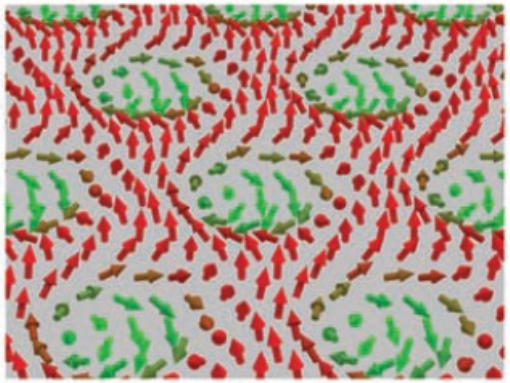
Spintornics with chiral spin structure

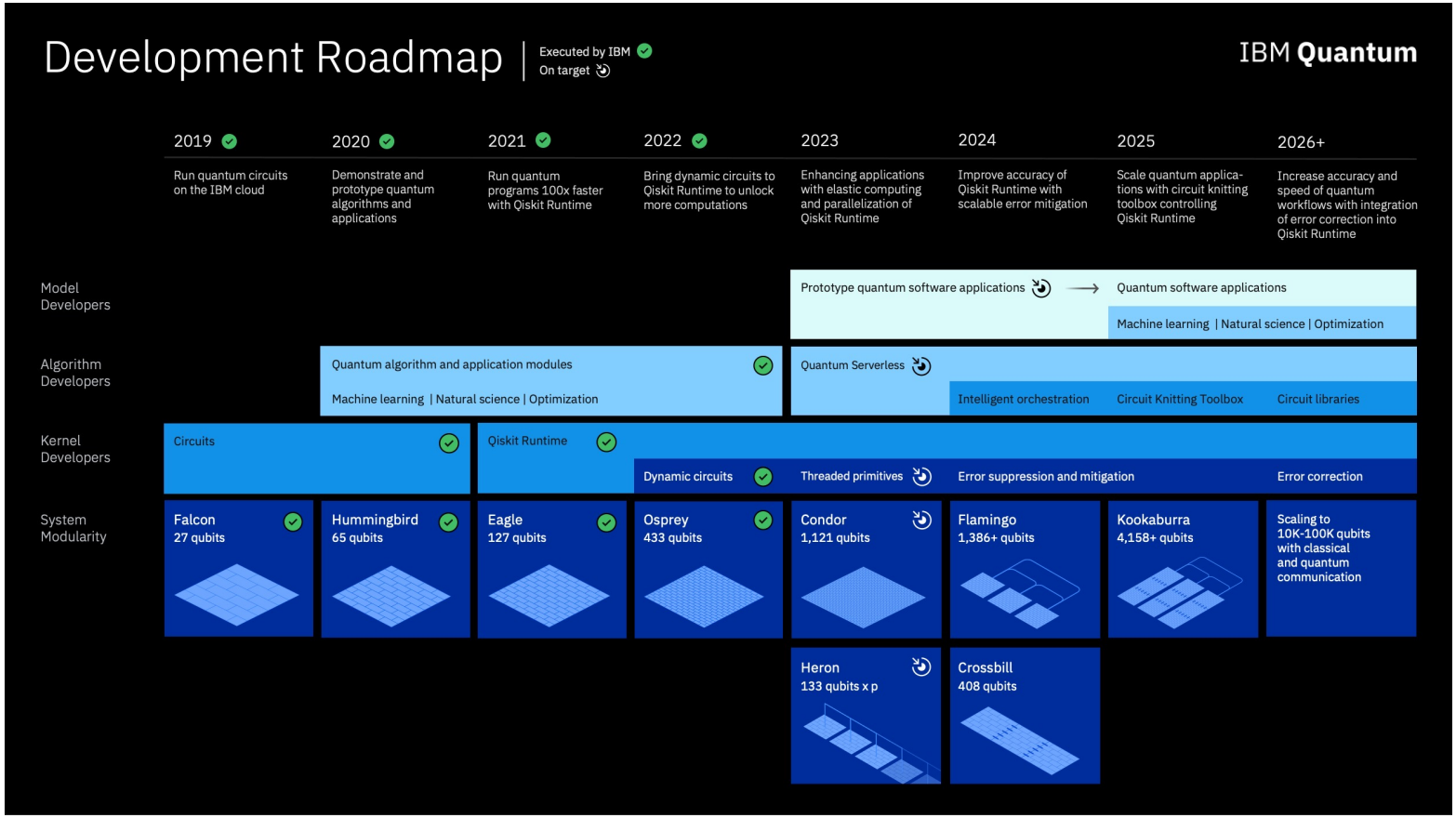
(Skyrmionics towards Quantum)



Chanyong Hwang

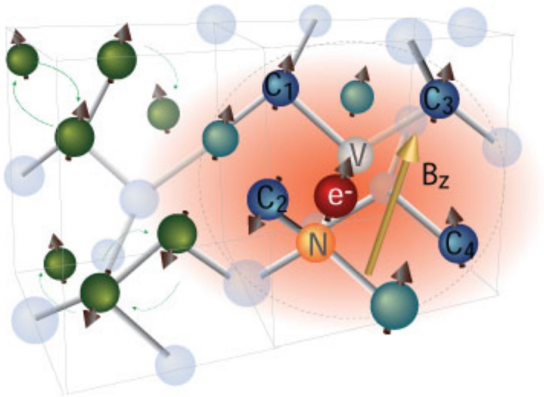
Q. Technology Institute

Korea Research Institute of Standards and Science



2033 100K qubit, May 2023.

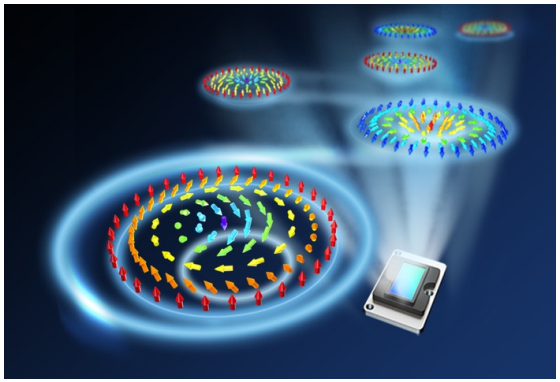
Quantum Spintronics



Single spin ⟷ **Chiral spin texture**

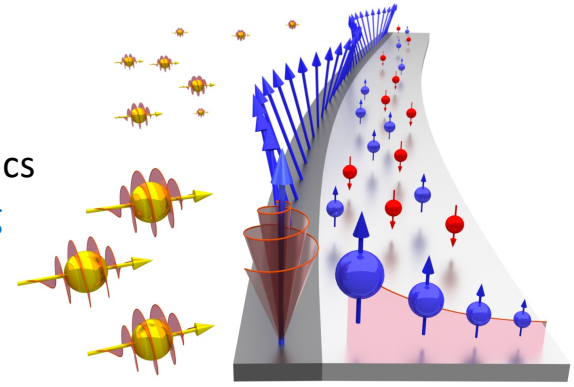
Quantum spin sensor

Magnetic skyrmion
Quantum skyrmionics
Skyrmion qubit
Majorana fermion

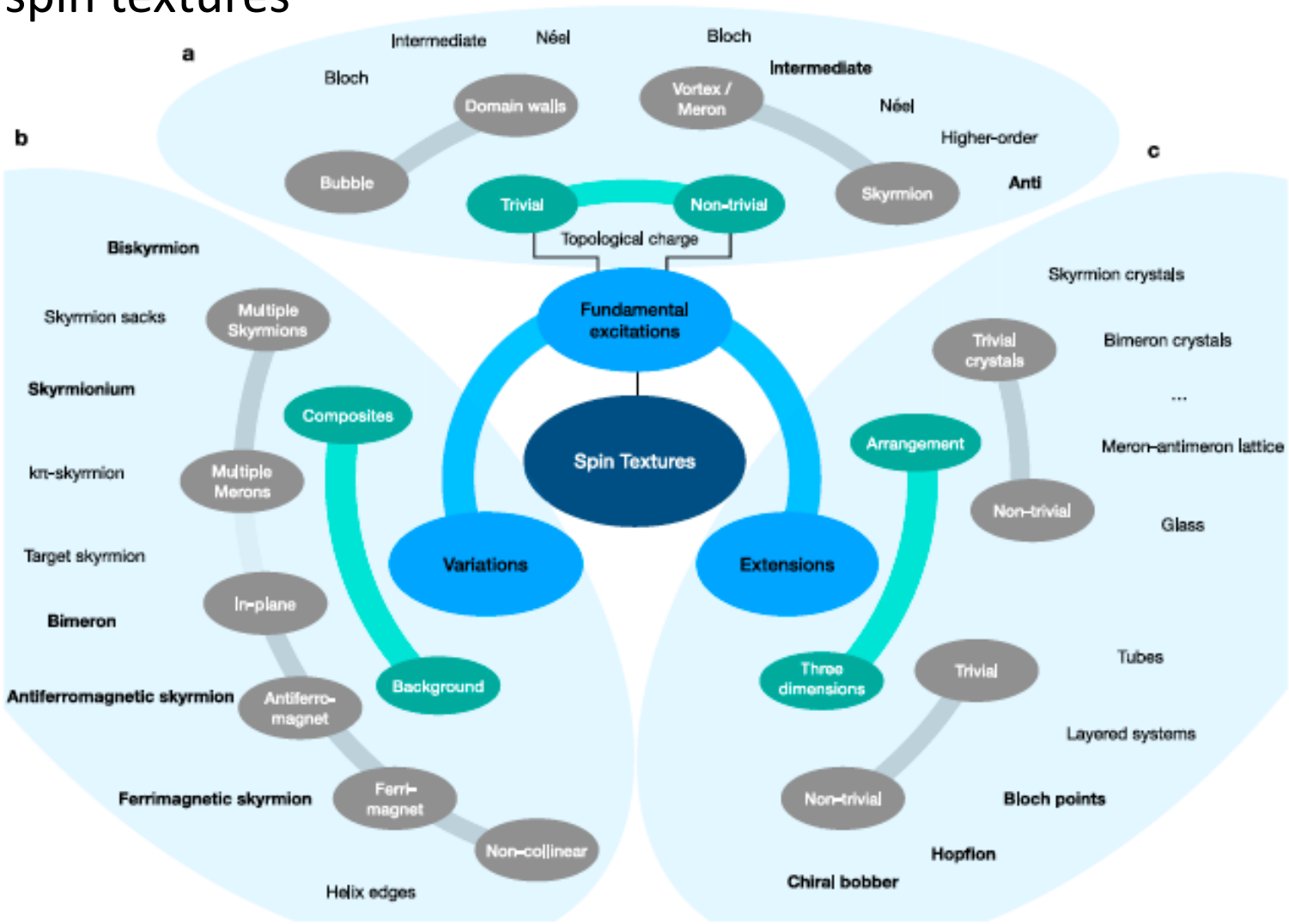


Magnonics

Quantum magnonics
Magnon squeezing
Magnon BEC

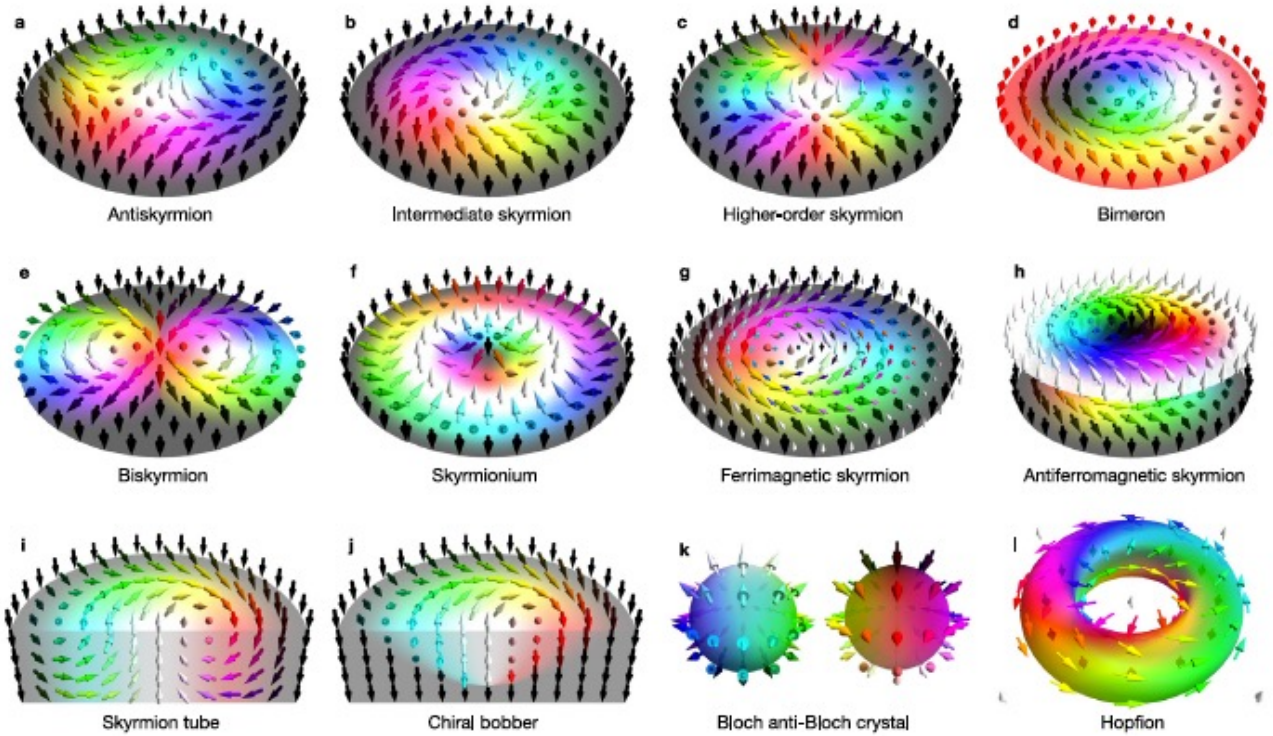


Complex spin textures



Phys. Reports 2021

Non-trivial topological spin texture

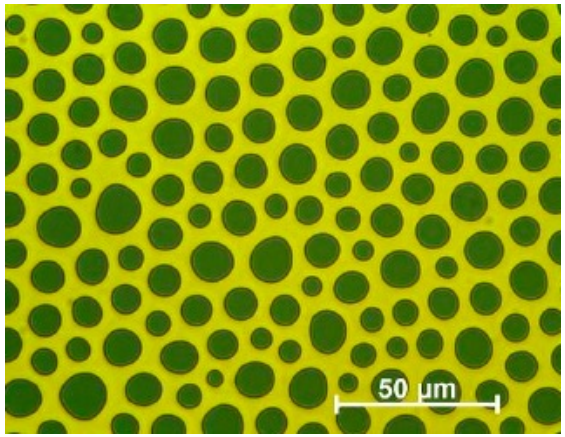


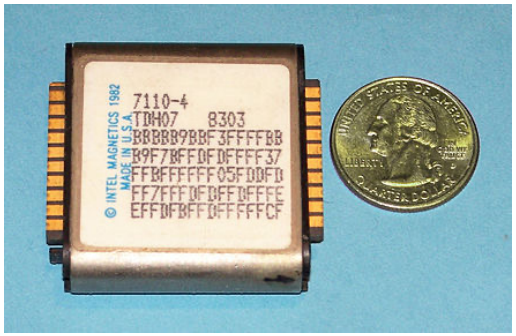
$$n_{\mathrm{Sk}}(\boldsymbol{r}) = \frac{1}{4\pi}\boldsymbol{m}(\boldsymbol{r}) \cdot \left[\frac{\partial \boldsymbol{m}(\boldsymbol{r})}{\partial x} \times \frac{\partial \boldsymbol{m}(\boldsymbol{r})}{\partial y}\right] \qquad N_{\mathrm{Sk}} = \int n_{\mathrm{Sk}}(\boldsymbol{r})\, \mathrm{d}^2 r,$$

Phys. Rept. 895, 1, 2021

Magnetic Bubbles

hot in 1970~80's
in plate geometry, bubbles are stabilized by dipole fields.



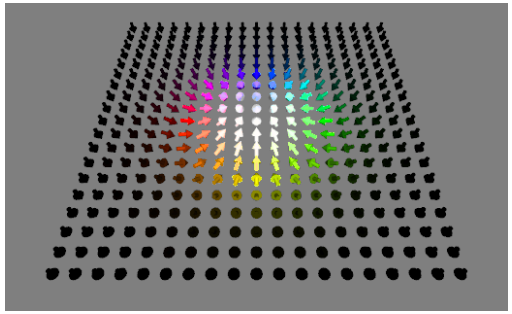


Wikipedia

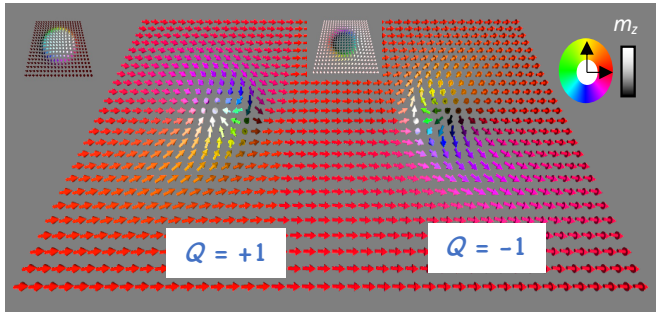
Magnetic Skyrmion :

a particle-like topological object whose topological number (Q) cannot be changed by a continuous deformation of the field configuration**.**

Out-of-plane skyrmion



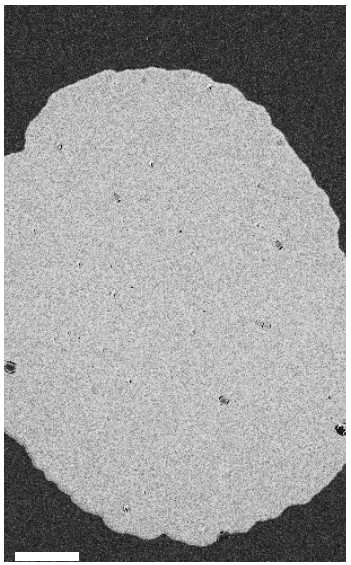
In-plane skyrmion ; Bimeron



Phys. Rev. Applied 12, 064054 (2019)
Nat. Comm. 10, 5603(2019)
Nano Lett. 22, 8559(2022)

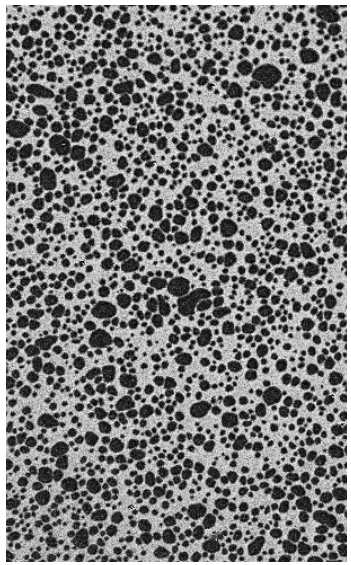
$$Q = \frac{1}{4\pi}\int \mathbf{m}\cdot\left(\partial_x\mathbf{m}\times\partial_y\mathbf{m}\right)dxdy$$

Bubble Filled State with Strong PMA system



10 μm

3 kOe in-plane
10 Oe out-of-plane



Sub/Ta/CoFeB/MgO/Ta

NPG Asia Materials 13, 20 (2021)

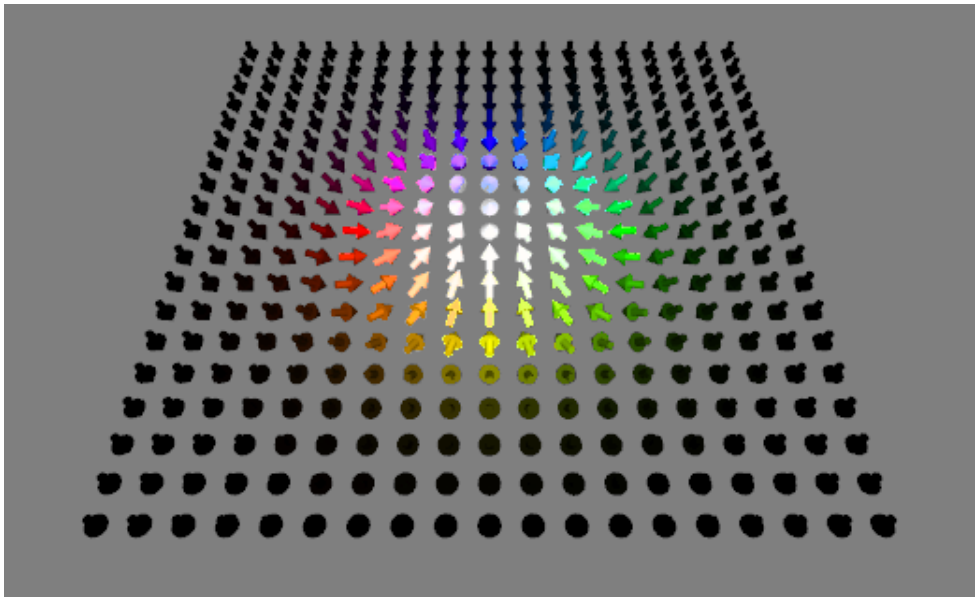
Moon et al. *NPG Asia Materials* (2021) 13:20
https://doi.org/10.1038/s41427-021-00290-3

NPG Asia Materials

ARTICLE Open Access

Universal method for magnetic skyrmion bubble generation by controlling the stripe domain instability

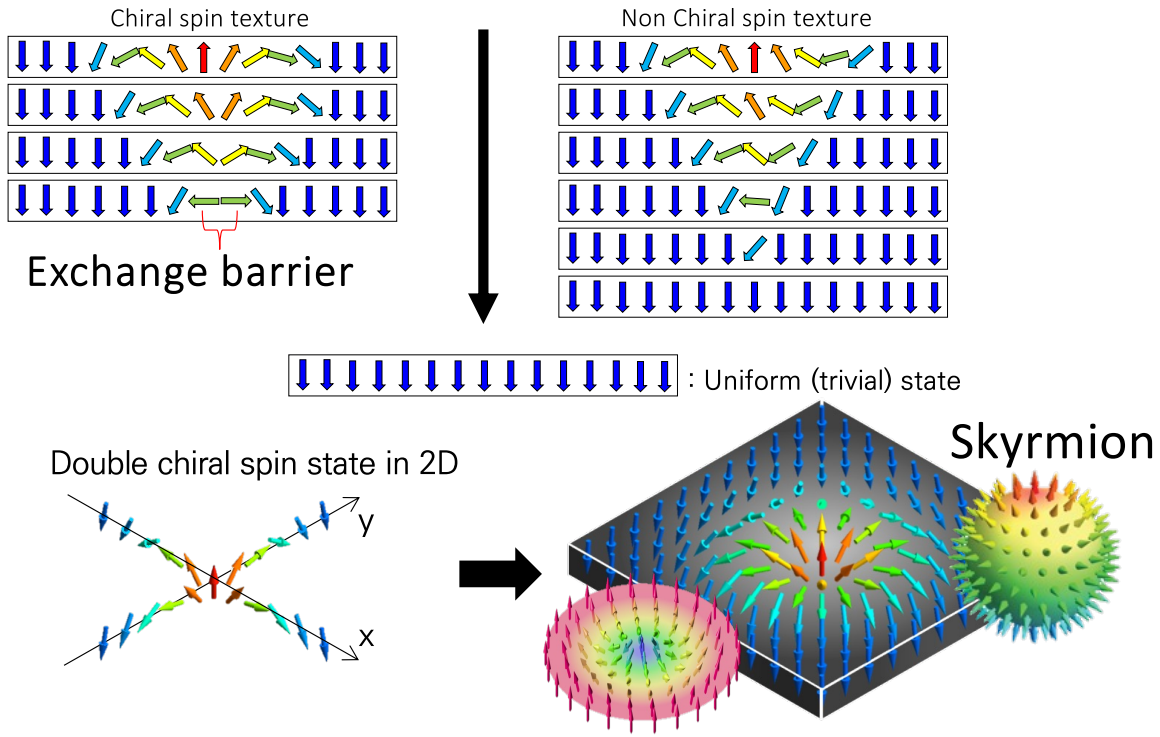
Magnetic Skyrmion



~ circular domain in perpendicular magnetization thin film
swirling topological defects in magnetic texture N_{sk} =1

Nat. Rev. Mater. 2, 1 (2017),
Phys. Rept. 895, 1 (2021),
J. Appl. Phys. 124, 240901 (2018),
J. Phys. D. Appl. 53, 363001(2020),
J. Phys.:Condens. Matter 32, 143001(2020)

Continuous transformation and Skyrmion

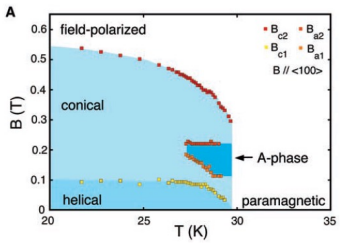


History of Magnetic Skyrmion

- Prediction of skyrmions to exist in magnetic materials with certain competing interactions in 1989s by Bogdanov & coworkers.

- Possibility of magnetic skyrmions in helical magnet MnSi

  Nature, 442, 801 (2006)

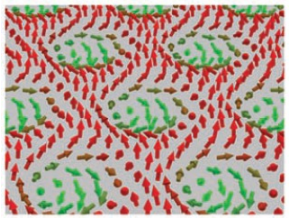


Observation of the formation of a magnetic structure with hexagonal symmetry perpendicular to magnetic field in the cubic B20 compound MnSi

- Experimental observation

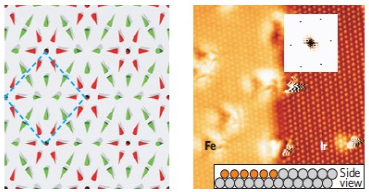
  Muhlbauer et al. Science 323, 915 (2009). Yu et al. Nature 465 (2010)

"nots were impractical to work"

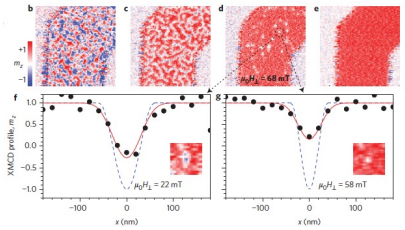


On thin film

1 ML Fe on Ir(111)

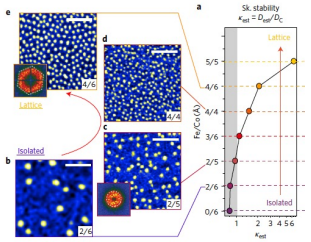


S. Heinze et al., Nat. Phys. 2011



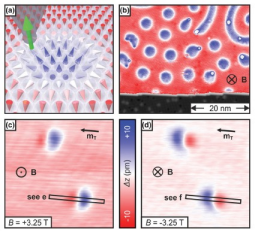
Nat. Nanotech 11, 444. (2016)

$Pt/Co/Pt/(Ir/Co/Pt)_{10}/Pt$



Nat. Materials 16, 898 (2017)

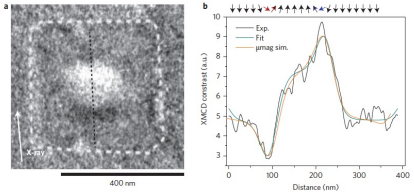
2 ML PdFe on Ir(111)



2 nm size

N. Romming et al., PRL 2015

Pt/Co(1 nm)/MgO



Nat. Nanotech. 11, 449 (2016)

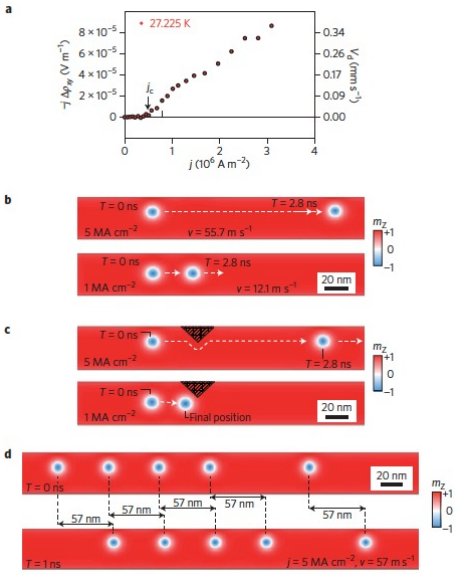
geometric confinement
without magnetic field

Individual Magnetic Skyrmion

Skyrmions on the track

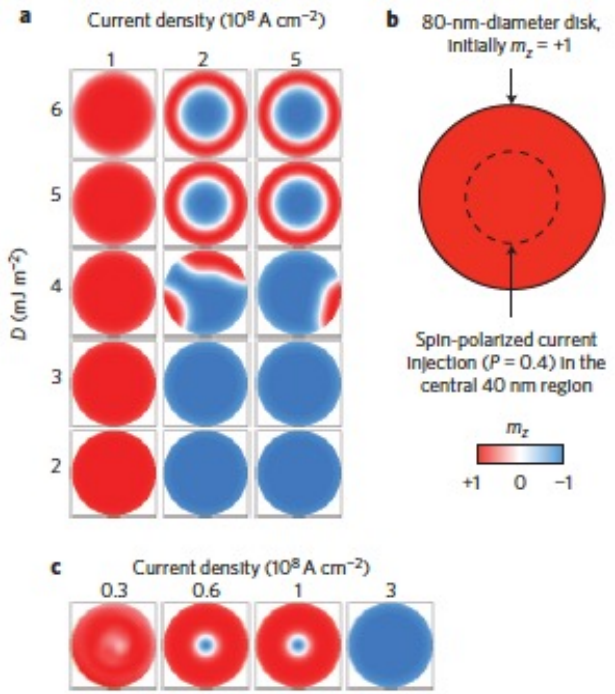
Albert Fert, Vincent Cros and João Sampaio

Magnetic skyrmions are nanoscale spin configurations that hold promise as information carriers in ultradense memory and logic devices owing to the extremely low spin-polarized currents needed to move them.

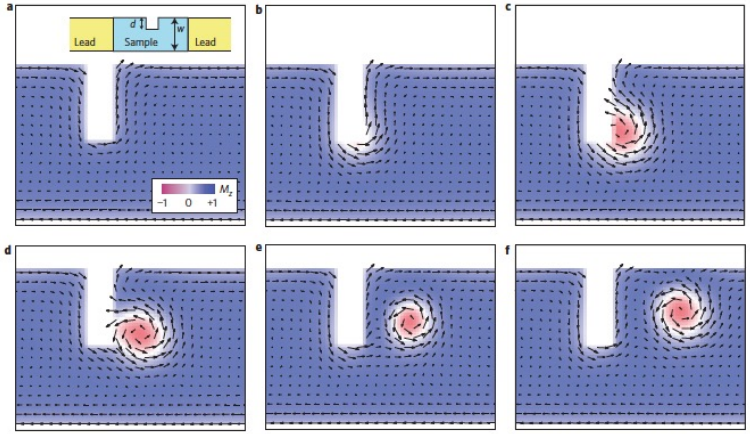


Nat. Nanotech. 8, 152 (2013)

simulation



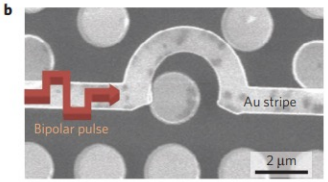
Nat. Nanotech. 8, 839 (2013)
by spin-polarized current injection



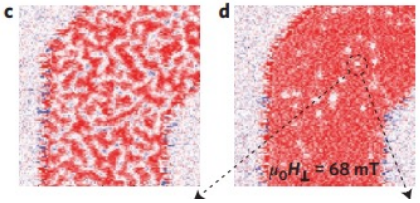
Nat. Nanotech. 8, 742(2013)
j = 3.6 x 10^{11} Am^{-2}

GENERATION OF INDIVIDUAL MAGNETIC SKYRMION

by magnetic fields

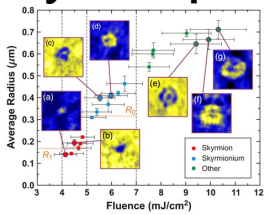


Nat. Mater. **15**, 501 (2016)

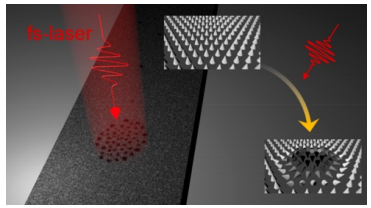


Nat. Nanotech. **11**, 444 (2016)

by laser pulses

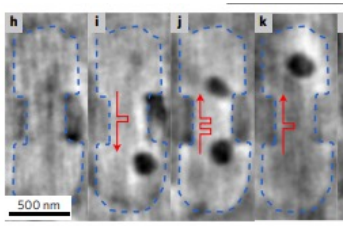


PRL. 110, 177205 (2013)

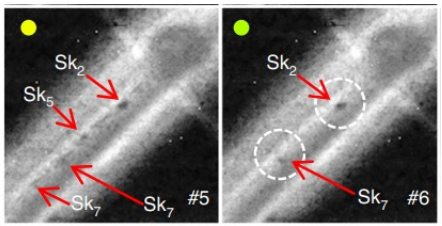


Nano Lett. **18**, 7362 (2018)

by current-induced spin torque

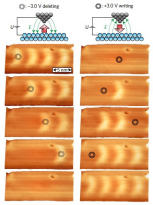


Nat. Nanotech. **12**, 1040 (2017)



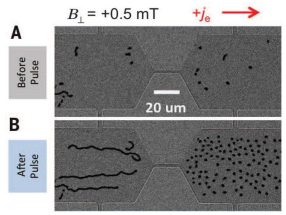
Nat. Electron. **1**, 288 (2018)

by E field



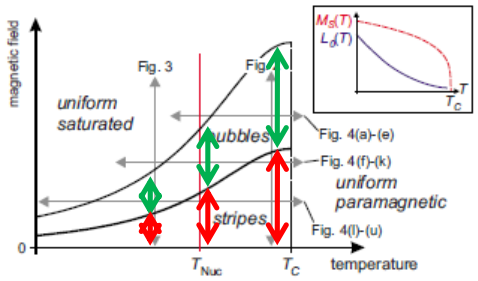
Nat. Nanotech. 12, 123(2017)

by current



Science 349, 283 (2015)

Universality in Stripe-Bubble-Uniform Phase

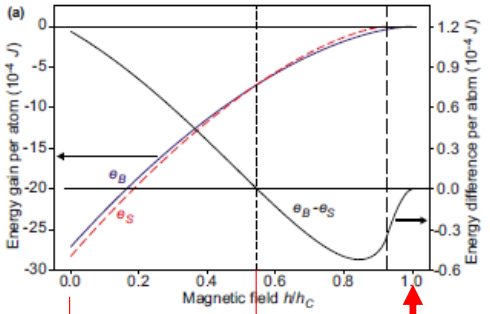


N. Saratz, et al., PRB 82, 184416 (2010)

:fixed ratio

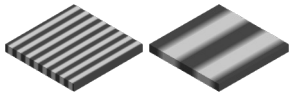
Detailed parameters are not important !

Perpendicular magnetic field vs. Energy

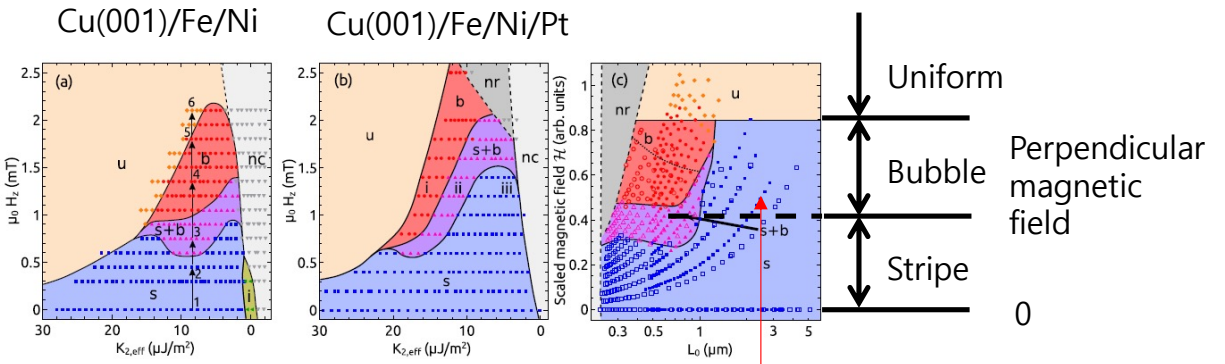


Stripe Bubble Uniform

Uniform becomes global minimum
~Bubbles disappear



Universality in Stripe-Bubble-Uniform Phase (DMI)



PRB 96, 144408 (2017)

Thin stripe

Thick stripe

L_0 stripe width with zero field

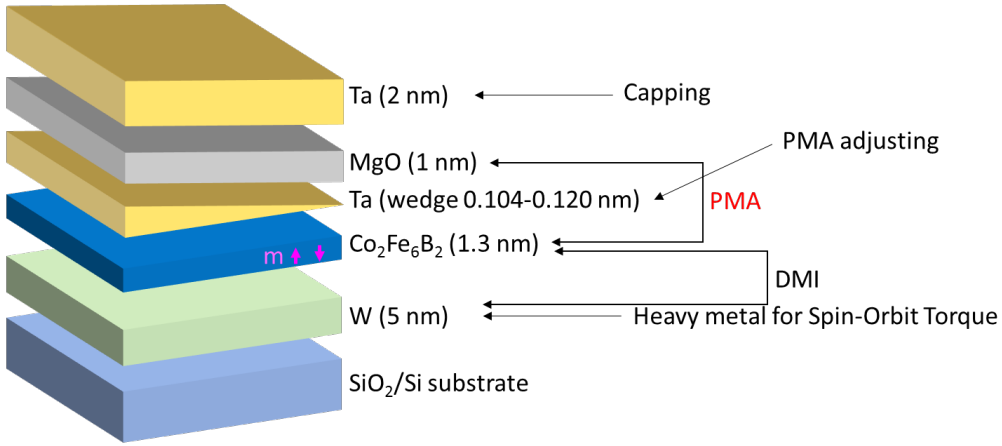
Hard to convert stripes into bubbles

:Too thick stripe

Is there any way to move from stripe to bubble phase or to make bubble phase with PMA Sample?

Skyrmion at RT

Stability of Skyrmion ~ $\frac{\mathrm{DMI} \times \mu_0 M_s}{\mathrm{PMA}}$

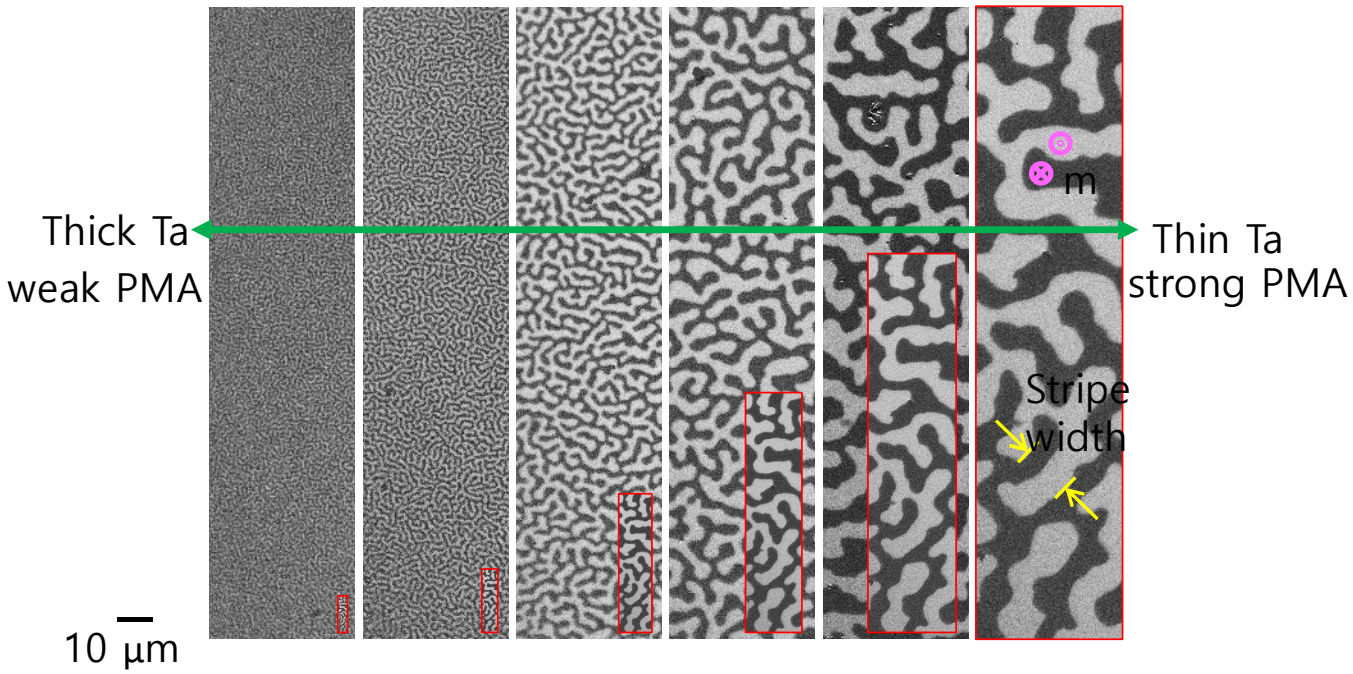


PMA is dominant at the CoFeB/MgO interface while DMI is determined at the W/CoFeB interface.

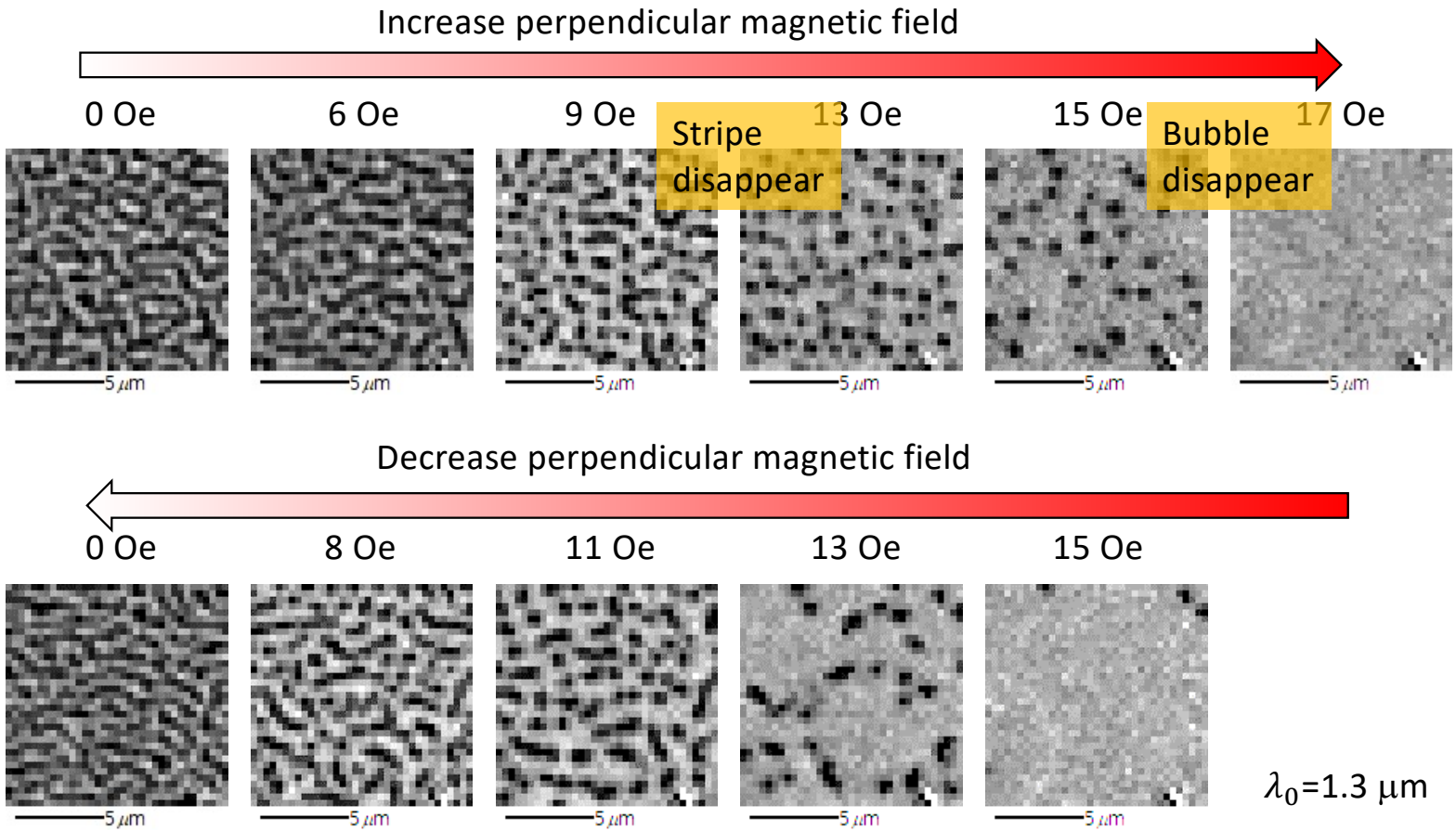
We expect that along the Ta wedge, PMA is changed while DMI and Magnetic moment keep constant.

Domain Patterns at Zero Field

● Observation by Magneto-optical Kerr effect microscope

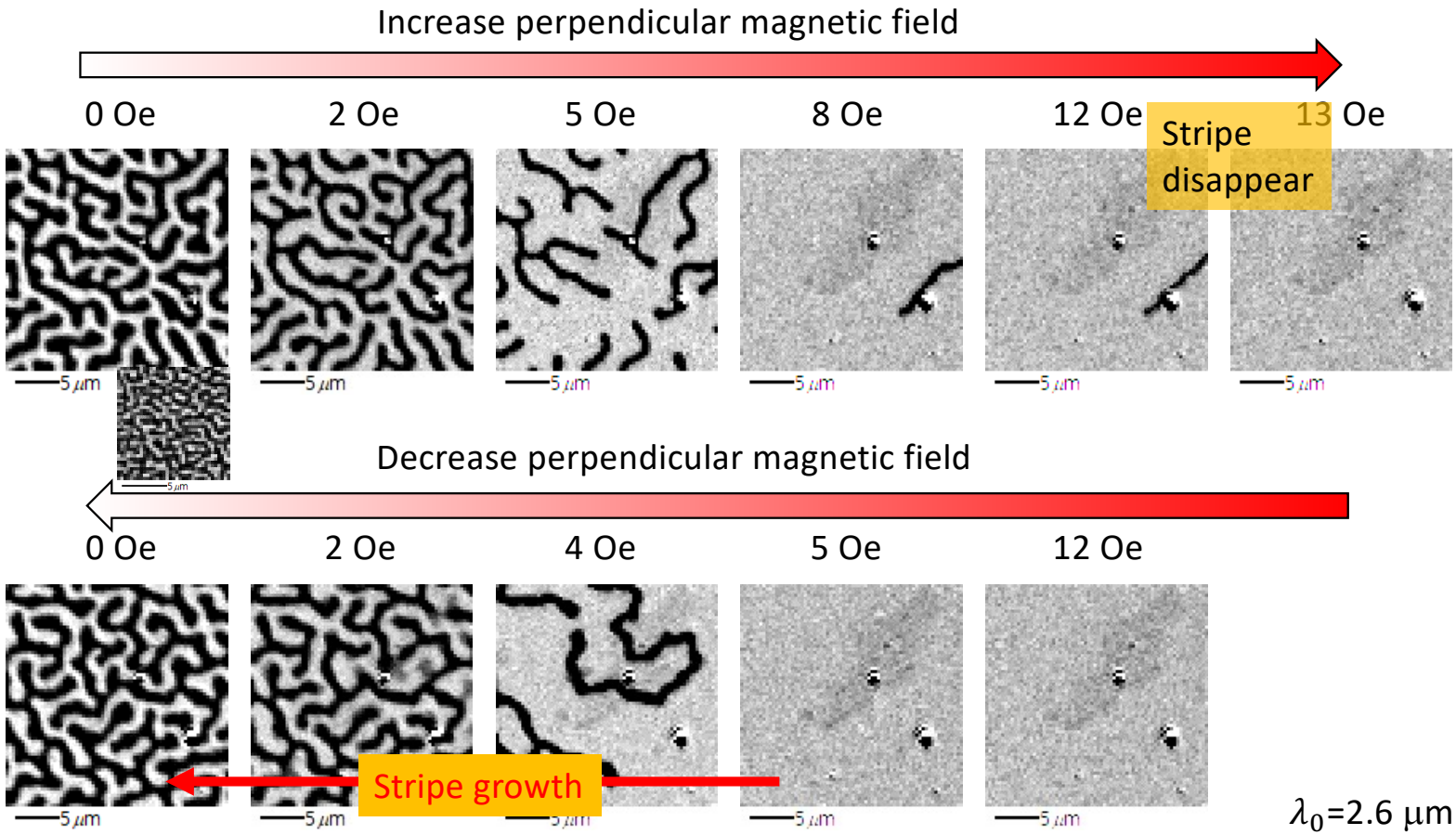


Magnetization state: thin stripe



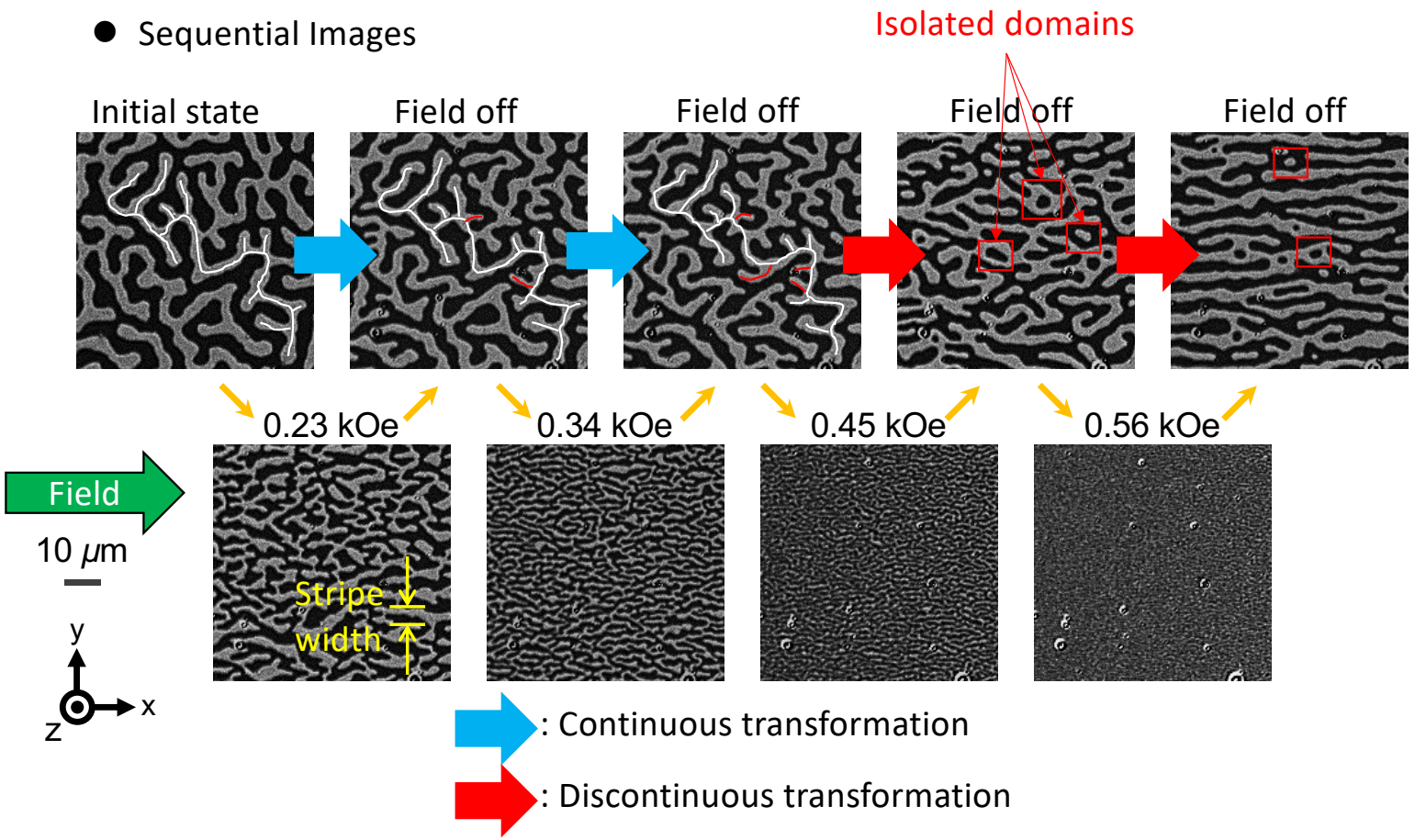
λ_0=1.3 μm

Magnetization state: thick stripe

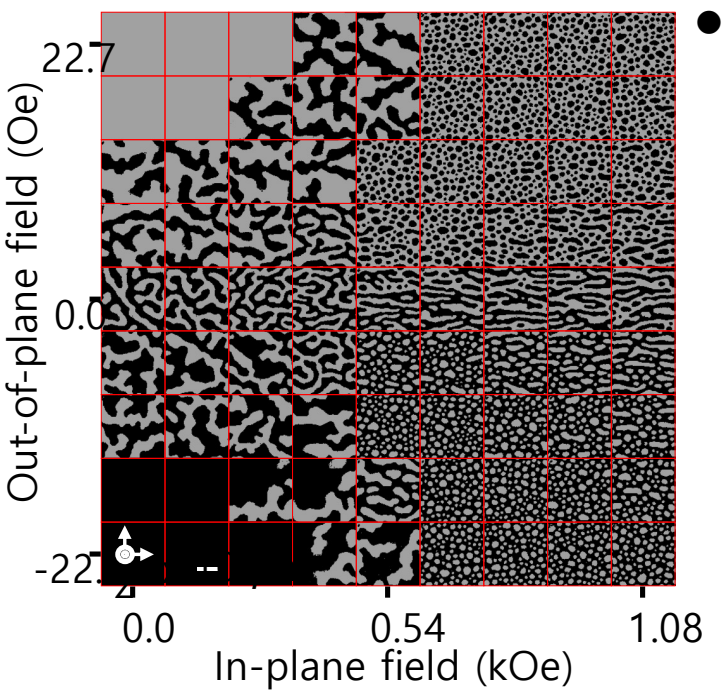


λ_0=2.6 μm

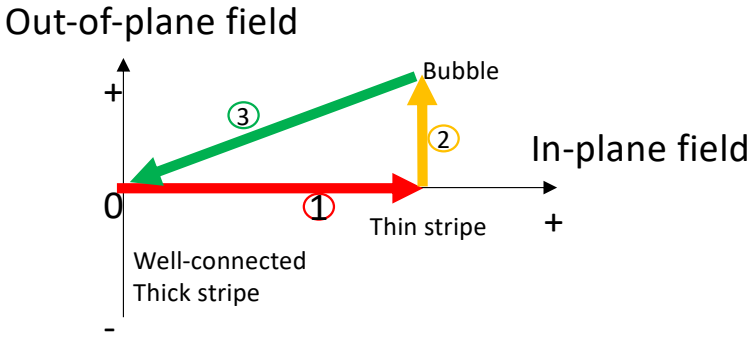
In-plane magnetic field



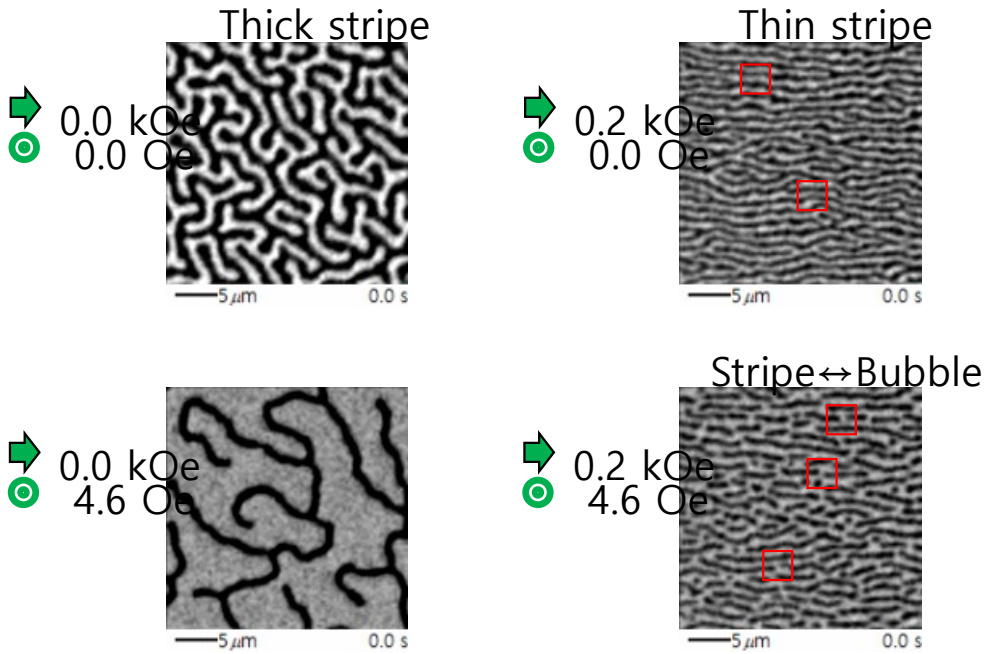
Experimental Phase Diagram



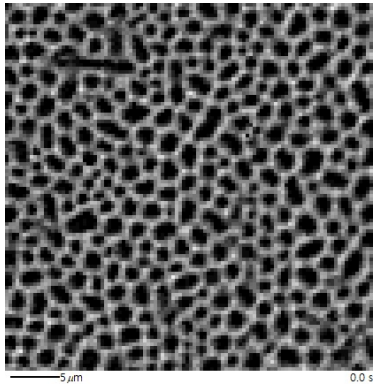
● Zero field images



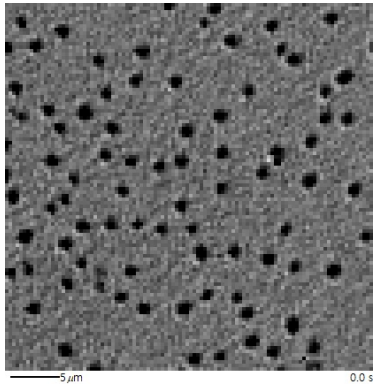
Stripe at T : Thermal Fluctuation



Skyrmion Motion by Current



Current: 4×10^8 A/m^2
Out-of-plane field : 0 Oe

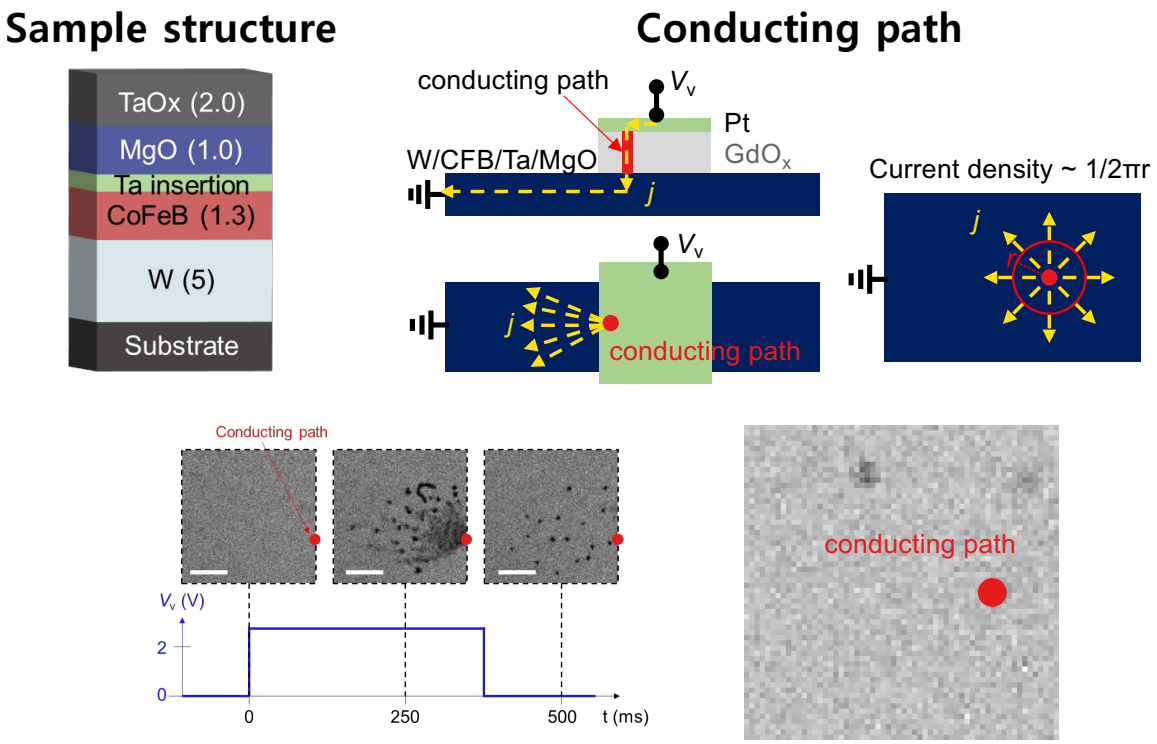


Current: 5×10^8 A/m^2
Out-of-plane field : 10 Oe

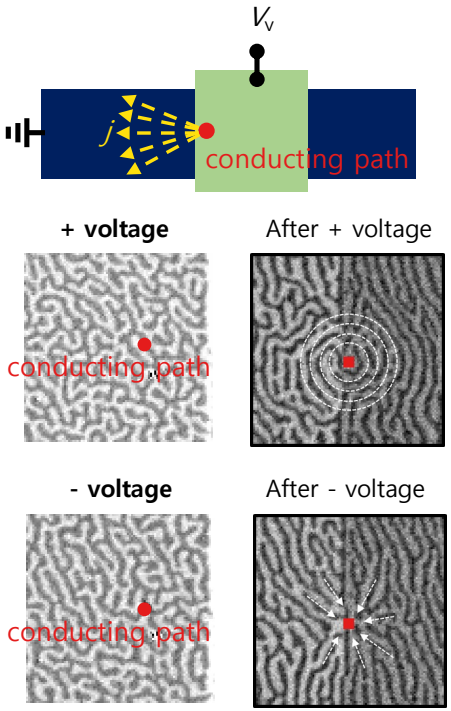
Only skyrmion with chirality can be moved by current
➔ The observed circular domains are skyrmion !

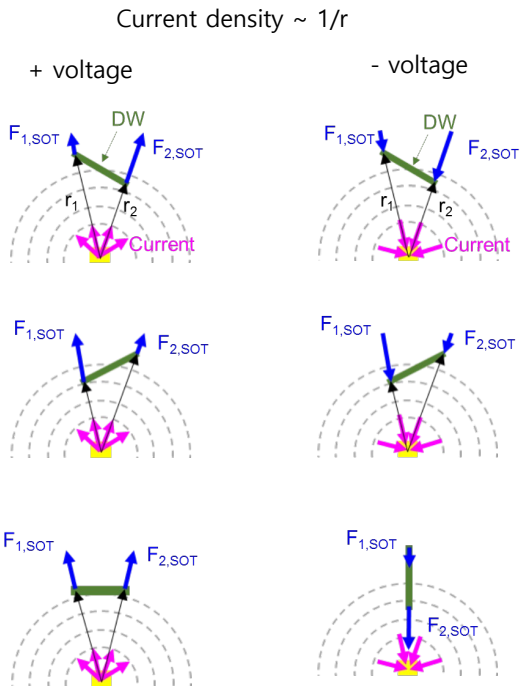
Indivisual Magnetic Skyrmion

1. Skyrmion Generation by a vertical Current Injection

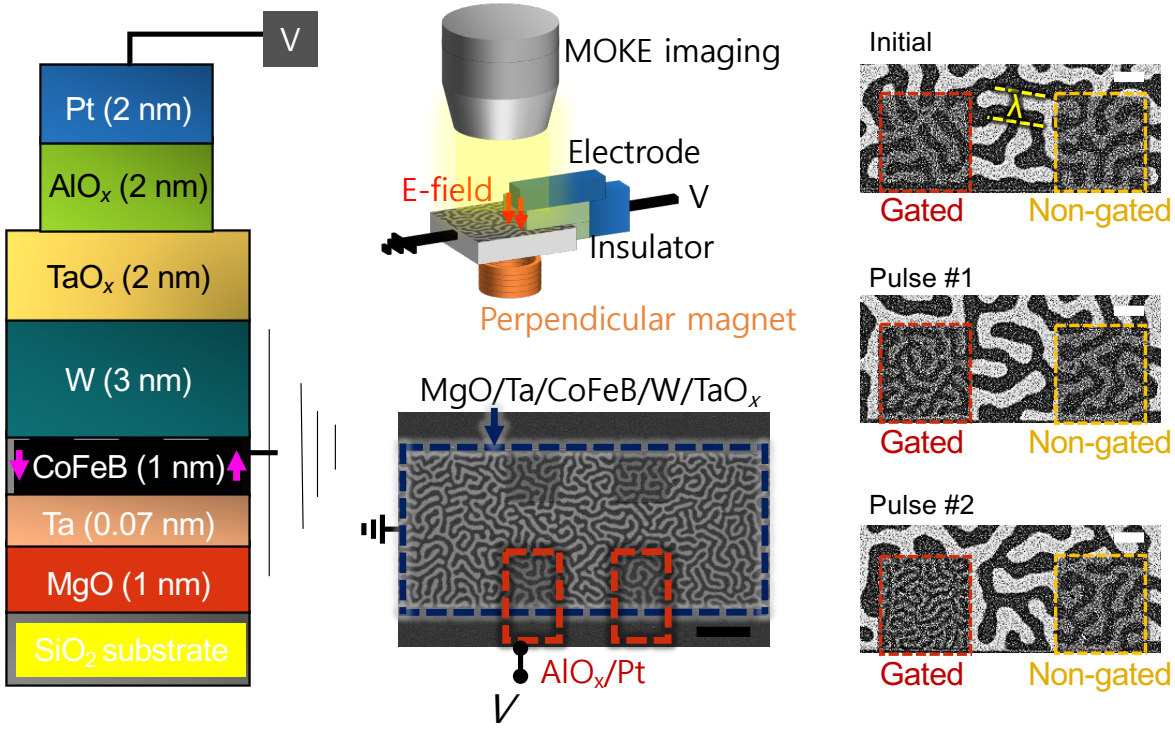


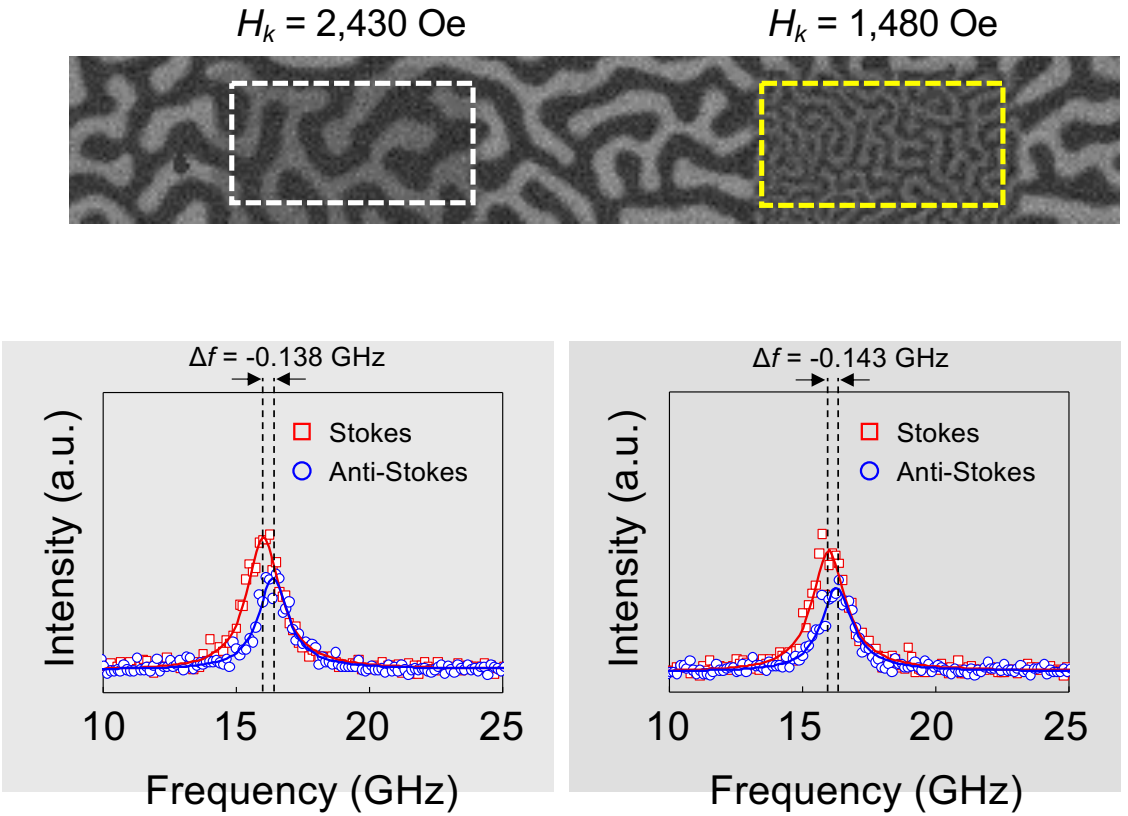
Formation of concentric & radial stripe

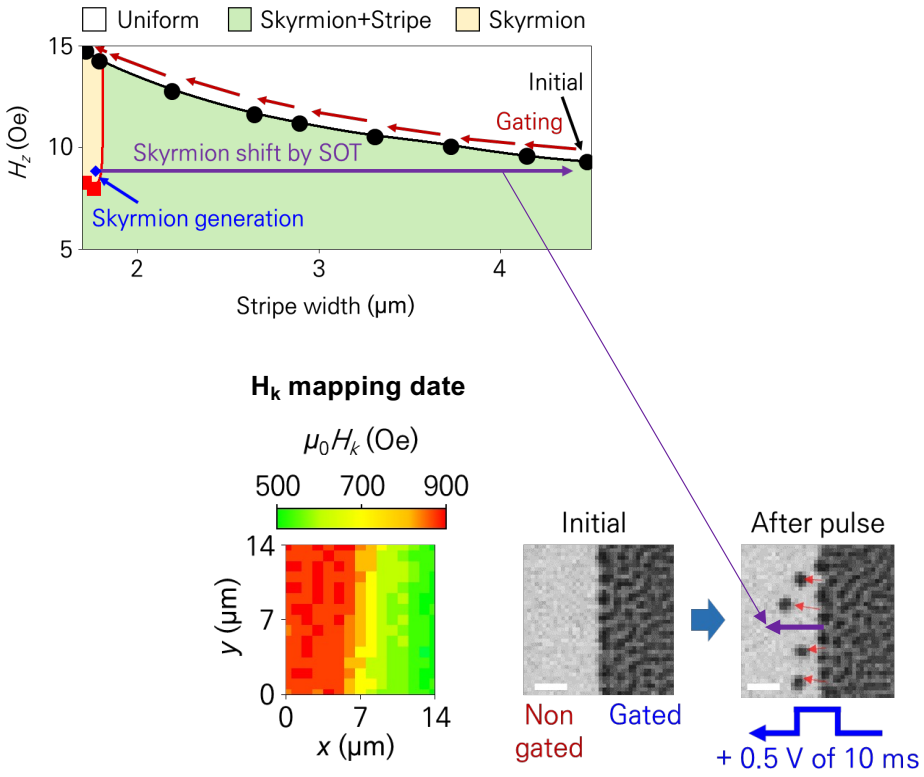




2. VCMA

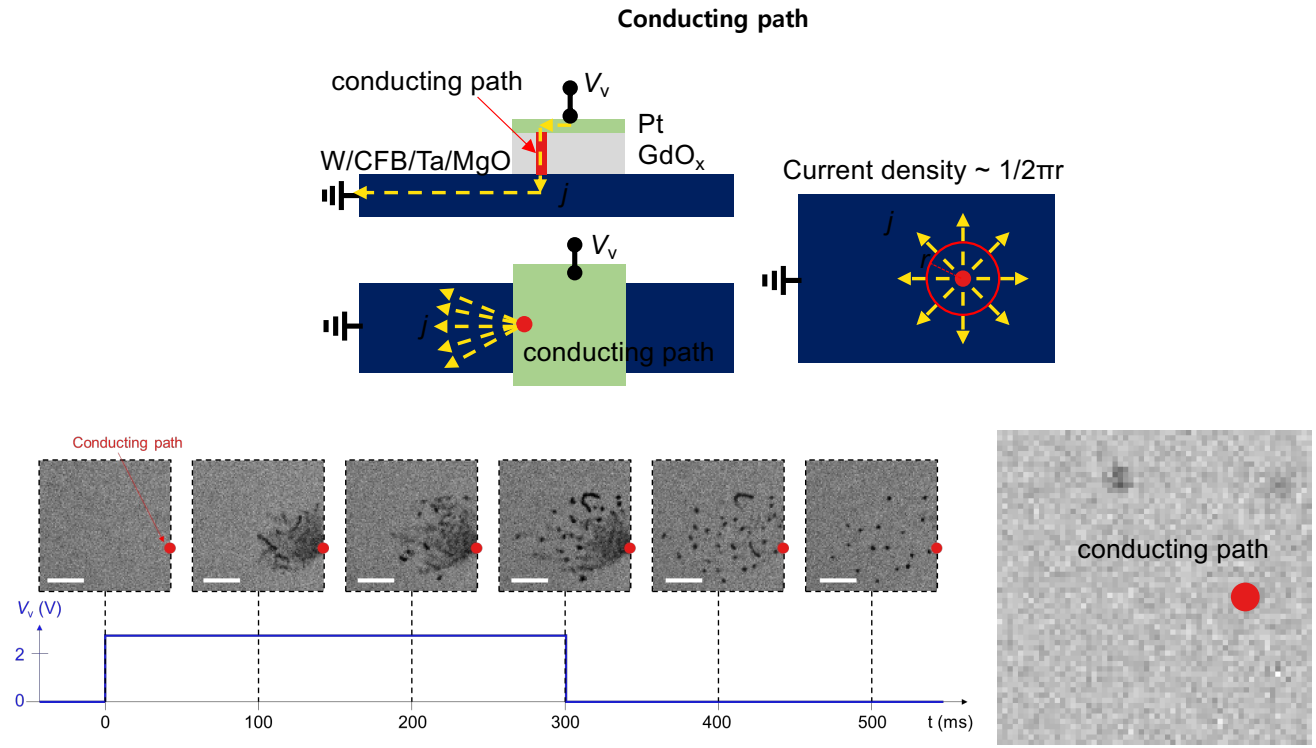

V
Pt (2 nm)
AlO$_x$ (2 nm)
TaO$_x$ (2 nm)
W (3 nm)
CoFeB (1 nm)
Ta (0.07 nm)
MgO (1 nm)
SiO$_2$ substrate
MOKE imaging
Electrode
E-field
V
Insulator
Perpendicular magnet
MgO/Ta/CoFeB/W/TaO$_x$
AlO$_x$/Pt
V
Initial
Gated
Non-gated
Pulse #1
Gated
Non-gated
Pulse #2
Gated
Non-gated


H_k = 2,430 Oe
H_k = 1,480 Oe
Δf = -0.138 GHz
Δf = -0.143 GHz
Stokes
Anti-Stokes
Intensity (a.u.)
10
15
20
25
Frequency (GHz)

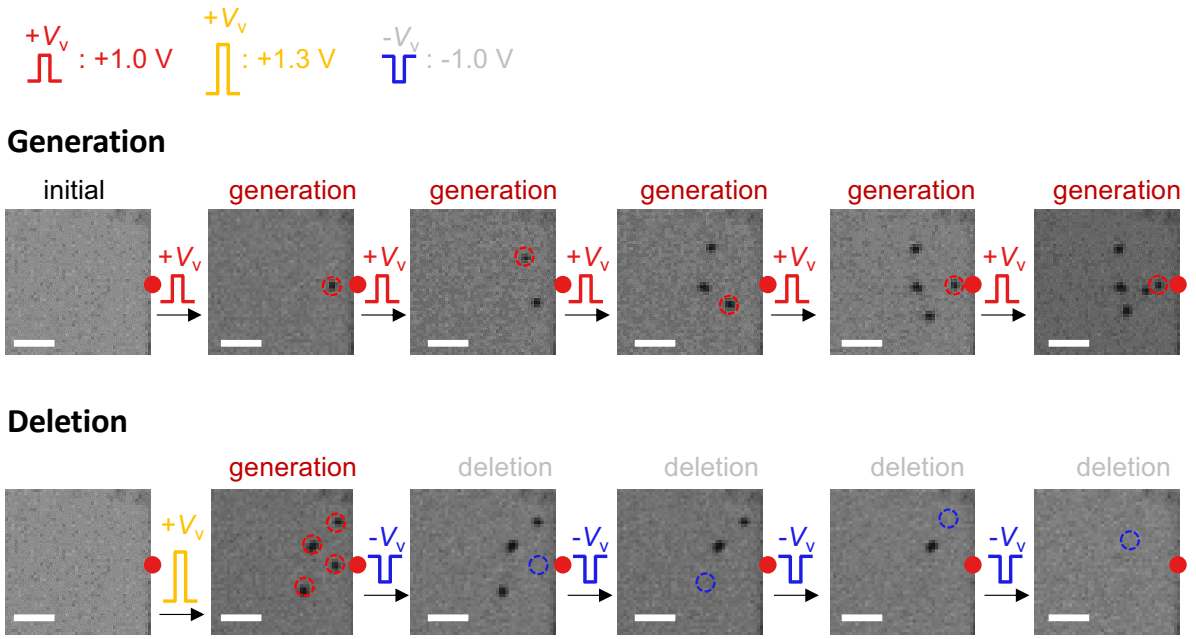

Uniform
Skyrmion+Stripe
Skyrmion
15
10
5
H_z (Oe)
Initial
Gating
Skyrmion shift by SOT
Skyrmion generation
2
3
4
Stripe width (μm)
$\mathbf{H_k}$ mapping date
$\mu_0 H_k$ (Oe)
500
700
900
14
7
0
y (μm)
0
7
14
x (μm)
Initial
After pulse
Non gated
Gated
+ 0.5 V of 10 ms

Skyrmioncs
Magnetic racetrack memory

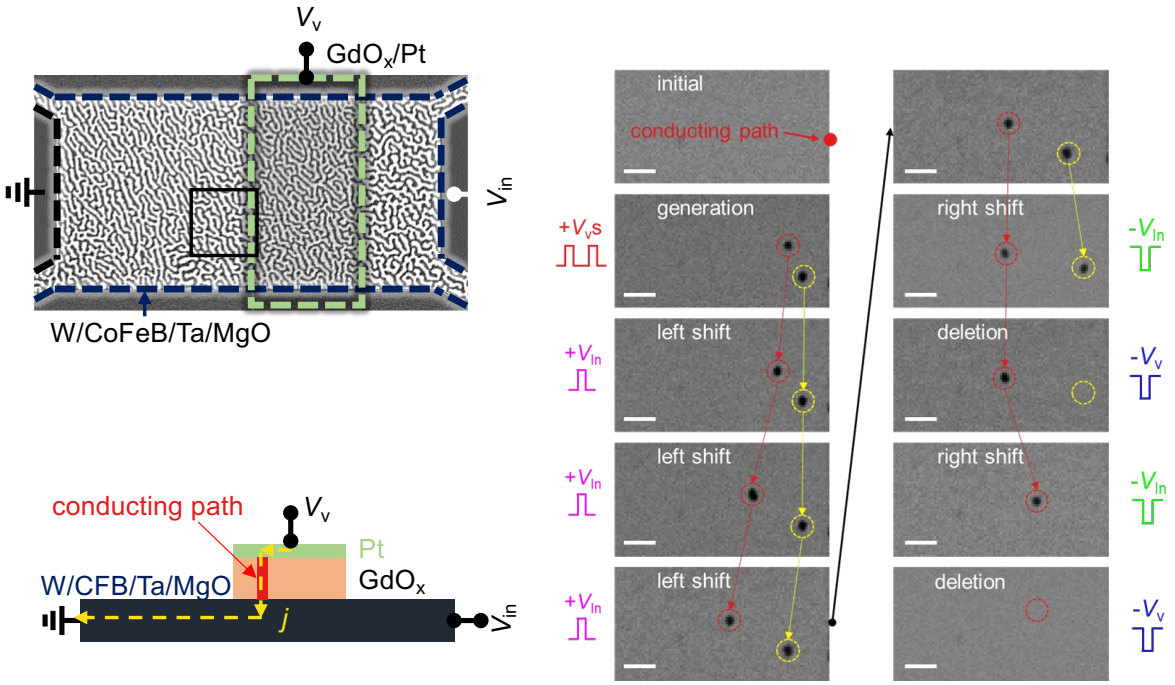
Skyrmion Generation by a vertical Current Injection



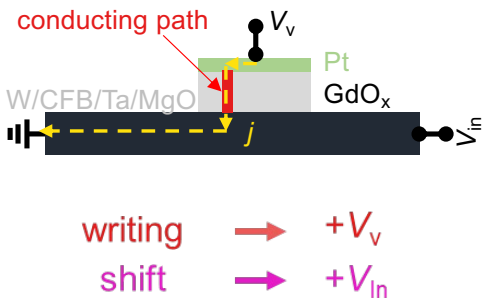
Electrical Single Skyrmion Generation/Deletion

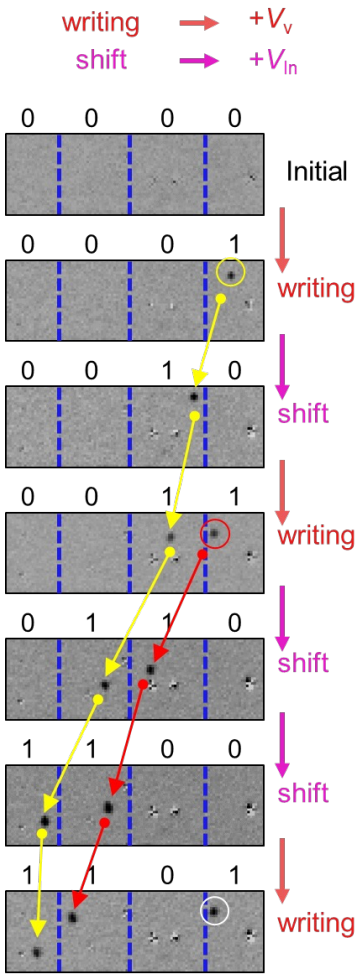


Electrical Skyrmion shift

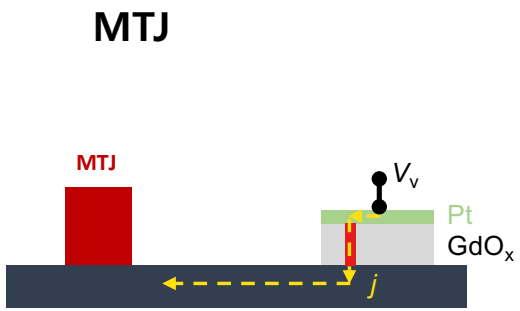


Skyrmion Racetrack Memory

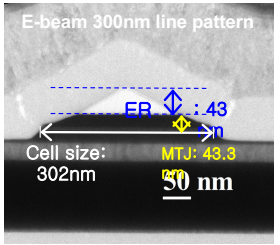


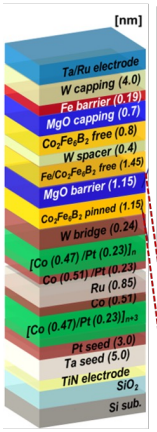


Electrical Detection of a Skyrmion

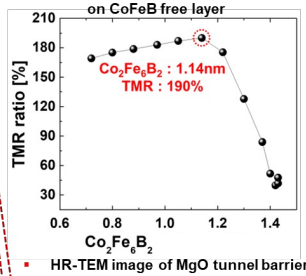


Courtesy to
Prof. J. Park

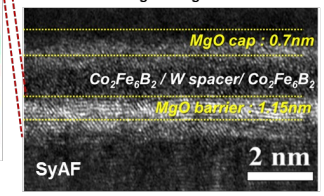




- TMR ratio dependency on CoFeB free layer

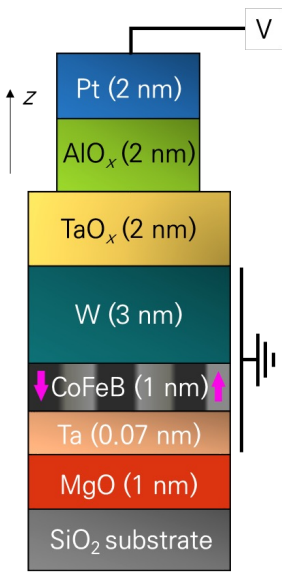


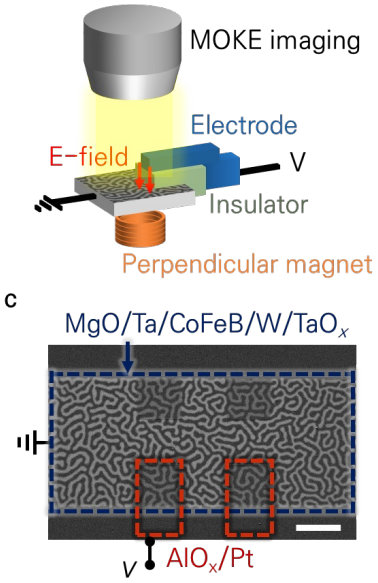
- HR-TEM image of MgO tunnel barrier

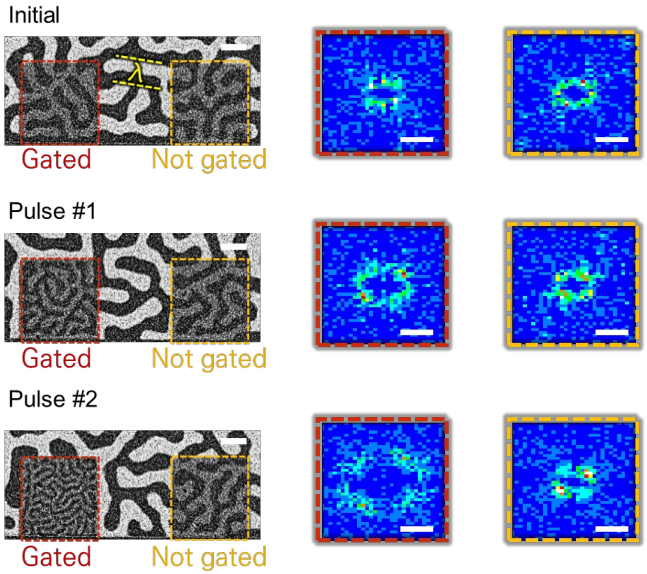


Skyrmioncs Transistor

VCMA



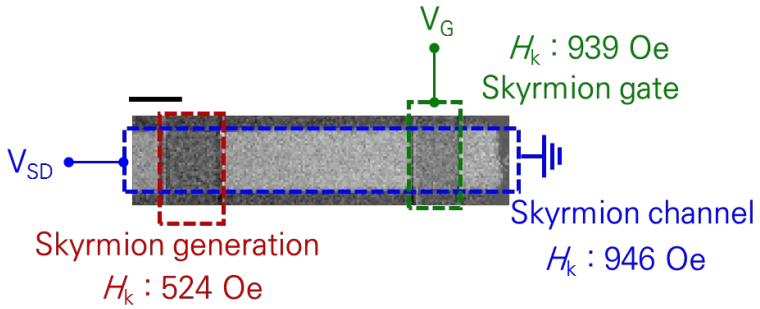




$$\lambda_0 \sim \exp\sqrt{K_{\text{eff}}}$$

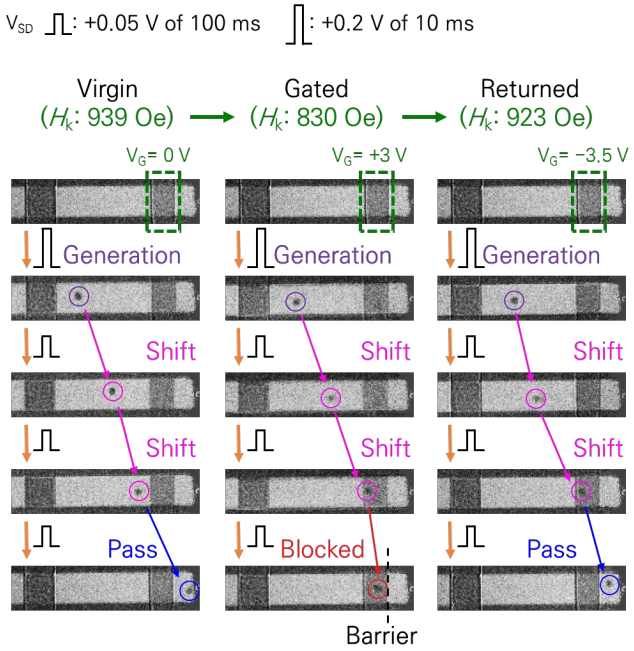
Skrymion Transistor

Device geometry



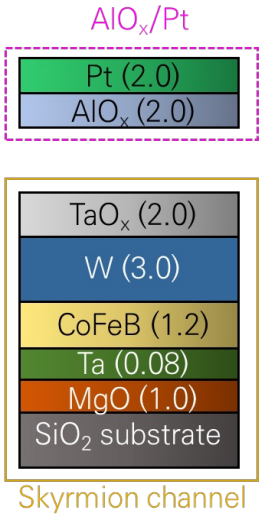
A skyrmion transistor is a electrical device to switch skyrmion motion.

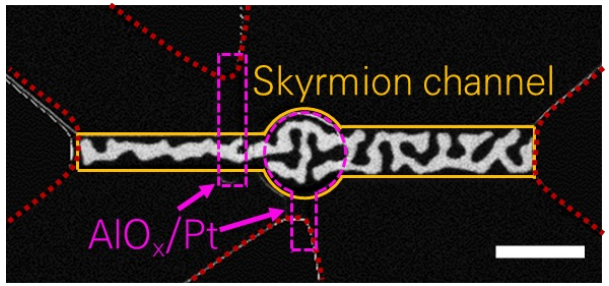
Skrymion Transistor

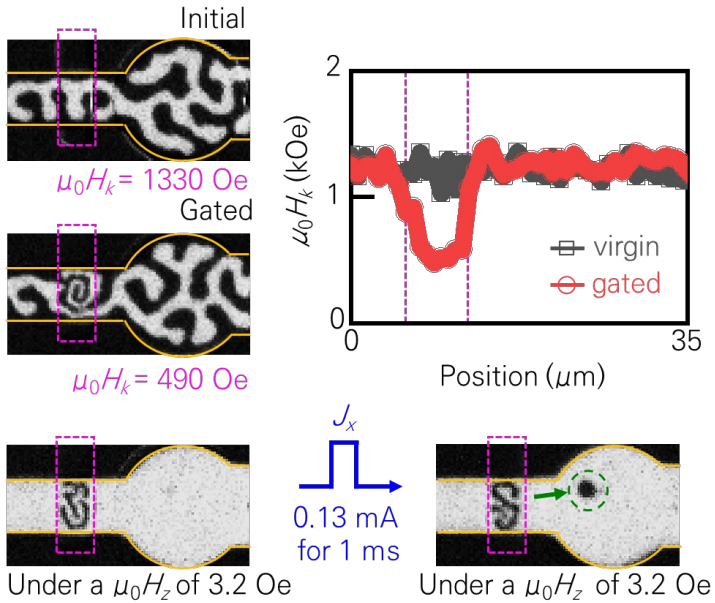


Skyrmioncs
Neuromorphic Device

Homeostasis function







References for our Skyrmion work

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NPG Asia Materials 13, 20 (2021)
JMMM 539, 168381(2021)
Scientific Report 11, 20970 (2021)
Adv. Mater. 33, 2104406(2021)
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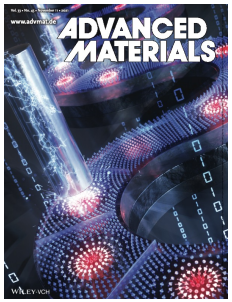
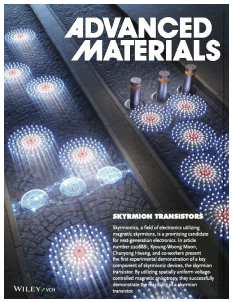
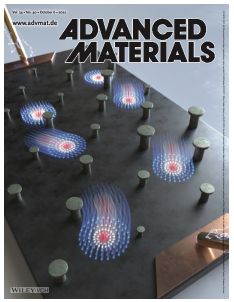
Nano Letters 22, 8430 (2022)
APEX 15, 123001(2022)
Adv. Mater. 35, 2208881(2023)
Adv. Mater. 2312013(2024)

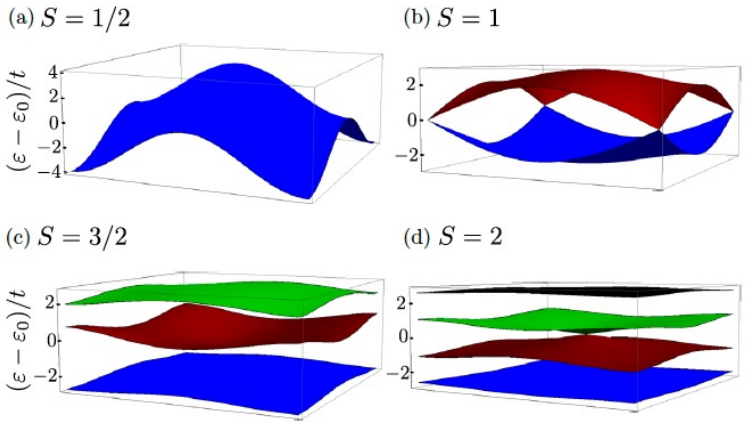




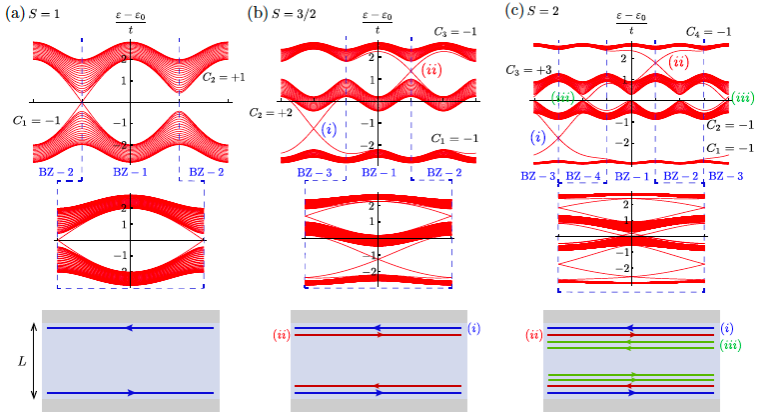


Skyrmions on the lattice

Skyrmion bands and edge state



Skyrmion bands (Q = 1) in the square lattice for different spin numbers.
As S increases, bands become less dispersive .
When S is integer value, Direac points near ϵ_0.



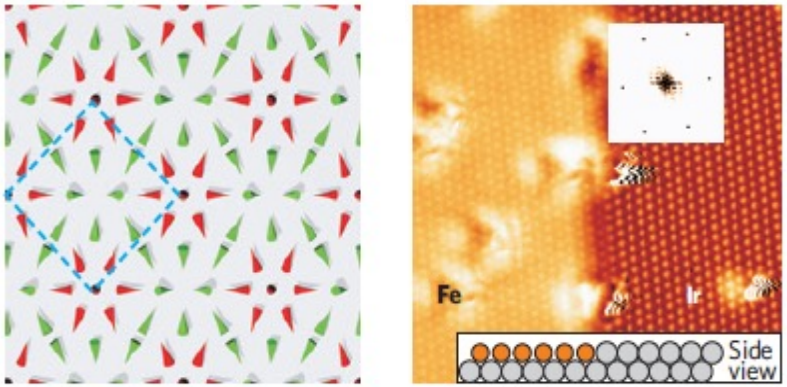
Band structure of skyrmions (Q = 1) in a rectangular strip with L = 20a
The bottom panels show the chirality of the edge modes within the projected bulk gaps.

Quantum macrospin

S spin quantum number

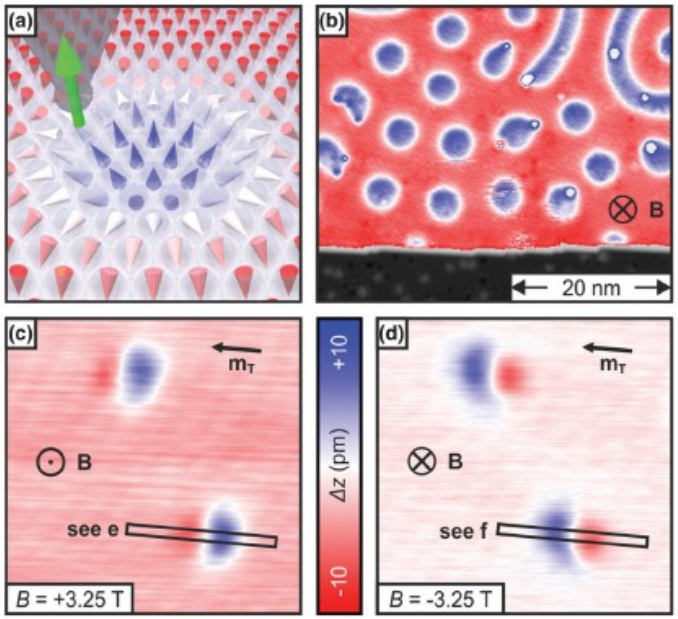
IJMP B 2019

1 ML Fe on Ir(111)



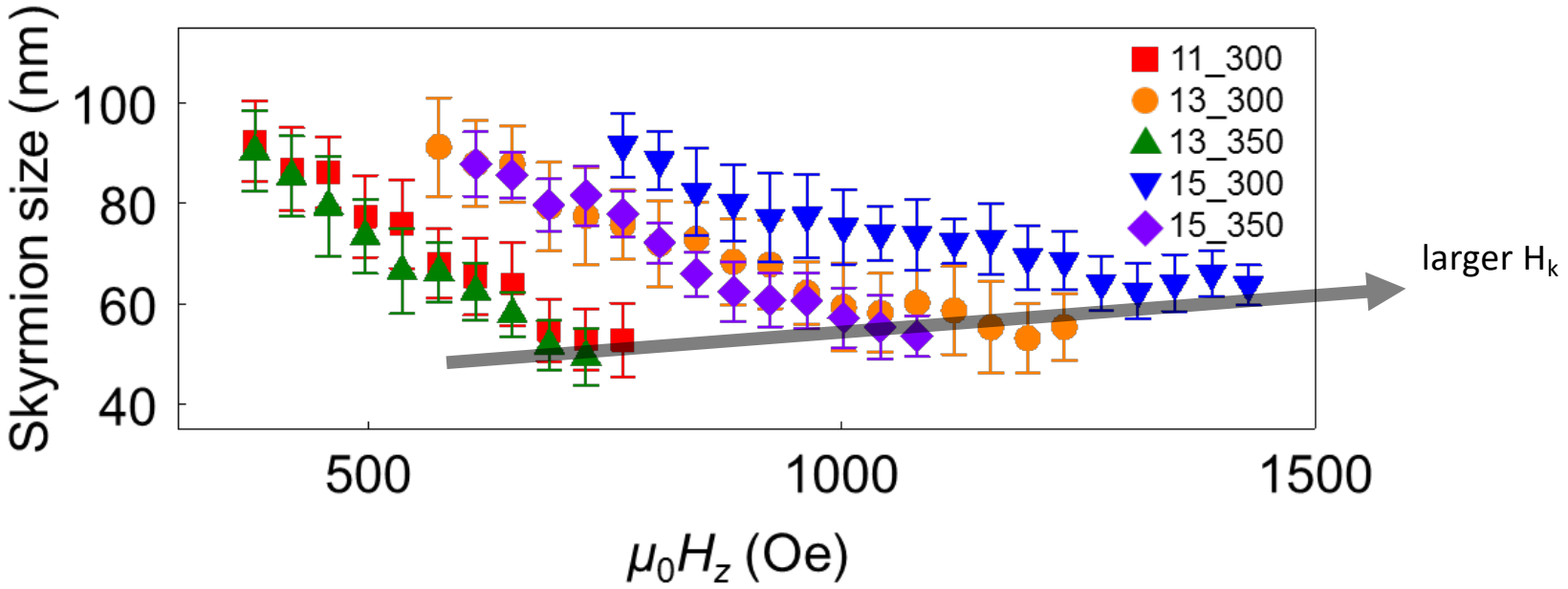
S. Heinze et al., Nat. Phys. 2011

2 ML PdFe on Ir(111)



N. Romming et al., PRL 2015

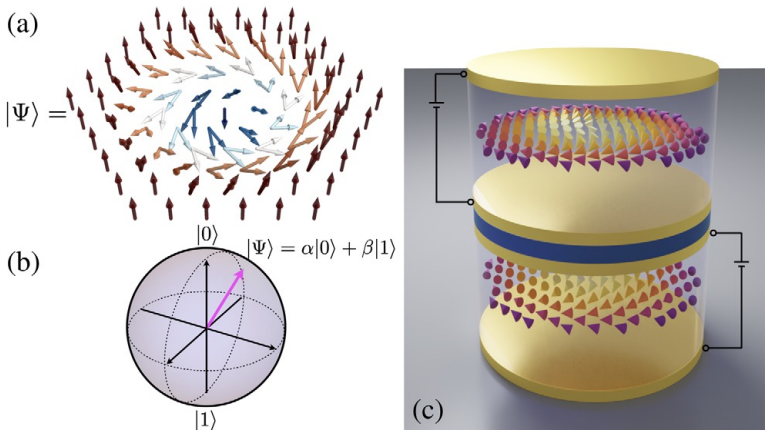
Shrinking down to nm scale



ALS Beamline 6.1.2

In-preparation

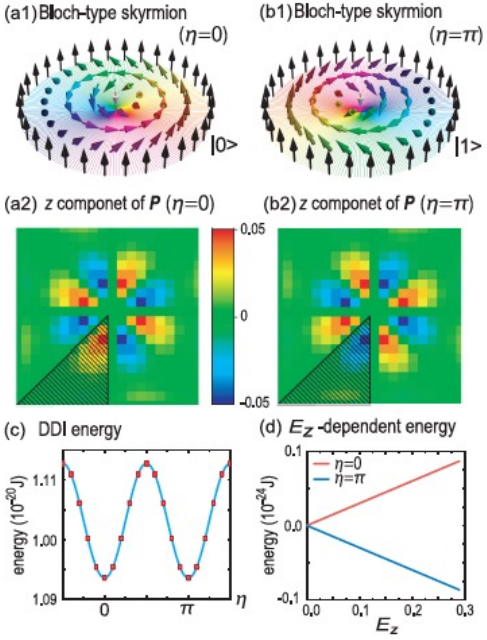
Skyrmion Qubit



- skyrmion qubits based on the energy-level quantization of the helicity degree of freedom.
- control the energy-level spectra with external parameters, including electric and magnetic fields

Phys. Rev. Lett. 127, 067201 (2021)

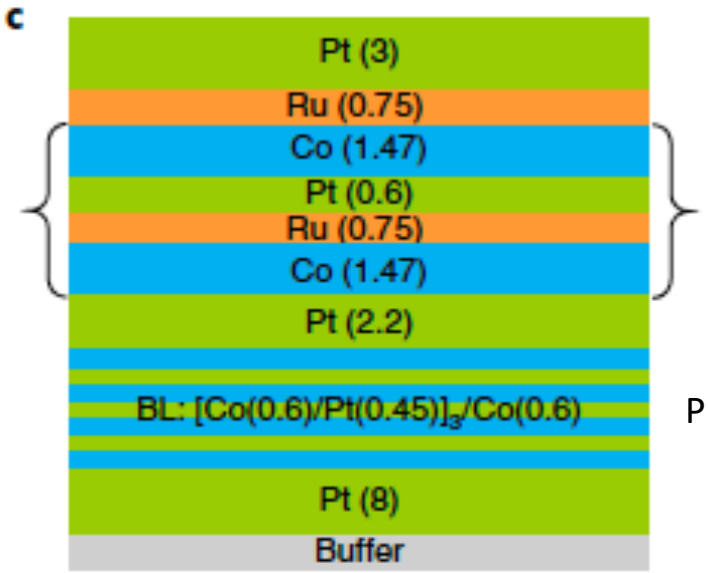
Universal quantum computation



two helicity states of a Bloch-type nanoscale skyrmion in frustrated magnets

Phys. Rev. Lett. 130, 106701 (2023)

Tuning the Skyrmion radius



SAF

PMA magnetic multilayers

Variables

1. film thickness, layer composition,
2. magnetic coupling, uncompensated M
3. DMI, PMA, M……..

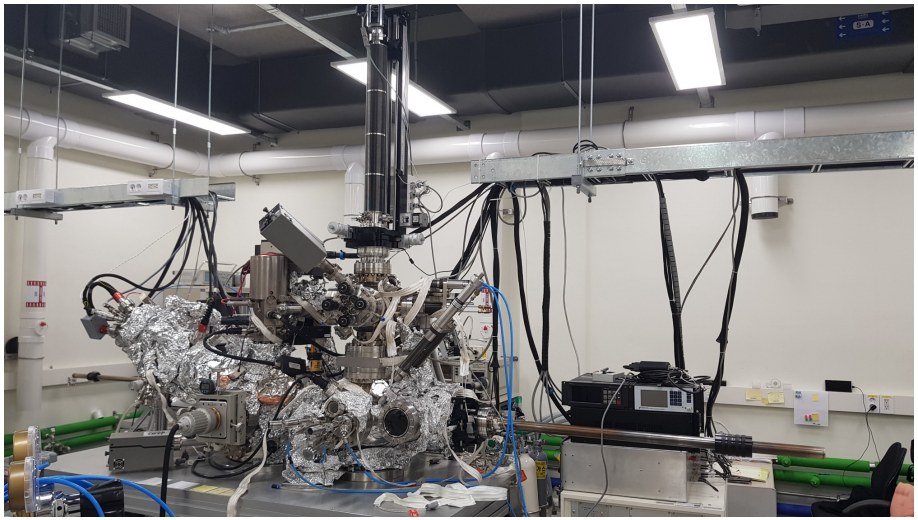
hugh number of stacking sequences……

Legland et al., Nature Materials 2020

To reach the Q phenomena of magnetic skyrmion

- nm scale size
- tunning the skyrmion radius with material parameters

SEMPA (10nm, 40 ns(down to 1ns) resolution)



Quantum Spin Team at KRISS


Dr. Chanyong Hwang


Dr. Kyoung-woong Moon

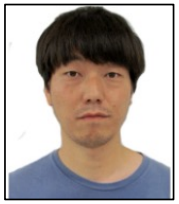

Dr. Changsoo Kim


Dr. Seungmo Yang


Dr. Woojoo Lee


Mr. Sangsun Lee

Post Doc


Dr. Kyungmo Ahn


Dr. Ja Hyun Koo


Dr. Jongwan Son


Dr. Sungho Park


Dr. Minkyu Park


Dr. Yeong Hoon Lee


Dr. Sung Soo Hahn


Dr. Hee Dong Kim

Ph.D. Students

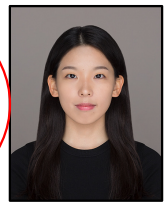

Tran Thi Toan


T. Nyamma


T. Bolortsetseg


Taesung Ju


Jeong Woo Seo

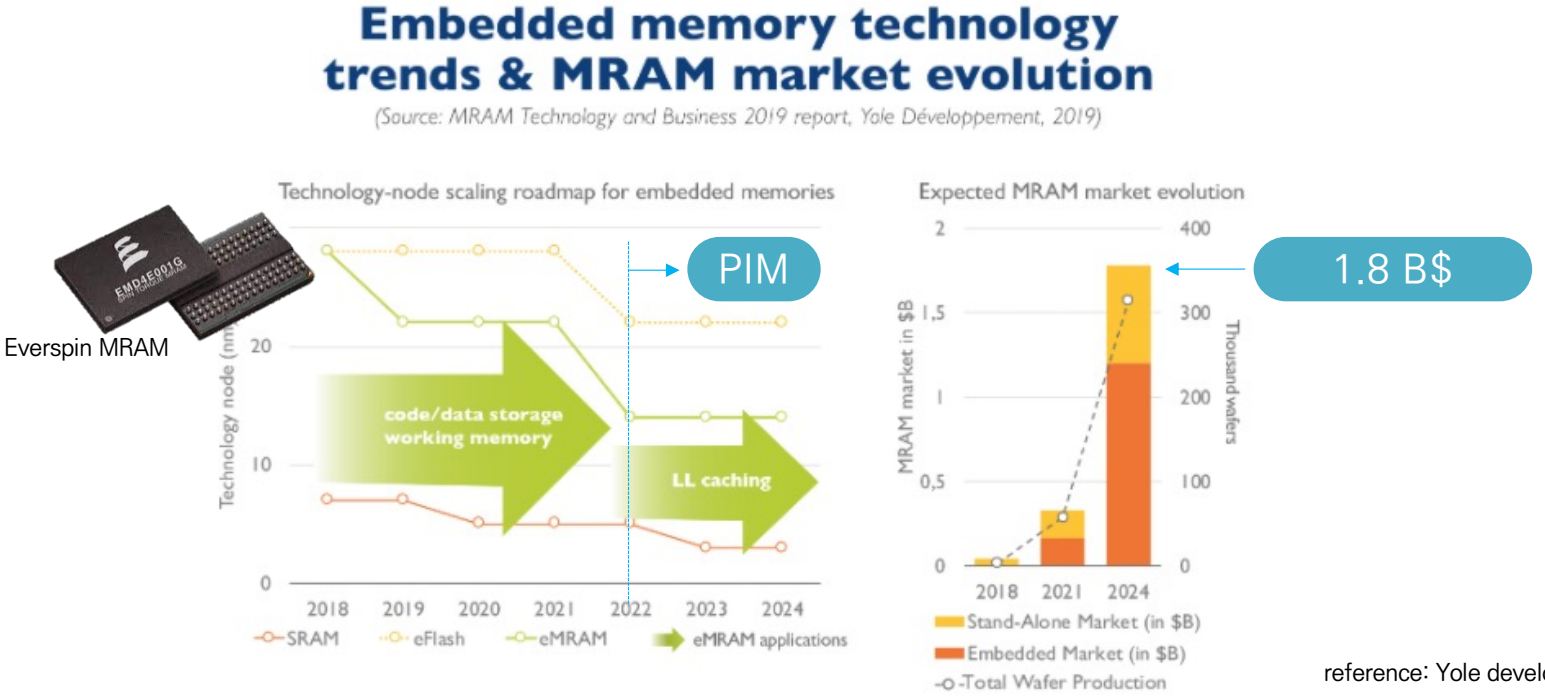

Yuri Han


Suseong Im


Hyungseok Kim


Sijin Park

Rapid Expansion of MRAM market

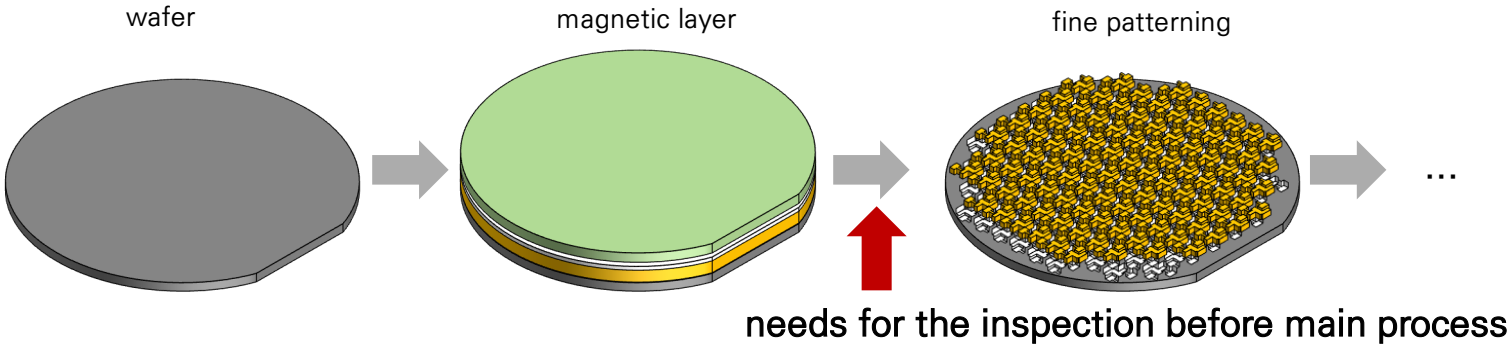


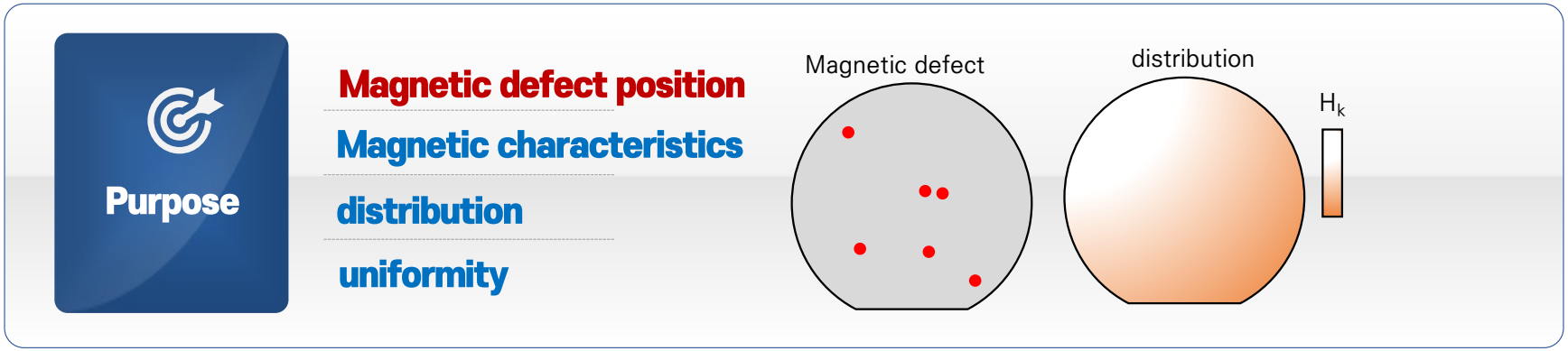
reference: Yole development

NEED for fast inspection for MRAM

Research Purpose

Wafer-scale inspection device

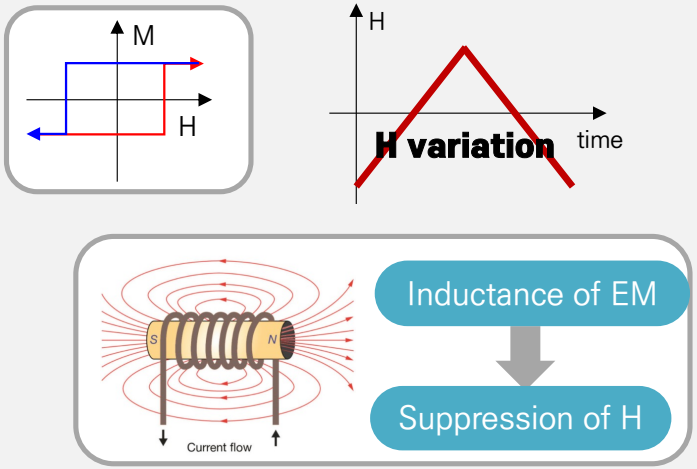




Limit for the current method

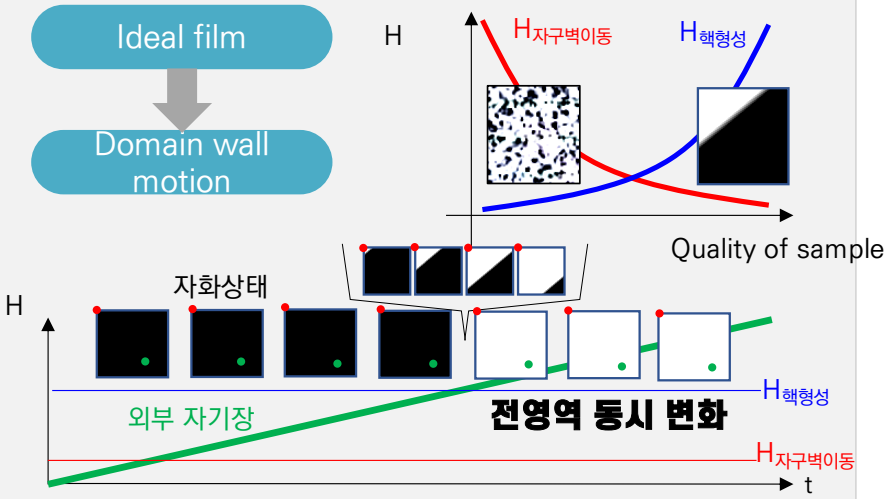
➔ Critical field for M critical phenomena

Time for the sweeping H



Huddle for fast scan

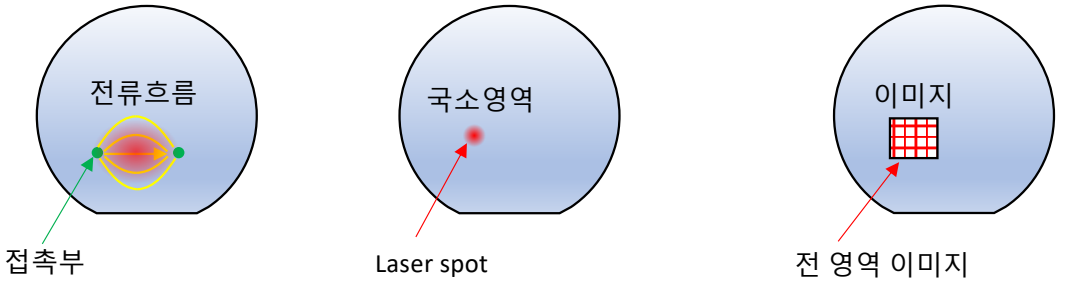
Critical field uncertainty



Problem of reliability

Current suppliers

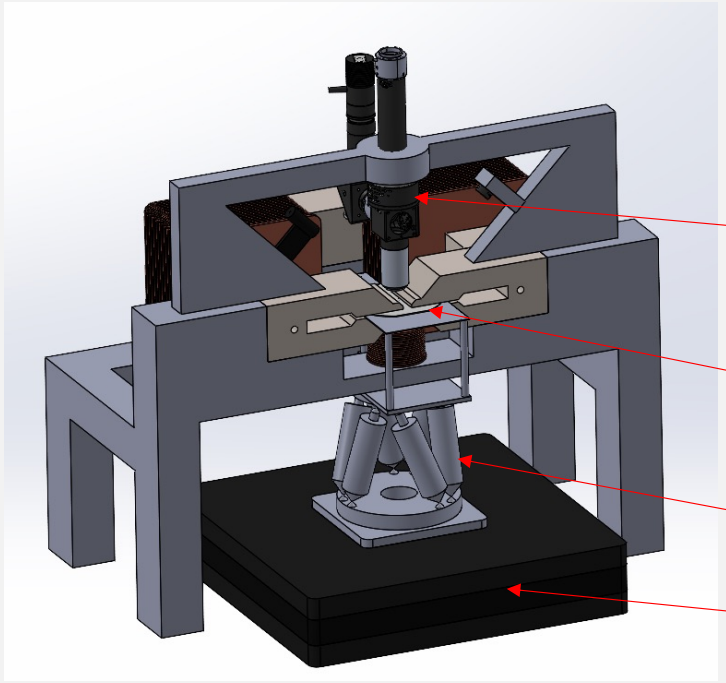
	Hprobe	KLA (microsense)	ours
Method	electrical	optical(local)	optical(whole area)
contacts	✓	X	X
resolution	~ 100 μm	~ 1 μm	~ 1 μm (variable)
H variation	✓	✓	X

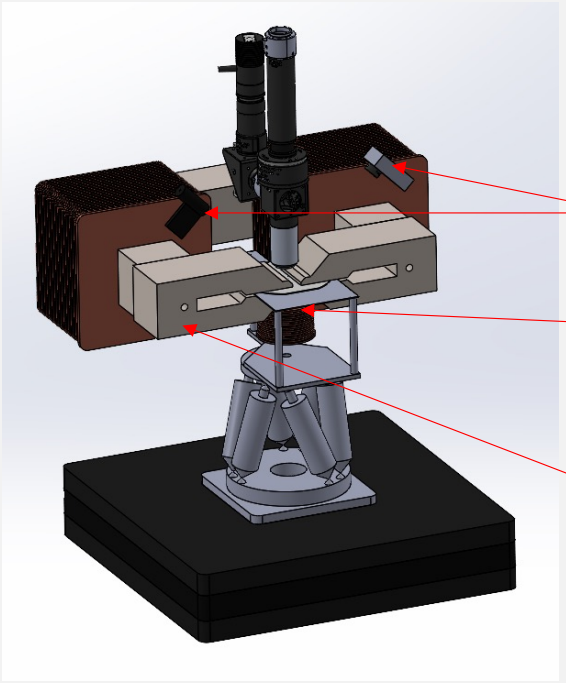


Uniformity check over the whole wafer

System Design

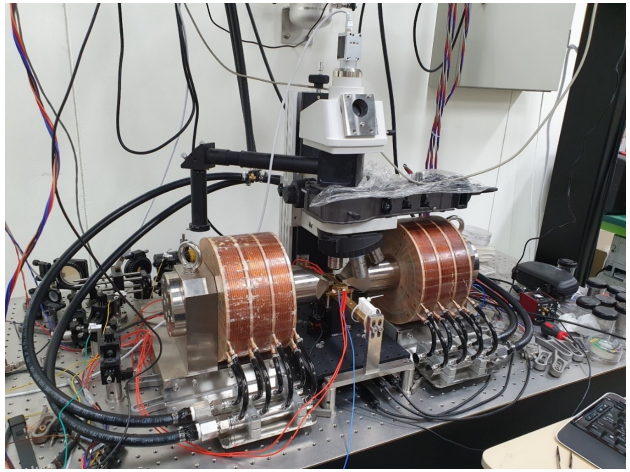
전체 도식도



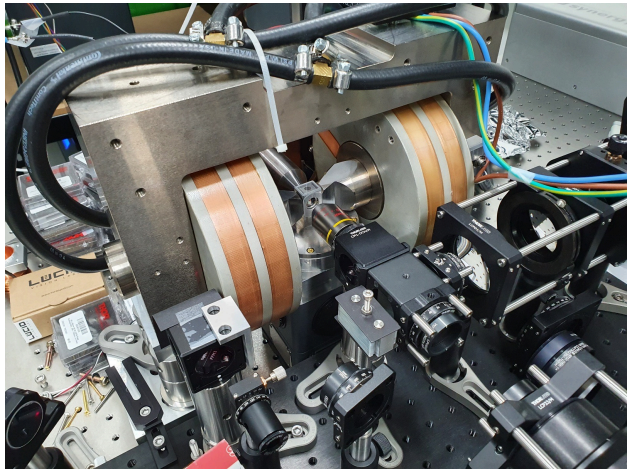


Thank you for your attention!

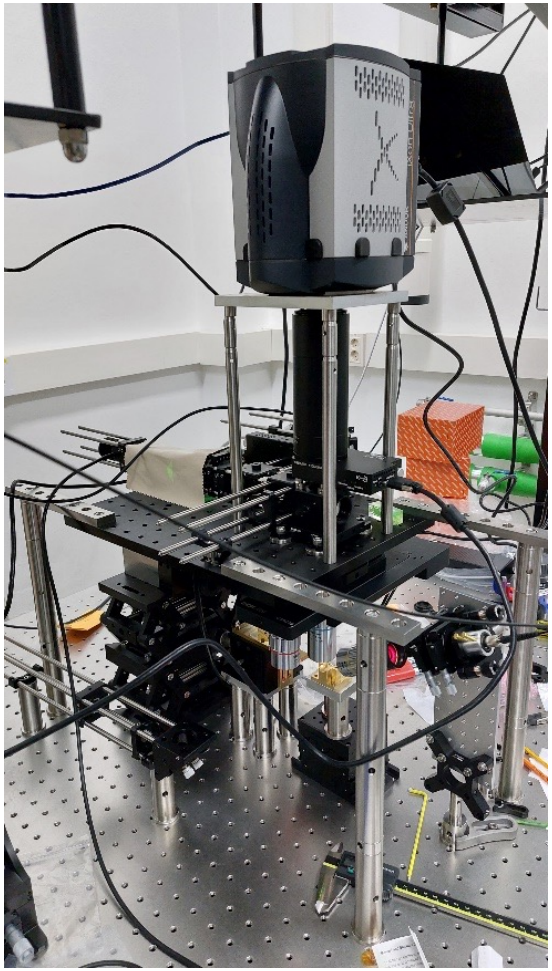
MOKE Microscopy



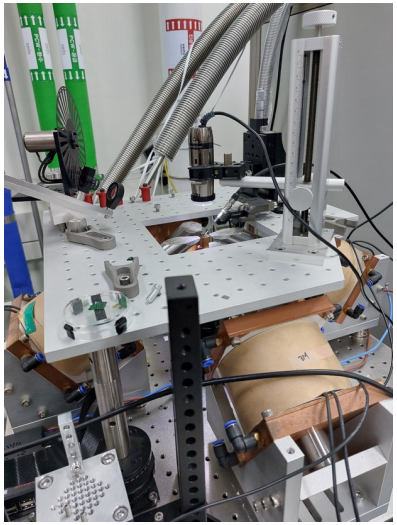
LT MOKE Microscopy



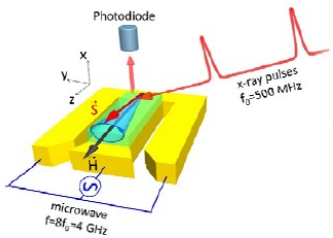
Dark-field MOKE Microscopy

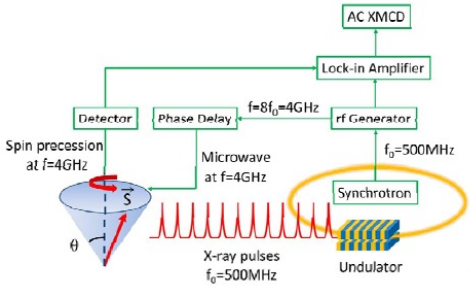


(ST)FMR



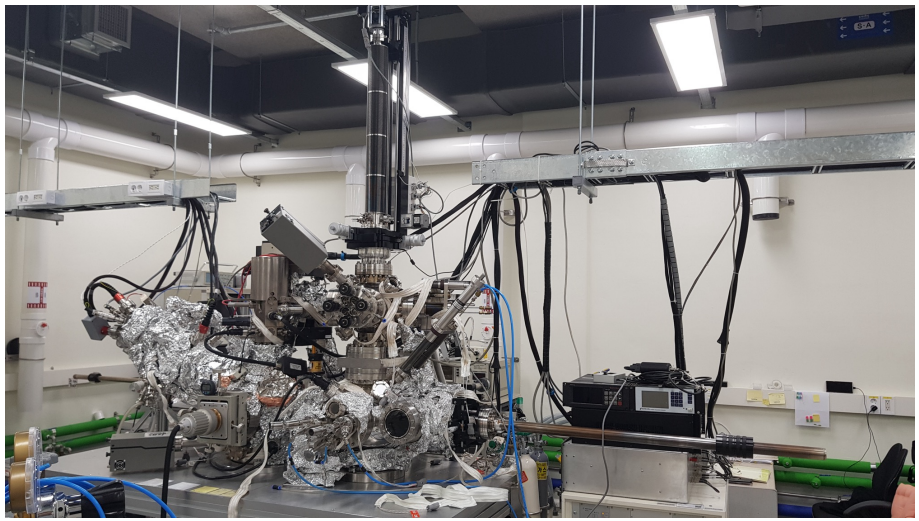
XFMR (PAL 2A1)

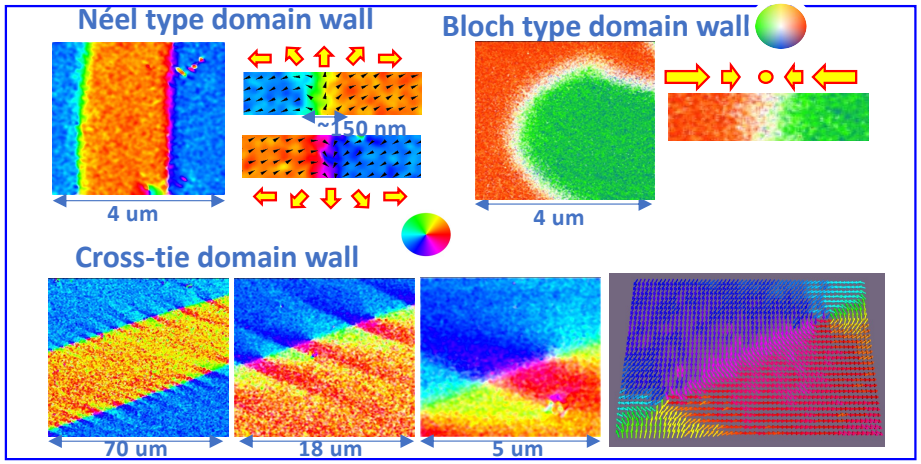




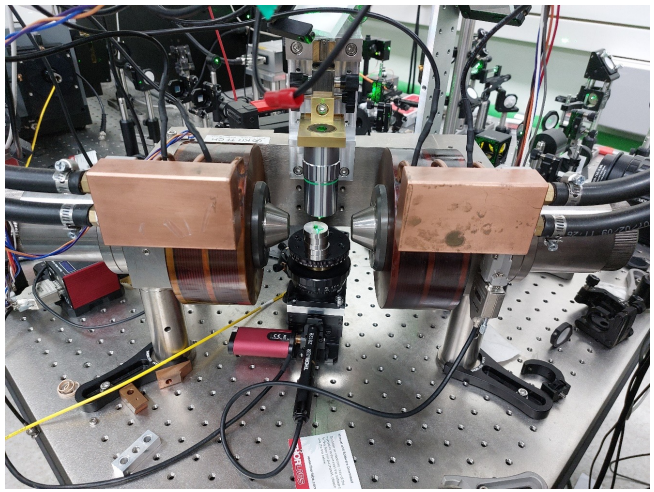
Birefringence Microscope+ vector magnet (under const.)

SEMPA (Now time resolved upto 40 ns)

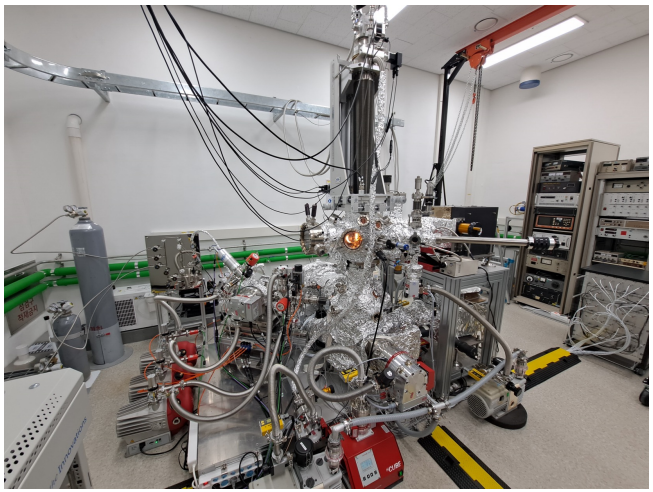




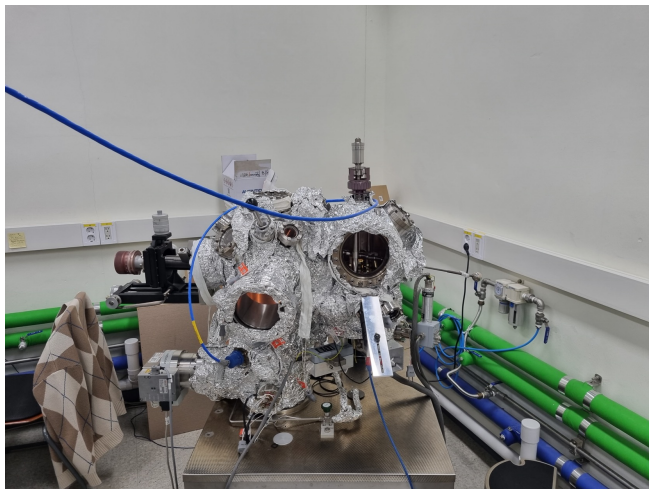
BLS microscopy + Raman



ARPES + MBE+ time resolved (this year)

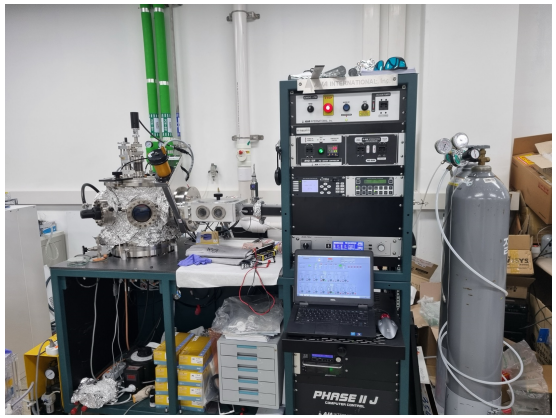


STM 1, 2



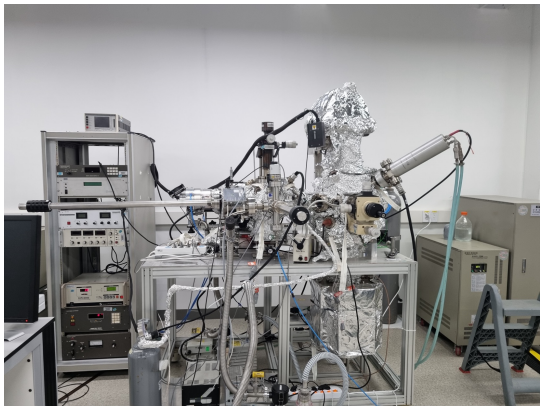
CVD

Sputter System



ALD

XPS



VSM