XI Workshop Chile-México
sobre Magnetismo Nanociencias y sus Aplicaciones
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Modulated Cylindrical Magnetic Nanowires

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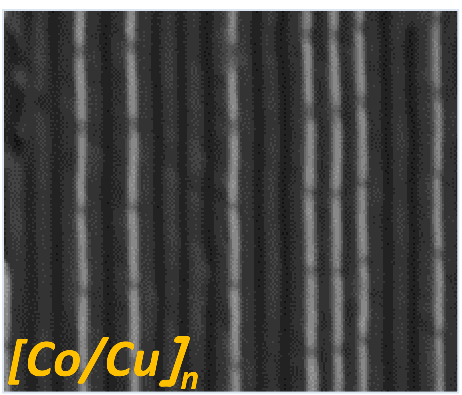
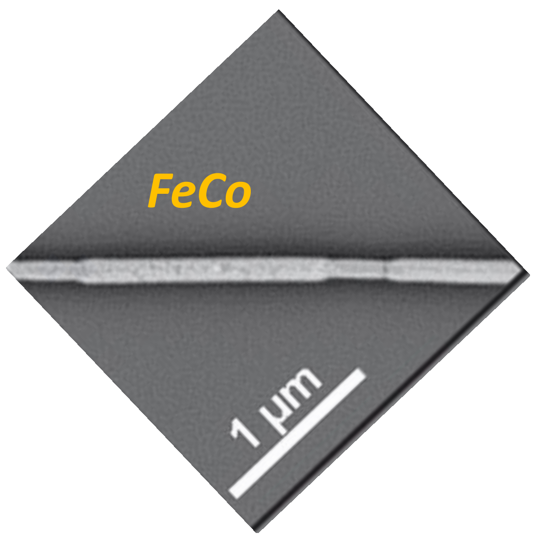
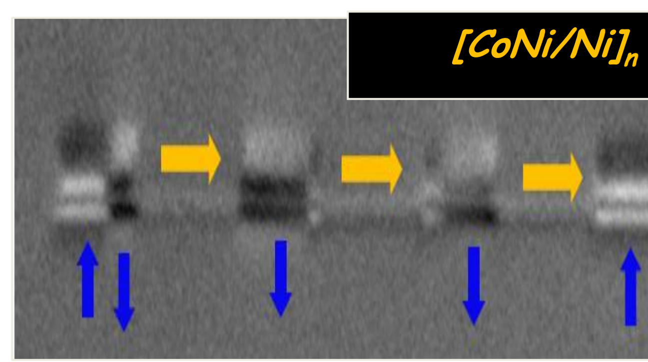
wp.icmm.csic.es/gnmp/







Cylindrical Nanowires:

- Particularities of Cylindrical nanowires

a) Rôle of Geometry (topological effects)

b) Controled anisotropy (crystalline)

c) Tailoring the diameter & composition modulations (pinning)

- Applications:

3D nanostructures, Sensors, Bio-Functionalization, Novel materials

- This presentation:

Domains and Reversal processes in modulated nanowires:

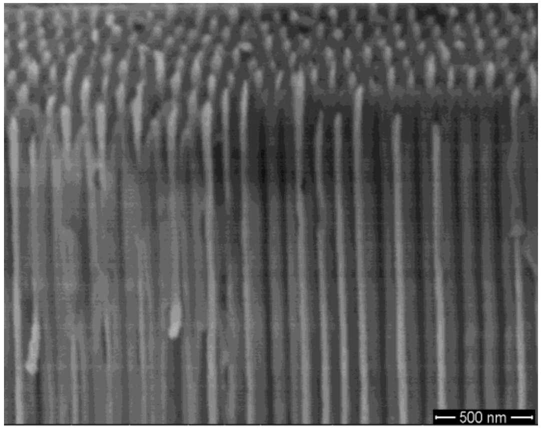
- ***in geometry (diameter, antinotches)***
- ***in composition (multi-segmented FM/M & FM/FM)***

What types of magnetic Nanowires are we talking about ?

- families of cylindrical nanowire arrays prepared at ICMM/CSIC

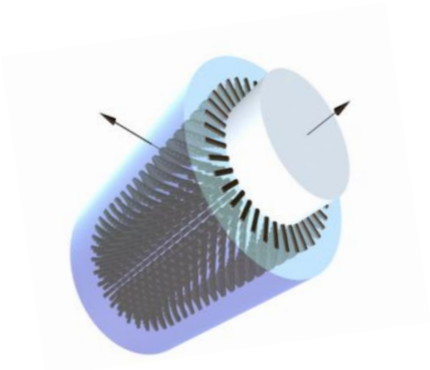
Diameter range: 20 to 200 nm
Lenght: 200 nm to 40 μm

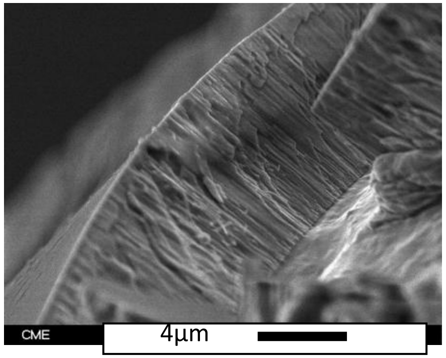
1a.- Nanowires in planar (disks) templates: Nanodots, Nanorods



Co out-of-plane nanowires

1b.- Radial nanowires in Cylindrical (rod) template

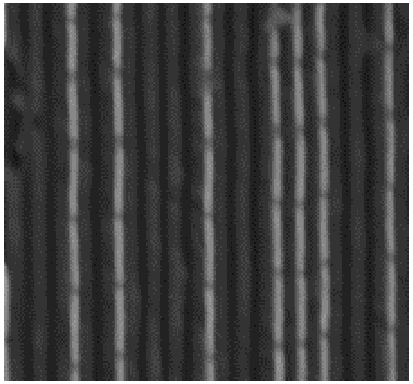


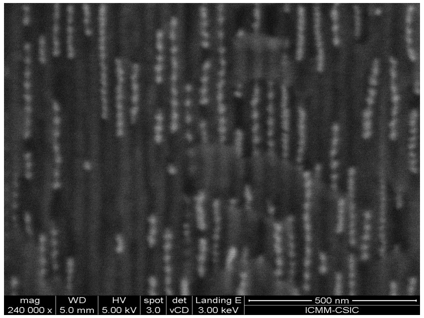


Co radial nanowires

Modulated Nanowires prepared at ICMM/CSIC

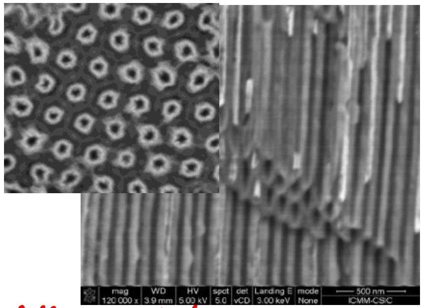
2a.- Longitudinal compositional modulations
Multisegmented, Multilayer,



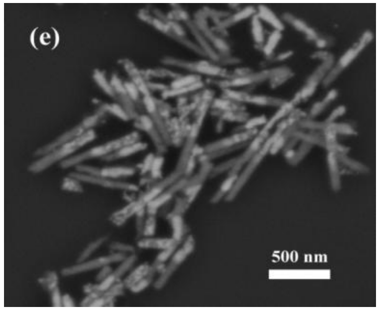


Co/Cu FeCo/Cu
Multisegment/layer

2b.- Radial compositional modulations
Nanotubes, Core/Shell

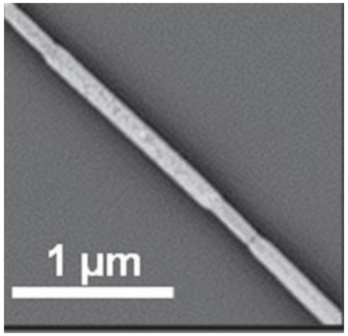


Ni nanotubes

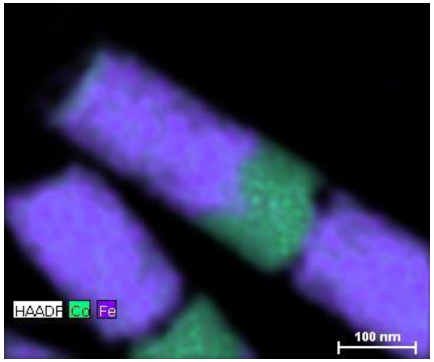


Fe/Au core&shell

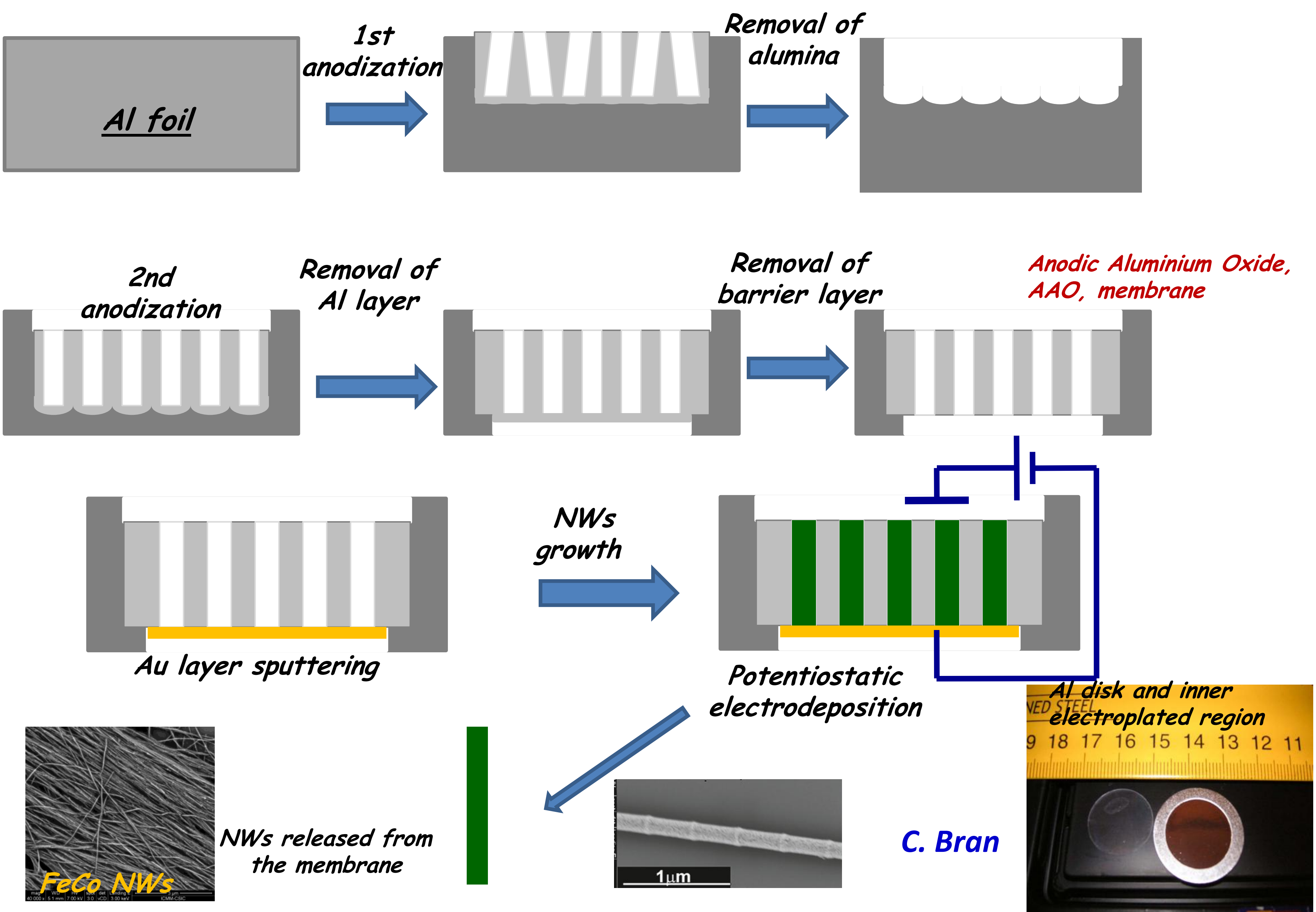
2c.- Diameter-Modulated



CoFe Co/Fe
diameter modulated



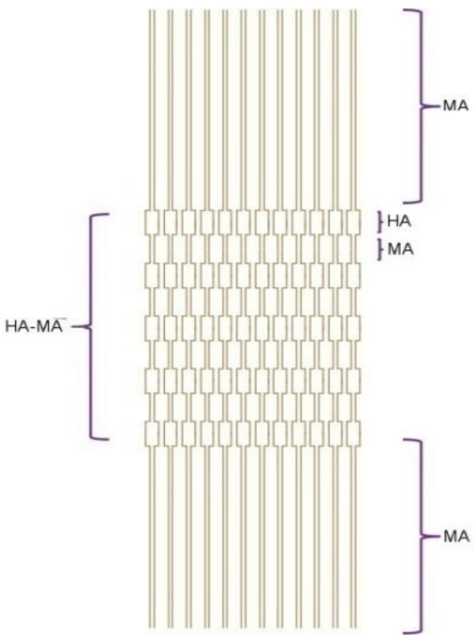
Synthesis procedure: AAO template + metals Electroplating

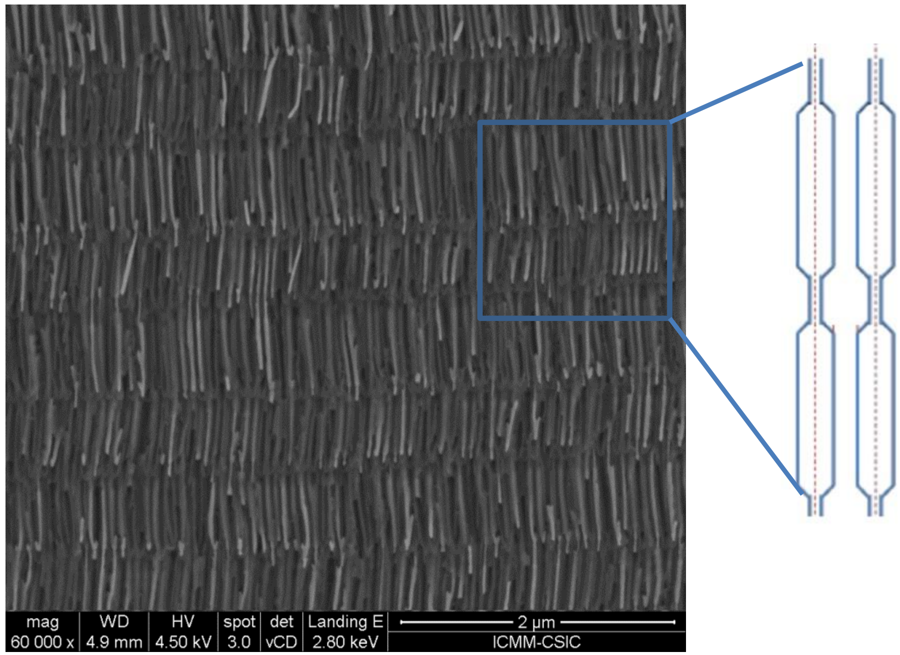


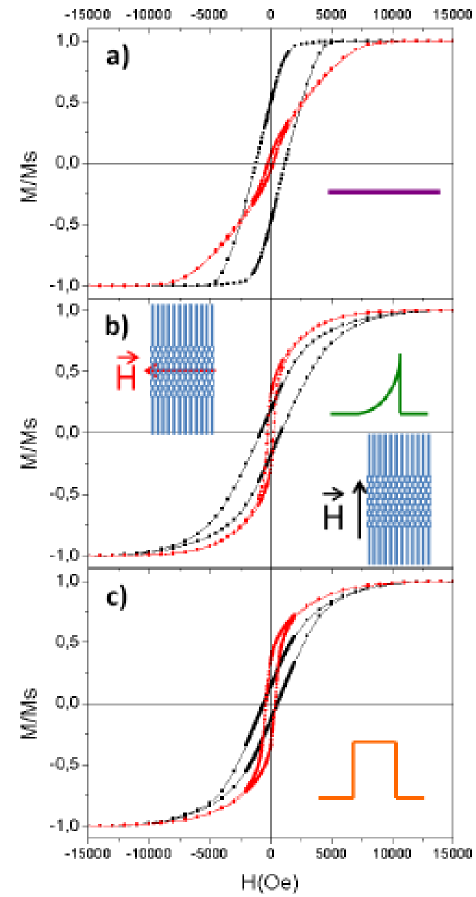
Growing nanowires with modulated diameter (Co & CoFe)

Grown inside Hard-Mild pulsed anodized templates

Co nanowires

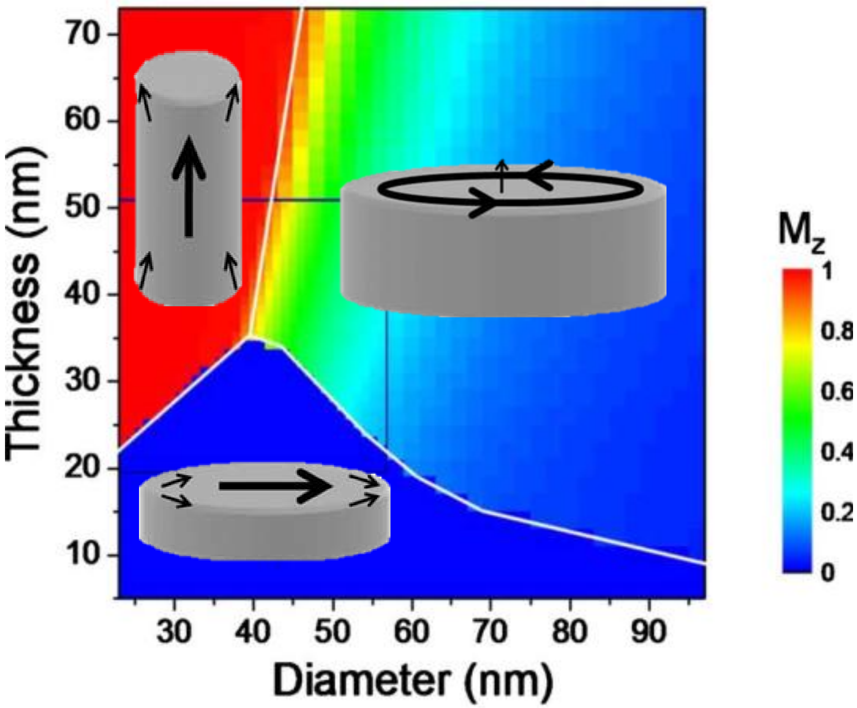






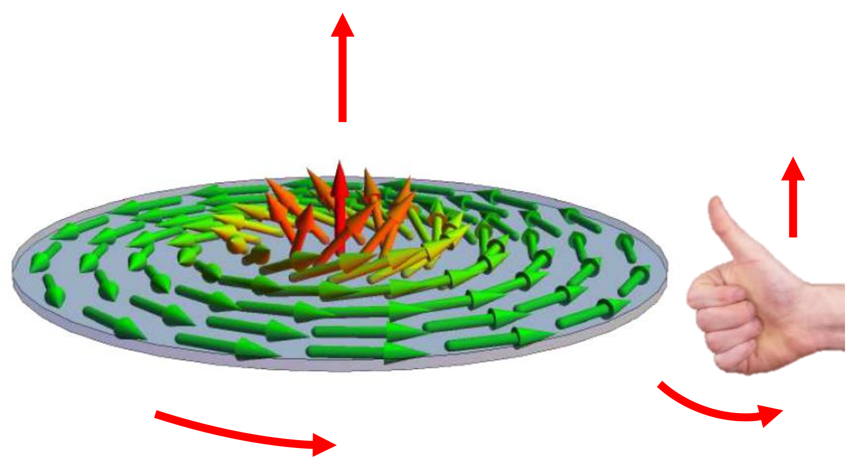
Minguez et al, Nanotechnology 2014

Cylindrical Geometry and Magnetic states



Ground states in Py nanorods
(no crystalline nor magnetostrictive anisotropy)

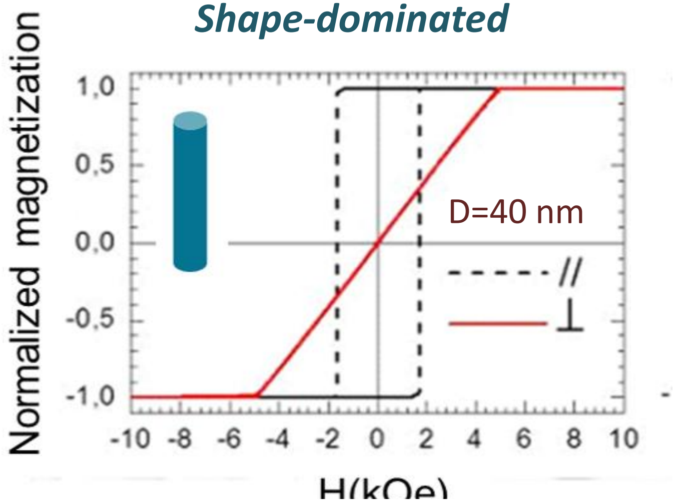
Vortex



Micromagnetic modeling of the reversal process in individual nanowires with various cristal symmetries

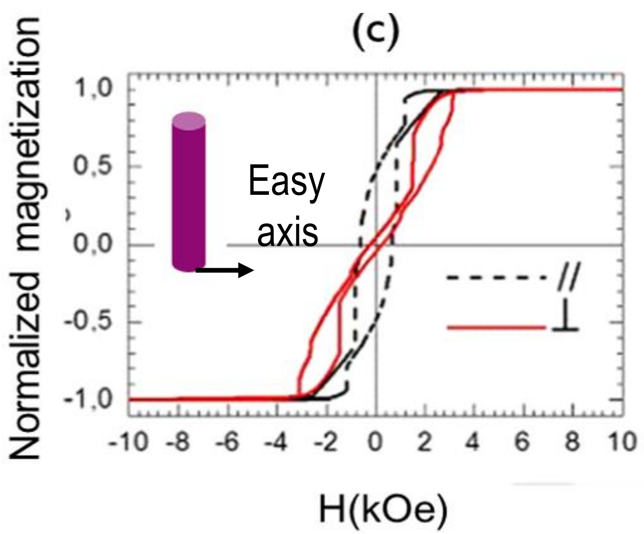
Shape-dominated

FeNi
bcc



Balance crystalline vs. shape anisotropies

Co
hcp



- **bcc, fcc (e.g., FeNi): axial easy axis**

  shape overcomes crystalline anisotropy

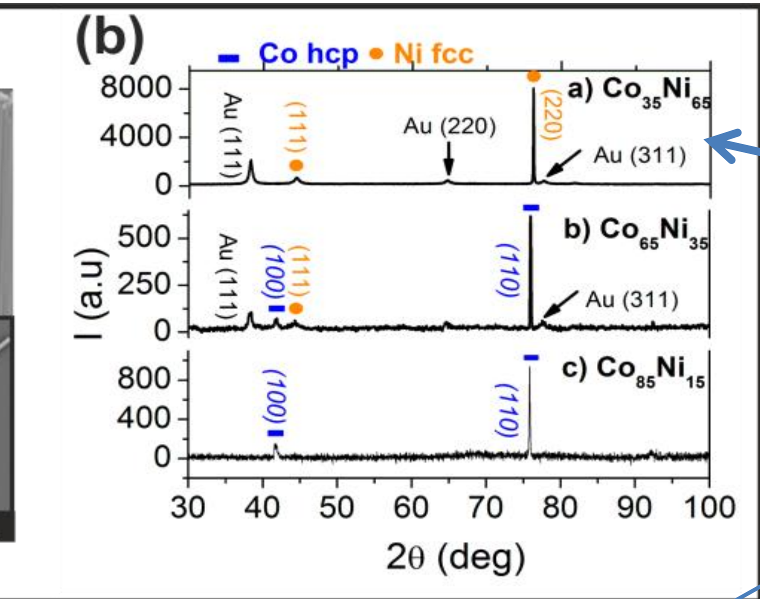
- **hcp (e.g. Co): transverse easy axis**

  strong crystalline anisotropy

  balances shape anisotropy

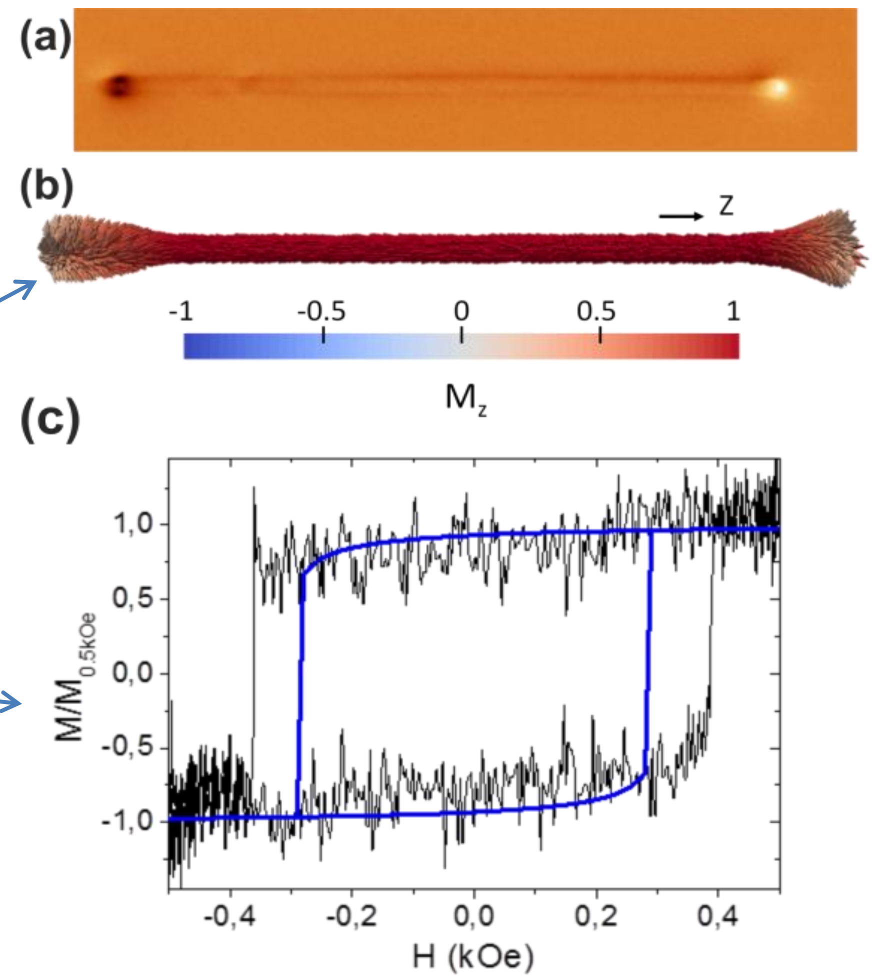
Ivanov *et al*. *J. Phys. D: Appl. Phys.* 46, 485001 (2013)

Crystal symmetry & Domains & Reversal in $Co_xNi_{(100-x)}$ alloy Nanowires



<u>fcc cubic</u> $Co_{35}Ni_{65}$ nanowire:

Single Axial Domain, a Magnetic Dipole



(a) MFM image at remanence

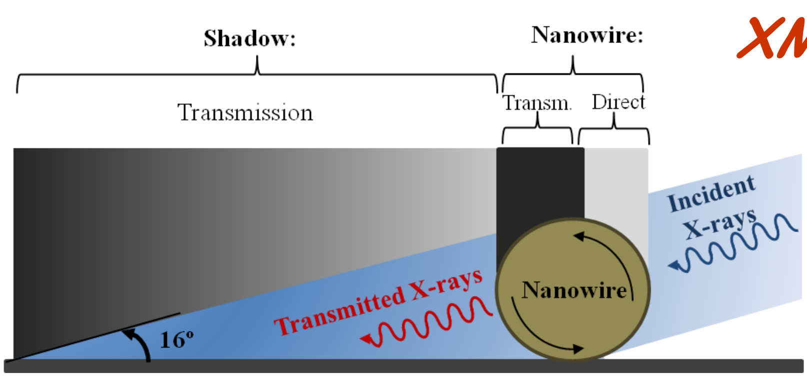
(b) Simulated magnetization distribution

(c) MOKE (black) and **simulated (blue)** loops

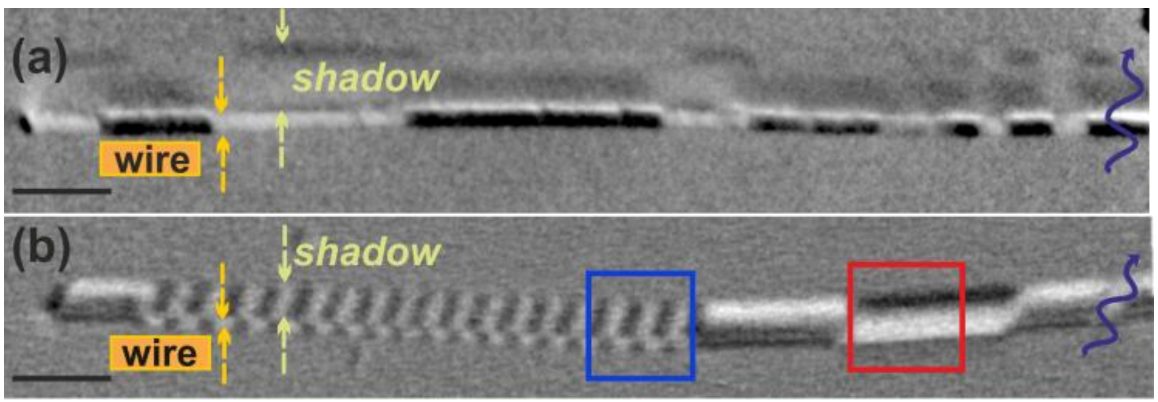
Transverse and Vortex Domains in CoNi alloy nanowires

XMCD/PEEM: surface and inner domain structure

Synchrotron Light

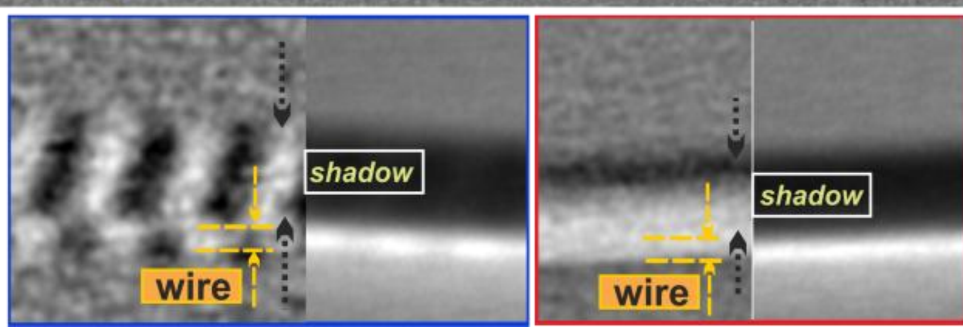


Photoemission Electron Microscopy with
X-ray circular magnetic dichroism



hcp $Co_{85}Ni_{15}$

hcp, fcc $Co_{65}Ni_{35}$



Transverse Domains

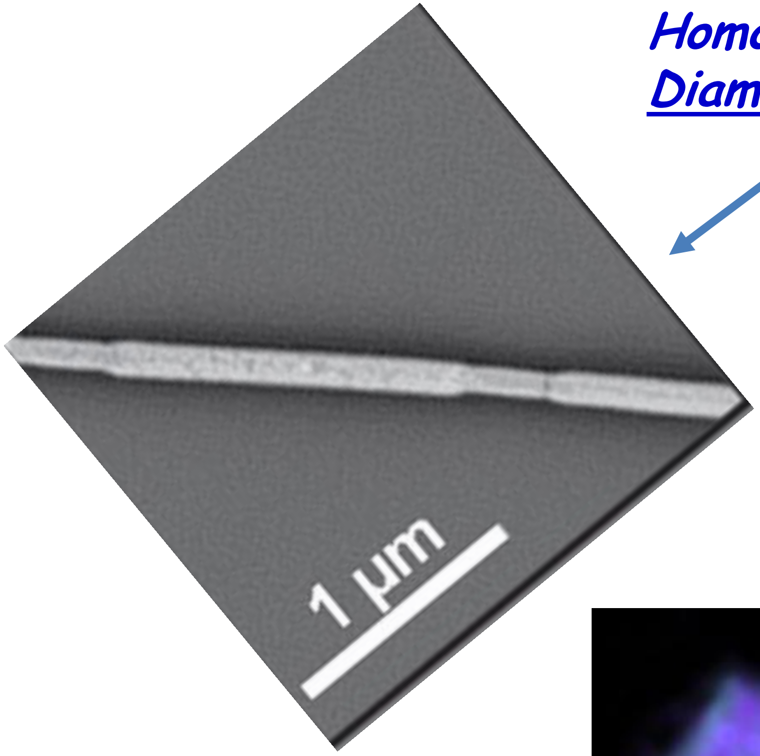
Vortex Domains

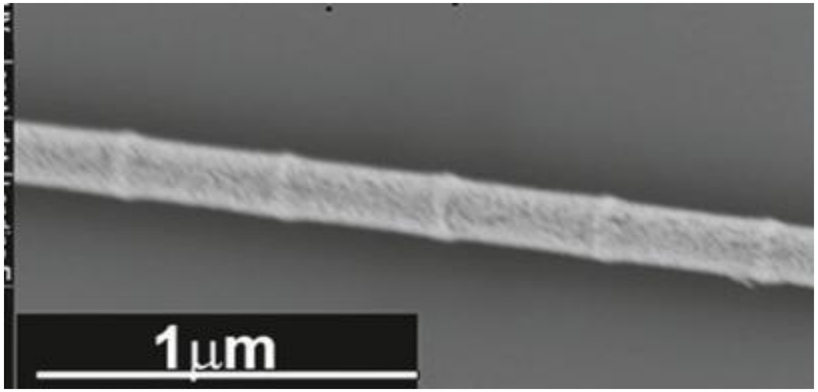
Bran et al
Phys Rev B 2017

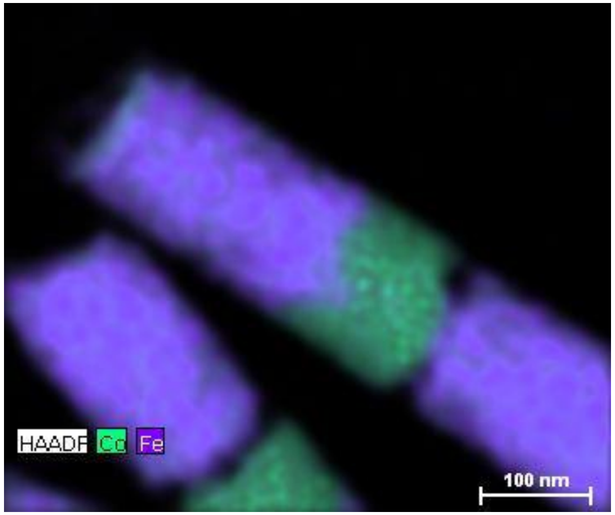
Periodically Modulated Cylindrical Nanowires

A) Geometry-Modulations:

FeCo Nanowires
Homogeneous compositon plus
Diameter modulations or Antinotched

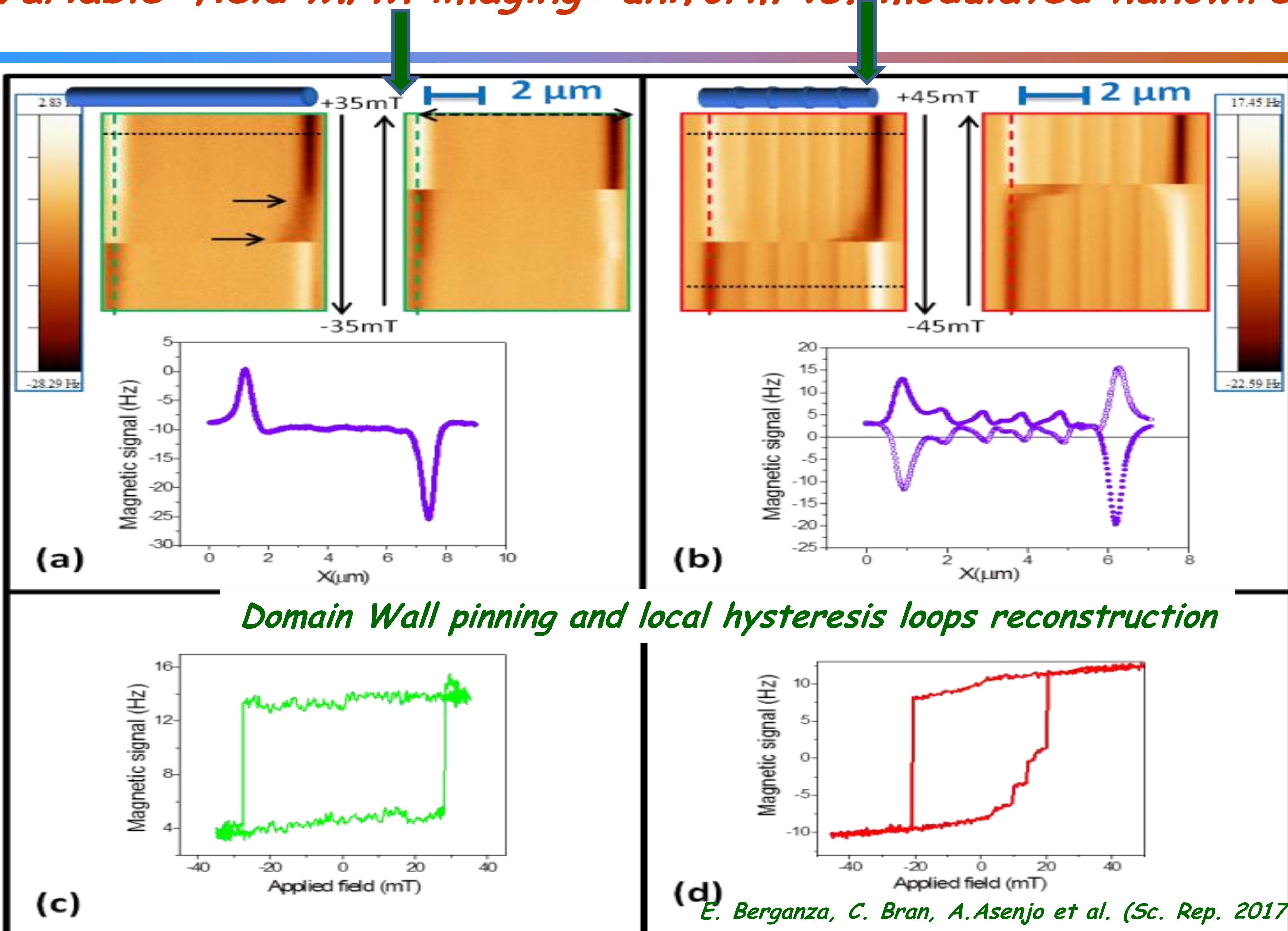






Fe/Co Nanowires
Composition Modulated plus
Notched like

Variable-field MFM imaging: uniform vs. modulated nanowires



Domain Wall pinning and local hysteresis loops reconstruction

E. Berganza, C. Bran, A.Asenjo et al. (Sc. Rep. 2017

Kerr effect in individual modulated nanowires ($Fe_{27}Co_{68}Cu_5$)

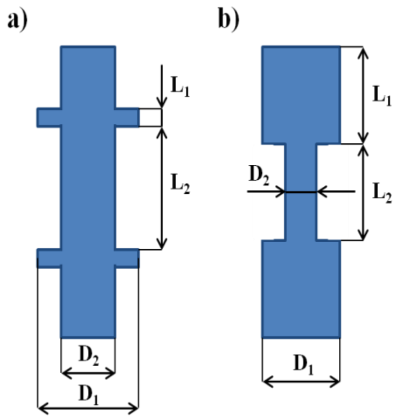
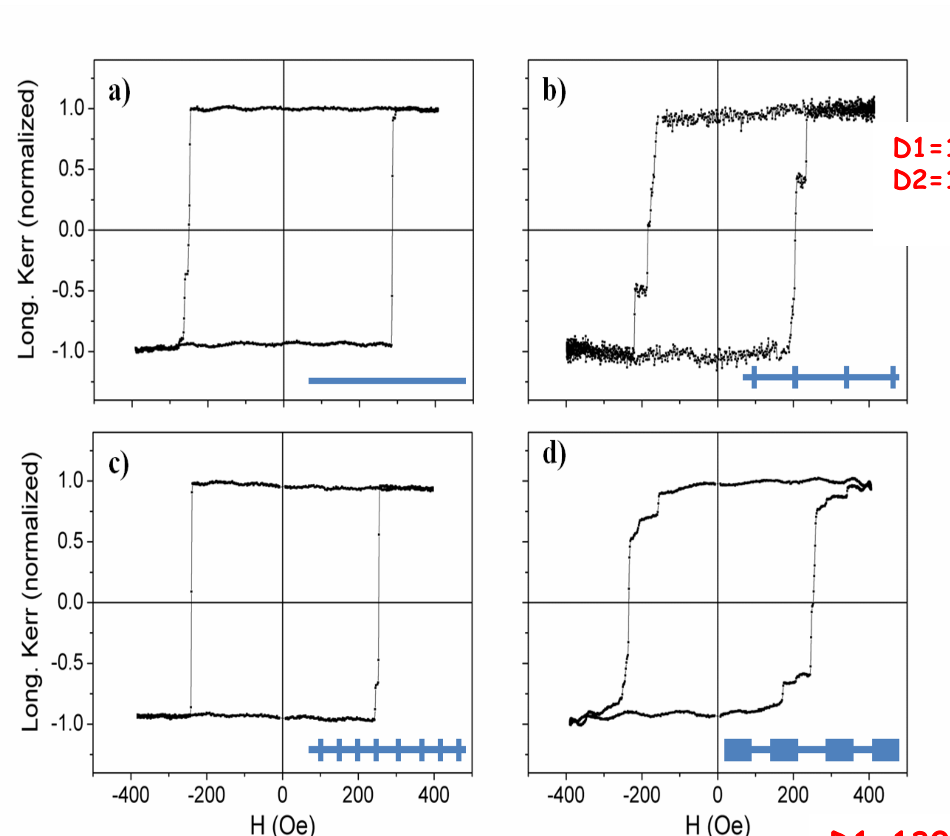


Diagram with two types of modulations

D1=150nm

D1=150nm, L1=800nm
D2=170nm, L2= 50 nn



D1=150nm, L1=800nm
D2=170nm, L2= 50 nm

D1=130nm, L1=1000nm
D2=100nm, L2= 300 nm

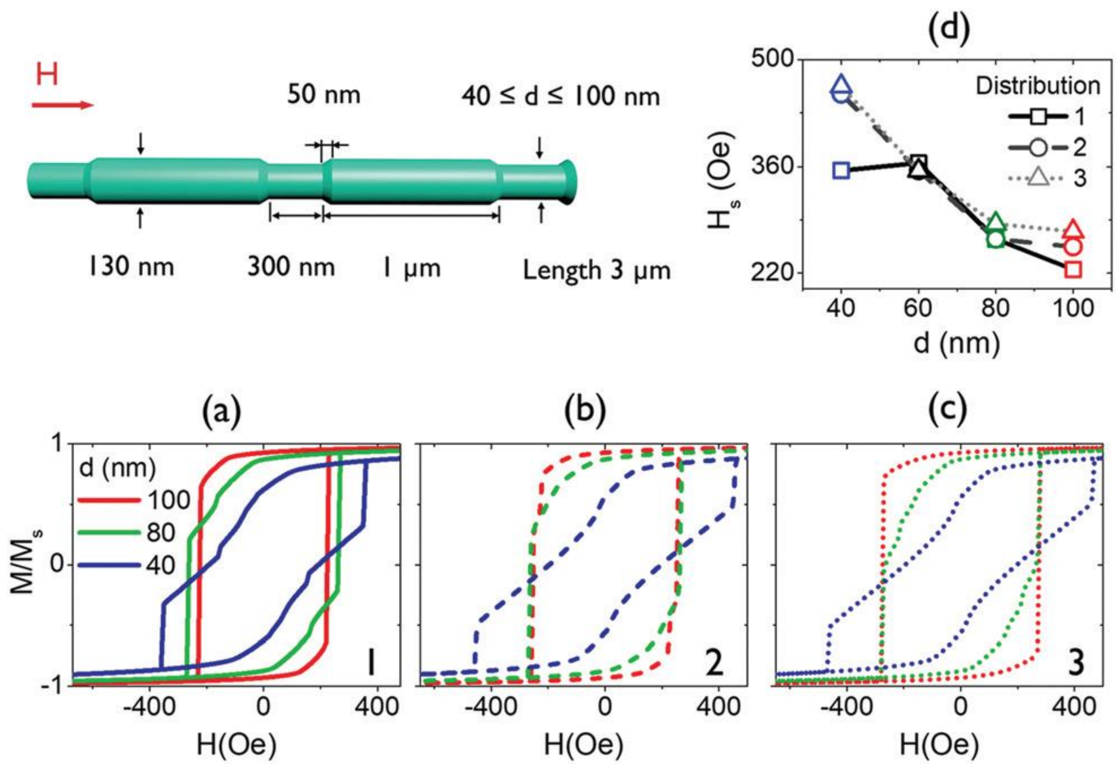
E. Palmero, C. Bran et al
Nanotechnology (2015)

The presence of single or several Barkhausen jumps are detected depending on geometry denoting the pinning effect at diameter transitions

Pinning in diameter-modulated FeCo nanowires: from topological protection to the “corkscrew” mechanism

Large diameter: 130 nm; constant
Thin diameter: 100 down to 40 nm

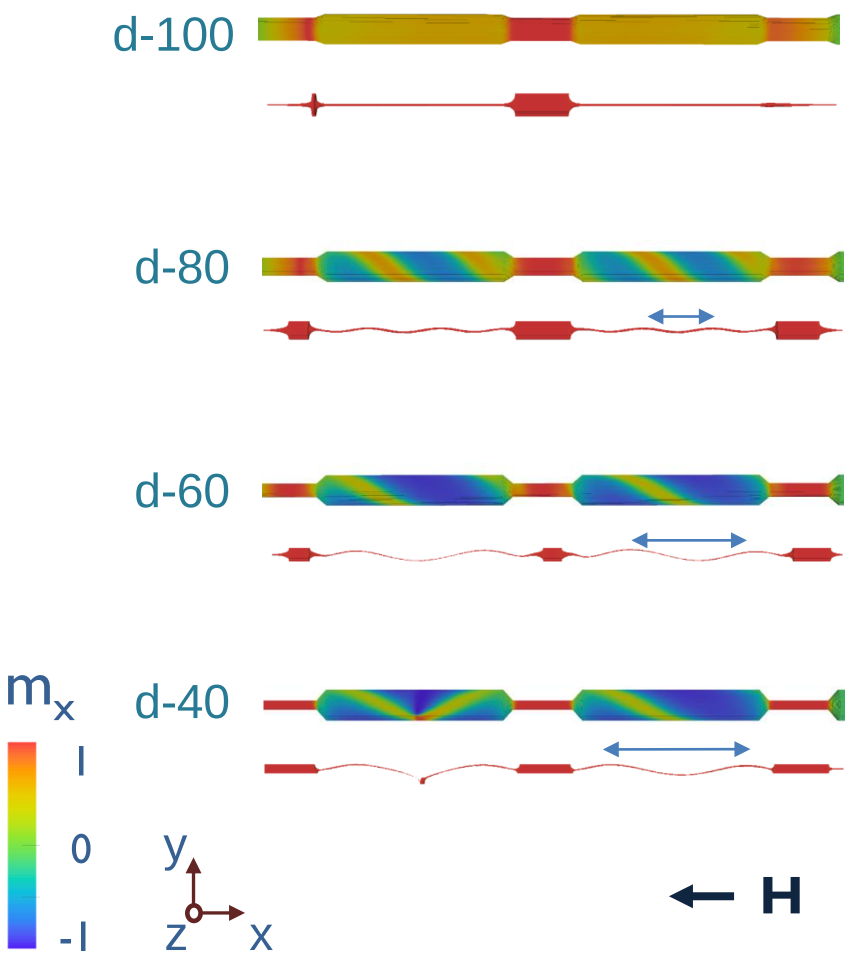
Micromagnetic (mumax) simulations



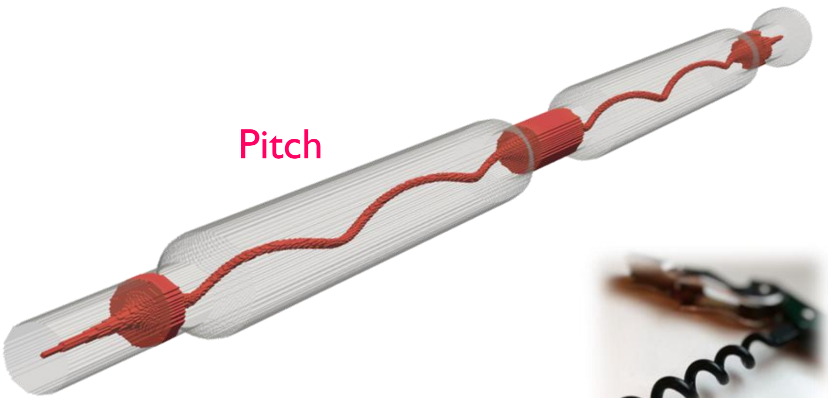
JA Fernandez-Roldan et al., Nanoscale 2018

FeCo NWs with modulations in diameter and the ‘corkscrew’ pinning

Large diameter: 130 nm



The corkscrew pinning



In Strong regime ‘Corkscrew’ pinning:

- **Narrow segments** are axially magnetized
- **Wide segments** show a structure with a core describing an helical configuration

JA Fernandez-Roldan et al Nanoscale 2018

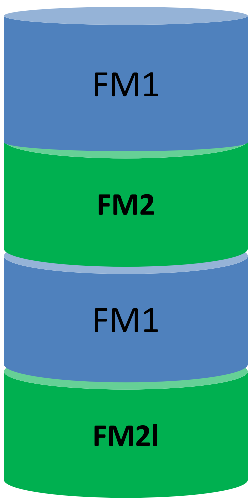
B) Compositional-Modulations: Multisegment nanowires

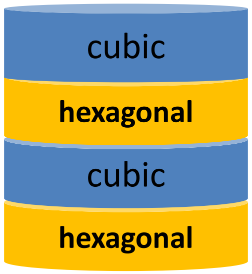
B1) Ferromagnetic/Ferromagnetic (i.e., $[CoNi/Ni]_n$), $[CoNi/CoNi]_n$)

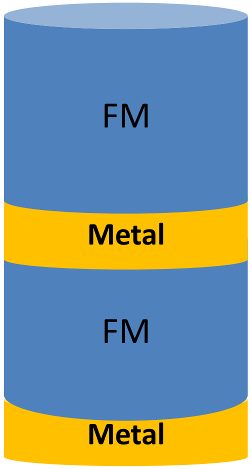
Anisotropy Modulation: Transverse, Vortex, Axial Domains

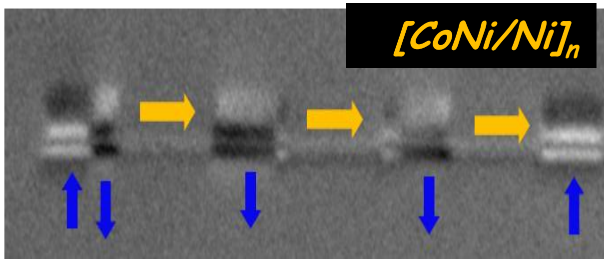
B2) Magnetic / Non-Magnetic (i.e., $[FeCo/Cu]_n$, $[Co/Au]_n$, $[Ni/Au]_n$)

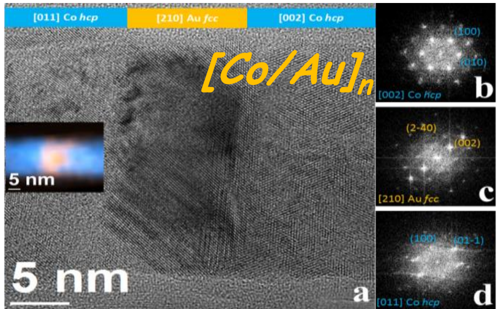
Magnetization Ratchet (stepped & unidirectional reversal)







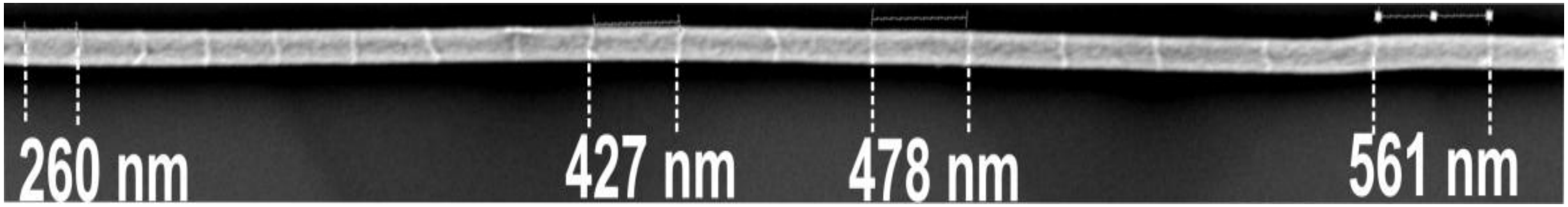


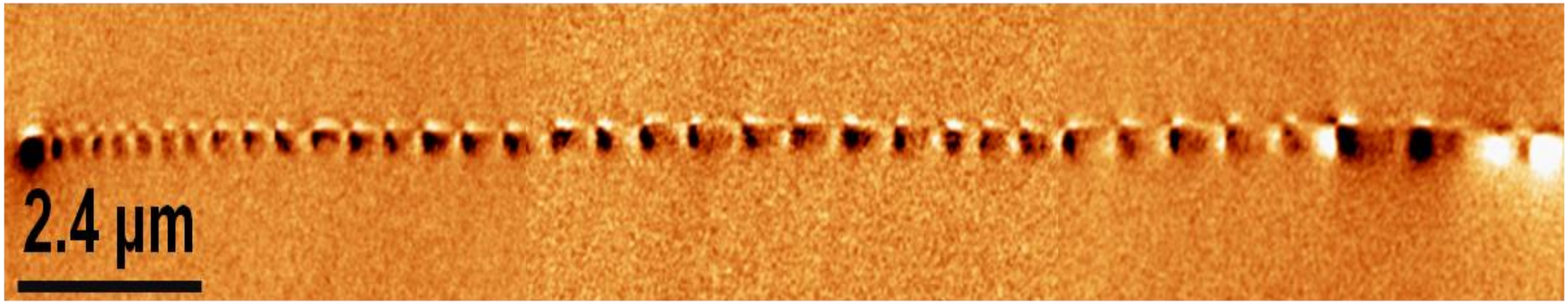


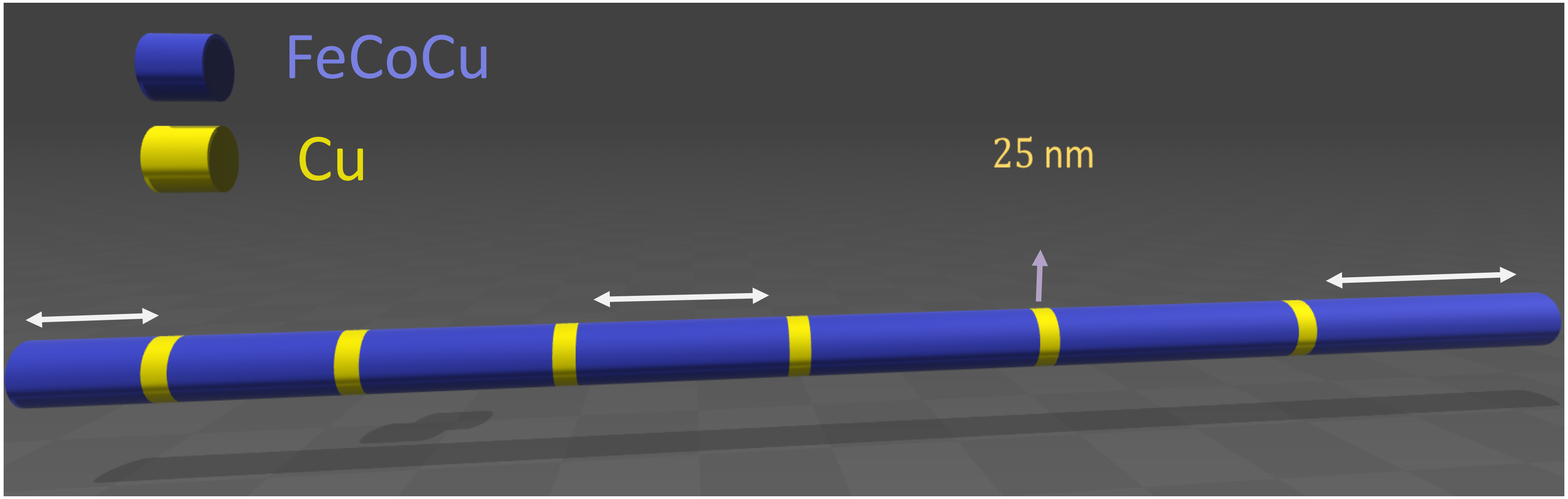
Designed Multisegmented FeCoCu/Cu NWs with increasing segment length

fcc cubic FeCoCu segments increasing in length from 200 nm to 900 nm

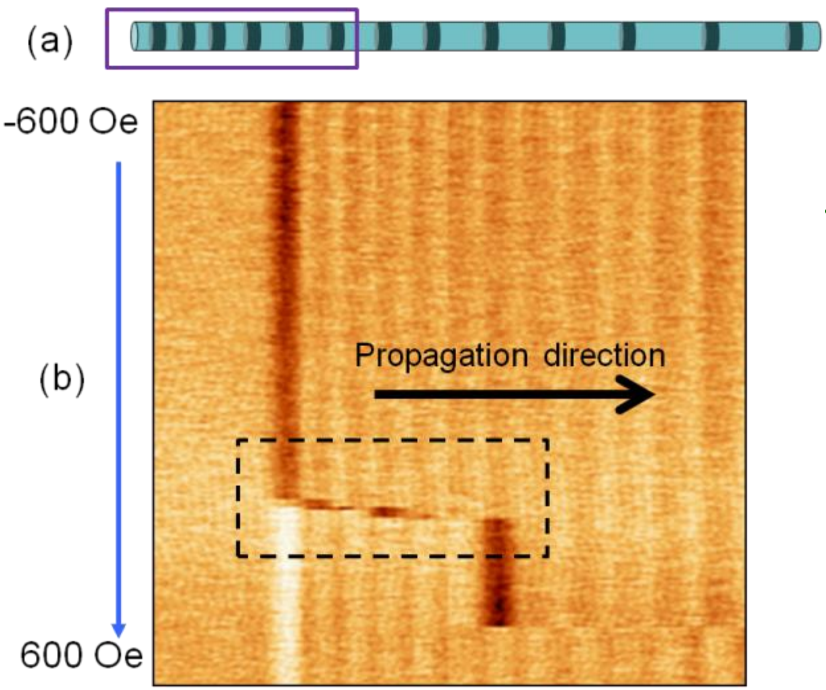
Diameter: 120 nm; Cu layers thickness: 25 nm





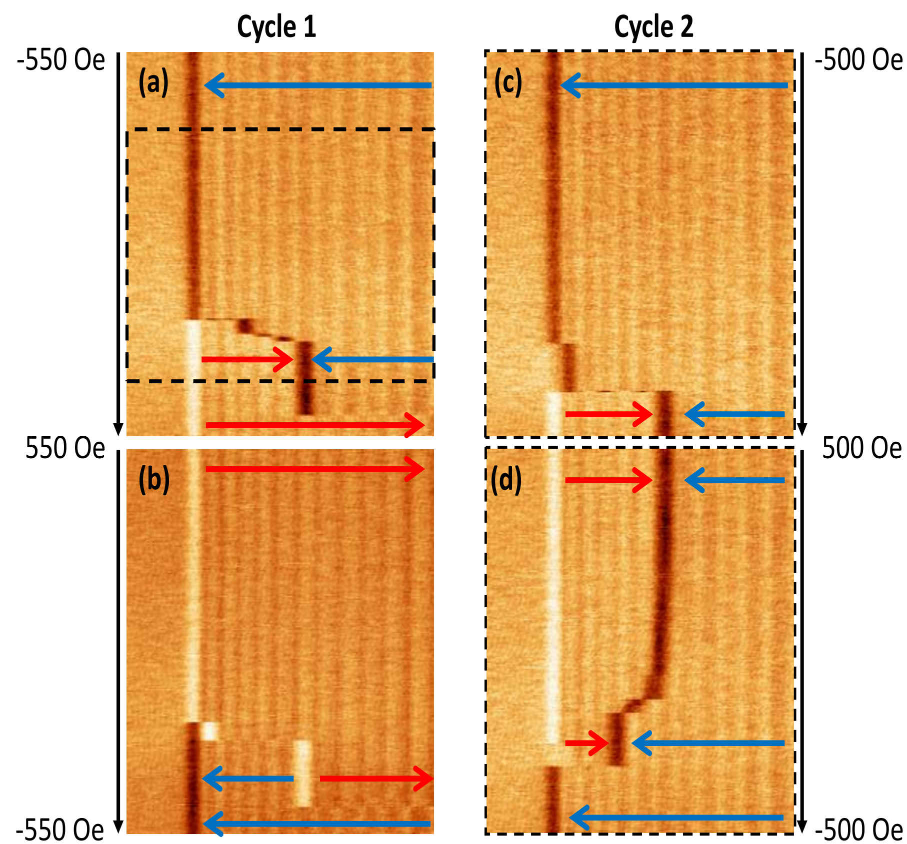


Unidirectional reversal in Multisegmented FeCoCu/Cu NWs



Imaging the end part of the wire 20 μm long

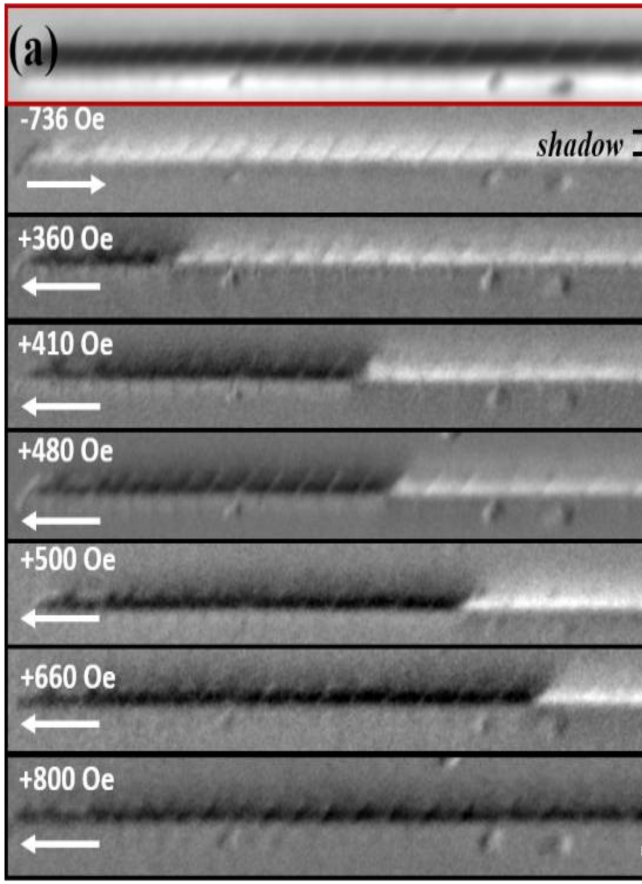
Reversal starts at the end with sorther segments irrespective of the field direction



MFM imaging under variable field
A.Asenjo, M. Jaafar

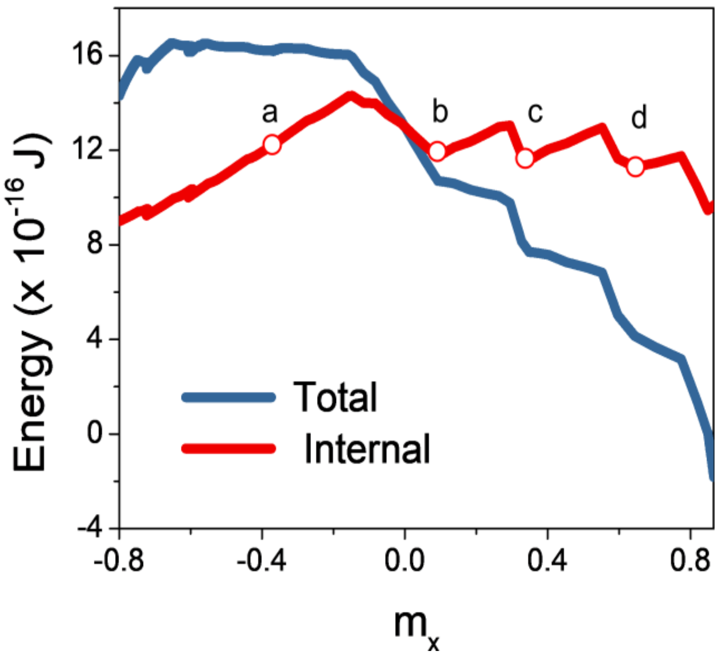
Unidirectional reversal in Multisegmented FeCoCu/Cu NWs XMCD-PEEM images; the Magnetization Ratchet

Bran et al., ACS Nano 12 (2018) 5932

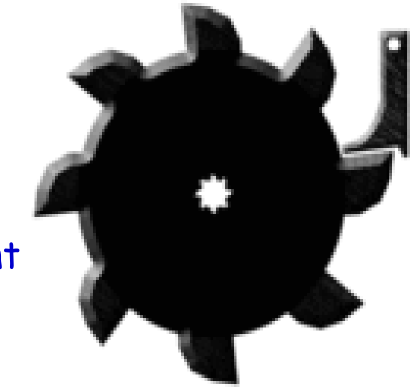


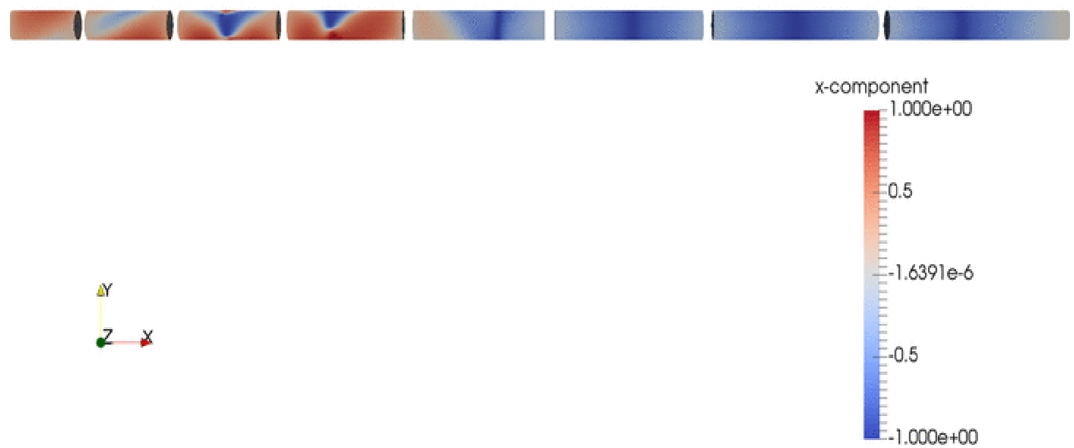
XAS images (above, circled in red) where Cu segments can be identified.
Selected PEEM images under increasing applied field along the leftward (a) and rightward (b) polarity.
The inset in (b) shows the reconstructed hysteresis loop.

Unidirectional reversal in FeCoCu/Cu NW: Micromagnetic Simulations of Magnetization Ratchet



Magnetic energy a function of the longitudinal magnetization component





- Demagnetization starts at the nanowire end with shorter segments, irrespective of H direction
- The energy displays a ratchet-like potential created by the increasing shape anisotropy of longer segments, the exchange energy and the pinning sites
- Magnetization process in each segment takes place by the formation of vortices and skyrmion tube states followed by final collapse of internal core
- Statically, large segments seem to demagnetize simultaneously while dynamically the propagation is also sequential. The structural defects may produce pinning.

Bran et al., ACS Nano 12 (2018) 5932

Fernandez-Roldan, et al. Nanoscale, 10 (2018)

Summary.-

* The circular symmetry promotes the spontaneous development of vortex domains and more complex structures with spins in a circumferential path

* Cylinders offer specific advantages such as the possibility to tailor the DW type, to adjust their stability during propagation, or to suppress the Walker breakdown

* Tailored composition typically includes Co in order to introduce crystalline anisotropy: engineering the domains (axial, transverse, vortex)

* Electrochemical route, less expensive, allows for the engineering of specific geometrical and compositional profiles with periodical modulations in diameter (e.g., notches and antinotches)
or in composition, containing alternating segments/layers of FM/FM, or FM/M

* Outcome: Anisotropy Modulation to Magnetization Ratchet

mag	WD	HV	spot	det	Landing E	500 nm
240 000 x	5.0 mm	5.00 kV	3.0	vCD	3.00 keV	ICMM-CSIC

ICMM/CSIC

- Nanowires Growth & Characterization Cristina Bran
- MFM imaging Agustina Asenjo & Eider Berganza
- Kerr effect Rafael Perez del Real & Ester Palmero
- Simulations: Oksana Chubykalo-Fesenko, JoseA Fernandez Roldan, Yurii Ivanov

Collalborations

- PEEM-XRCD Lucia Aballe & Michael Förster (ALBA)
- Combined Electroplating & ALD nanowires Victor Prida (Un. Oviedo)
- HRTEM & FMR Michael Farle & team (Un. Duisburg), Cesar Magen (INA)
- Lorentz & Holography Andrey Chuvilin (Nanogune), Yurii Ivanov (KAUST)
- ESTEEM Etienne Snoek & team (CEMES-CNRS)
- Biofunctionalization: Jose Rivas (INL); Sensors: Jürgen Kosel (KAUST)

Group of Nanomagnetism and Magnetization Processes, Madrid

CSIC

wp.icmm.csic.es/gnmp/