Nucleation, stabilization and manipulation of magnetic skyrmions

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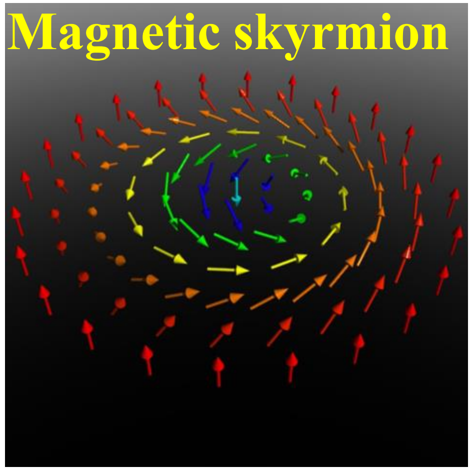
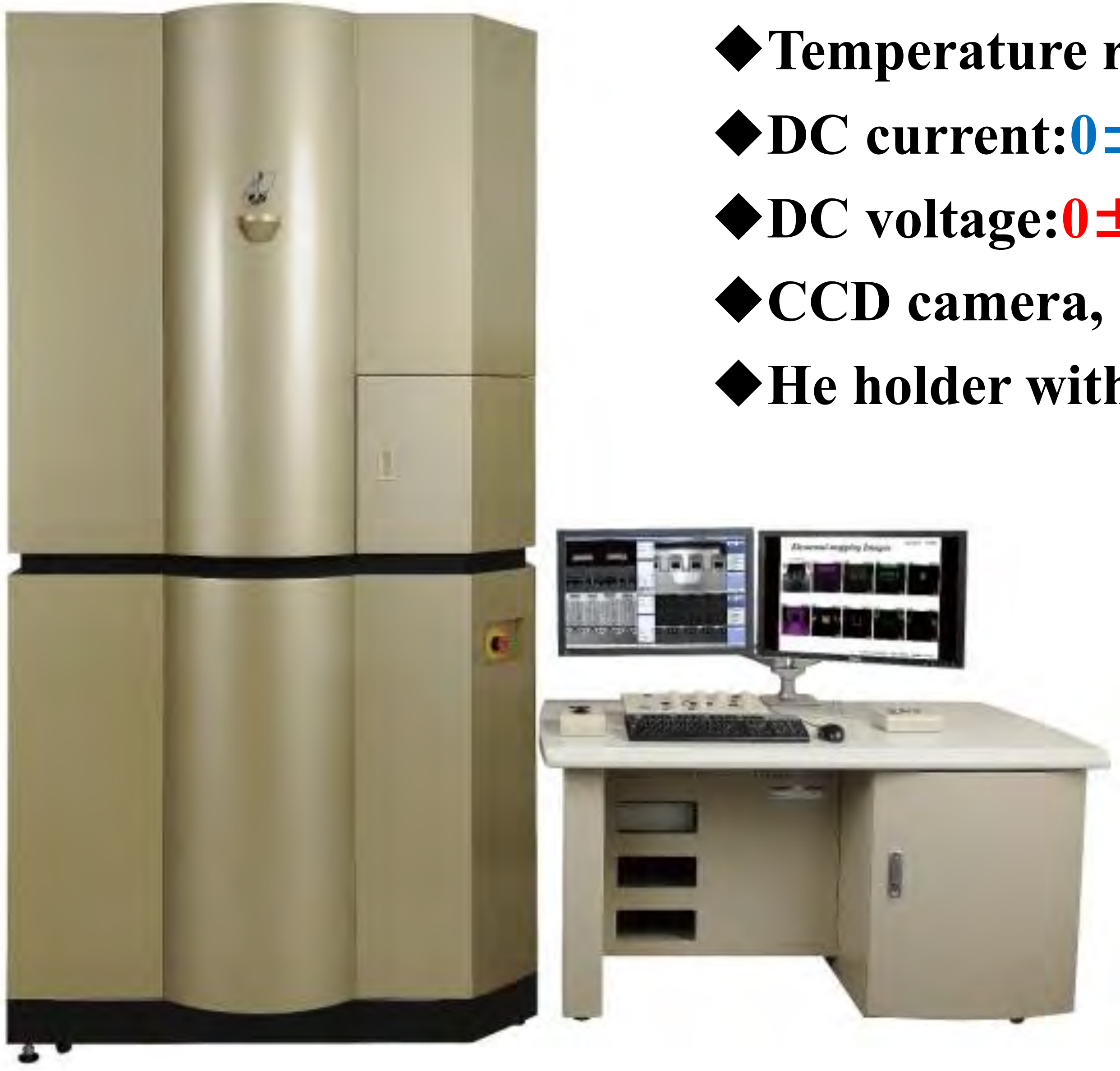


Multifunctional TEM/STEM(HREM, DPC-STEM, Lorentz TEM, EELS, EDS, SAED)



◆Temperature range: 5K – 500 K

◆DC current:0±100 mA

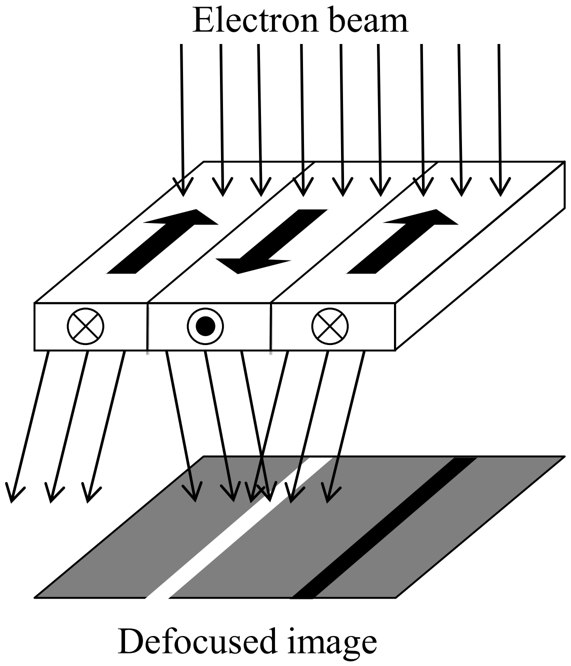
◆DC voltage:0±40 V

◆CCD camera, CMOS camera

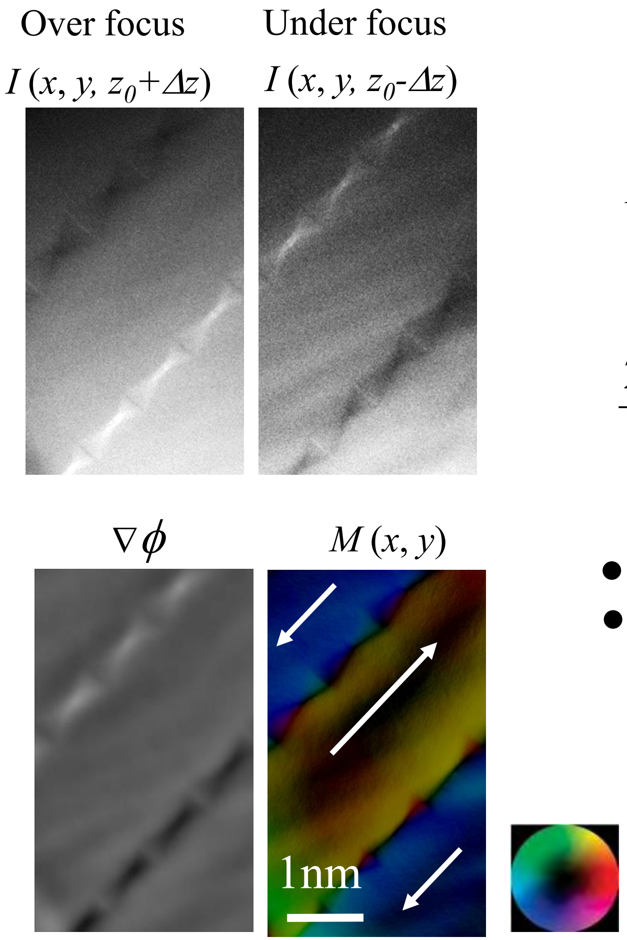
◆He holder with ten electrodes

Nanofabrication (FIB, E-lithography)

Lorentz TEM (Fresnel mode) is a useful technique to realize magnetization texture



Lorentz force



$$\frac{\partial I}{\partial z} \approx \frac{I(x, y, z_0+\Delta z) - I(x, y, z_0-\Delta z)}{2\Delta z}$$

$I(x,y,z)$: Electron intensity at image planes

Transport of intensity equation (TIE)

$$\frac{2\pi}{\lambda}\frac{\partial I(xyz)}{\partial z} = \nabla_{xy}\left[I(xyz)\nabla_{xy}\phi(xyz)\right]$$

$\phi(x,y,z)$: The phase distribution of electron wave

- M. R. Teague, *J. Opt. Soc. Am.* 73 (1983) 1434.
- K. Ishizuka and B. Allman, *J. Electron Microsc.*, 54 (2005) 191

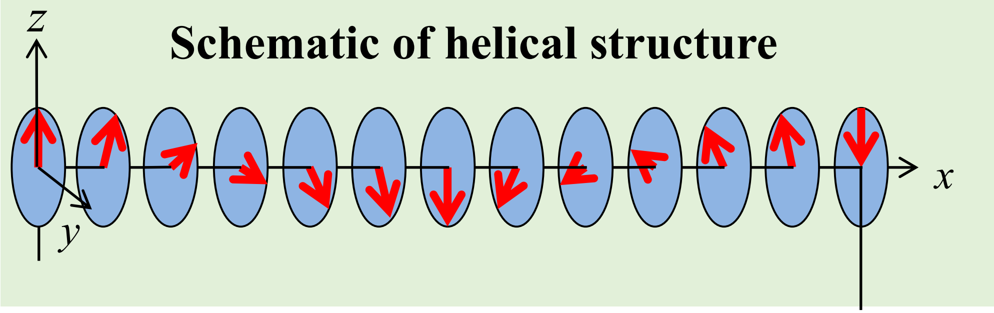
$$\nabla\phi(xyz) = -\frac{e}{\hbar}(M \times n)t$$

M: Spontaneous magnetization in the sample
t: Thickness of the sample

◆Lorentz TEM sample geometry: 2D thin film

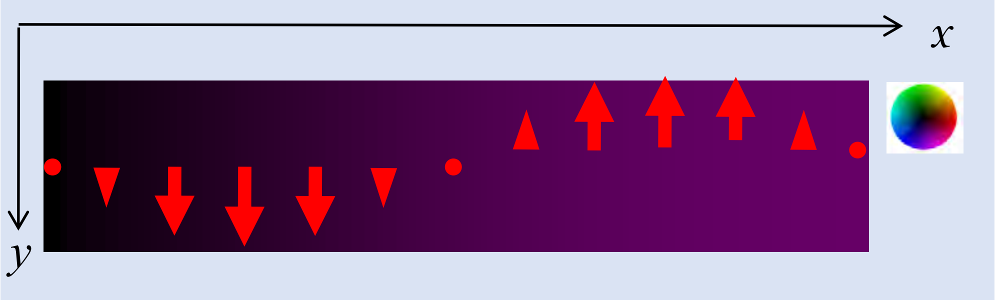
(sample thickness t (< 200 nm) is much smaller than the sample size (from several tens to several hundreds micrometers)

Magnetic twins can be projected by Lorentz TEM

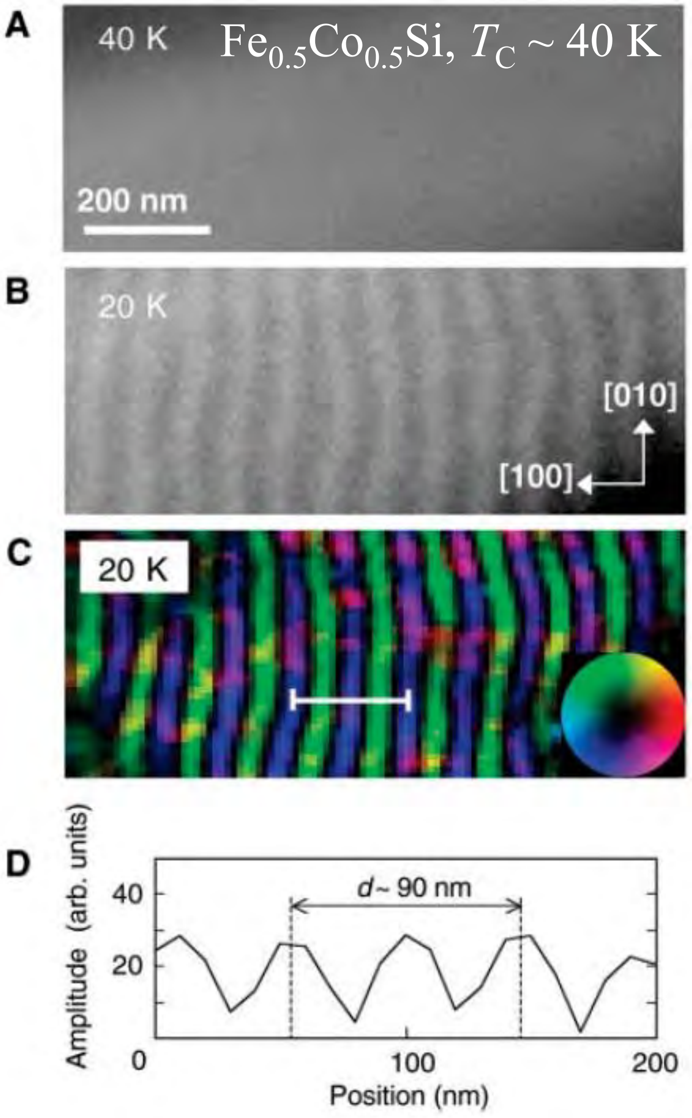


Schematic of helical structure

In-plane (2D) spin texture of helical structure can be projected by LTEM



z || electron beam



M. Uchida, et al, Science (2006)

Lorentz TEM observations for skyrmion within magnetic field

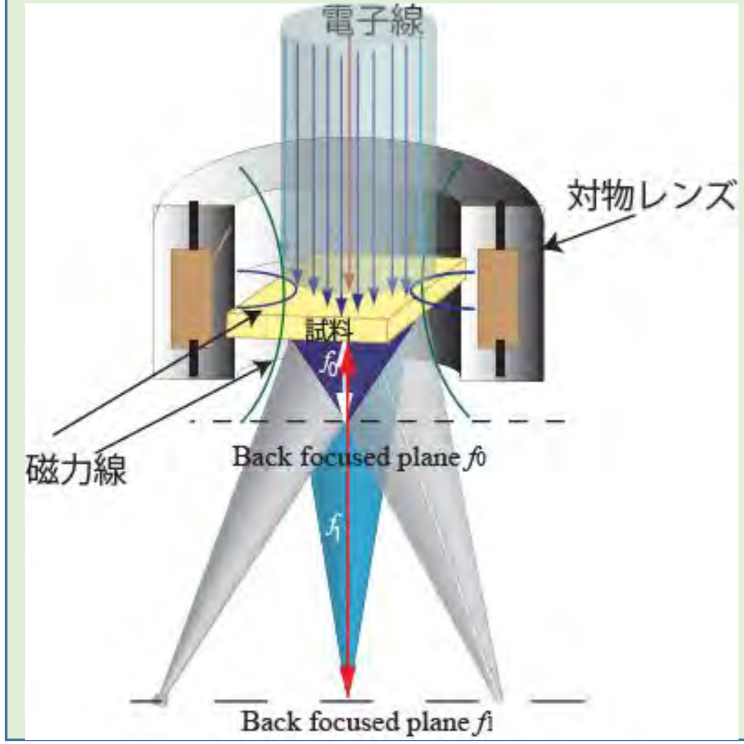
Problems:

- The original Lorentz TEM is used to perform the spontaneous magnetic domain structure for the magnetic materials without bias fields by using the special Lorentz transmission electron microscope
- However, we need bias fields to create skyrmions in B20 compounds

Improvements:

- Lorentz TEM performance is carried out in commercial transmission electron microscopes
- The tunable magnetic field is induced with changing the objective lens-current

Changes of the lens-current



The tunable magnetic field is induced by the objective magnetic lens

$$B_z \approx \frac{B_0}{1+(z/a)^2}$$

B_0 : a maximum field ($Z = Z_0$)
a : the half-width at half maximum of Bz

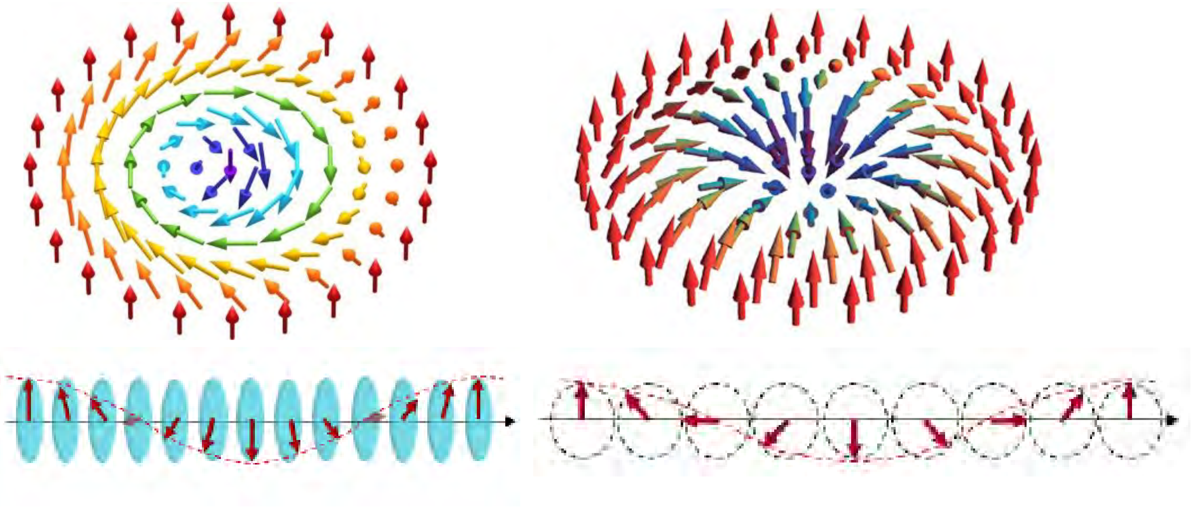
$$B_0 \propto I_{obj}$$

XY., et al., JEM 45, 273 (2010); *Nature* 465, 901 (2010)

Skyrmion：topological spin texture

Bloch-type skyrmion

Neel-type skyrmion

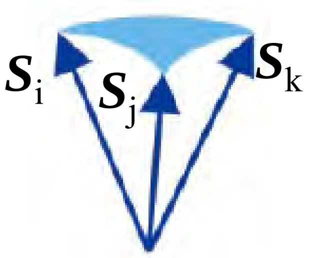


Topological number *Ns*

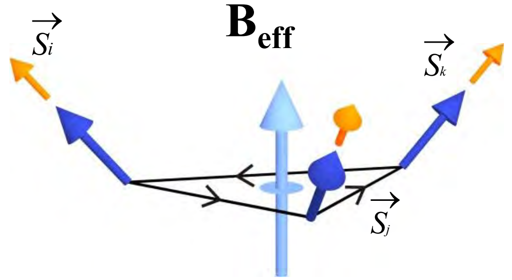
$$N_s = \frac{1}{4\pi}\int \vec{n} \cdot \left(\frac{\delta \vec{n}}{\delta x} \times \frac{\delta \vec{n}}{\delta y} \right) \delta x \delta y$$

$$\vec{n} = \frac{\vec{M}(r)}{\left|\vec{M}(r)\right|}$$

Ω : solid angle



Berry phase ➡ effective fictitious field



Emergent field

$$\mathbf{B}^z_{\text{eff}} = -\phi_0 / A$$

$$\phi_0 = h/e$$

A: Surface area of skyrmion

(Emergent field is in inverse proportional to the square of skyrmion radius)

- **Topological particle**
- **Emergent field**

N. Nagaosa and Y. Tokura, **Nat. Nanotech.** (2013)

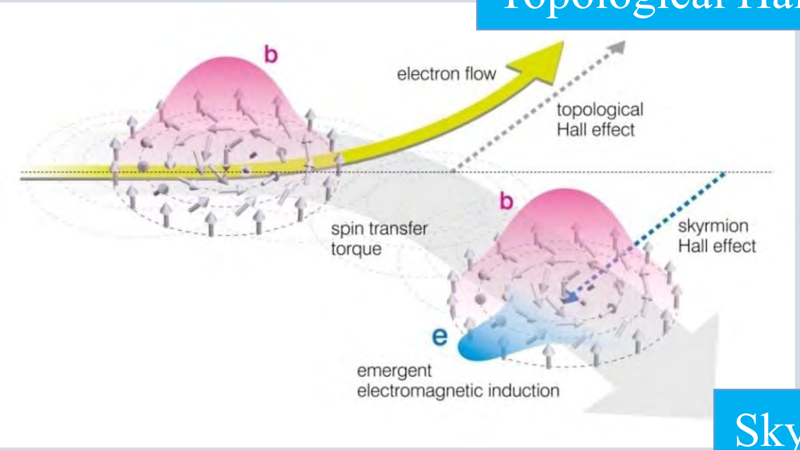
Nontrivial emergent phenomena

Electromagnetic induction

Moving magnetic flux produces the transverse electric field

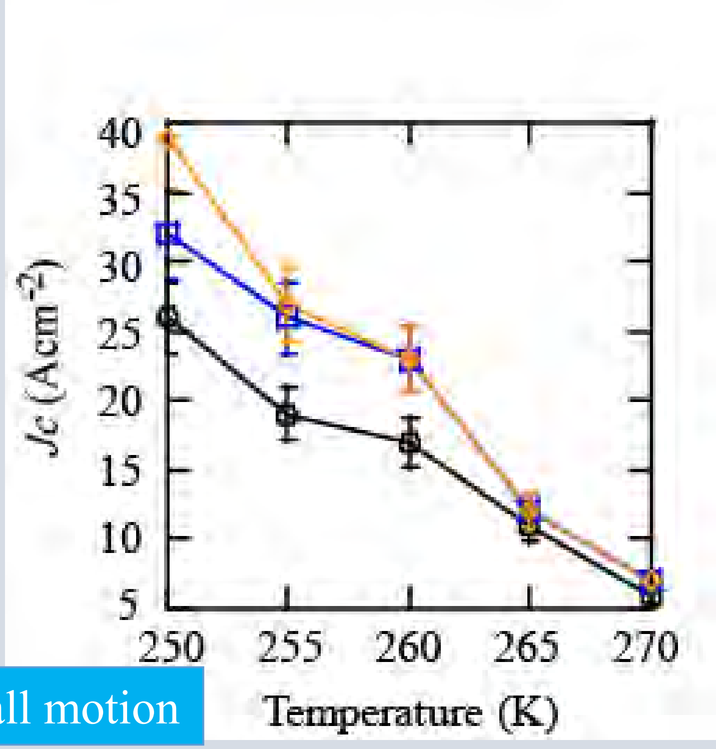
$$\mathbf{e} = -\frac{1}{c}\left[\mathbf{V}_{\parallel} \times \mathbf{h}\right]$$

Topological Hall effect



N. Nagaosa and Y. Tokura, **Nat. Nanotech.** (2013)
J. Zhang, *et al.*, **PRL** (2011)
T. Schulz, et al., Nat. physics (2011)

Ultra-low Current-driven SkX motion in FeGe thin plate



Skyrmion Hall motion

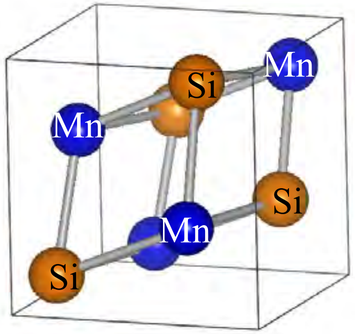
$J_{c\ \mathrm{Sk}} \sim 10^5\ \mathrm{A/m^2} << J_{c\ \mathrm{FM}}$

X.Z.Yu, *et al.* Nat. Commun. (2012)

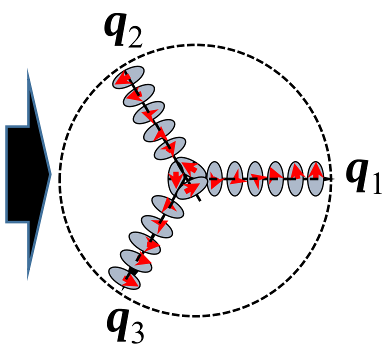
Magnetically-induced the formation of skyrmion lattice in B20 compounds

Crystal structure

- **Cubic**
- **Noncentrosymmetric**



$B \perp \boldsymbol{q}$

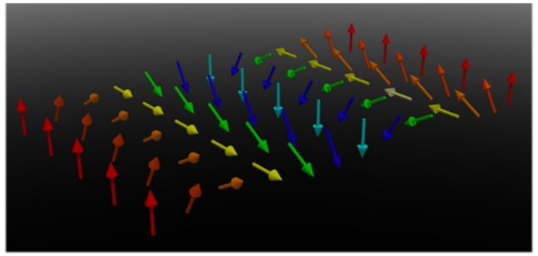


Spin Hamiltonian

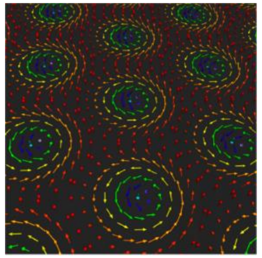
$$H = \int dr \left[\frac{J}{2} (\nabla \vec{M})^2 + \alpha \vec{M} \cdot (\nabla \times \vec{M}) \right]$$

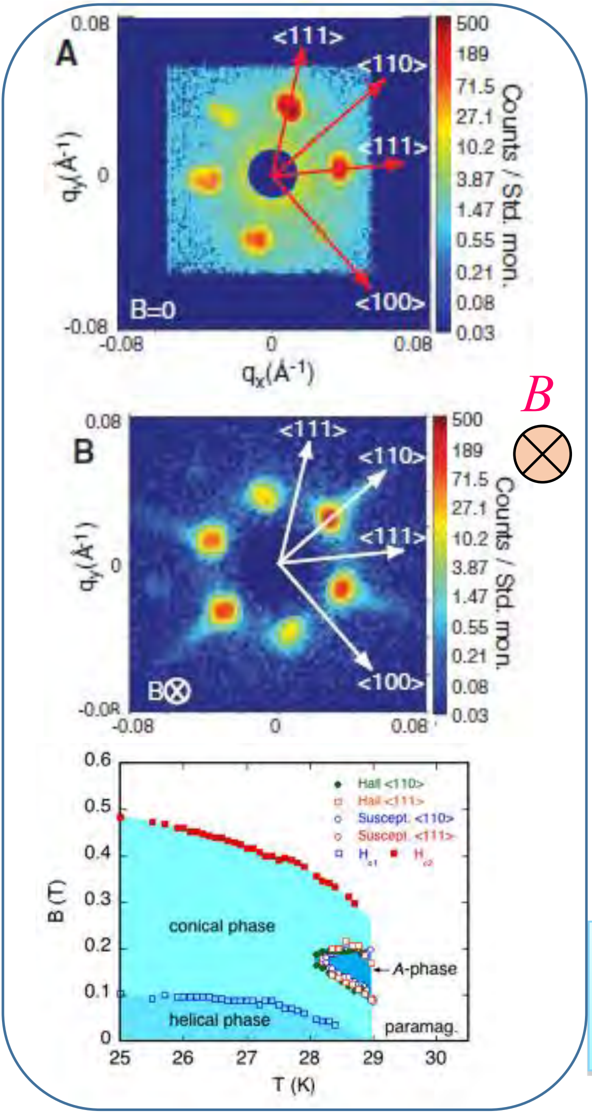
Magnetic structure

Ground state:
spiral with q ~ α/J



Magnetically-induced the formation of SkL





B ⊗

- First observation for SkL in a prototype skyrmion material
- It is hardly to confirm the topological spin texture for a single skyrmion by SANS
- Narrow window for SkL phase in a bulk MnSi

Phase diagram in a bulk MnSi

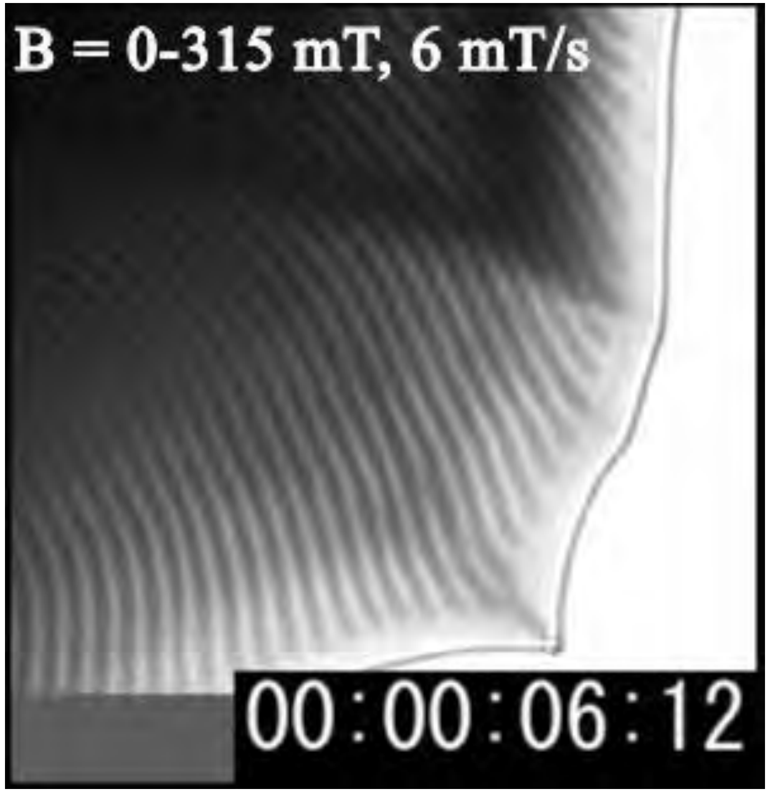
S. Mühlbauer. *et al. Science* **323**, 915 (2009)

We need a imaging technique to confirm the topological nature of skyrmions as well as their lattice forms

Topics Ⅰ - 1

Nucleation of magnetic skyrmions in chiral-lattice magnets under magnetic field

A chiral-lattice FeGe, 260 K



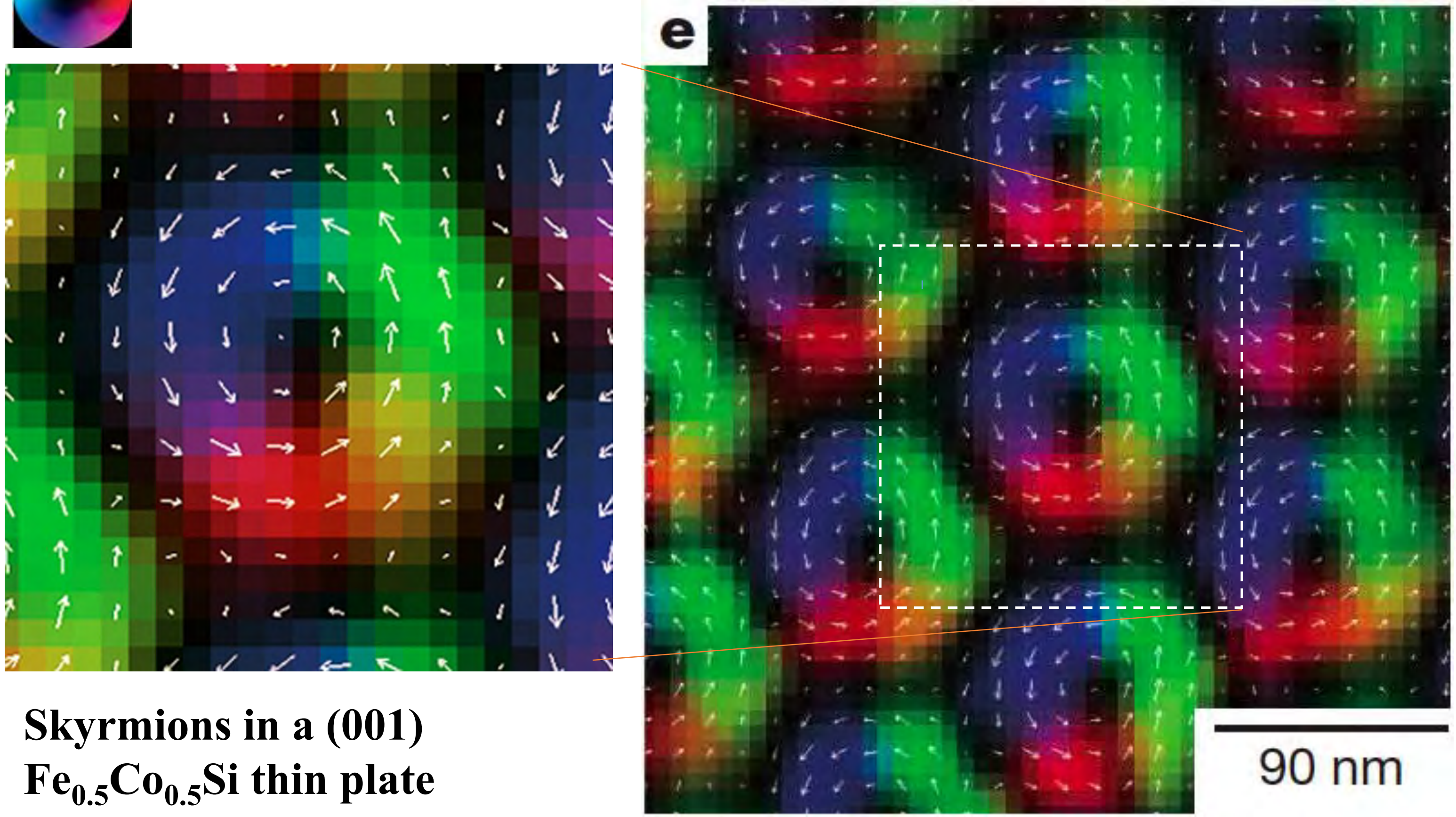
The B (⊥ the plate plane) induces the phase transition in two magnetic systems:

Stripes → SkX → FM

XZ. Yu, *et al.*,
Nat. Commun (2012, 2014)

First real-space observation of magnetic skyrmion in a chiral-lattice magnet $Fe_{0.5}Co_{0.5}Si$

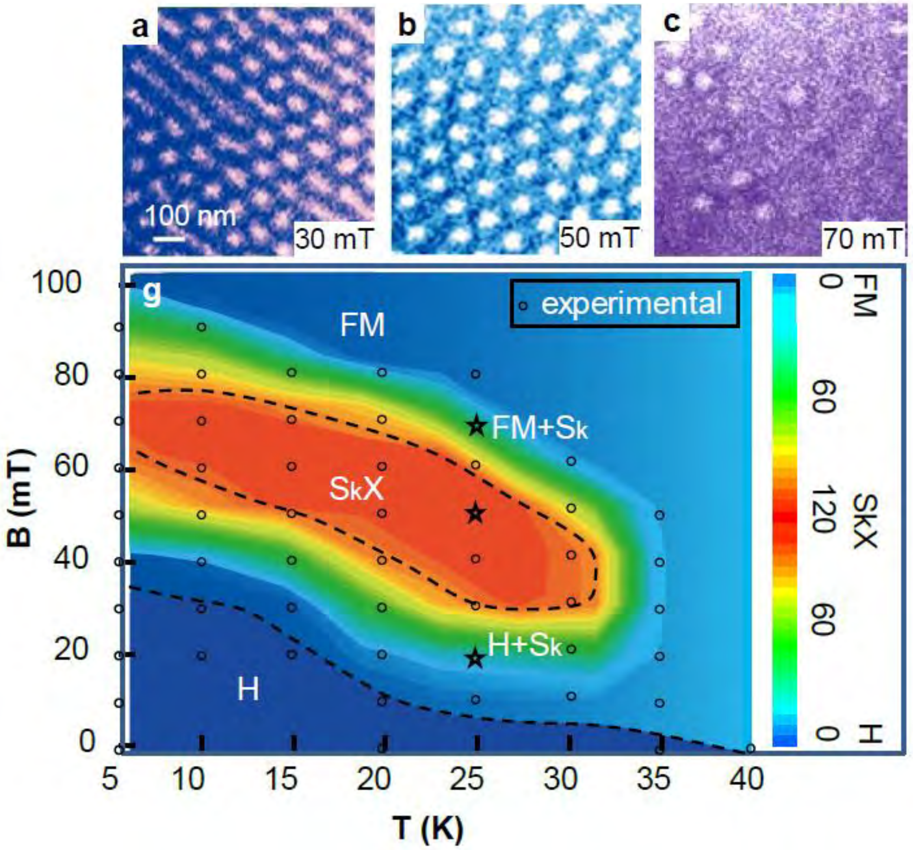
In collaborations with Profs. Tokura, Nagaosa, Onose, Han; Drs. Matsui, Kanazawa



Skyrmions in a (001) $Fe_{0.5}Co_{0.5}Si$ thin plate

XY, *et al.*, *Nature* **465**, 901 (2010)

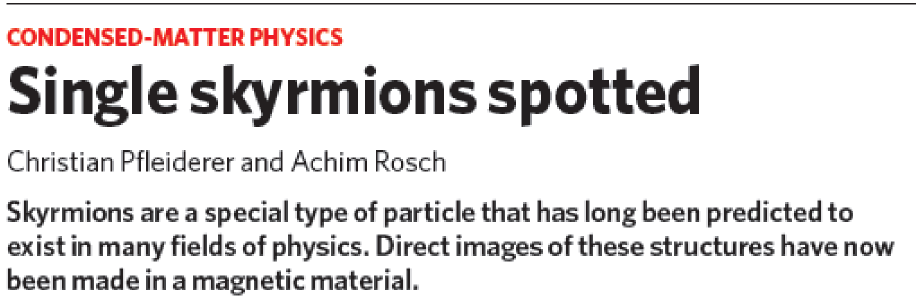
B (⊥plane) = 50 mT, T = 25 K



- 2D SkL is robust in a thin chiral-lattice magnet
- Isolated skyrmions have been realized

Realization of isolated skyrmions

News and views of Nature

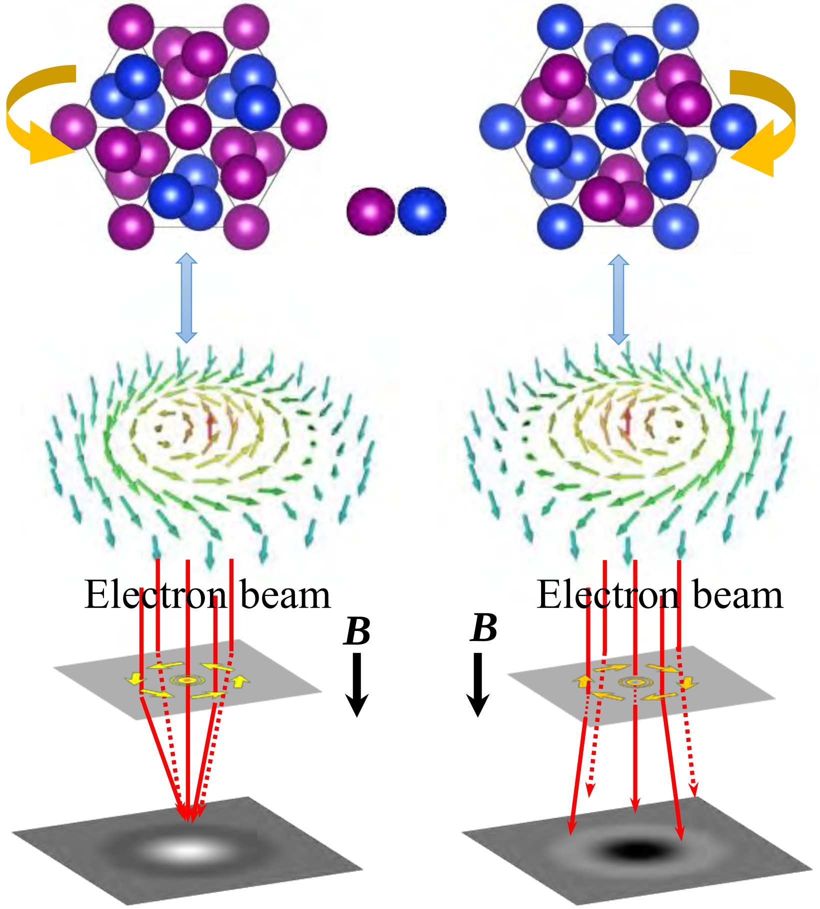


CONDENSED-MATTER PHYSICS

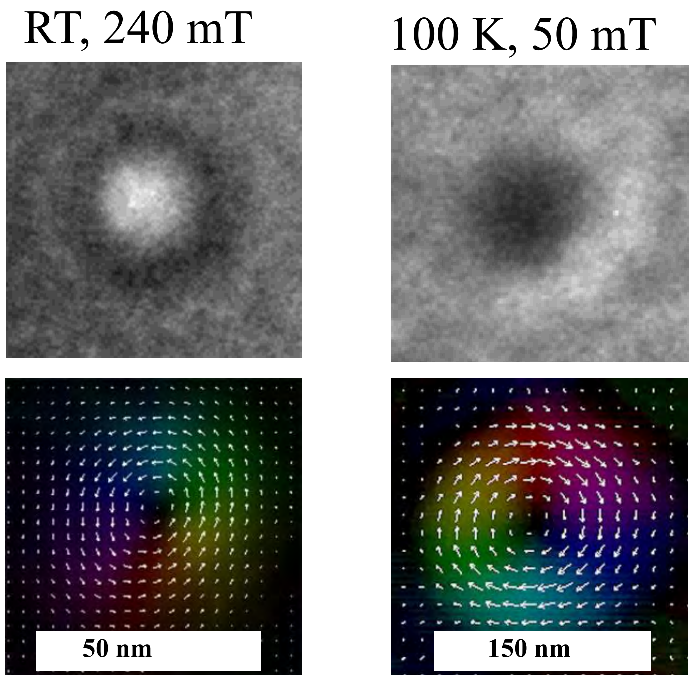
Single skyrmions spotted

Christian Pfleiderer and Achim Rosch

Skyrmions are a special type of particle that has long been predicted to exist in many fields of physics. Direct images of these structures have now been made in a magnetic material.



Over-focused image plane



XY & Y. Tokura, JEOL news (2015)

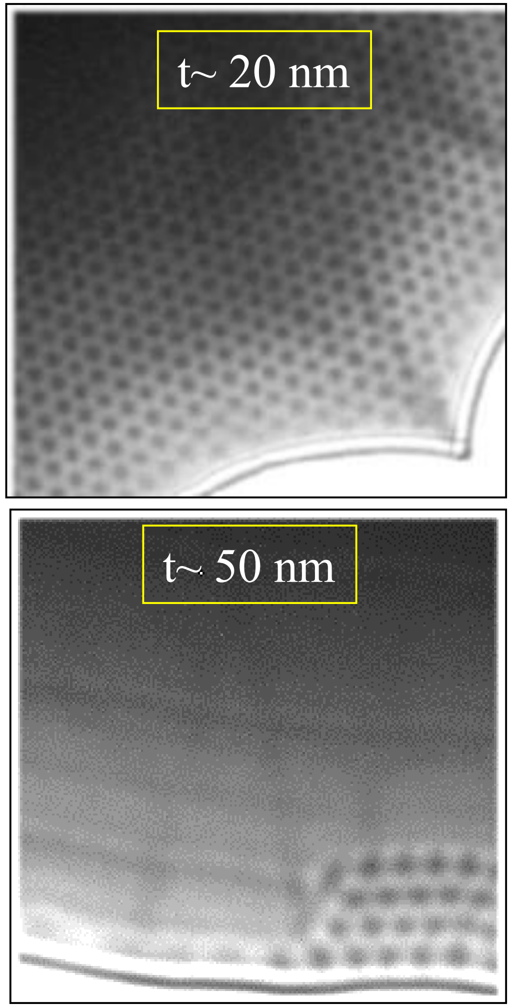
One to one correspondence of skyrmion helicity and crystal chirality in chiral-lattice systems

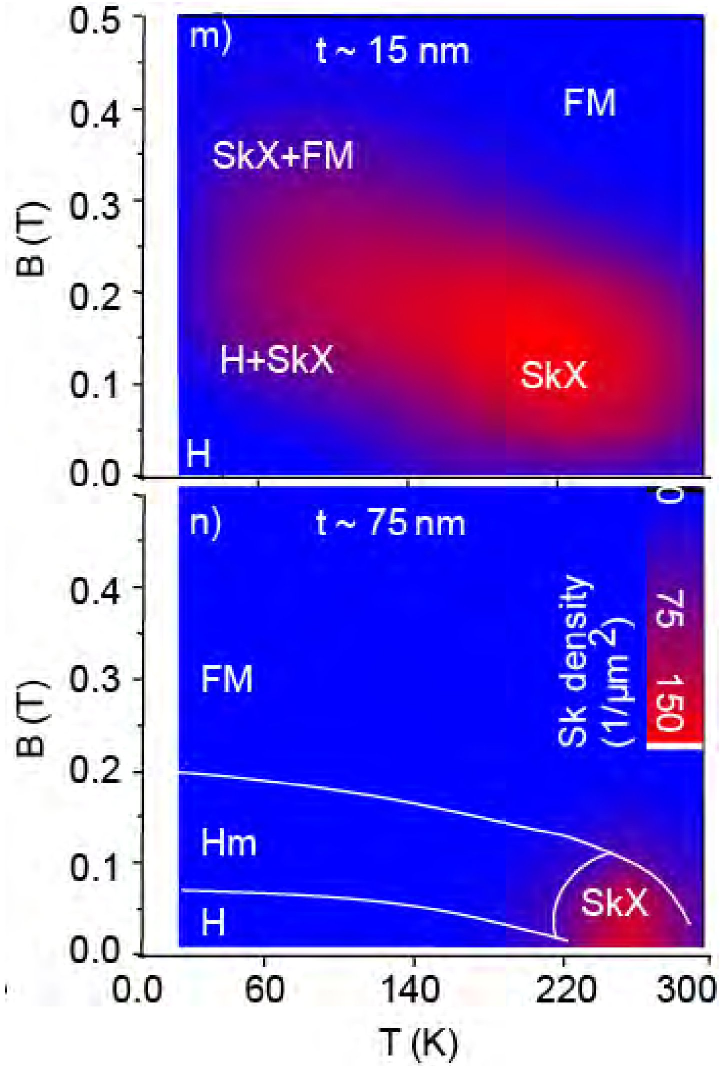
S. Shibata, XY., et al., Nat. Nanotech. (2013); D. Morikawa, XY., et al., PRB (2013)

Stability of the thermodynamically stable SkX in FeGe

T = 200 K, B = 150 mT

200 nm



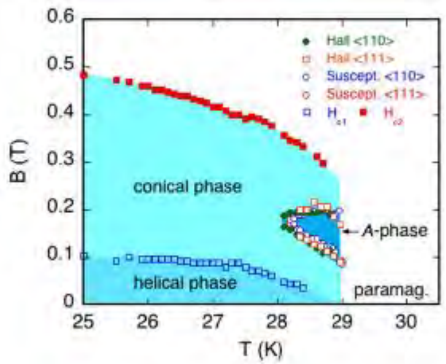


The thinner the sample is, the more stable SkX is.

XY, *et al.*, **Nat. Mater.** (2011)

SkX phase diagrams depending on sample thickness (t)

Phase diagram in a bulk MnSi



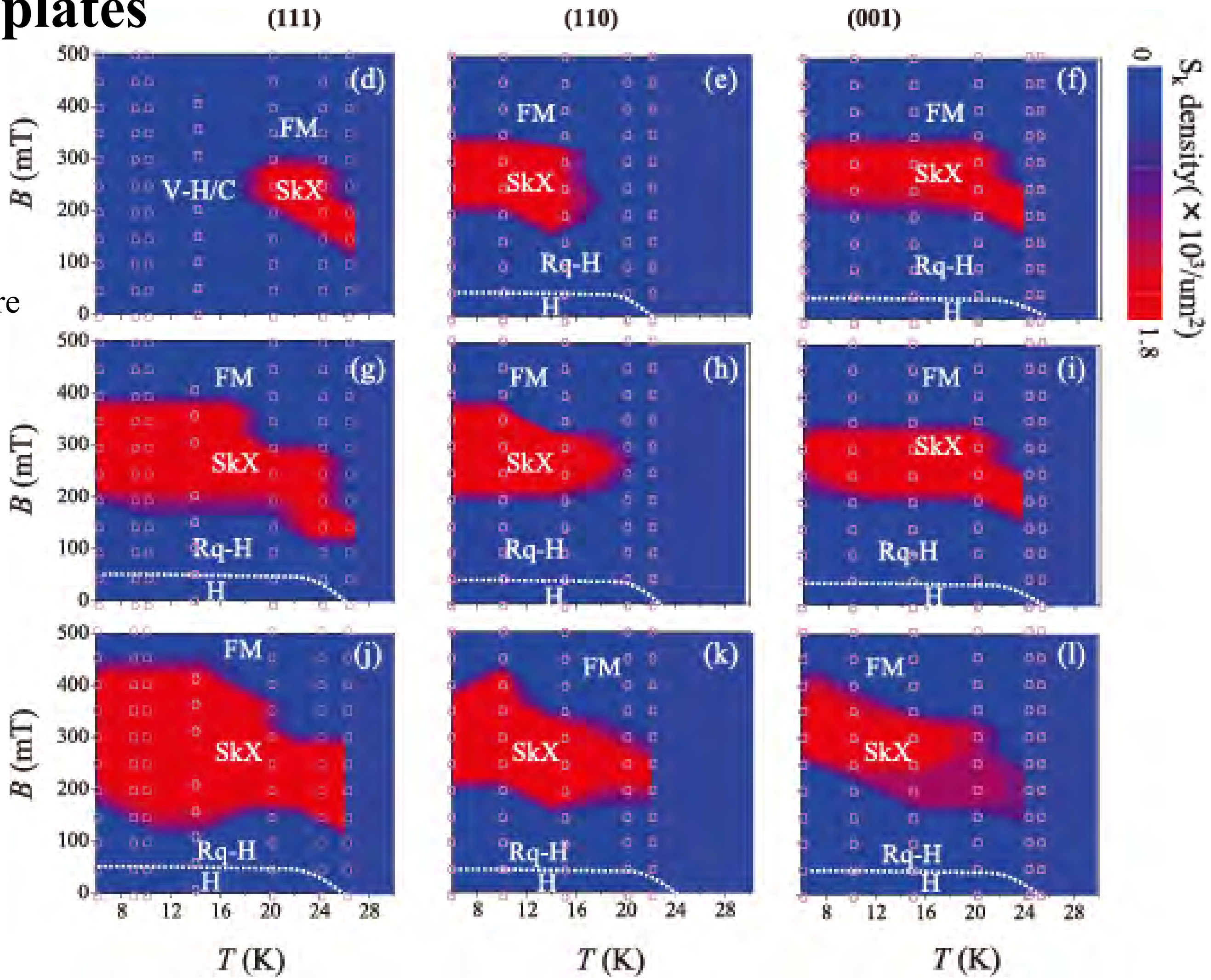
MnSi thin plates

$t \sim 5\ \lambda$

$t \sim 3\ \lambda$

$t < 3\ \lambda$

λ: period of helical structure



XY, *et al.*, **Phys. Rev. B** (2015)

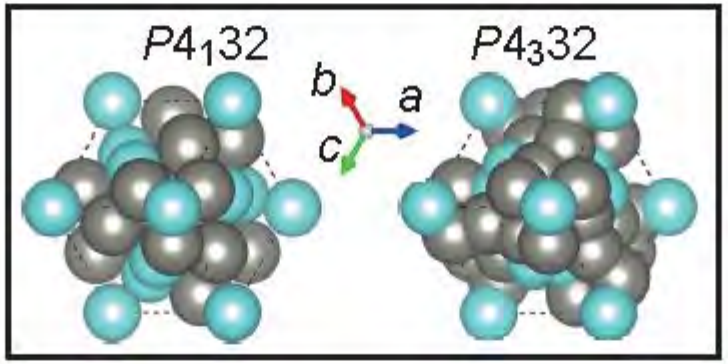
◆ The thinner the crystal plate is, the wider SkX phase is in the T-B plane.

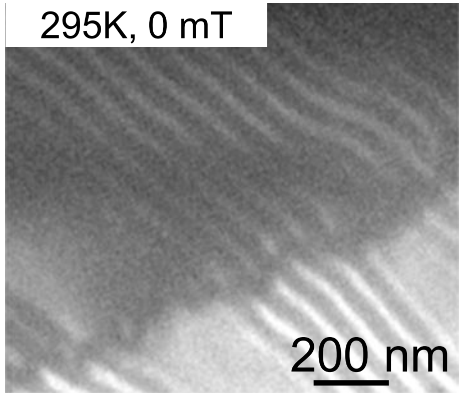
◆ Compared to Sk phase in (110) and (001) films, Sk phase shirked in the thicker (111) MnSi film (>75nm).

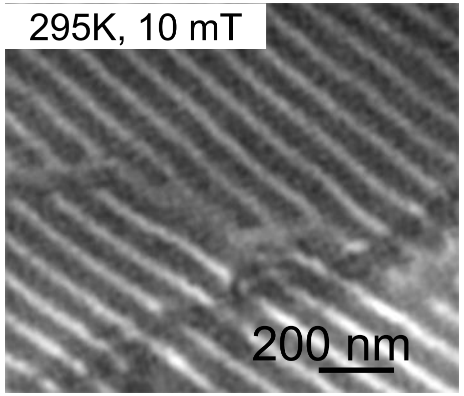
Transformation of square to triangular SkL in a Co-Zn-Mn

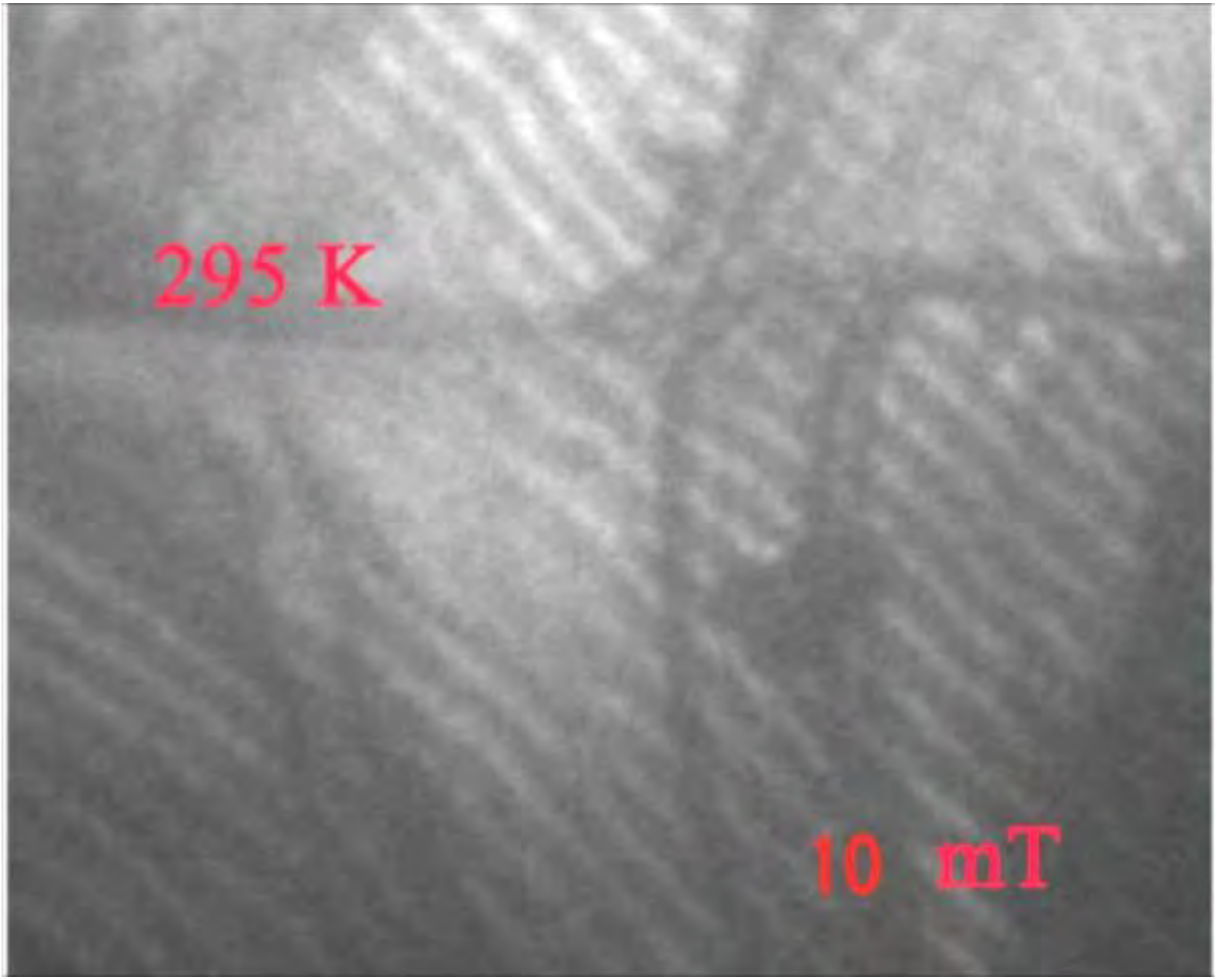
(001) $Co_8Zn_9Mn_3$

$T = 295K$



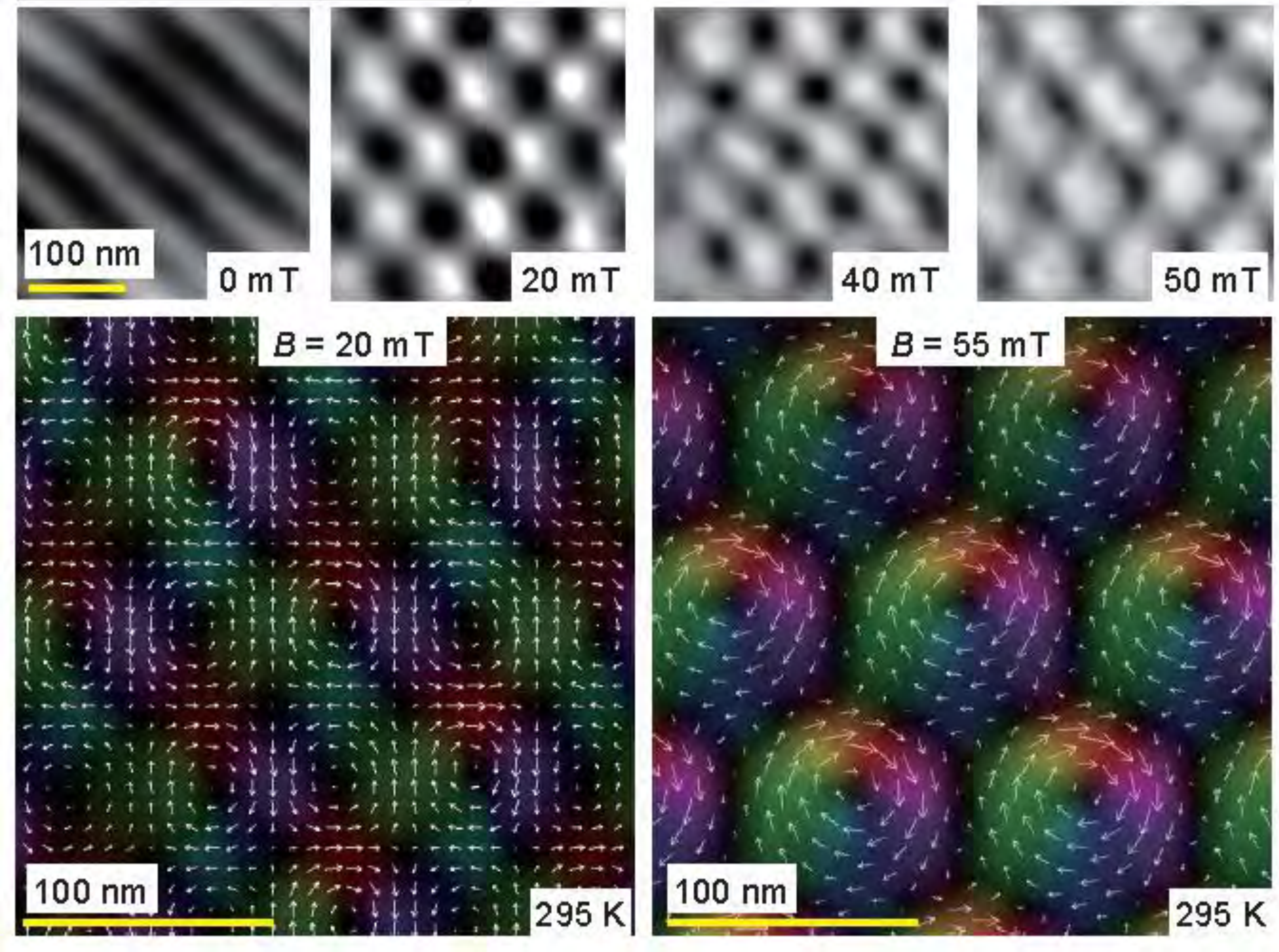


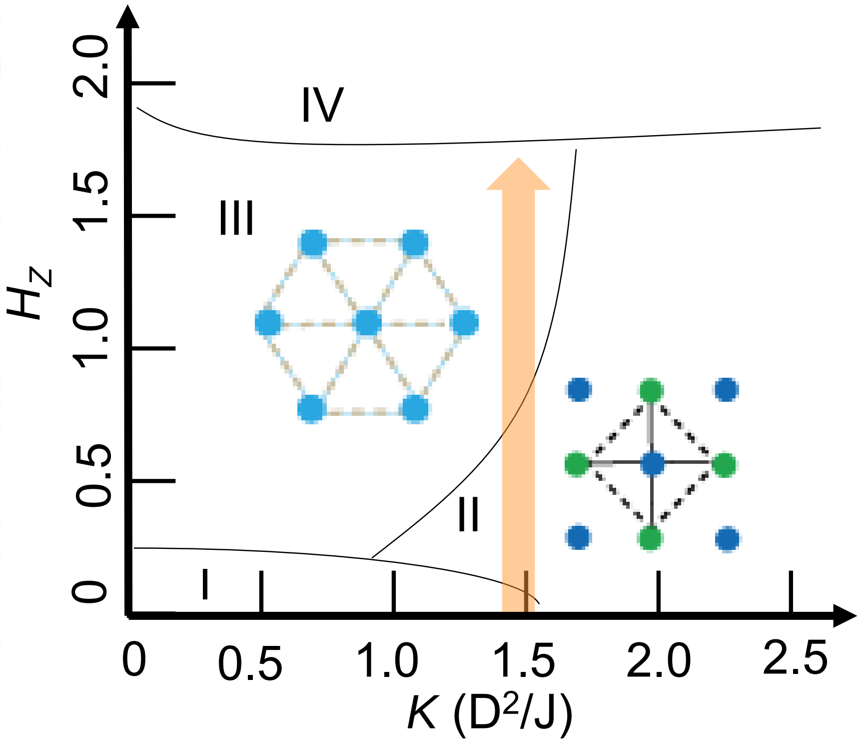




Transformation of a square lattice to a triangular lattice at the RT

(001) $Co_8Zn_9Mn_3$



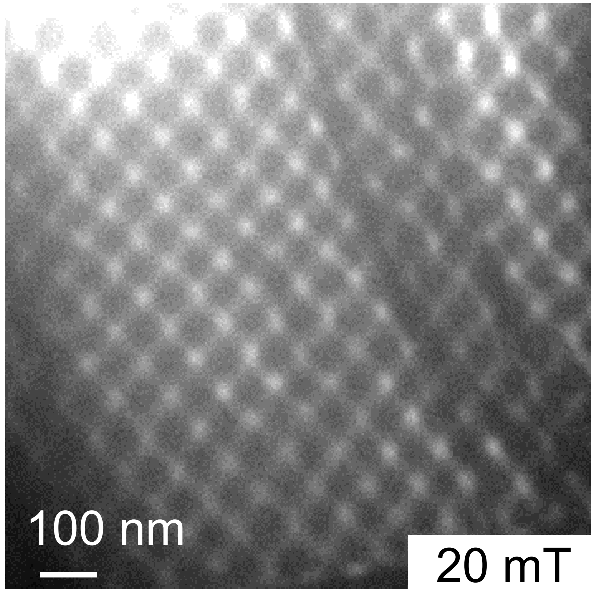


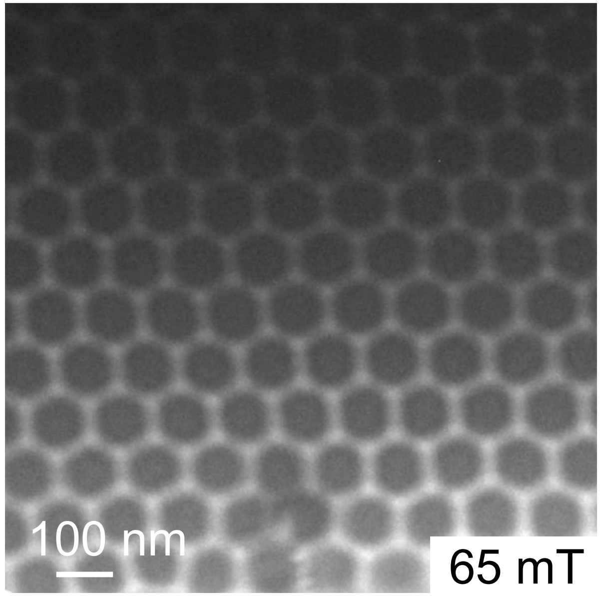
I : spin spiral
II: squire lattice of skyrmions
III: hexagonal lattice of skyrmions
IV: spin spiral conical structure

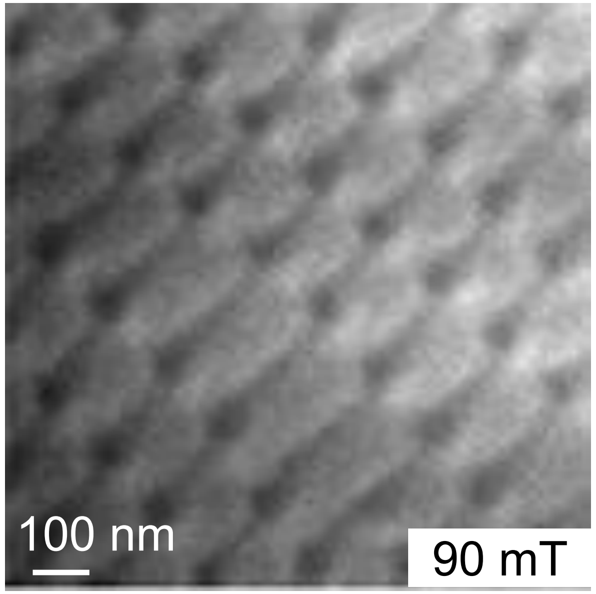
Phys. Rev. B: 80, 054416 (2009); 91, 224407 (2015)

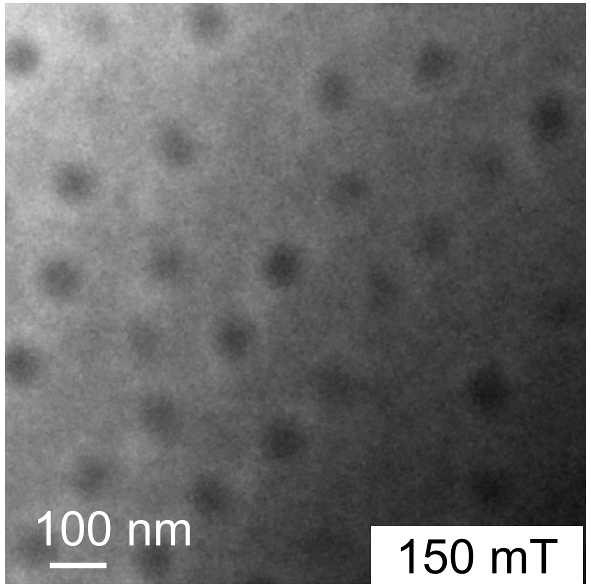
XY, et al. in preparation

Various states of skyrmion aggregate at RT

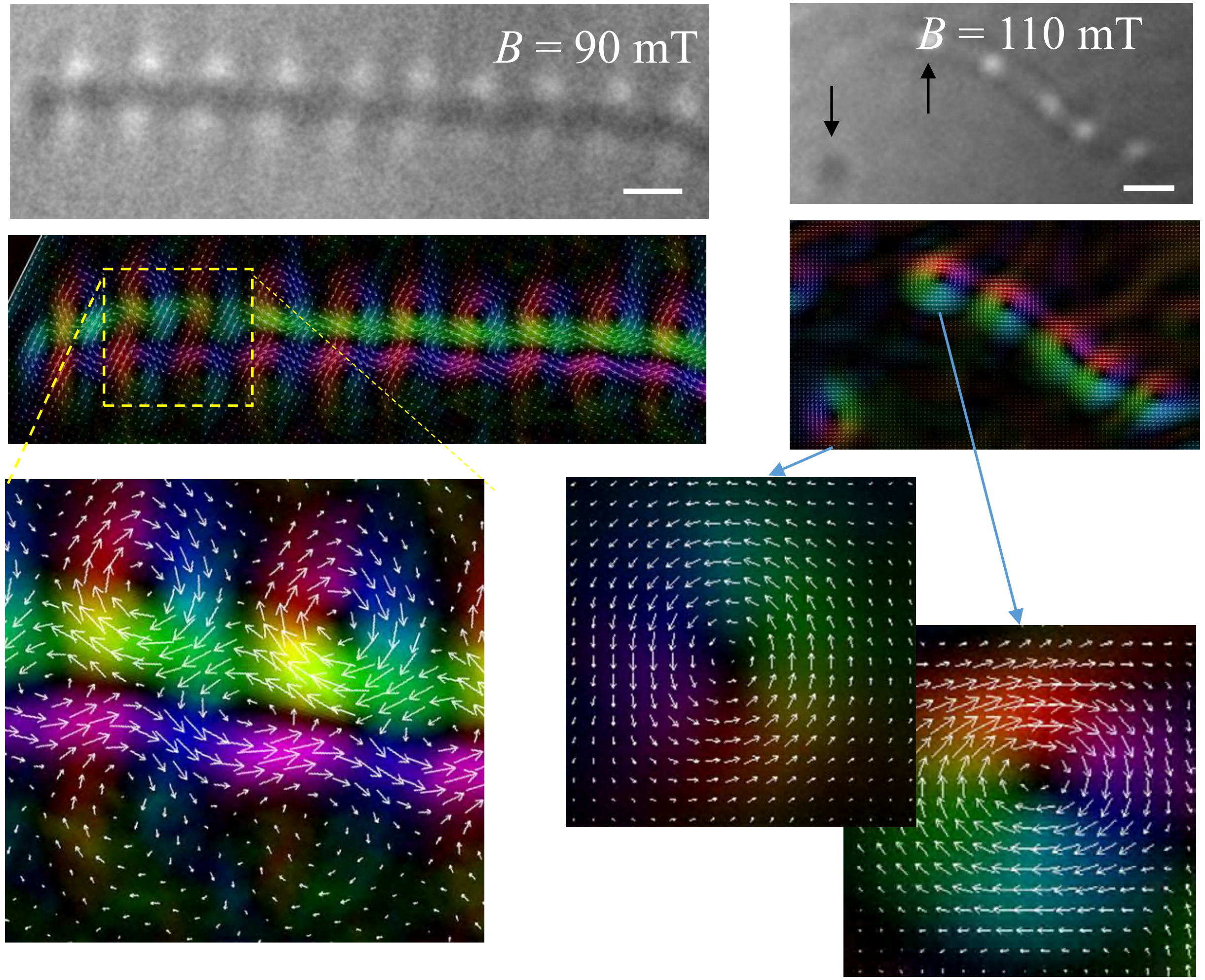








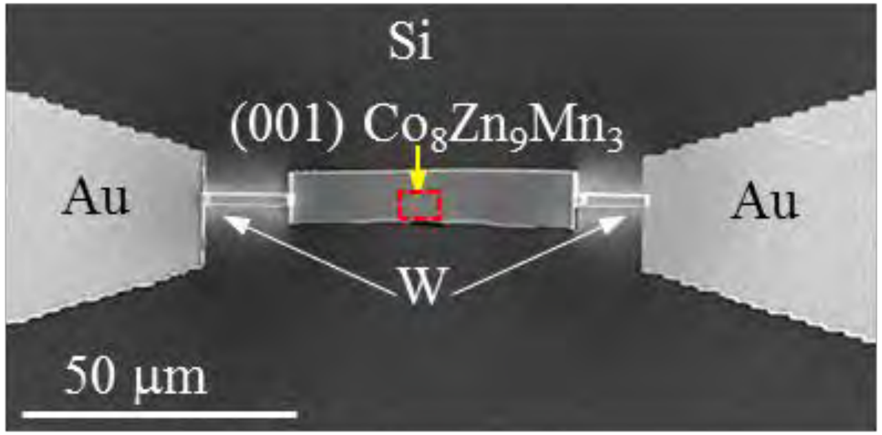
Skyrmion strings at 250 K

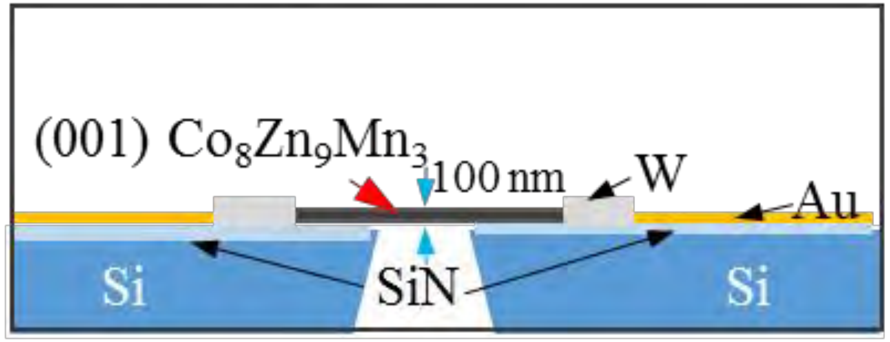


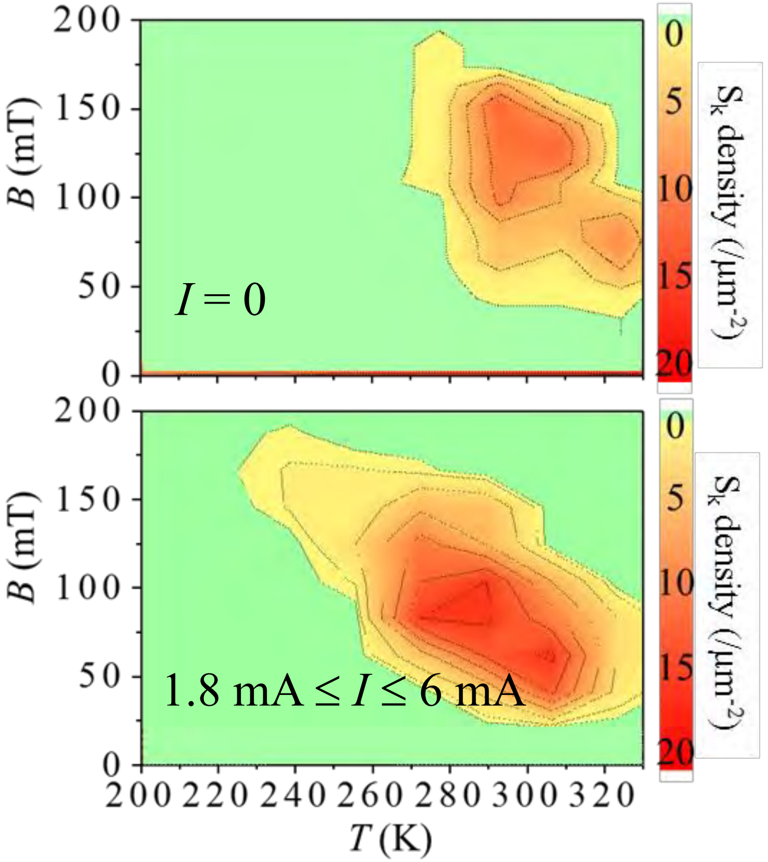
Scale bars are 100 nm

Topic Ⅰ -2: Nucleation of magnetic skyrmions under current excitation

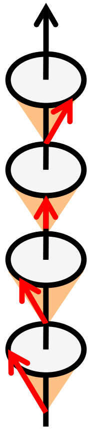
XY, et al.,
Adv. Mater., 2017

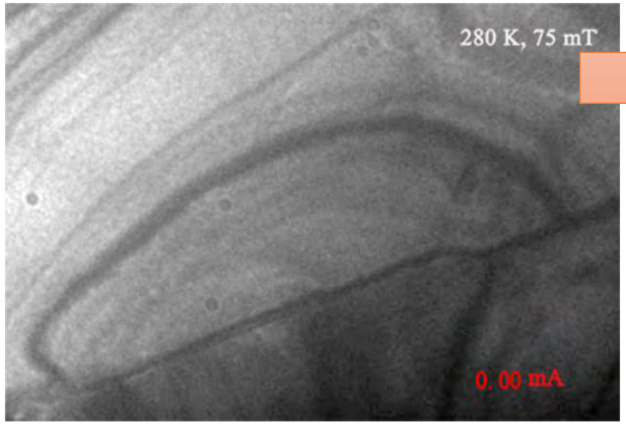




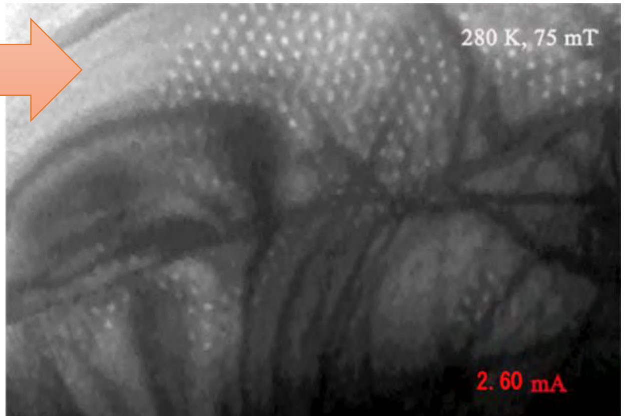


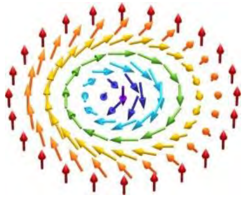
Conical structure
q//z





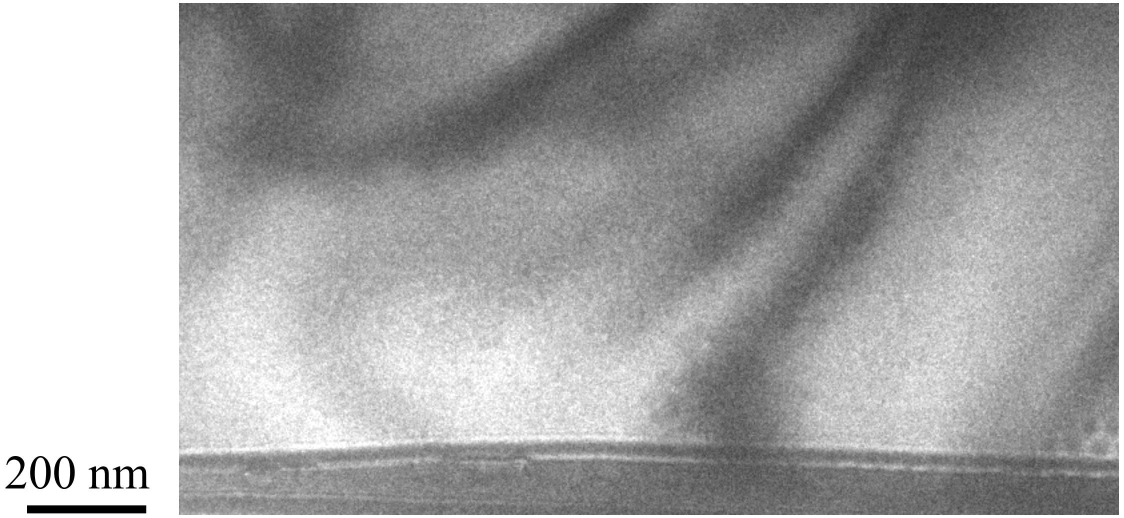
Dc current-induced the formation of skyrmions

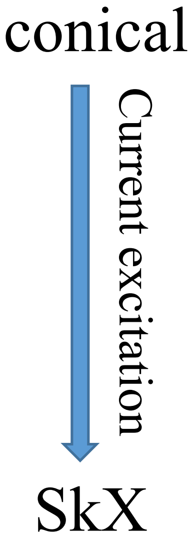


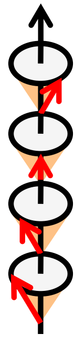


Electric current-induced topological phase transition

FeGe, 180 K, 160 mT



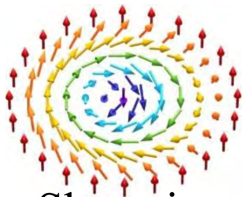




Uniform contrast in defocused Lorentz TEM image

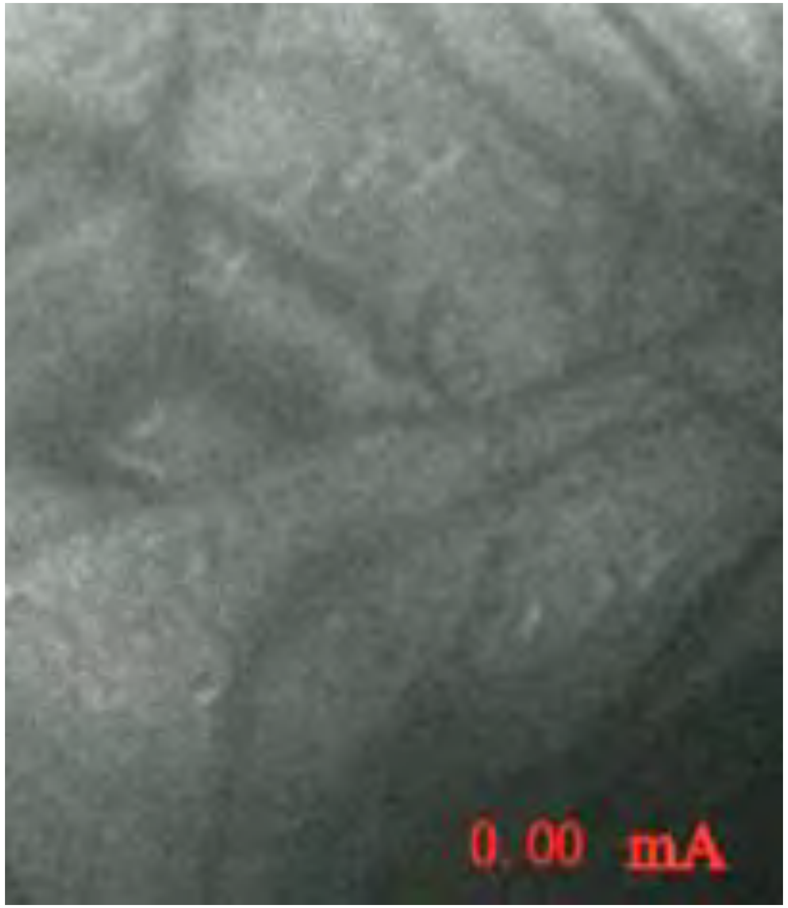
Conical phase

($q \perp$ plate plane)



Skyrmion

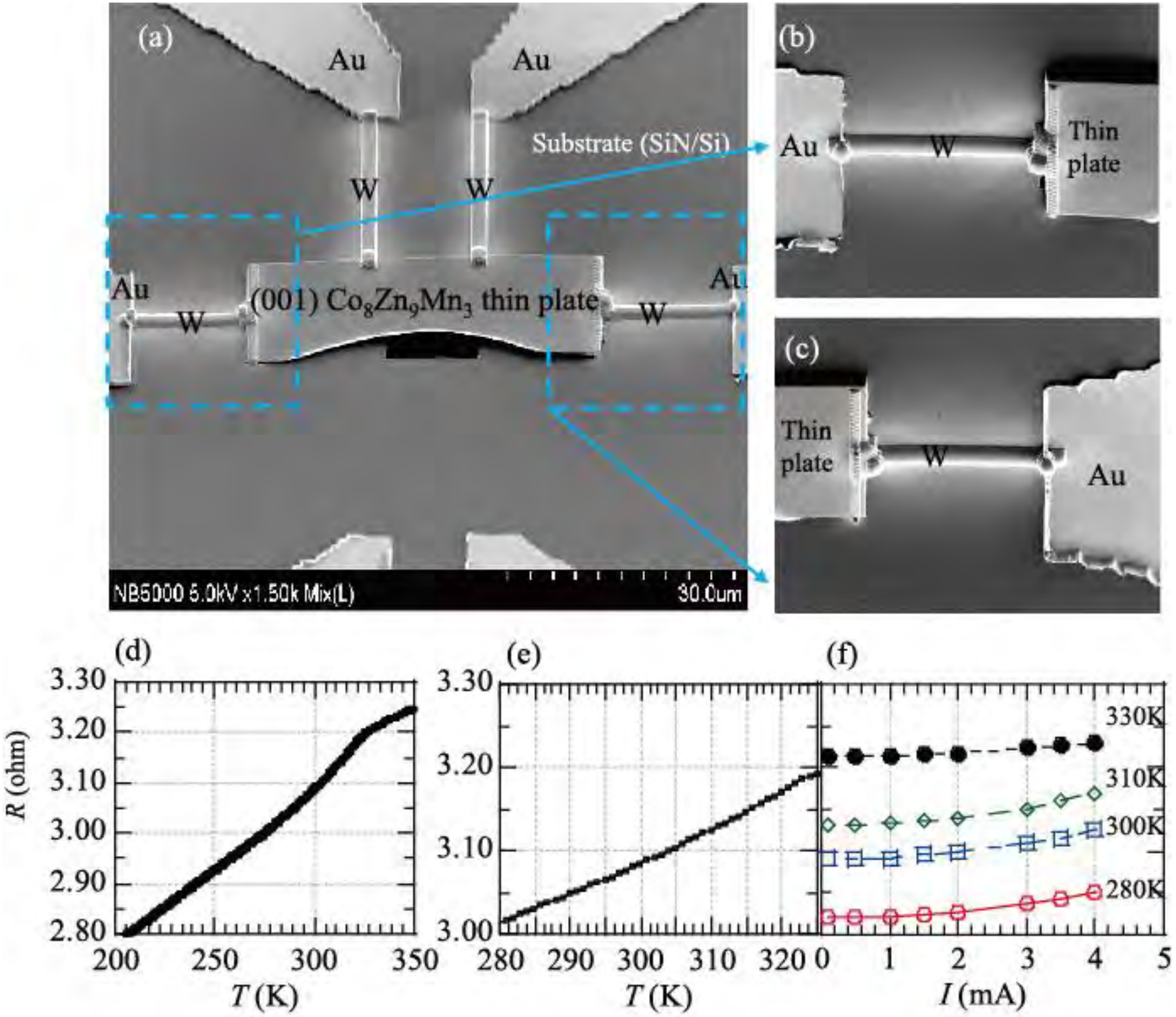
Co-Zn-Mn, RT, 100 mT



500 nm

XY, et al. *Adv. Mater*. (2017)

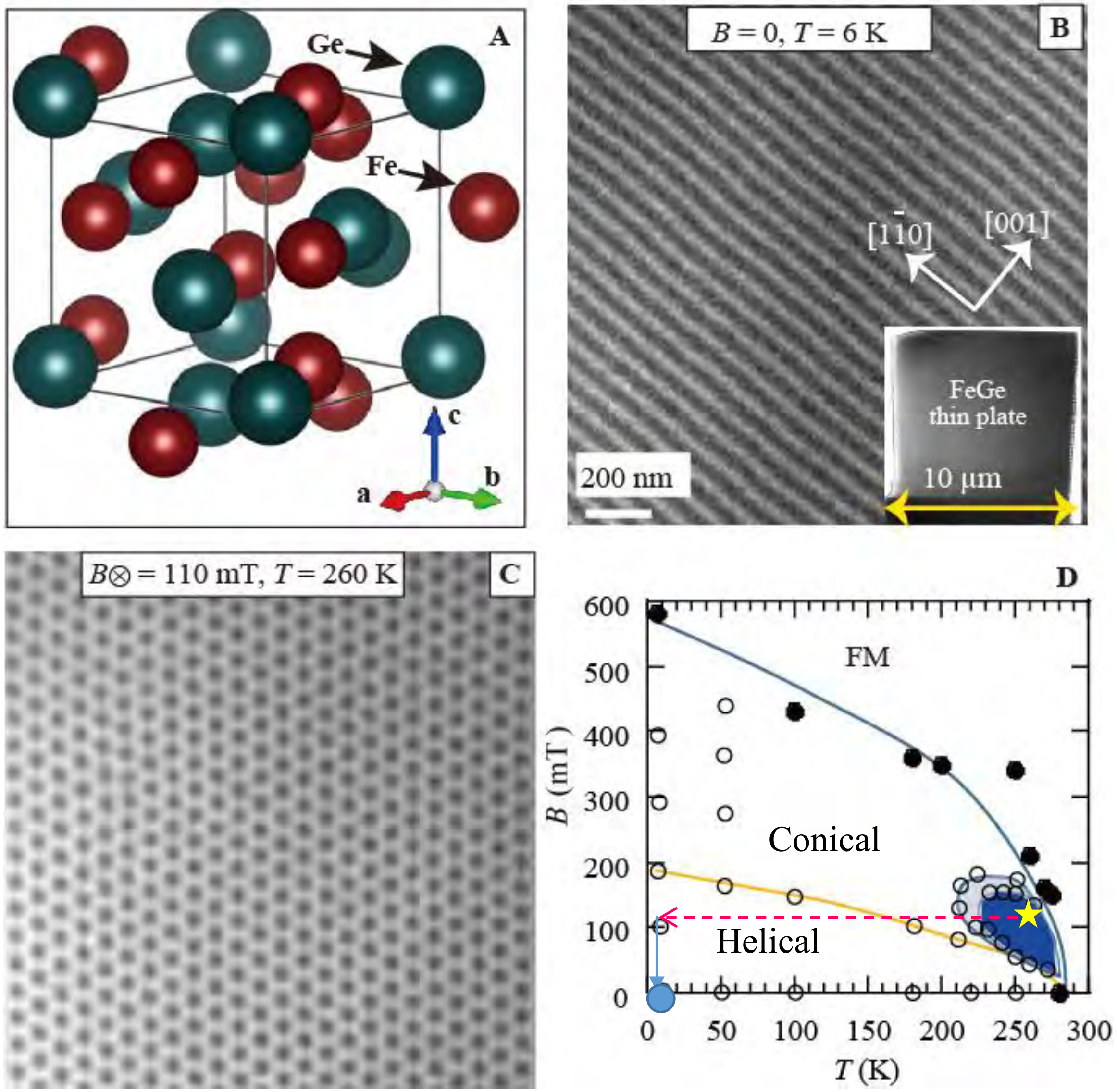
Estimation of Joule heating effect

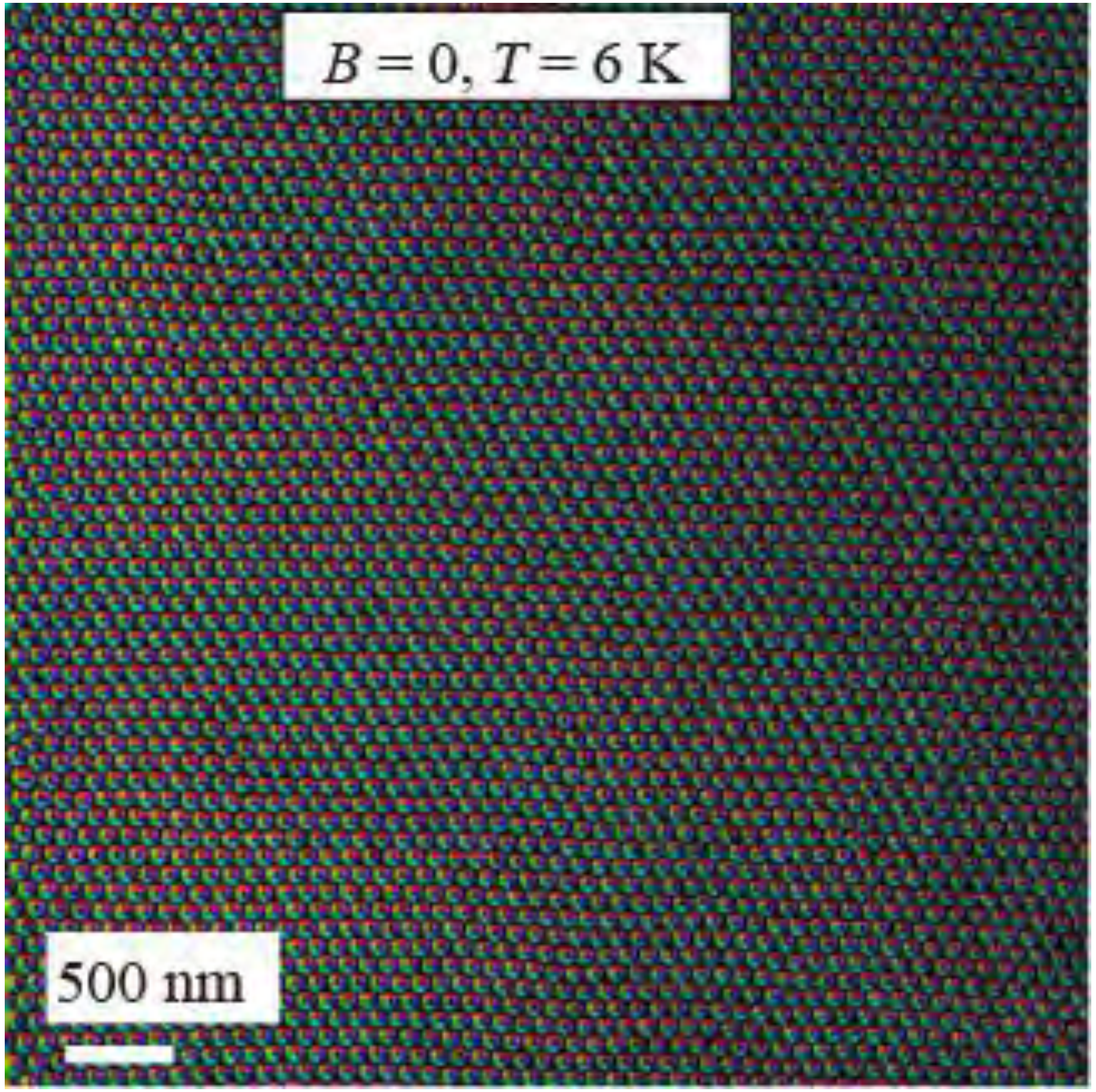


2~3 K @4 mA

Topics Ⅰ - 3

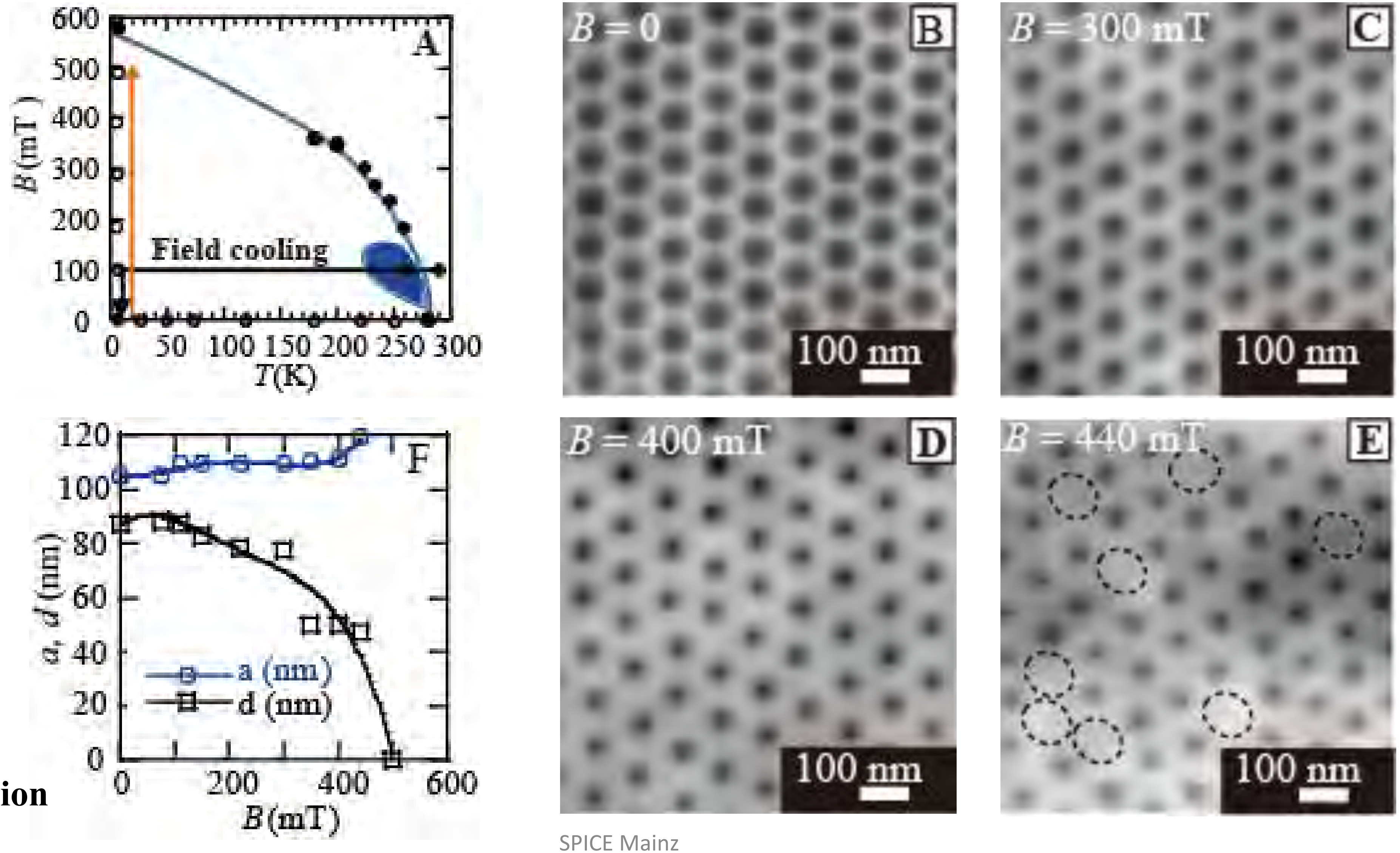
Robust zero-field SkX in a FeGe thin plate





Changes of the quenched SkX with an increase of the bias-field

B//z

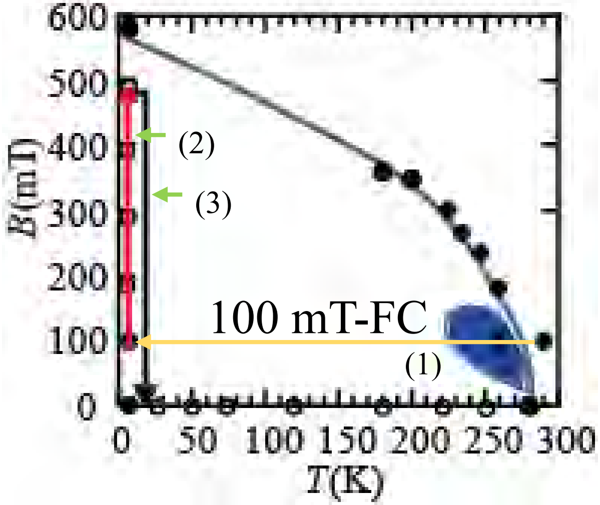


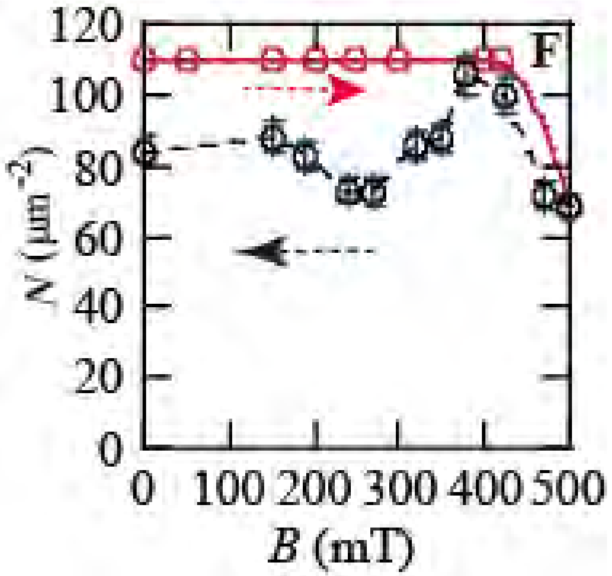
XY, et al. in preparation

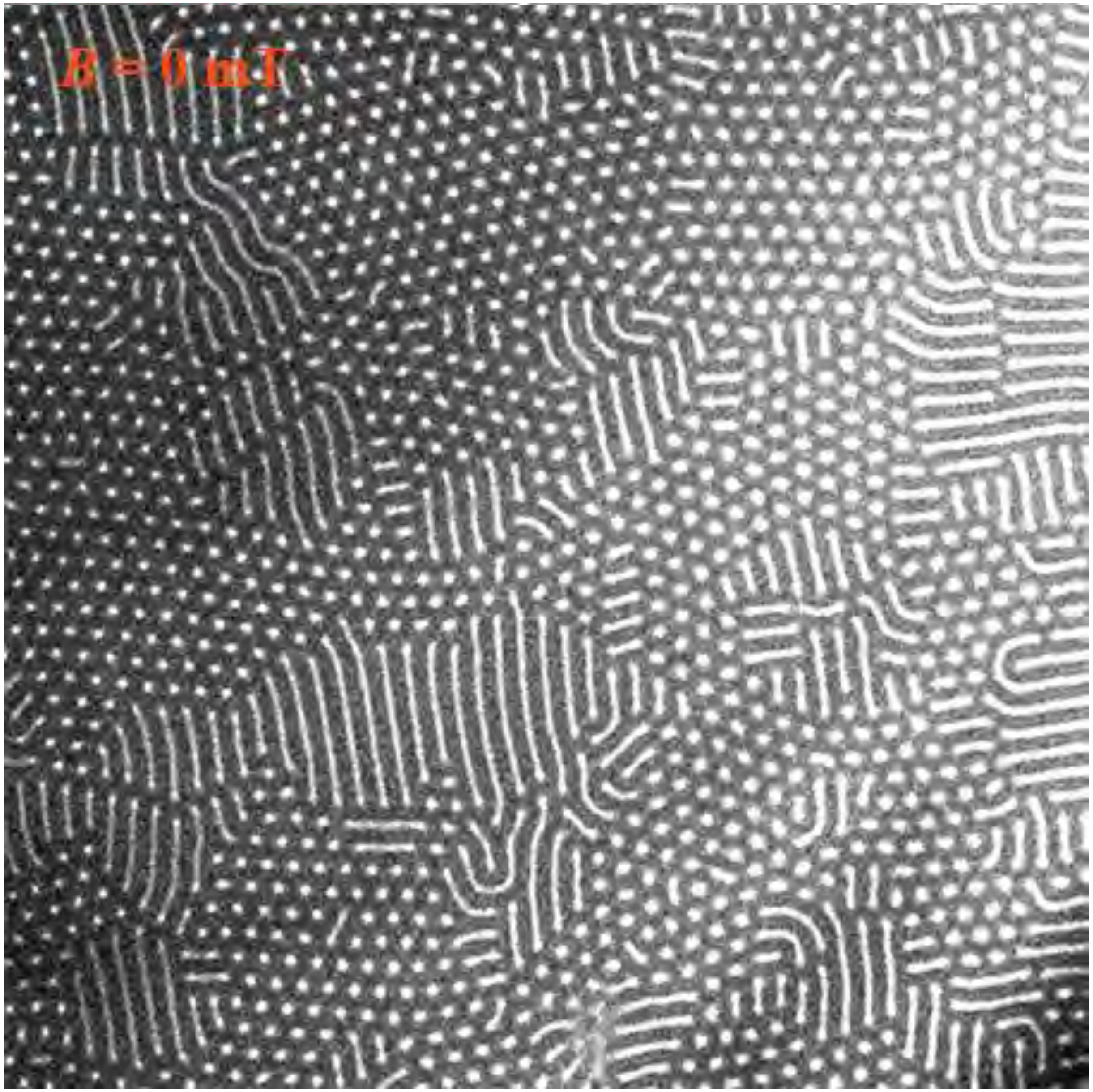
Crystallization of skyrmions and phase separation with a decrease of the bias field

$T = 6$ K

B//z

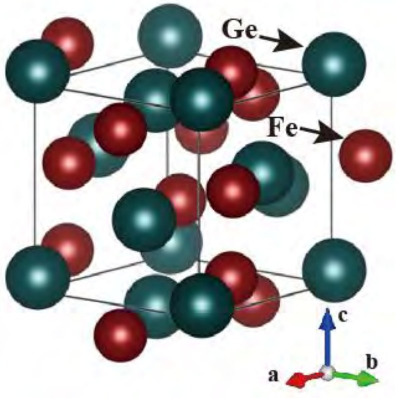


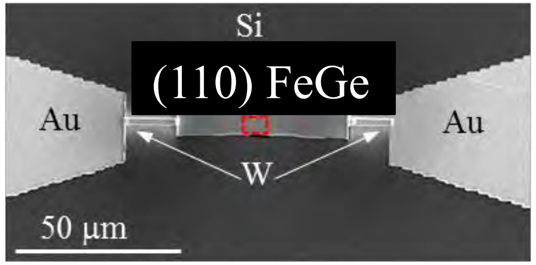


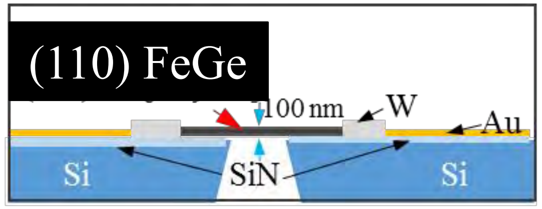


Topic Ⅱ-1: skyrmion Hall motion with electric current flow

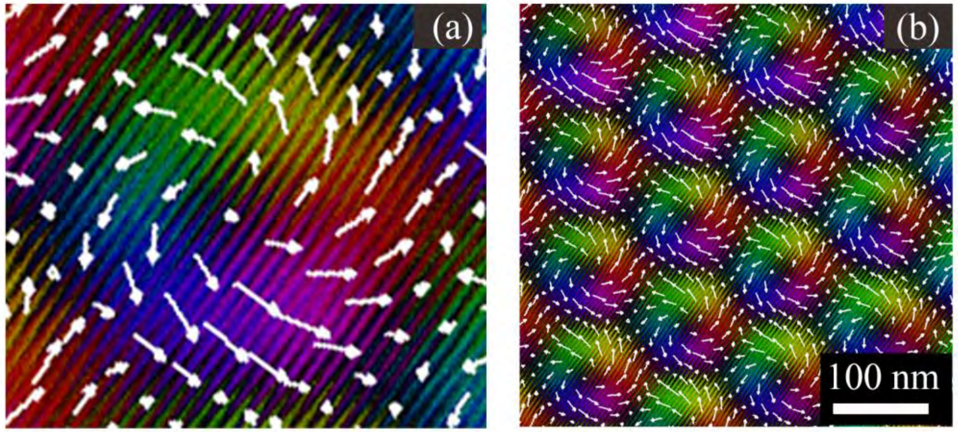
B = 160 mT
T= 210 K







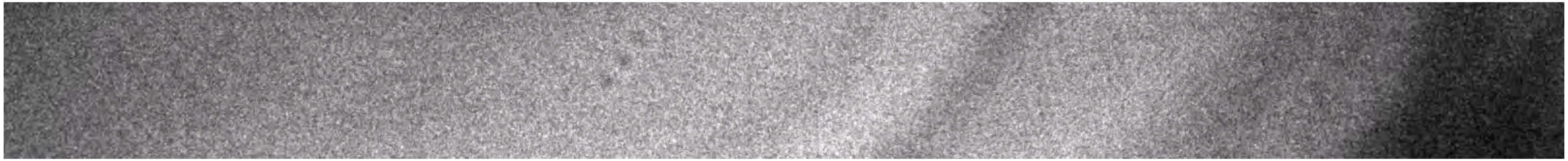
Skyrmion & Skyrmion lattice (observed by DPC-STEM)



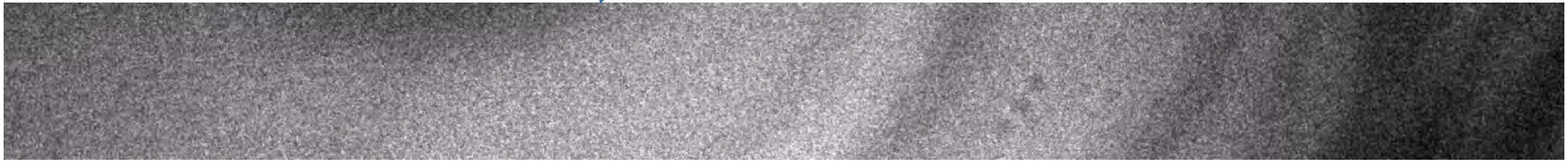
XY, et al. in preparation

$J = 7.8\ 10^7$ A･m^{-2}

200 nm

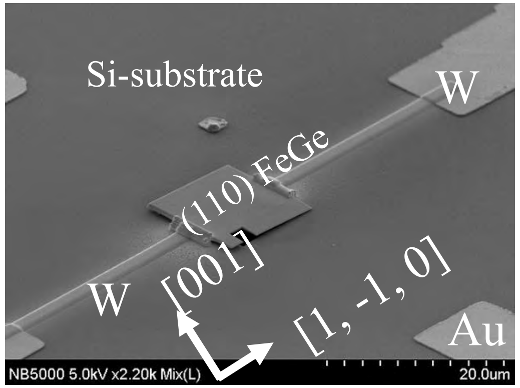


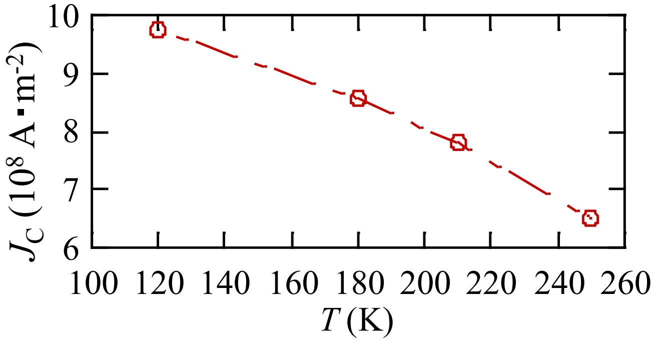
$J = 8\ 10^7$ A･m^{-2}



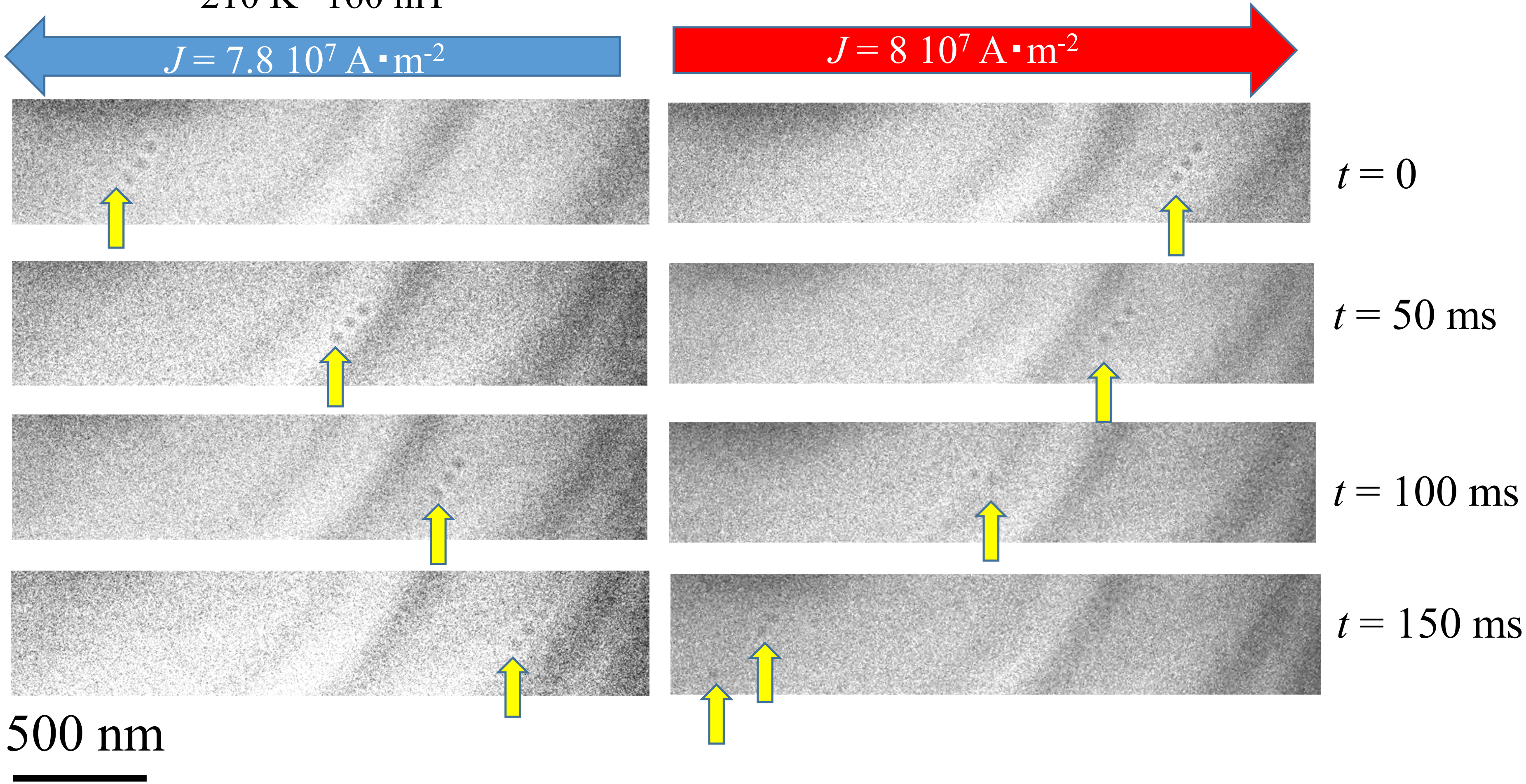
Skyrmion Hall motion with electric current flow

FeGe, $J_{\mathrm{C}} \sim 10^{8}\ \mathrm{A \cdot m^{-2}}$





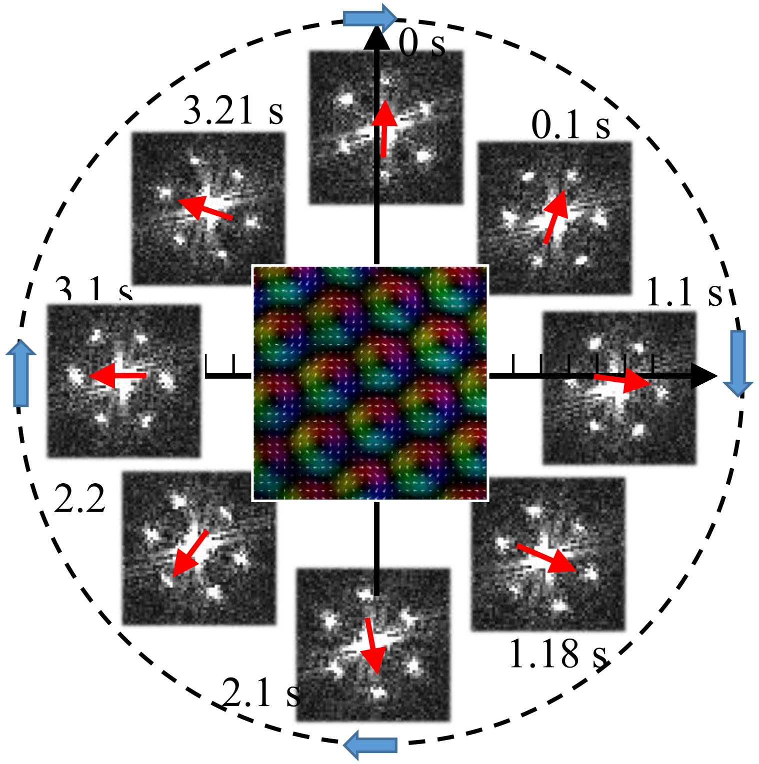
210 K 160 mT



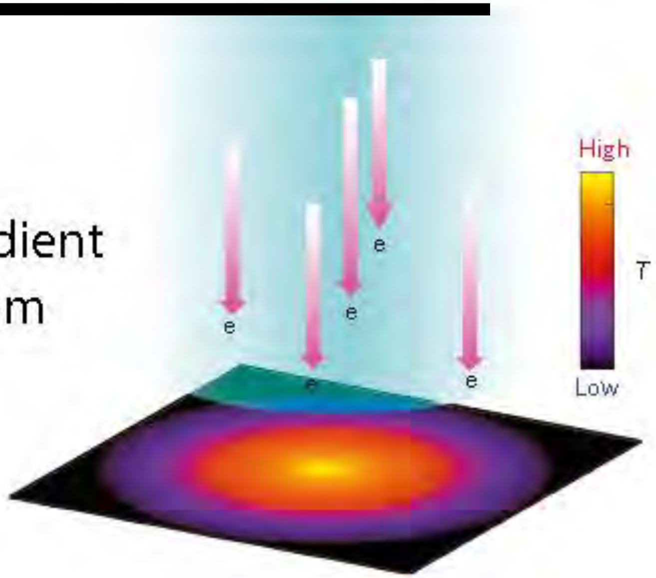
Unidirectional rotation of SkL in a Cu_2OSeO_3 thin plate

Cu_2OSeO_3: d_{Sk} ~ 50 nm

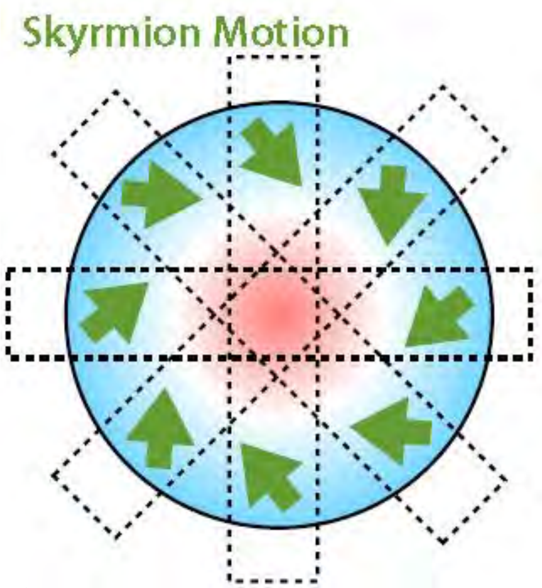
T = 35 K, B ⊗= 65 mT

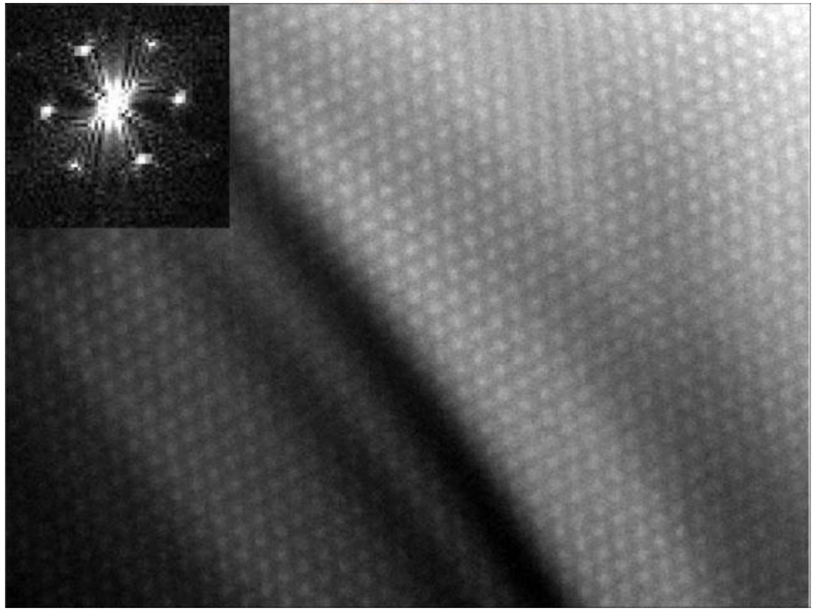


- Concentric thermal gradient created by electron beam



- Unidirectional rotational motion of skyrmion lattice


Skyrmion Motion



M. Mochizuki, *et al. Nat. Matter*. (2014)
X.Z. Yu and Y. Tokura, JEOL news (2015)

Summary

- 2D SkX as well as isolated skyrmions has been realized over a wide temperature range (6K~ 350 K) by means of Lorentz TEM.
- The fertile lattice forms as well as the bound skyrmions have been realized with tuning magnetic anisotropy in chiral-lattice compounds.
- Zero-field SkX can be stabilized with quenching of thermodynamically stable SkX in chiral-lattice magnets.
- Magnetic skyrmions can be excited by electric current .
- The *in-situ* Lorentz TEM observations have demonstrated a current-induced dynamical phase transition from a non-topological phase (conical phase) to a topological SkX phase.
- Lorentz TEM observations captured the skyrmion Hall motion with low-current (~ 10^8 A/m^2) and thermal current.

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Thank you for your kind attention!

We are recruiting the young researchers who are interested in topological spin texture

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