Nanomagnetism in 3D
SPICE workshop
Ingelheim, 30/04/2024

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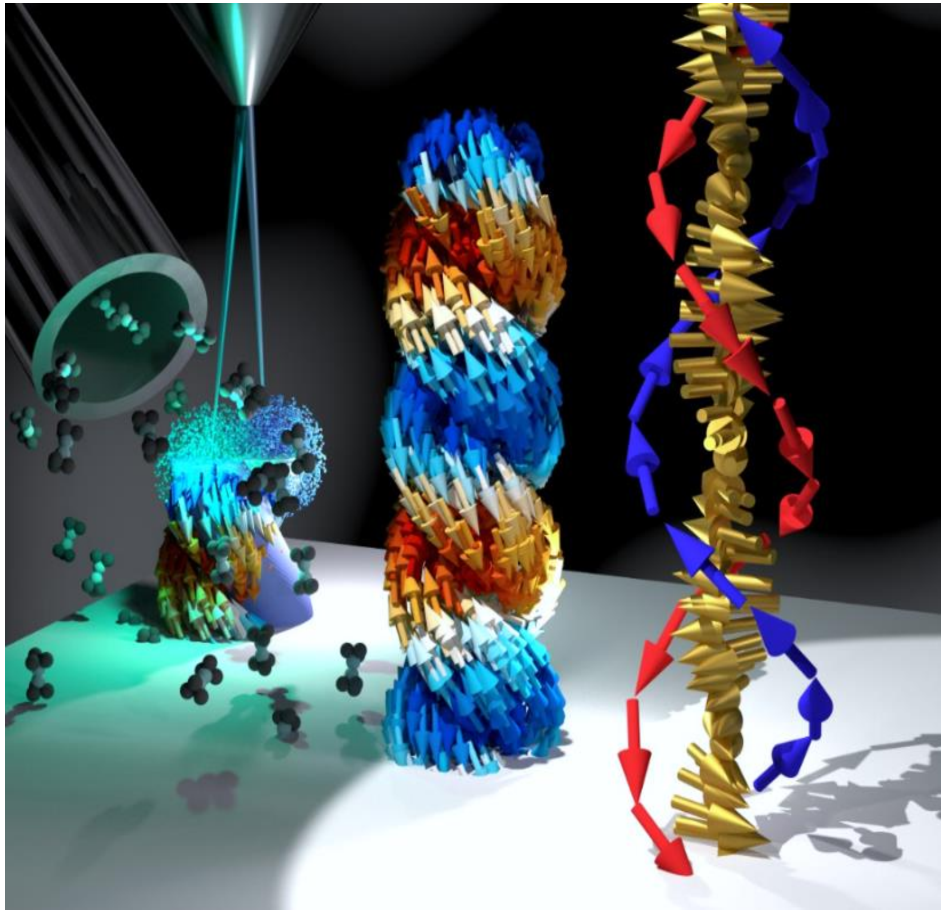
http://tuwien.at/phy/iap/3dnano

Tutorial on synthesis of 3D magnetic nanostructures



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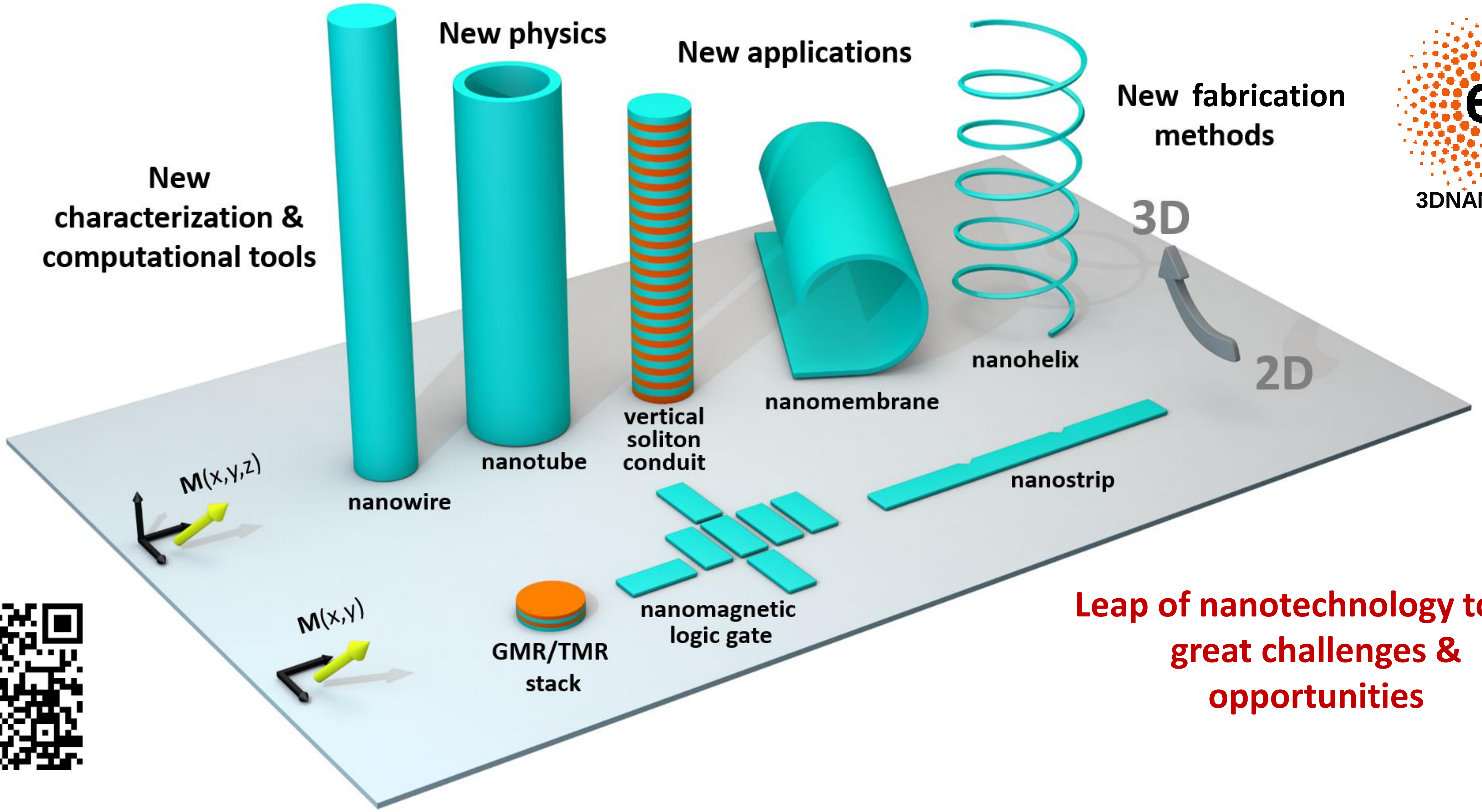
Contributors: Sam Ladak, Kai Liu, Denys Makarov, CD Phatak, Sandra Ruiz-Gómez (Benjamin Jungfleisch, Peter Fischer)

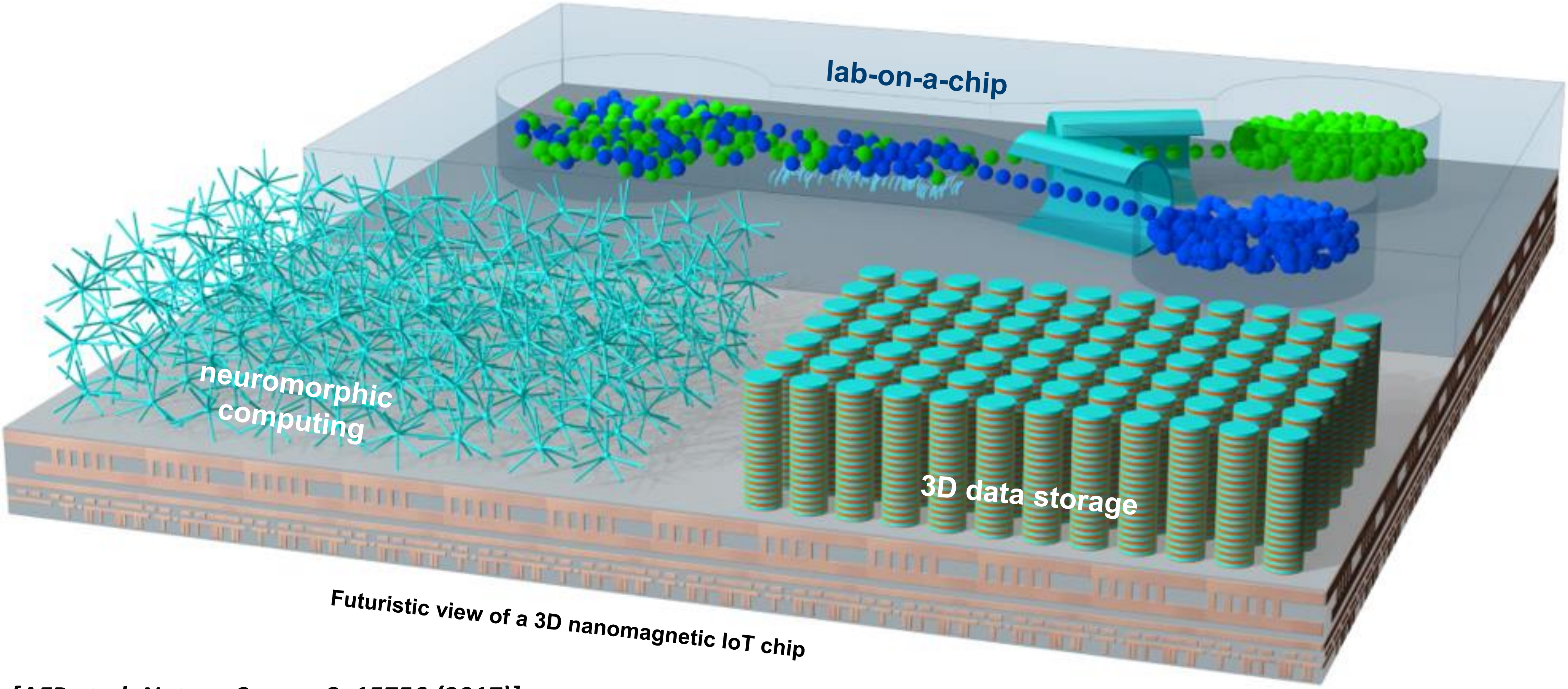
Three-dimensional nanomagnetism



3DNANOMAG

Leap of nanotechnology to 3D: great challenges & opportunities

3D nanomagnetism for future green technologies



Futuristic view of a 3D nanomagnetic IoT chip

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

Some key features of a synthesis technique for 3D nanomagnetism

Geometry
- How complex can the 3D geometries be

Scales:
- Spatial resolution & nanomagnetism lengthscales (10s-100s nm)
- Growth rates: Single element vs collective phenomena
- Multiscale possible (hierarchy)

Materials:
- Magnetic vs polymer/non-magnetic
- Magnetic properties: M_s, A_{ex}, α …
- Variety of elements & types (ferro, antiferro…)
- Tuneability: composition, crystallinity…

Thin film deposition:
- Degree of conformality
- Minimum/Maximum thickness attainable
- Quality of interfaces

Technology:
- Stage of maturity: emergent vs consolidated : for fundamental studies /real applications
- Compatibility/complementarity with other methods
- On-chip integration possible
- Electrically, optically accessible
- Reproducibility
- Cost

Synthesis techniques for 3D nanomagnetism covered in this tutorial

Nanofabrication

Direct-write	FEBID/FIBID	Two-photon polymerization	FIB
Templates	AlO_x & polycarbonate membranes	Self-assembly	Nanocomposites
PVD-thin film based	Rolled-up	Free-standing	GLAD

In combination with growth techniques

By itself	PVD	CVD	ALD	Electro-deposition	Electroless deposition	Bulk	Nanoparticle

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Nanofabrication

Direct-write	**FEBID/FIBID**	**Two-photon polymerization**	**FIB**
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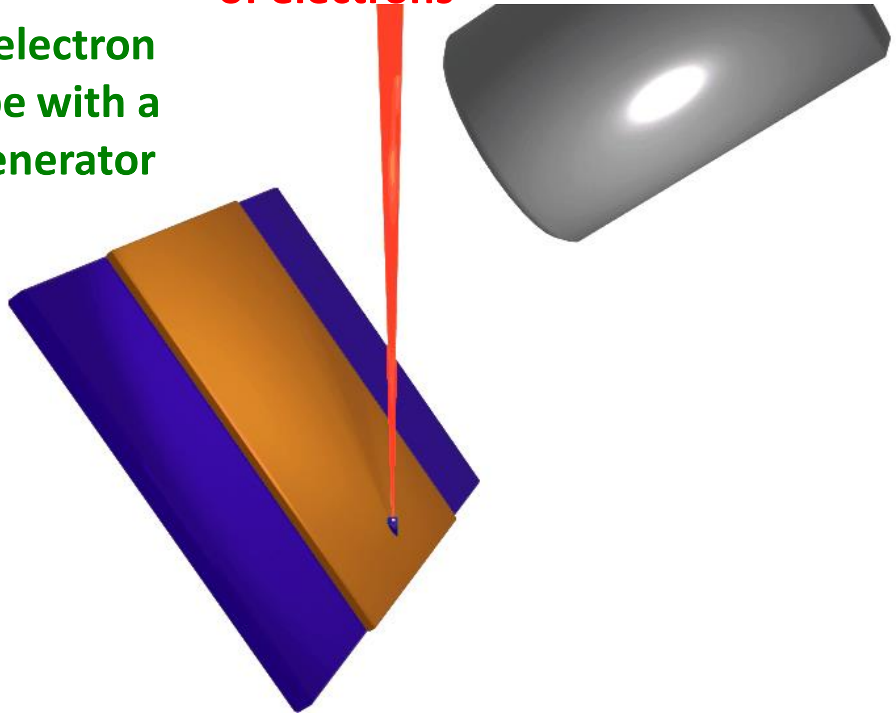
Focused electron/ion beam induced deposition (FEBID/FIBID)

Focused beam of electrons

Gas injector system

Scanning electron microscope with a pattern generator

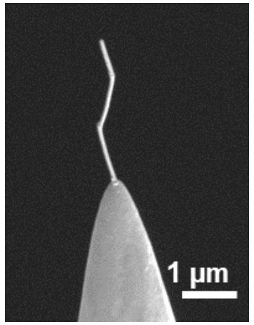


FEBID: Local Chemical Vapor Deposition induced by a focused beam of electrons

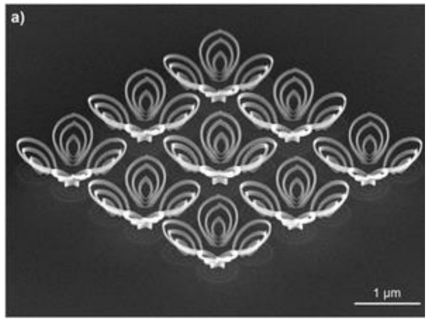
$$2Co_2(CO)_8 \xrightarrow{20\text{-}80^oC} Co_4(CO)_{12} + 4CO$$

$$Co_4(CO)_{12} \xrightarrow{100^oC} 4\ Co + 12\ (CO)$$

1-step lithography process

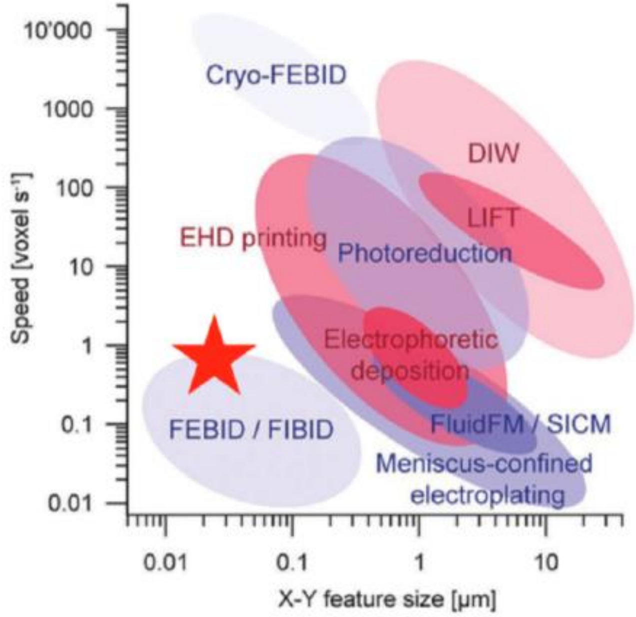


Growth on almost any substrate



Great performance for 3D nanofabrication

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



Nano-patterning resolution

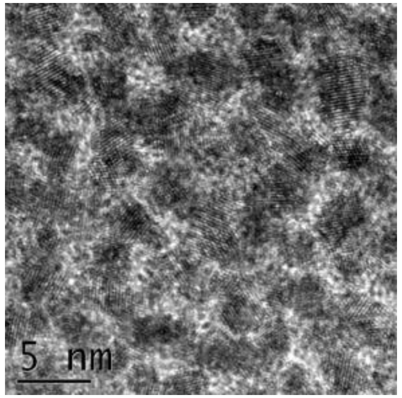
[Hirt et al, Adv. Mater. 29, 1604211 (2017)]

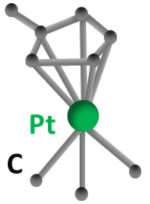
Unique tool for nano-prototyping & low-throughput 3D nanolithography

Materials grown by FEBID/FIBID

Dirty metals

Typically 15-20% (at.) metal, rest carbon & oxygen



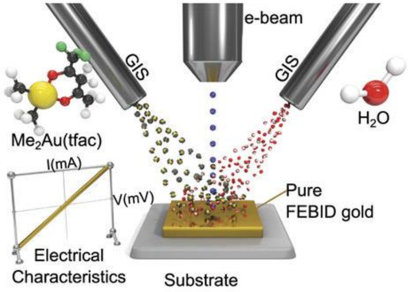


$(CH_3)_3Pt(CpCH_3)$

$Me_2Au(tfac)$

[AFP et al, Phys. Rev. B 79, 174204 (2009)]

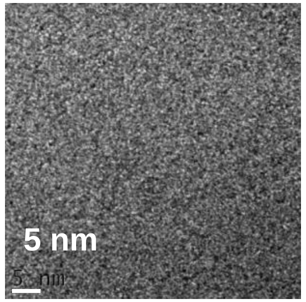
Ways to create pure (Pt & Au) FEBID materials:

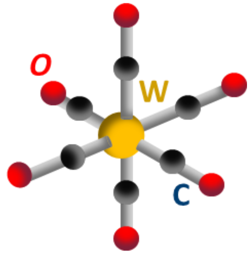


Post-growth methods/ reactive gases during growth

[Winkler et al, ACS Appl. Mater. Interfaces 9, 8233 (2017); Shawrav et al, Sci. Rep. 6, 34003 (2016)]

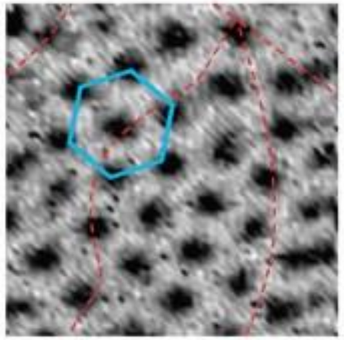
Superconducting materials

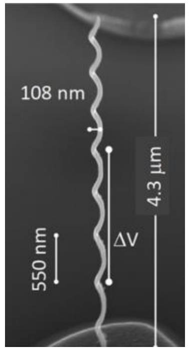


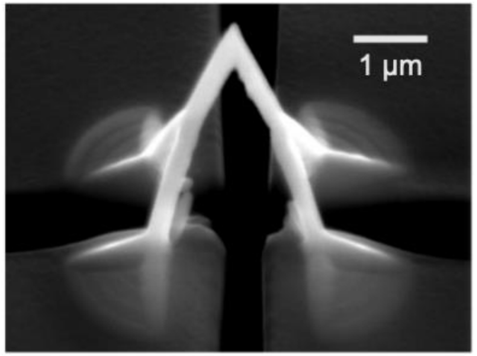


$W(CO)_6$

$(CH_3CH_2)Pb$







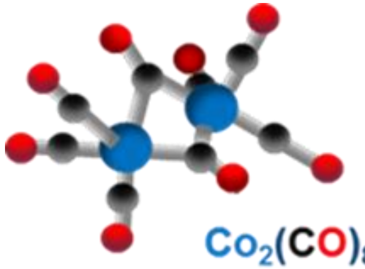
[Guillamón, Fernández-Pacheco et al, New J. Phys. 10 093005 (2008); Nature Phys. 5, 651 (2009)]

[Córdoba et al, Nano Lett. 19, 12, 8597 (2019)]

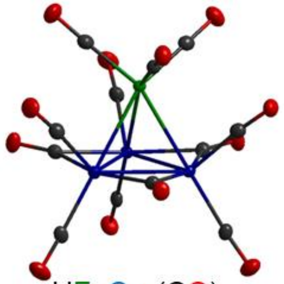
[Zhakina et al, arxiv.org/2404.12151]

Direct writing of functional superconducting materials

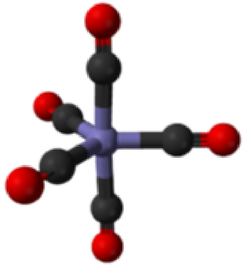
Direct writing of ferromagnetic metals by FEBID



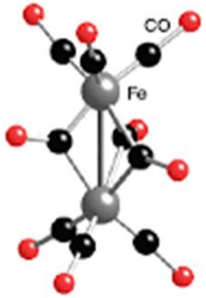
$Co_2(CO)_8$



$HFeCo_3(CO)_{12}$



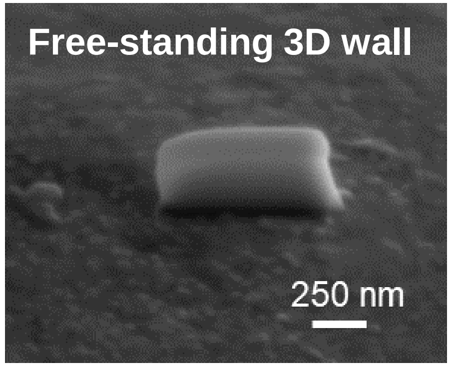
$Fe(CO)_5$

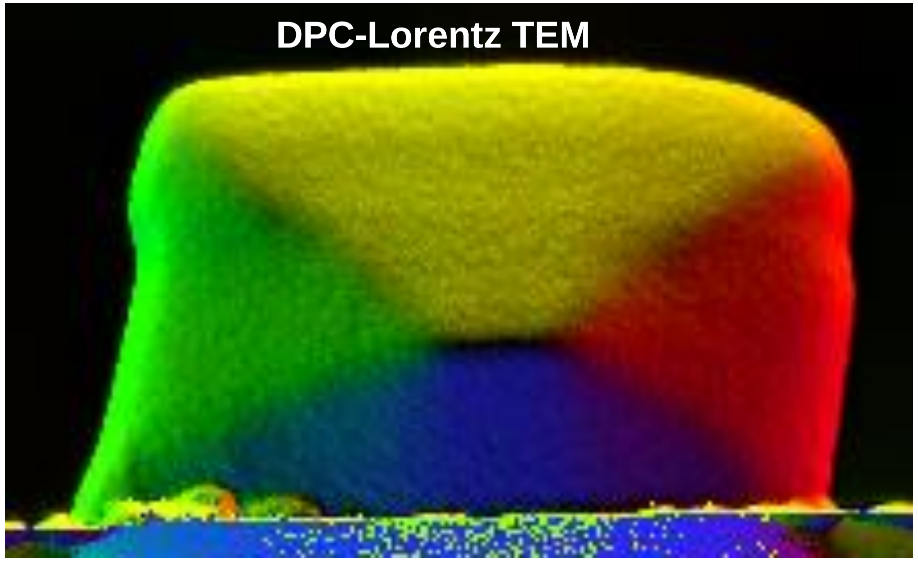


$Fe_2(CO)_9$

85-95% cobalt, iron or CoFe alloy under suitable growth conditions

M_r

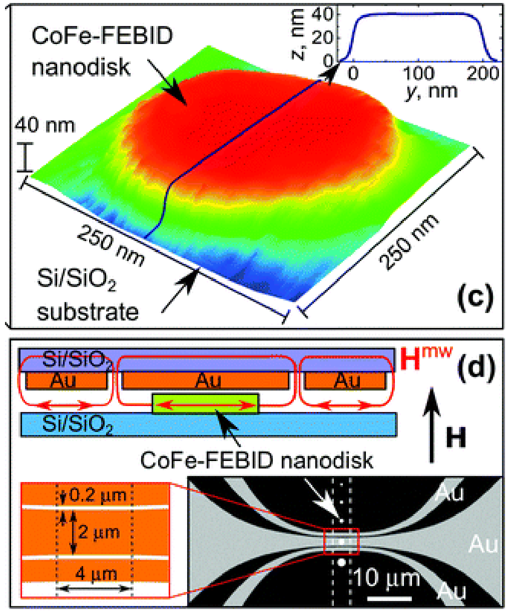




Growth of high-purity nanocrystalline/amorphous ferromagnets @ lateral resolutions ≈ 40 nm

High saturation magnetisation
M_s = 0.9 -1.3 MA/m

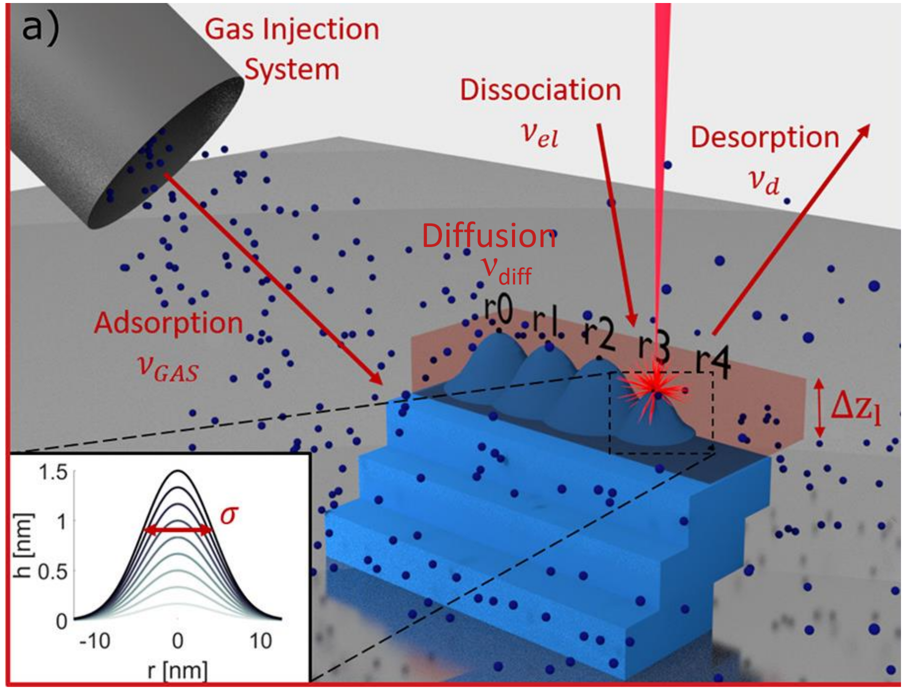
Grain sizes ≈ 3 -10 nm



Decay lengths of SWs for CoFe ~ 10 µm

[Dobrovolskiy et al, Nanoscale 12 21207 (2020)]

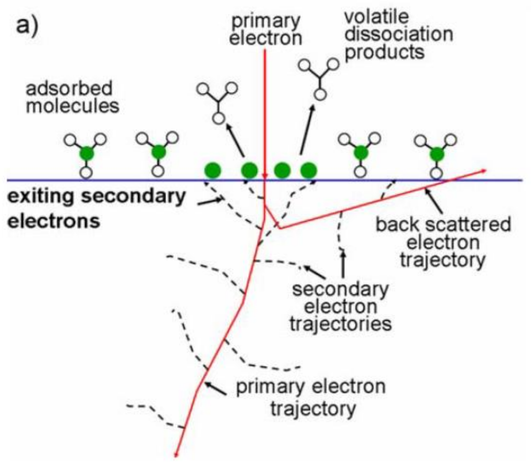
Fundamentals of FEBID: continuum model + Monte Carlo simulations



FEBID continuum model – characteristic frequencies

$$\frac{\partial\theta}{\partial t} = \nu_{GAS}(1-\theta) - \nu_d\theta - \nu_{el}\theta + \nu_{diff}\,\theta$$

$\nu_{GAS} = \frac{sF}{N_0}$	$\nu_1 = \nu_0 e^{\frac{-E_1}{k_B T}}$	$\nu_e = \sigma J$	$\nu_{diff} = D\nabla^2\theta$
GIS gas supply	**Thermal desorption**	**Electron Dissociation**	***Gas Diffusion***



Monte Carlo simulations

- Gas dynamics
- Electron-matter interactions

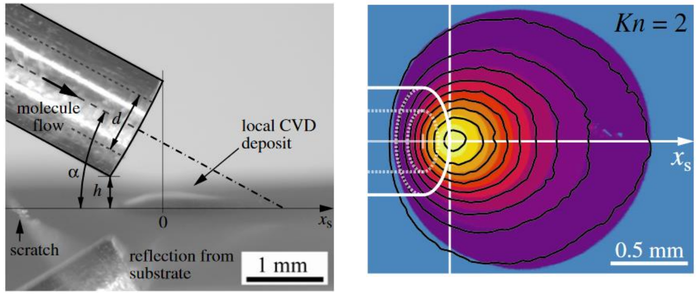
[Utke et al, J. Vac. Sci. Technol, 26, 1197 (2008)]

[Sanz-Hernández, AFP et al, Beilstein J. Nanotechnol 8, 2151-2161 (2017)]

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

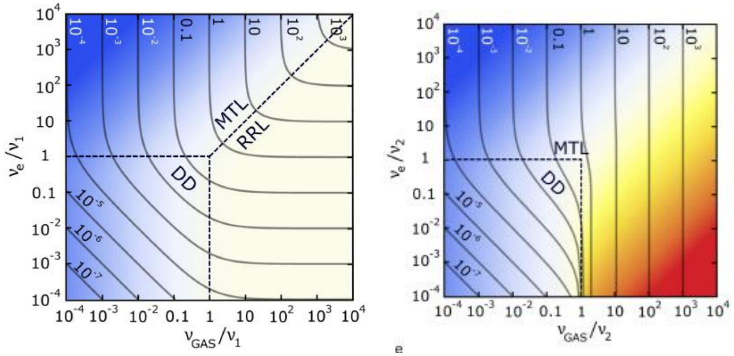
Recent FEBID computational tools

Gas injector system simulator



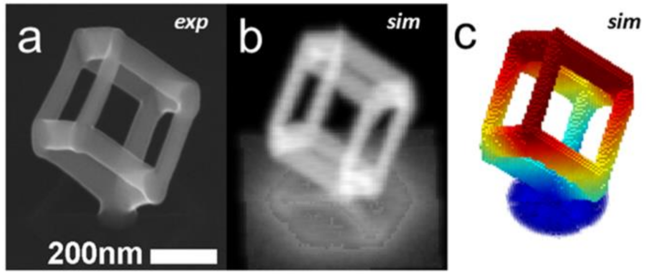
[Friedli et al, J. Phys. D: Appl. Phys. 42, 125305 (2009)]

FEBID frequency maps



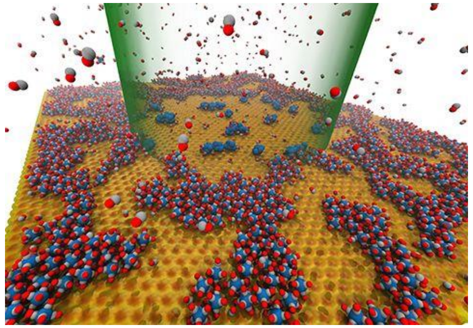
[Sanz-Hernández & AFP, Beilstein J. Nanotechnol 8, 2151-2161 (2017)]

Monte-Carlo + continuum model simulator



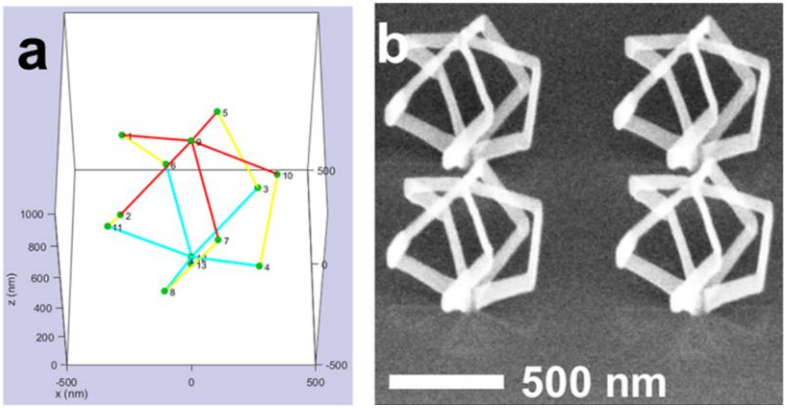
[Fowlkes et al, ACS Nano 10, 6163 (2016)]

FEBID @ the molecular level

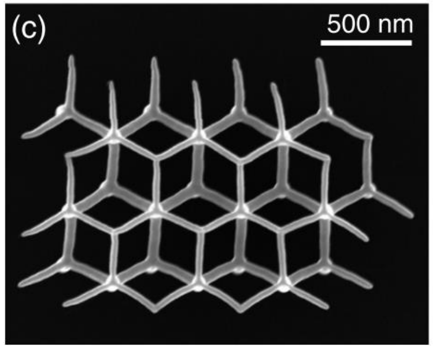


[Sushko et. al. Eur. Phys. J. D 217, 70283 (2016)]

3D nano-printing of nanowire-based structures



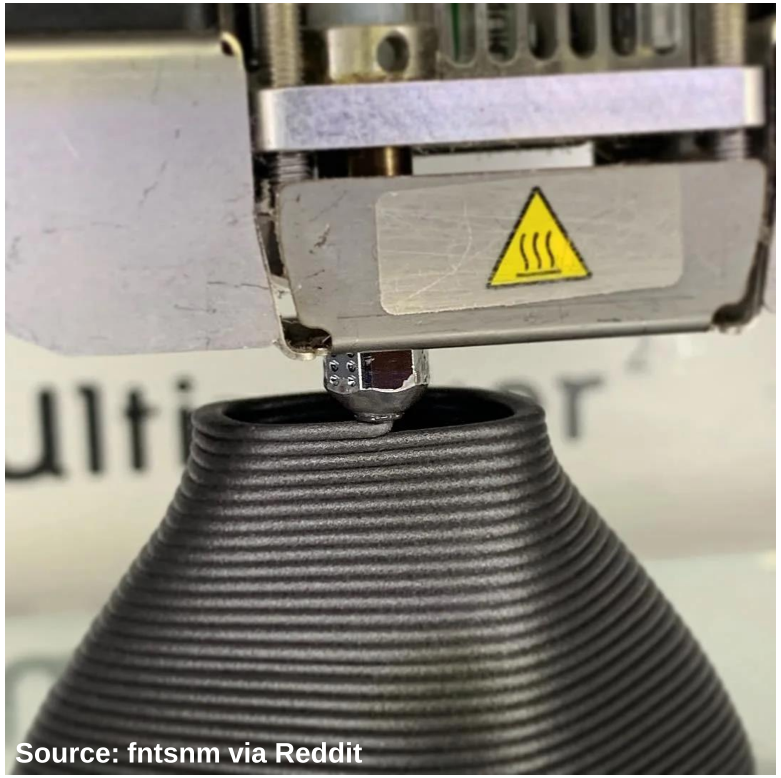
[Fowlkes et al., ACS Appl. Nano Mater. 1, 1028 (2018)]



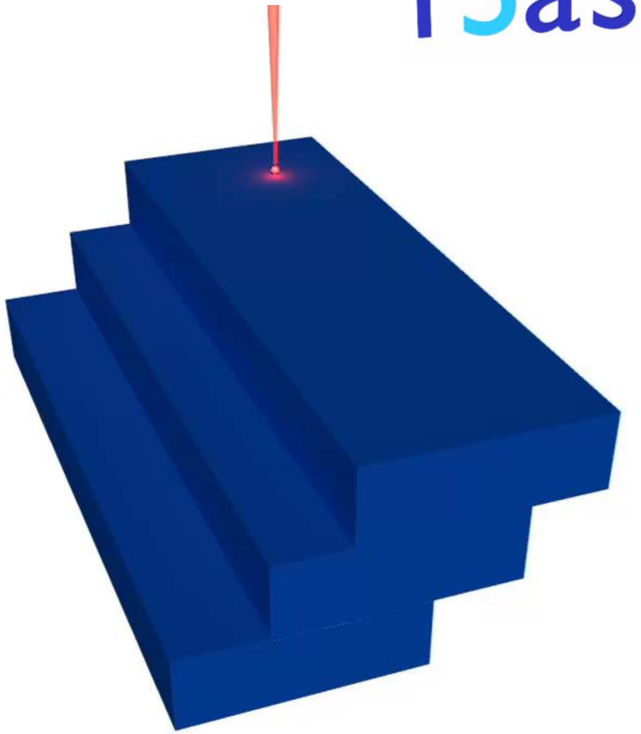
[Keller, Huth et al., Scientific Reports 8, 6160 (2018)]

f3ast software: 3D printing at the nanoscale by FEBID

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



Standard 3D printer extruder: Macro/microscale



FEBID: Nanoscale

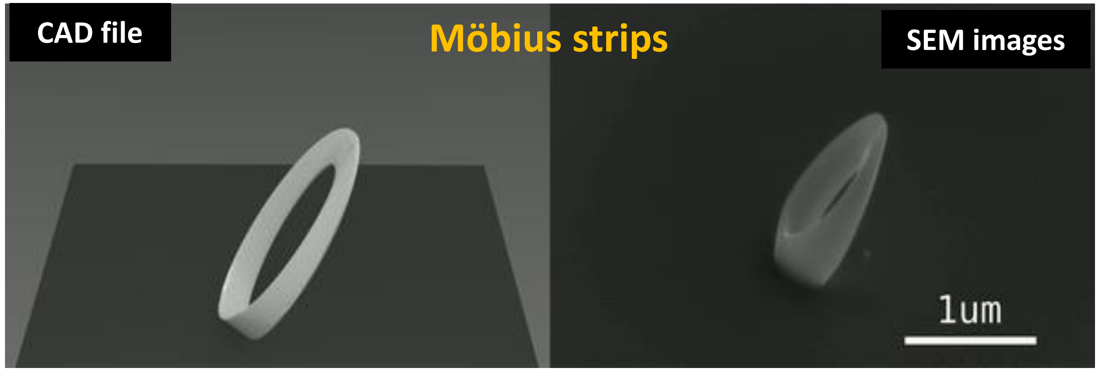
f3ast

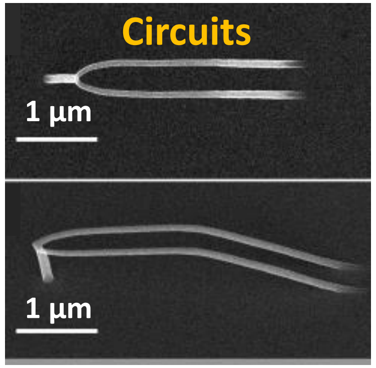
FEBID 3D Algorithm for STream file generation

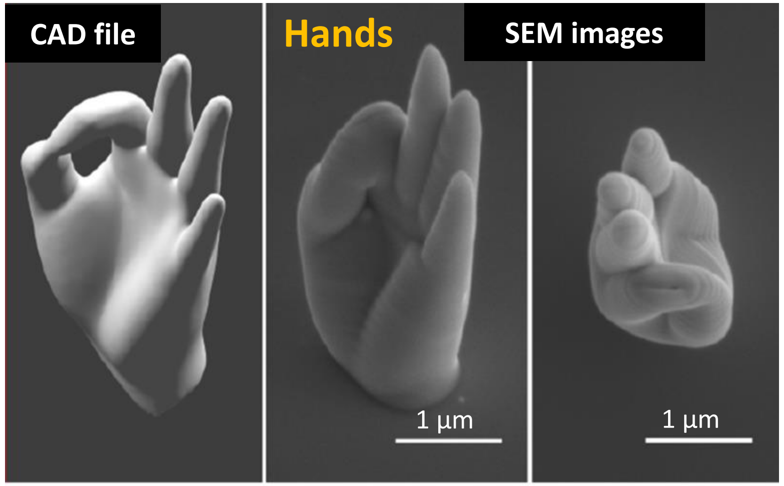
First FEBID code:

- **Able to print arbitrary 3D geometries**
- **Rigorously based on theory of FEBID processes**
- **Simple two-step calibration procedure → start to 3D print**

3D printing of complex nano-geometries by f3ast software

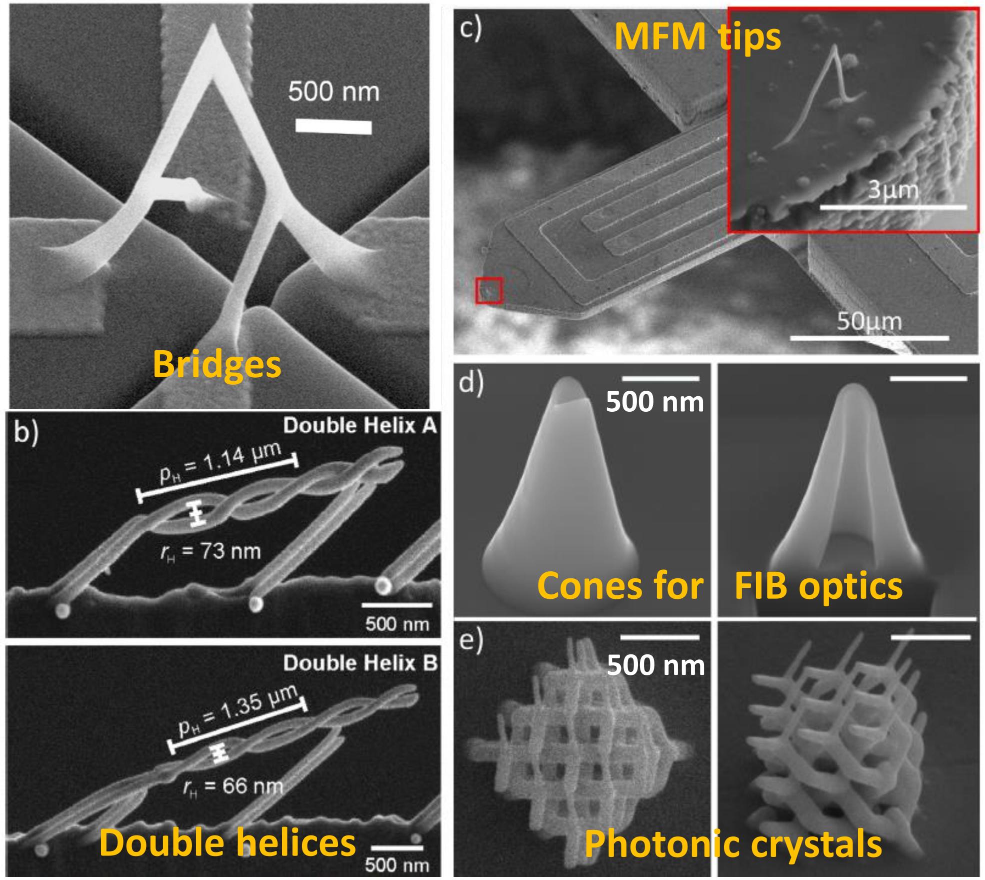






3D printing of arbitrary geometries with resolution of tens of nm

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



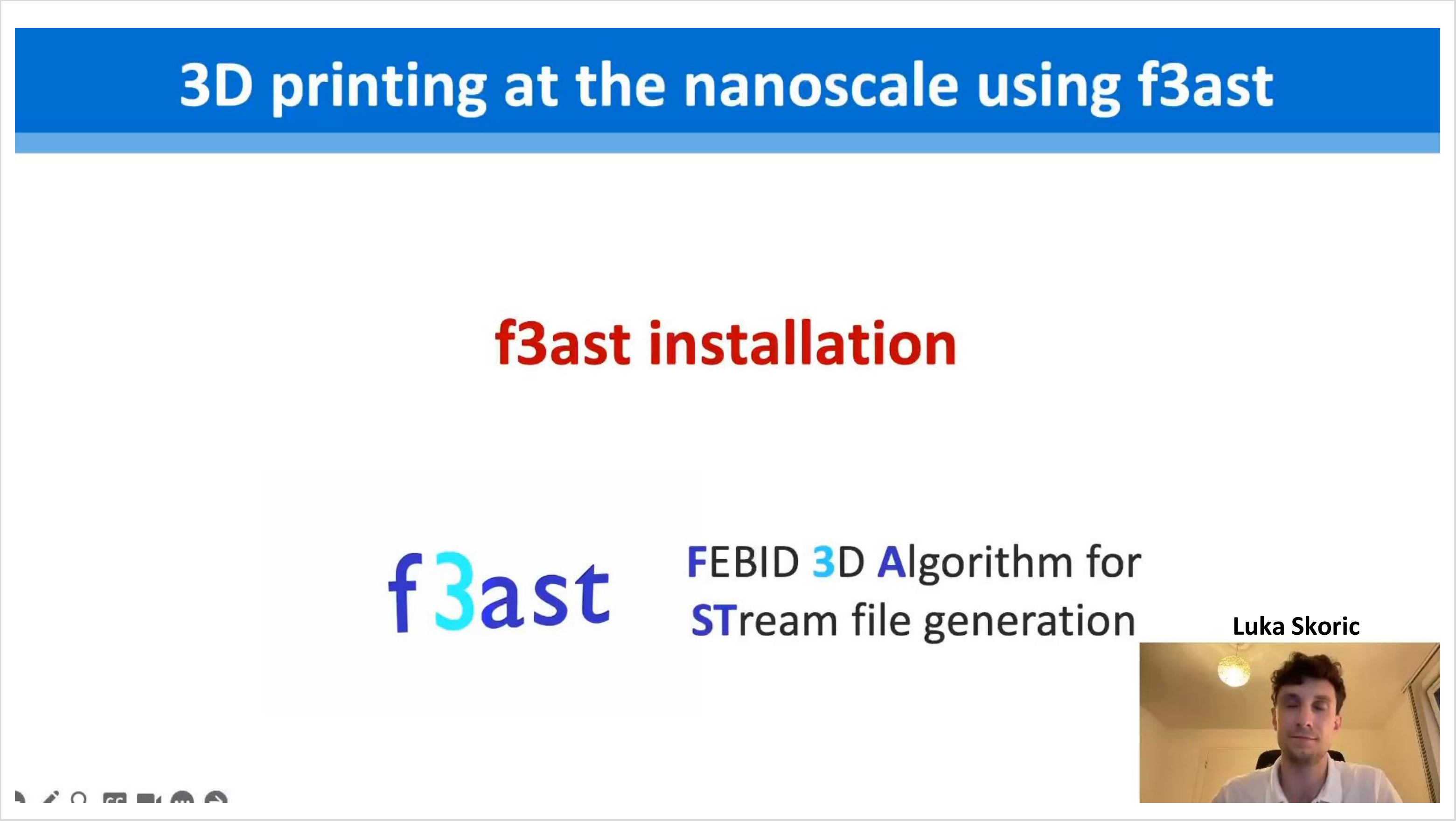
[L. Skoric PhD thesis, St. John's College Cambridge (2021)]

f3ast: 3D nano-printing platform open to the community

f3ast

Open access since 2022: https://github.com/Skoricius/f3ast

YouTube channel launched recently!: www.youtube.com/@f3ast-nanofab

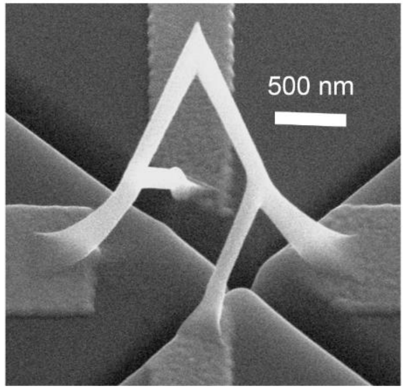


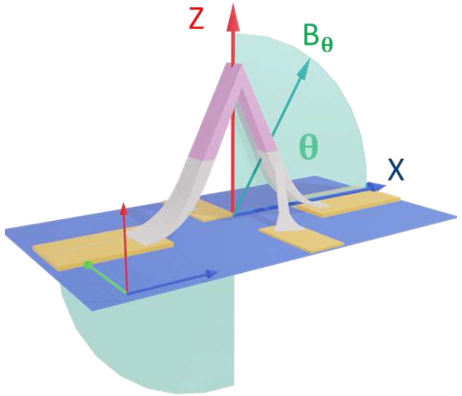
Tutorial videos:

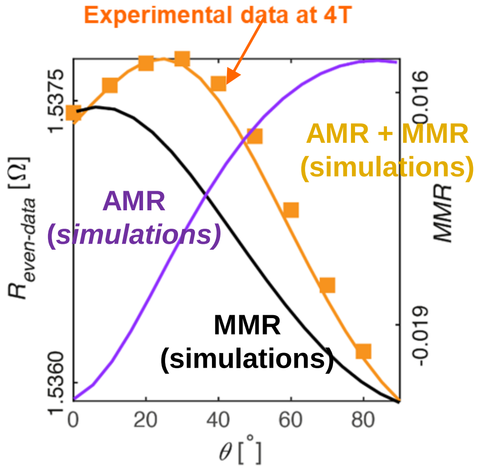
How to install & navigate through the software; how to perform 3D printing experiments, fundamentals of the algorithm… and a few surprises!

Direct writing of nanowire-based structures

3D bridge circuits



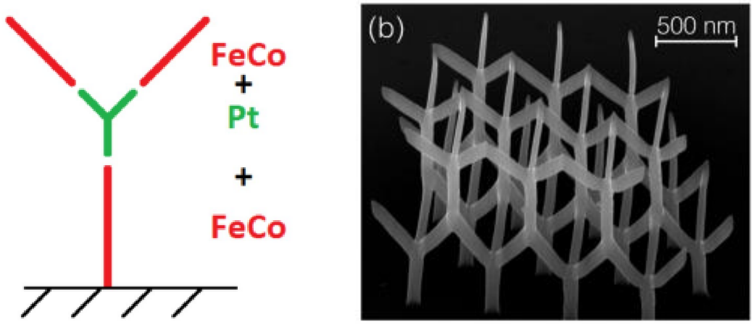




Unconventional dependences of magnetotransport signals (Hall effect, MR) due to 3D geometry

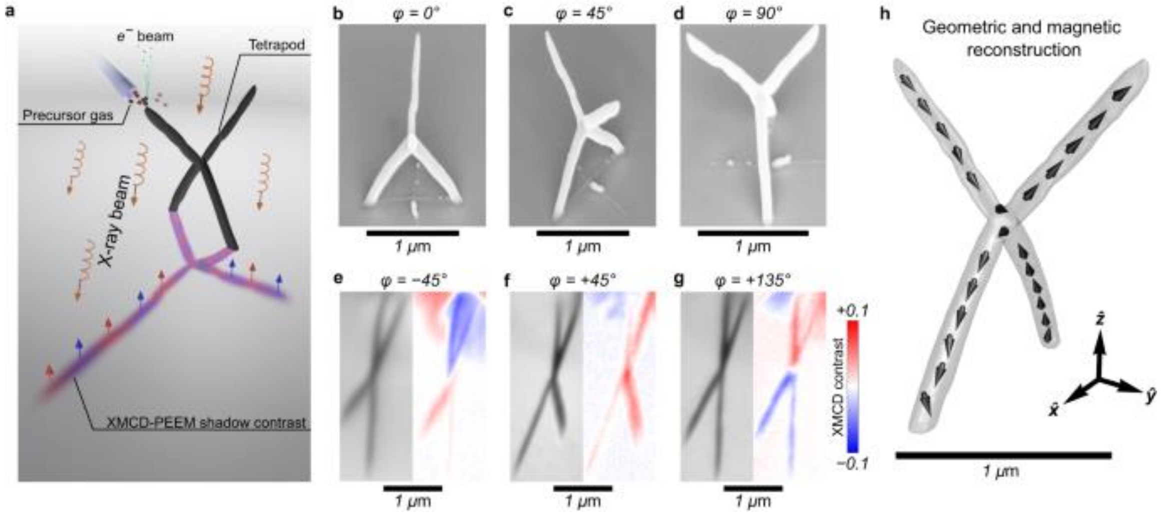
[Meng, AFP et al, ACS Nano 15, 6765 (2021)]

Artificial spin lattice elements



Tetrapods characterized by Hall magnetometry

[Keller et al, Sci Rep. 8, 6160 (2018)]

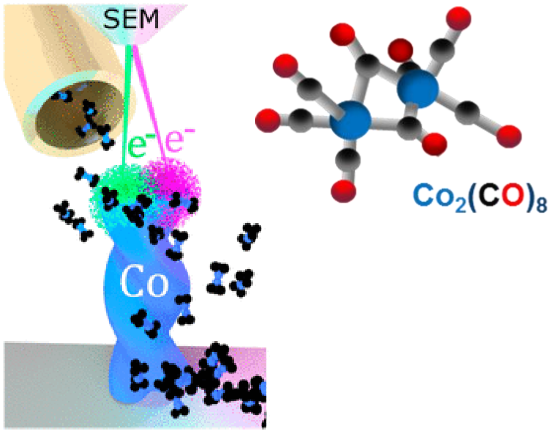


Higher order vorticity 3D spin textures at the vertices

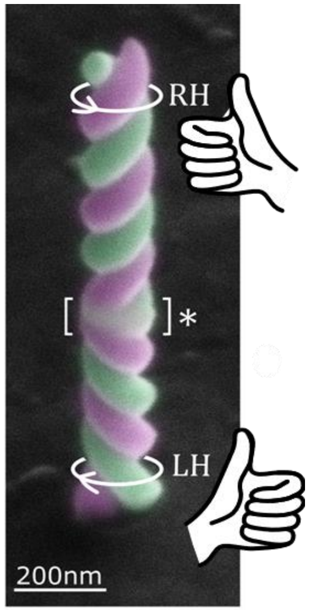
[Volkov et al, Nature Comm. 15, 2193 (2024)]

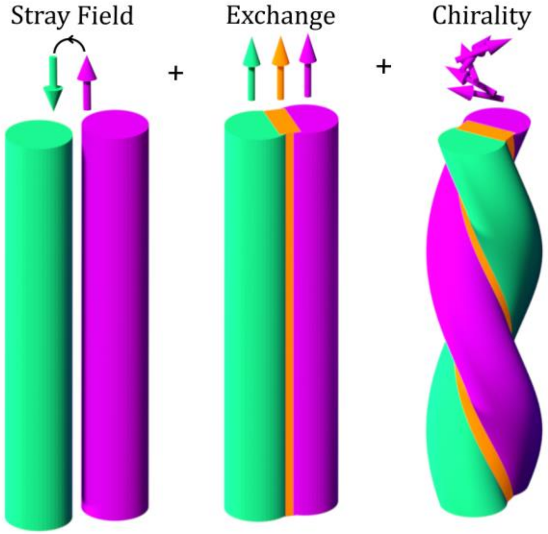
Direct writing of helical nanomagnets

[Sanz-Hernández, AFP et al, ACS Nano 14, 8084 (2020)]
Donnelly, AFP et al, Nature Nano 17, 136 (2022)]



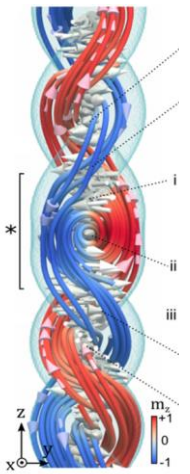
Chirality interface



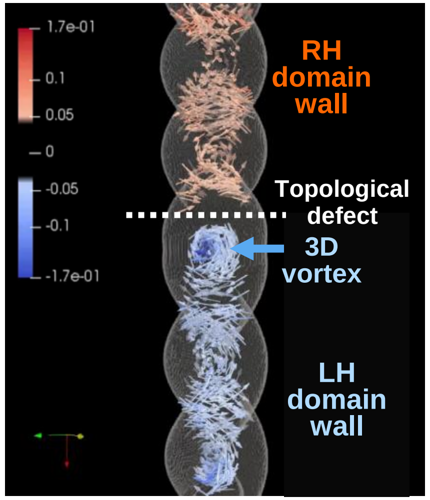


Competition of magnetic energies in helical geometry

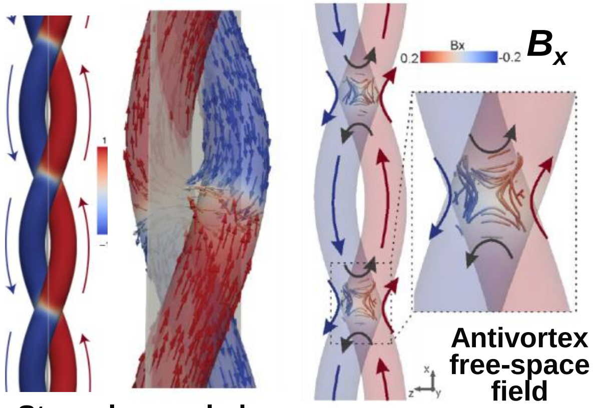
Magnetisation
$\vec{m}$



Magnetic chirality
$= \vec{m} \cdot (\nabla \times \vec{m})$



Imprinting of topological spin states:
3D spin textures & defects



Strongly coupled DWs in double helix

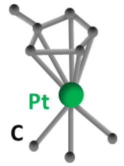
Cross-tie B wall

Antivortex free-space field

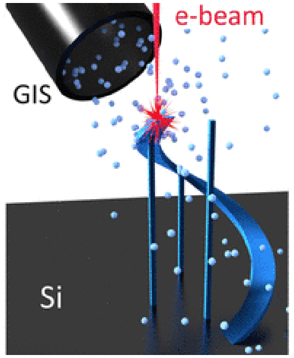
Formation of topological free-space *B* fields with complex nanoscale-localised gradients:
unconventional computing & sensing

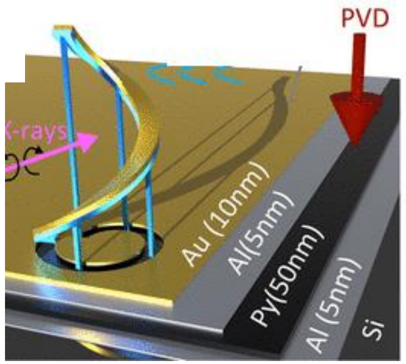
Domain wall devices via PVD + FEBID

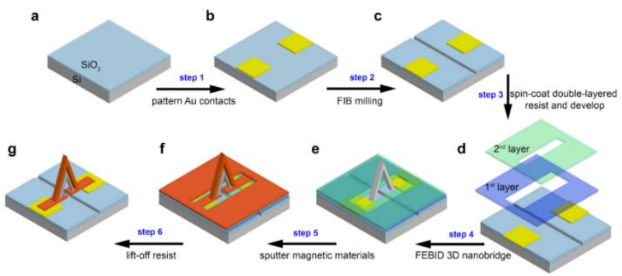
Hybrid 3D nanofabrication: FEBID + PVD



$(CH_3)_3Pt(CpCH_3)$



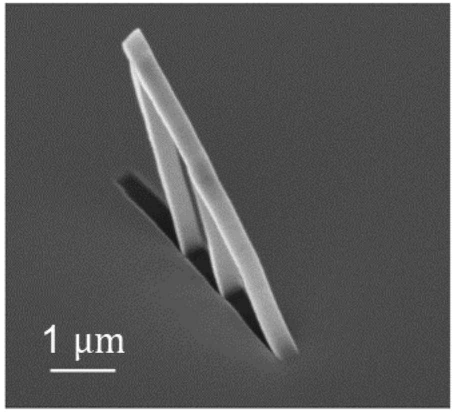


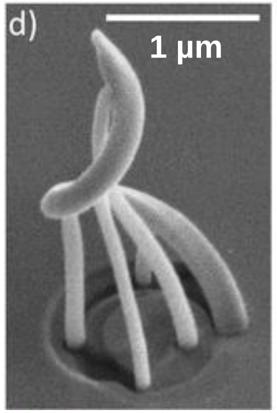


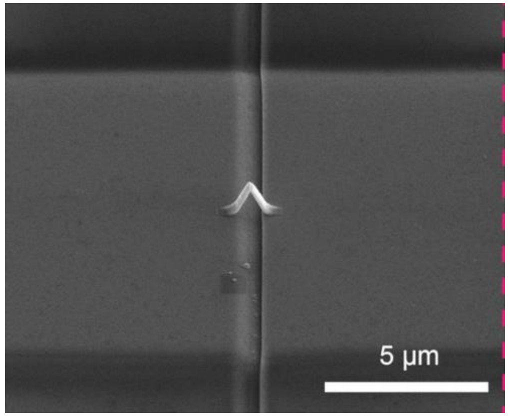
Step 1: 3D nano-printing of non-magnetic scaffold

Step 2: Deposition of ferromagnetic thin films

Multistep (if electrical connection needed): Combined with EBL & FIB



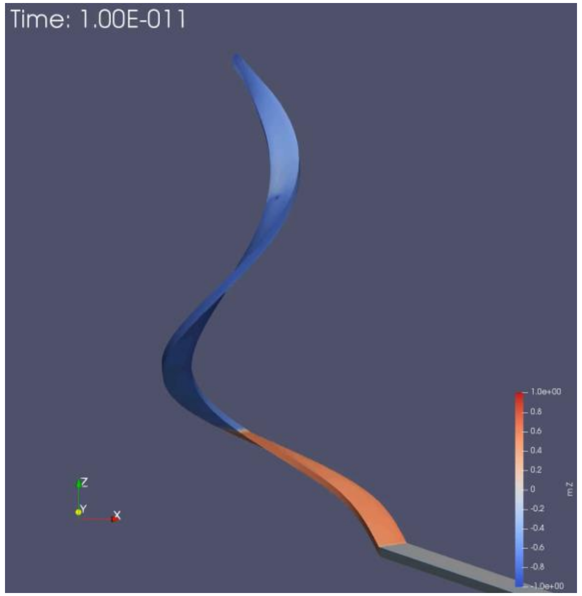


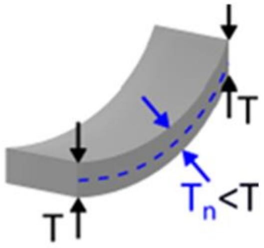


[Sanz-Hernández, AFP et al, ACS Nano 1, 11066 (2017)]

[Skoric, AFP et al, ACS Nano 16, 8860 (2022)]

[Meng, AFP et al, Micromachines 12, 859 (2021)]

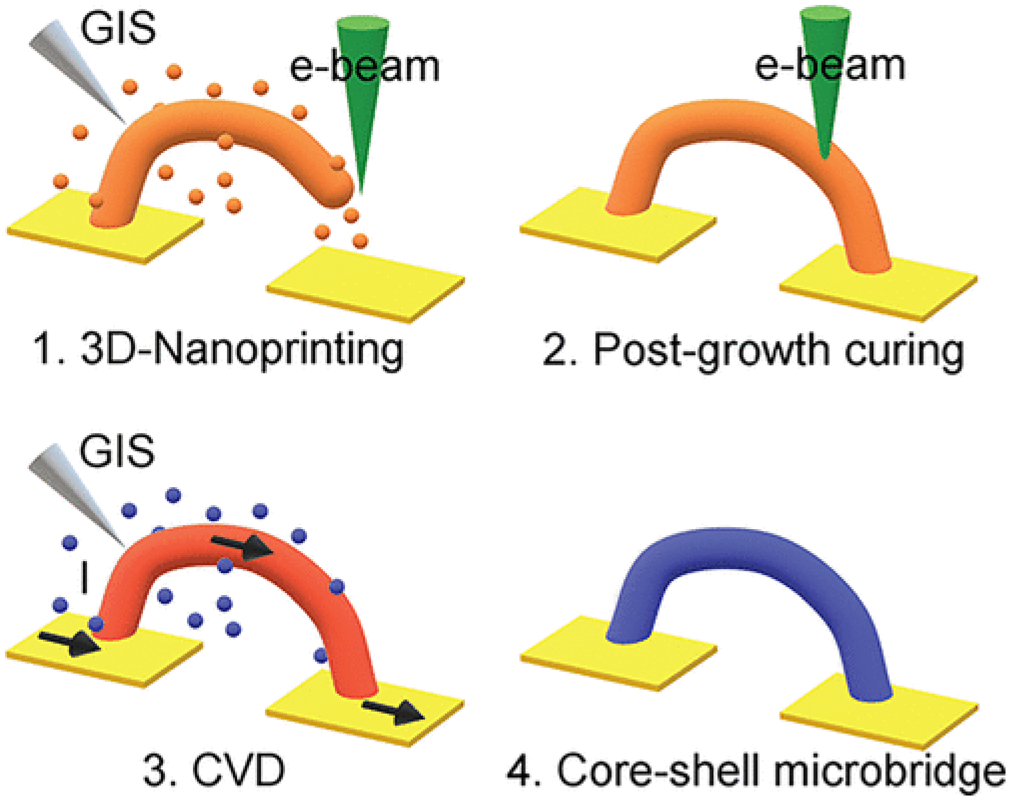


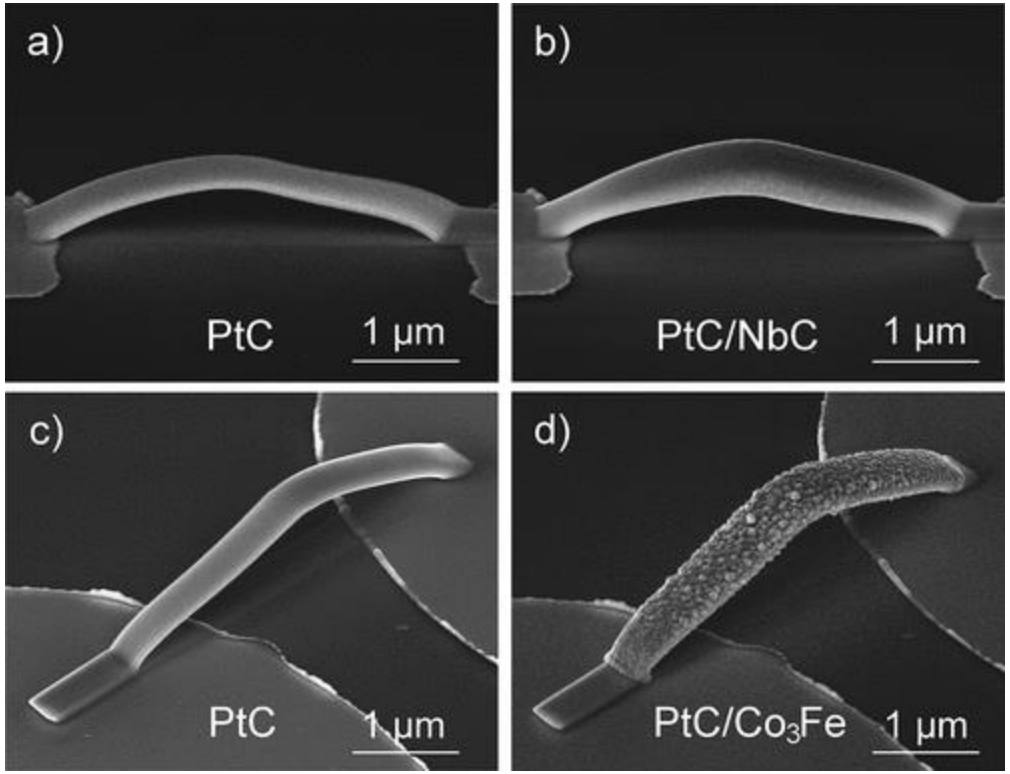


3D magnetic "nano-elevator" of domain walls
Automotion due to large thickness gradients imprinted by 3D geometry

PVD (non-conformal) + 3D geometries: shadowing, textures, BUT high-quality materials, functional interfaces…

Thermal CVD on electrically-connected FEBID circuits

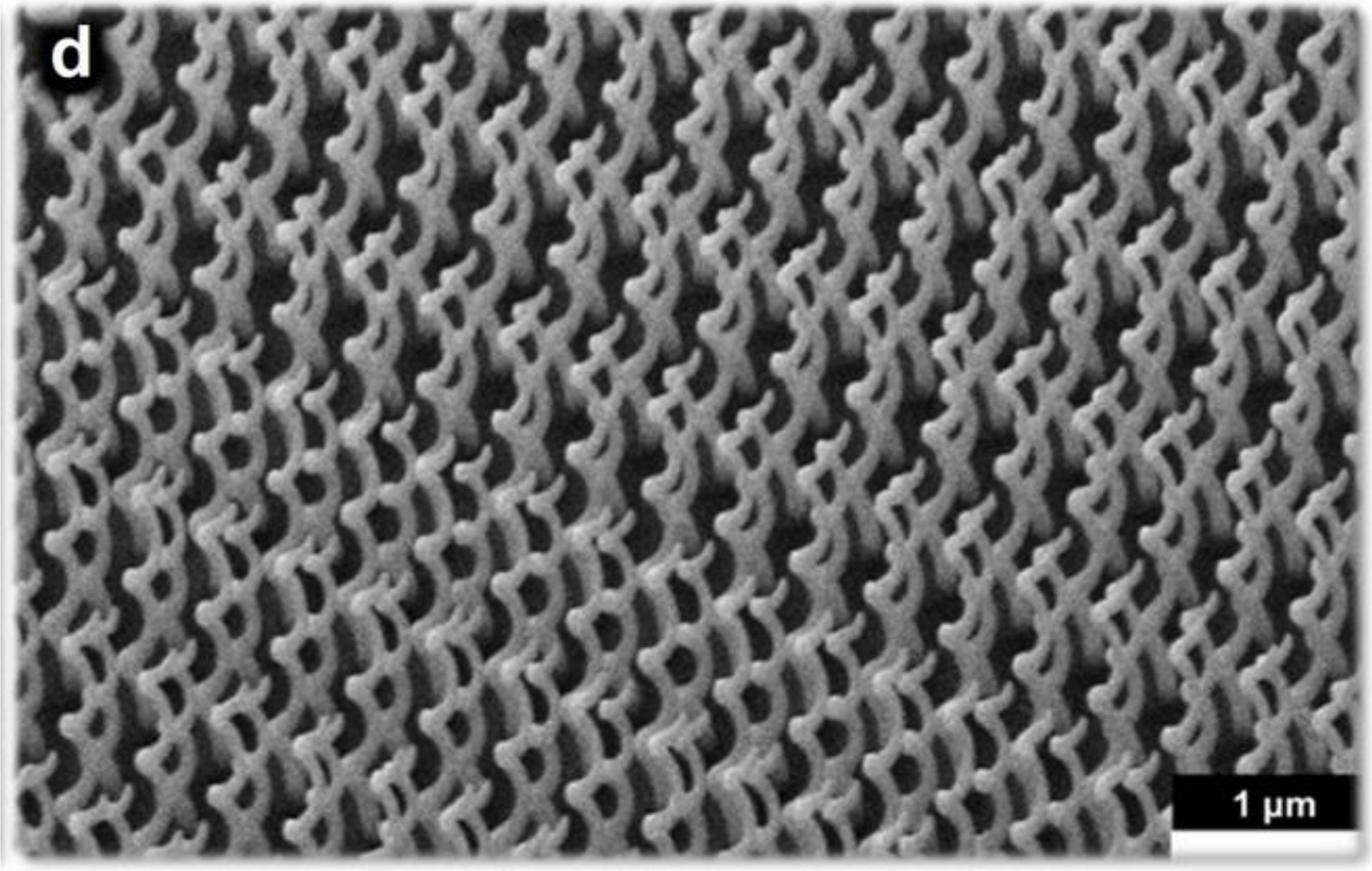




Site-Selective Chemical Vapor Deposition around FEBID structures
Conformal deposition only at the circuits addressed electrically

[Porrati et al, ACS Nano 17, 4704–4715 (2023)]

Largest scales targeted by FEBID



40 x 40 array of Pt helices

[Esposito, Marco, et al. "Nanoscale 3D chiral plasmonic helices with circular dichroism at visible frequencies." ACS Photonics 2.1 (2014): 105-114.]

FEBID is great for single-3D nanostructure studies:

- Unmatched resolution
- Direct-write of ferromagnetic materials

but… main drawbacks

- Limited number of precursors
- No epitaxial
- Residual carbon if not optimised
- Poor interfaces
- Difficult on-chip integration
- High cost
- Slow

Synthesis techniques for 3D nanomagnetism covered in this tutorial

Nanofabrication

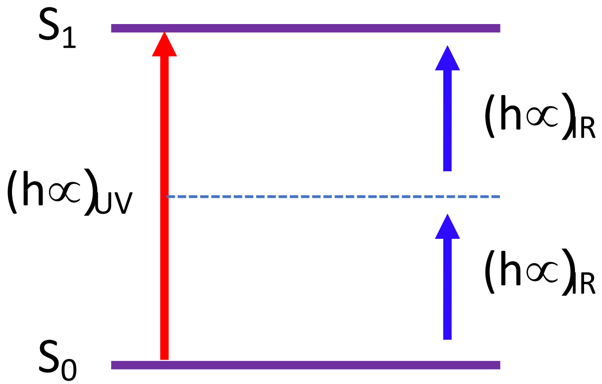
Direct-write	FEBID/FIBID	Two-photon polymerization	FIB
Templates	AlO_x & polycarbonate membranes	Self-assembly	Nanocomposites
PVD-thin film based	Rolled-up	Free-standing	GLAD

In combination with growth techniques

By itself	PVD	CVD	ALD	Electro-deposition	Electroless deposition	Bulk	Nanoparticle

Two-photon lithography

* thanks to Sam Ladak



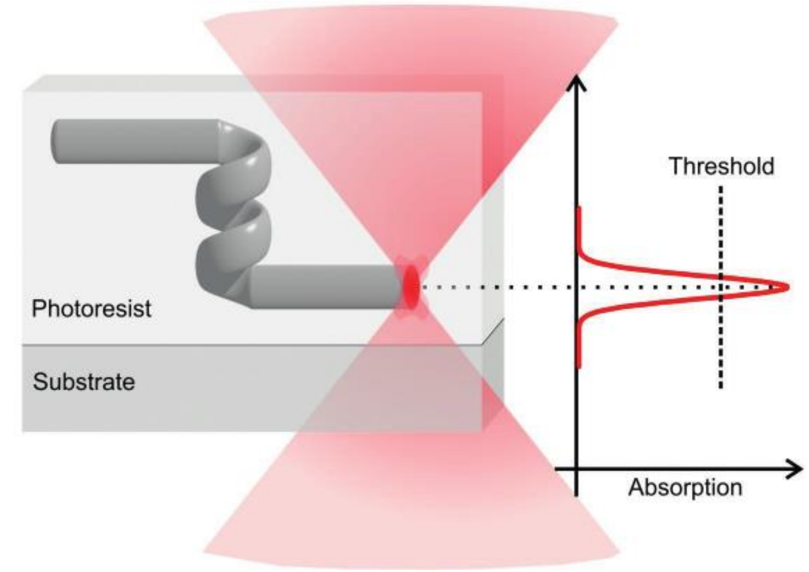
Two-photon absorption

$$\frac{dW}{dt} = \frac{8\pi^2\omega}{c^2 n^2} I^2 \operatorname{Im}\left[\chi^{(3)}\right]$$

Third-order non-linear optical process:

- low probability.
- tightly focused pulsed laser required (fs or ps)

Quadratic dependence: feature sizes below the diffraction limit (hundreds of nm)



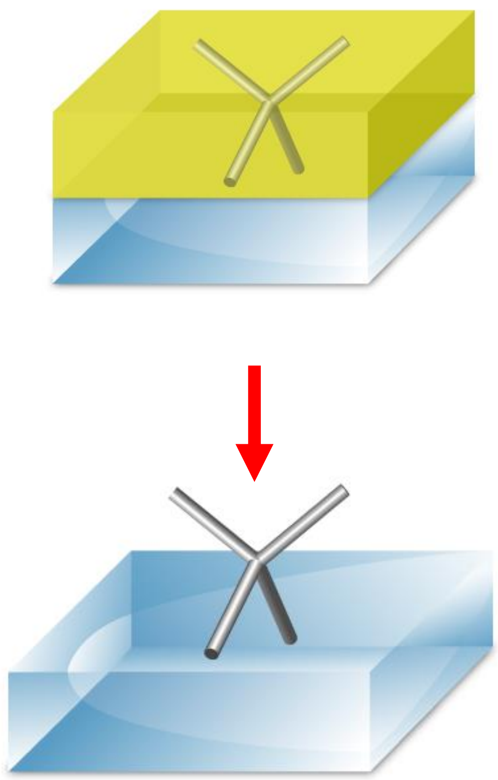
Exposure only within focal volume of laser

Combination of galvo-mirrors and piezo-stage for fast/highest resolution process

Two photon lithography + thin film deposition methods

* thanks to Sam Ladak

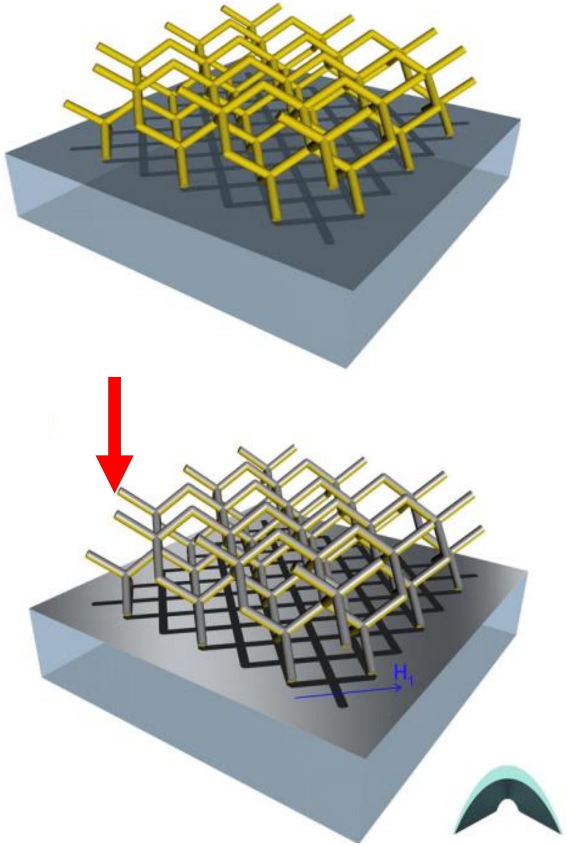
2PL+ Electrodeposition



Wires, solid geometries

Williams et al. Nano Research 11, 845 (2018)
Sahoo et al. Nanoscale 10, 9981 (2018)
Gliga et al. Materials Today 26, 100-101 (2019)

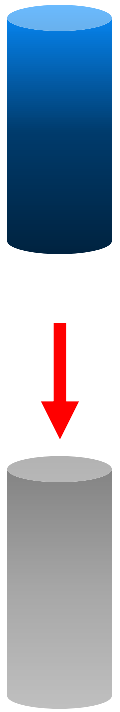
2PL + PVD



Wires, open-shell geometries

Donnelly et al. PRL 114, 115501 (2015)
May et al. Communications Physics 2, 13 (2019)
May et al. Nature Communications 12, 3217 (2021)

2PL + Electroless deposition or ALD

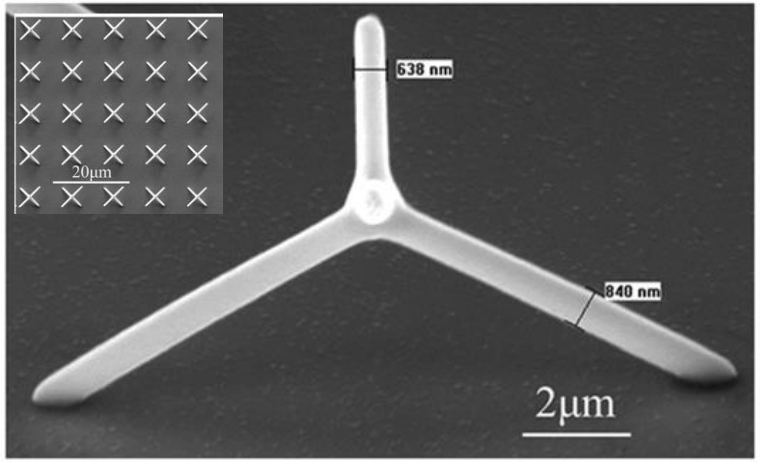


Nanotubes, closed-shell geometries

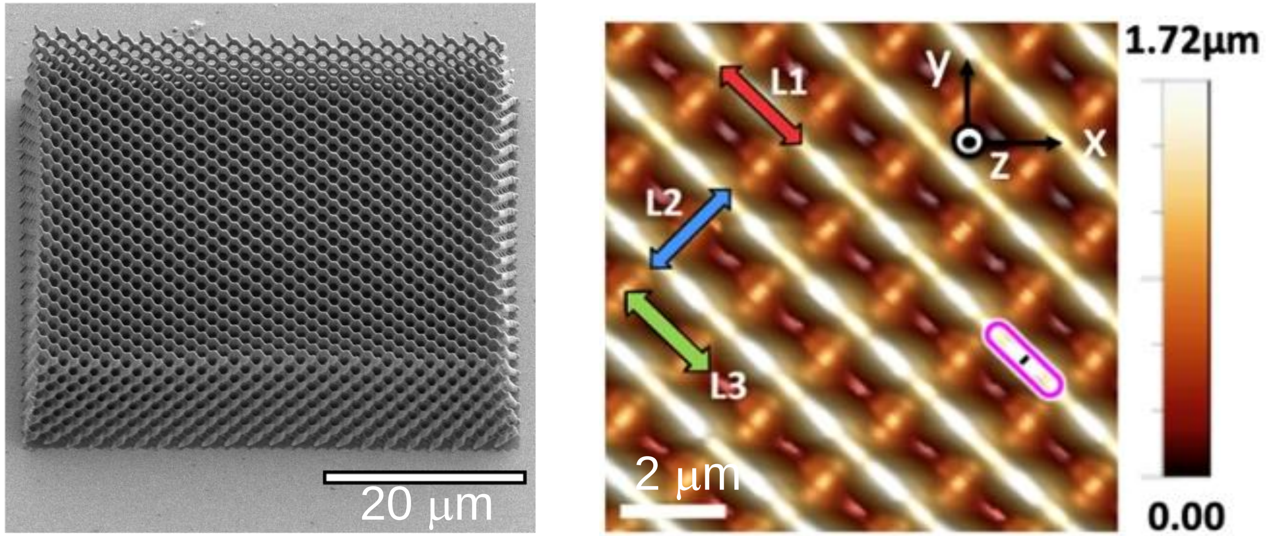
Gliga et al. Materials Today 26, 100-101 (2019)
Gui et al. Advanced Materials 35, 2303292 (2023)

Examples of recent works – Ladak's group

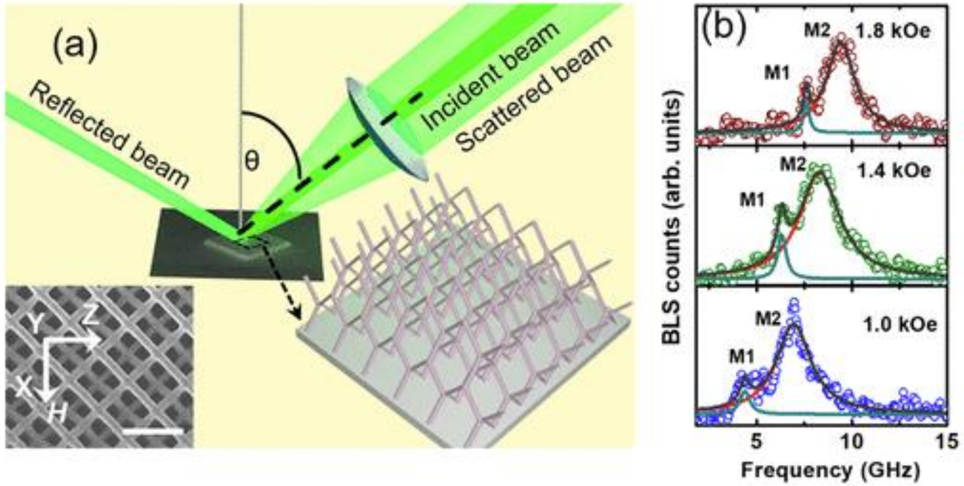
* thanks to Sam Ladak



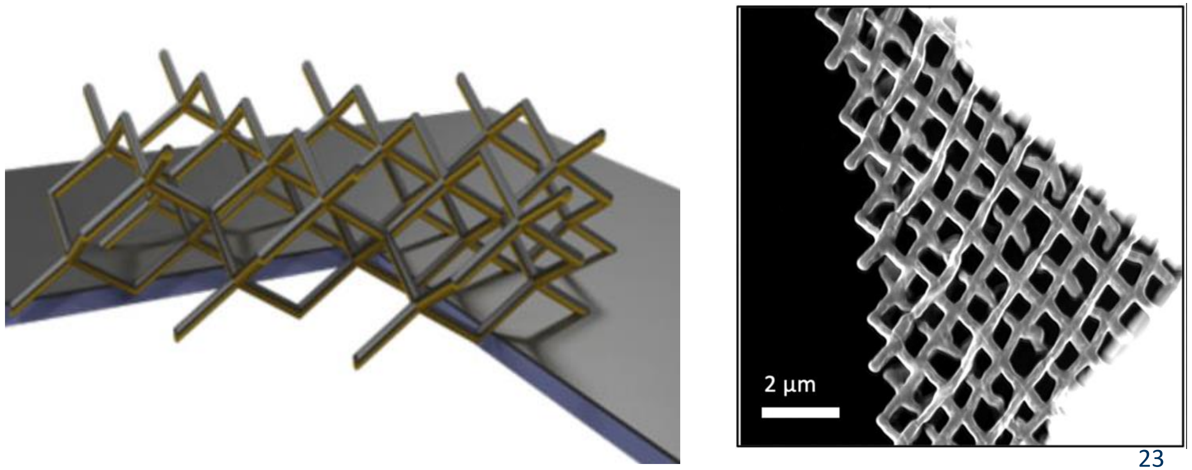
[Sahoo et al. Nanoscale 10, 9981 (2018)]



[May et al. Nature Communications 12, 3217 (2021)]



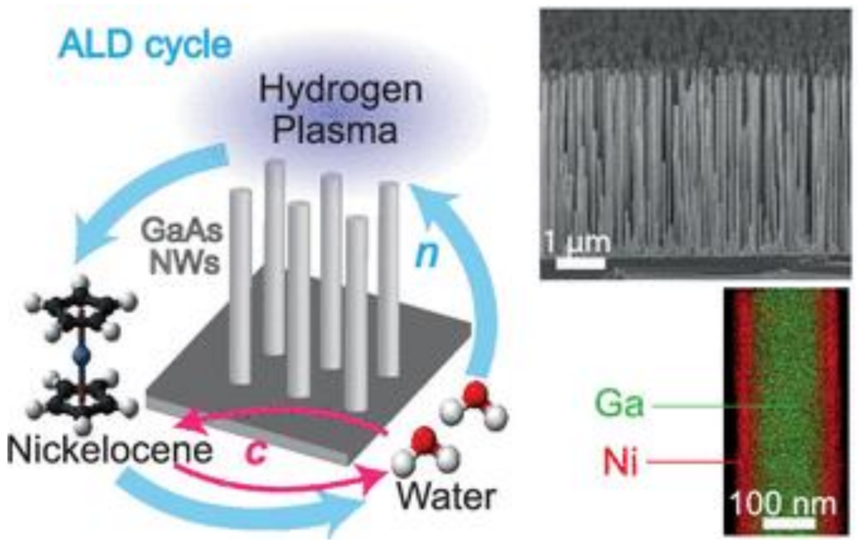
[Sahoo et al. Nano Letters 21, 4629 (2021)]



[Harding et al. APL Materials 12, 021116 (2024)]

ALD of ferromagnetic metals (Ni and NiFe)

Plasma-enhanced ALD for conformal deposition of FM metals

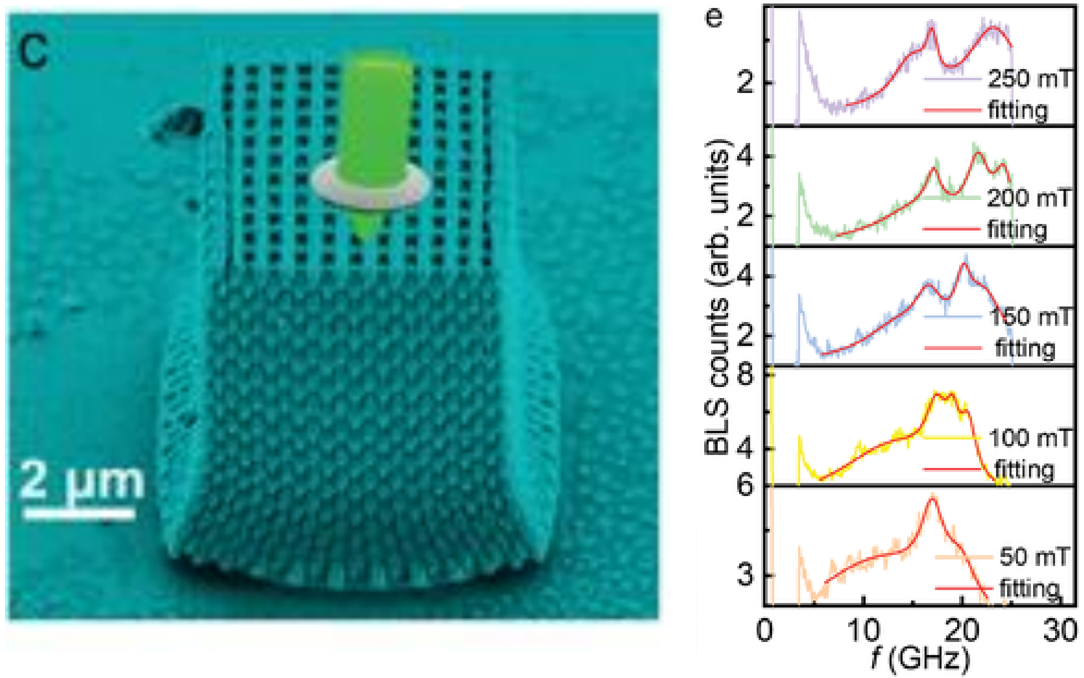


ALD: Conformal, atomic-level (self-limiting process) control of thickness, great for oxides. Here, FM metals:

Nickelocene as precursor
Water as the oxidant agent
Hydrogen for in-cycle plasma-enhanced reduction

[Giordano et al, ACS Appl. Mater. Interfaces 12, 36 (2020)]

3D artificial magnonic lattice



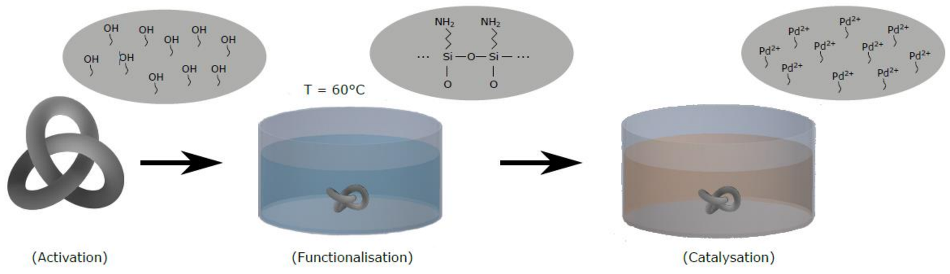
Observation of distinct Surface spin-wave modes in woodpile structure: large dipolar & exchange coupling in 3D

[Guo et al Advanced Materials 35.39 (2023): 2303292]

Electroless deposition of permalloy

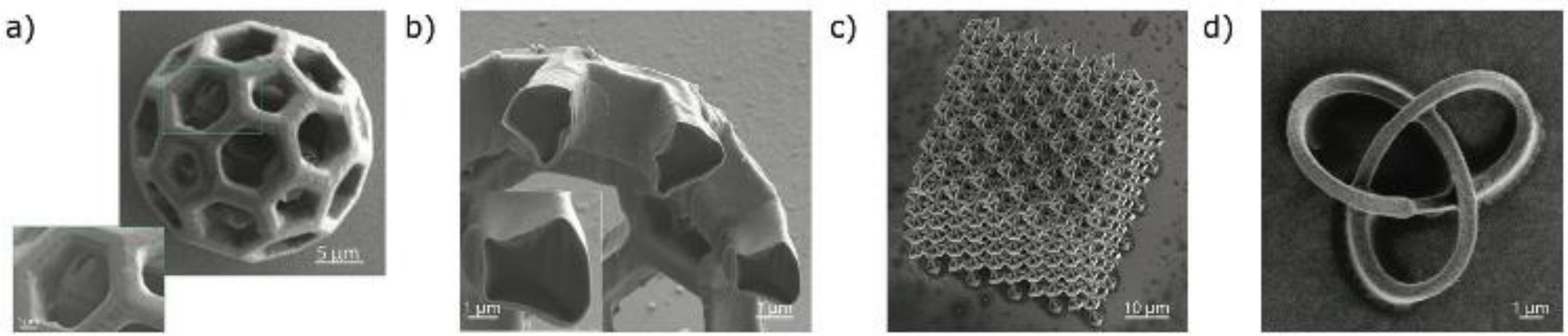
Reductant $\longrightarrow$ Oxidation product + ze$^-$ (1)

M^{z+} + ze$^-$ $\longrightarrow$ M (2)



Electroless deposition

Similar process than electrodeposition, but without applying potentials or currents
Catalytic process with sample immersed in liquid, promoted by reduction agent



Successful coverage of a variety of 3D geometries

[Pip et al, Small 16, 2004099 (2020)]

Synthesis techniques for 3D nanomagnetism covered in this tutorial

Nanofabrication

Direct-write	FEBID/FIBID	Two-photon polymerization	FIB
Templates	AlO_x & polycarbonate membranes	Self-assembly	Nanocomposites
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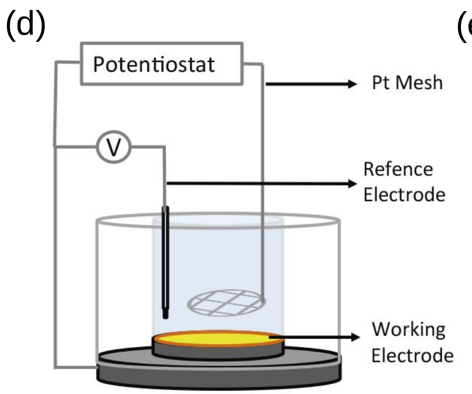
In combination with growth techniques

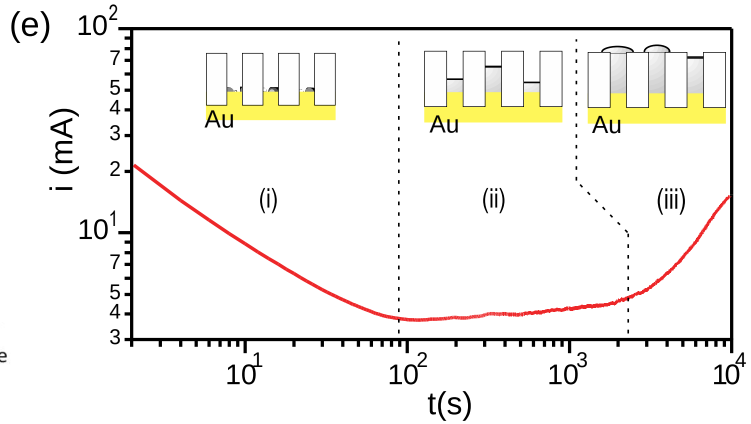
By itself	PVD	CVD	ALD	Electro-deposition	Electroless deposition	Bulk	Nanoparticle

Electrodeposition of templates: fundamentals

* thanks to Sandra Ruiz-Gómez

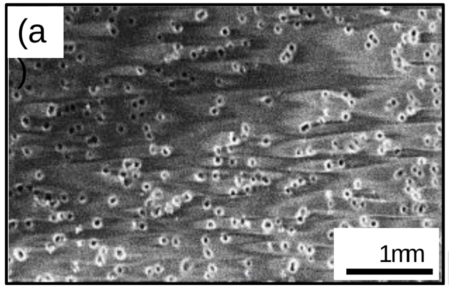
Electrodeposition process



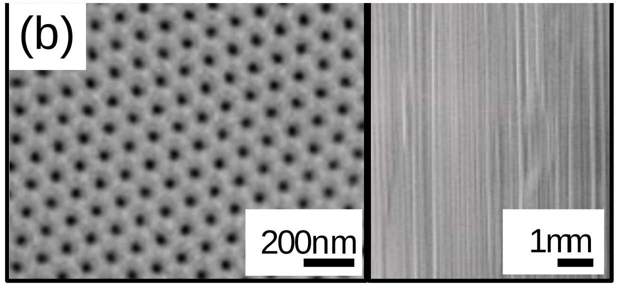


Back electrode (cathode)
Potential between cathode and reference electrode in electrochemical cell
Current monitoring to control growth regimes

Templates for nanowire deposition: very large areas possible



Etched ion-track polymeric nanoporous membranes (random, 10-100nm diameter)



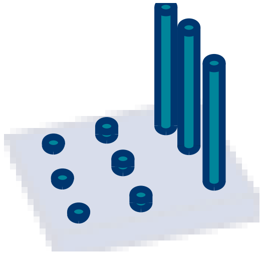
Self-organized alumina templates (self-organized, hundreds to tens of nm)

Electrodeposited systems: great flexibility

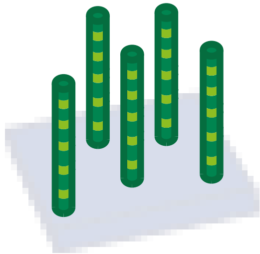
* thanks to Sandra Ruiz-Gómez

Versatile technique

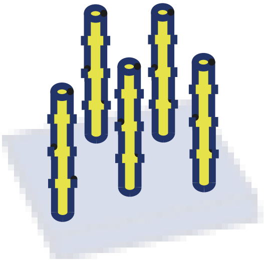
Nanodots and Nanowires



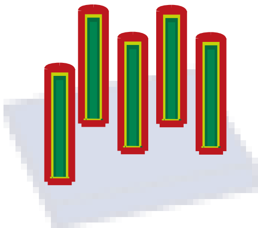
Chemically modulated NWs



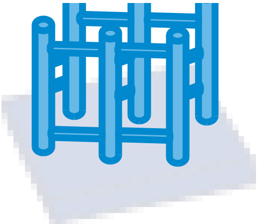
Bamboo-like NWs



Multi-shell NWs



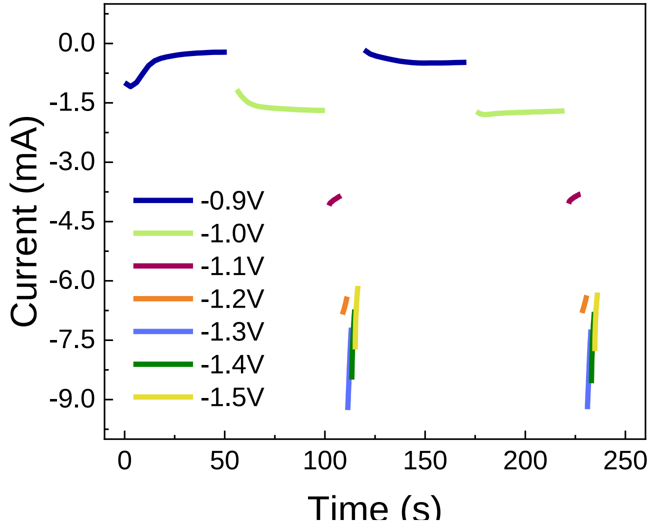
Lattices of interconnected NWs

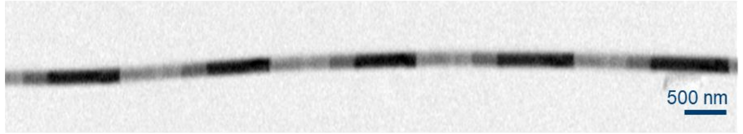


- ✓ High quality materials
- ✓ Conformal growth
- ✓ Wide range of materials (alloys, oxides, …)
- ✓ Combination with e.g. ALD
- ✓ Cheap

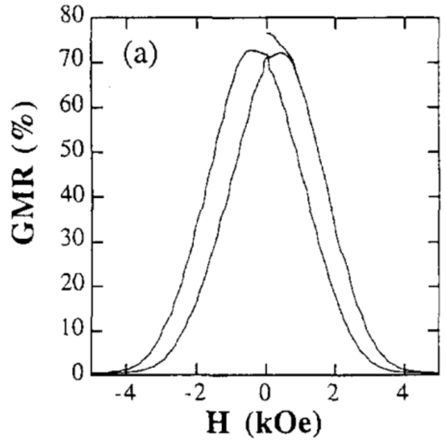
More limited geometries than direct write

Multilayered materials





- Dark areas: Fe rich regions
- Brighter areas: Ni rich regions



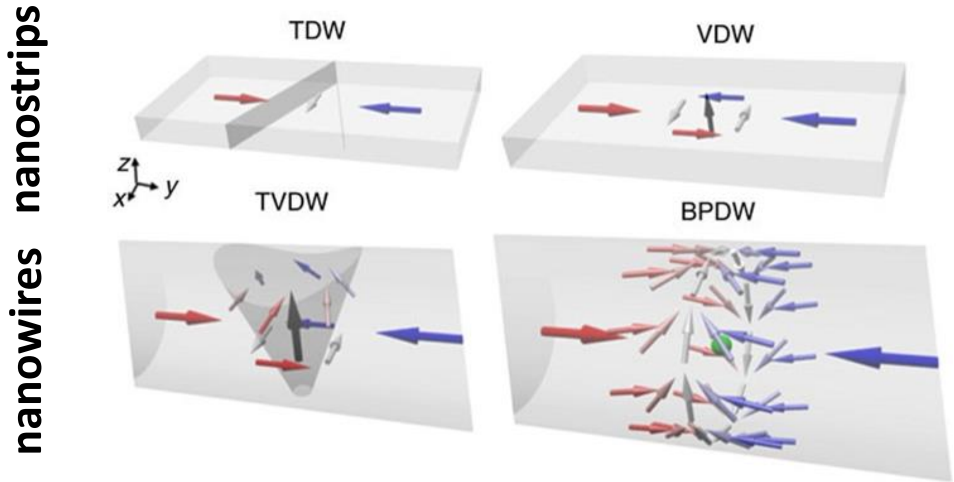
Capable of creating multilayered materials down to 5 nm aprox in thickness

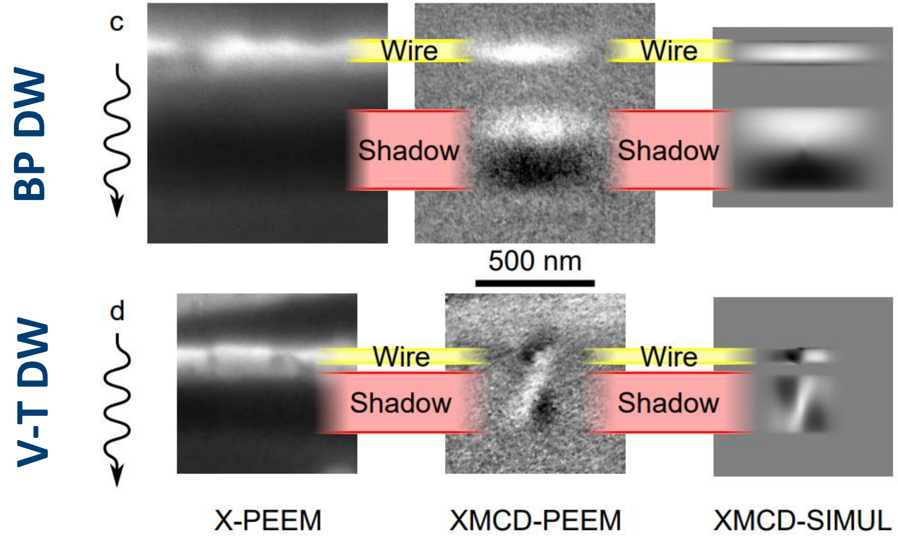
Not capable to grow ultra-thin layers with e.g. PMA or DMI

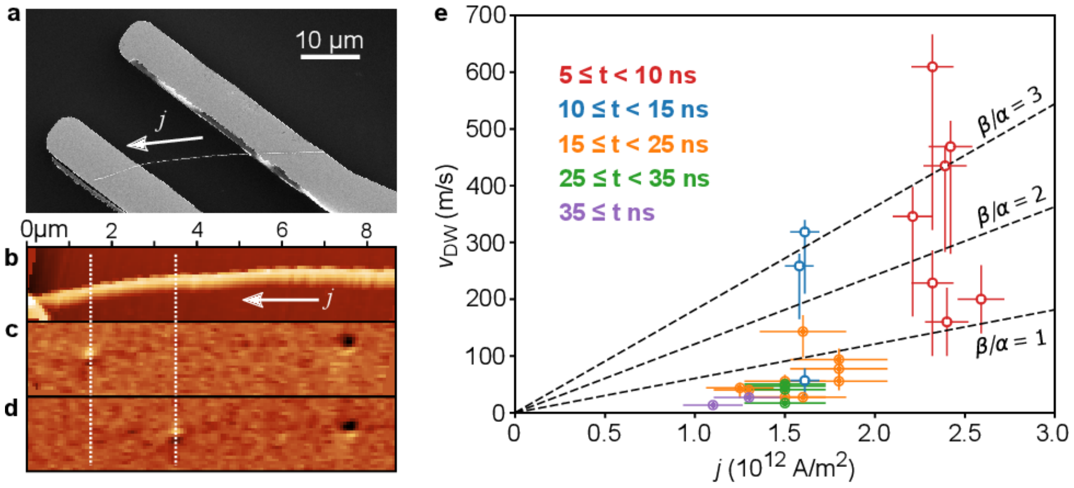
[Piraux et al. JMMM 175.127-136 (1997)]

Domain walls in cylindrical nanowires: spin singularities

[Da Col, Phys. Rev. B 89, 180405 (2014)
Schöbitz et al, Phys. Rev. Lett. ***123****, 217201 (2019)]*







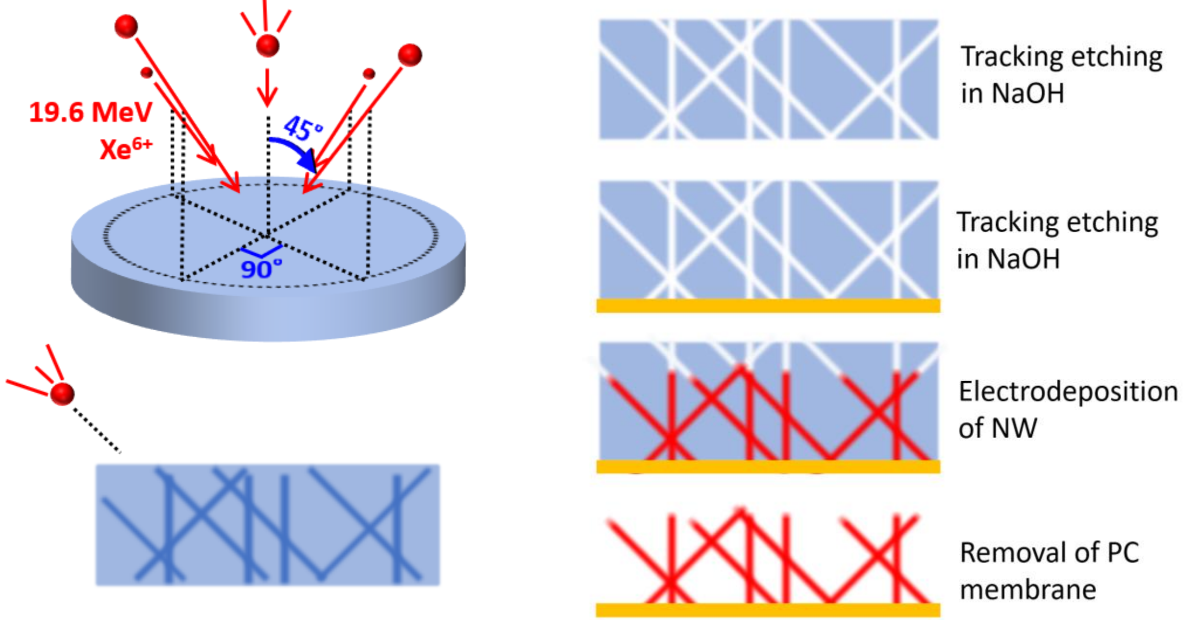
Experimental observation of Bloch-point domain walls

Strong influence of Oersted field to stabilize them & favour high-speed motion

Formation of highly-interconnected 3D nanowire networks

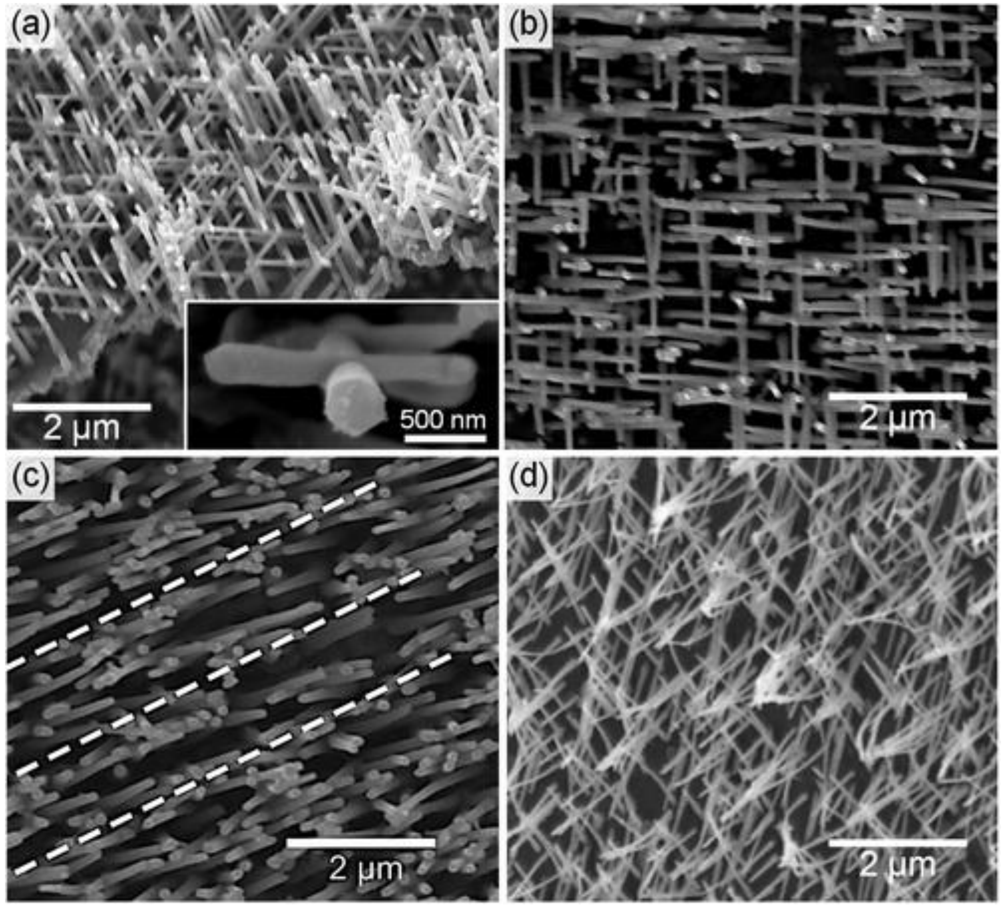
* thanks to Kai Liu

[Burks, Liu et al, Bull. APS ***58****, U20.07 (2013)*
Burks, Liu, et al, Nano Lett. ***21****, 716 (2021)]*



Polycarbonate membranes etched at multiple angles (normal incidence + additional irradiation at 45-degree colatitude angle

Continum propagation of domain walls identified by FORC (memristive behaviour)

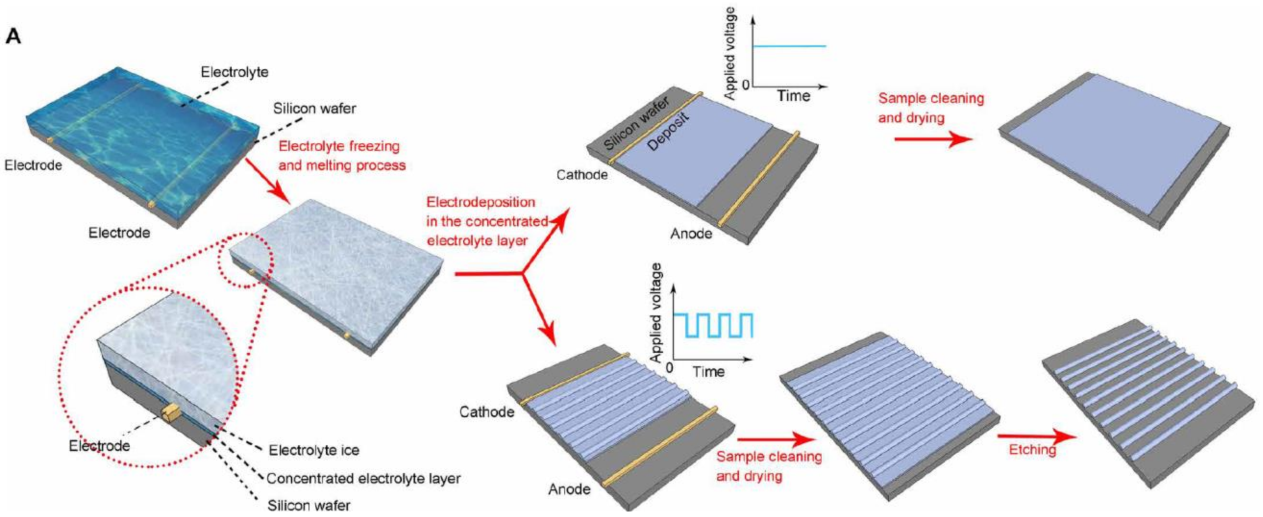


Quasi-ordered Interconnected metallic nanowire networks constructed via multiple angle ion-tracking and electrodeposition

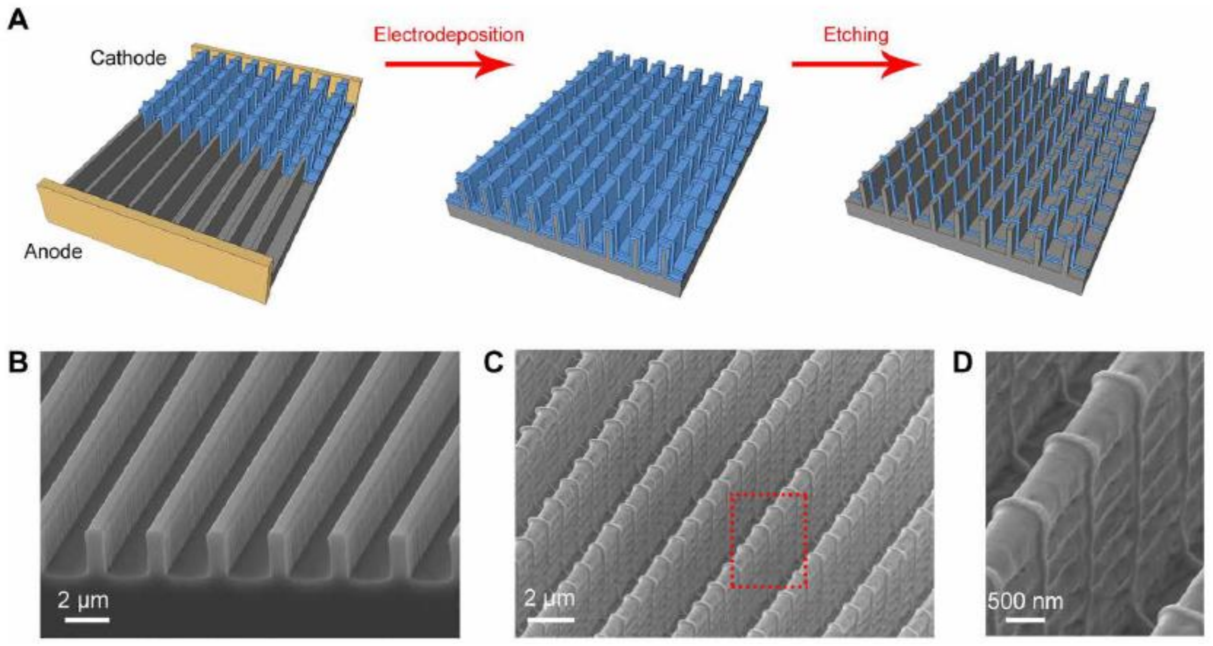
Growth of nanowires by electrodeposition without a template

* thanks to Kai Liu

[Chen et al., Sci. Adv. 8, eabk0180 (2022)]



Freezing of the electrolyte solution
Ultra-thin electrolyte in between substrate and frozen film: thickness modulated by voltage across lateral electrodes



Applied to pre-patterned substrates:
3D racetracks!

Synthesis techniques for 3D nanomagnetism covered in this tutorial

Nanofabrication

Direct-write	FEBID/FIBID	Two-photon polymerization	FIB
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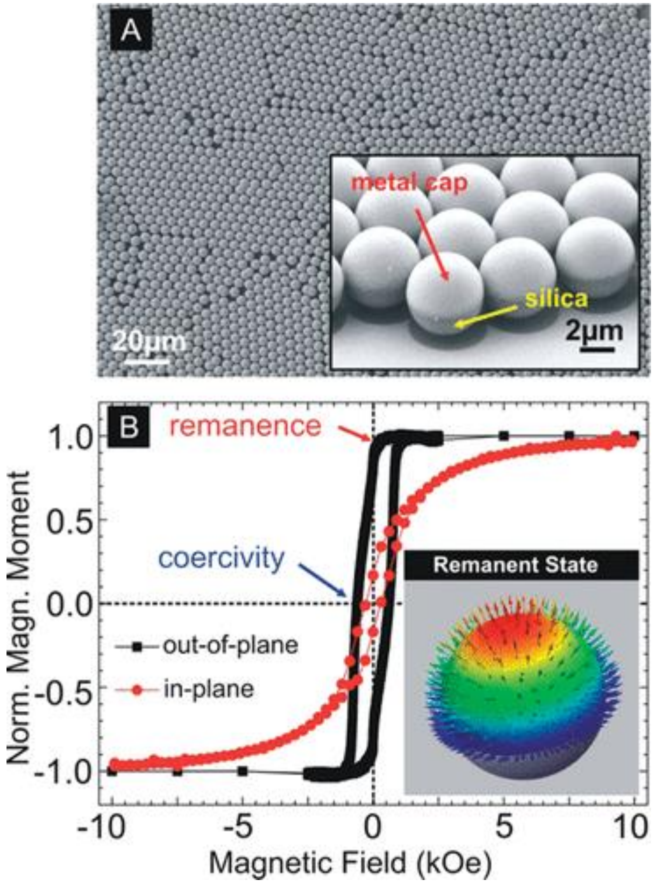
In combination with growth techniques

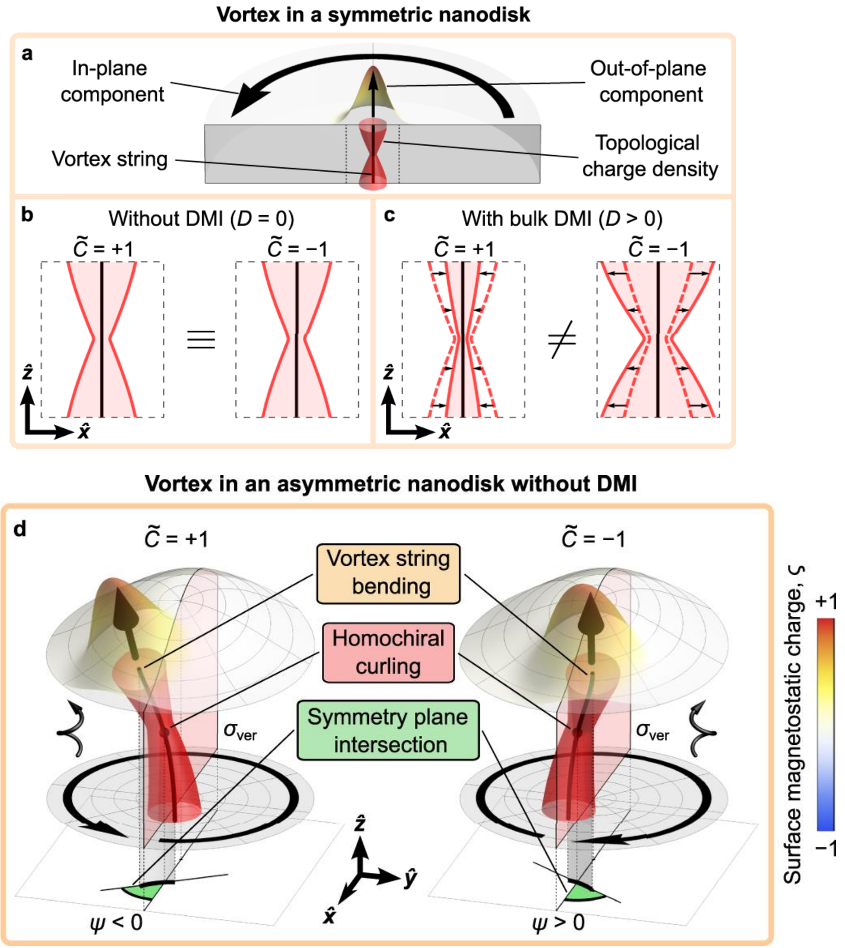
By itself	PVD	CVD	ALD	Electro-deposition	Electroless deposition	Bulk	Nanoparticle

Self-assembled nanoparticles + PVD



Self-powered colloidal Janus motors

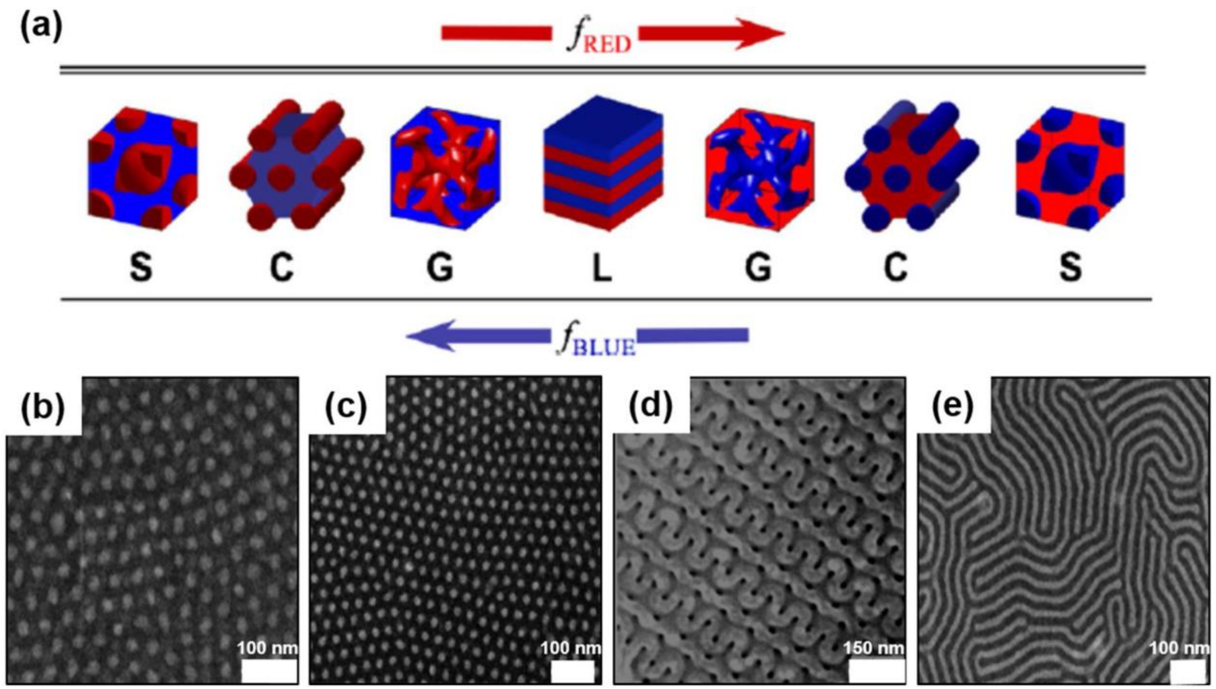
[Baraban et al, *ACS Nano* 6, 3383–3389 (2012)]



Source of curvature-DMI

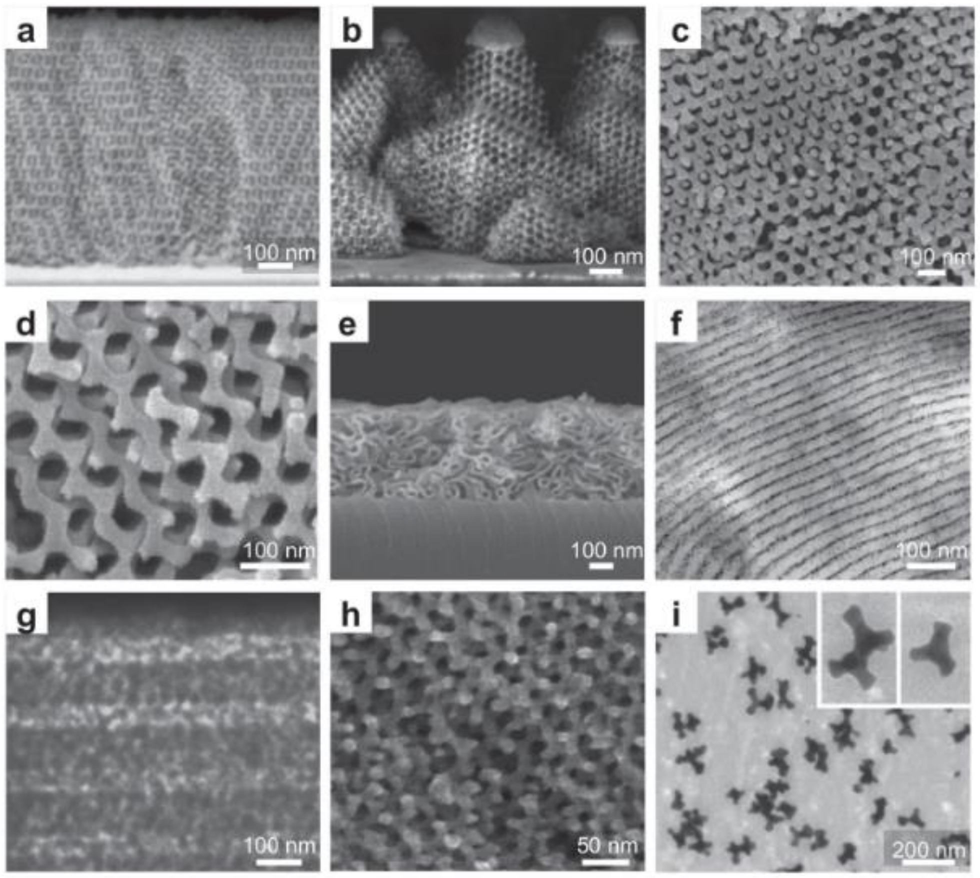
[Volkov et al, Nature Com. 14, 1491 (2023)]

Block co-polymer self-assembly



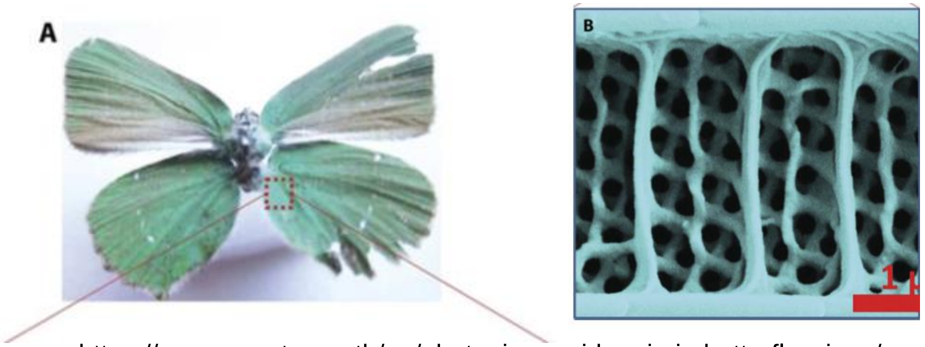
BCP morphologies based upon respective volume fraction change between two/three constituent polymer blocks

[Cummins et al. Nano Today 35 100936 (2020)]

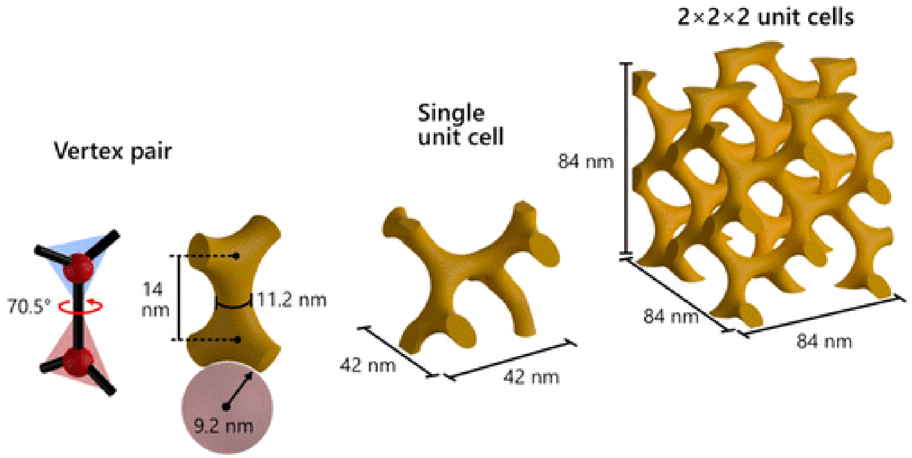


[Ross et al, Adv. Mater. 26, 4386 (2014)]

Single and double gyroid nanostructures

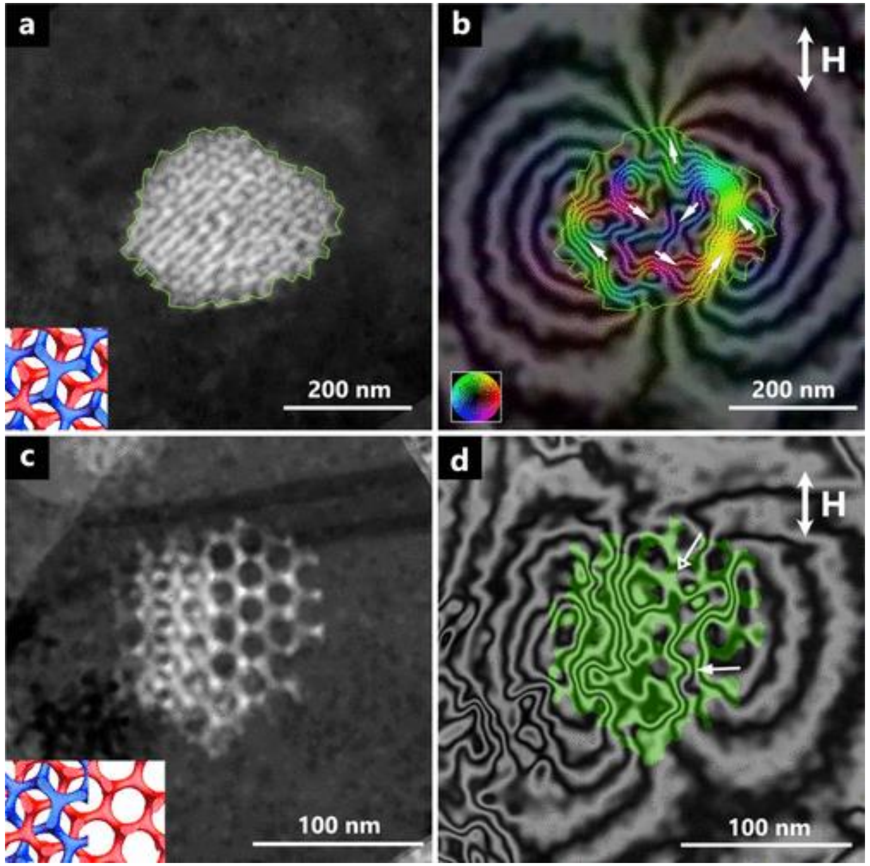


https://www.nanotec.or.th/en/photonic-gyroids-mimic-butterfly-wings/



Electrodeposited material inside the extremely small 3D gyroid templates

[Llandro et al, Nano Lett. 20, 3642–3650 (2020)]



Observation of complex magnetic remanent states in single and double gyroid structures: route towards high interconnectivity, frustration & curvature effects

Synthesis techniques for 3D nanomagnetism covered in this tutorial

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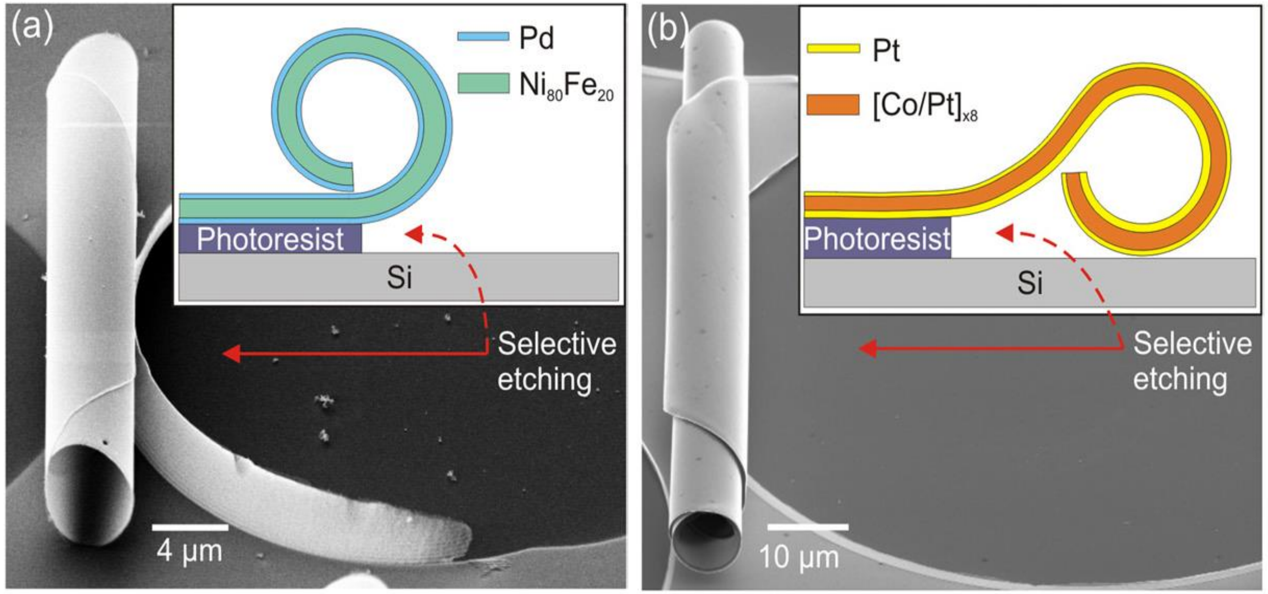
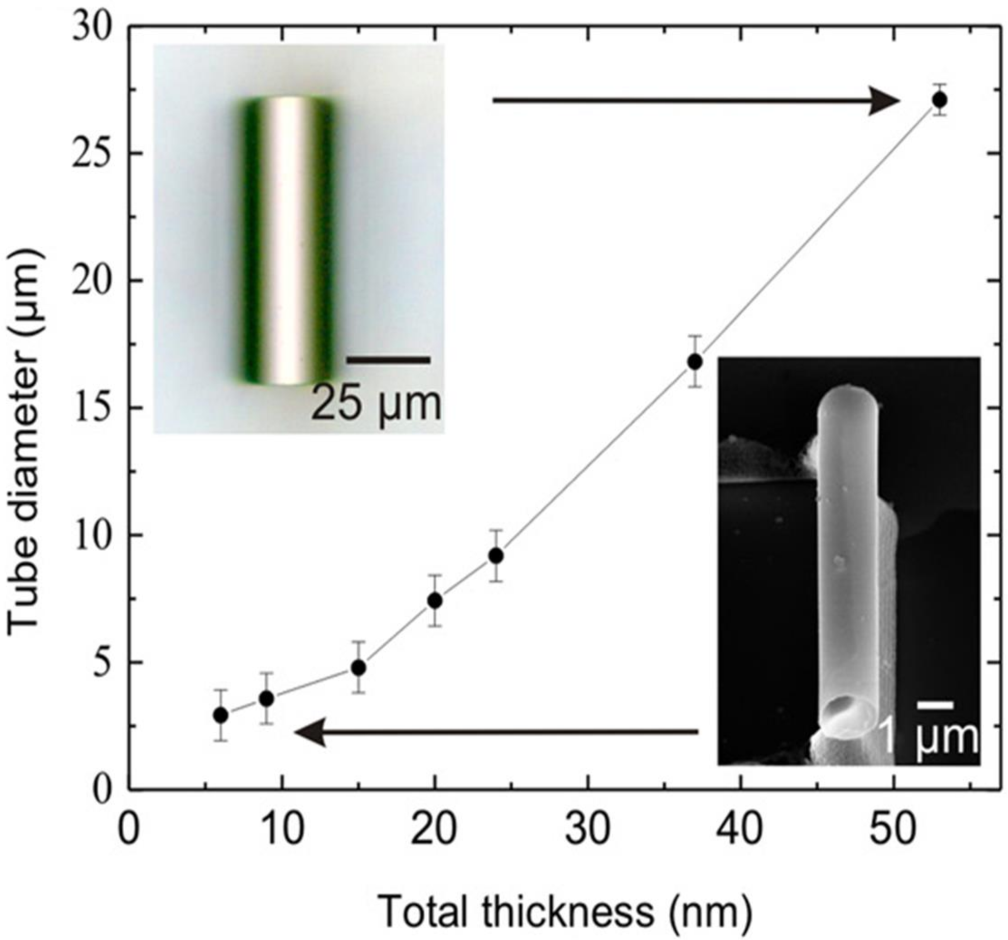
Rolled-up technology

* thanks to Denys Makarov



Photoresist acting as sacrificial layer
Roll-up depends on strain

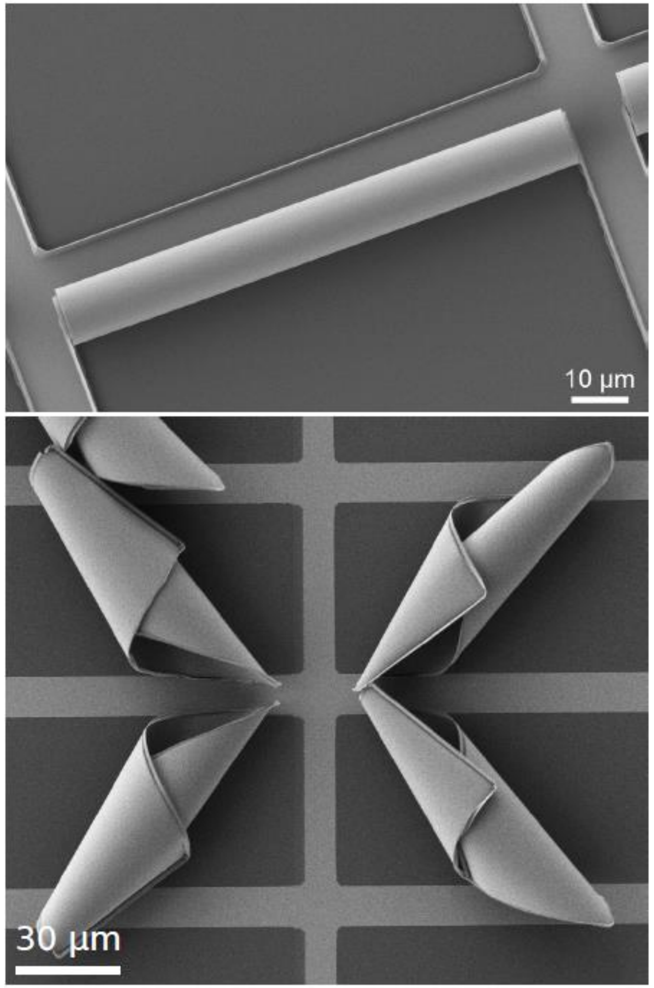


Tunable diameter (typically a few micron) of rolled-up tubes
Control of number of windings in “Swiss-roll architecture”
Wide class of materials, including multilayered heterostructures

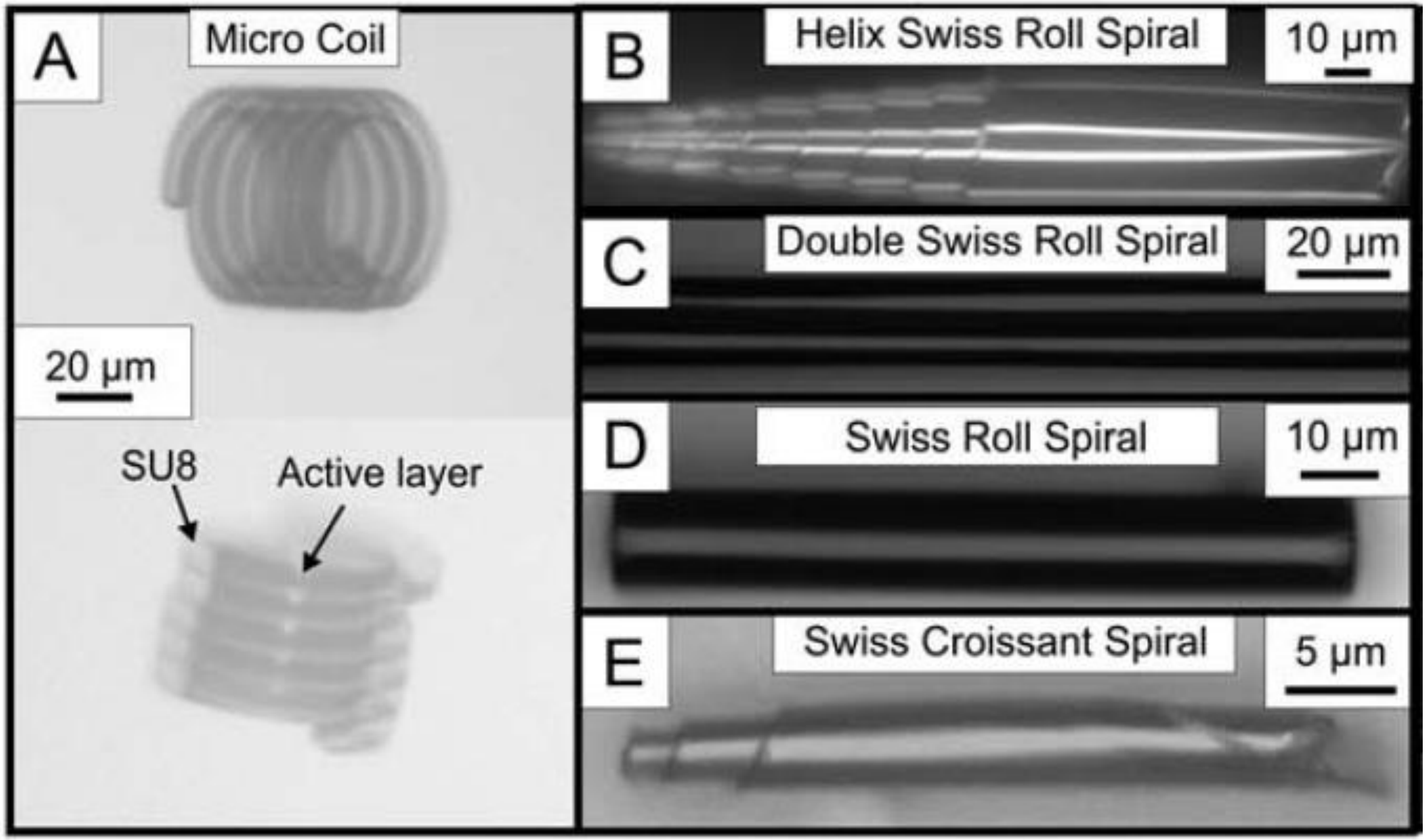
[Bermúdez-Ureña et al., *J. Phys. D: Appl. Phys.* **42**, 055001 (2009)]
[Mei et al., Adv. Mater. ***20****, 4085 (2008)]*

Strain-engineered architectures (“Origami”)

* thanks to Denys Makarov

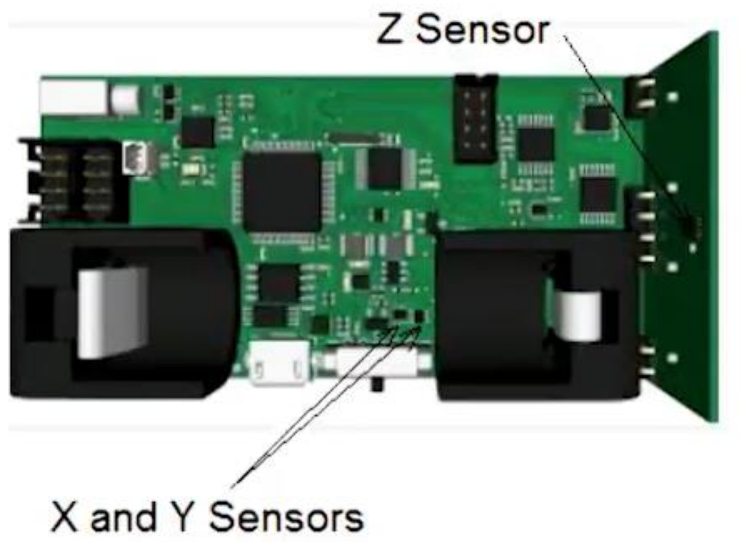


Courtesy: Robert Streubel



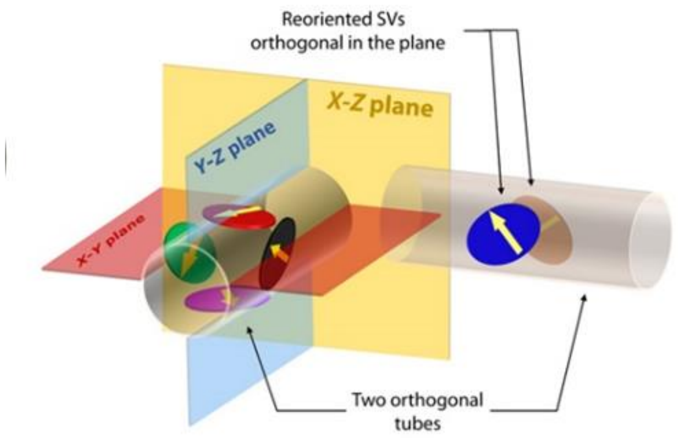
[Smith et al., Phys. Rev. Lett. ***107****, 097204 (2011); Smith et al., Soft Matter* ***7****, 11309 (2011)]*

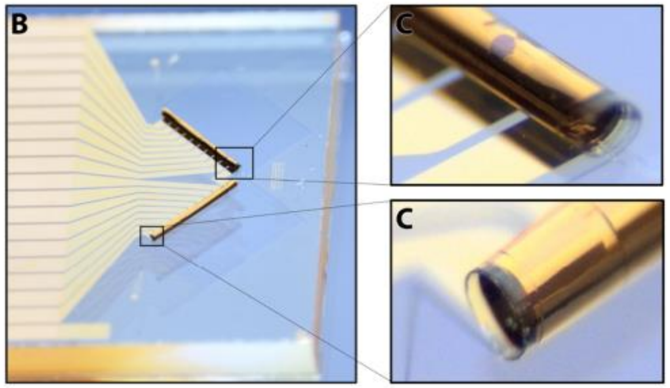
Straightforward on-chip integration: 3D field nanomagnetic sensors



https://rutronik-tec.com/infineon-3d-magnetic-sensor-tlv493d-a1b6-for-consumer-and-industrial-markets/

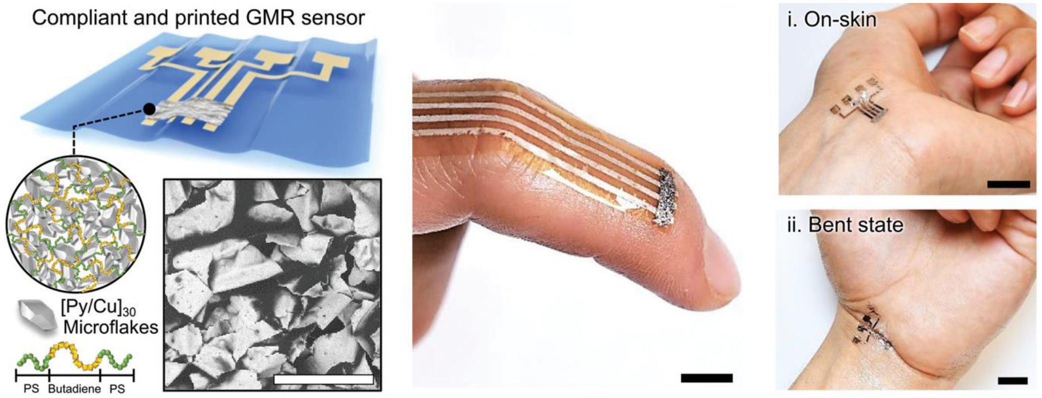
Standard approach for 3D magnetic field micro-sensors:
3 linear Hall sensors: additional daughter board for z-axis→ complex and costly
How to do it micro/nano?





[Ha et al, Adv. Mater. 33, 2005521 (2021)]

Rolled-up technology : GMR sensors on different planes
Vector angular encoders in all directions



Towards flexible magnetic electronics
e-skin susceptible to strain & magnetic fields

[Becker et al, Sci. Adv. 5 : eaay7459 (2019)]

Synthesis techniques for 3D nanomagnetism covered in this tutorial

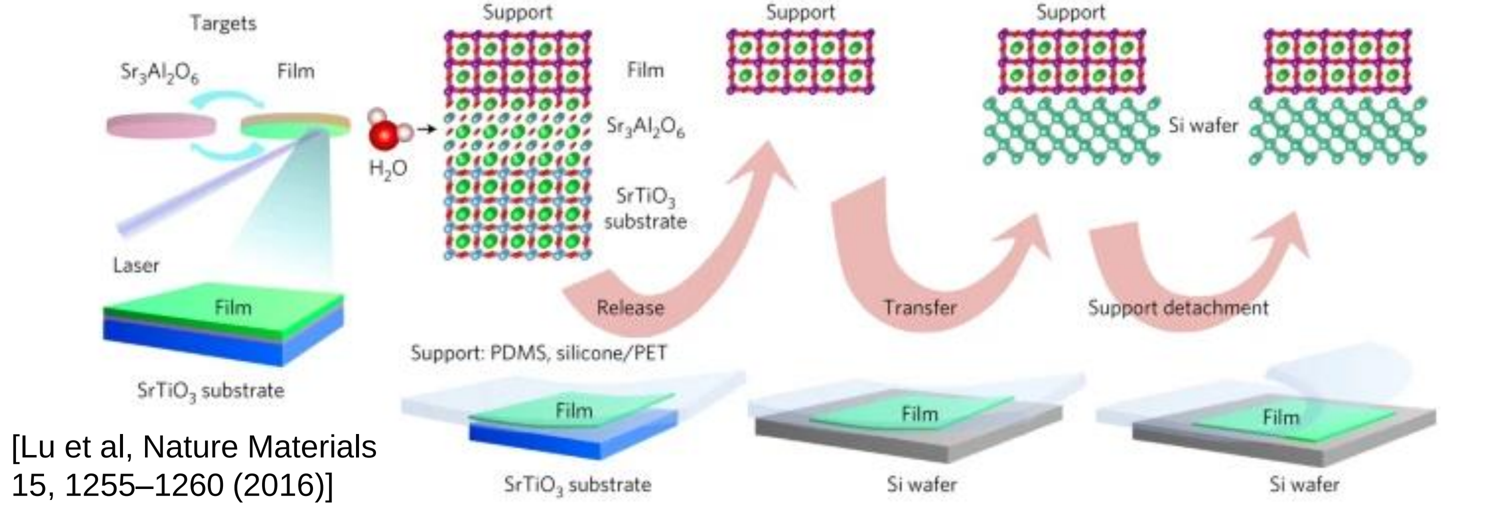
Nanofabrication

Direct-write	FEBID/FIBID	Two-photon polymerization	FIB
Templates	AlO_x & polycarbonate membranes	Self-assembly	Nanocomposites
PVD-thin film based	Rolled-up	Free-standing	GLAD

In combination with growth techniques

By itself	PVD	CVD	ALD	Electro-deposition	Electroless deposition	Bulk	Nanoparticle

Free-standing metallic layers on pre-patterned substrates for 3D racetracks

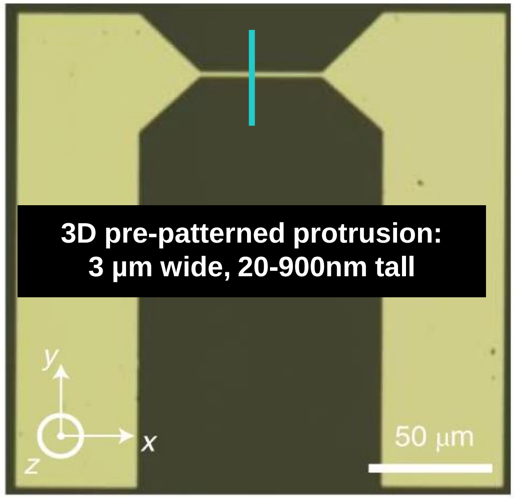


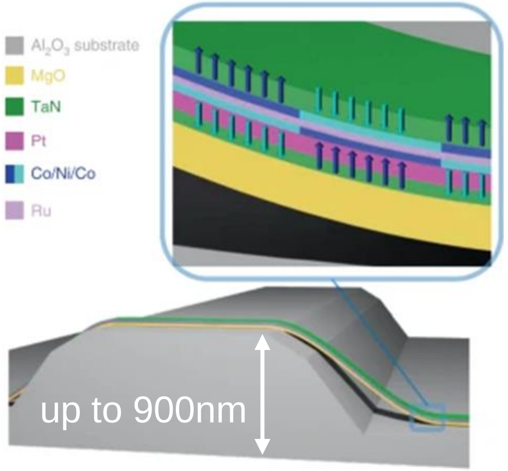
[Lu et al, Nature Materials 15, 1255–1260 (2016)]

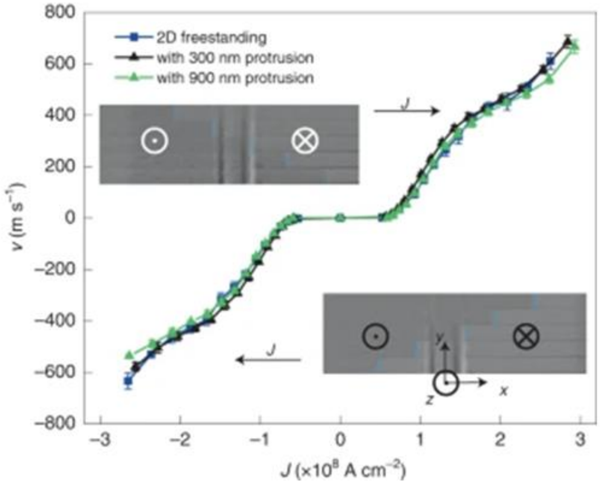
Fabrication method previously applied to oxides

Proof-of-concept method for the fabrication of 3D vertical racetracks

SOT- based CIDWM highly unaffected, particularly for SAFs



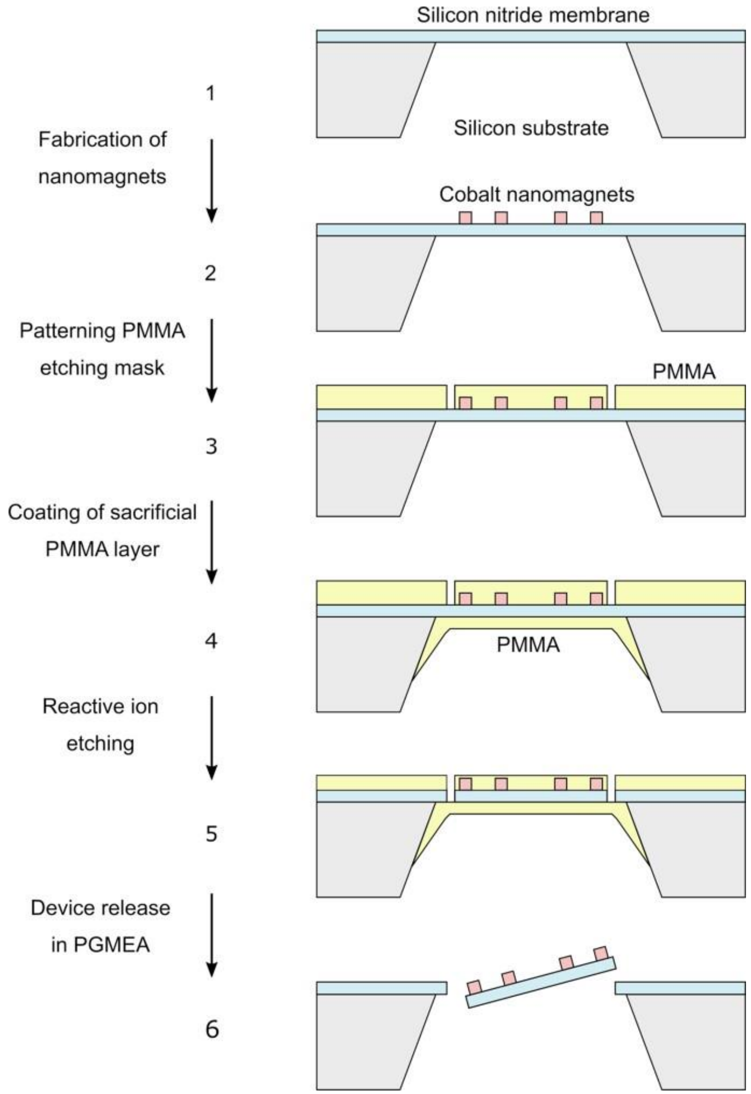




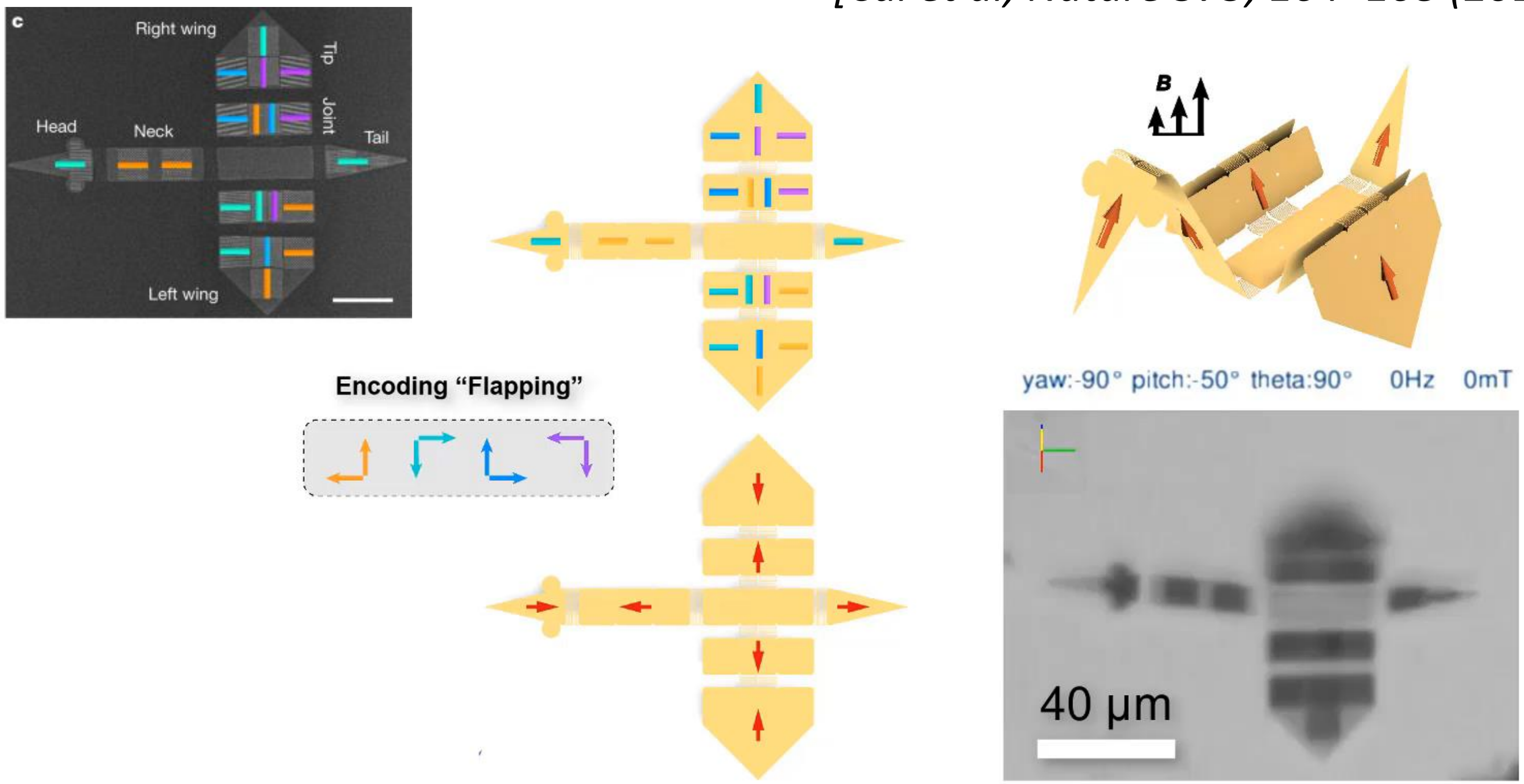
Freestanding-2D vs Freestanding-3D

[Gu et al, Nature Nanotechnology 17, 1065–1071 (2022)]

Free-standing micro robot with multiple motion degrees of freedom

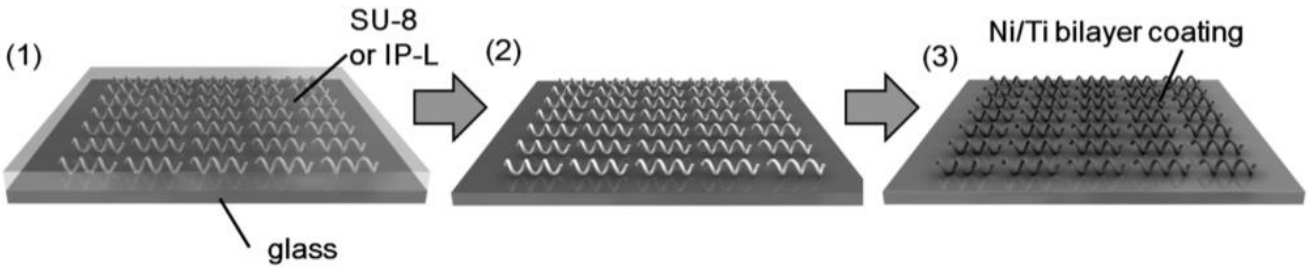


[Cui et al, Nature 575, 164–168 (2019)]

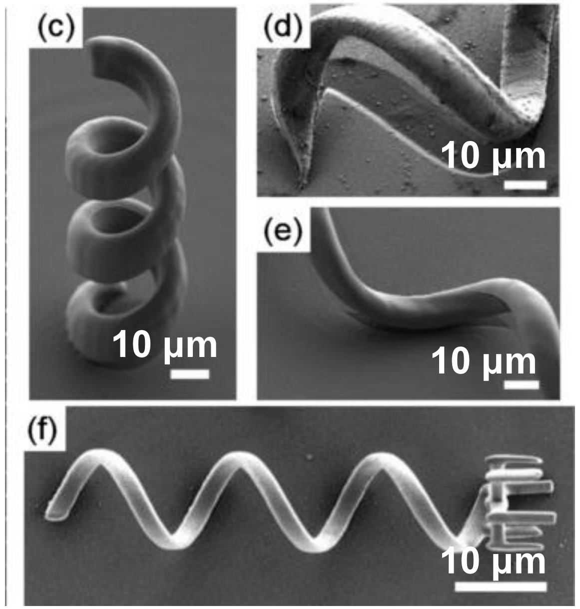


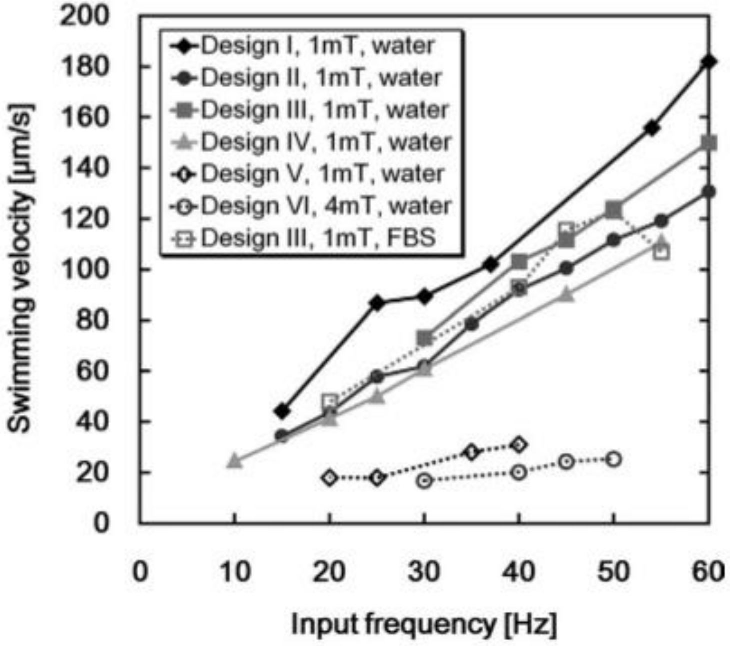
Artificial reprogrammable bird microbot formed by nanomagnets connected via soft sections
Encoding for flapping, hovering, turning & side-slipping

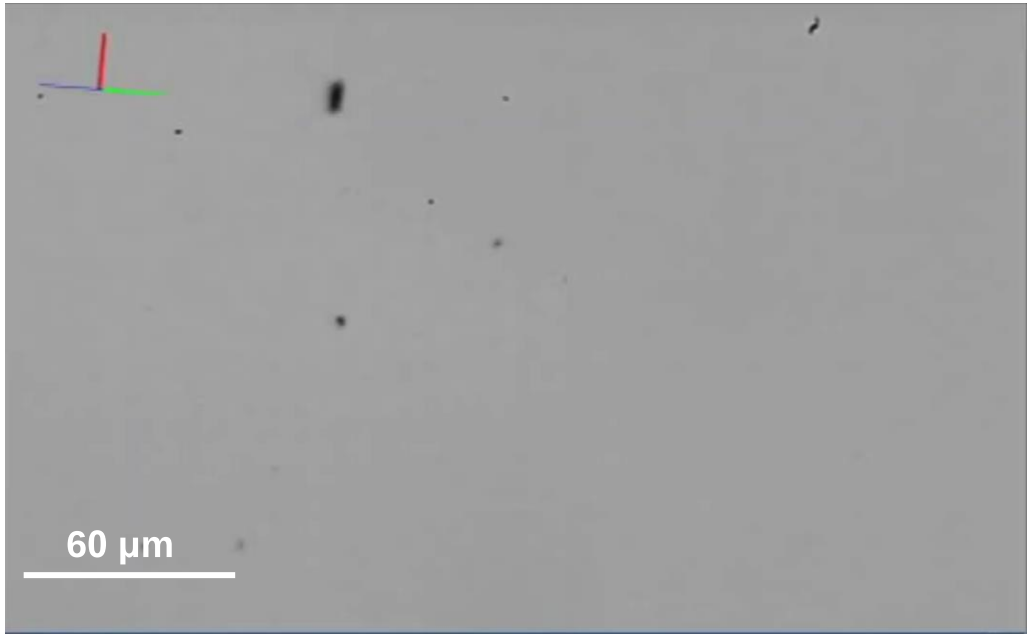
Helical micro-swimmers with SU8 lithography



SU-8 optical lithography +e-beam evaporation for micrometric helical structures







- **Bio-compatible**
- **Remotely driven by rotating fields coupled to chiral geometry**
- **Excellent swimming performance**
- **New optimised geometries for multiple swimming strokes**

[Tottori et al, Adv. Mater. 24 811-816 (2012)]

Synthesis techniques for 3D nanomagnetism covered in this tutorial

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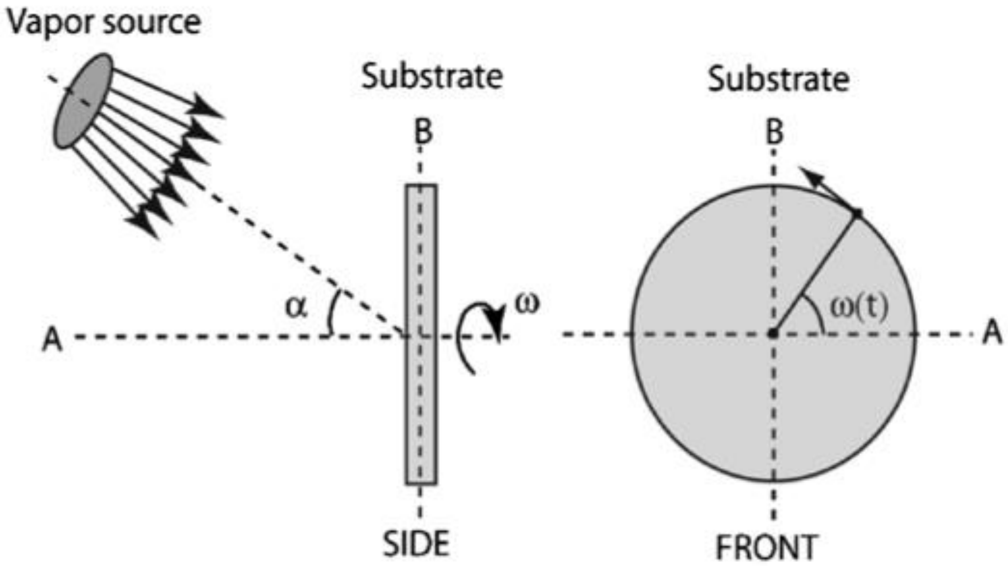
Glancing Angle Deposition (GLAD)

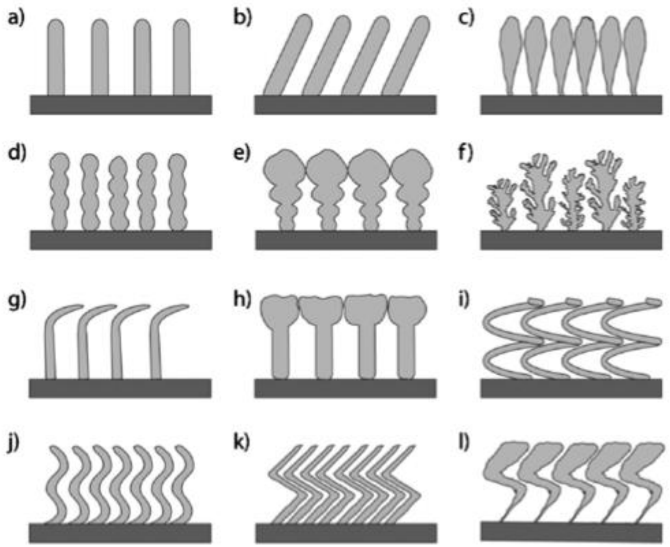
* thanks to CD Phatak



Nanostructure morphology controlled by

- Incoming particle flux at a high angle (α ~ 80 - 90°)
- Substrate rotation (speed, direction)

Possible geometries



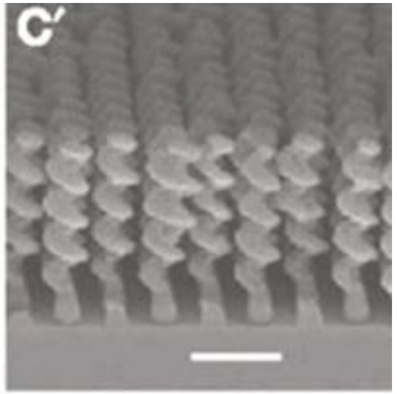
Site specificity

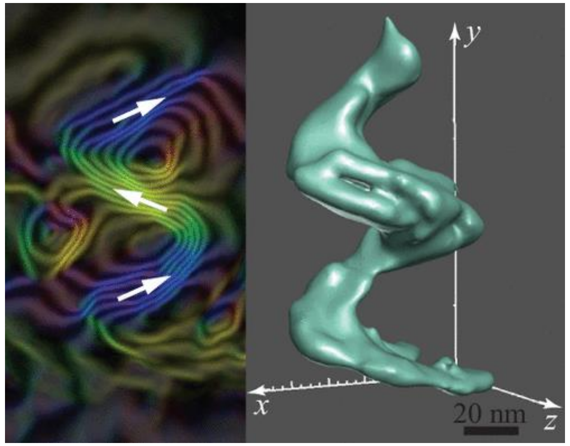
Double layer resist

Pre-patterned Au dots

[K. Robbie, et al. Review of Scientific Instruments 75(4), 1089–1097 (2004)]

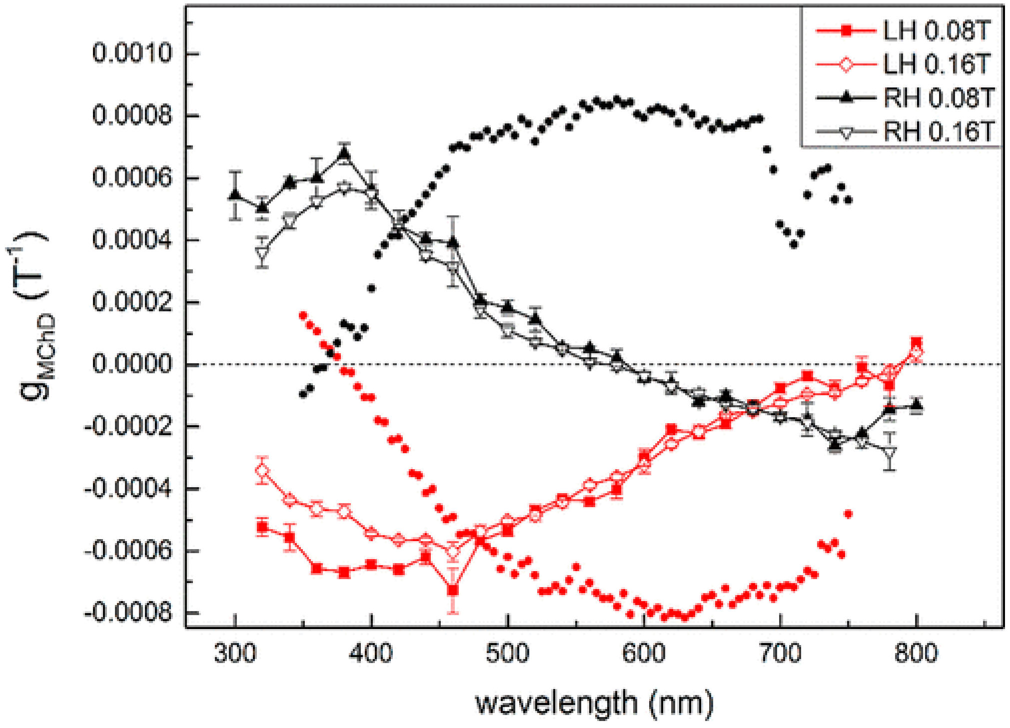
Magneto-chiral dichroic effects in GLAD helices

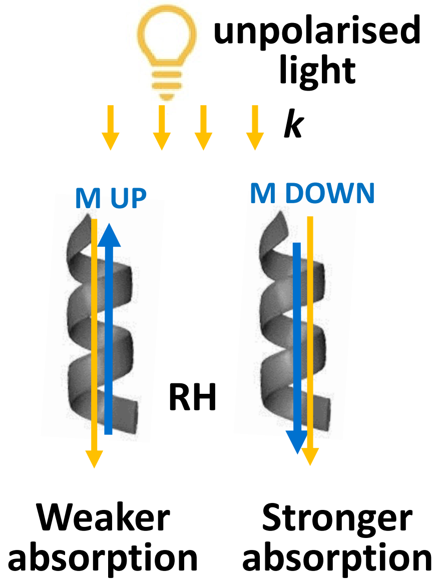




Chiral artificial nanomaterial: helical monodomain antiparallel state

[Eslami et al, ACS Photonics 1, 1231–1236 (2014); Phatak et al, Nano Letters 14,759-764 (2014)]





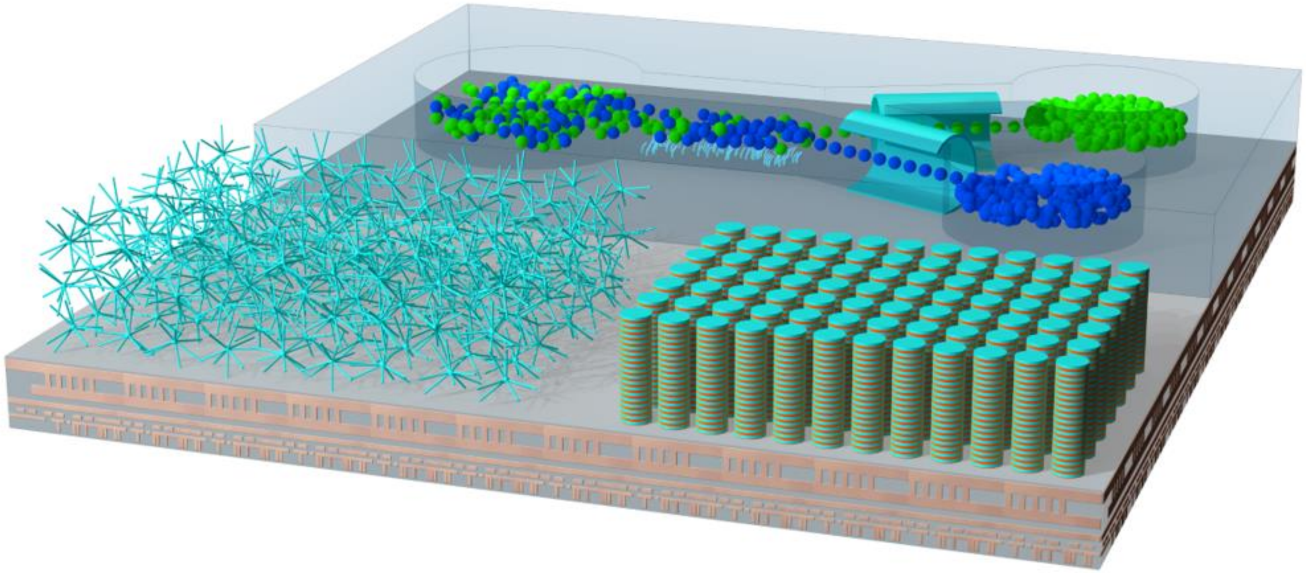
Magnetochiral dichroic effect observed in the visible

Effect normally present in molecules: simultaneous spatial & time reversal symmetry breaking

Conclusions & thank you

Synthesis of 3D nanomagnets:

- Flourishing field leading to new scientific discoveries
- Application to real technologies is currently limited
- Each technique has prons & cons
- Combination leads to advanced functionalities



Thank you to all contributors: Sam Ladak, Kai Liu, Denys Makarov, CD Phatak, Sandra Ruiz-Gómez, (Benjamin Jungfleisch, Peter Fischer)