Chirally Coupled Nanomagnets

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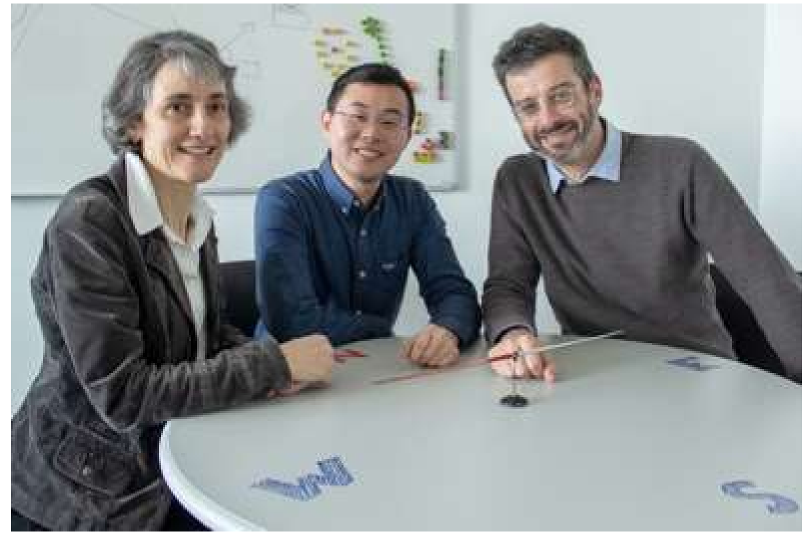
Photo: Paul Scherrer Institute, Markus Fischer

PAUL SCHERRER INSTITUT PSI

ETH zürich

Acknowledgement:



ETH Zürich

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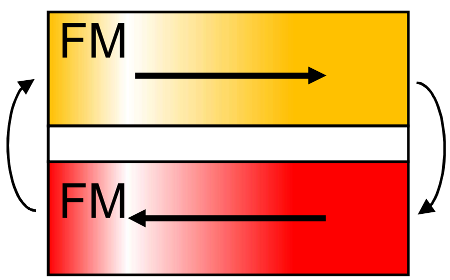
***Lab for Micro &Nanotechnology*:** Vitaliy Guzenko

Background

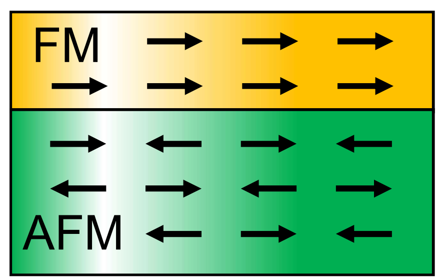
Magnetically coupled nanomagnets have multiple applications in non-volatile memories, logic gates, and sensors.

In a *vertical* structure, nanomagnets can be coupled by various mechanisms:



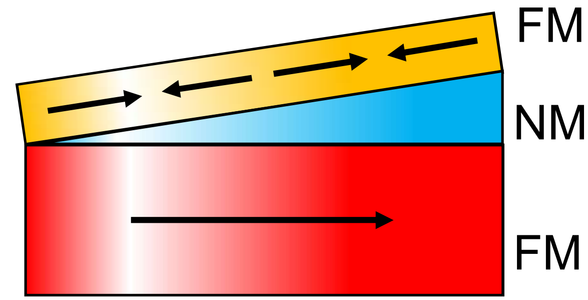
Magnetostatic coupling

dipolar interaction



Exchange bias

exchange interaction



Oscillatory interlayer coupling

RKKY interaction

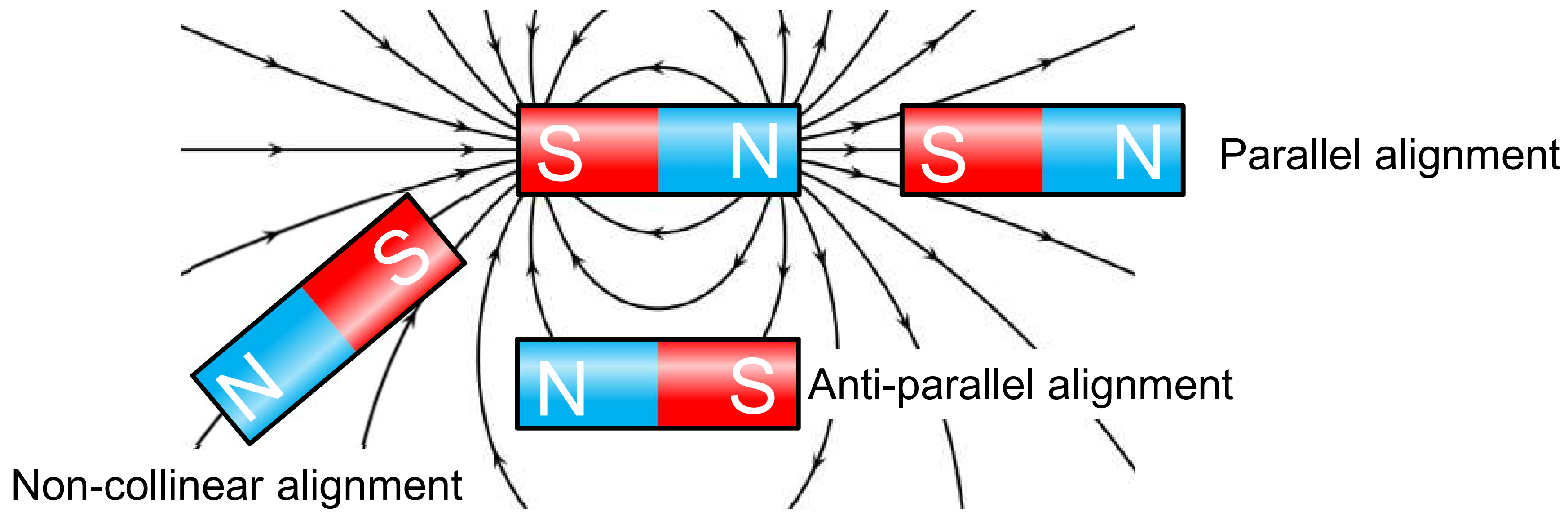
⇩

Giant magnetoresistance (GMR) effect

Background

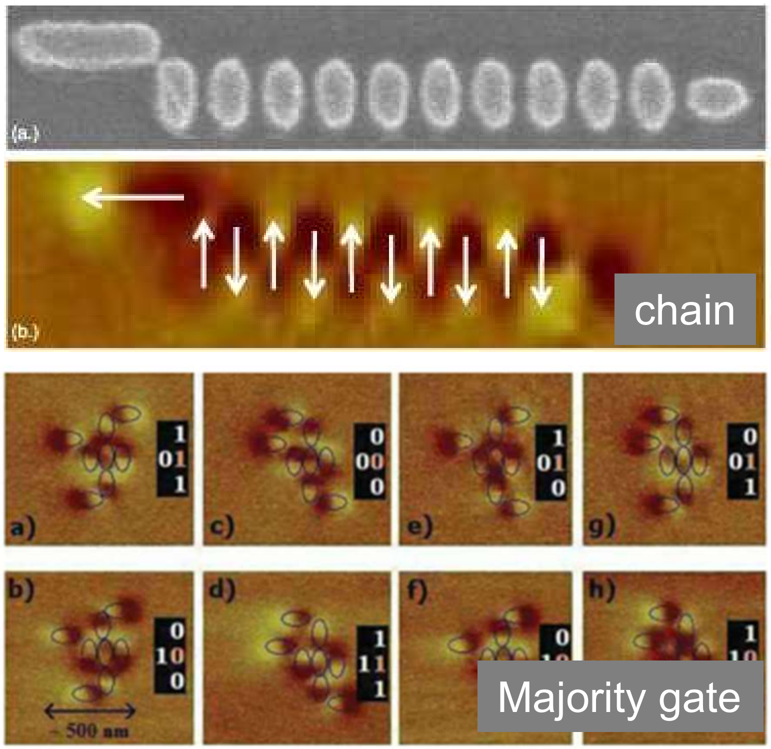
Magnetically coupled nanomagnets have multiple applications in non-volatile memories, logic gates, and sensors.

In a *lateral* structure (more freedom to design devices), nanomagnets are usually coupled by dipole-dipole interaction



ETH PSI

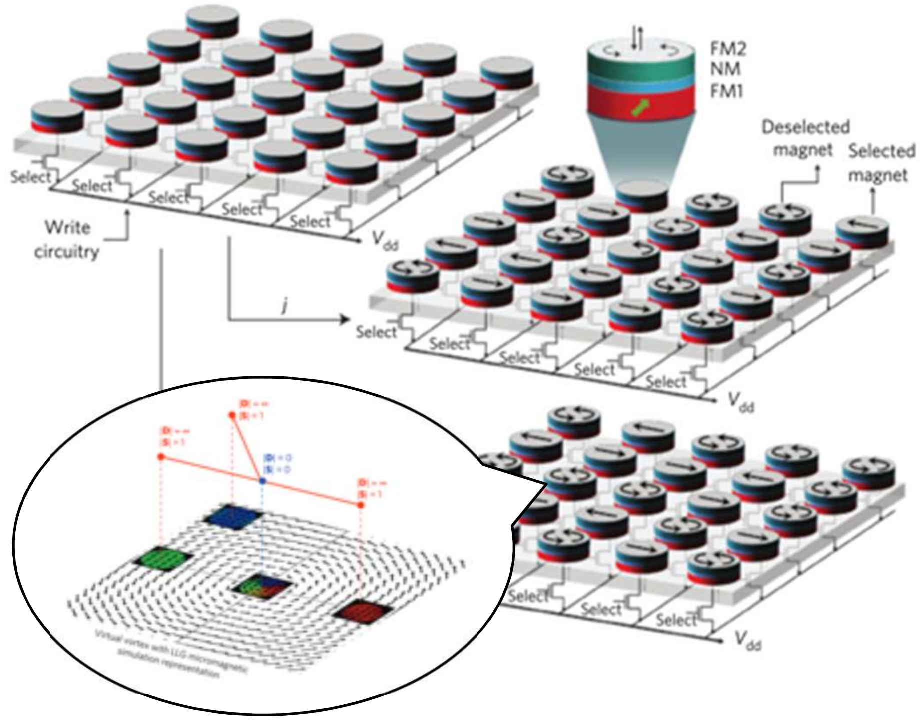
- Nanomagnet logic
  for Boolean operation



A. Imre, et al. Science 2005

Dipolar coupling between
single domain nanomagnet

- Image recognition
  of Non-Boolean operation



S. Bhanja, et al. Nat. Nano 2016

Dipolar coupling between
magnetic vortex state and
single domain state

To achieve reliable and scalable nanomagnet devices (e.g. electric-controlled nanomagnet logic with low error rate)

- **High coupling strength (large nanomagnet volume)**

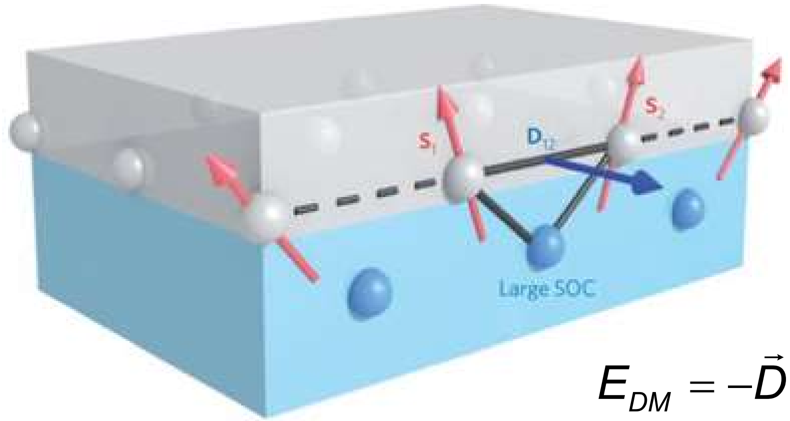
$$E_{\mathrm{dipolar}} = -\frac{\mu_0 M_{\mathrm{S}}^2 \boxed{V_{\mathrm{nanomagnet}}^2}}{4\pi|r|^3}[3(m_1 \cdot \vec{r})(m_2 \cdot \vec{r}) - m_1 \cdot m_2]$$

- **Electrically control of magnetization (small film thickness) (e.g. spin-orbit-torques switching of magnetization)**

$$J_{\mathrm{switch}} = \alpha \frac{4\pi e}{h} \frac{M_{\mathrm{S}} \boxed{t_{\mathrm{nanomagnet}}}}{\theta_{\mathrm{SH}}}\left(H_{\mathrm{K}} + \frac{N_{\mathrm{d}} M_{\mathrm{S}}}{2}\right)$$

Can we implement an interfacial effect to achieve strong lateral coupling in a thin film system?

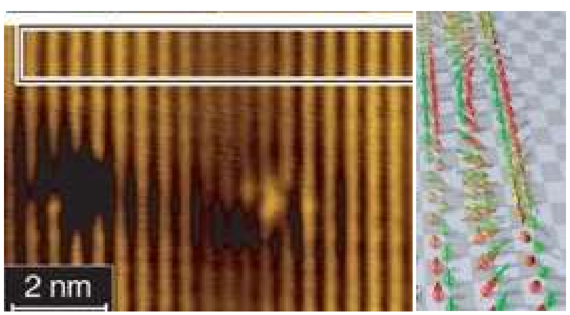
Interfacial Dzyaloshinskii–Moriya interaction (iDMI)



I. Dzyaloshinsky, JPCC 1958
T. Moriya, Phys. Rev. 1960
M. Bode, et al. Nature 2007

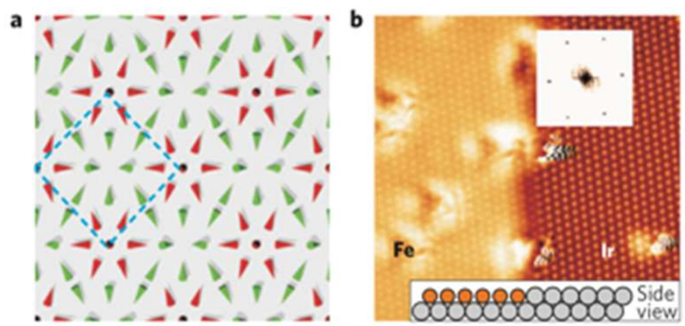
$$E_{DM} = -\vec{D}\cdot(\vec{S}_1\times\vec{S}_2)$$

➢ Homogeneous system



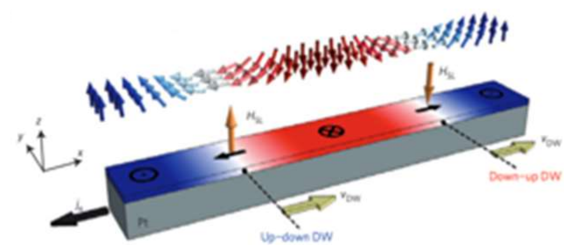
M. Bode, et al. Nature 2007

Chiral spin spiral texture



S. Heinze, et al. Nat. Phys. 2011

Magnetic skyrmion



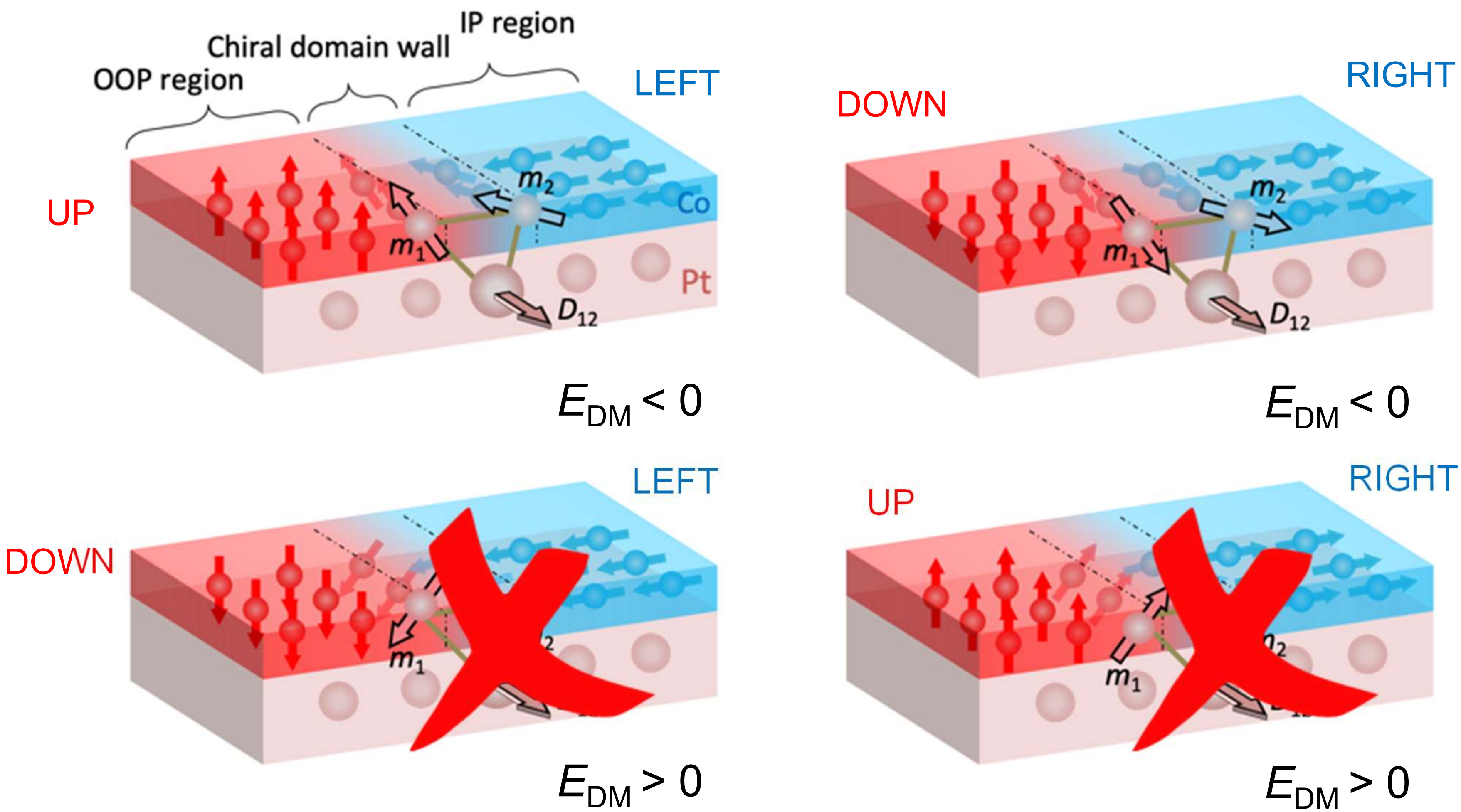
S. Emori, et al. Nat. Mater. 2013

Chiral domain-wall

Basic concept

- Pattern magnetic anisotropy in nanomagnet elements

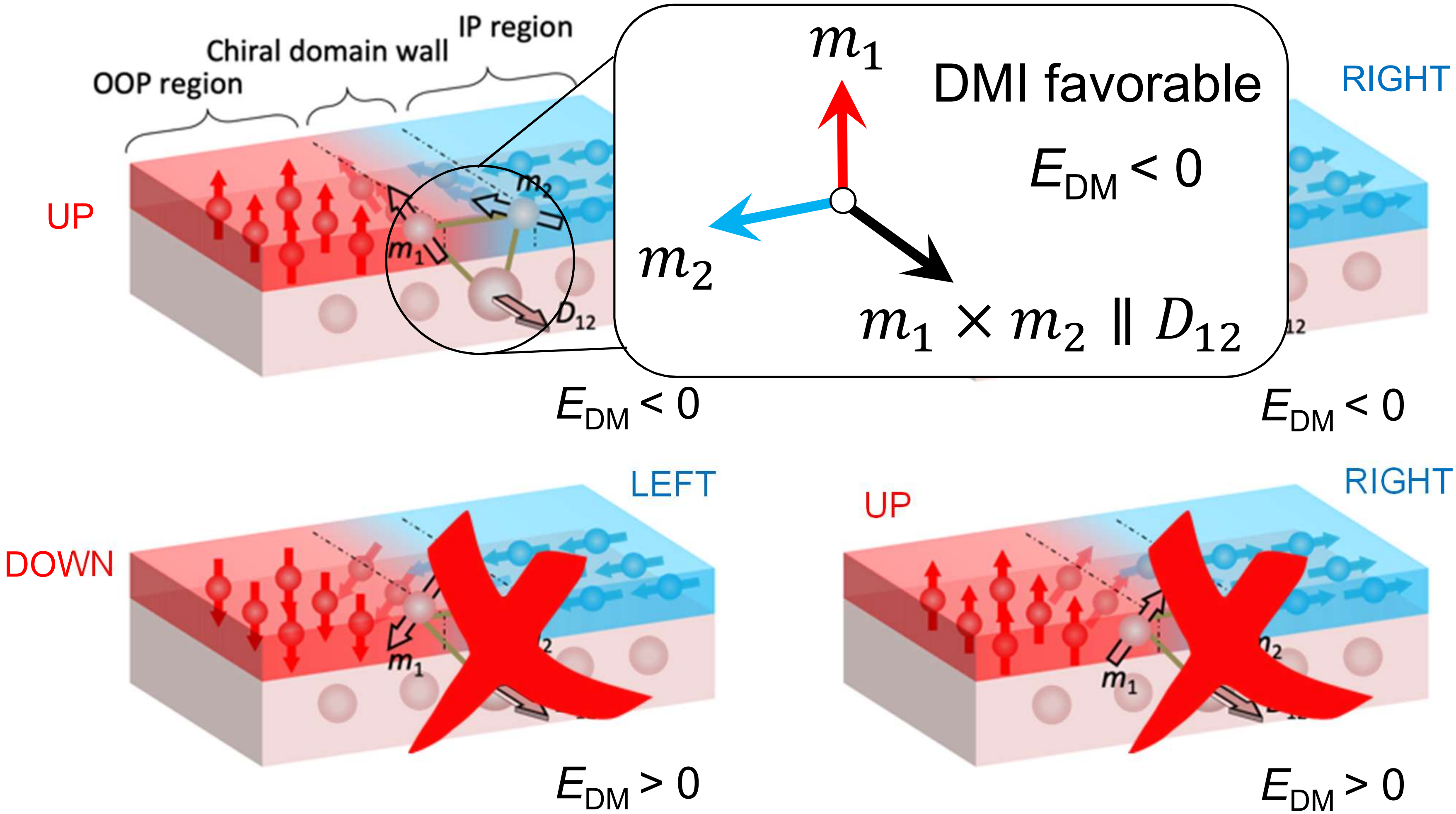
Simplest case: an OOP-IP element



Basic concept

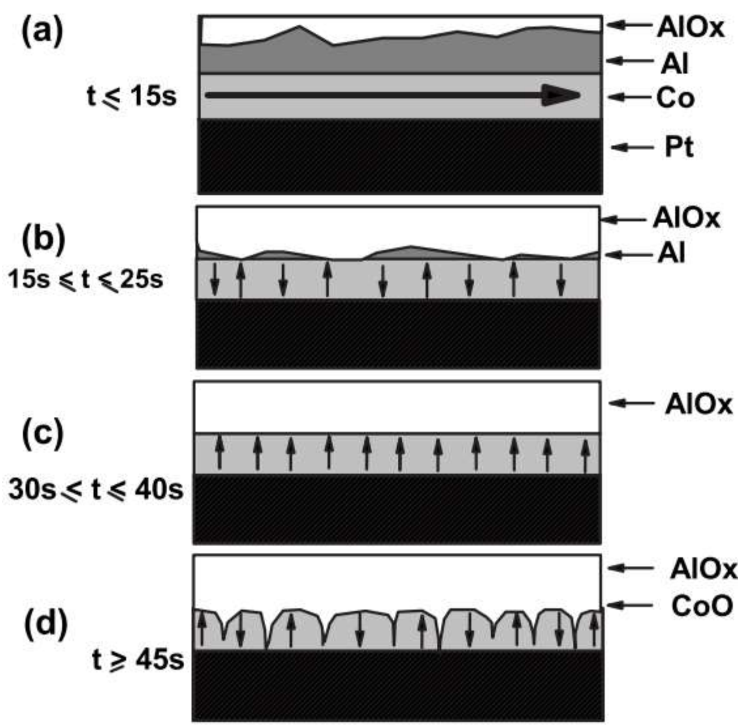
- Pattern magnetic anisotropy in nanomagnet elements

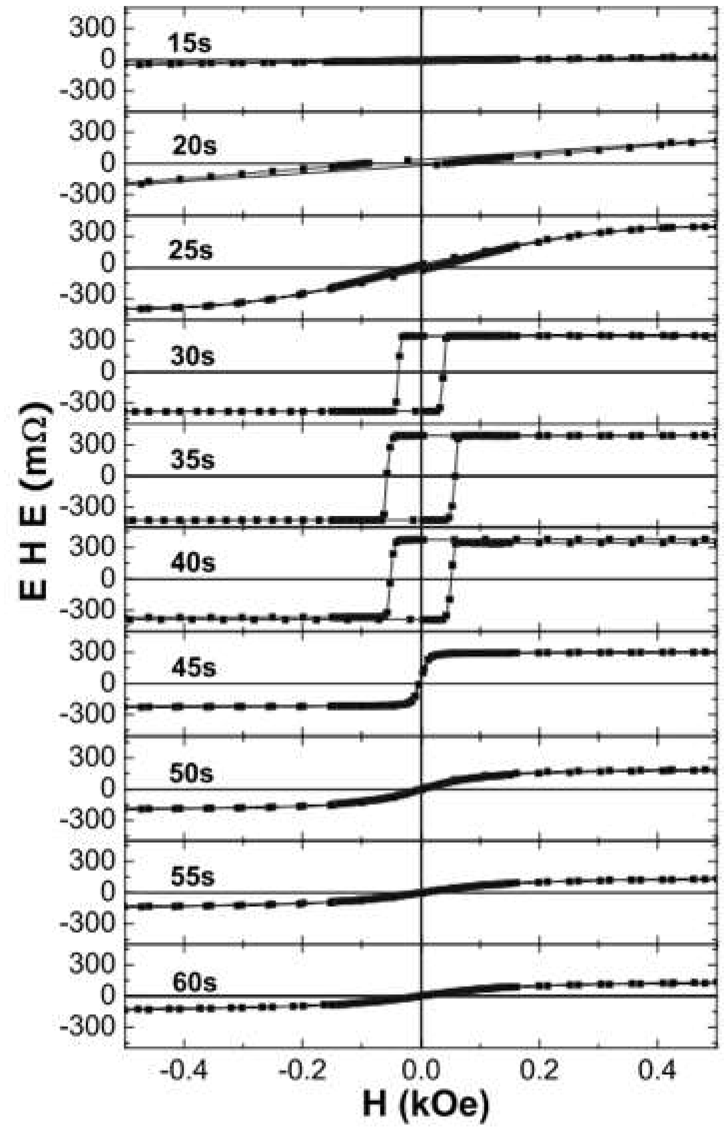
Simplest case: an OOP-IP element



Interfacial perpendicular magnetic anisotropy

- Pt/Co/AlOx(Al) trilayer



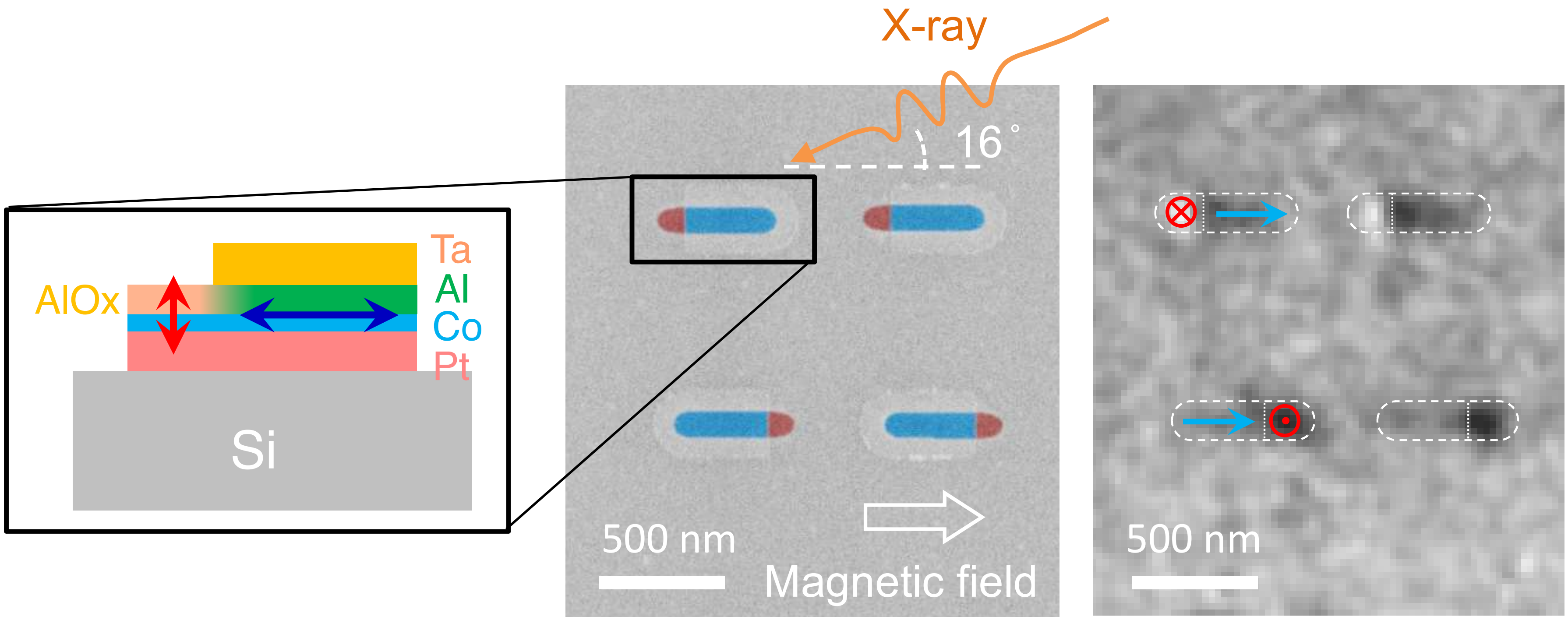


A. Manchon, et al. J. Appl. Phys. 2008
B. Rodmacq, et al. Phys. Rev. B 2009

Chiral coupling

Direct observation of chiral coupling between OOP and IP in Pt/Co/AlOx

by X-ray photoemission electron microscopy (PEEM: $I_{\text{XMCD}} \propto M \cdot v_{X-ra}$)

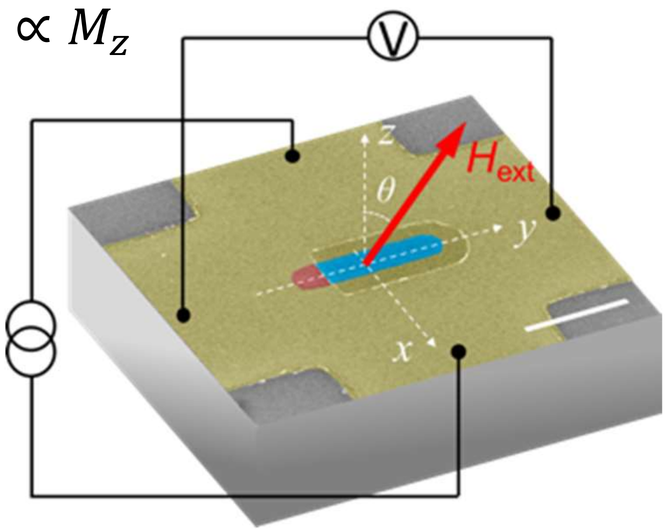


SEM

PEEM XMCD

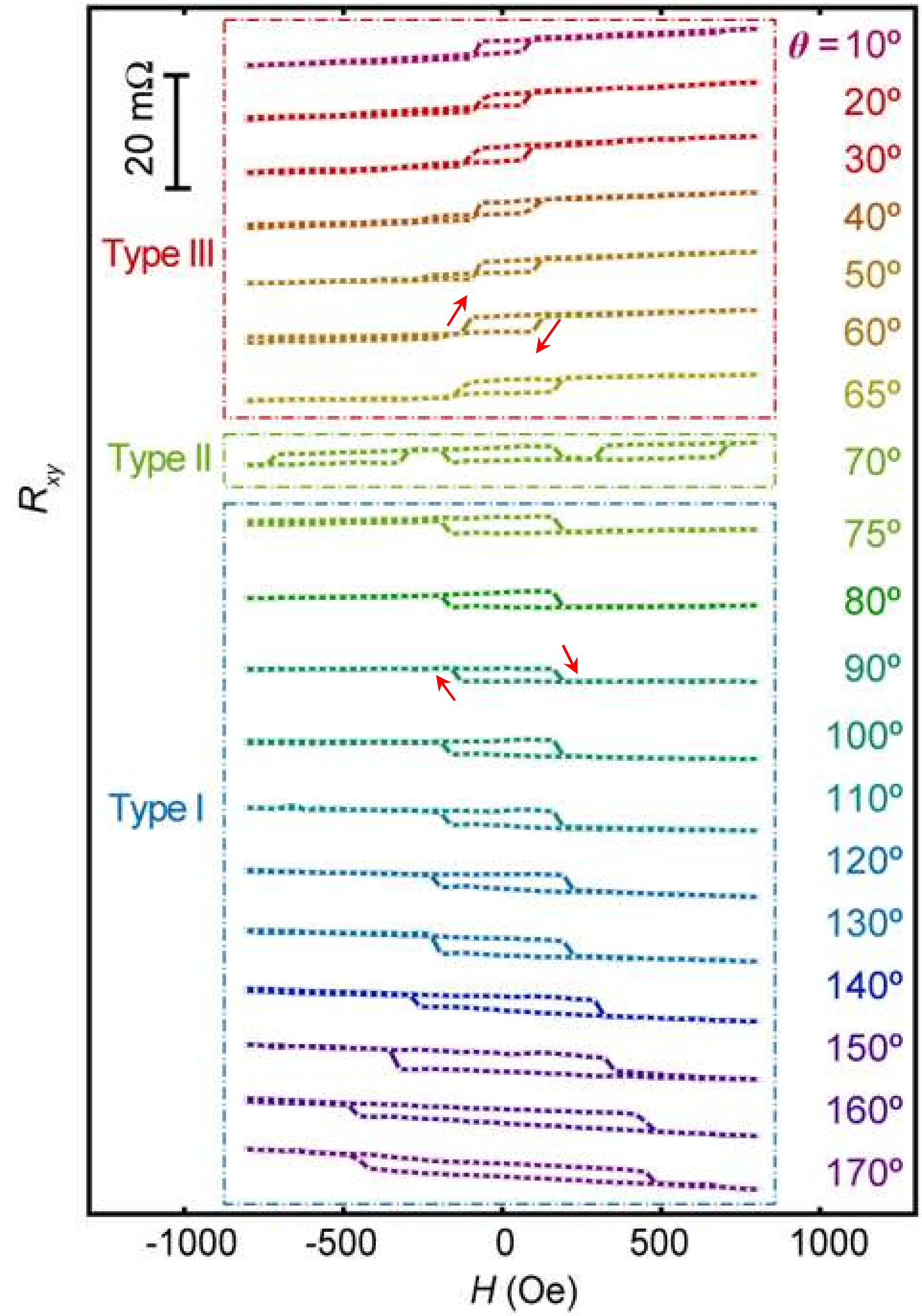
- Stable states ↓→, →↑
- Fixed left-handed chirality

$R_{xy} \propto M_z$



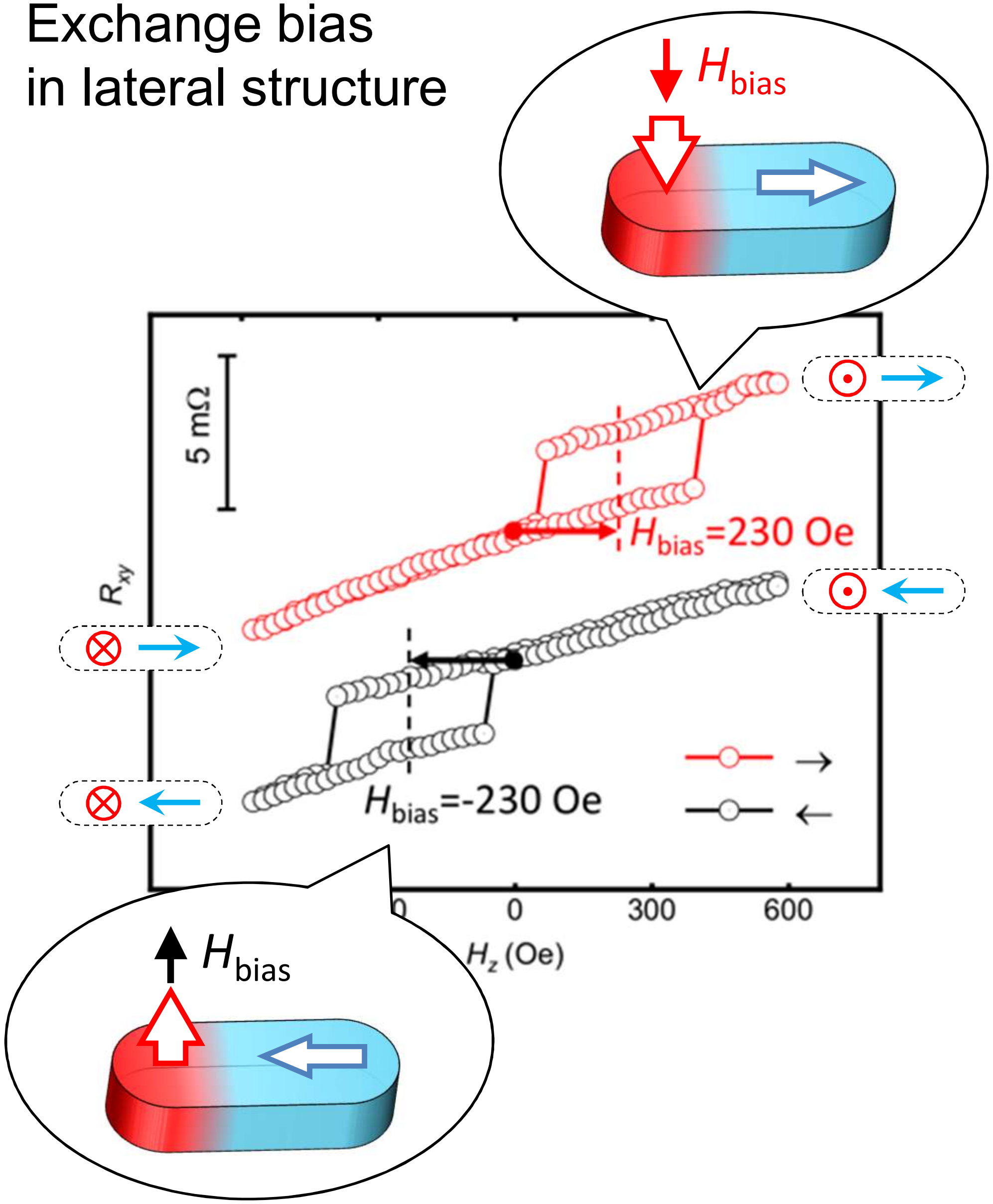
Electric measurement to quantify the coupling strength

E_{DM} = 3.48 eV (120 nm)
D ~ -0.9±0.1 mJ/m^2

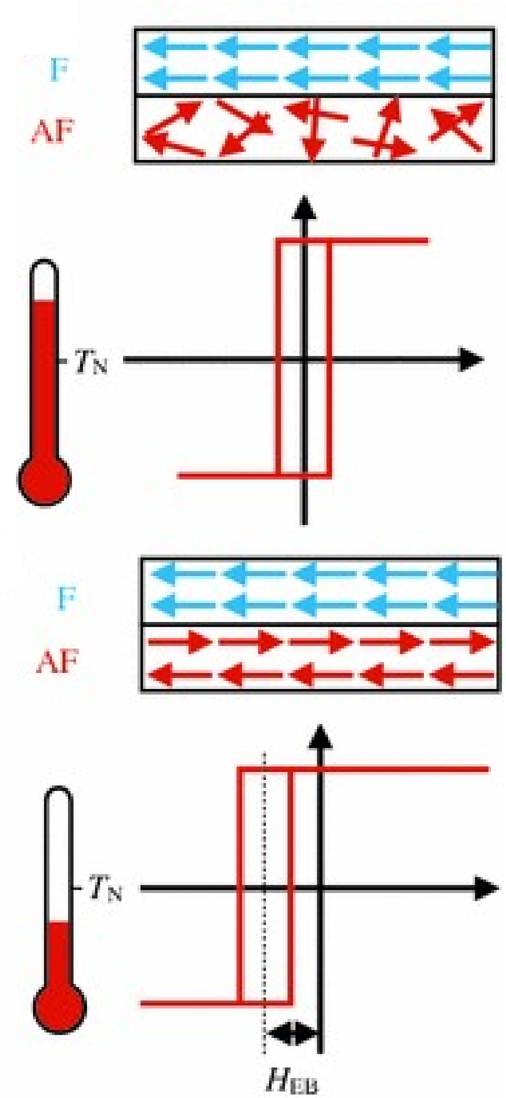


Application I: Lateral exchange bias

Exchange bias
in lateral structure

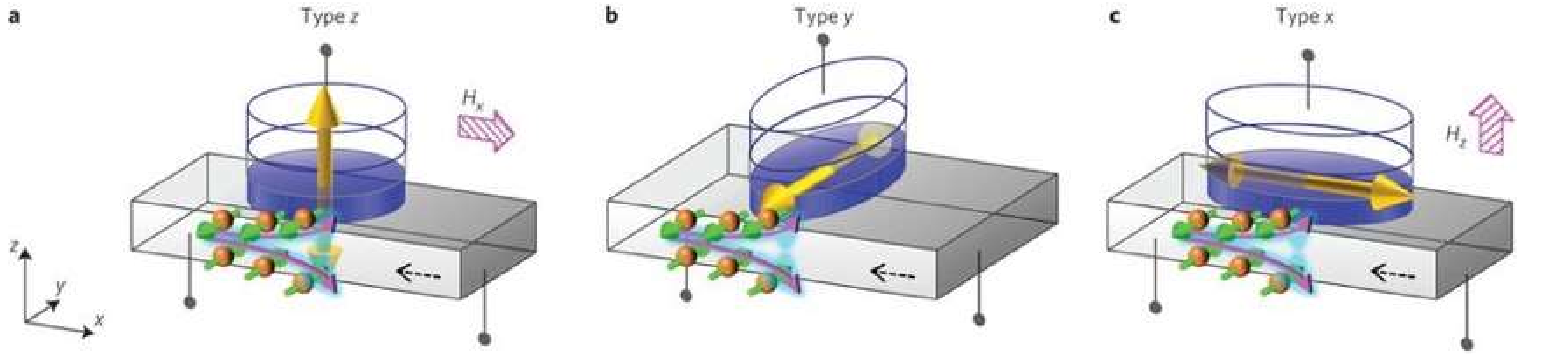


Exchange bias
in layered structure



Application II: Field-free switching

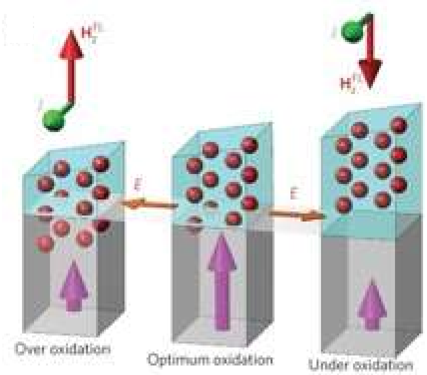
Current-induced magnetization switching by spin-orbit torques (SOTs)

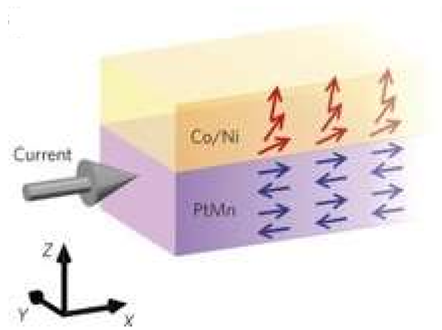


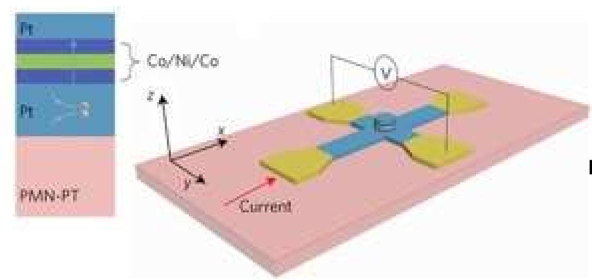
For OOP magnetization, it requires external field to break symmetry to achieve current-induced switching.

I. M. Miron, et al. Nature 2011
L. Liu, et al. Science 2012
S. Fukami, et al. Nat. Nano. 2016

Various field-free switching methods:







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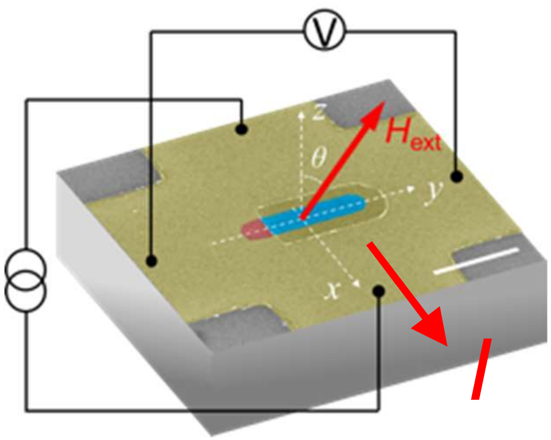
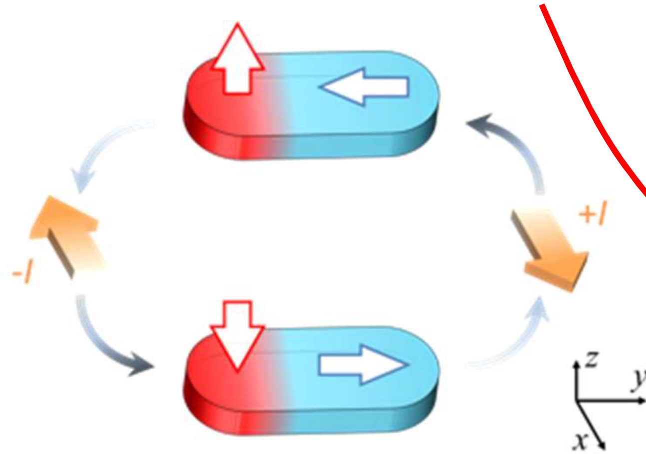
G. Yu, et al. Nature Nano. 2014

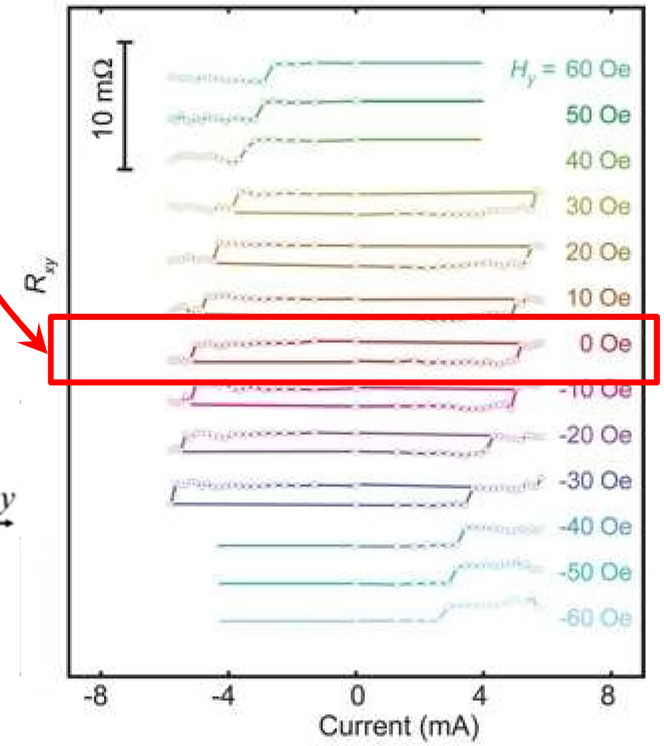
S. Fukami, et al. Nature Mater. 2016

K. Cai, et al. Nature Mater. 2017

Switching at zero field

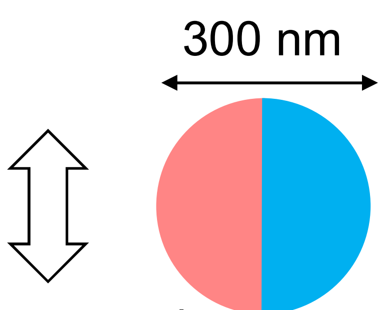




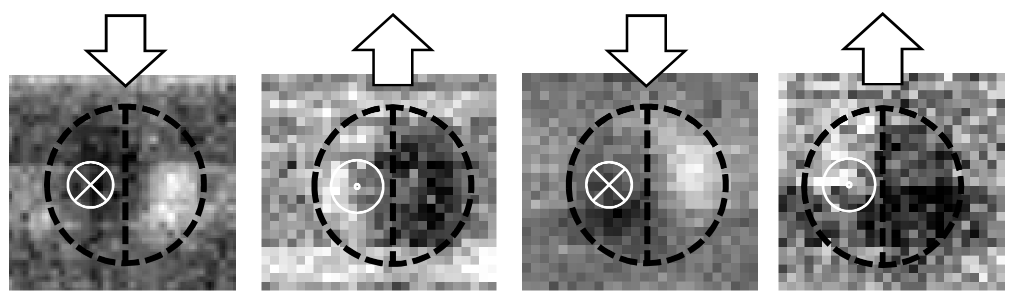


Break the symmetry by chiral coupling

Field-free switching with reduced IP region:

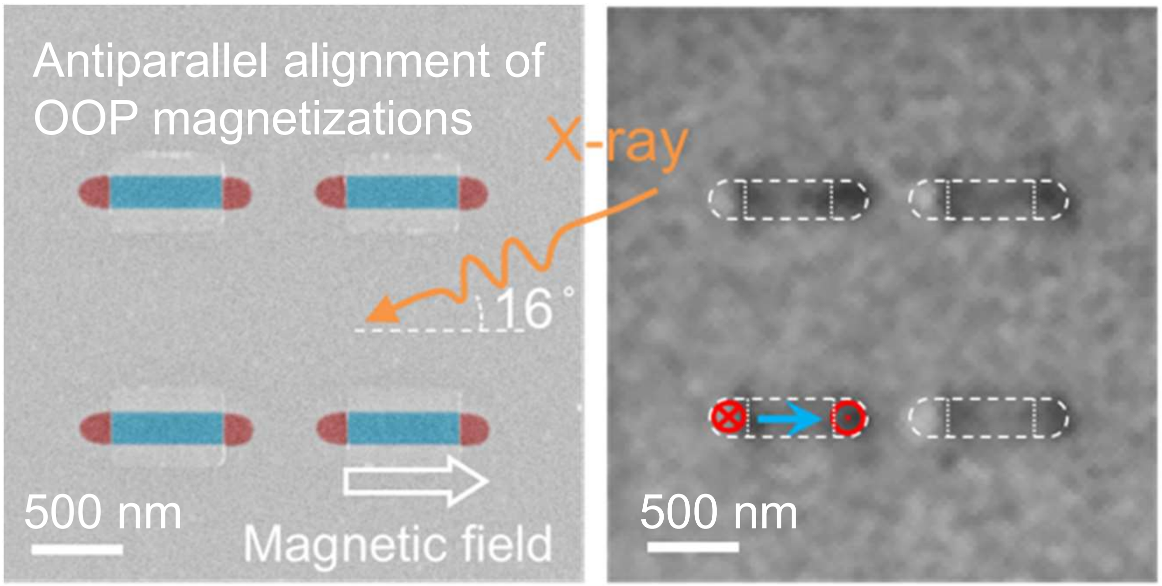


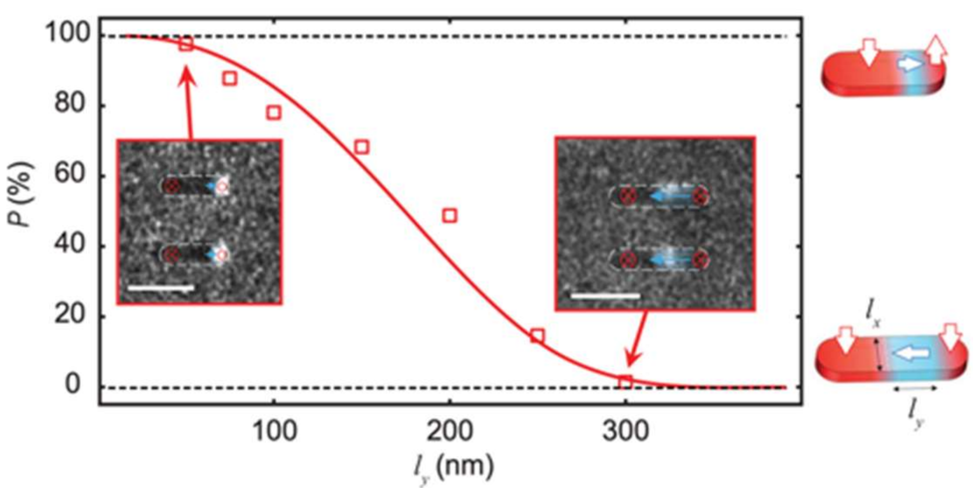
Current pulse
~8×10^11 A/m^2
100 ns



Scanning transmission X-ray microscopy XMCD

Application III: Synthetic anti-ferromagnet





When IP and OOP region both are small, the IP and OOP magnetizations can be mutually switched

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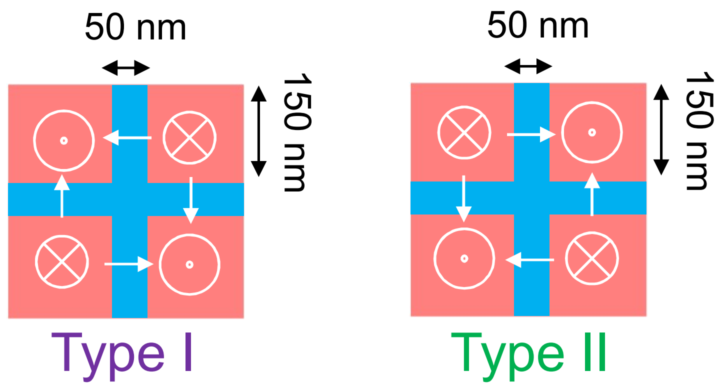
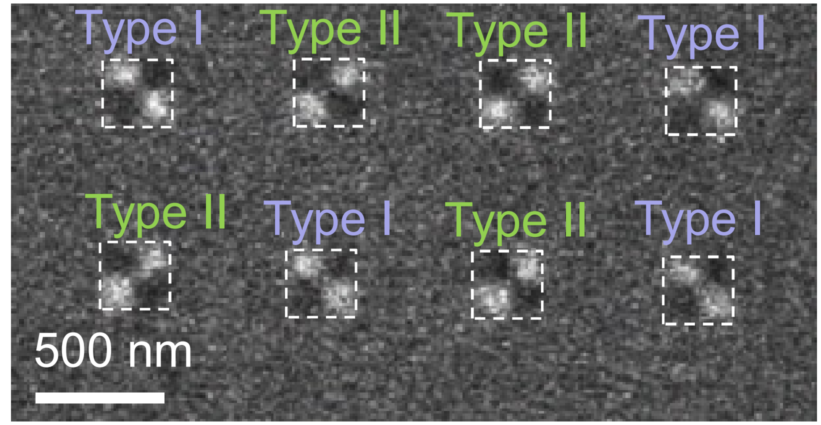
Collective phenomena in chirally coupled system

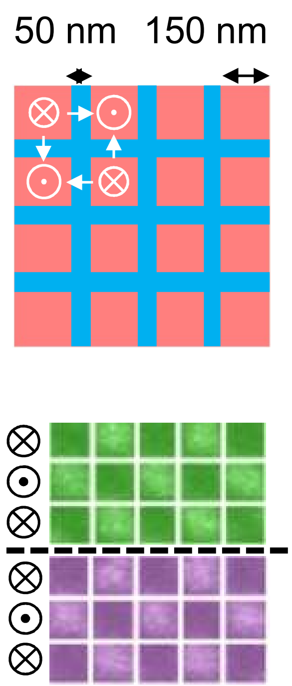
2D coupled nanomagnets

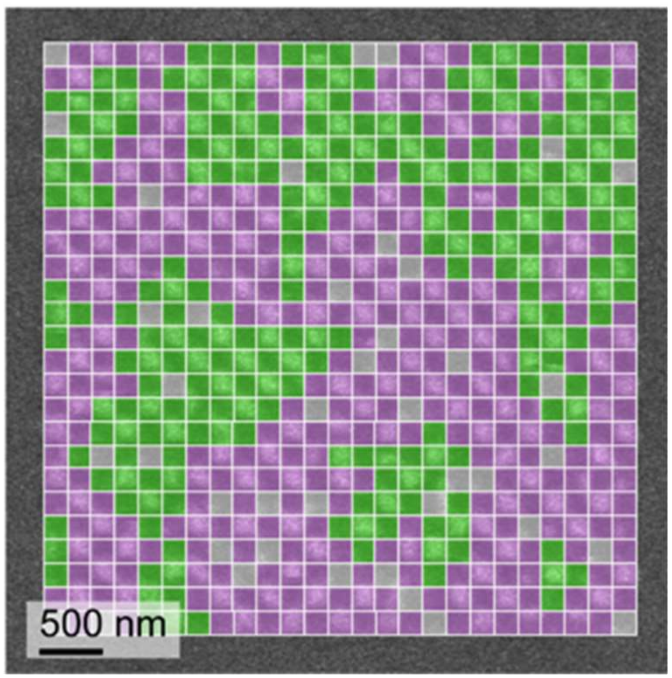


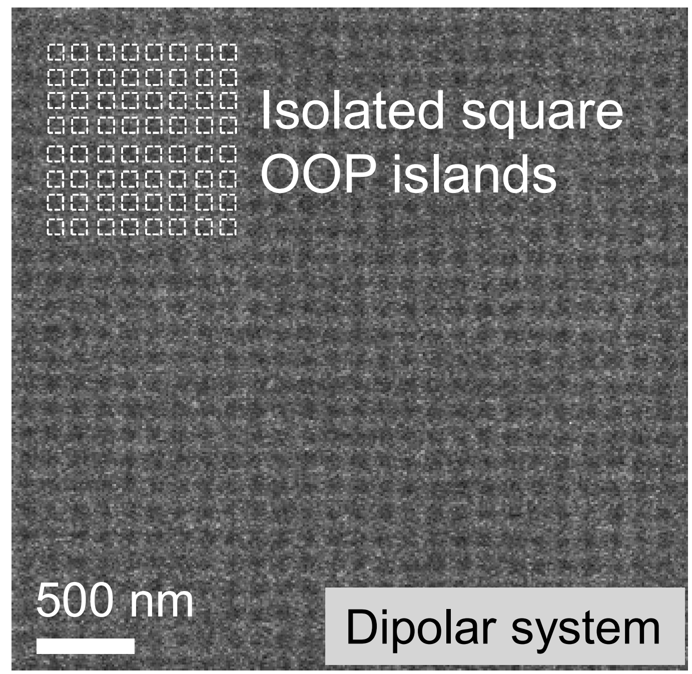
Square lattice



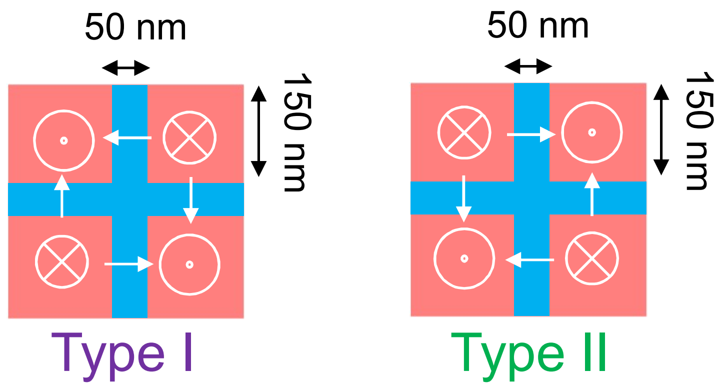
Initialized with $-H_z$



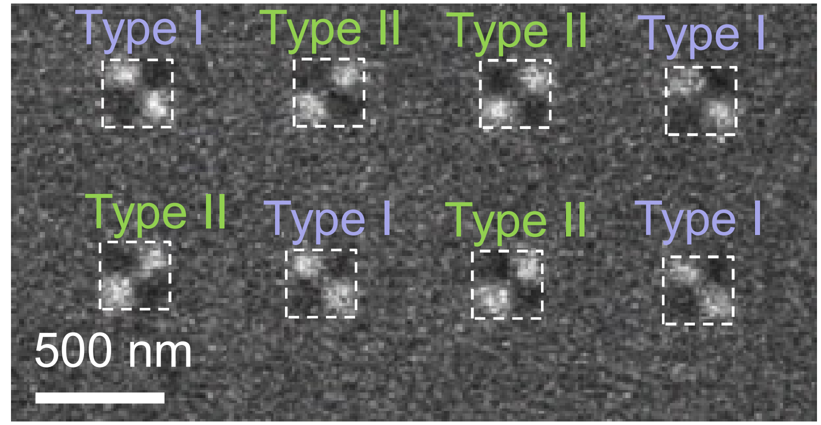




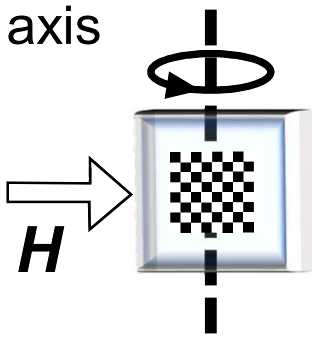
2D coupled nanomagnets

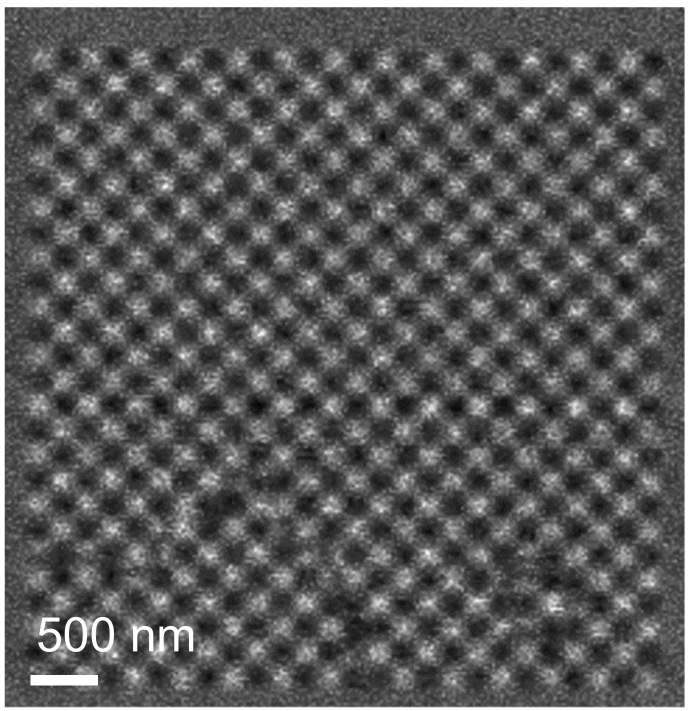


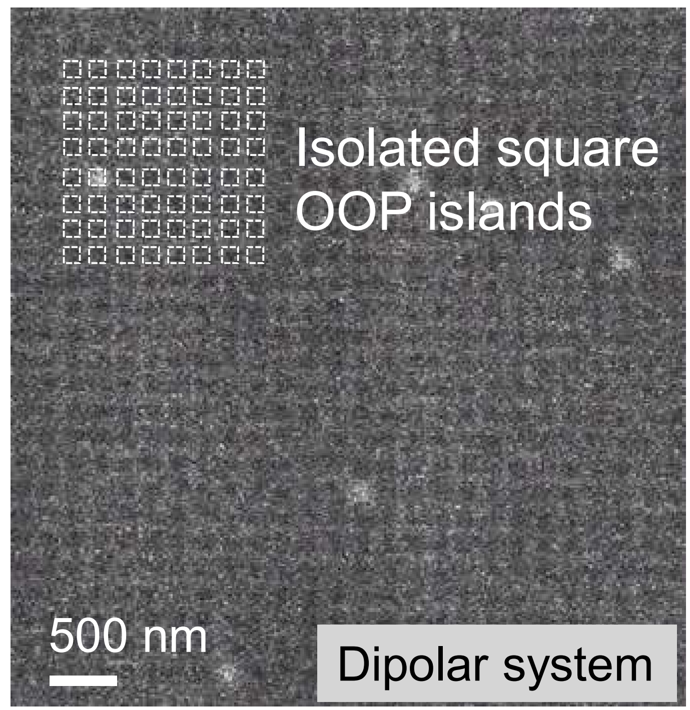
Square lattice



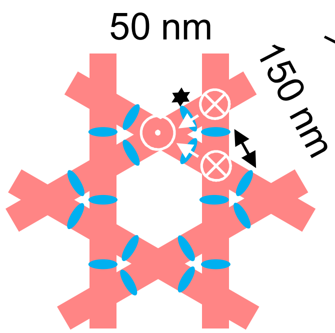
Rotation axis



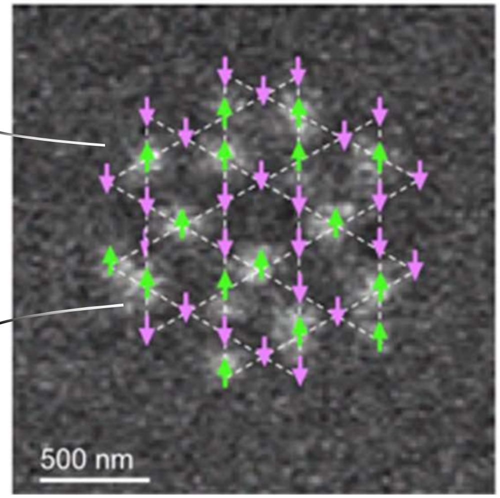


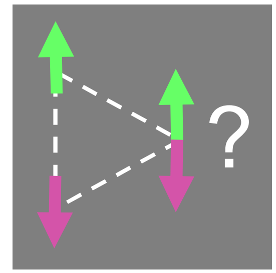


2D coupled nanomagnets



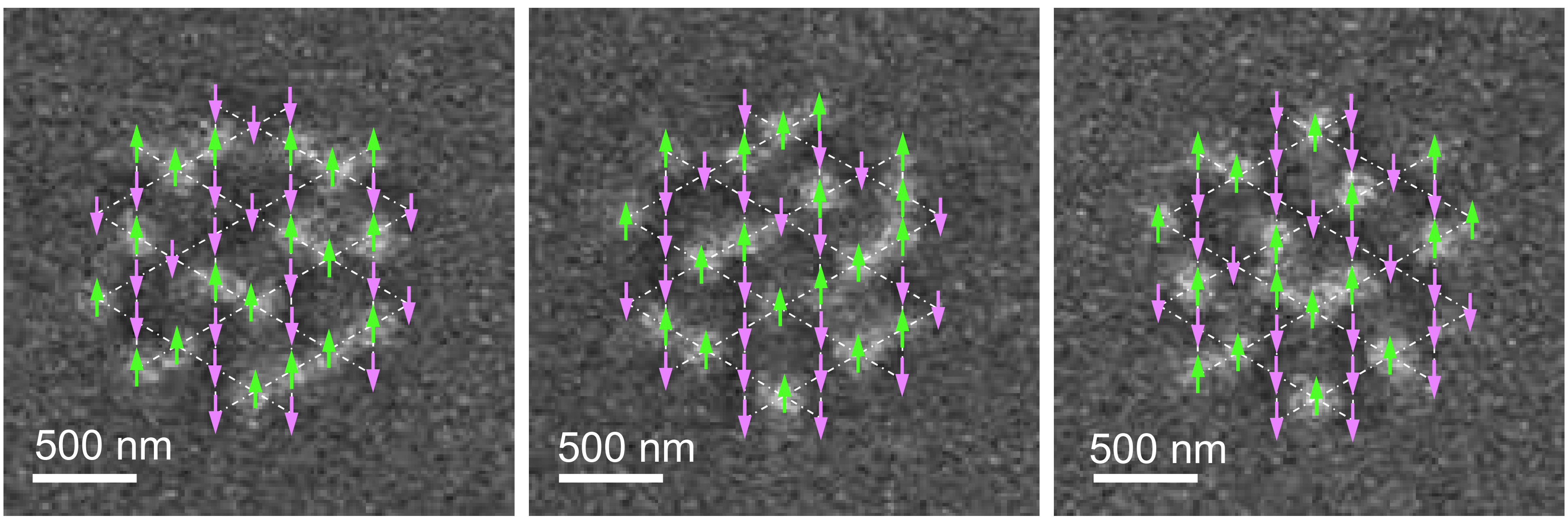
Kagome lattice



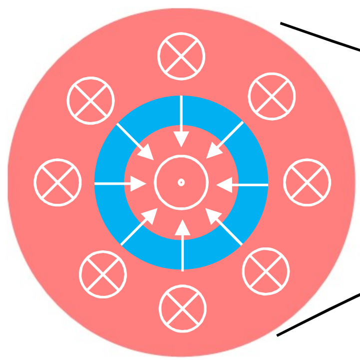


Frustration

Various frustrated configurations measured in the same device

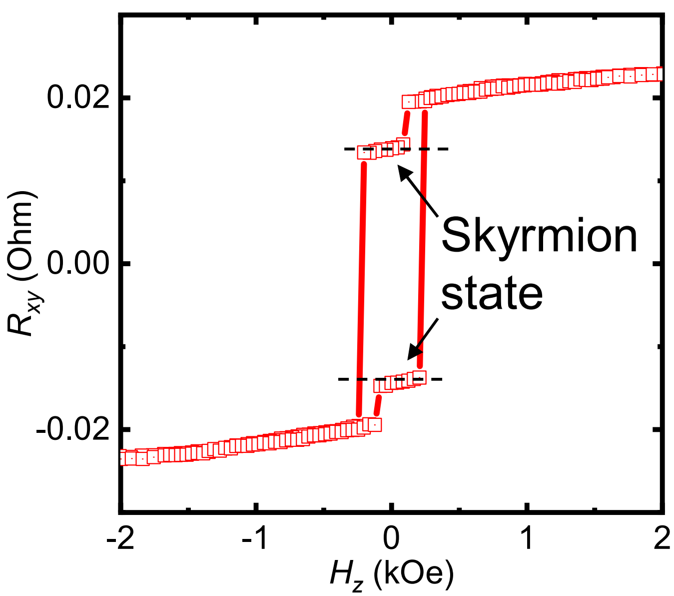


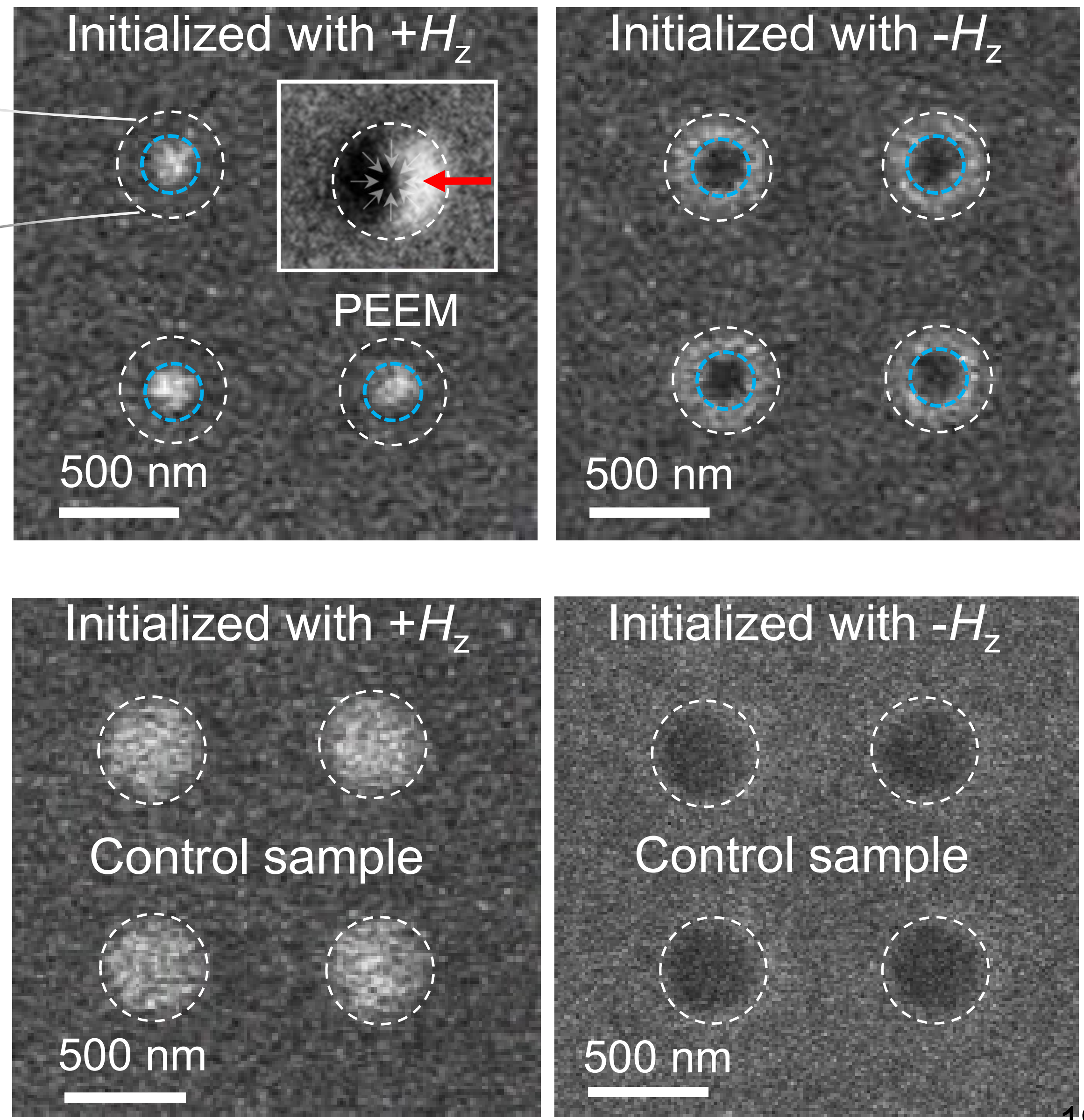
Application IV: Chiral nano-patterns



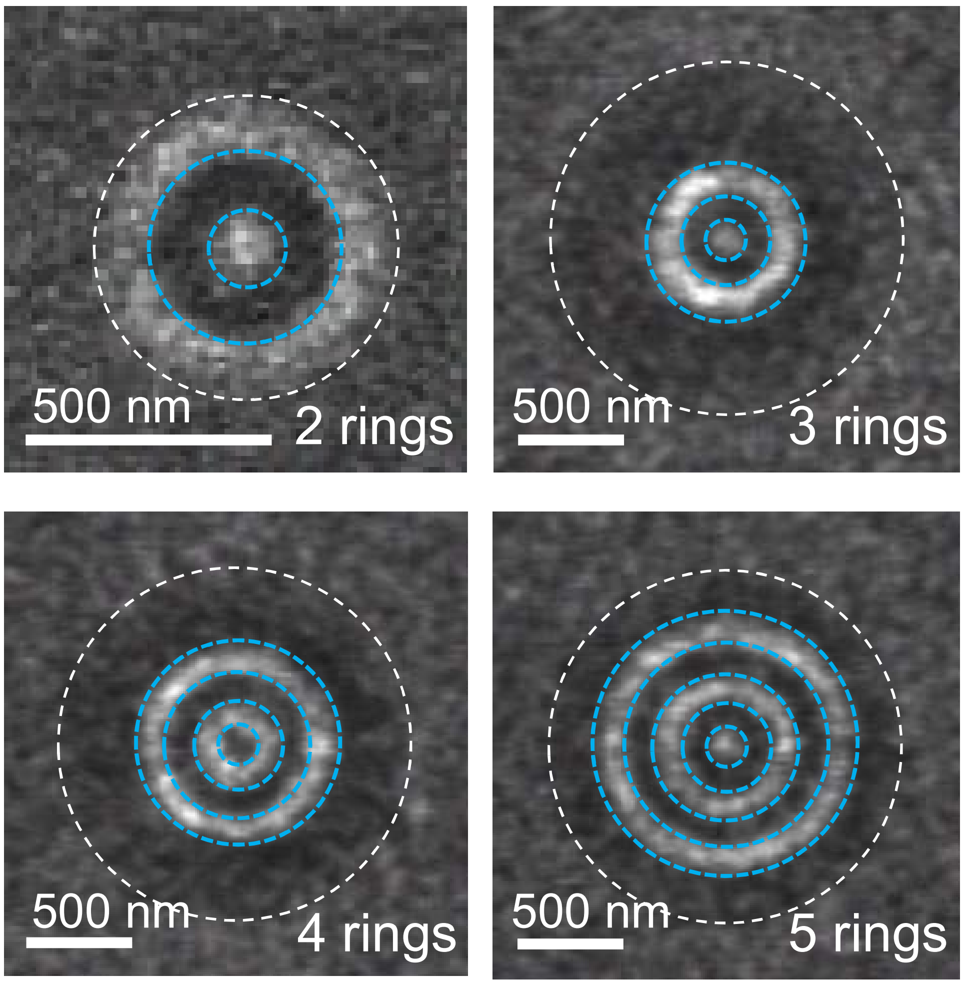
Synthetic skyrmion
at zero field

Hall measurement

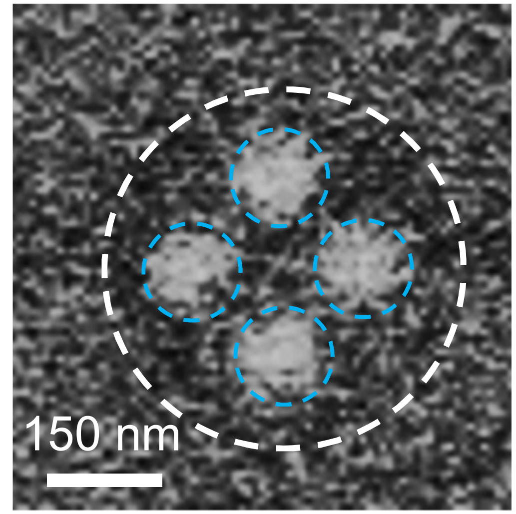




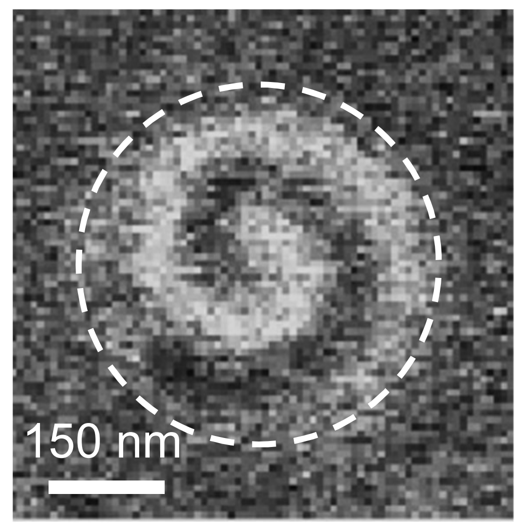
Multi-π Skyrmion: several IP rings



Skyrmion package



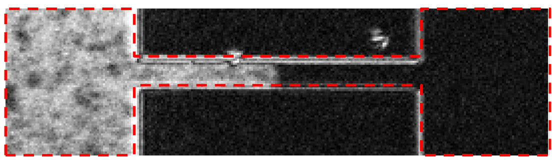
Spiral pattern



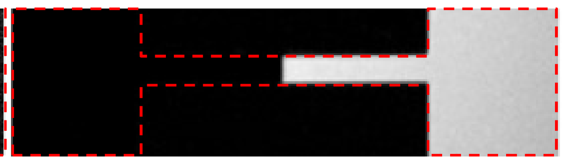
Application V: Chiral DW injector

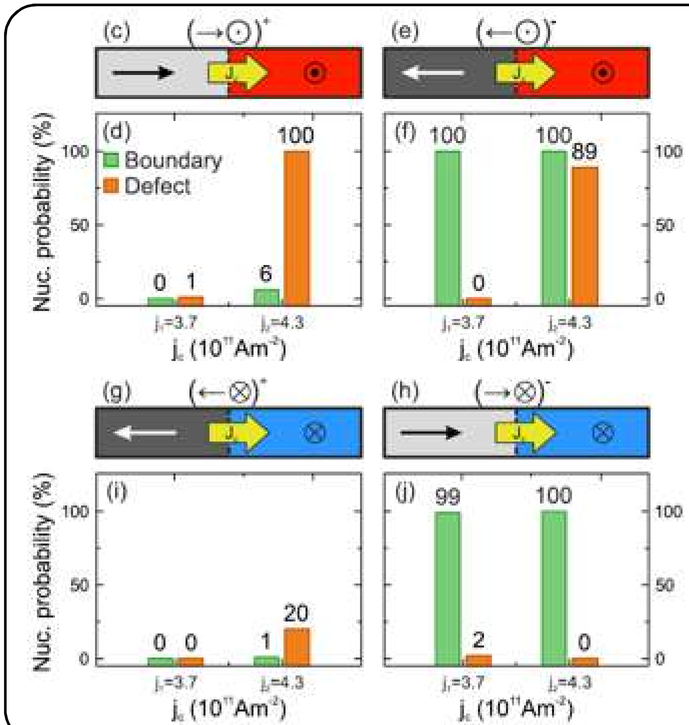
Magnetic racetrack with IP-OOP structure

Longitudinal mode



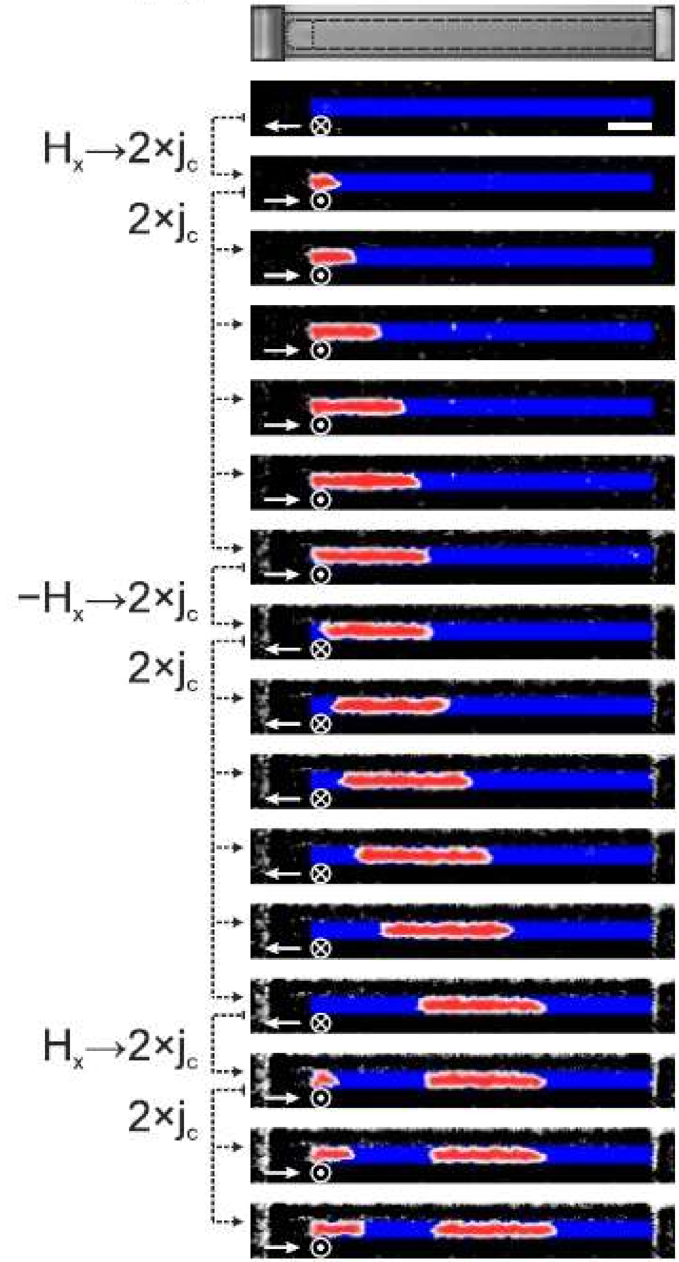
Polar mode

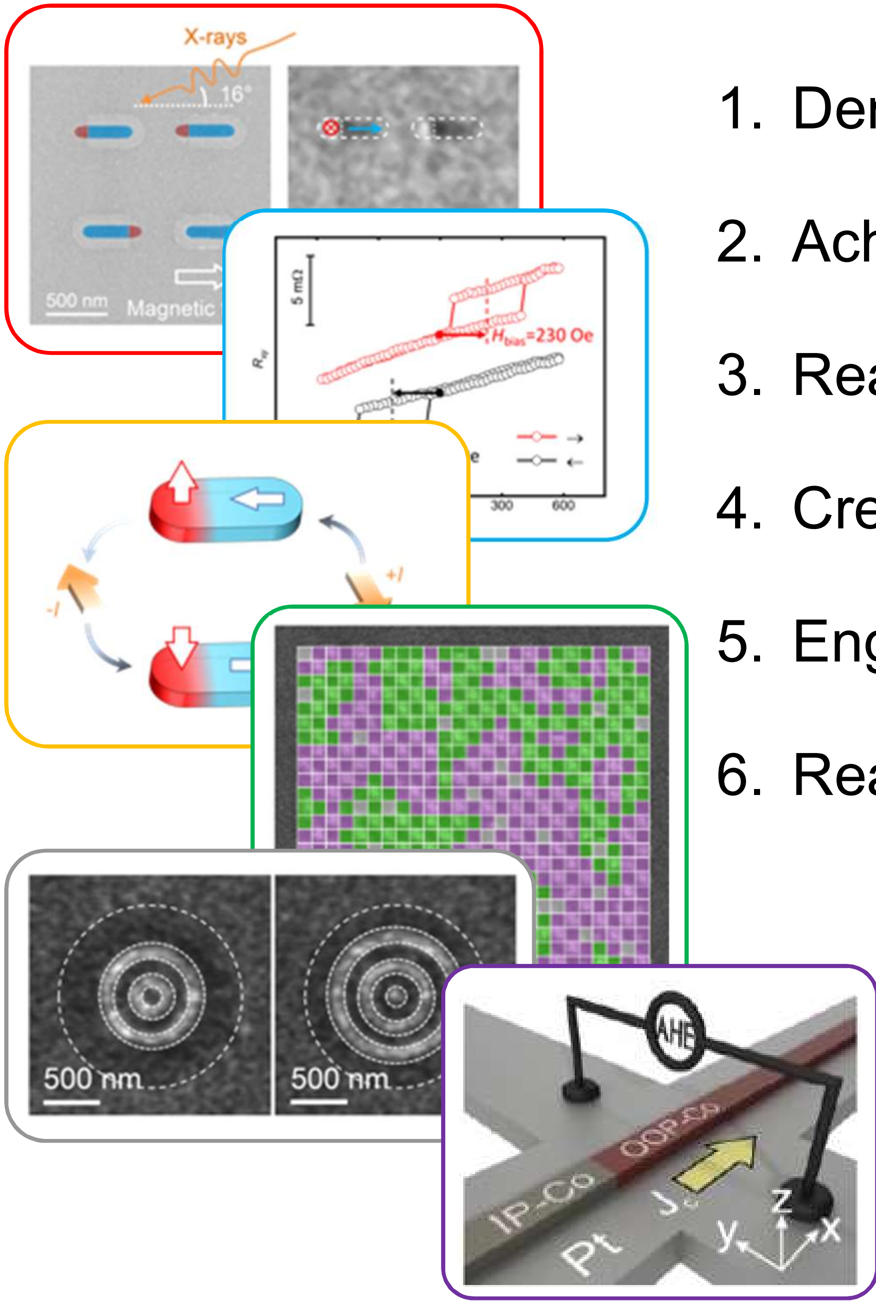




Nucleate ⊗ with ←

Nucleate ⊙ with →





Conclusions

1. Demonstrated strong chiral coupling
2. Achieved lateral exchange bias
3. Realized field-free switching
4. Created novel synthetic antiferromagnets
5. Engineered chiral nano-patterns
6. Realized chiral domain-wall injection

Z. Luo, et al., *Chirally coupled nanomagnets*. ***Science*** 363, 1435 (2019).

T.P. Dao, et al., *Chiral domain wall injector driven by spin −orbit torques*. ***Nano Lett.*** 19, 5930 (2019).