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Three-dimensional spintronics: “Faster, higher, stronger”

Amalio Fernández-Pacheco

SPICE online seminar, 02/02/2022

INMA Instituto de Nanociencia y Materiales de Aragón
CSIC Consejo Superior de Investigaciones Científicas
Universidad Zaragoza 1542
University of Glasgow
University of Cambridge

Information technology revolution

In a few decades

Future

©sdecoret

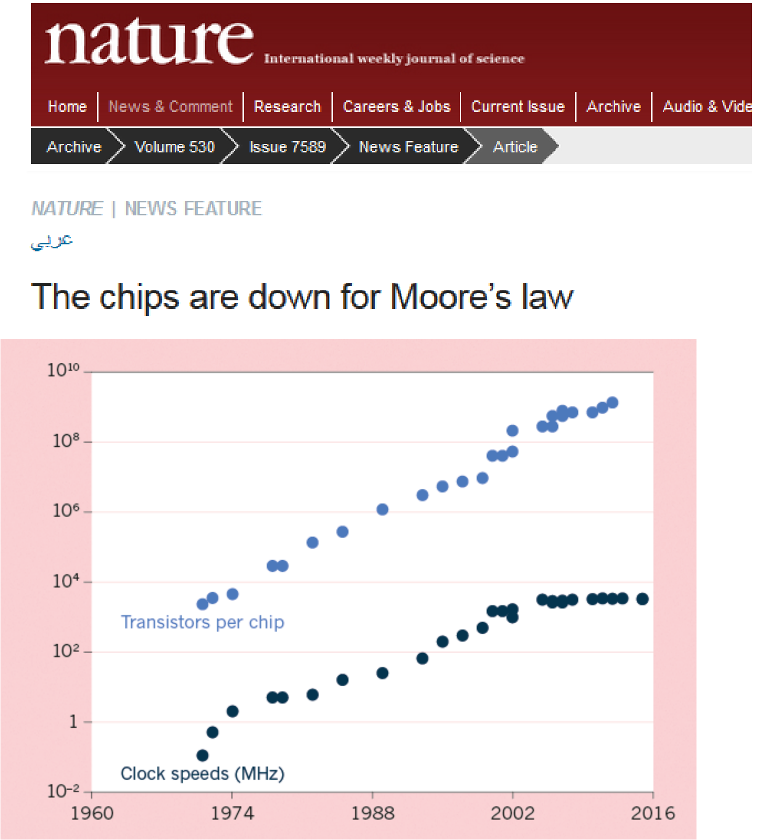
5G, AI, IOT, Big Data

From 12,000 BC to 2003: Total data generated by humans ~ 5 EB

By 2025: Generation of ~ 460 EB/day

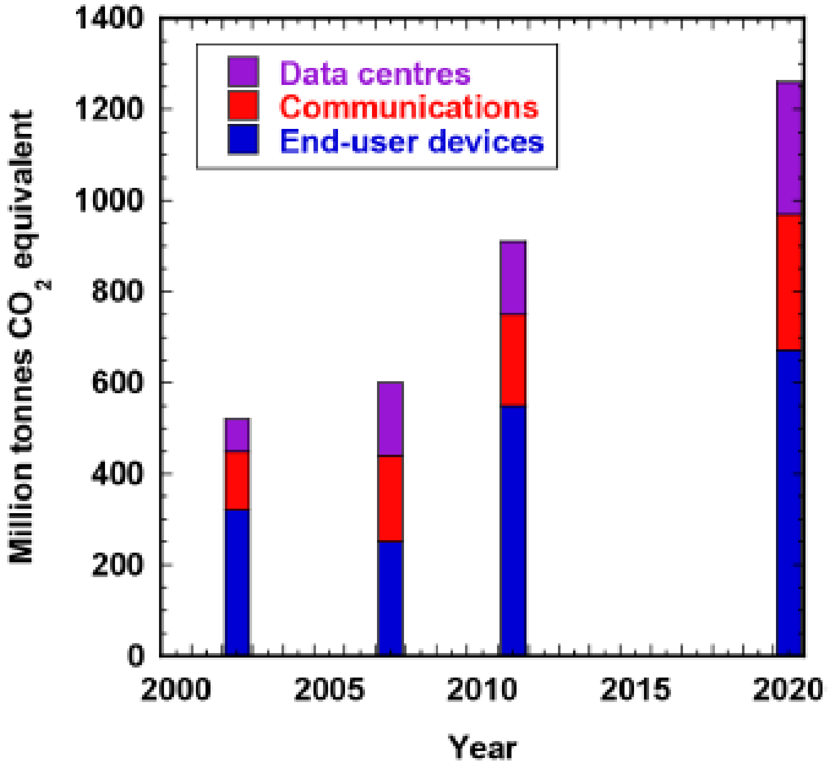
Sources: Techjury.net, SchoolOfLife

But huge challenges ahead…



Slowing down of Moore's Law (valid since 1960s)

[EU ICT Energy Strategic Research Agenda (2016)]



By 2025: Communication industry responsible for 20% of electricity consumption in the world

Source: DataSphere (2018)

Need of new technologies:

- Based on systems exploiting new physical phenomena
- More sustainable
- Multifunctional

Spintronics on the news: new generation of computing devices

MRAM-info

Home | About us | What is MRAM? | STT-MRAM | MRAM companies | Conferenc

Home » MRAM News » Samsung Foundry to start offering STT-MRAM by 2019

Samsung Foundry to start offering STT-MRAM by 2019

EXTREMETECH

IBM Unveils 19TB SSD With Everspin MRAM Data Cache

By Joel Hruska on August 7, 2018 at 7:30 am | Comments

INNOVATION NEWS NETWORK

SPINTEC extends the scalability of magnetic memory below 10nm

Research & Discovery | 21st August 2018

Spintronics-info

Posted: Jun 16, 2013

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Home » NEC and Tohoku University developed a spintronics text...

NEC and Tohoku University developed a spintronics text-search chip that cuts power reduction by 99%

Samsung Newsroom

Samsung Demonstrates the World's First MRAM Based In-Memory Computing

Korea on January 13, 2022

EurekAlert! AAAS

NEWS RELEASE 19-MAY-2021

Wireless and battery-free spintronic energy harvester

Peer-Reviewed Publication

TOHOKU UNIVERSITY

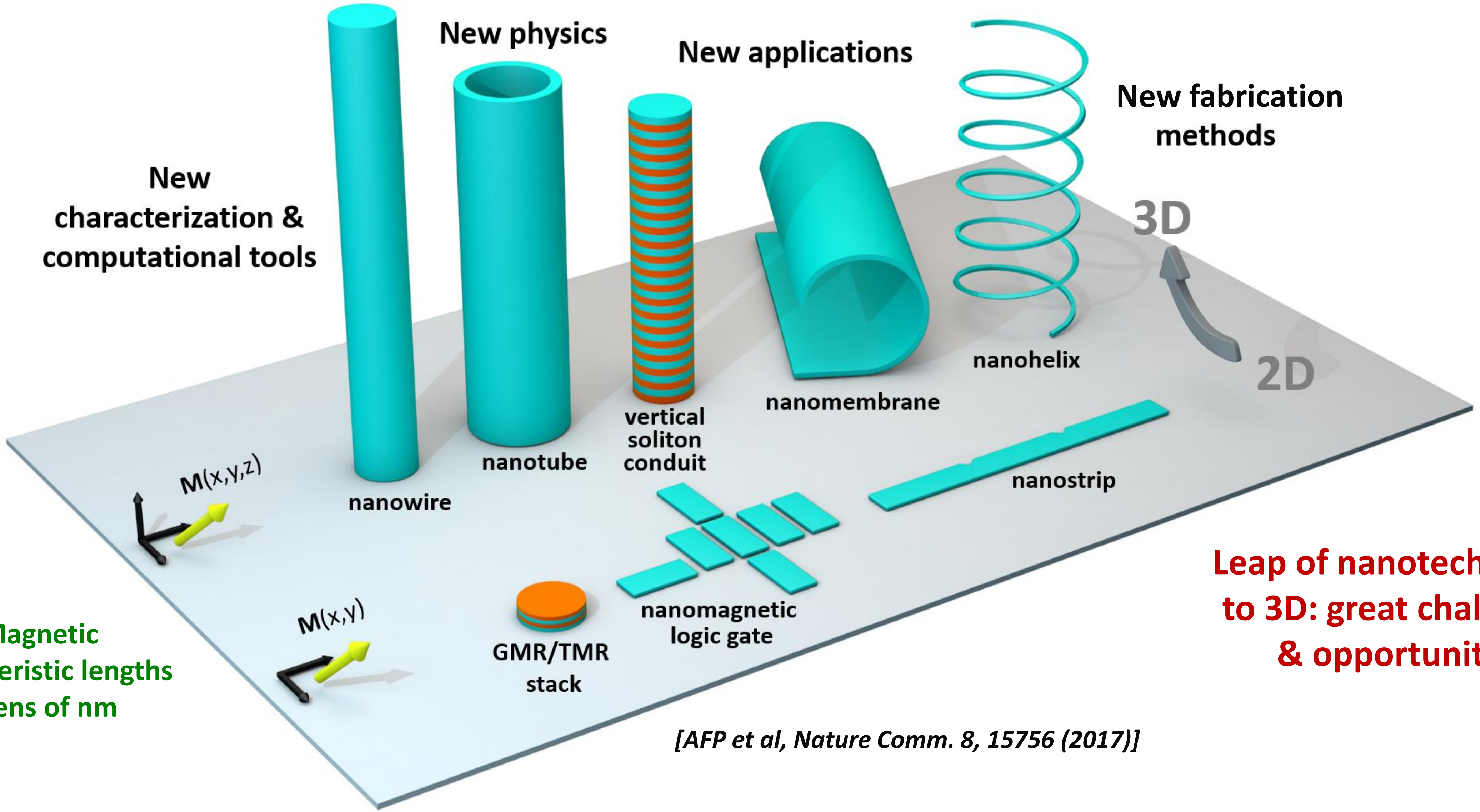
physicsworld

ADVANCED MATERIALS | RESEARCH UPDATE

Coupled spintronic neurons learn to recognize vowels

31 Oct 2018 Isabelle Dumé

Three-dimensional spintronics: “higher, faster, stronger”

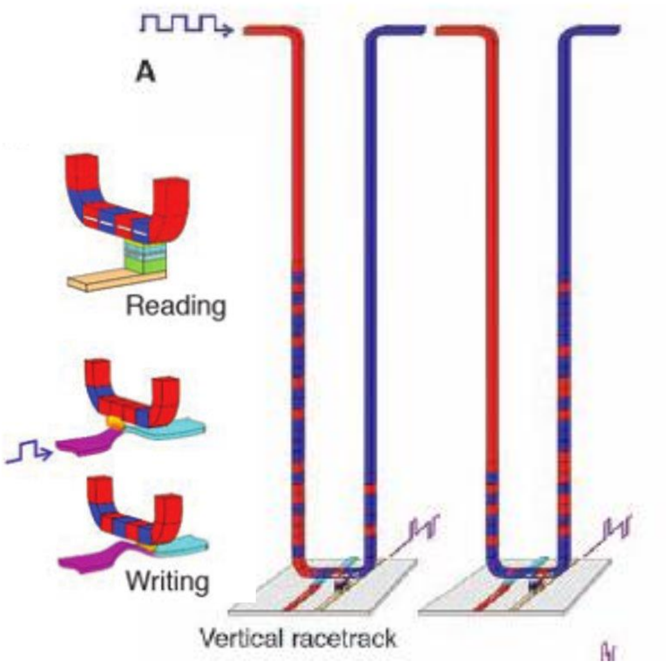


Magnetic characteristic lengths ~ tens of nm

Leap of nanotechnology to 3D: great challenges & opportunities

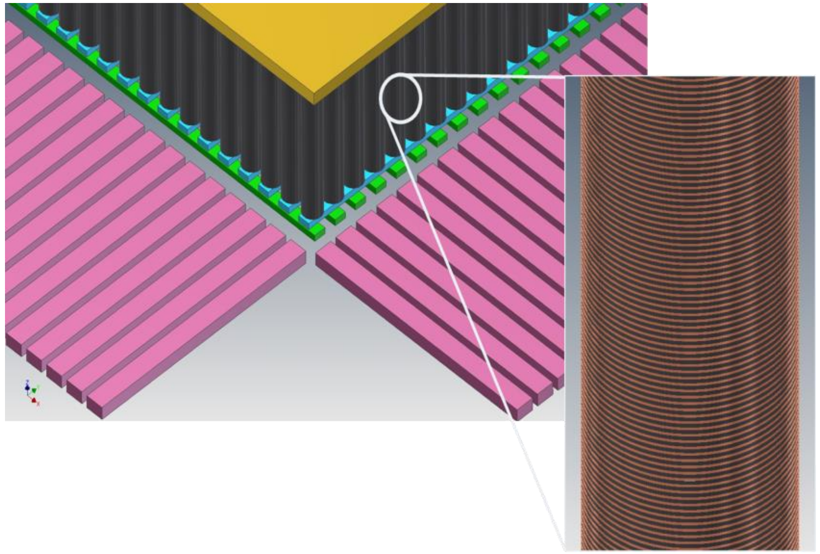
[AFP et al, Nature Comm. 8, 15756 (2017)]

3D spintronic devices: non-volatile & new functionalities



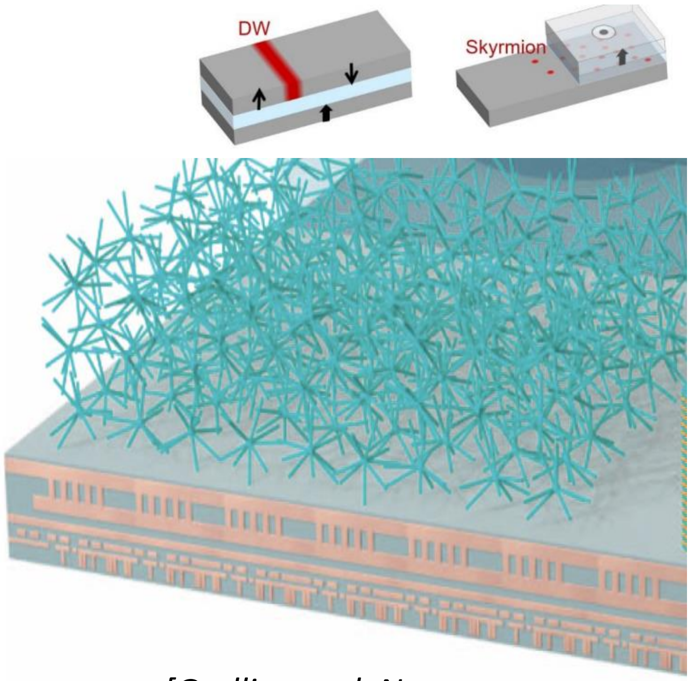
[Parkin et al. Science 320, 190 (2008)]

High-density storage & memory nanowire devices



[Lavrijsen, AFP, Cowburn et al. Nature 493, 647 (2013)]

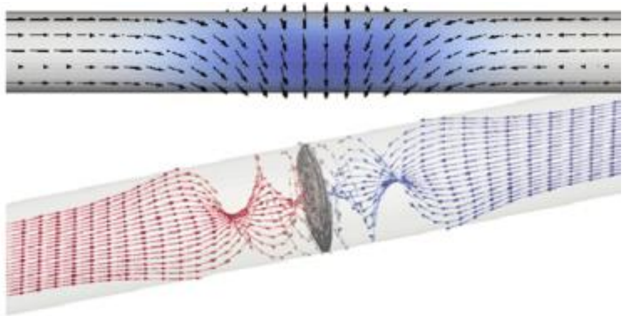
Multilayer thin film based memory & logic devices with vertical functionality



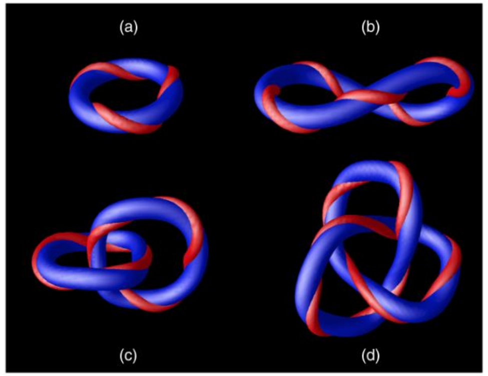
[Grollier et al. Nature Electronicas 3, 360 (2020)]

Ultra-high interconnectivity for spintronic neuromorphics

New magnetic effects emerging in 3D

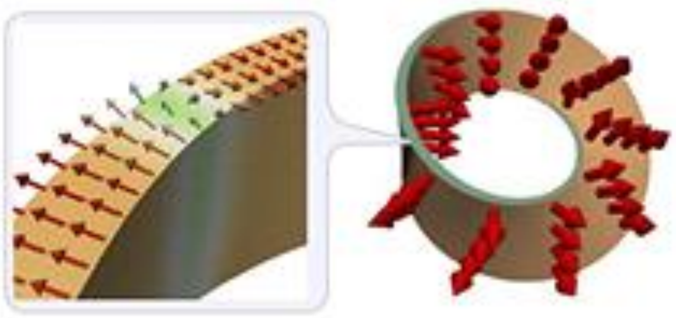


[Da Col, Phys. Rev. B 89, 180405 (2014); Thiaville et al, Spin dynamics in magnetic structures III 161 (2006)]

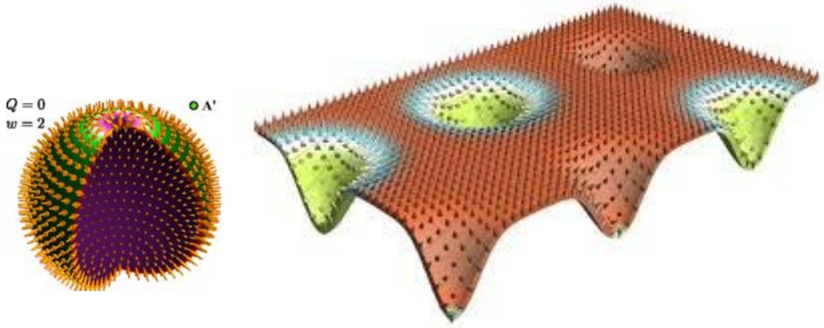


[Sutcliffe Phys. Rev. Lett. 118, 247203 (2017)]

New types of spin textures

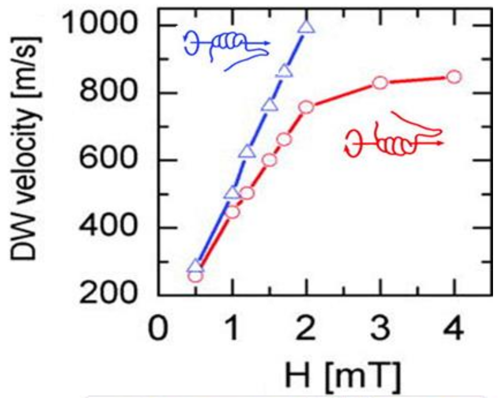


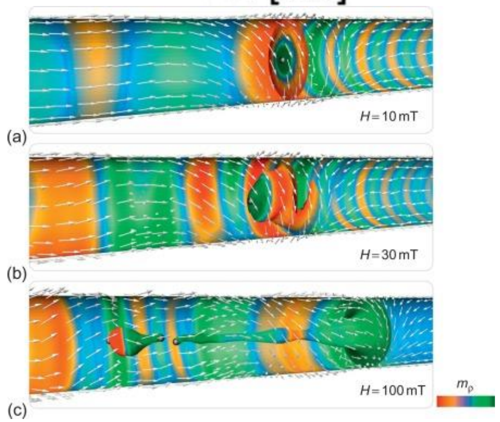
[Pylypovskyi, Phys. Rev. Lett. 114, 197204 (2015)]



[Kravchuk et al, Phys. Rev. B 94, 144402 (2016);]

Topology & curvature for control of spin states

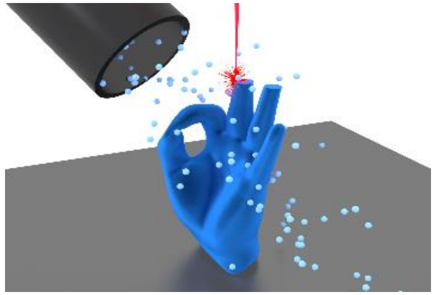




[Hertel, J. Phys. Cond. Mat. 28, 483002 (2016)]

Magnetochiral effects to overcome fundamental limits in 2D

Outline

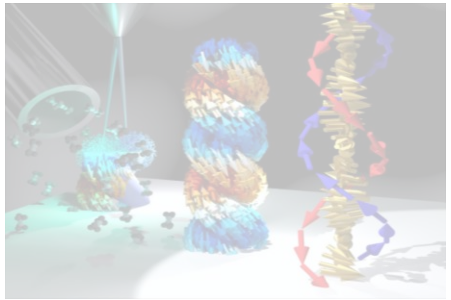


3D printing of nanomagnets

- Layer-by-layer growth of complex shaped 3D nanostructures

3D magnetic nano-circuits

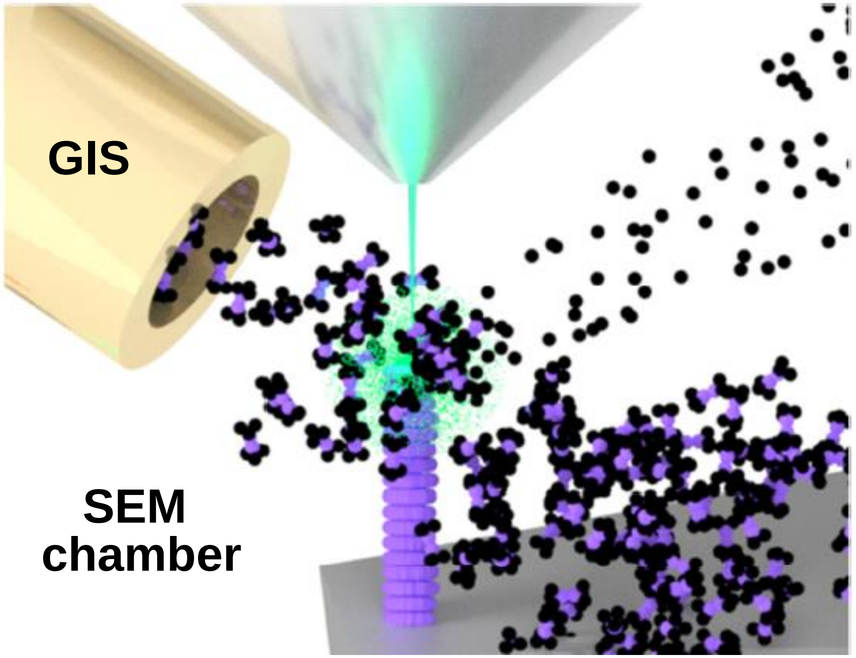
- Dark-Field Magneto-Optical Kerr effect
- Magnetoelectrical effects in a 3D geometry



Strongly interacting chiral nanostructures

- Imprinting of chiral spin textures & topological defects
- Creation of magnetic stray fields with topological features

Focused electron beam induced deposition (FEBID)

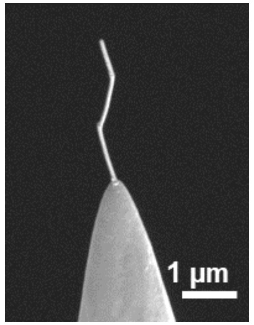


FEBID: Local Chemical Vapor Deposition induced by a focused beam of electrons in the keV range

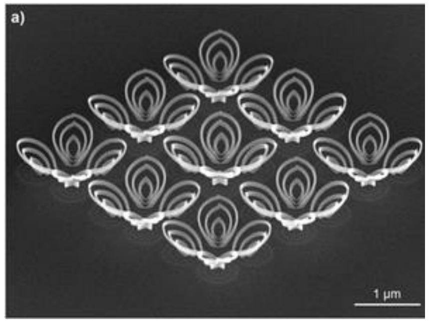
[Utke et al, J. Vac. Sci. Technol, 26, 1197 (2008)]

Unique tool for 3D nano-prototyping

1-step lithography process

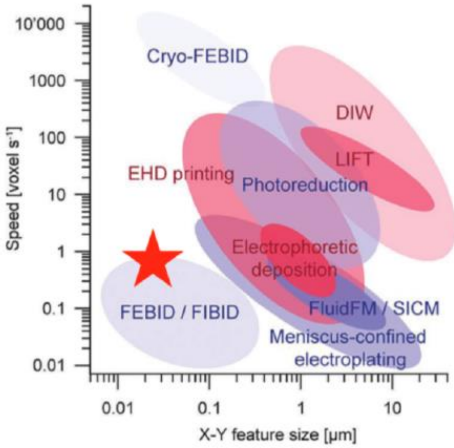


Growth on almost any substrate



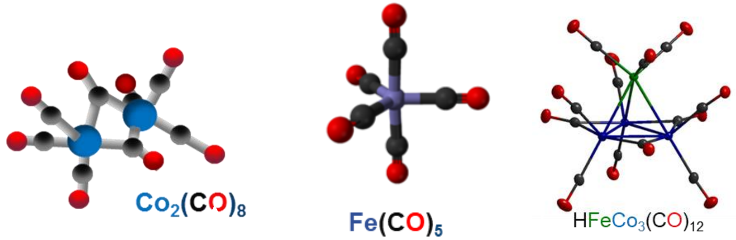
Great performance for 3D nanofabrication

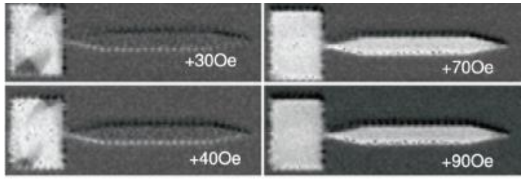
[Winkler et al, J. Appl. Phys. 125, 210901 (2019)]



Nano-patterning resolution

[Hirt et al, Adv. Mater. 29, 1604211 (2017)]



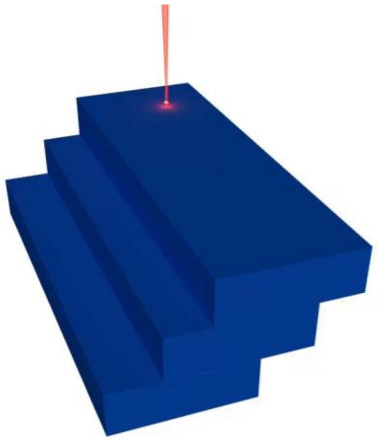


Direct writing of ferromagnetic metals

[AFP et al. Materials 13, 3774 (2020)]

New framework for nanoscale 3D printing by FEBID

Layer-by-layer growth of complex 3D objects



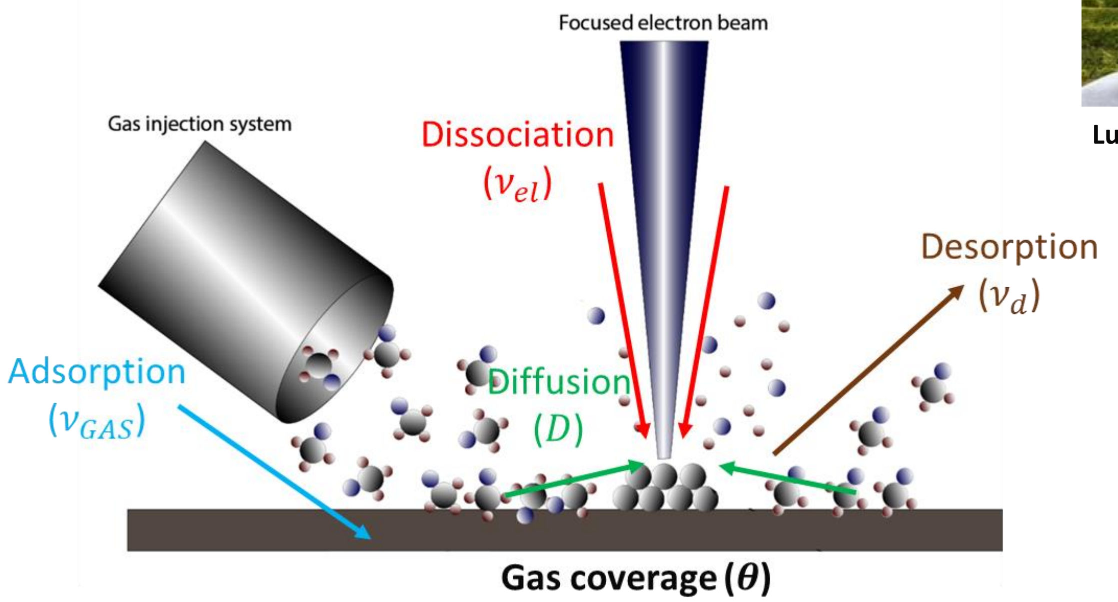
Deposits interact via proximity effects within a layer

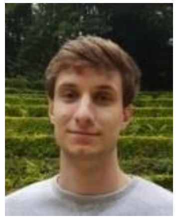
Contributions from all deposits need to sum up to the layer height:

$$Layer\ height = \sum_j GR(d_{ij})t_j$$

d_{ij} the distance between points i and j

t_j dwell time at point j





Luka Skoric

Based on FEBID continuum model

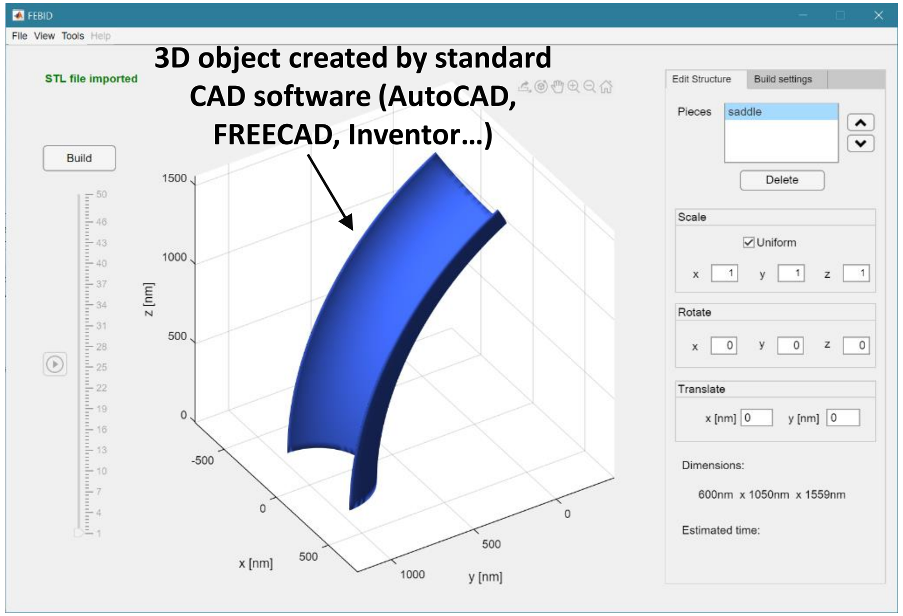
[Sanz-Hernández & AFP, Beilstein J. Nanotechnol. 8, 2151 (2017)]

$$h \propto \frac{\nu_{GAS}\nu_{el}(r)}{\nu_{GAS} + \nu_d + \nu_{el}(r)} t$$

Simple two-step calibration procedure without needing complex simulations

[Skoric et al, Nano Lett. 20, 184 (2020)]

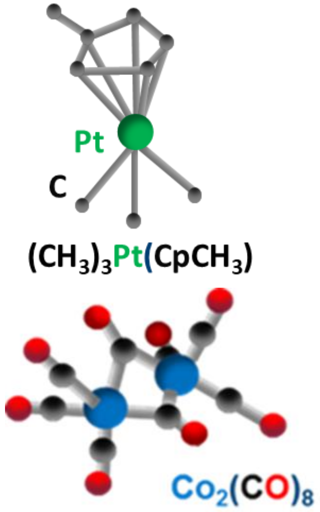
The 3D printing algorithm in action

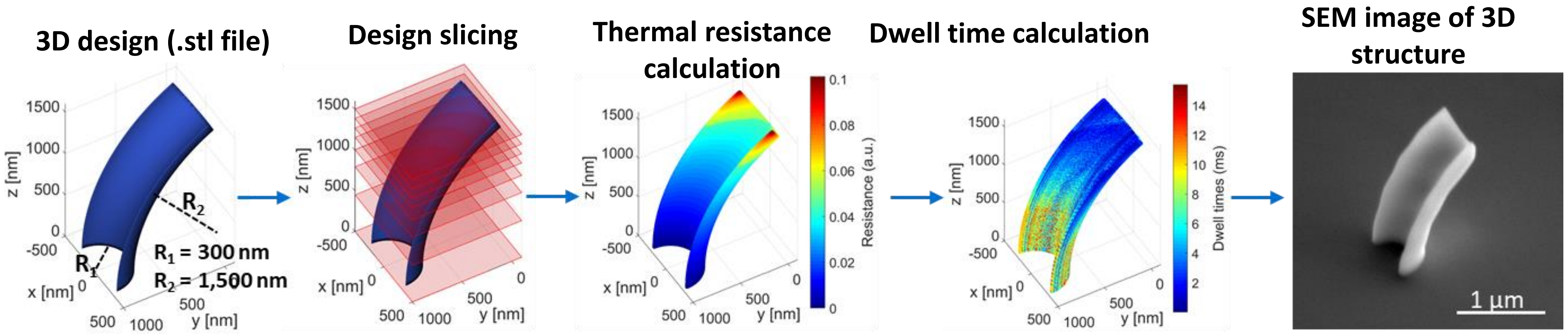


[Skoric et al, Nano Lett. 20, 184 (2020)]

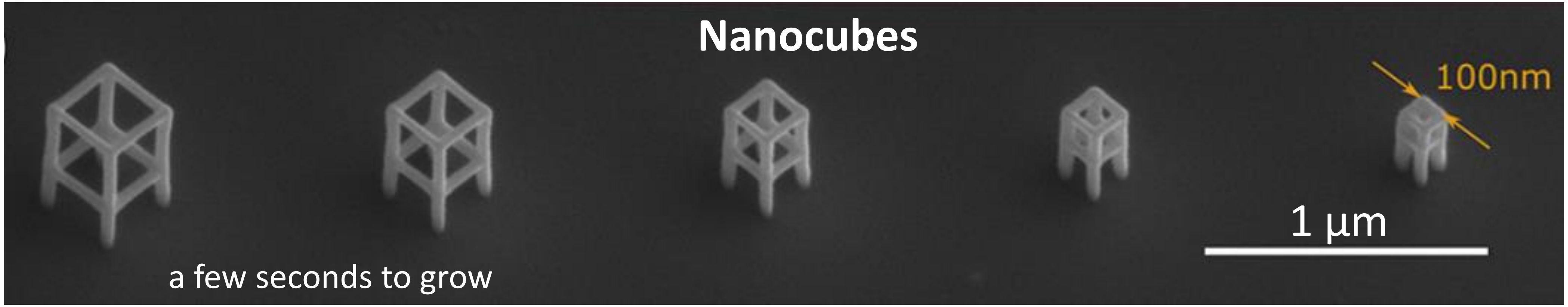
Algorithm & computational program successfully tested:

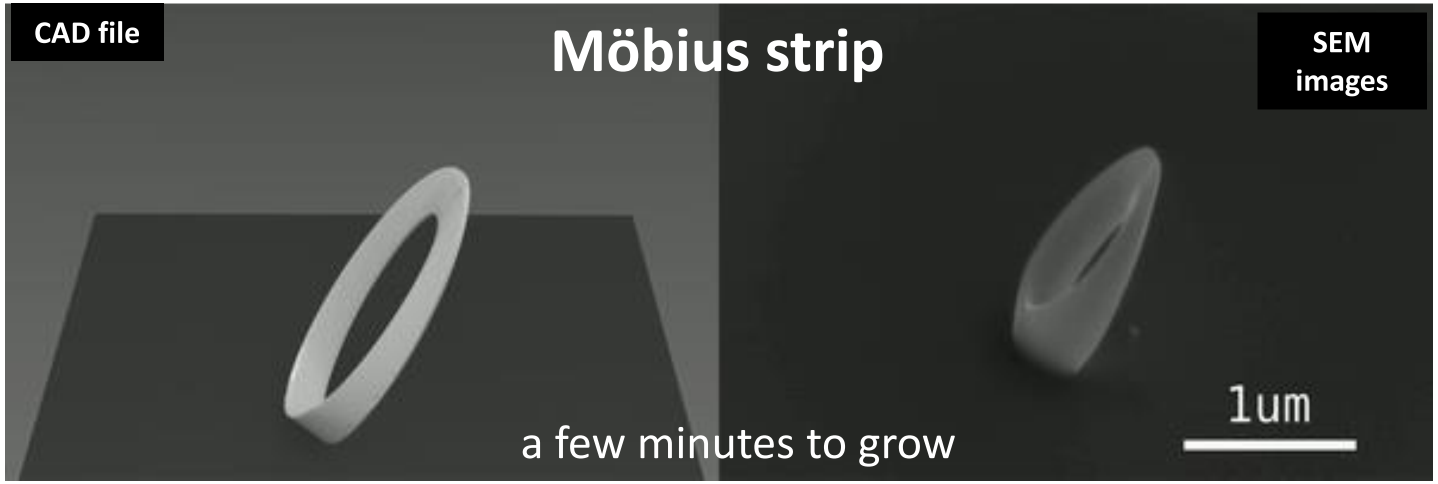
- **For a range of 3D complex geometries with features down to hundreds of nm**
- **Two precursors**
- **Five different microscopes**

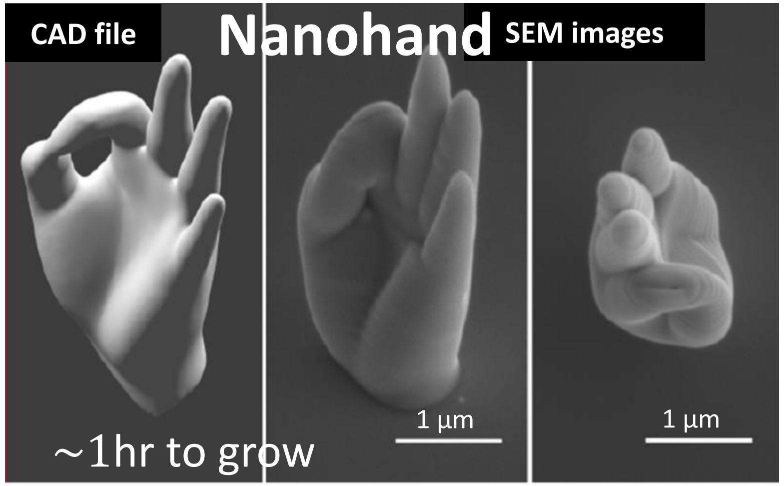




Ultra-advanced 3D nano-printing process



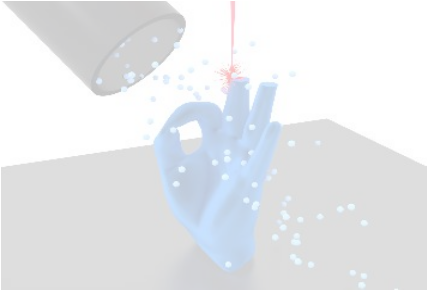




Resolution of ≈ 100 nm for complex 3D geometries & ≈ 40nm for those based on single nanowires

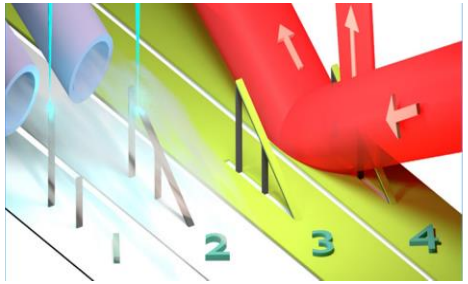
[Skoric et al, Nano Lett. 20, 184 (2020)]

Outline



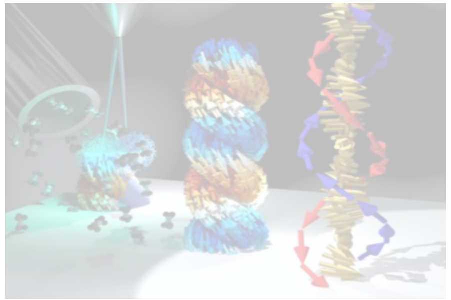
3D printing of nanomagnets

- Layer-by-layer growth of complex shaped 3D nanostructures



3D magnetic nano-circuits

- Dark-Field Magneto-Optical Kerr effect
- Magnetoelectrical effects in a 3D geometry

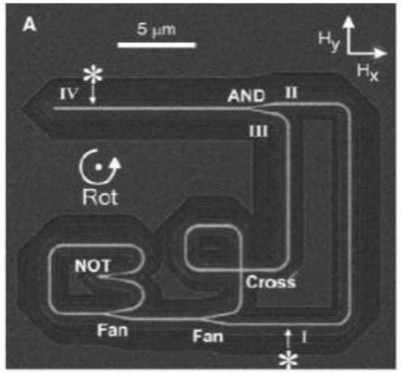


Strongly interacting chiral nanostructures

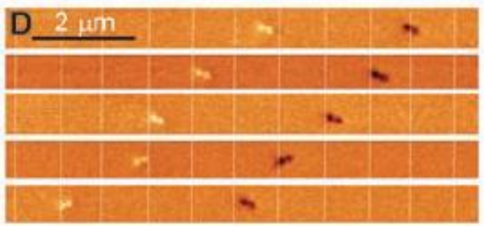
- Imprinting of chiral spin textures & topological defects
- Creation of magnetic stray fields with topological features

Magnetic nanowire devices

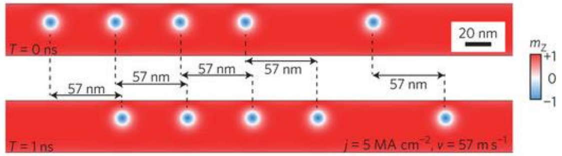
2D devices



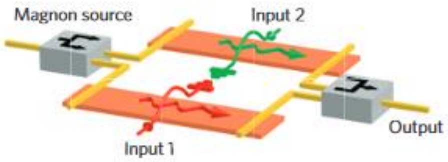
[Allwood et al, Science 309, 1688 (2005)]



[Parkin et al Science 320, 190 (2008)]

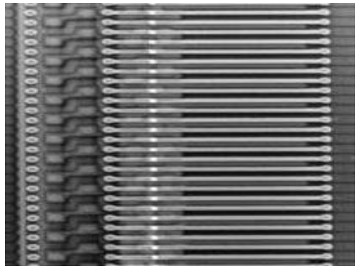


[Fert et al, Nature Nano 8, 152 (2013)]



[Chumak et al, Nature Phys. 11, 453 (2015)]

2D nanowire devices already realised in the lab: motion of domain walls, skyrmions, spin waves



2D racetrack prototype

IBM

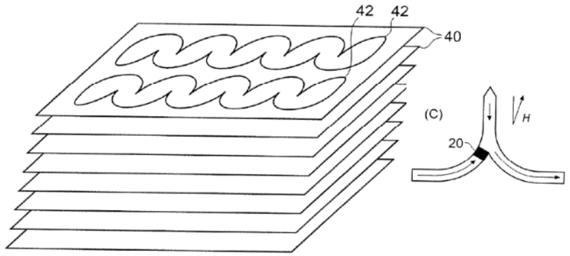
[Annunziata, Electron Devices Meet. (IEDM), IEEE Int. (2011)]

novotechnik

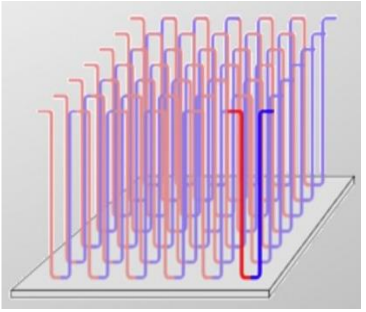
Siedle Group http://www.novotechnik.de

A memory prototype & a commercial sensor already exist

3D devices



[Cowburn et al. US 2007/0047156 A1]

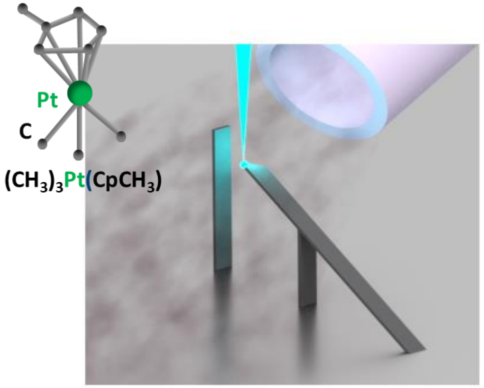


[Parkin et al. Science 320, 190 (2008)]

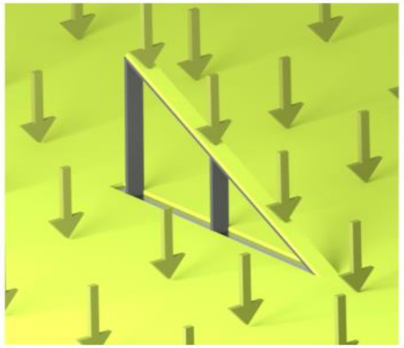
Proposed, but great barriers ahead

First steps towards 3D nanowire devices

Nanofabrication

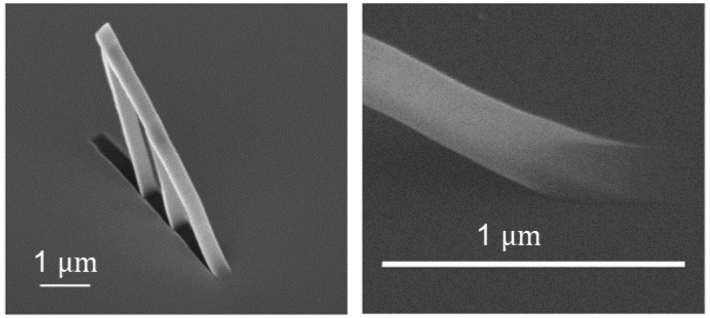


Step 1: 3D nano-printing of non-magnetic scaffold



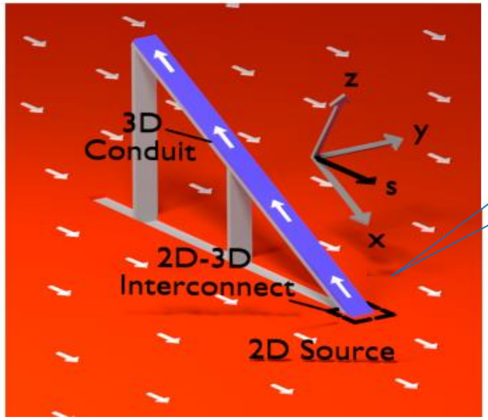
Step 2: Evaporation of ferromagnetic thin film

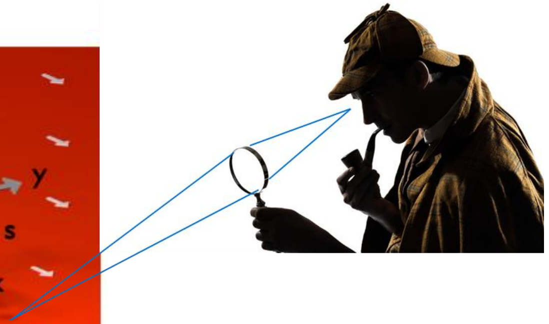
Hybrid method for nanofabrication: FEBID + PVD



[Sanz-Hernández, AFP et al, Nanomaterials 8, 483 (2018)]

Characterisation

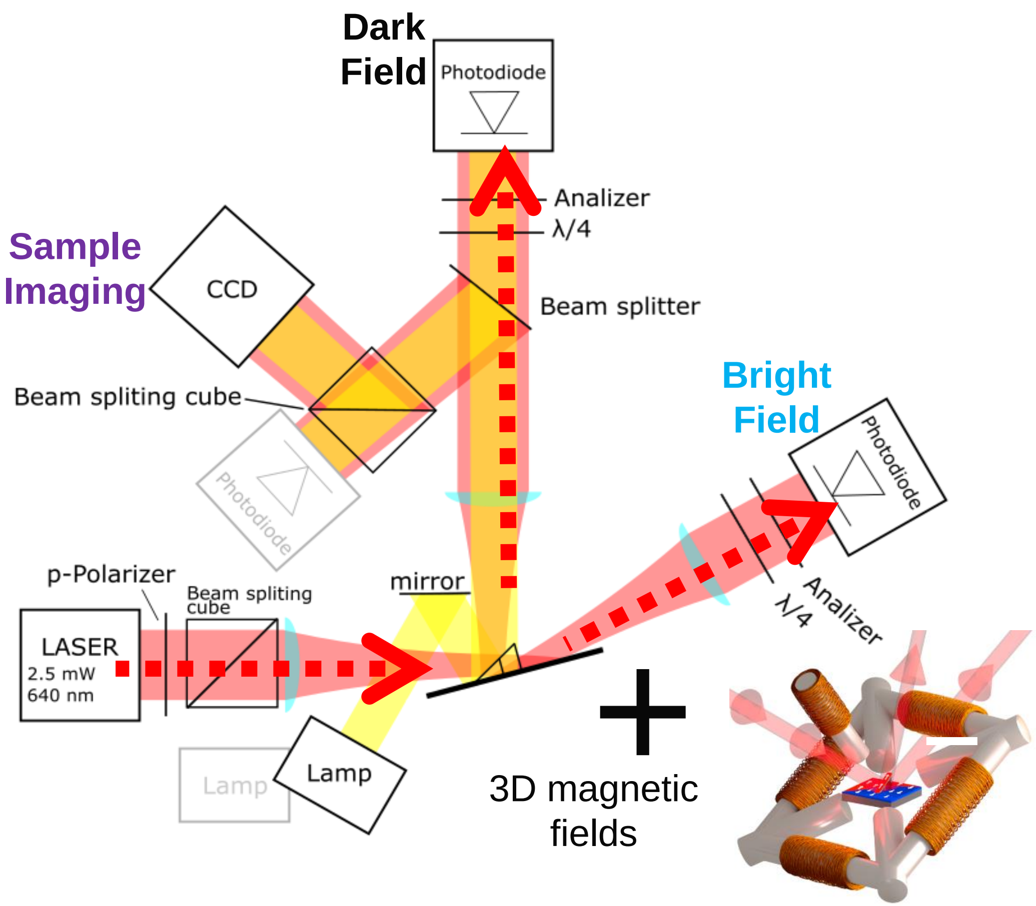


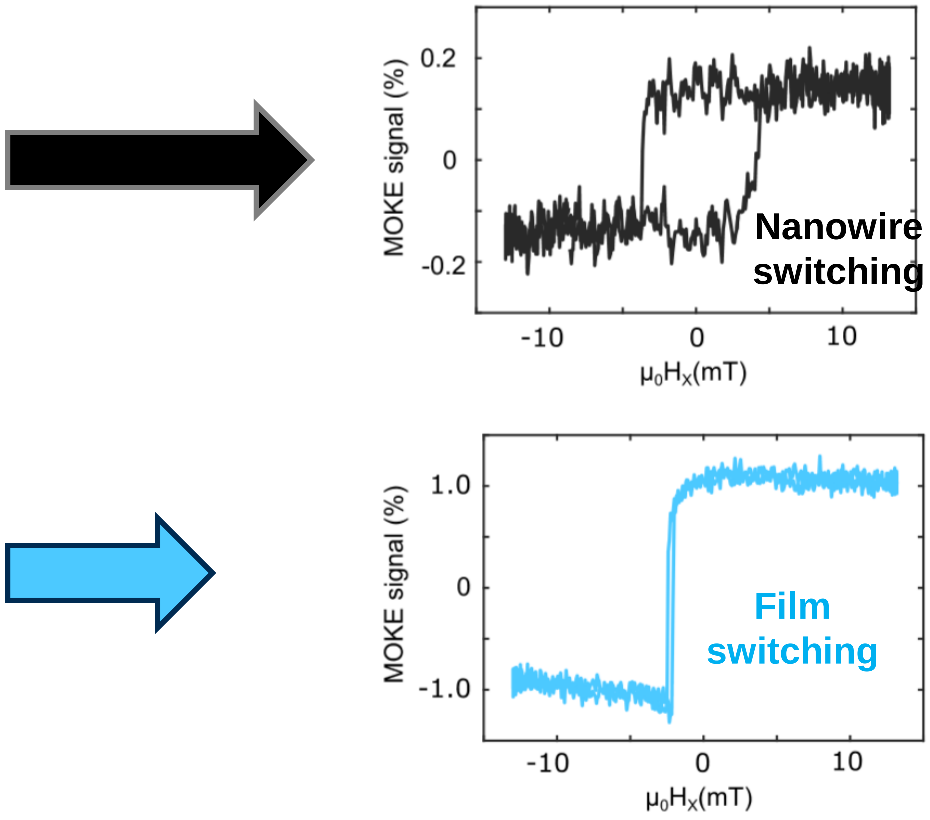


How to probe 3D magnetic interconnectors in the lab?!

The Dark-Field magneto-optical Kerr effect

Dédalo
Sanz-Hernández





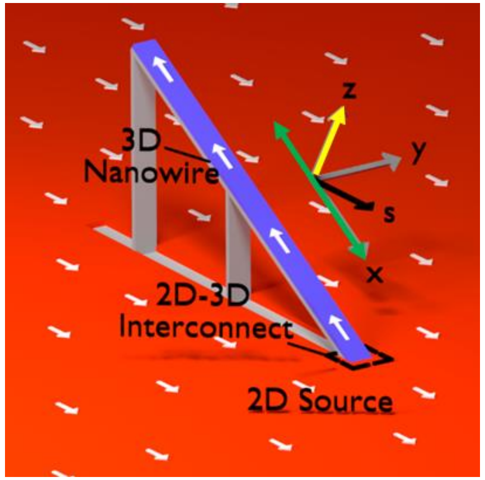
New MOKE technique for 3D nanomagnetism

Independent & simultaneous detection of film and nanowire switching

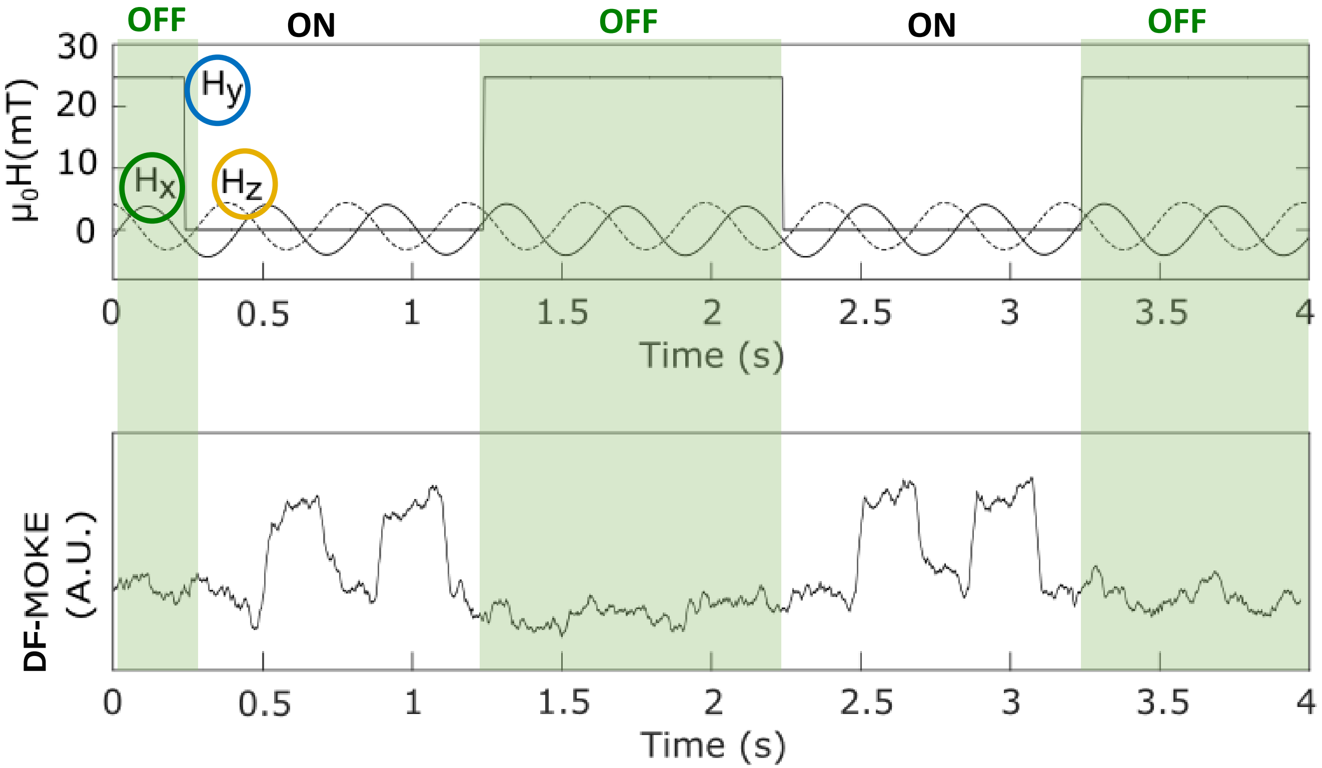
[Sanz-Hernández, AFP et al, ACS Nano 1, 11066 (2017)]

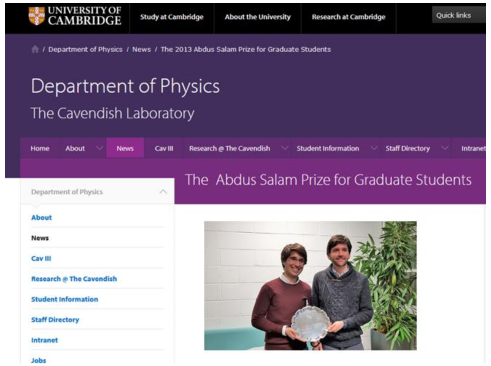
Domain wall 3D motion: injection + trapping

H_x : propagating field
H_z: biasing field
H_y : gating field



3D DW injection experiment under vector magnetic fields





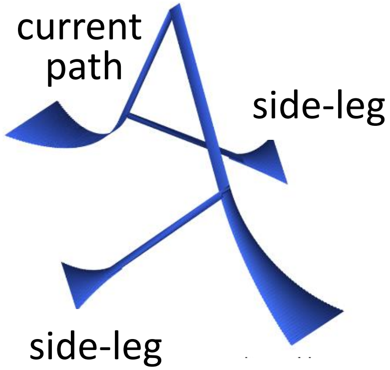
Abdus Salam award 2017/18 for best PhD work at the Cavendish Lab in Cambridge

First experimental controlled domain wall injection into a 3D nanowire circuit

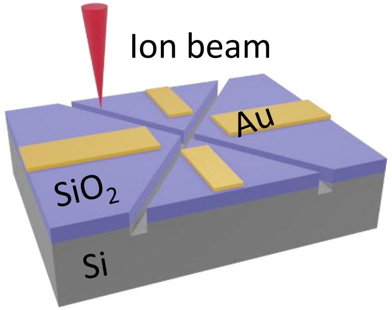
[Sanz-Hernández, AFP et al, ACS Nano 1, 11066 (2017)]

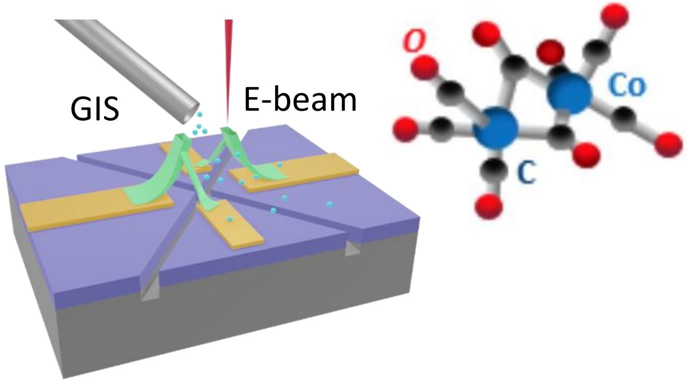
Magneto-electrical properties of 3D nanomagnetic circuits

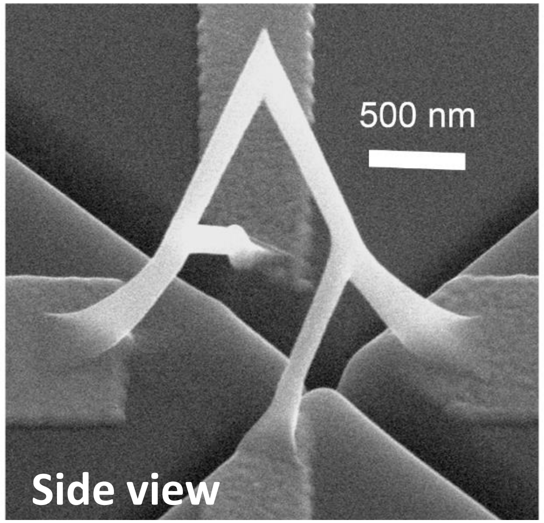
CAD model

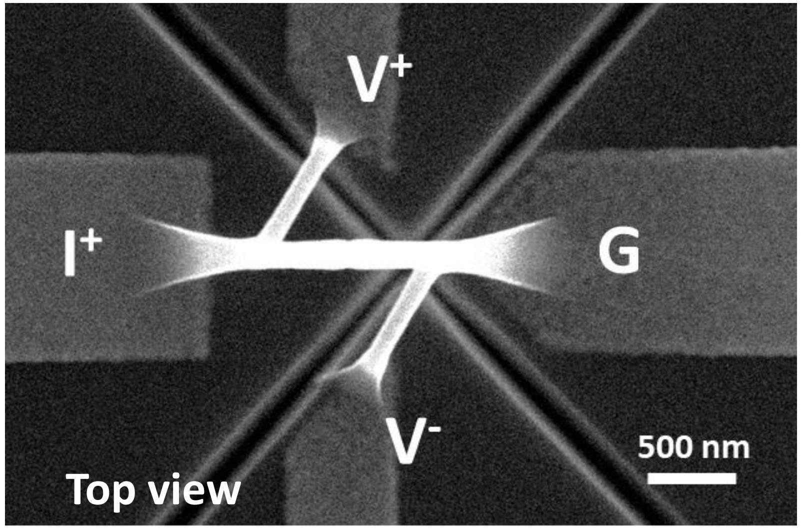


Pre-patterned contacts









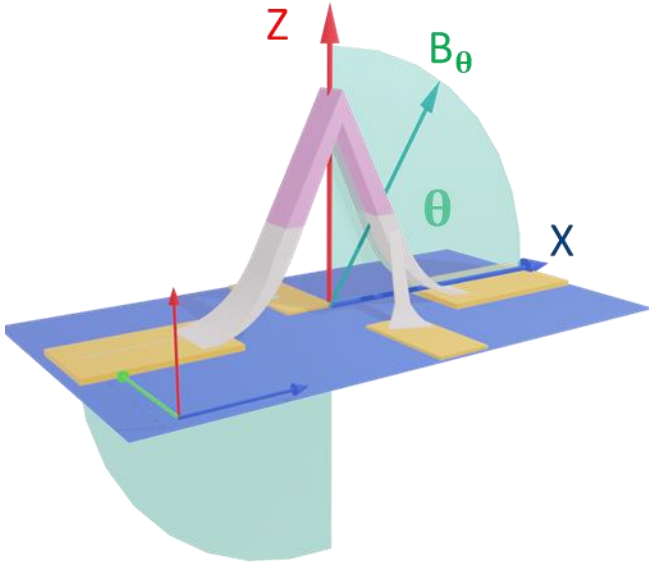
Fanfan Meng

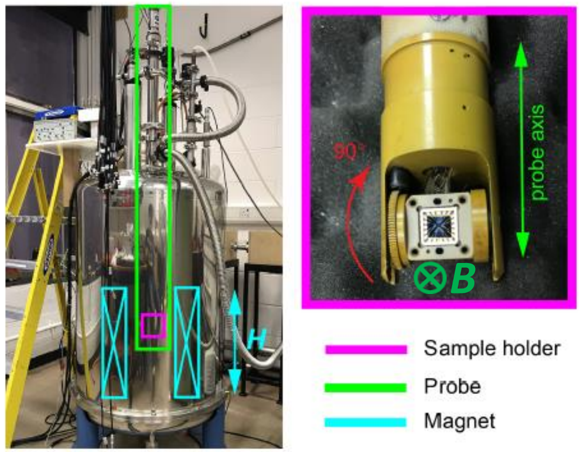
Claire Donnelly

Integration of a 3D cobalt bridge in a microelectronic circuit: study of 3D magnetoelectrical effects

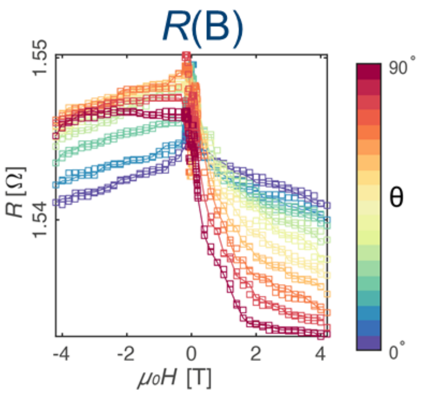
[Meng, AFP et al, ACS Nano 15, 6765 (2021)]

Hall effect & Magnetoresistance contributions





3D current and magnetization → superposition of different magnetoelectrical effects



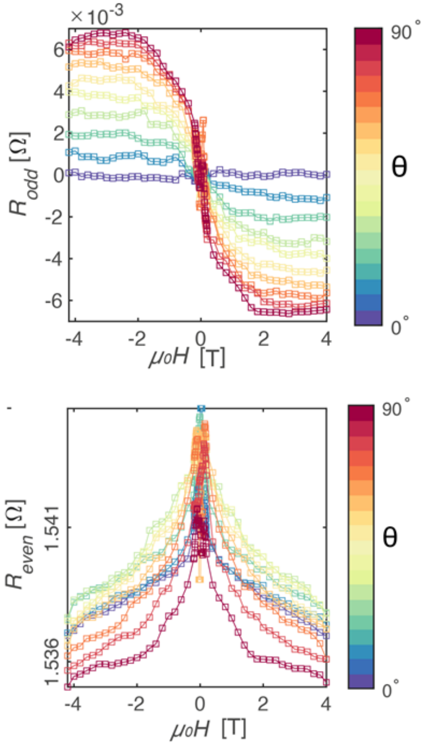
Raw data

$$R_{odd} = \frac{[R(\mathrm{B}) - R(-\mathrm{B})]}{2}$$

Hall effects

$$R_{even} = \frac{[R(\mathrm{B}) + R(-\mathrm{B})]}{2}$$

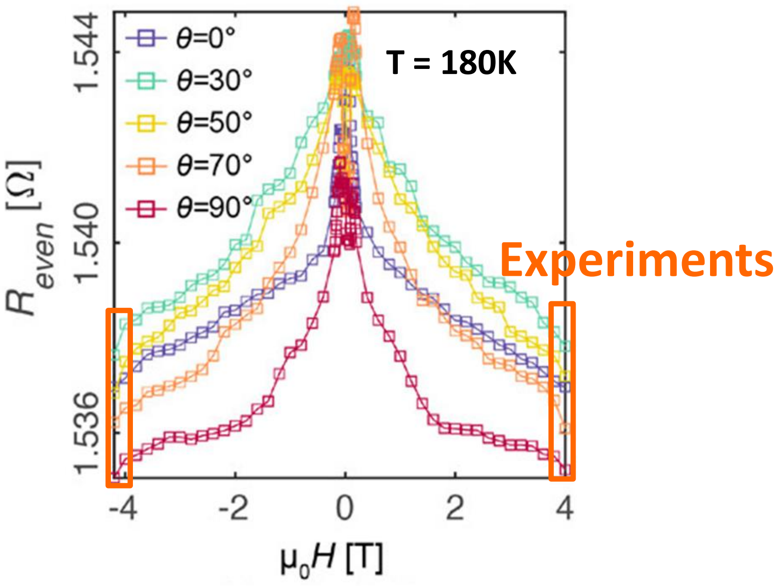
magnetoresistances

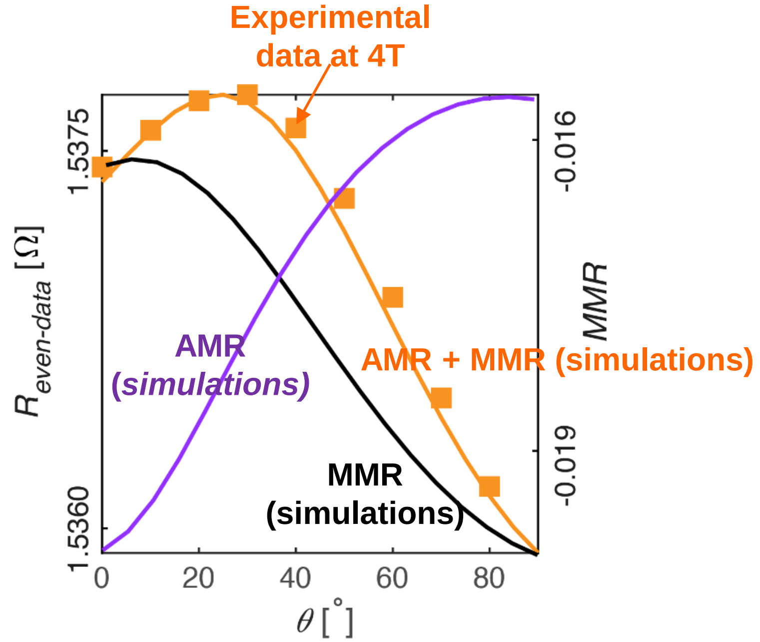


Separation of odd & even contributions

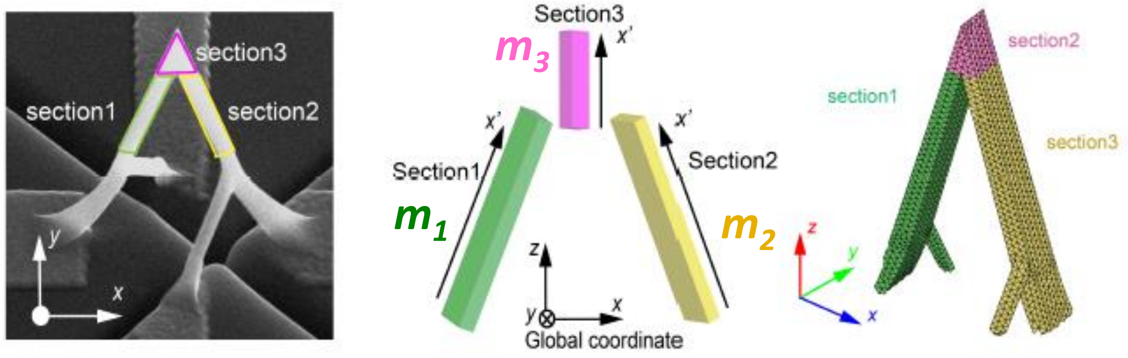
[Meng, AFP et al, ACS Nano 15, 6765 (2021)]

Magnetoresistance in a 3D nano-bridge at high fields





Simulations: non-interacting multi-macrospin model



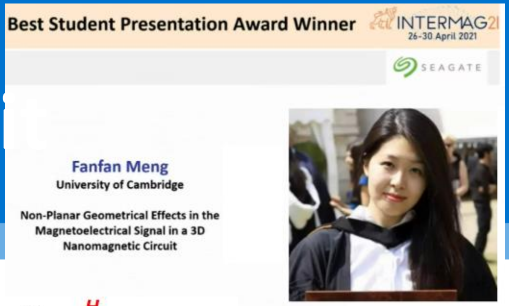
Large contribution of magnon magnetoresistance to total signal

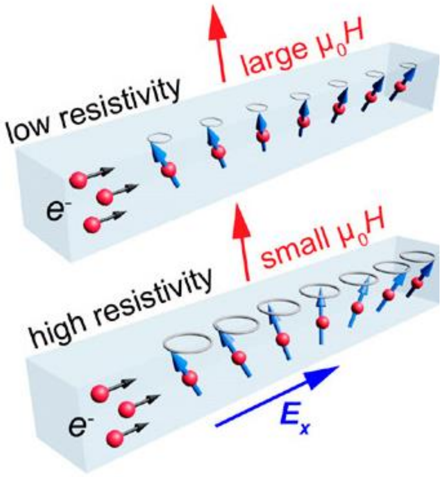
[Nguyen et al, Appl. Phys. Lett. 99, 262504 (2011)]

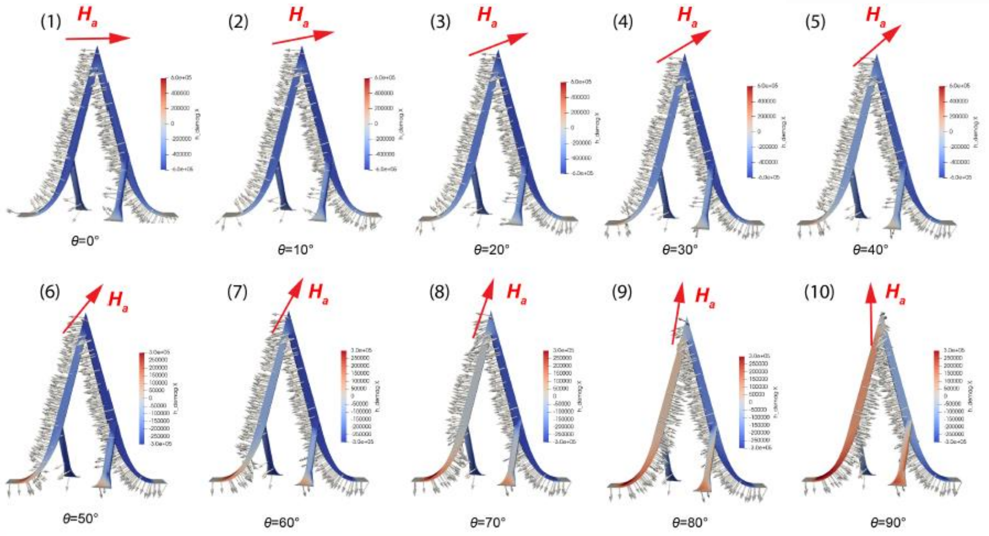
& non-trivial angular dependence

[Meng, AFP et al, ACS Nano 15, 6765 (2021)]

Effect of demagnetising field in 3D nanomagnetic circui

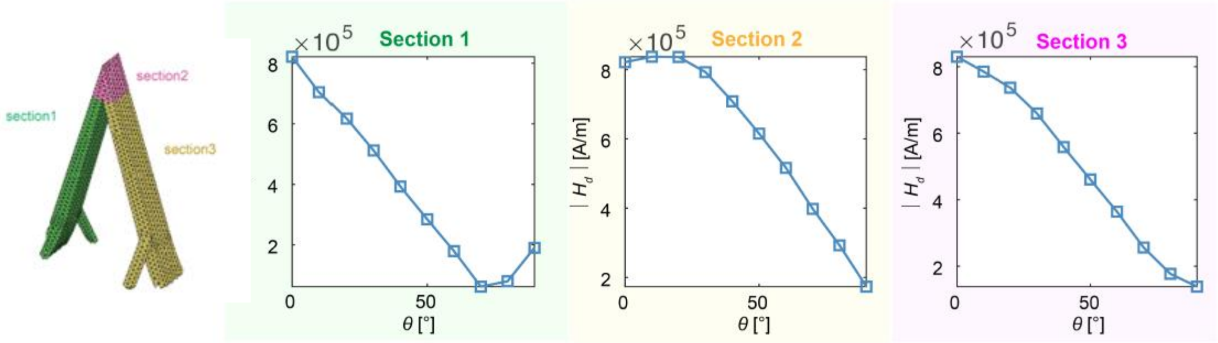






$$\Delta\rho_{MMR}(T, B_{eff}) \propto \frac{B_{eff}T}{D(T)^2}\ln\left(\frac{\mu_B B_{eff}}{k_B T}\right)$$

[Raquet et al., Phys Rev. B. 66, 024433 (2002)]



$$B_{eff} = \underbrace{\mu_0(M_s + H_a}_{\text{total induction}} + \underbrace{H_d}_{\text{demagnetizing field}})$$

total induction

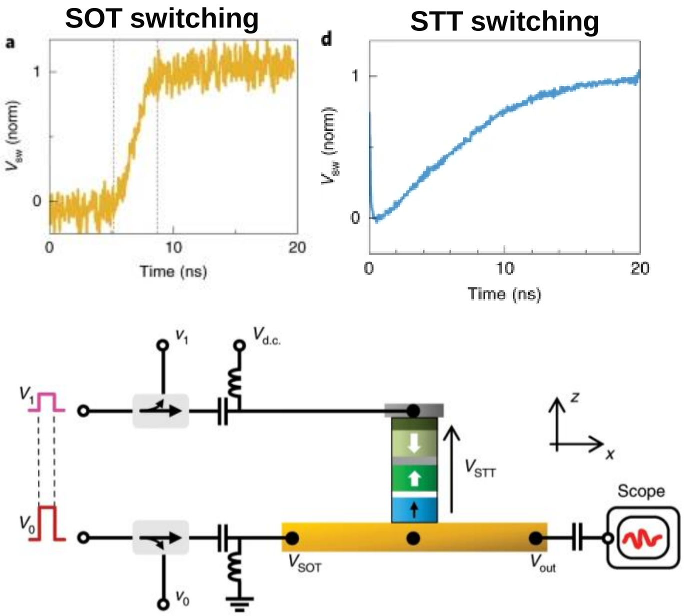
demagnetizing field

Non-trivial demagnetizing field in 3D geometry leads to complex angular dependence of MR

[Meng, AFP et al, ACS Nano 15, 6765 (2021)]

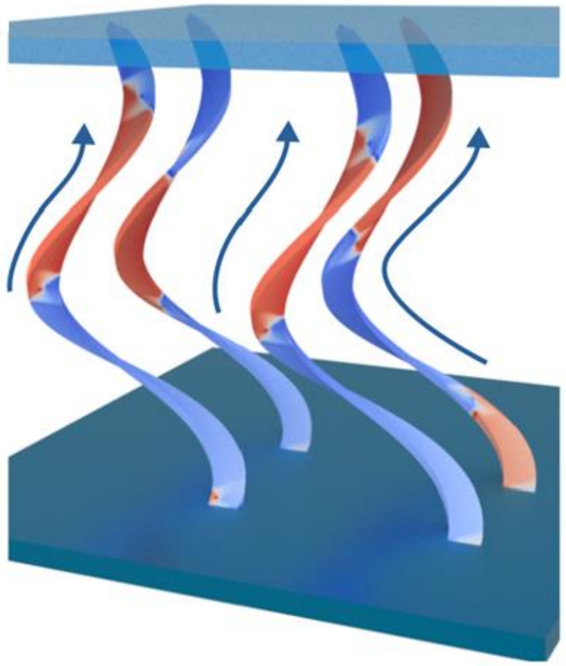
Transmission of magnetic information between functional planes

Standard way to move spin textures in magnetic interconnectors or switch magnetisation:
magnetic fields, spin transfer-torque, spin orbit torque…
→ Problems faced with this approach: low heat dissipation, multiple spin-to-charge conversion
[Park et al, IEEE J. Solid-State Circuits 50, 204213 (2015)]



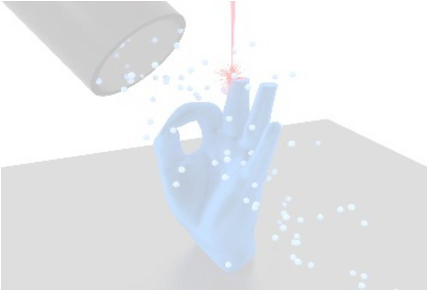
[Grimaldi et al, Nature Nature Nano 15, 111(2020)]

New proposal: Exploit geometrical effects for 3D automotion of magnetic information



[Skoric, AFP et al, arXiv:2110.04636 (2020)]

Outline

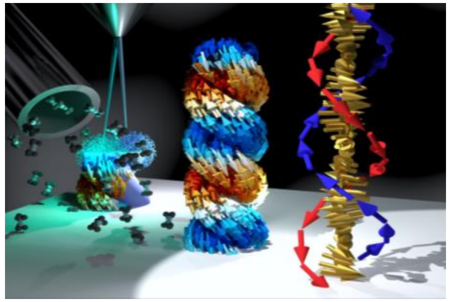


3D printing of nanomagnets

- Layer-by-layer growth of complex shaped 3D nanostructures

3D magnetic nano-circuits

- Dark-Field Magneto-Optical Kerr effect
- Magnetoelectrical effects in a 3D geometry

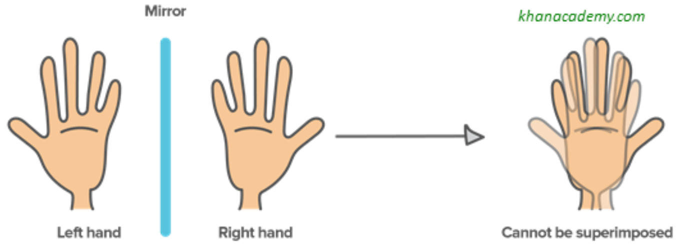


Strongly interacting chiral nanostructures

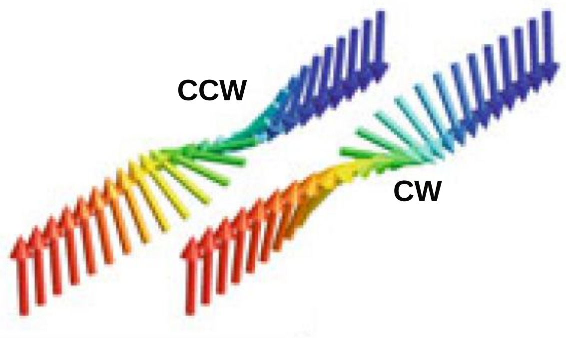
- Imprinting of chiral spin textures & topological defects
- Creation of magnetic stray fields with topological features

Chirality & magnetism

Chirality or handedness refers to the property structures that cannot be superimposed on their mirror image"
[Kelvin (1904), Larmor (1900) , Eddington (1946)]
Onmipresent in nature, e.g. DNA, molecules (flavour, toxicity, drug efficiency)…



Chiral magnetism

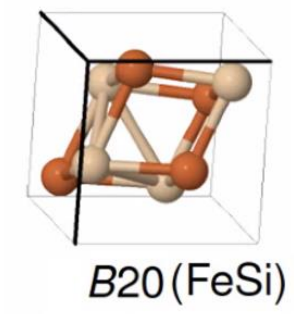


In general, magnetic textures are not chiral or both chiralities are degenerate in energy

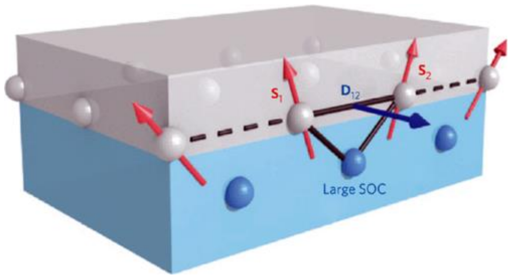
Symmetry breaking + Spin-orbit coupling = Emergence of antisymmetric exchange (Dzyaloshinskii–Moriya interaction: DMI)

[Moriya et al, Phys. Rev. 120, 91 (1960)]

$$H^{DM} = -\mathbf{D}_{ij}\,(\mathbf{S}_i \times \mathbf{S}_j)$$



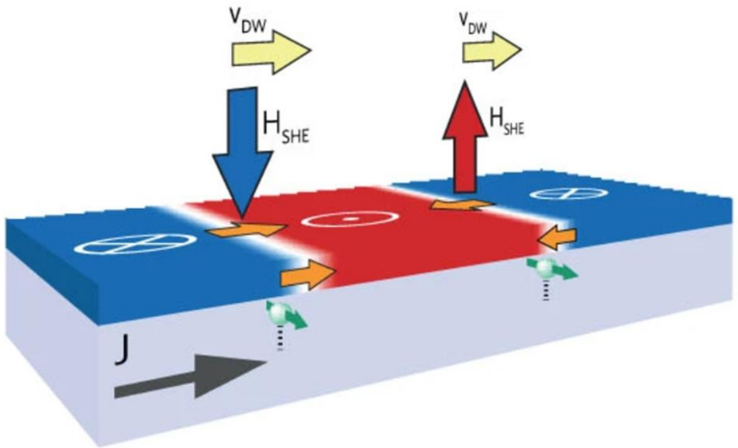
Non-centro symmetric crystal



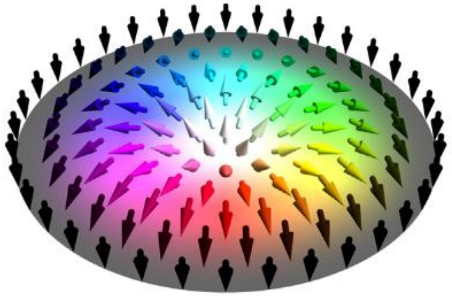
DMI interaction in thin magnetic layer interfaced with a heavy metal

Chiral magnetism for spintronics

Magnetic chirality: key concept of modern spintronics

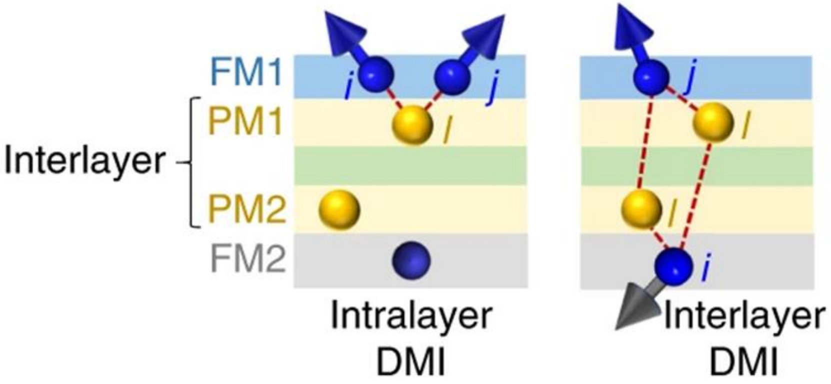


Unidirectional motion of domain walls in racetrack memory at low current
[Parkin et al, Nature Nano (2015)]



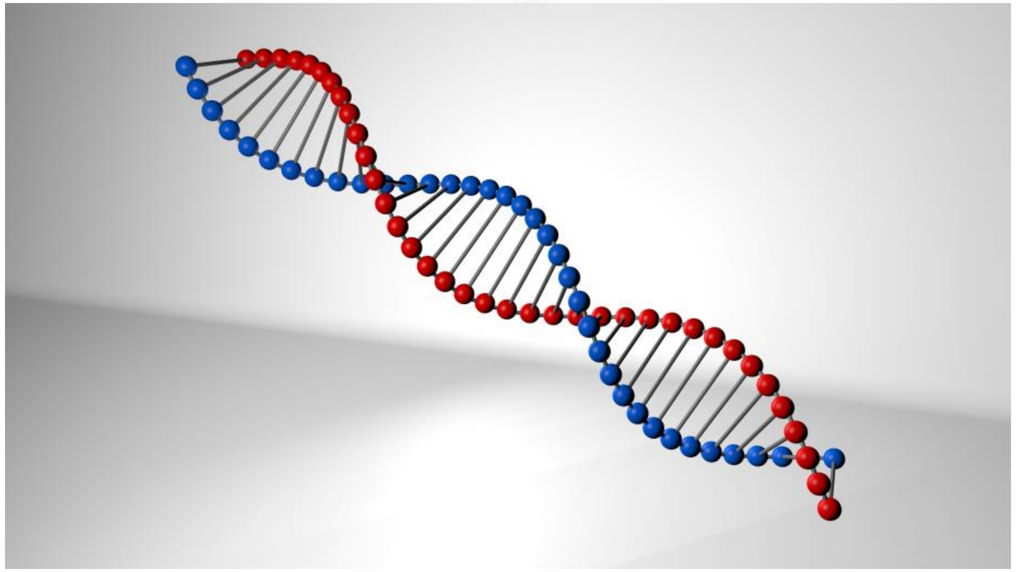
Formation of non-trivial topological spin textures e.g. skyrmion
[Göbel et al, Phys. Reports 895, 1 (2021)]

Long range chiral interactions reported experimentally for the first time

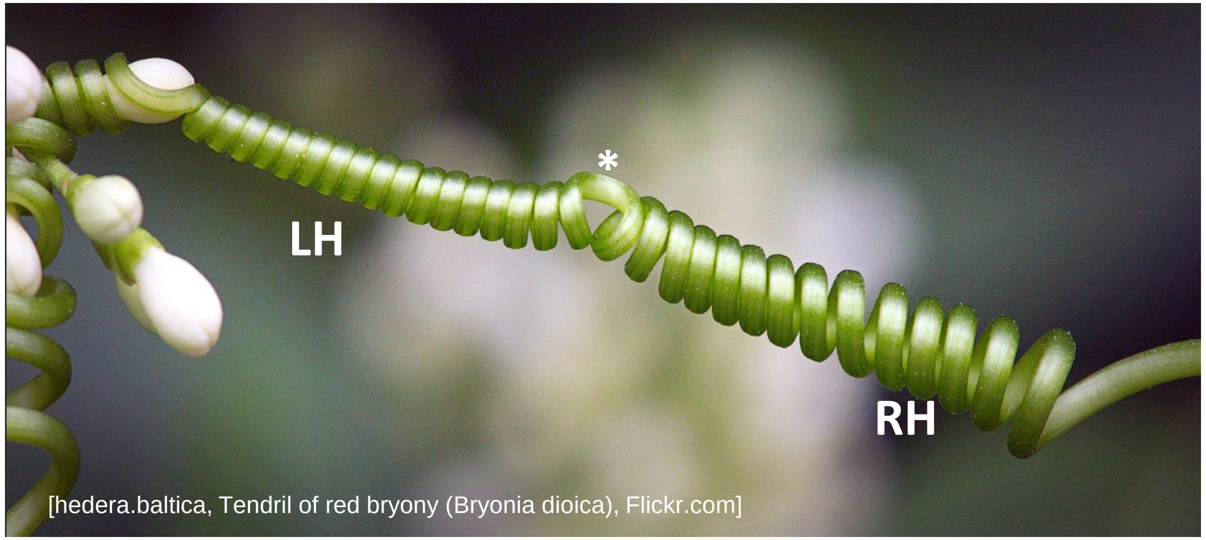


[AFP et al, Nature Materials 18, 679–684 (2019)
Han et al, Nature Materials 18, 703–708 (2019)]

Chirality in nature: helical geometries



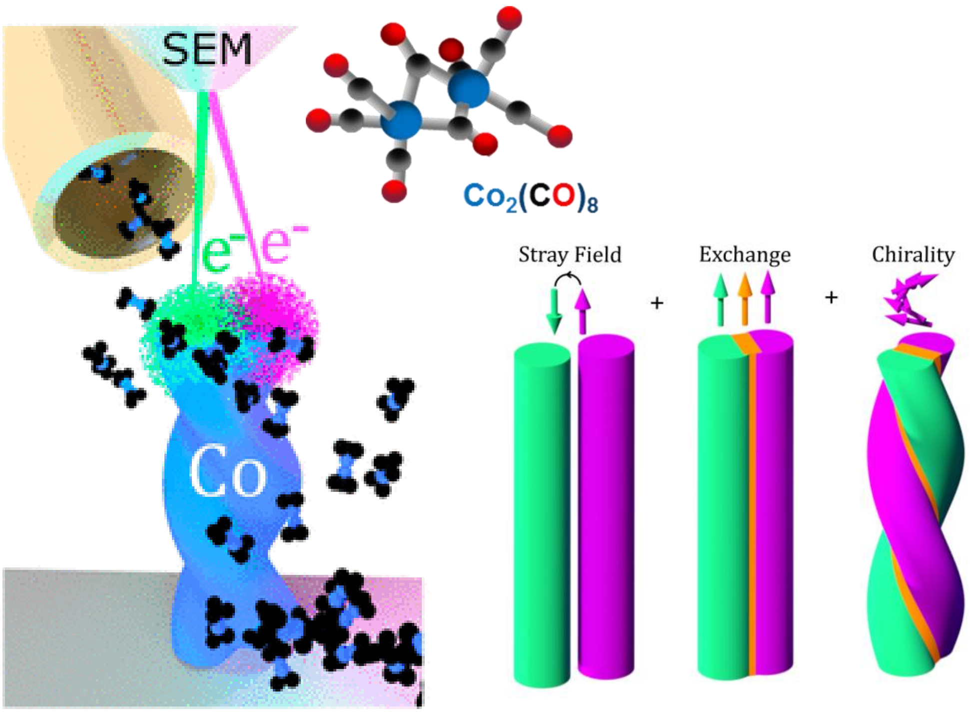
Double strand structure in DNA



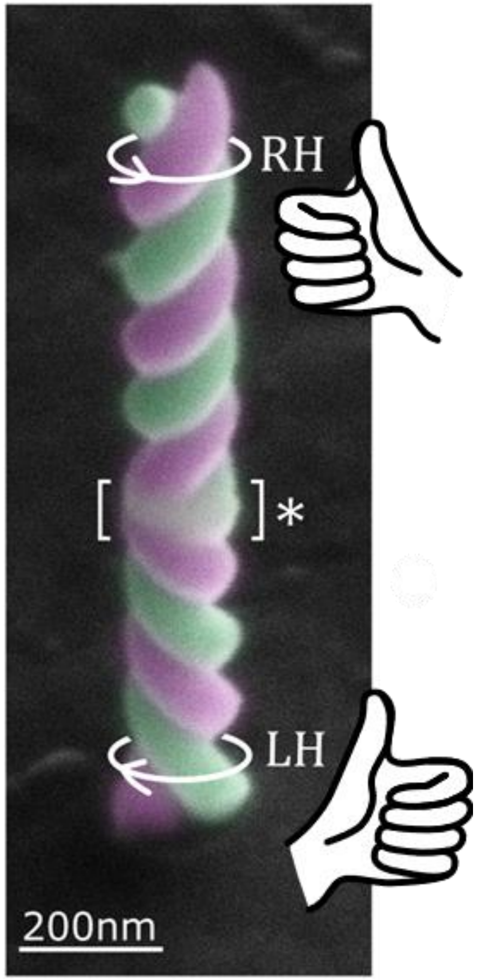
Reversal of chirality via a topological defect (tendril perversion)

Magnetic double nano-helix grown by FEBID

[Sanz-Hernández, AFP et al, ACS Nano 14, 8084 (2020)]



Tendril perversion

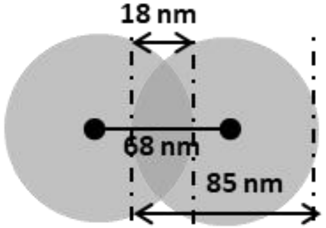


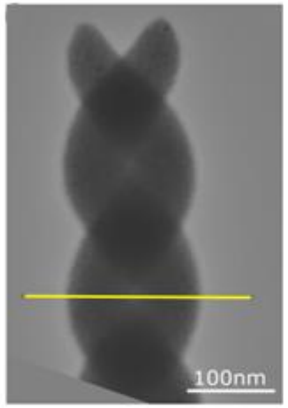
Coloured SEM image

Dédalo Sanz-Hernández

Aurelio Hierro Rodríguez

Claire Donnelly

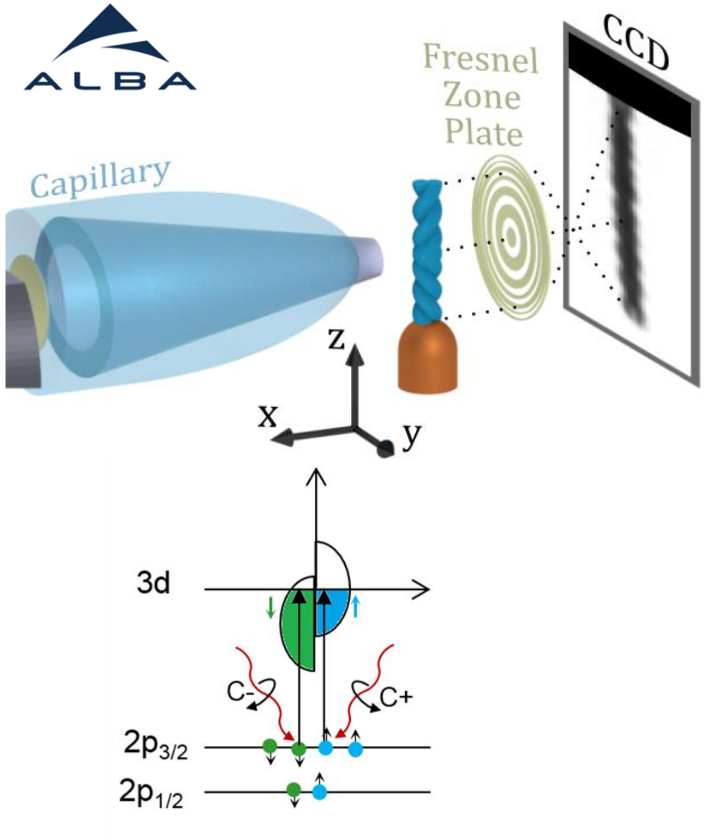




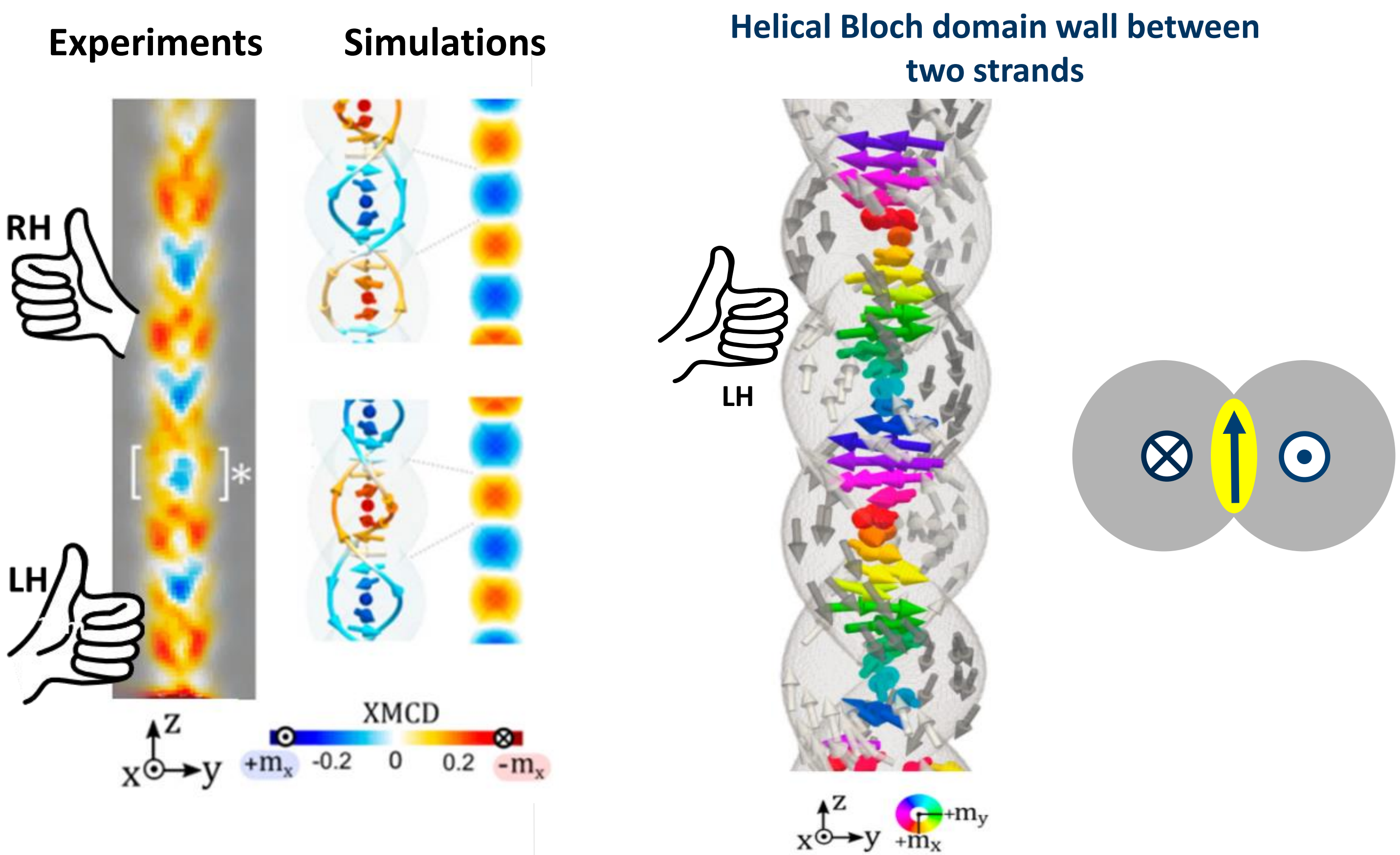
TEM image

Magnetic double nano-helix grown by FEBID with overlapping strands & variable chirality along space via tendril perversion

Imaging of inter-strand domain walls in double helices



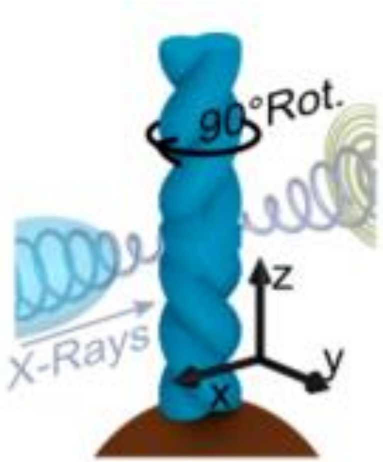
Soft X-ray transmission magnetic microscopy exploiting XMCD at ≈ 30 nm resolution



Antiparallel magnetic state between strands leads to chiral Bloch domain wall between them

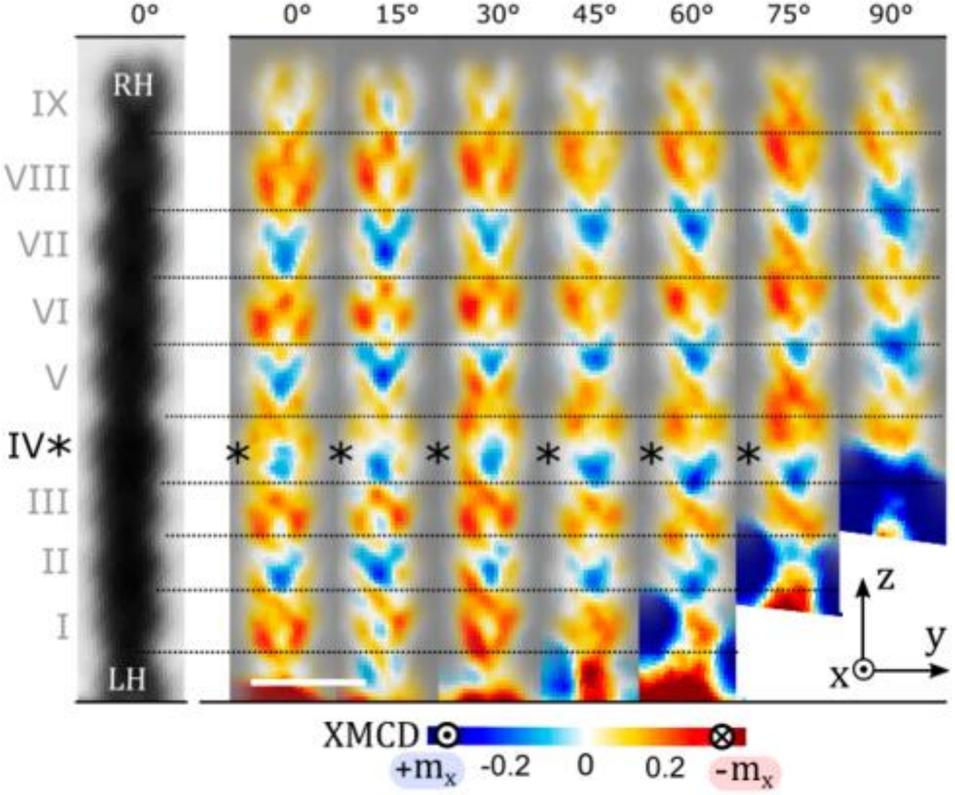
[Sanz-Hernández, AFP et al, ACS Nano 14, 8084 (2020)]

Imaging magnetic state of perversion at multiple angles

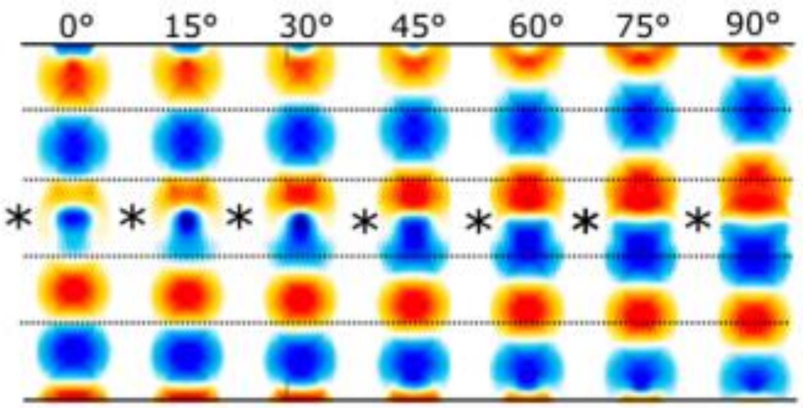


Magnetic imaging at different rotating angles

Experiments



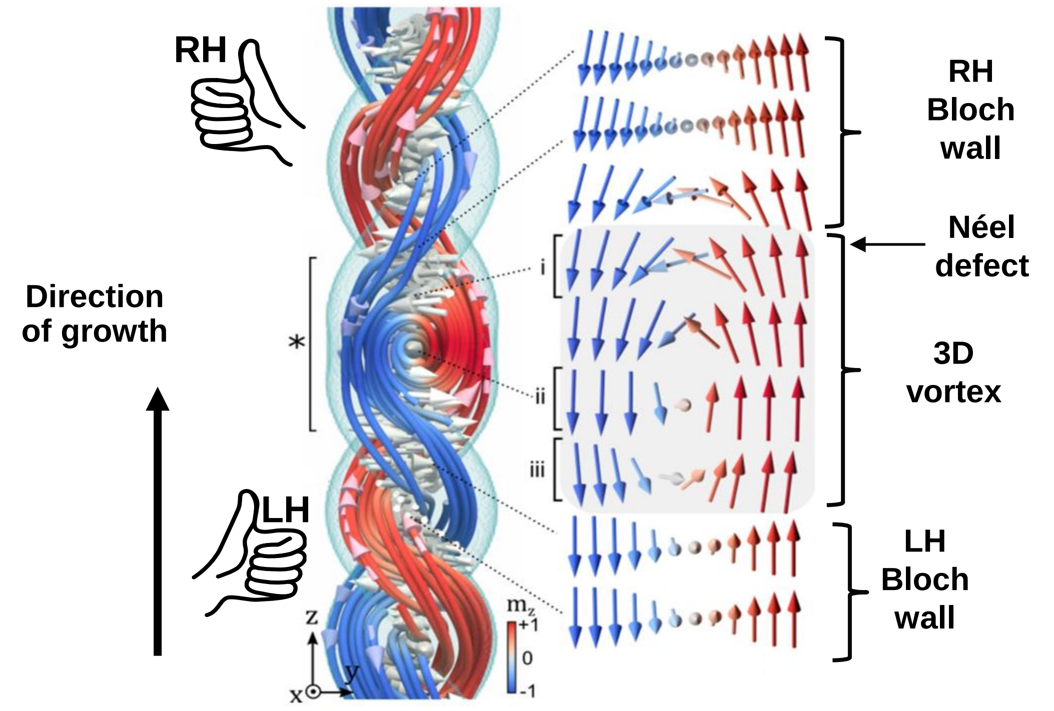
Simulations



Agreement between experiments & simulations: what magnetic state is present at the perversion?

[Sanz-Hernández, AFP et al, ACS Nano 14, 8084 (2020)]

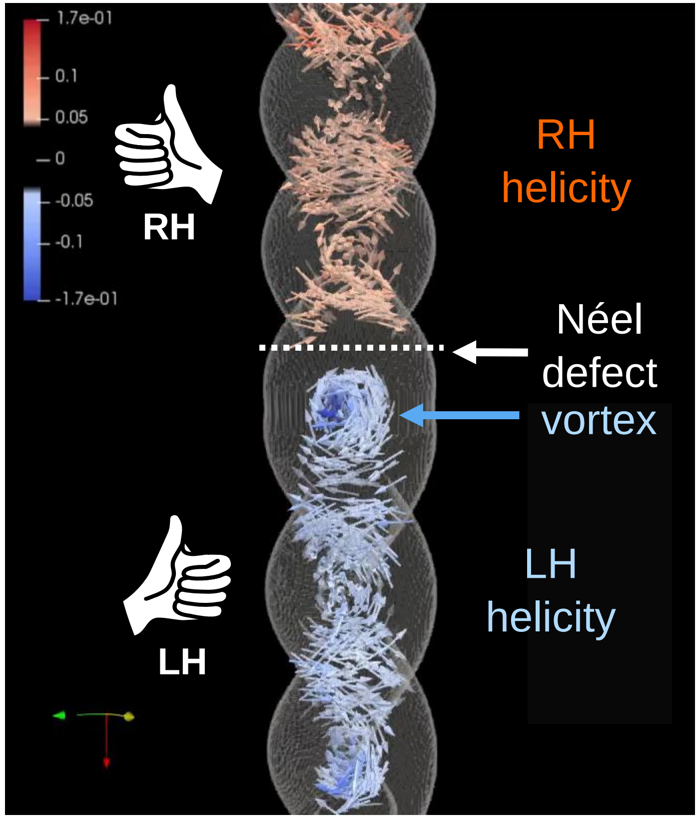
Imprinting of chiral spin textures & topological defects



3D asymmetric vortex formed at the chirality interface

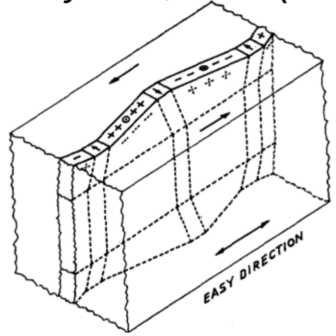
Geometrical chirality controls the magnetic chirality of the Bloch domain wall

Visualization of magnetic helicity = $\vec{m} \cdot (\nabla \times \vec{m})$



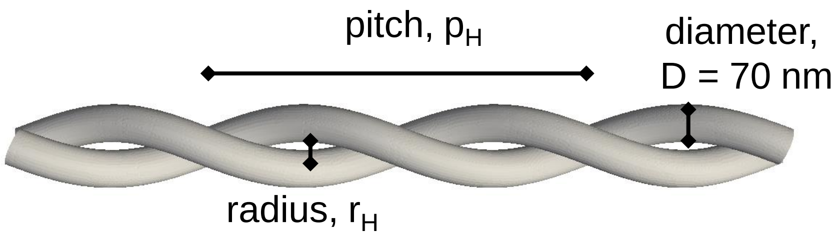
Néel defect at the upper part of the vortex to match opposite chirality of the two helices

Analogous to Néel lines interfacing Bloch walls of opposite chirality in crystals *[Shtrikman et al, J. Appl. Phys. 31, 1304 (1960)]*

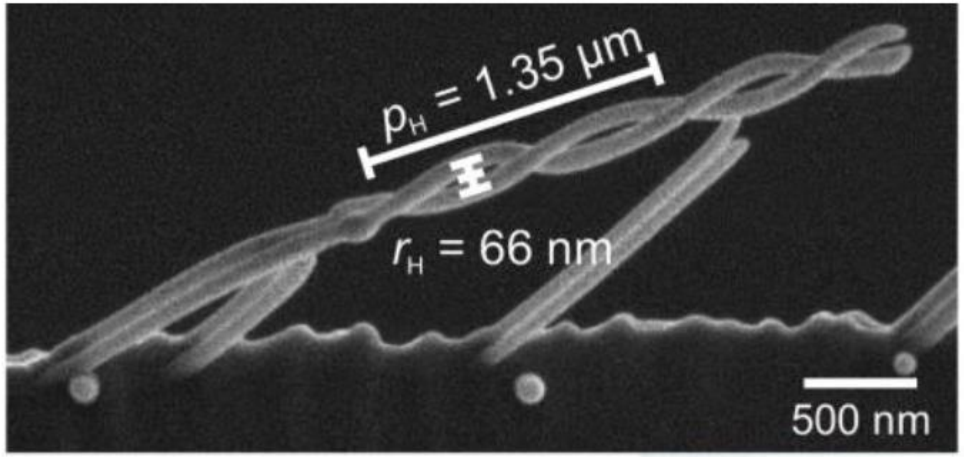


[Sanz-Hernández, AFP et al, ACS Nano 14, 8084 (2020)]

Double helix nanostructures with non-overlapped strands

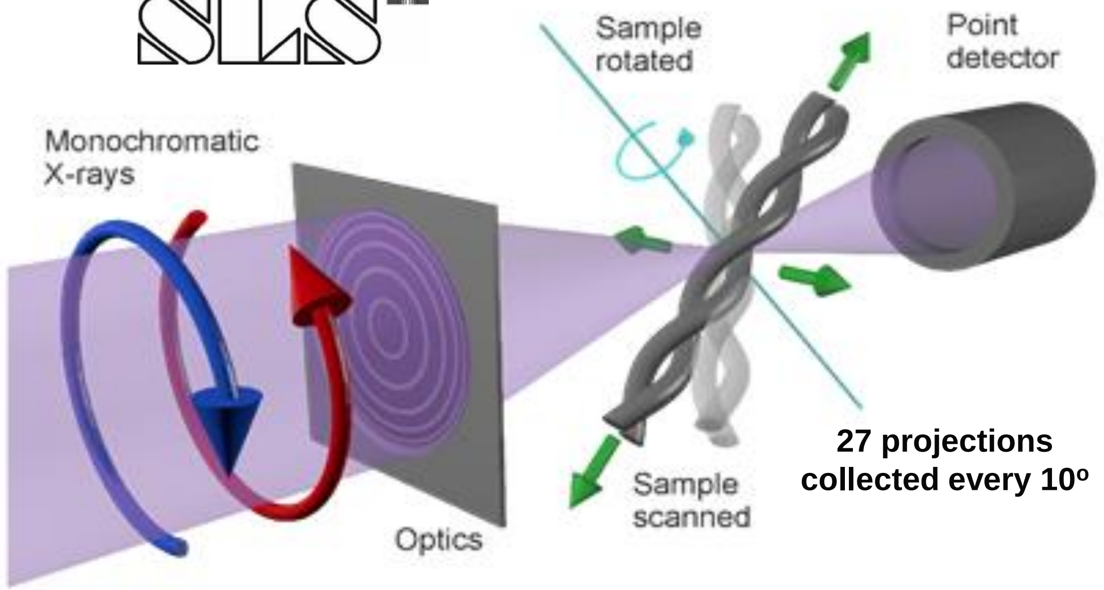


CAD design for 3D nano-printing



SEM image of one double helix structure

SWISS LIGHT SOURCE SLS



27 projections collected every 10º

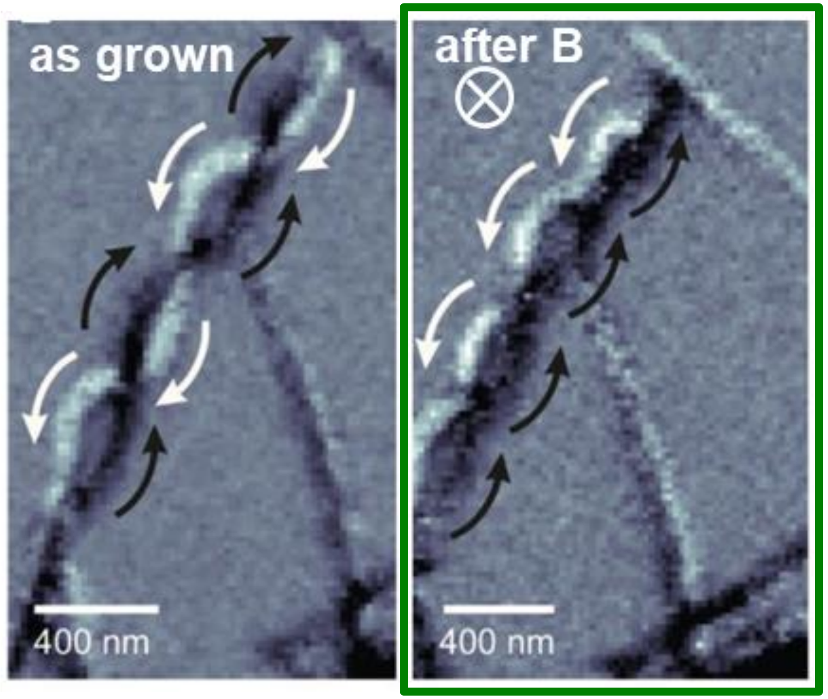
[Witte et al, Nano Lett. 20, 1305 (2020)]

Claire Donnelly

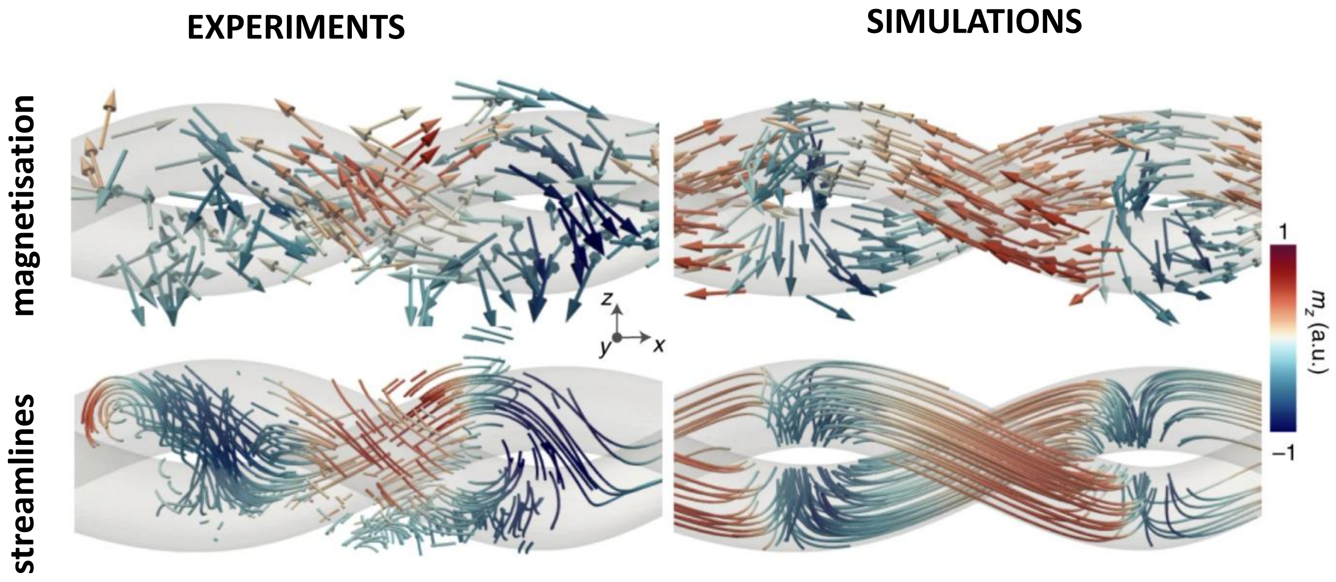
Tomographic laminography using scanning transmission X-ray magnetic microscopy (STXM)

[Donnelly, AFP et al, Nature Nanotechnology (2021), https://doi.org/10.1038/s41565-021-01027-7]

Formation of strongly coupled “locked” domain walls



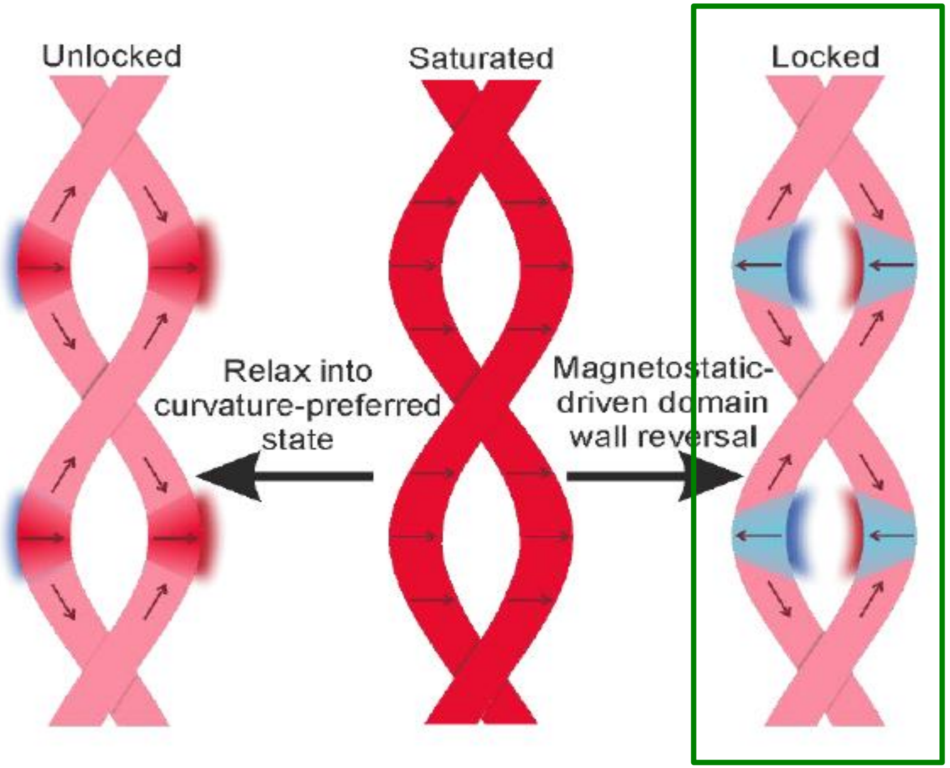
X-ray microscopy measurements at zero field for one projection



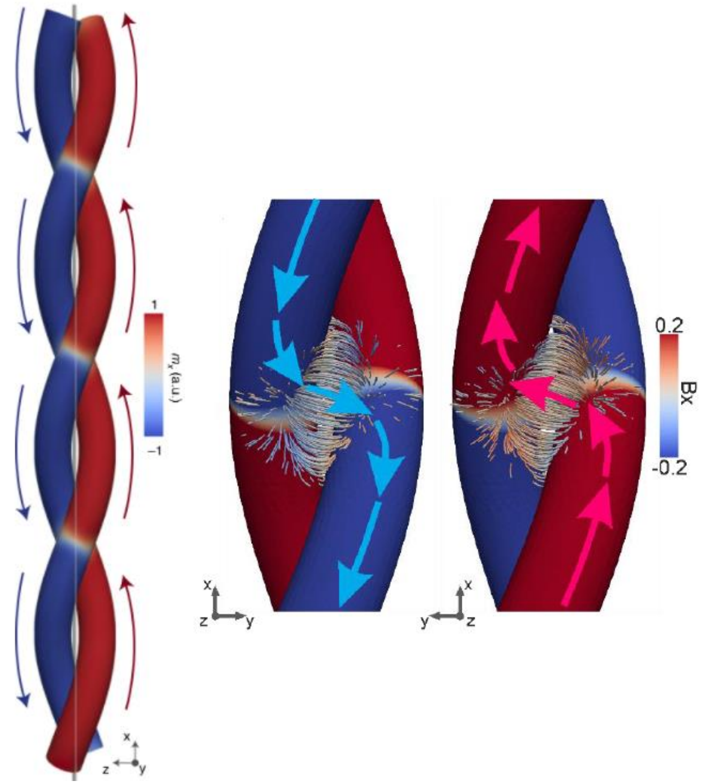
3D reconstruction of magnetisation vector: “Locked” domain wall pairs dominated by strong magnetostatic interactions

[Donnelly, AFP et al, Nature Nanotechnology (2021), https://doi.org/10.1038/s41565-021-01027-7]

Locked domain walls via strong inter-strand magnetostatic interaction



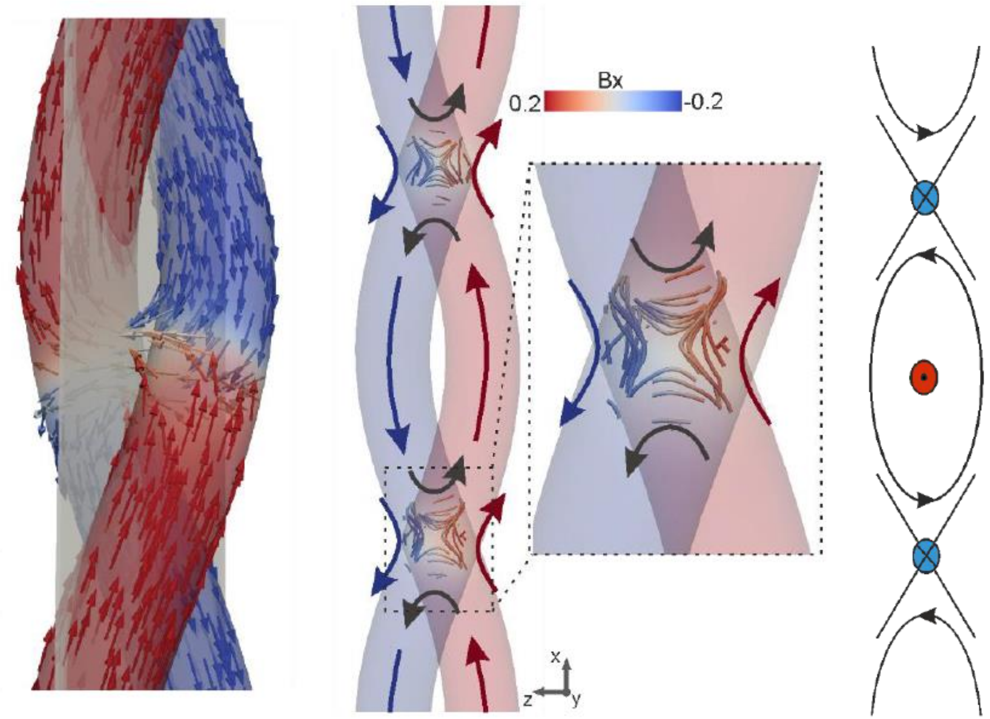
Inter-strand magnetostatic interactions between domain walls leads to locked state



Pairs of head-to-head/tail-to-tail domain walls in chiral geometry: channelling of stray field

[Donnelly, AFP et al, Nature Nanotechnology (2021), https://doi.org/10.1038/s41565-021-01027-7]

Locked wall pairs lead to nanoscale stray fields with topological features



$$w_{b^1} = \frac{1}{2\pi}\int_{-L/2}^{+L/2} ds\, \partial_s \varphi = -1$$

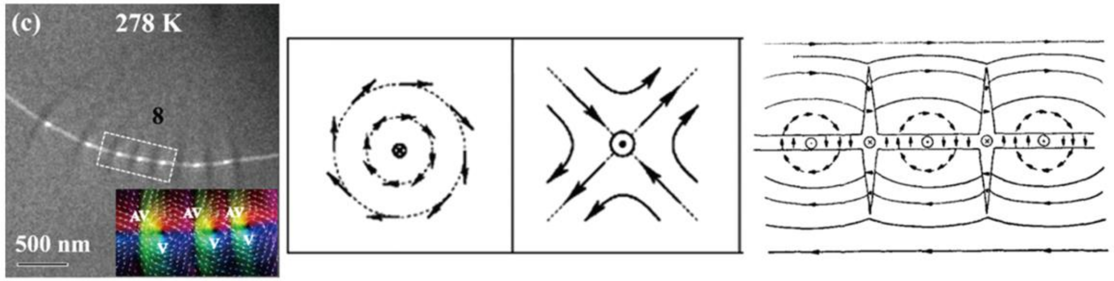
$\mathit{with}\ \mathbf{b} = (b_x, b_z)$ = *(cos φ(s), sin φ(s)).*

normalised in plane projection

Antivortex formed by free-space magnetic field

- **Vortex of M in the helices**
- **Antivortex of H in the free space**

→ **"Cross-tie"-like wall in B across the whole space**



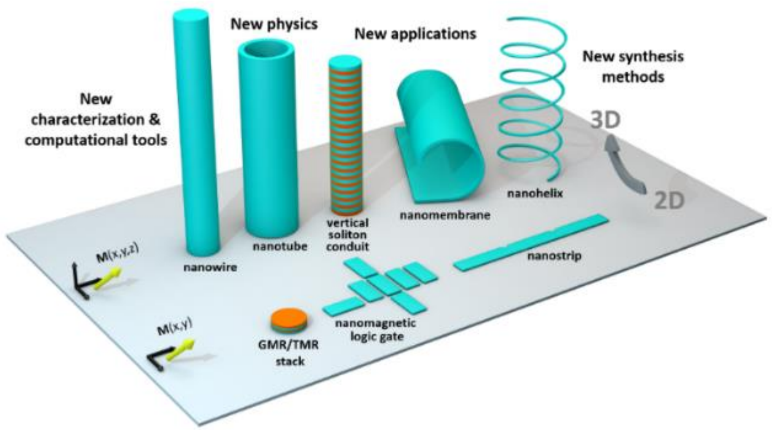
Cross-tie domain wall in M measured by Lorentz microscopy

[Zhang et al. Acta Mater. 140, 465 (2017)]

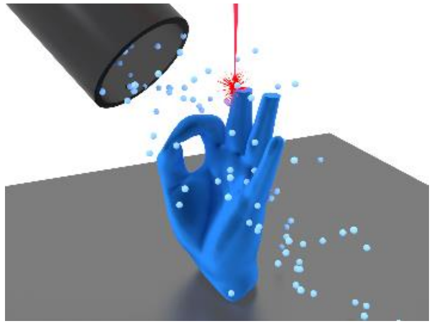
Topological field textures with complex gradients localised at the nanoscale: spin ice, neuromorphic spintronics, magnetic imaging, cold atom trapping….

[Donnelly, AFP et al, Nature Nanotechnology (2021), https://doi.org/10.1038/s41565-021-01027-7]

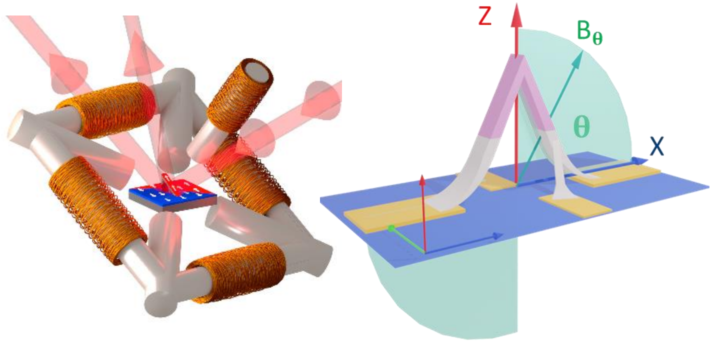
Conclusions & outlook



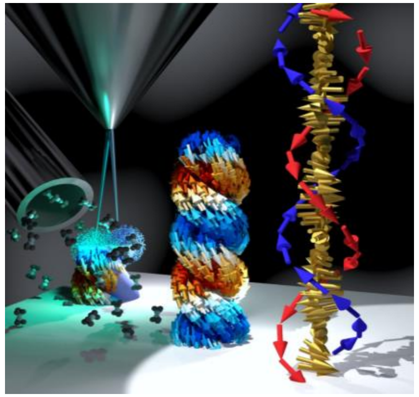
3D spintronics:
Emerging field with exciting new phenomena to explore & great potential for future technologies



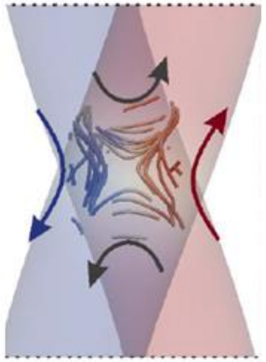
3D nano-printing:
New framework for the fabrication of arbitrary geometries



3D magnetic interconnectors:
Magneto-optic & magneto-electric effects in 3D geometries



Geometrical control of magnetic chirality: Imprinting of chiral spin textures & topological defects



3D geometries & topological B fields: 3D nanopatterning to control *M* (material) and *H* (free space)

3DNANOMAG
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amaliofp@unizar.es

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Thank you. Questions?

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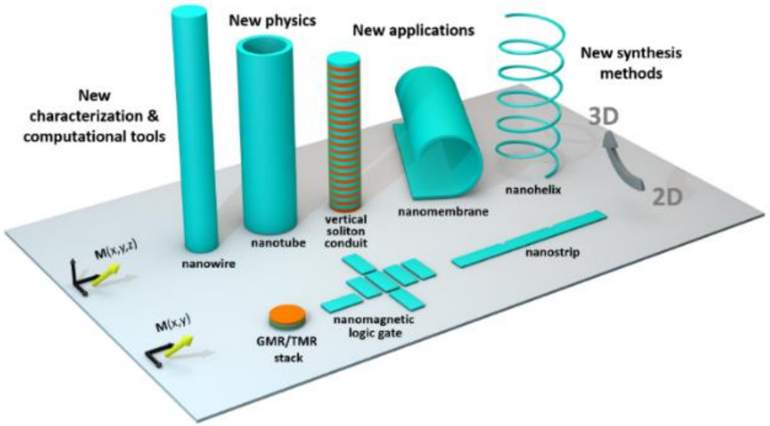
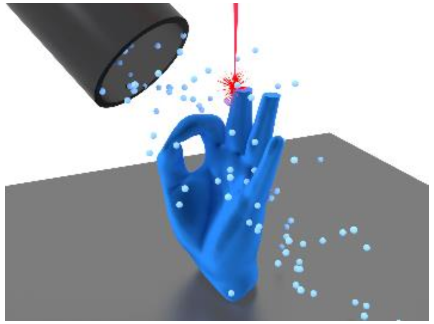


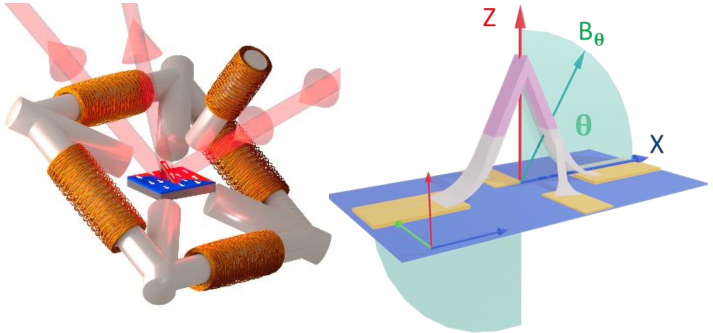
3D spintronics:
"Faster, higher, stronger… together"

Recent reviews:

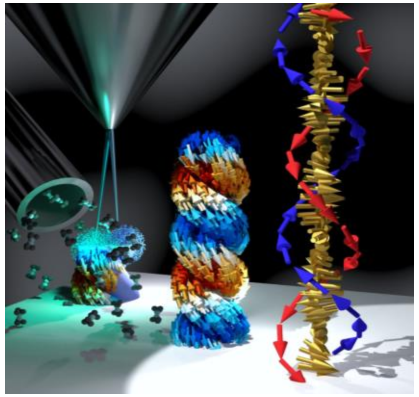
Streubel et al, J. Phys. D Appl. Phys. 49, 363001 (2016)
Hertel, J. Phys. Cond. Mat. 28, 483002 (2016)
AFP et al, Nature Comm. 8, 15756 (2017)
Staňo et al, Handbook Magn. Mater. 27, 155-267 (2018)
Fischer, AFP et al, APL Materials 8, 010701 (2020)
Streubel et al, J. Appl. Phys. 129, 210902 (2021)
Makarov et al, Adv. Mater. 27, 2101758 (2021)
Sheka, J. Appl. Phys.129, 210902 (2021)



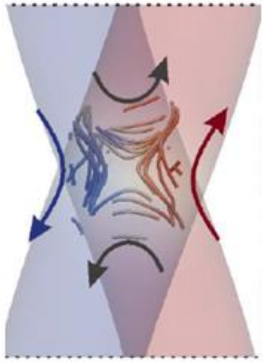
3D nano-printing:
New framework for the fabrication of arbitrary geometries



3D magnetic interconnectors:
Magneto-optic & magneto-electric effects in 3D geometries



Geometrical control of magnetic chirality: **Imprinting of chiral spin textures & topological defects**



3D geometries & topological B fields: **3D nanopatterning to control *M* (material) and *H* (free space)**