CYLINDRICAL MAGNETIC NANOWIRES: GEOMETRY, MAGNETISATION AND APPLICATIONS

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Emerging magnetism phenomena are observed in curvilinear nanostructures. Particularly, cylindrical metallic nanowires are attracting much attention because of their singular magnetic configurations and remagnetisation processes as determined by advanced microscopy techniques and micromagnetism. Profiting of curvature, applications are envisaged in spintronics, spincaloritronics, sensors, robotics or biomedicals.

Emerging curvilinear magnetic nanostructures

The effects of the curvature on the magnetism of nanostructures is increasingly attracting the attention of the magnetic community. Curvilinear magnetism explores purely geometry-induced effects so that, the manipulation of curvature enables the realisation of chiral magnetic textures with unprecedented novel phenomena, where nanomaterials are expected to lead to a new generation of technological applications [1].

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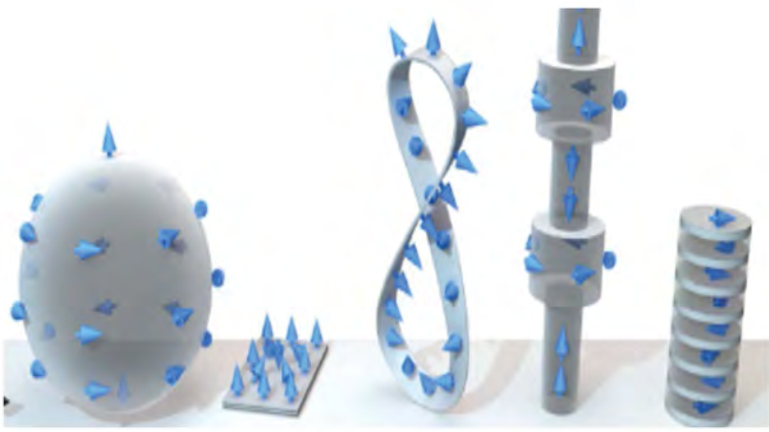


▲ **FIG. 1:** Novel 3D curvilinear magnetic nanostructures: from a magnetic sphere with vortex configuration to a magnetic thin film element with a skyrmion, a Möbius strip with perpendicular magnetisation, a modulated cylindrical nanowire, and an antiferromagnetic superlattice with a soliton in the center (adapted with permission from Ref.1 A. Fernandez-Pacheco *et al.*, Nature Comm. 8 (2017) 15756), Copyright 2017, Springer Nature).

Theoretical studies and sophisticated experimental techniques have recently established that curvature by itself induces exchange driven interactions as specific magnetic anisotropy and antisymmetric exchange (*i.e.*, interfacial Dzyaloshinkii-Moriya interaction), but also non-trivial topological nanostructures, induced magnetochirality, or spin waves emission during the domain wall motion in the magnonic regime. Topologically protected spin textures as skyrmions are novel curved structures studied in 2D nanostructures under the action of fields and current while more exotic magnetic configurations are predicted in curvilinear nanostructures as nanowires, nanohelices or rolled up flexible thin films and multilayers [2].

Applications based on individual and patterned arrays of nanomagnets are in progress, however their technology requires a deeper knowledge & control of the magnetism of individual units. 3D nano-architectures are candidates to substitute current 2D technologies in areas of magnetic recording, spintronics or memory devices (Figure 1).

3D Cylindrical Nanowires

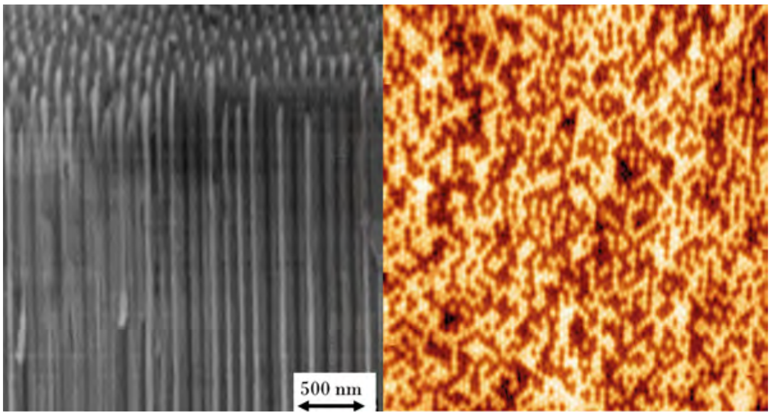
The simplest case of curved nanomagnet is that of cylindrical nanowires, NW [3]. Their controlled growth (*i.e.*, diameter from 20 to 400 nm and length from 100 nm to 40 μm) is currently achieved by less-expensive electrochemical routes. Metallic magnetic elements and alloy nanowires with desired composition are electrodeposited inside the porous of templates previously prepared by tailored anodisation processes (Figure 2).

Theoretical and micromagnetism studies predicted novel remagnetisation aspects as a magnetochiral-induced asymmetric wall velocity, the presence of Bloch-point walls, the lack of their Walker breakdown, or the appearance of skyrmion tubes as an extension of the skyrmions in planar films [1-3]. The 3D magnetic configuration of nanowires, conventionally considered as 1D materials, has been determined thanks to most advanced experimental techniques. Particularly, synchrotron light allowing for Photo-Electron Emission Microscopy, PEEM, and X-ray Transmission Electron Microscopy, XTEM, with X-ray Magnetic Circular Dichroism, XMCD, analysis in combination with micromagnetic simulations have enabled the unveiling the internal magnetisation distribution within the circular cross section of nanowires. Vector Field Electron nanotomography, VFET, permits the reconstruction of 3D magnetic field inside the nanowires, while Scanning Nitrogen-Vacancy Magnetometry, SNVM, resolves local magnetic inhomogeneities. In short, the radial and axial profiles of perpendicular and axial components of magnetic moments have been established [4].

Engineering cylindrical geometry, magnetic domains and reversal mechanisms

Two magnetic energy terms determine the domain structure and remagnetisation of nanowires: i) the intrinsic cylindrical shape anisotropy that is a function of the length to diameter aspect ratio, and ii) the magnetocrystalline anisotropy that reflects the crystal lattice symmetry (*i.e.*, cubic or hexagonal) which is essentially a function of the nanowire composition.

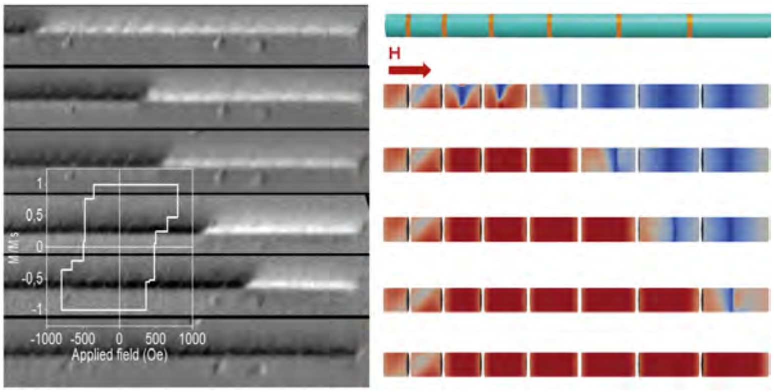
The cubic (fcc or bcc) crystalline anisotropy of FeCoNi nanowires with less Co content is mostly overcome by their shape anisotropy (*i.e.*, typically uniaxial). At remanence, cubic nanowires present a giant axial domain but at their ends where local closure structures reduce the total magnetic energy. Such nanowires behave as "ideal magnetic dipoles" as observed by magnetic force microscopy, MFM, where the axial remagnetisation takes place by fast propagation of a Bloch-point domain wall. Those nanowires with high Co content show hcp hexagonal symmetry with large anisotropy constant and near perpendicular magnetisation easy axis (*i.e.*, c-axis). They present complex transverse and vortex domain structures and remagnetise through rotational processes involving helical vortex and skyrmion-tube structures [5]. Most recent studies address the remagnetisation under current and magnetic field. Pulsed current of controlled amplitude generates non-uniform circumferential fields •••



▲ **FIG. 2:** Left: An array of standing Co nanowires; Right: magnetic force microscopy, MFM, image of an array of Ni nanowires at remanence, where the labyrinth distribution of dark/clear spots represents individual nanowires with up/down magnetization (courtesy of A. Asenjo).

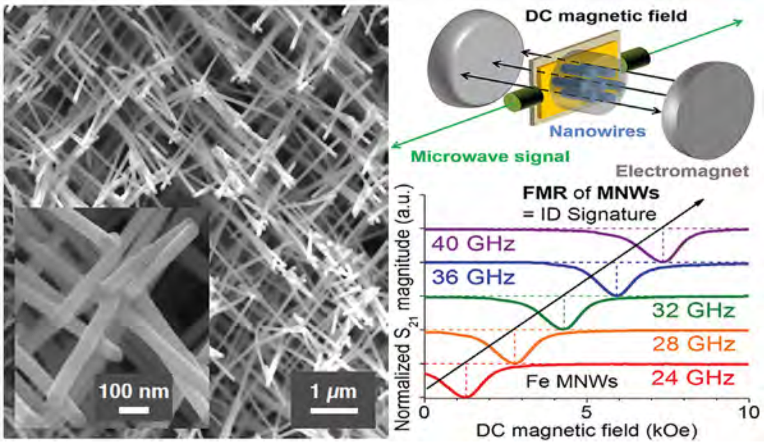
> **Cylindrical nanowires and their 3D arrays emerge as a new generation of nanomagnets with applications in novel spin-related phenomena, biomedicine and sensors devices.**

▼ **FIG. 3:** Left: PEEM images of the unidirectional magnetization ratchet of a FeCo/Cu multisegmented nanowire (120 nm diameter, 20 µm long) where the FeCo magnetic segments increase their length from the left end (see the upper scheme to the right), and sequence of PEEM images under indicated magnetic field, and reconstructed hysteresis loop in the inset. Right: Micromagnetic simulation of the remagnetization process starting at the shorter segments (adapted with permission from [6] C. Bran et al., ACS Nano 12 (2018) 5932, Copyright 2018, American Chemical Society).



NANOWIRES & APPLICATIONS

Cylindrical nanowires are candidates for applications in a wide spectrum of technologies [7]. Specifically, arrays of standing nanowires are proposed for hard magnets, while arrays of interconnected nanowires are considered as platforms to be tailored for memory, complex computation or neuromorphics as well as for spin-caloritronics and their magnetothermal response (Figure 4). Based on their 3D configuration, nanowires are viewed as potential building blocks for the "Internet-of-nanoThings" advanced nanotechnology where interconnected devices are expected to define a new network paradigm.

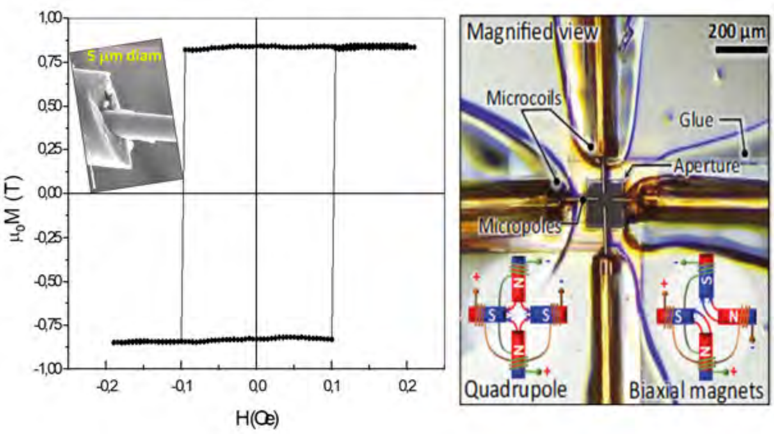


▲ **FIG. 4:** Left: Top view of interconnected nanowires network for spin-caloritronics (higher magnification in the inset) (adapted with permission from Ref. 8 T.C.S. Gomes et al., Nanomaterials 10 (2020) 2092, Copyright 2020, MDPI); Right: In ferromagnetic resonance, FMR, spectroscopy, the magnetic NWs are exposed to a radio-frequency, RF, microwave signal under a biasing DC magnetic field. By sweeping the RF frequency or DC field, the NWs absorption (i.e., the scattering parameter, S_{21}) varies which is used for its sensing (adapted with permission from [9] J. Um et al., ACS Appl. Nano Mater. 4 (2021) 3557, Copyright 2021, American Chemical Society).

••• (that eventually increase their temperature) that result in the remagnetisation under particular applied magnetic fields or helical anisotropy.

Tailoring the magnetisation process along the axial nanowire direction is very important for applications involving the controlled propagation of domain walls as in race-track-like memory, logic devices or shift registers. In this concern, a route is progressing by designing modulations along the nanowires to pin/depin the walls. These modulations can be in terms of diameter and/or composition. Modulations in NW diameter with homogeneous composition (*i.e.*, alternating segments of different diameter and length) give rise to stepped domain wall propagation where magnetic poles accumulate in the diameter-transition regions as observed by MFM, magneto-optic Kerr effect, MOKE, and Electron-Holography, EH.

▼ **FIG. 5:** Left: Bistable hysteresis loop with a single Giant Barkhausen jump in a magnetostrictive Fe-base amorphous microwire (SEM image inset); Right: Arrangement of four bistable Fe-base microwires & microcoils for multipolar local field design (i.e., quadrupole or biaxial magnet) (adapted with permission from Ref. 14 R. Huber et al., Nature Comm. 13 (2022) 3220, Copyright 2022, Springer Nature).



Modulations in composition consist of segmentations into alternating layers with different ferromagnetic, FM, character as for example FM1/FM2 segments. This type of modulations present alternating crystalline order (*i.e.*, cubic/hexagonal anisotropy as Ni/CoNi) resulting in segments with alternating axial/vortex-transverse easy magnetisation directions. Modulations can be also as FM/non-magnetic segments, where careful design of magnetic segments with increasing length from one end of nanowires allowed the observation of "magnetisation ratchet" by which remagnetisation in neighboring segments propagates sequentially in steps starting from the shorter segments, irrespective of the applied field direction (Figure 3).

Finally, great perspectives for nanowires applications are expected in the near future, however further knowledge of geometry-induced phenomena is still required as well as novel designs of nanowires and their 3D arrangements. That includes involving alternative magnetic materials, as antiferro or ferrimagnetic, or considering double segmentations geometry/composition. Particularly, spin-current effects and high-frequency magnetisation dynamic phenomena are most promising.

Multilayer nanowire arrays are particularly suitable for encoding in security systems and FMR identification (Figure 4), in spintronics as GMR reading heads or as magnetic carriers of information using unidirectional remagnetisation, a simple route towards future 3D memories and shift registers. Individual nanowires are proposed as components in nanorobotics (*i.e.*, hybrid magnetic head and polymeric tail, guided in fluids by magnetic action); in biomedical and oncology applications where tumor cells with embedded NWs are friction killed under low-frequency fields, or for antimicrobial activity [10]. ■

About the Author

Manuel Vazquez is Professor of Research Ad-Honorem in the Spanish Council for Research where he established the Nanomagnetism and Magnetisation Processes group, 2001. He has addressed the magnetism of micro/nanowires for many years. He served as President of the IEEE Magnetics Society, 2017/8, being Distinguished Lecturer Awardee, 2023; and as Secretary of the IUPAP Magnetism Commission, 2011/15. He received the Salvador Velayos Award of the Spanish Club of Magnetism, 2016.

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AMORPHOUS MICROWIRES: MAGNETIC BISTABILITY AND GIANT MAGNETOIMPEDANCE

An alternative family of magnetic wires, with micrometric diameter and atomic disorder, is successfully employed in many technical applications mostly as sensing elements in sensor devices [11]. These applications derive from their unique soft-magnetic behaviour including: i) Magnetic bistability between two stable remanent configurations with a giant axial domain where remagnetisation takes place by nucleation and propagation of a single domain wall (Figure 5), and ii) Giant magnetoimpedance effect, GMI, originating in the classical skin effect, by which the impedance drastically decreases when the microwire is submitted to static magnetic field or mechanical stress. While bistability is observed in highly-magnetostrictive microwires (*i.e.*, FeSiB alloys, 35 ppm magnetostriction), GMI requires non-magnetostrictive alloys (*i.e.*, Co-rich CoFeSiB, 0.1 ppm magnetostriction and coercivity in the range of mOe).
Applications based on microwires profit of their high-sensitivity and small size (*i.e.*, low-mass, low-energy supply), ultrasoft magnetism and high-frequency properties [12]. Among others, recent proposals using microwires include non-destructive rheological biomaterials characterisation or contactless sensing of intracranial pressure [13].

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