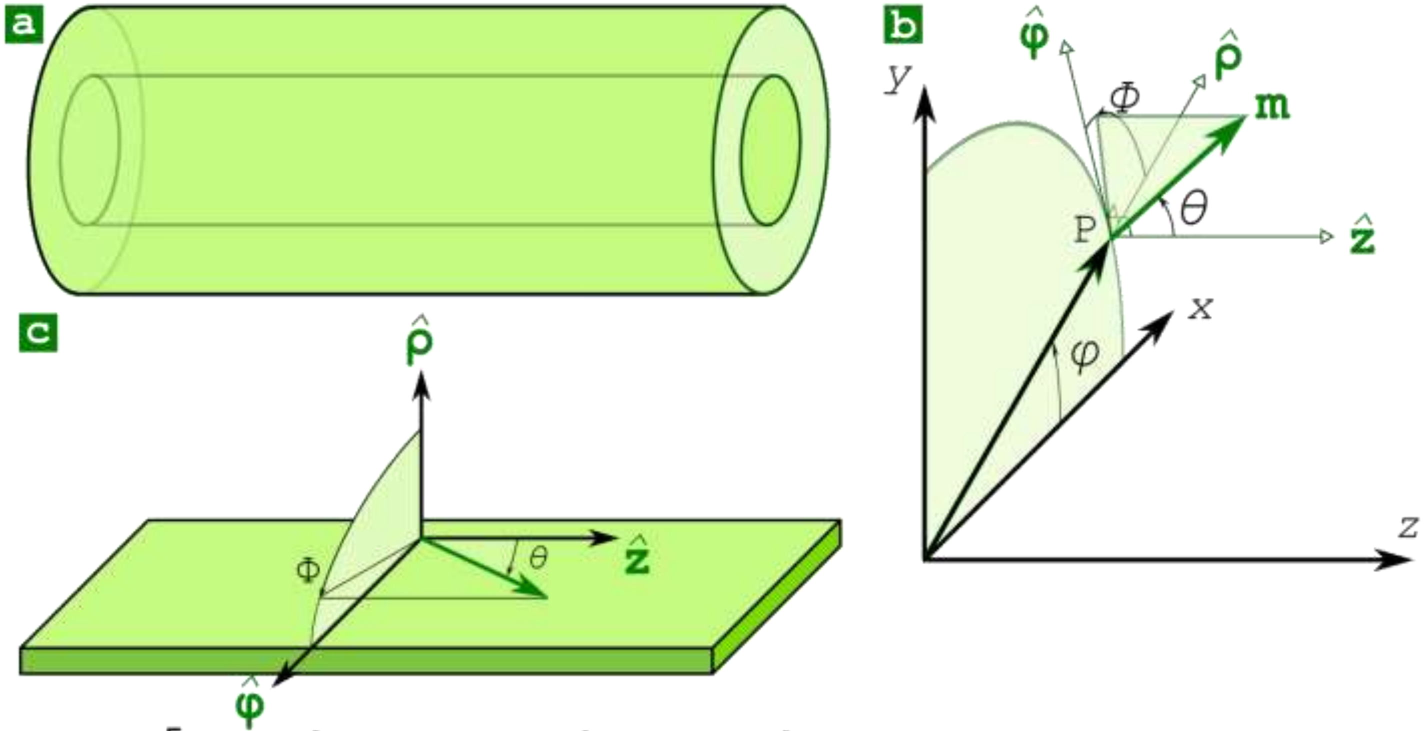


D. Sanz-Hernandez, Nanomaterials 8, 483 (2018)

Motivation for three-dimensional magnetization textures

Curvature effects





Exchange energy

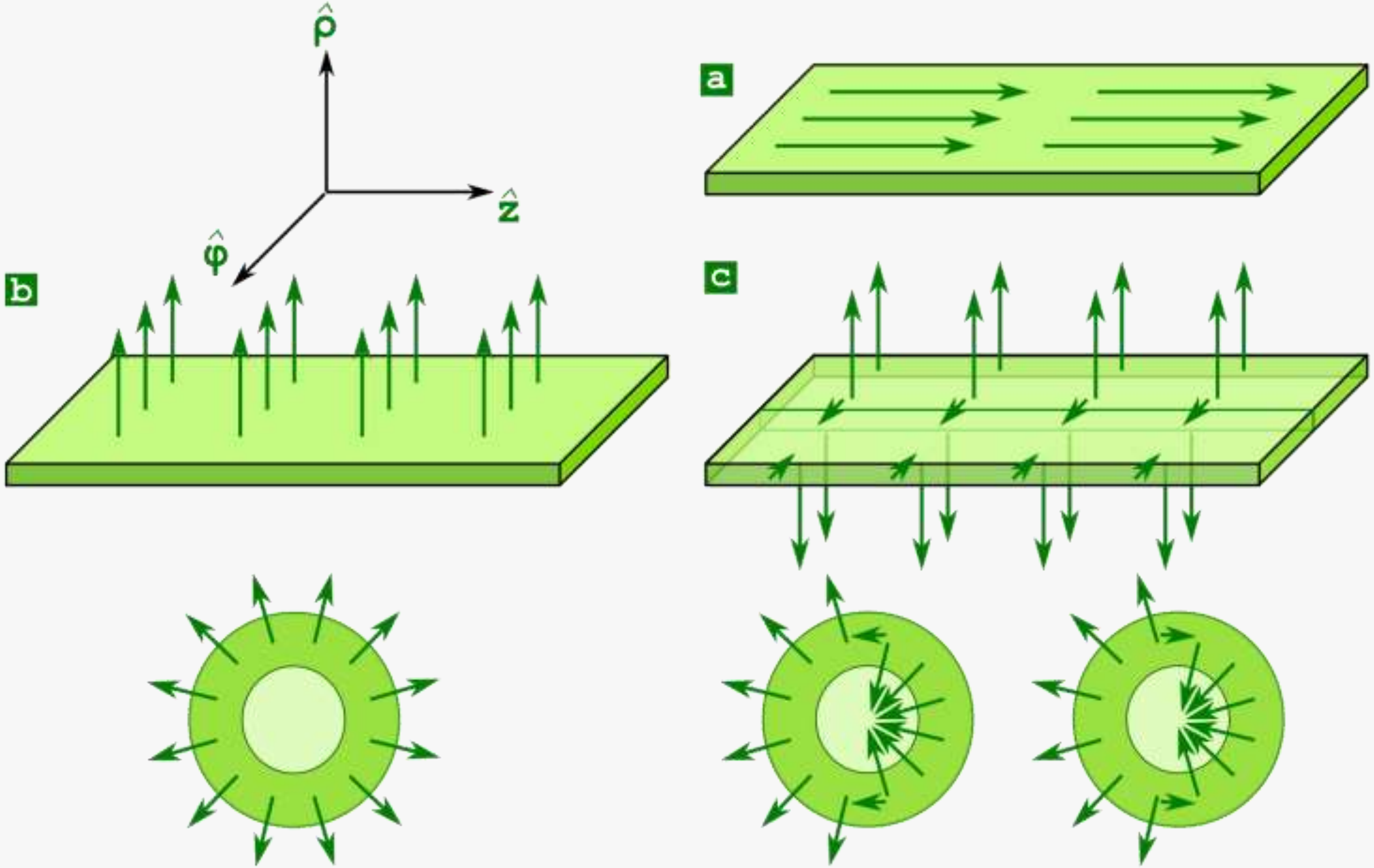
Specific case: cylindrical geometry

$$E_{\mathrm{ex}} = A\left[\left(\frac{\partial\theta}{\partial\rho}\right)^2 + \frac{1}{\rho^2}\left(\frac{\partial\theta}{\partial\varphi}\right)^2 + \left(\frac{\partial\theta}{\partial z}\right)^2 + \sin^2\theta\left(\frac{\partial\phi}{\partial\rho}\right)^2 + \frac{\sin^2\theta}{\rho^2}\left(1+\frac{\partial\phi}{\partial\varphi}\right)^2 + \sin^2\theta\left(\frac{\partial\phi}{\partial z}\right)^2\right]$$

Motivation for three-dimensional magnetization textures

Effective anisotropy and Dzyaloshinskii-Moriya energy

Specific case: cylindrical geometry



- Curvature-induced anisotropy
- Curvature-induced chirality

Motivation for three-dimensional magnetization textures

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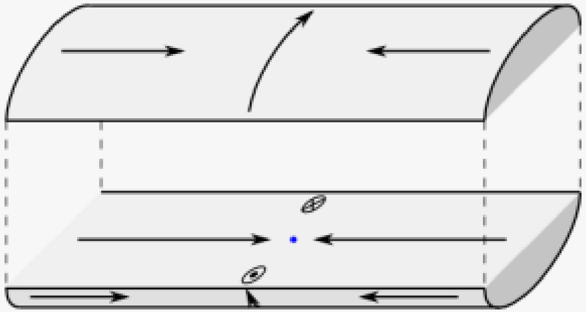
Magnetization dynamics: LLG equation

$$\frac{\mathbf{dm}}{\mathrm{d}t} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{\mathbf{dm}}{\mathrm{d}t}$$

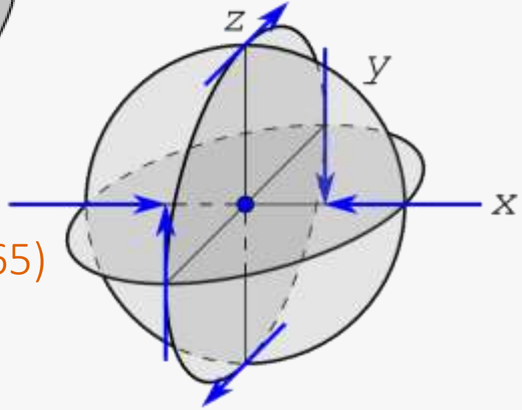
Specific topology of domain-wall in nanowire

- Bloch-point wall



A. Thiaville, Spin dynamics
in confined magnetic structures III, (2006)

- Bloch-point

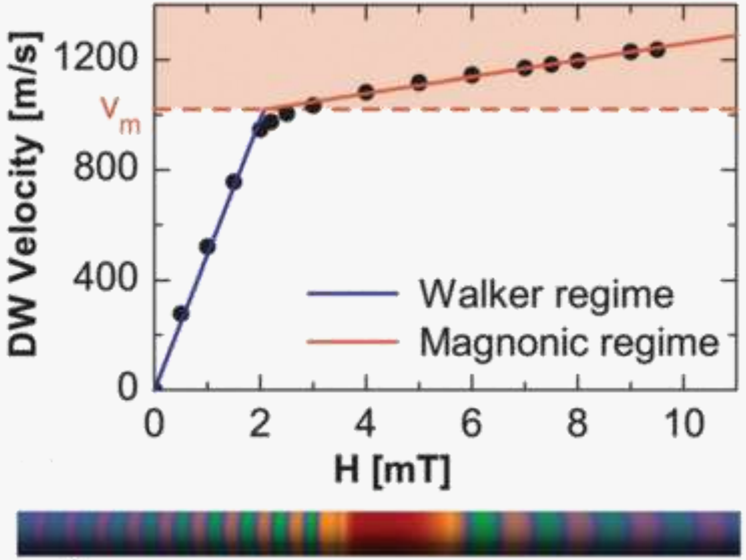


R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

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

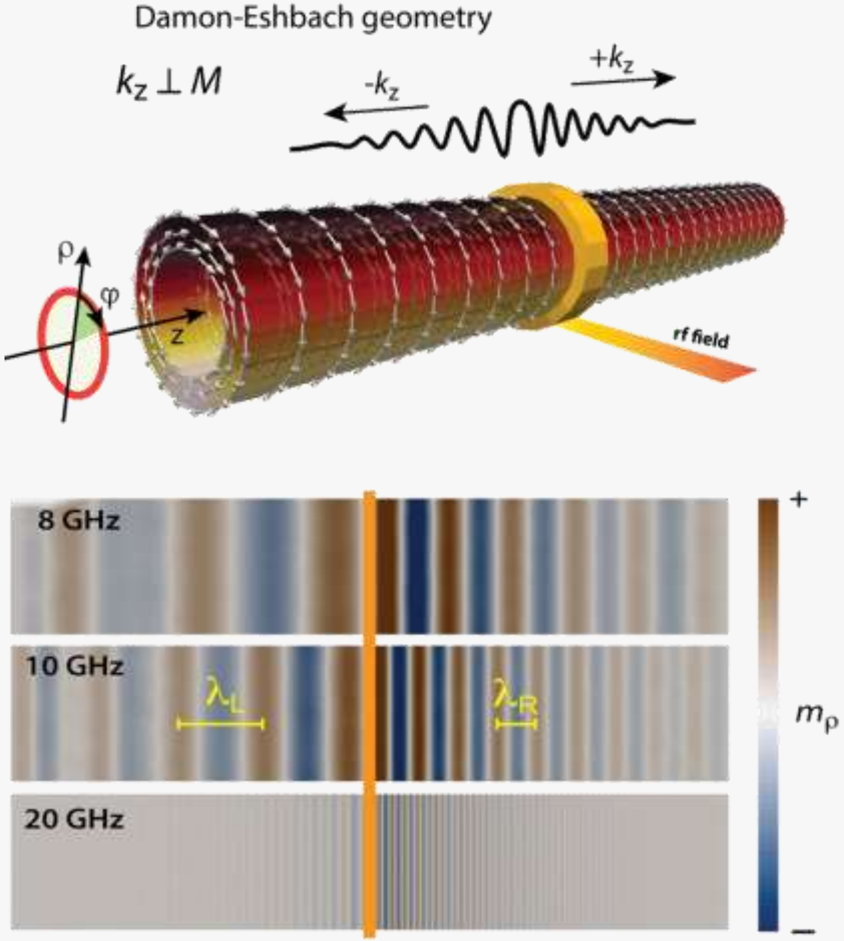
Magnonic limit

Tubes (similar to wires)



- Broad theoretical background
- No experimental report

Curvature-inducedNon-reciprocity of spin-wave propagation

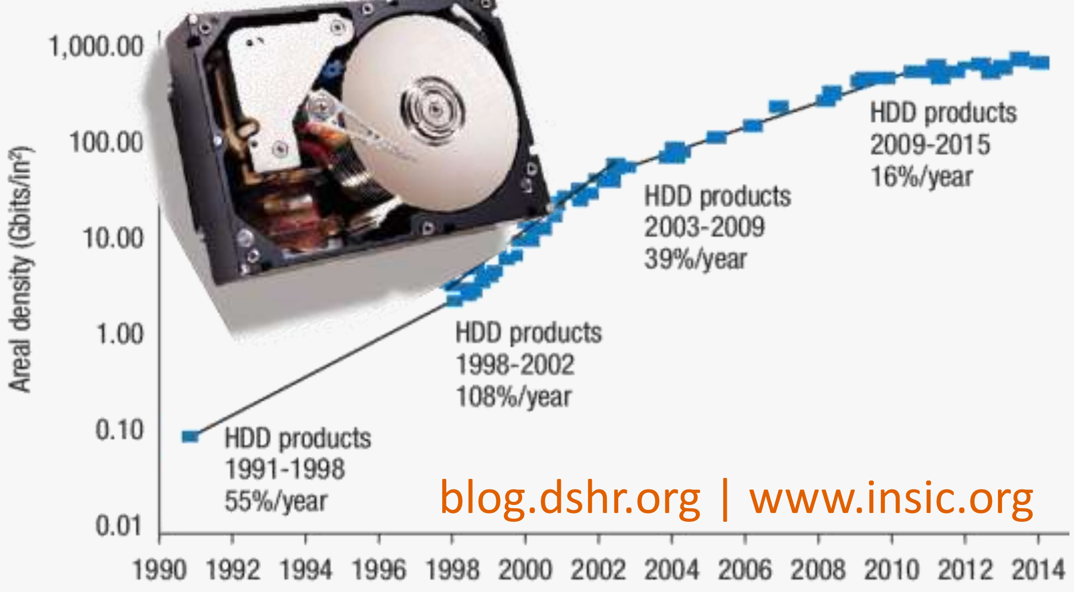


J. Otalora, Phys. Rev. Lett. 117, 22 (2016)

- Experimental results are emerging

Motivation for three-dimensional magnetization textures

HDD: staggering areal density



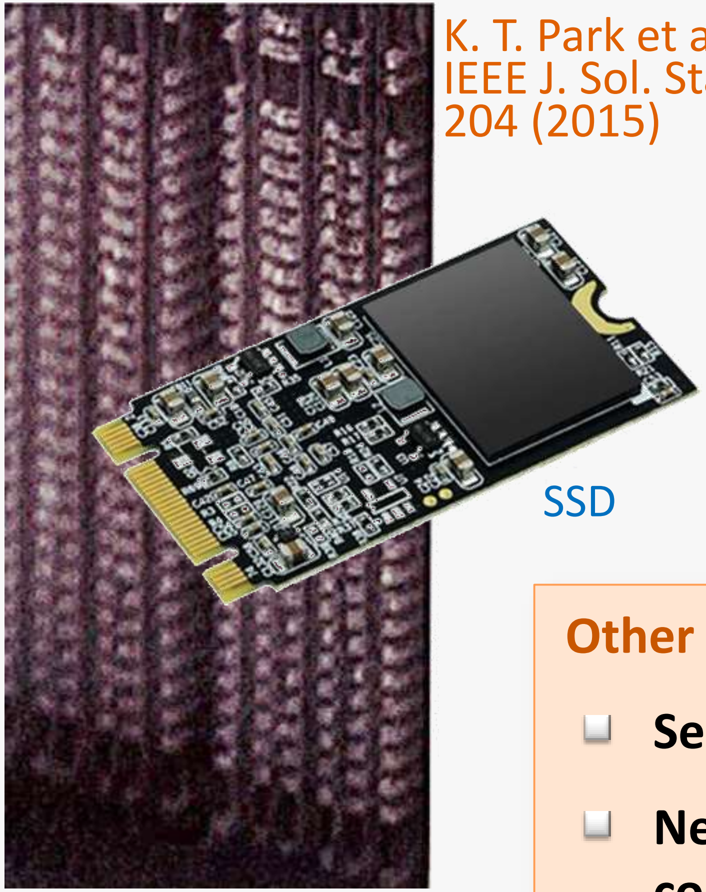
blog.dshr.org | www.insic.org

HDD vs Flash Cross-over in 2016

- 1Gb/mm2 → 600Gb/in2...
- Magnetic mass storage may only remain for niche applications

Technologies go 3D

K. T. Park et al., IEEE J. Sol. State Circ. 50 (1), 204 (2015)



SSD

24-layer 3D NAND Flash

Other targets

- Sensors
- Neuromorphic computing

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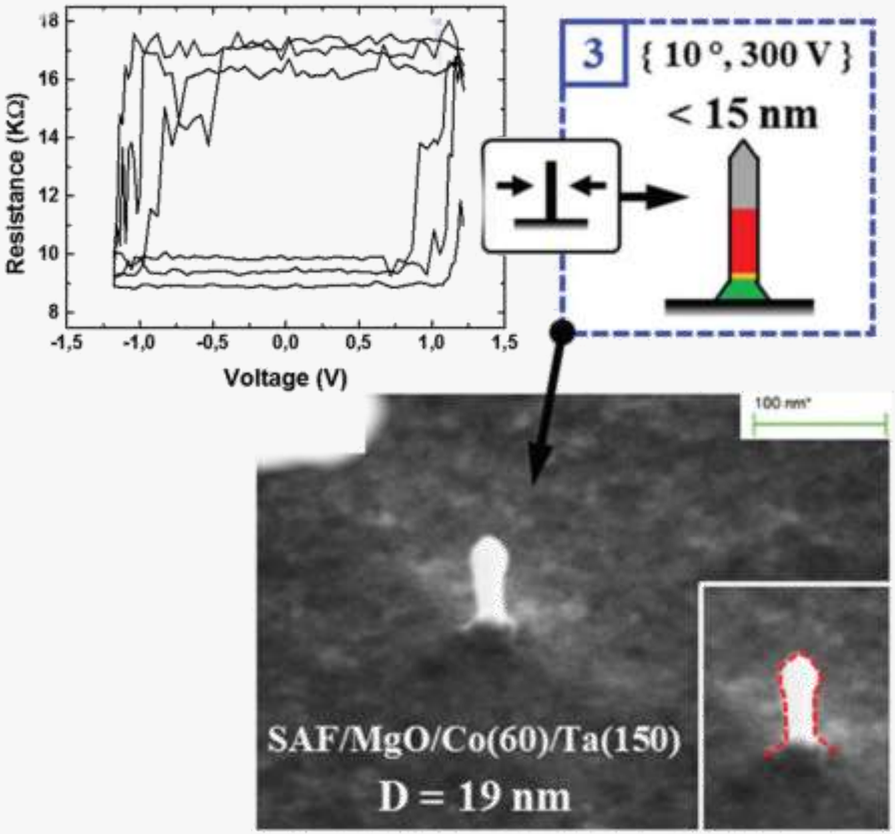
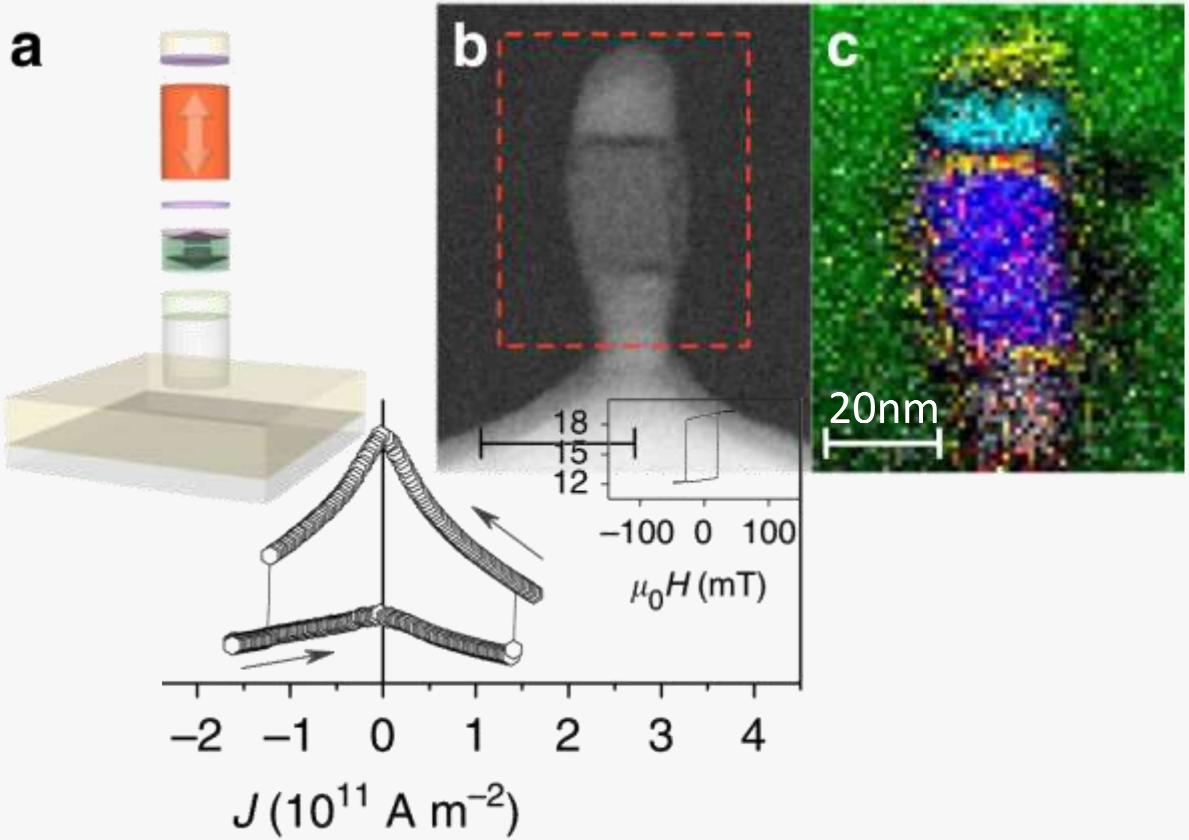
Example: emergence of 3D Magnetic RAM



N. Perrissin et al., Nanoscale 10, 25 (2018)

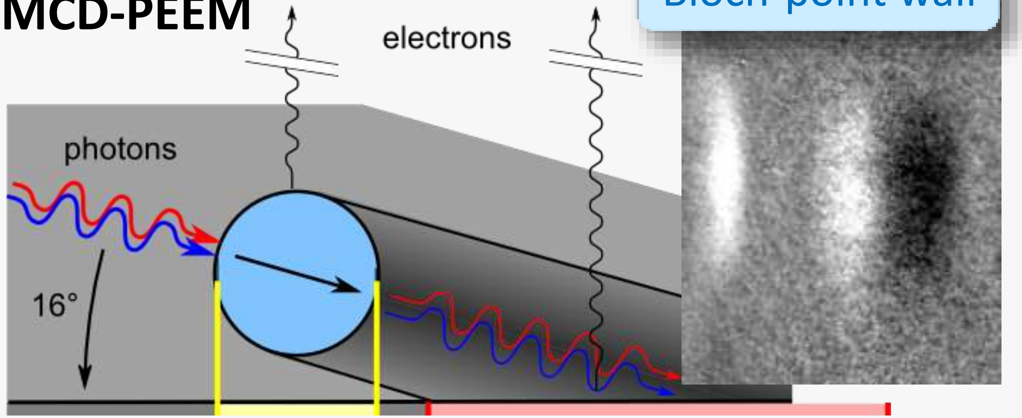


K. Watanabe et al., Nat. Comm. 9, 663 (2018)

3D magnetic imaging: current status

XMCD-PEEM

Bloch-point wall

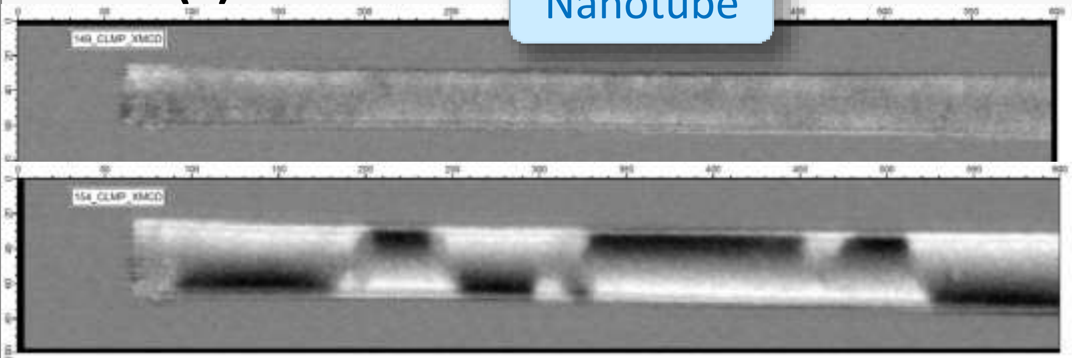


S. Da-Col et al., Phys. Rev. B (R) 89, 180405, (2014)

XMCD-(S)TXM

Nanotube

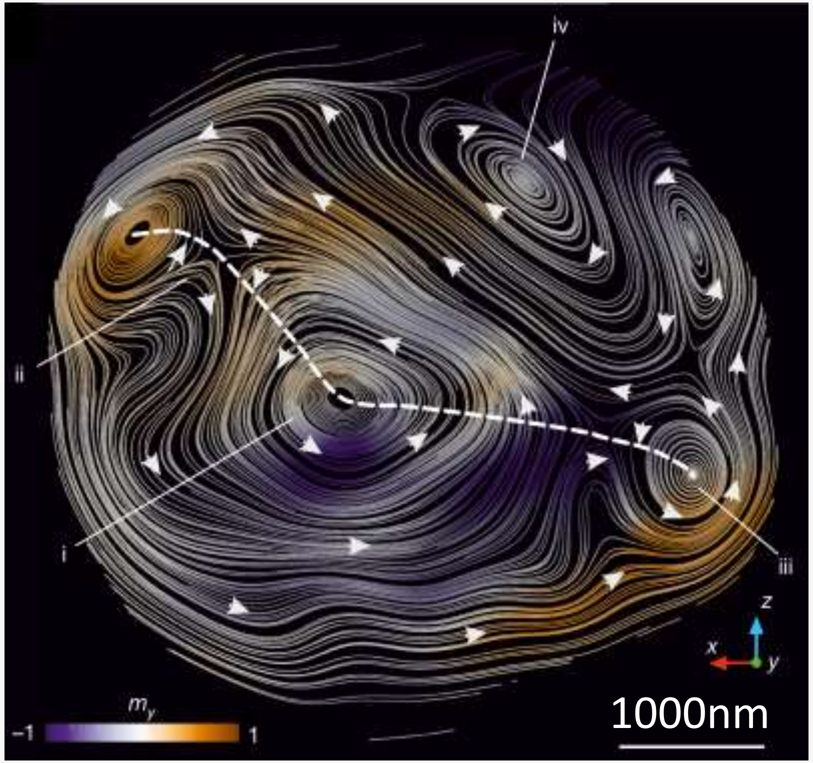
-20 mT



O. Fruchart, R. Belkhou, to be published

0 mT

Ptycho/tomography



Slice of vector tomography in a $GdCo_2$ nanopillar

C. Donnelly, Nature 547, 328 (2017)

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Challenges and opportunities

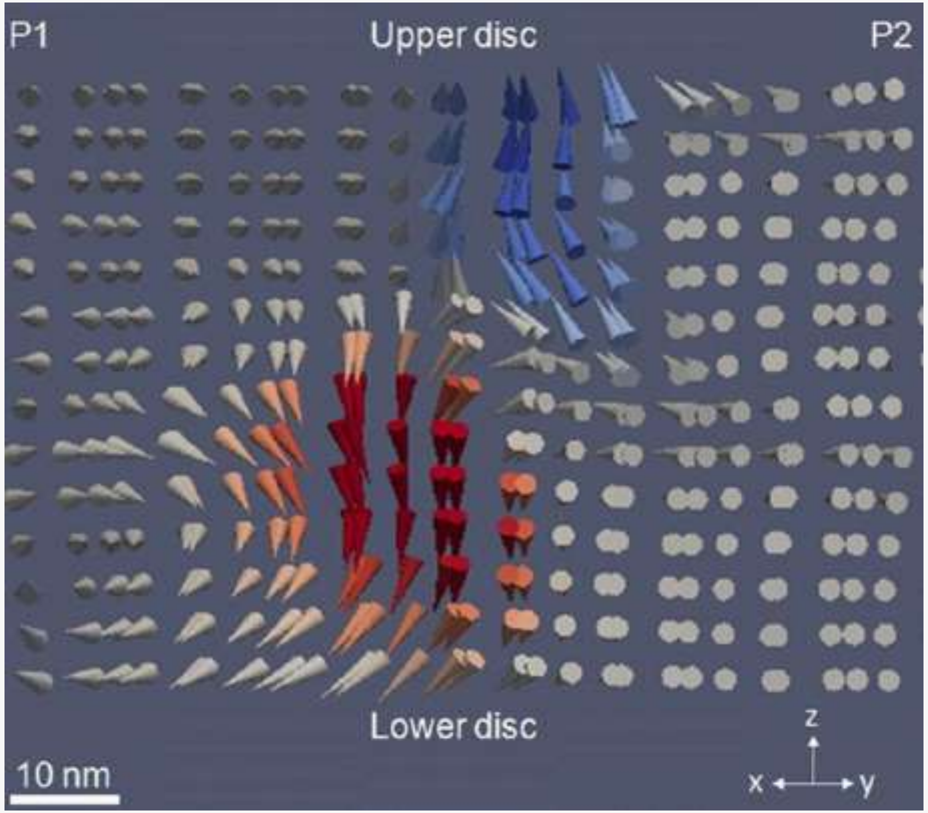
- Develop clear and competitive portfolio of PEEM, (S)TXM, ptychography
- "All-bunches" counting electronics for efficient time resolution
- Direct counting cameras: electrons (PEEM), photons (ptychography), challenge of time resolution.
- Challenge: 3d imaging at L edges of 3d elements. Higher flux, use alloys.
- 4d stacks (spectroscopy): more accurate 3d reconstruction?
- Operando

ENDSTATION & ANALYSIS

BEAM

Competitors

Vector tomography electron holography



T. Tanigaki et al., Nanolett. 15, 1309 (2015)

Pros and cons of various microsopies (personal views)

	Sp-STM	MFM	NV	BEMM	SEMPA	SPLEEM	TEM	XMCD -PEEM	XMCD-TXM	XMCD-Ptycho	SNOM
Resolution	<1nm	15nm	5-10 nm	1-5nm	10nm	10nm	1-2nm	25nm → 10nm	15nm	<20nm	50nm
Sensitivity	High	Med	High	Med	Med	High	Low	High	High	Med	Med
In-field	YES	Limited	Limited	YES	local	No?	Limited	No?	YES	YES	YES
Versatile*	No	YES	Yes	No	Limited	UHV	Limited	Yes	Limited	Limited	Limited
Dynamics	Part	Part	No	No	No	No	Part	Yes	Yes	Yes	Yes
Element-sensitive	Limited	No	No	No	Limited	Limited	Limited	Yes	Yes	Yes	No
	m_i	$\mathrm{H_d}$	$\mathrm{H_d}$	m_i	m	m	$m_{x,y}$	m_k	m_k	m_k	unsure

Thank you for your attention !

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