PF研究会「磁性薄膜・多層膜を究める」
2011年10月14日

スピントロニクス研究の進展と放射光への期待

京都大学化学研究所
小野輝男

Institute for Chemical Research
Division of Materials Chemistry
Nanospintronics Lab.

Activities in our Lab.

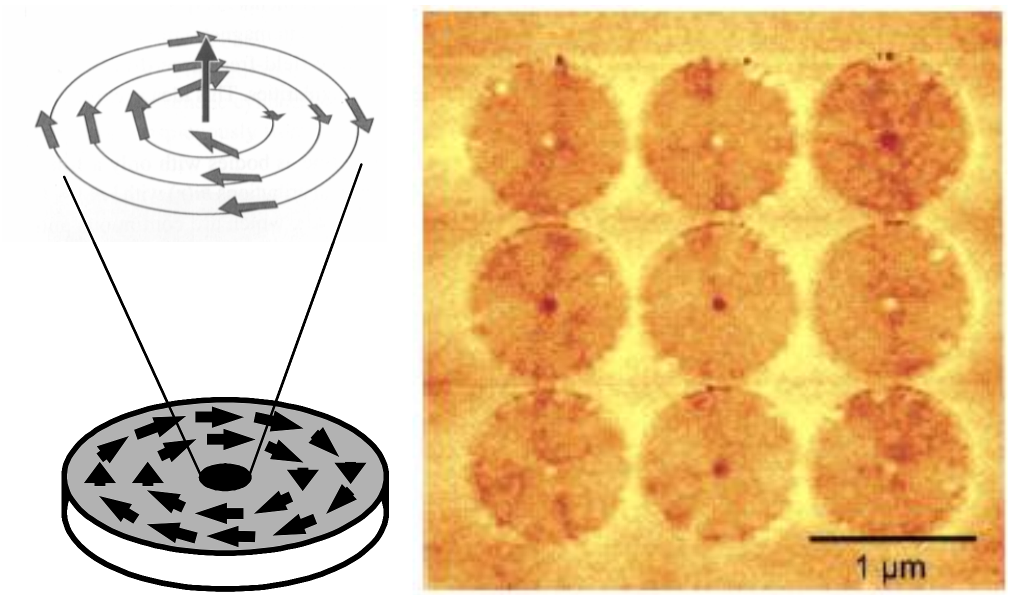
(1) Nanomagnetism

- Field-induced DW motion (Science 1999, PRL2008)
- Magnetic vortex core (Science 2000)
- Current-induced DW motion (PLR2004, N.Mat.2011)
- Current-induced magnetic vortex core switching (PRL2006,2008, N.Mat.2007)
- Electirc field control of magnetism (N.Mat.2011)
- GMR in pure Si (Nature 2009)

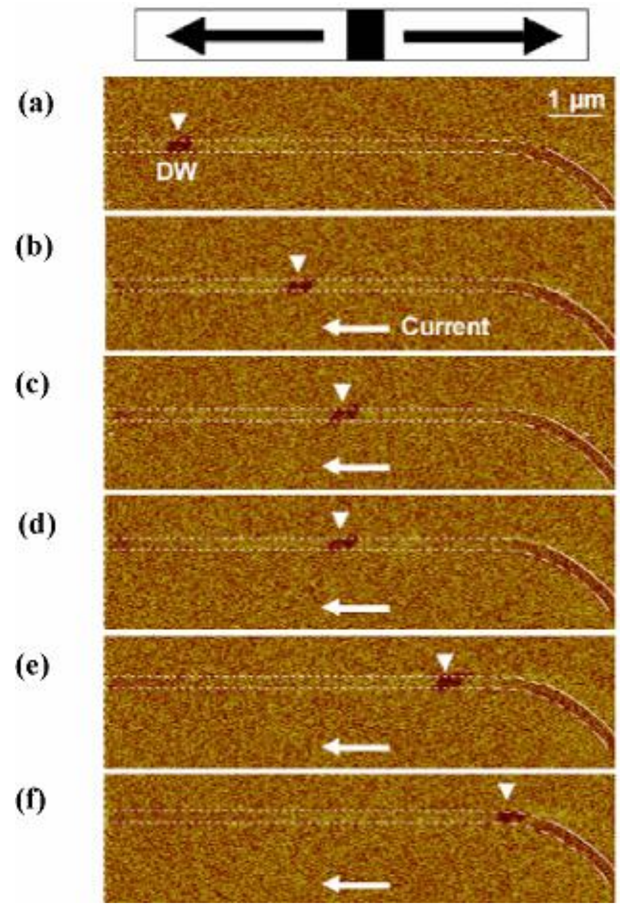
(2) Mesoscopic physics (Shot noise measurements)

- Experimental cofirmation of fluctuation thorem (PRL2010)
- Shot noise in Kondo system (PRL2011)
- Shot noise in MTJ (APL2010, 2011)

磁気渦と磁壁、そしてちょっとだけ放射光

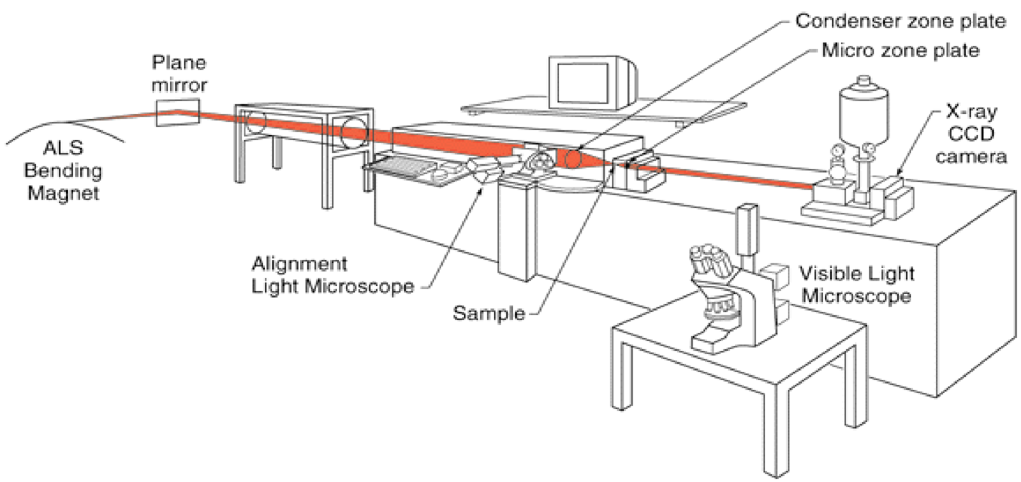


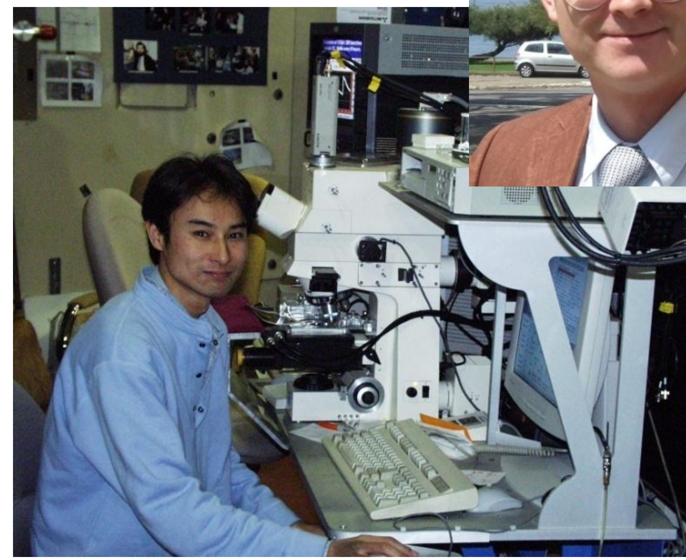
Vortex core, Science (2000)



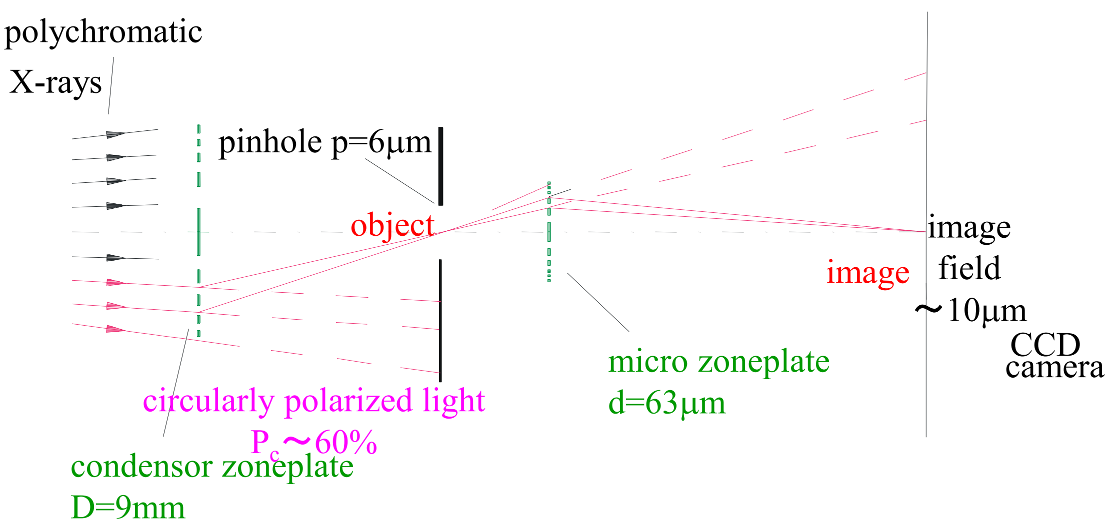
Current-induced DW motion,
Phys.Rev.Lett.(2004)

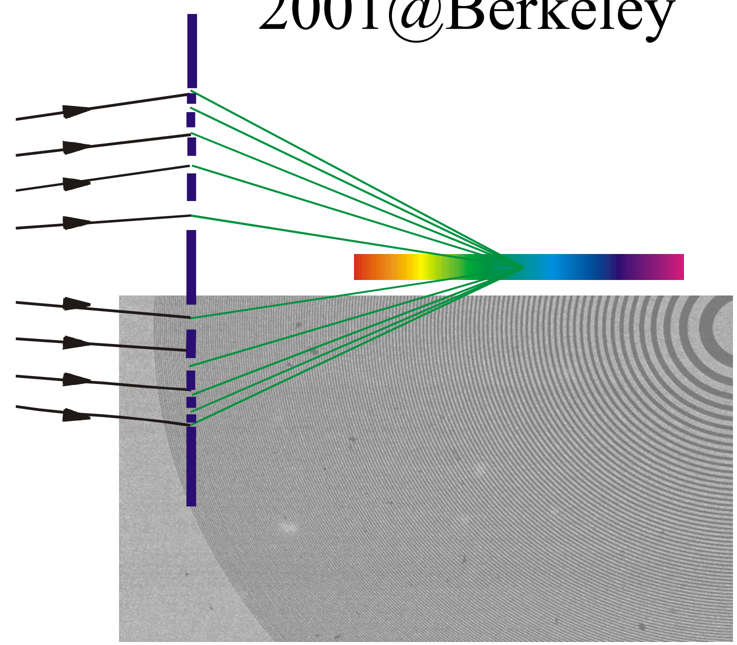
Magnetic Transmission X-ray Microscope @ ALS in Berkeley with Peter Fischer





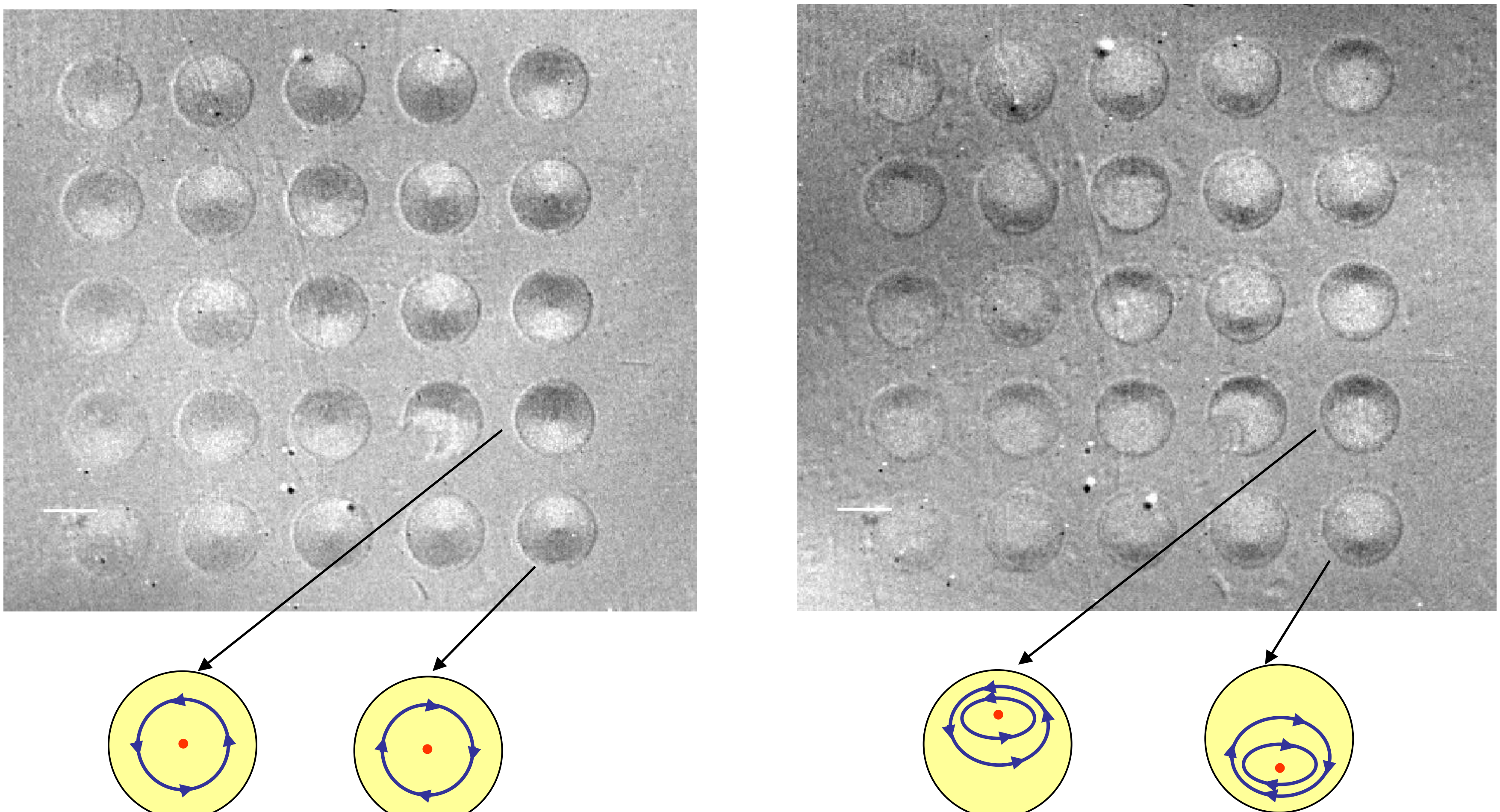
2001@Berkeley





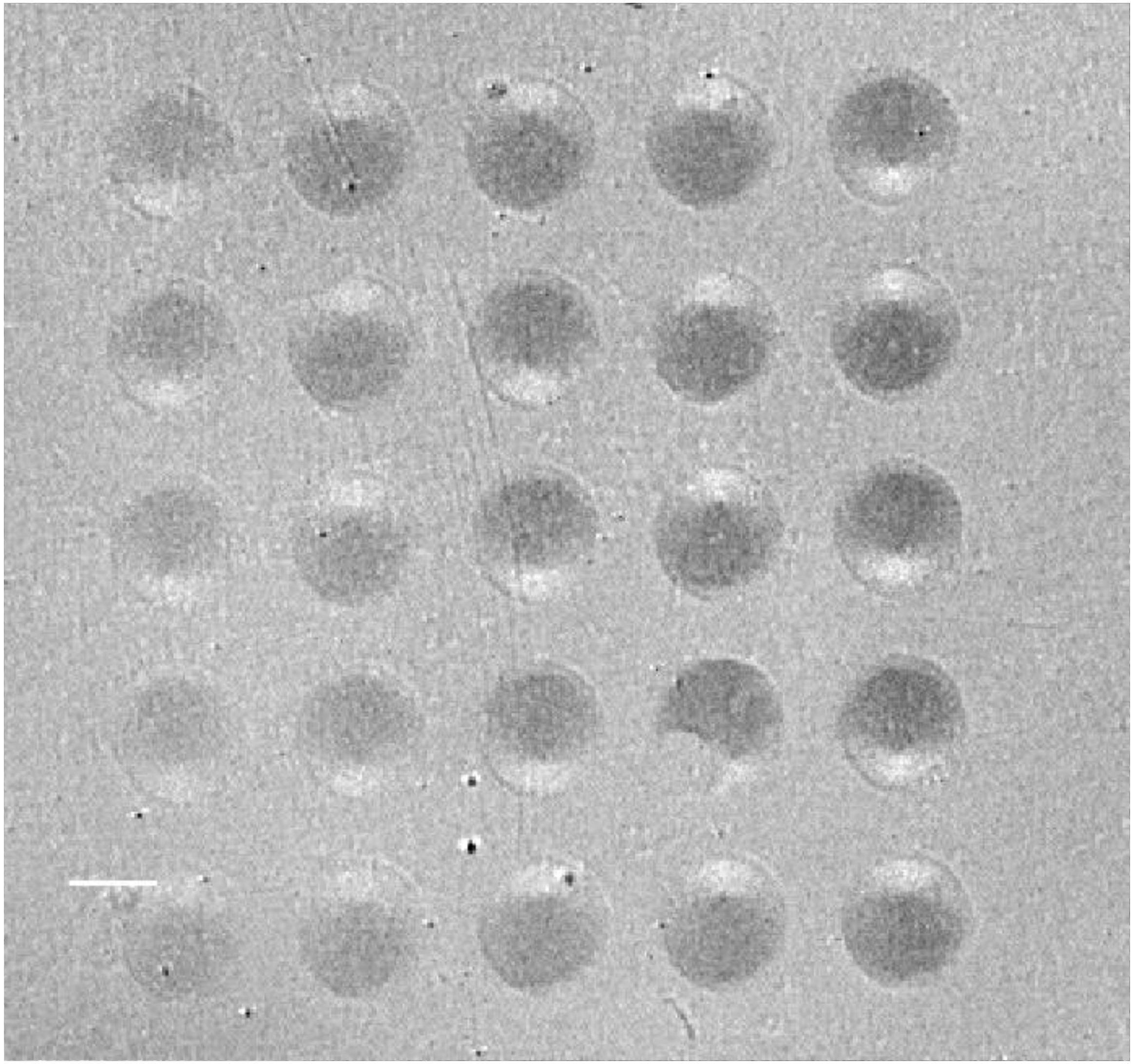
Magnetic domains in Permalloy disks

$H = 0$ Oe $\quad$ $H = 300$ Oe



2001@Berkeley

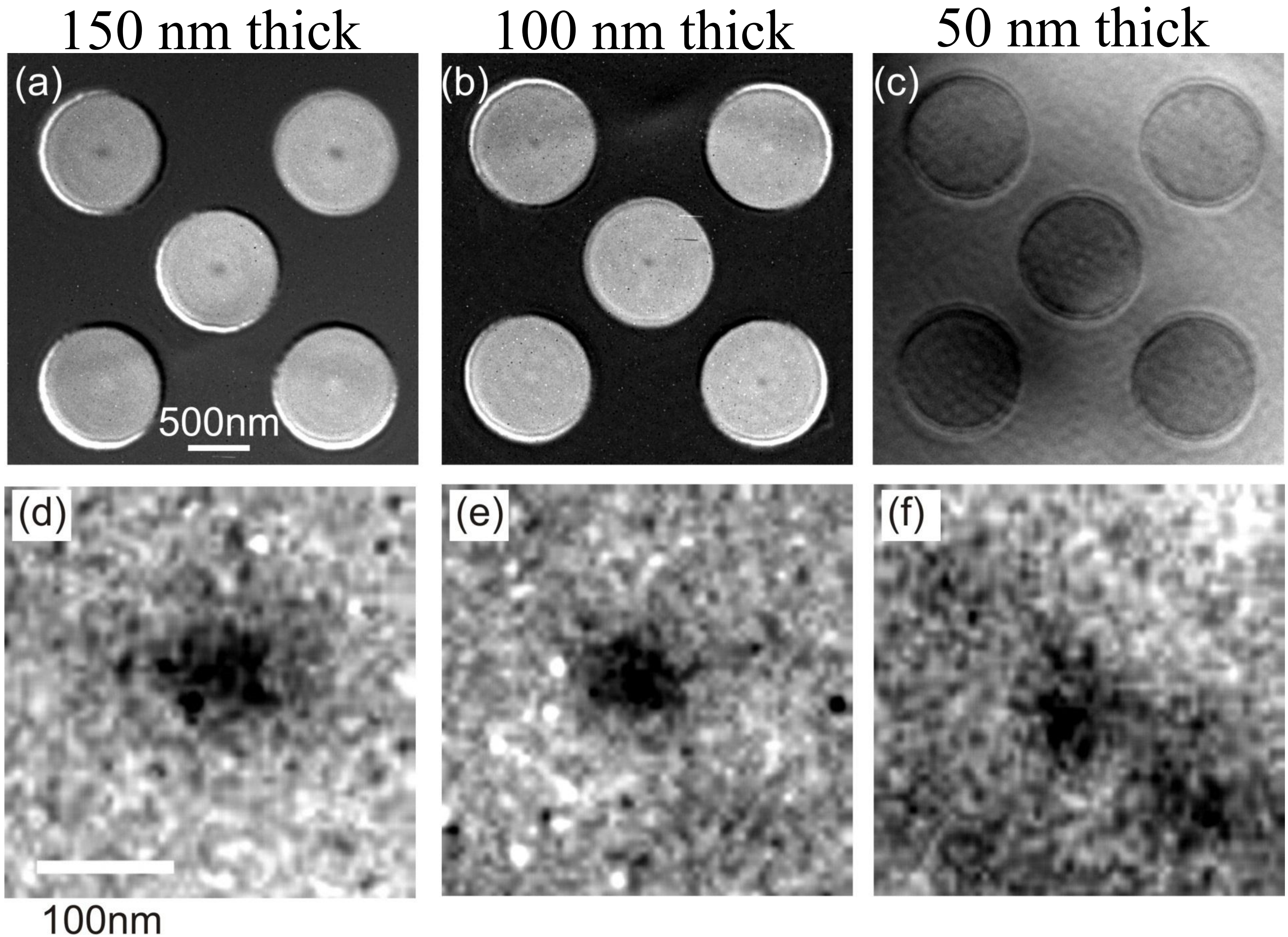
Magnetic domains in a 50nm PY dots



+0.5A
+0.3A
0A
-0.3A
-0.5A

Vortex core observation by MTXM

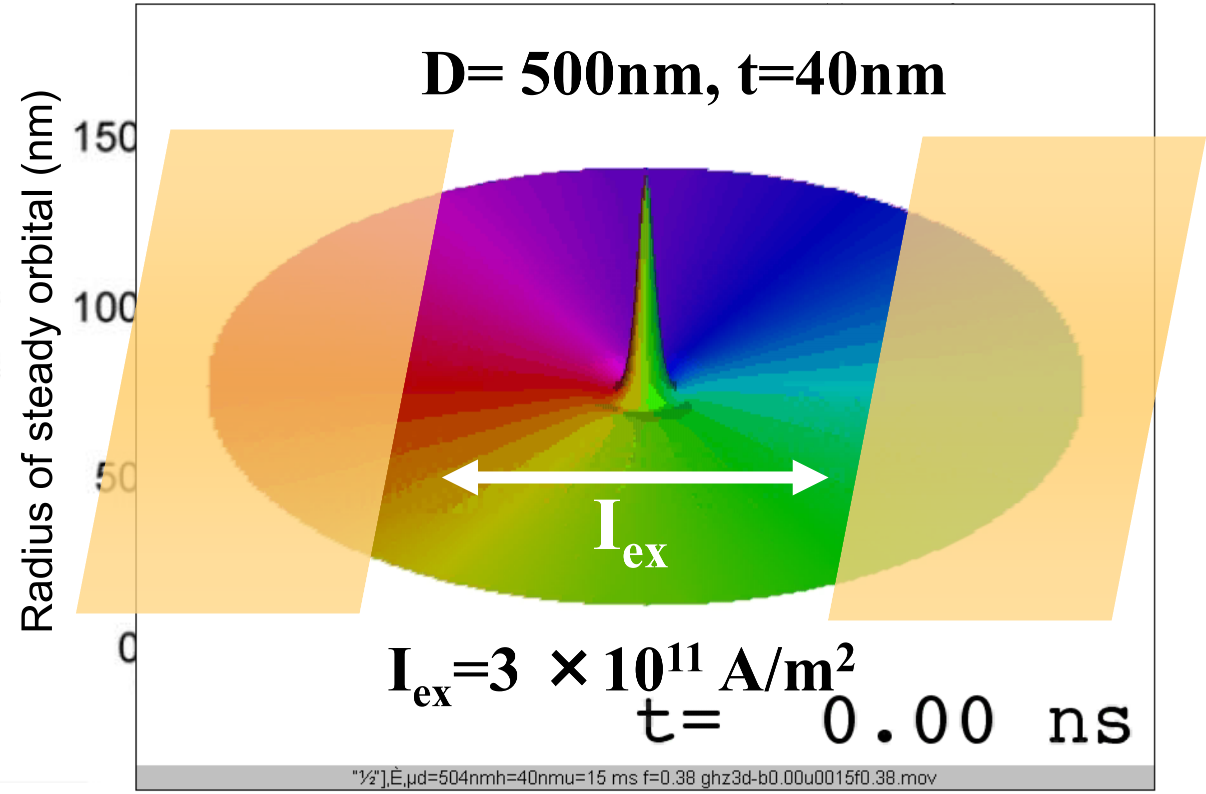
P. Fischer, M.-Y. Im, S. Kasai, K. Yamada, T. Ono, A. Thiaville PRB 83 212402 (2011)



Resonance of vortex core by AC current

-Micromagnetic simulation including spin transfer term-

$$\dot{\mathbf{m}} = -|\gamma|\mathbf{m}\times\mathbf{H} + \alpha\,\mathbf{m}\times\dot{\mathbf{m}} - u\frac{\partial \mathbf{m}}{\partial x}, \quad u = \frac{g\mu_B JP}{2eM_s}$$

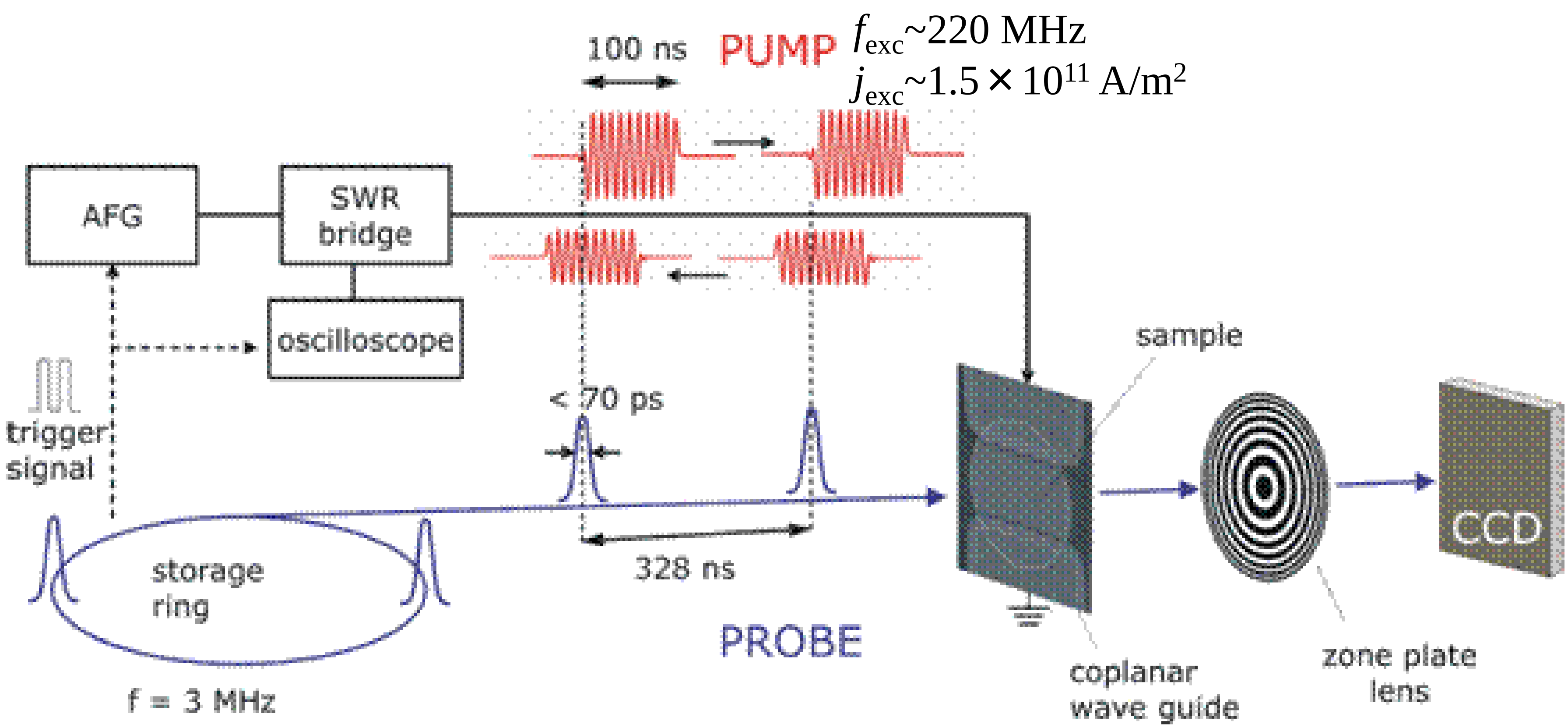


Experimental proof:

Resistance measurements, Kasai *et al.*, *PRL* 97, 107204 (2006).

X-ray microscope, Kasai *et al.*, *PRL*101, 237203 (2008).

Real-space imaging of current-induced resonant motion of vortex core by Magnetic Transmission X-ray Microscope



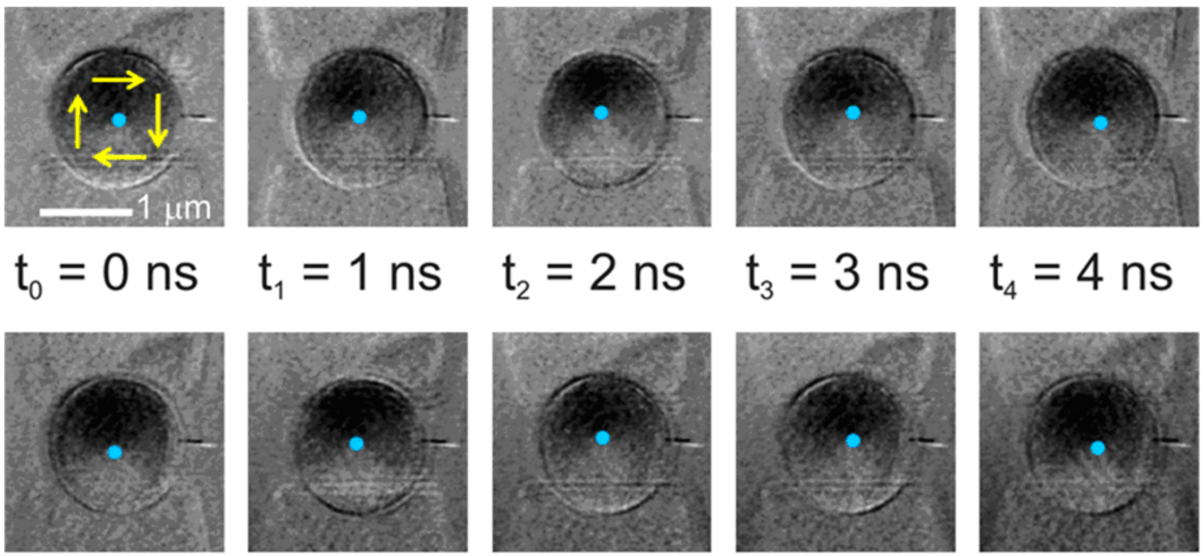
$Ni_{81}Fe_{19}$ dot d=1.5 μm, t=40 nm
on 200 nm-thick Si_3N_4 membrane

M-TXM with pump-probe method
(ALS: BL 6.1.2, Ni edge)

20nm space-resolution
70ps time-resolution

Time-resolved imaging of current-induced resonant motion of vortex core by Magnetic Transmission X-ray Microscope

Time-resolved image

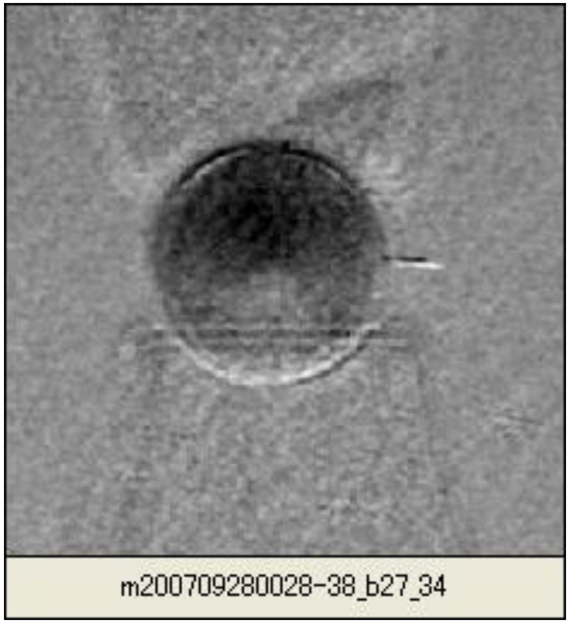


t_0 = 0 ns t_1 = 1 ns t_2 = 2 ns t_3 = 3 ns t_4 = 4 ns

t_5 = 5 ns t_6 = 6 ns t_7 = 7 ns t_8 = 8 ns t_9 = 9 ns

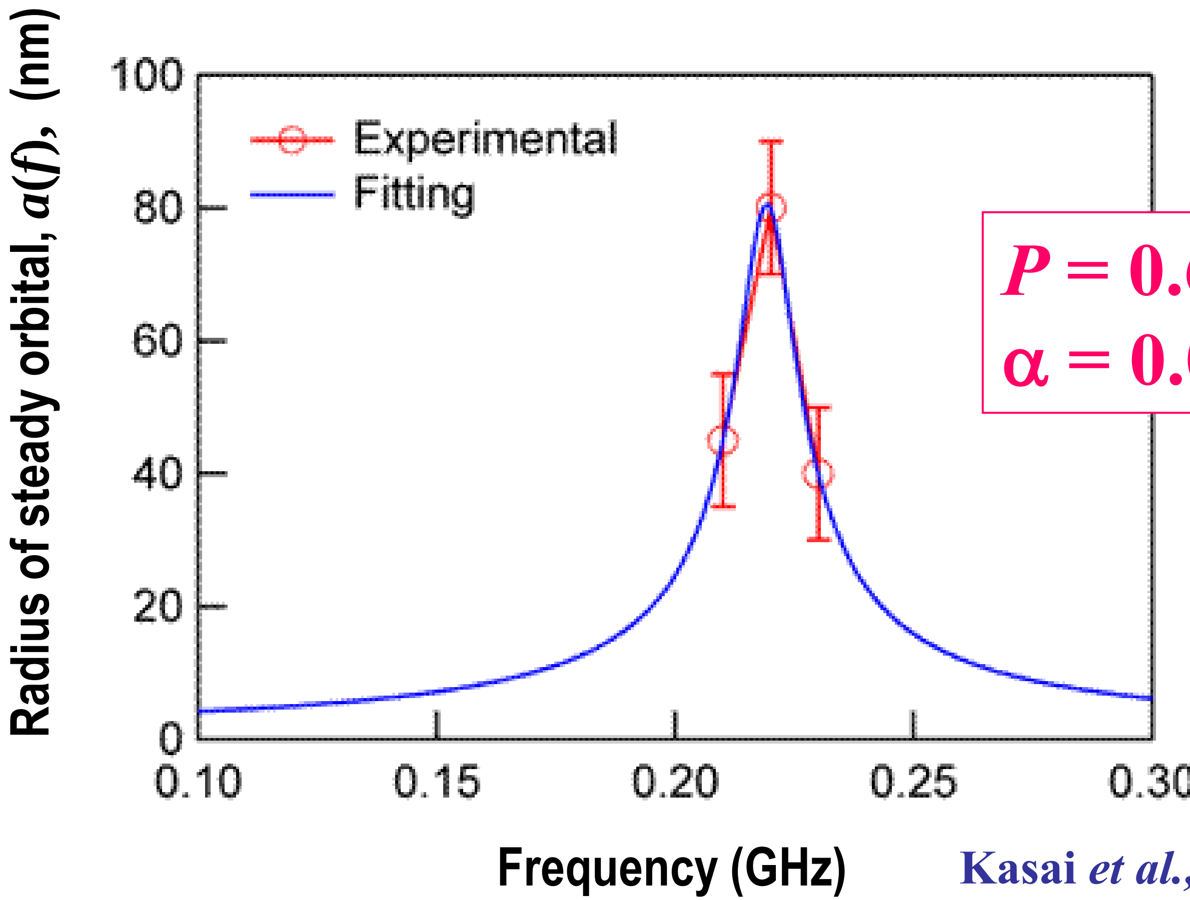
f_{exc}~220 MHz
j_{exc}~1.5×10^{11} A/m^2

Movie



Kasai *et al.*, *PRL* 101, 237203 (2008).

Fitting by analytical model



$P = 0.67 \pm 0.16$

$\alpha = 0.01 \pm 0.003$

Kasai ***et al.*****,** ***PRL*****101**, 237203 (2008).

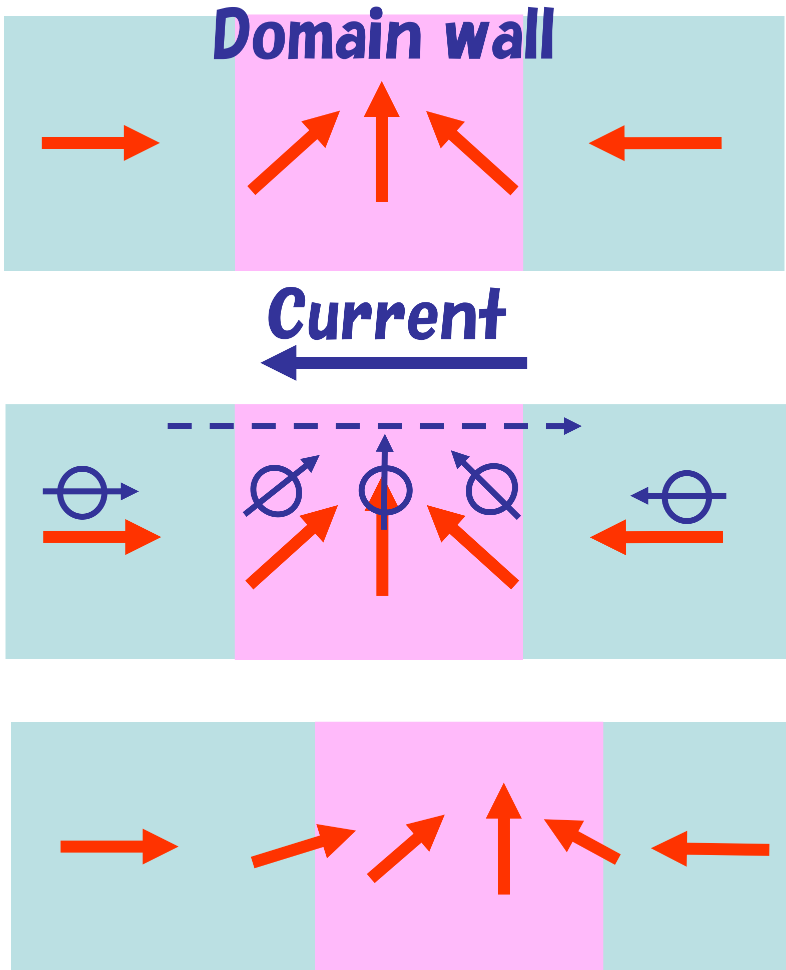
Determination of spin polarization though spin-transfer torque!

P determined from CPP-GMR measurements: *P*=0.7

J. Bass, W. P. Jr. Pratt, J. Magn. Magn. Mater. 200, 274 (1999)

Current-induced domain wall motion
(Action-reaction between electron & local moment)

Berger(1984)



Static domain wall

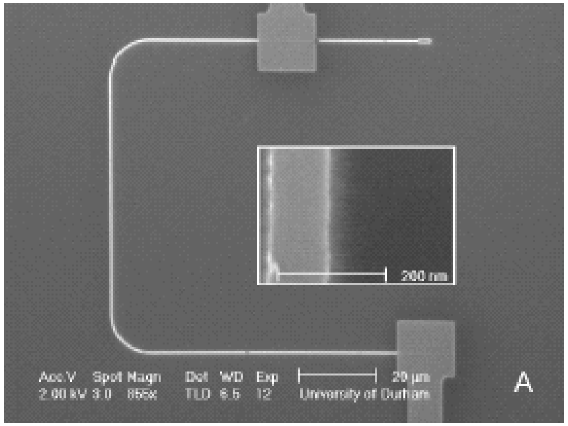
Spin rotates
anti-clockwise.

Action-reaction!
Adiabatic spin torque

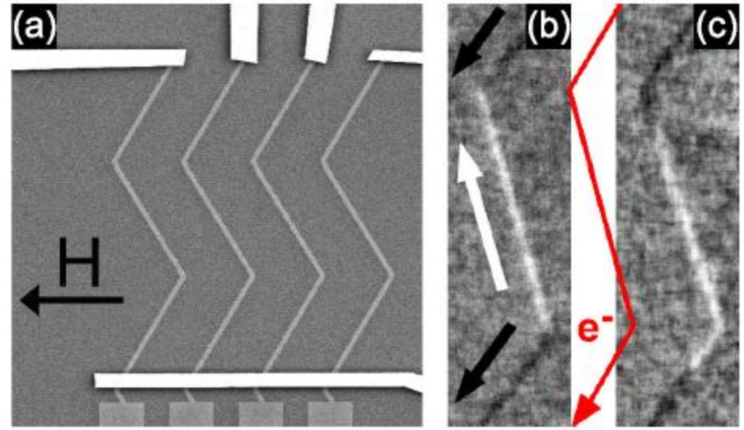
Local magnetic moment
should rotates clockwise.

DW motion by electric current without magnetic field!!

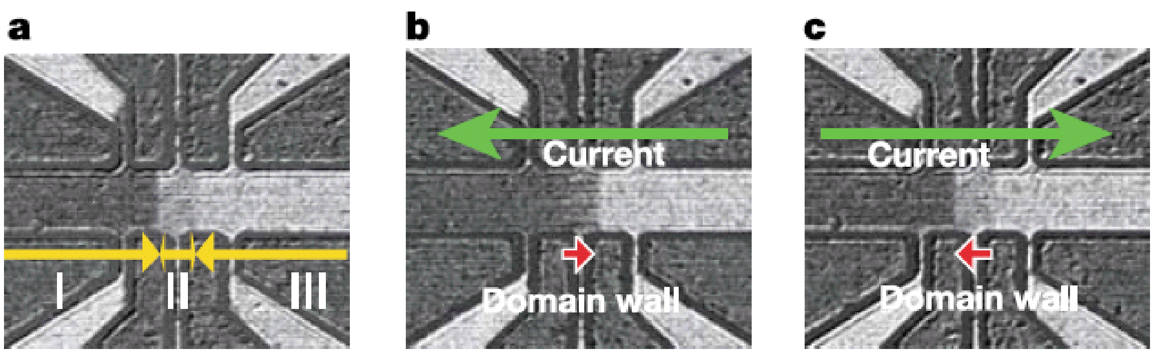
Experimental evidences



N. Vernier *et al.*,
Europhys. Lett. 65 (2004) 526.

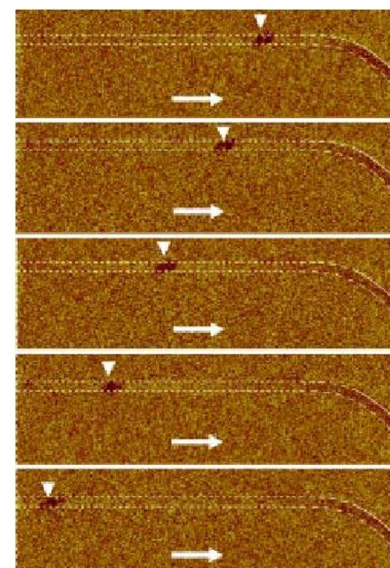


M. Klaui & R. Allenspach *et al.*,
Phys. Rev. Lett. 95 (2005) 526.



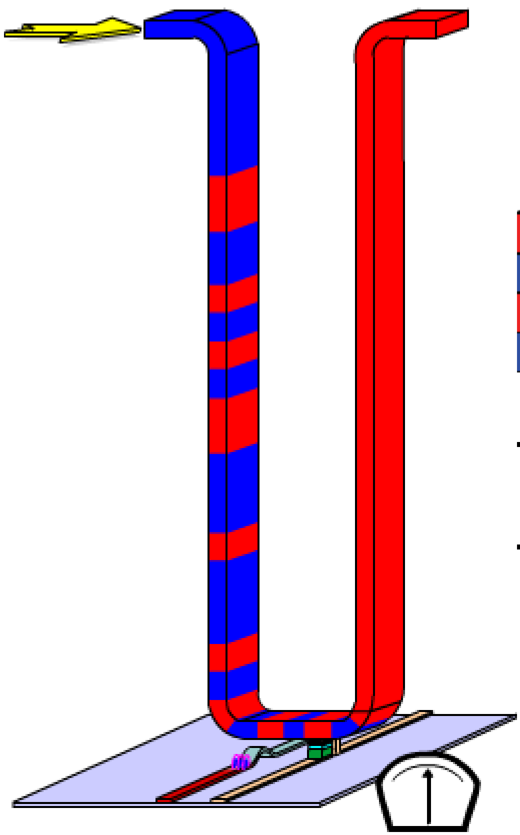
Initial state | After $I = -300$ µA (100 ms) | After $I = +300$ µA (100 ms)

M. Yamanouchi *et al.*,
Nature, 428 (2004) 539.

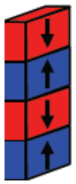


A. Yamaguchi et al., Phys. Rev. Lett., 92 (2004) 077205.

IBMによるMagnetic Racetrack Memoryの提案



磁壁電流駆動を用いた3次元メモリー



情報は磁壁に記録

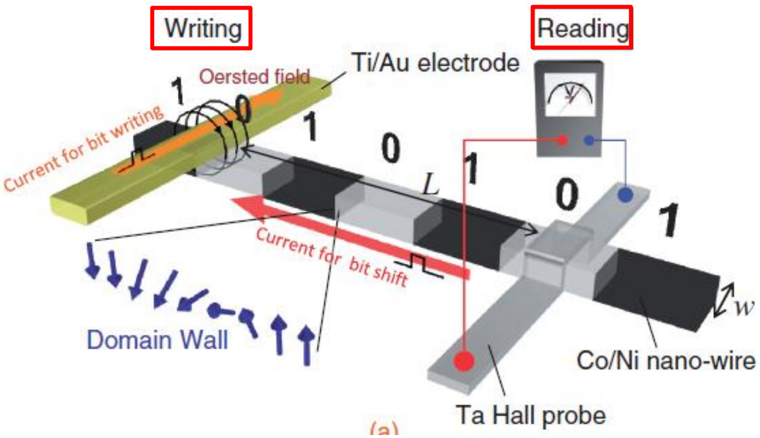
-ＨＤＤ並の情報量

-固体メモリー (DRAM, FLASH, SRAM...)並の安定性・高速性

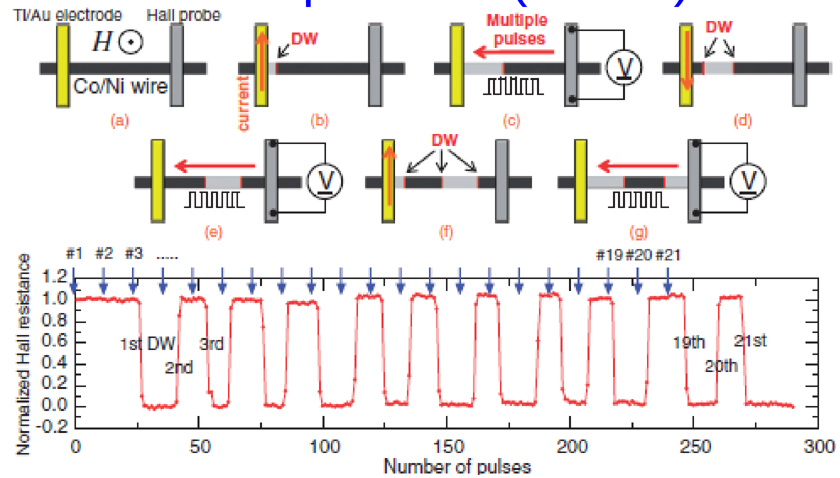
Courtesy of Stuart Parkin (IBM)

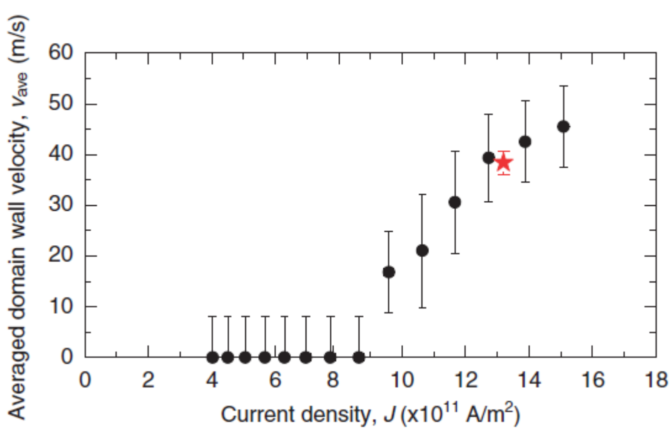
Race-track memory Demo.
Writing, Shifting, Reading

Applied Physics Express 3 (2010) 073004.

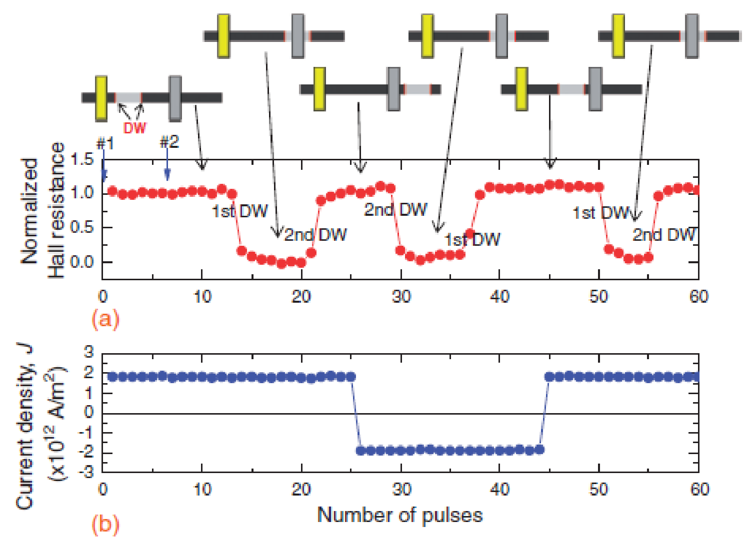


Shift operation (3DWs)



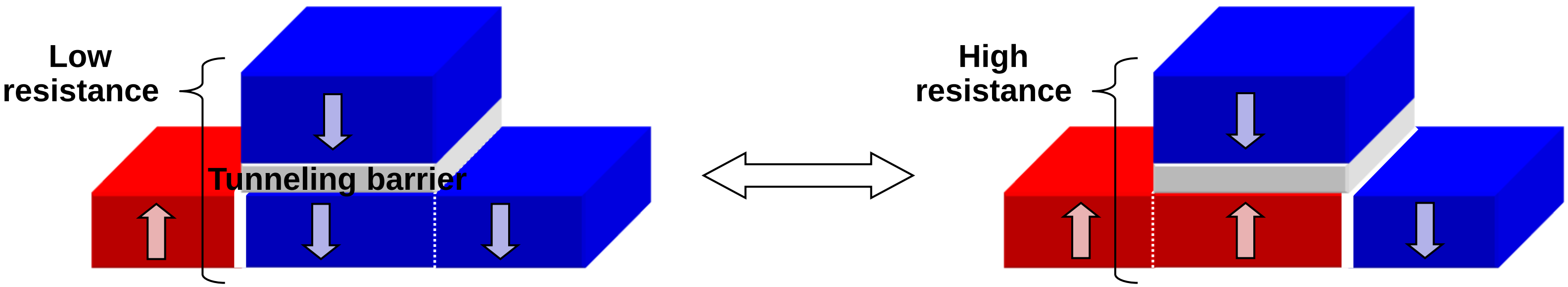


Back & forth operation (2DWs)



Mult-DWs motion with the same velocity as a single DW.

DW-MRAM proposed by NEC



Reading: TMR effect

Writing: Current-induced DW motion

⇩

Independent circuits for reading and writing

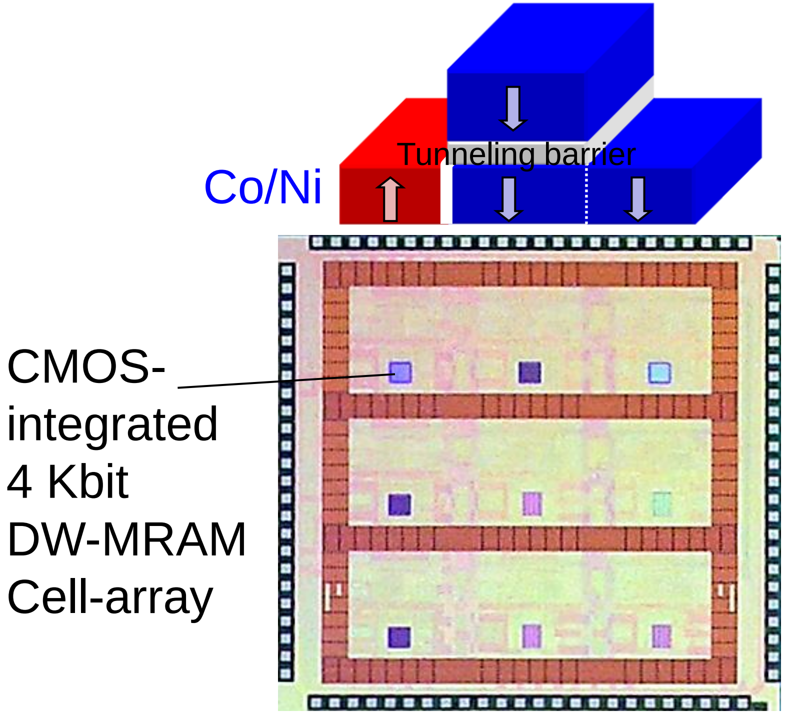
⇩

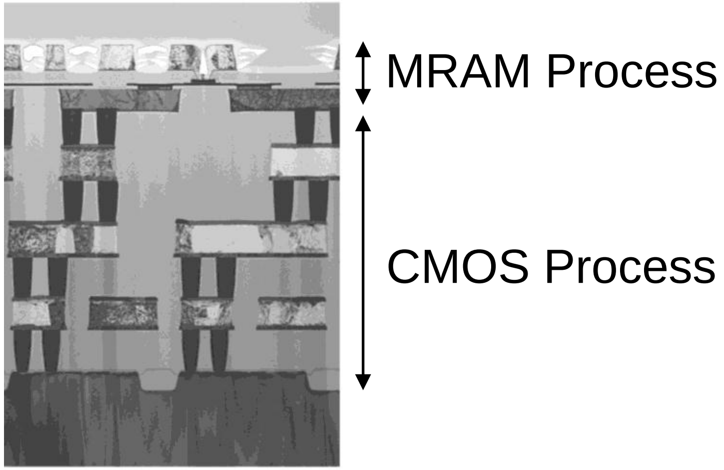
Fast operation

Replace SRAM

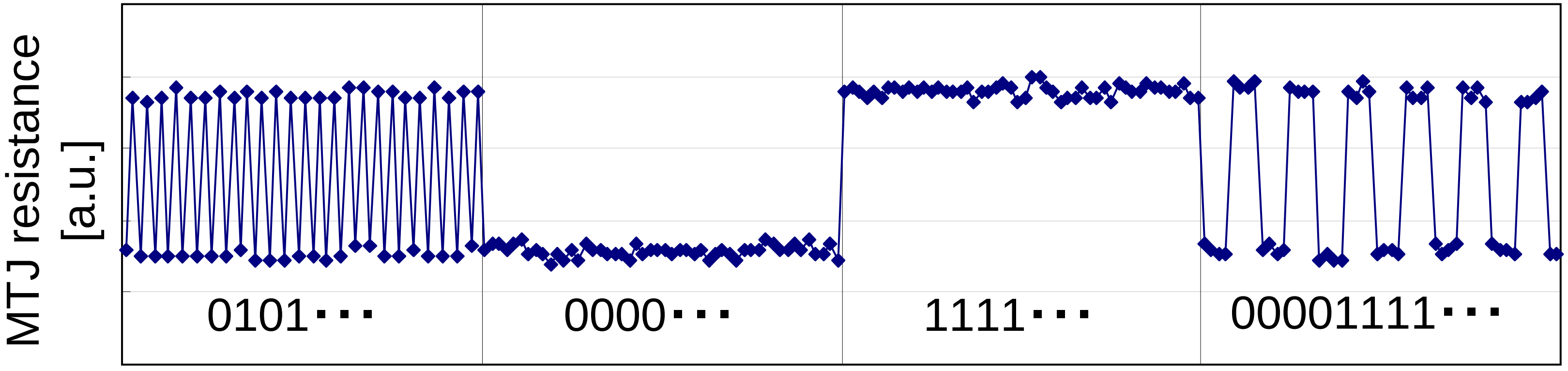
NEDO Spintronics nonvolatile devices project (2007-2011)

CIDW-MRAM Array Demo (NEC)





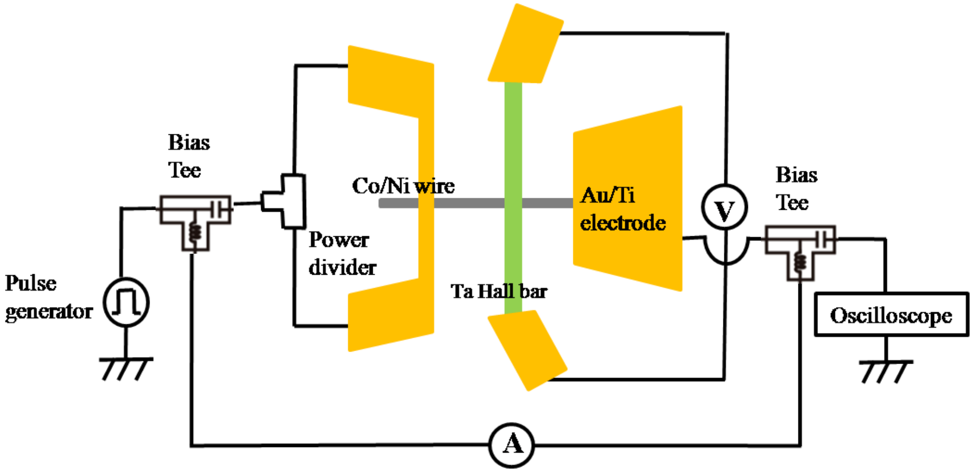
Cross Section
of Test Chip

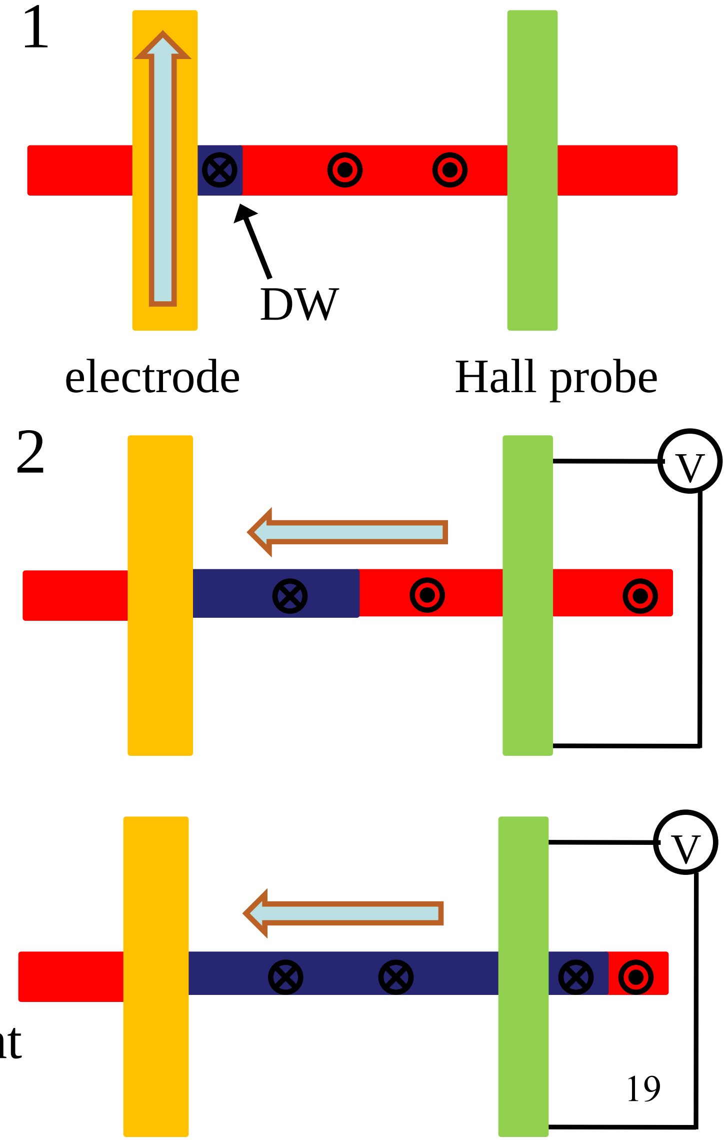


Write-Read Cycle >10^9

Symposium on VLSI Technology, 2009.6.17

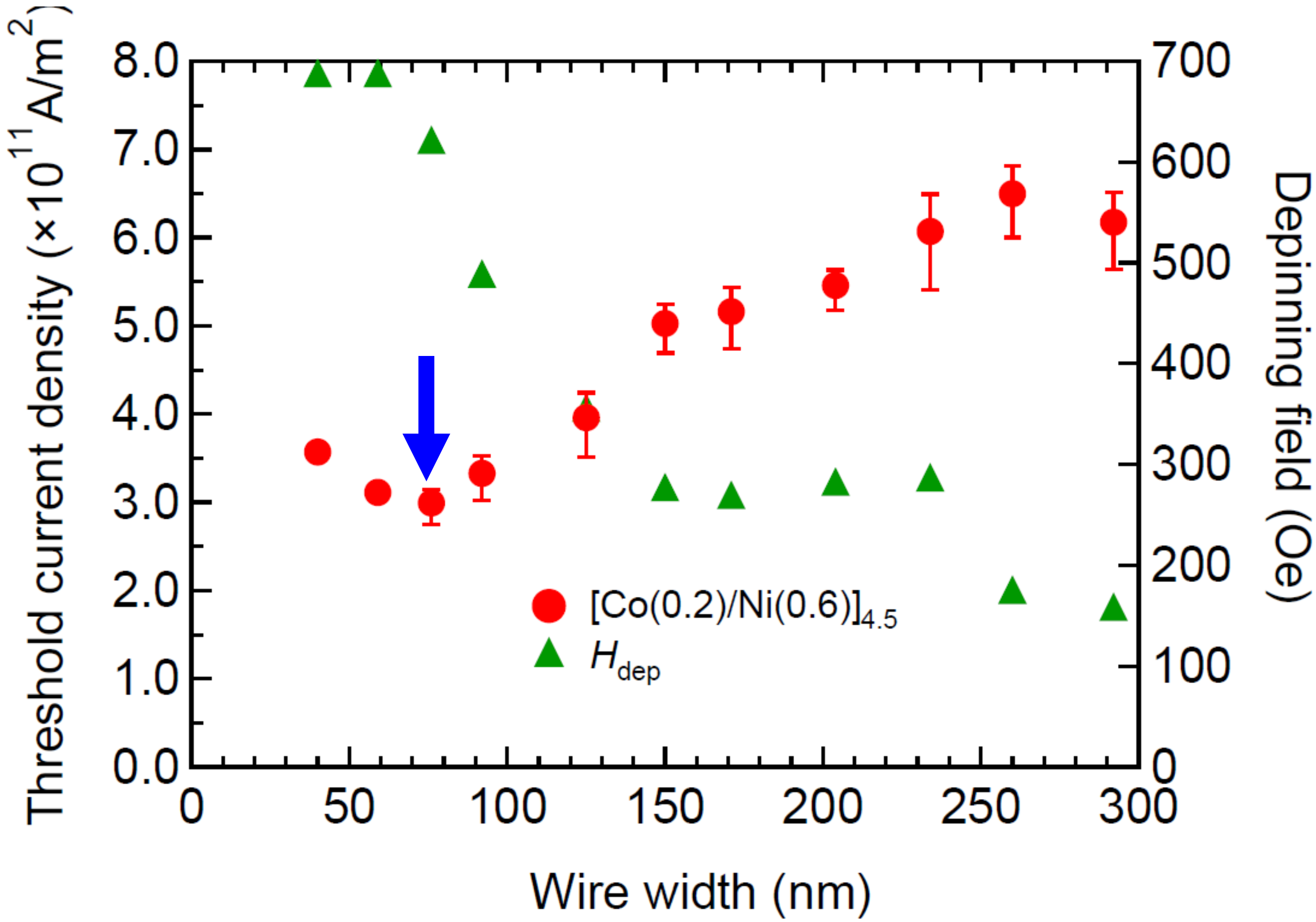
Current-induced DW motion
Co/Ni nanowire with perpendicular magnetization





1. DW injection by local magnetic field.
2. Current pulse application (15ns).
3. Hall measurement.
4. Continue process 2&3 until the total pulse duration reaches 1.5 μs.
5. Continue process 1-4 20 times for each current density.

J_{th} & H_{dep} v.s. wire width



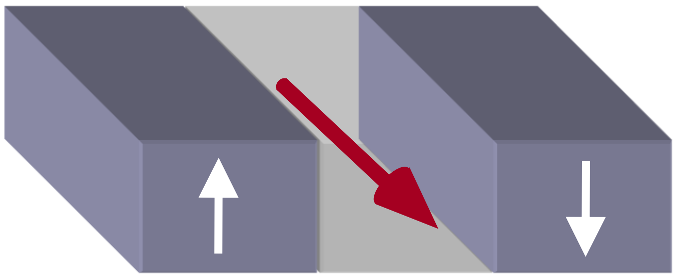
Why J_{th} minimum for specific width?

Koyama et al., Nature Materials 10 (2011)194.

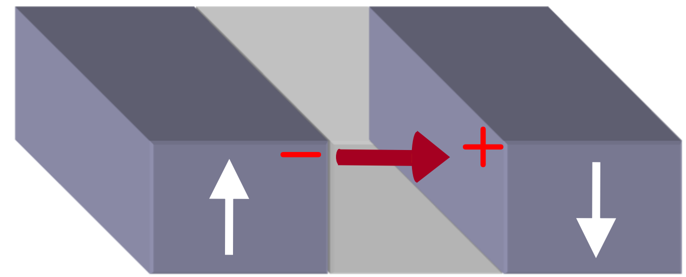
Why minimum Jc for specific dimension?

Bloch DW

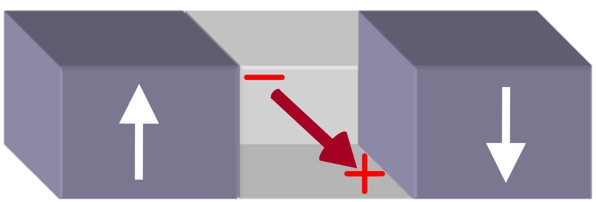
Neel DW



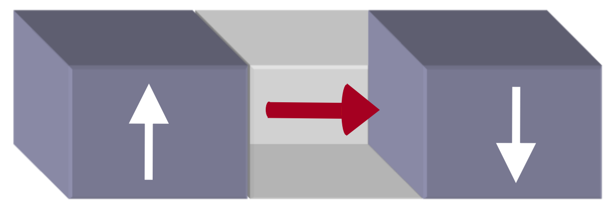
Energy
<



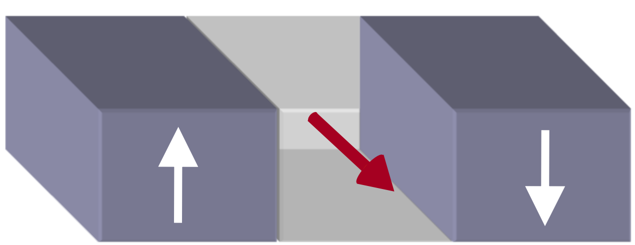
For current-driven DW motion,
Spin torque has to overcome the barrier of Neel wall!



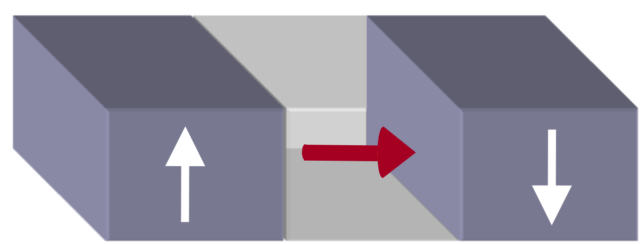
Energy
>



Spin torque has to overcome the barrier of Bloch wall!

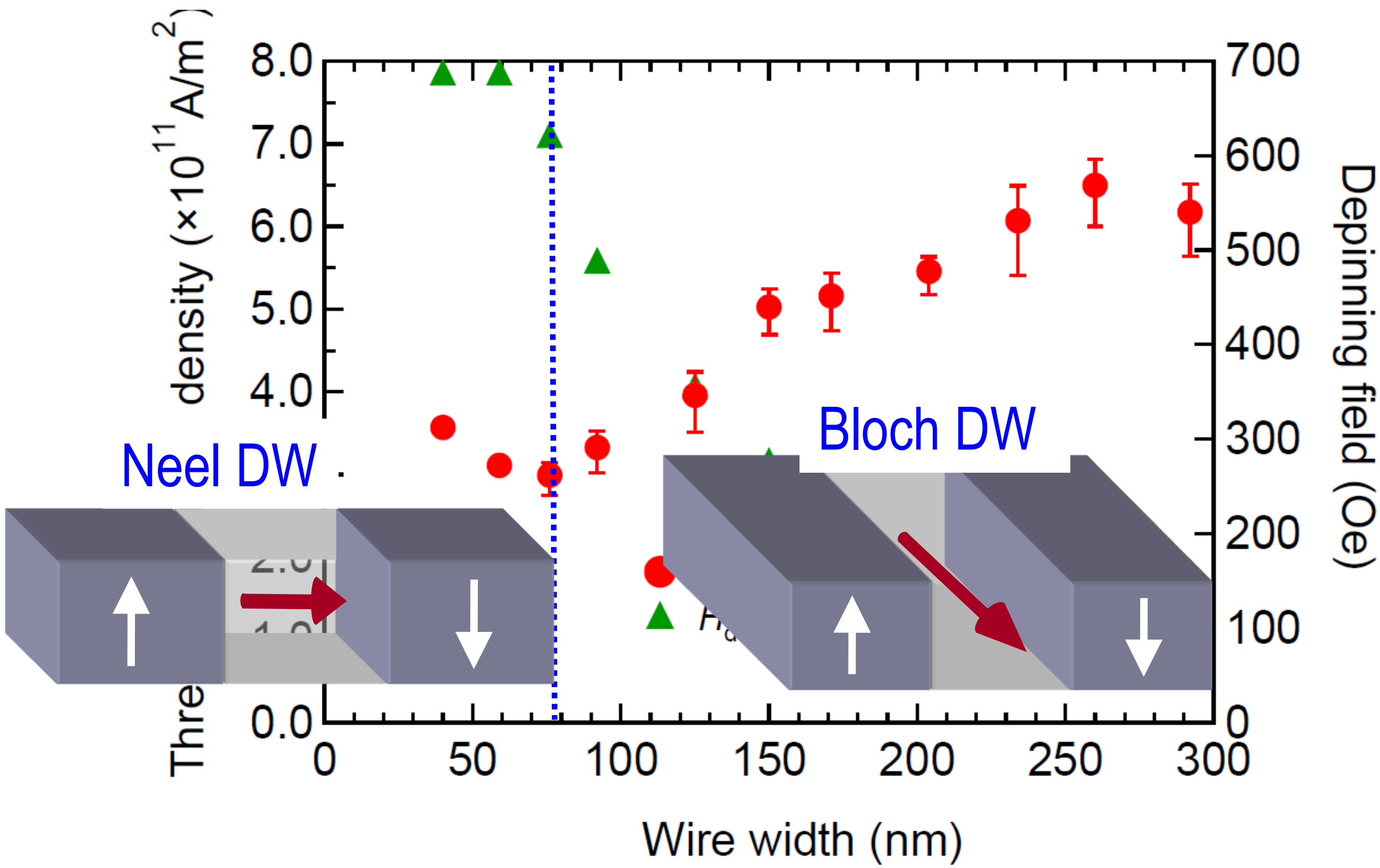


Energy
=



Resulting in J_{th} minimum

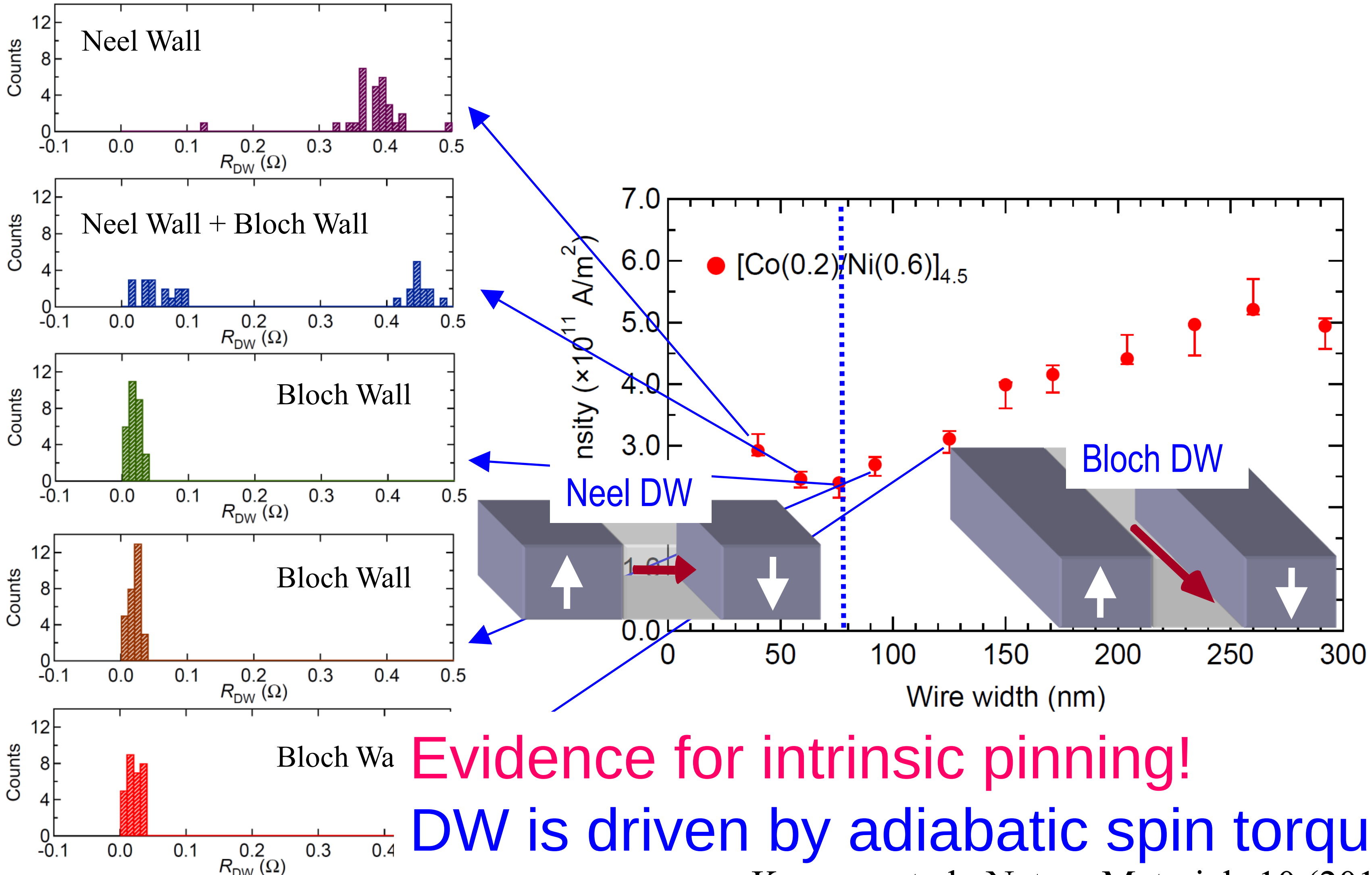
DW structure v.s. wire width



Check DW structure !

-> DW resistance measurements

DW resistances v.s. wire width



Evidence for intrinsic pinning!

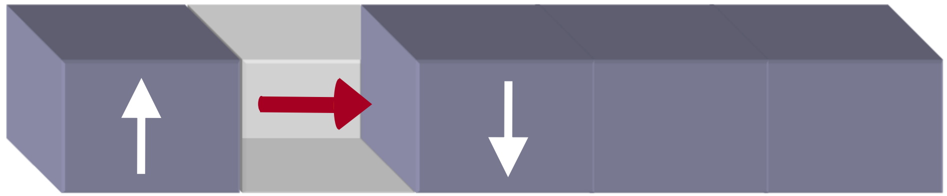
DW is driven by adiabatic spin torque.

Koyama et al., Nature Materials 10 (2011)194.

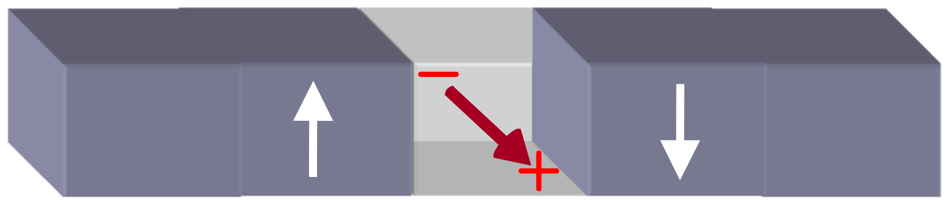
ネール磁壁とブロッホ磁壁　顕微鏡で見たいな。

Intrinsic pinning下の磁壁移動

(1)

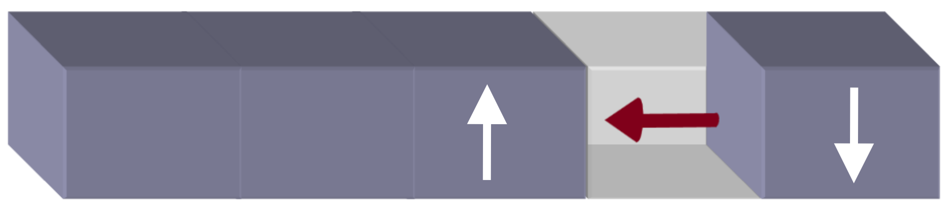


(2)



磁壁エネルギー最大状態
この直前に電流を切ると(1)へ
直後に電流を切ると(2)へ移動

(3)



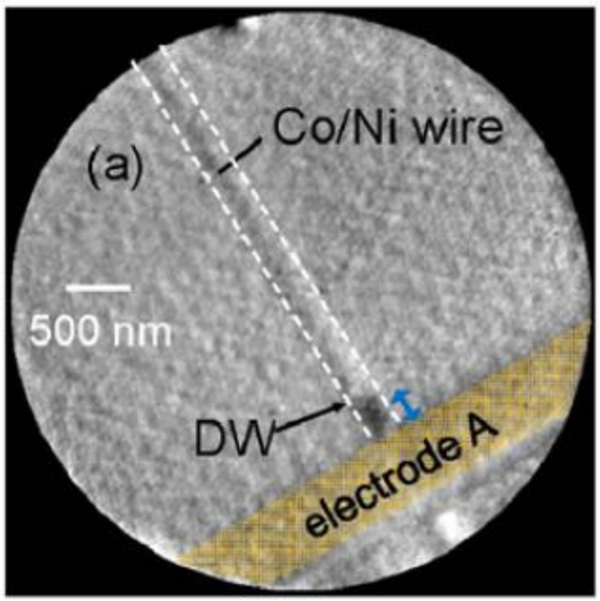
この磁壁のステップ移動を観察したい

Observation of CIDWM by PEEM @SPring8

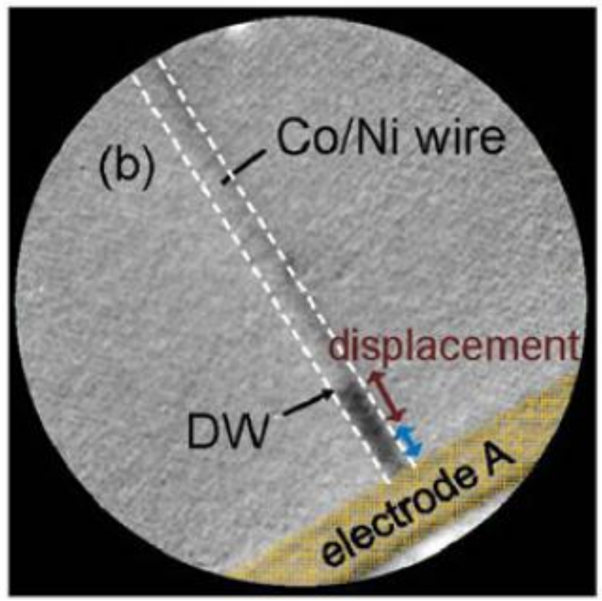
小山くん、千葉さん、大島さん、谷川さん、小嗣さん、大河内さん

N. Ohshima *et al.*, *J. Phys.: Condens. Matter* **23** (2011) 382202.

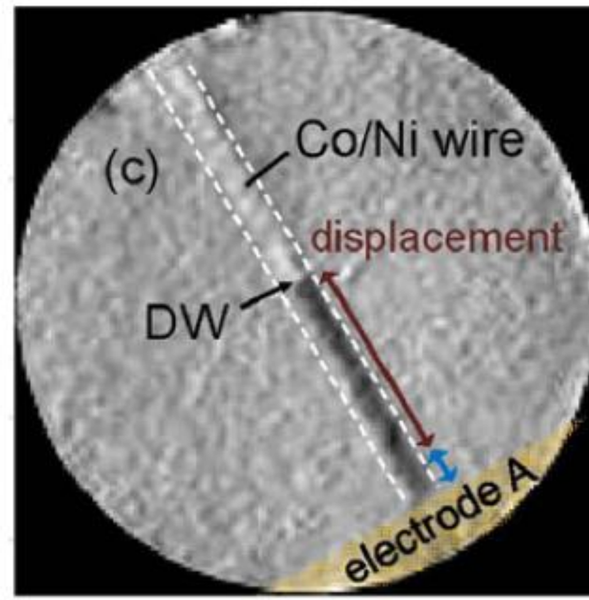
DW nucreation



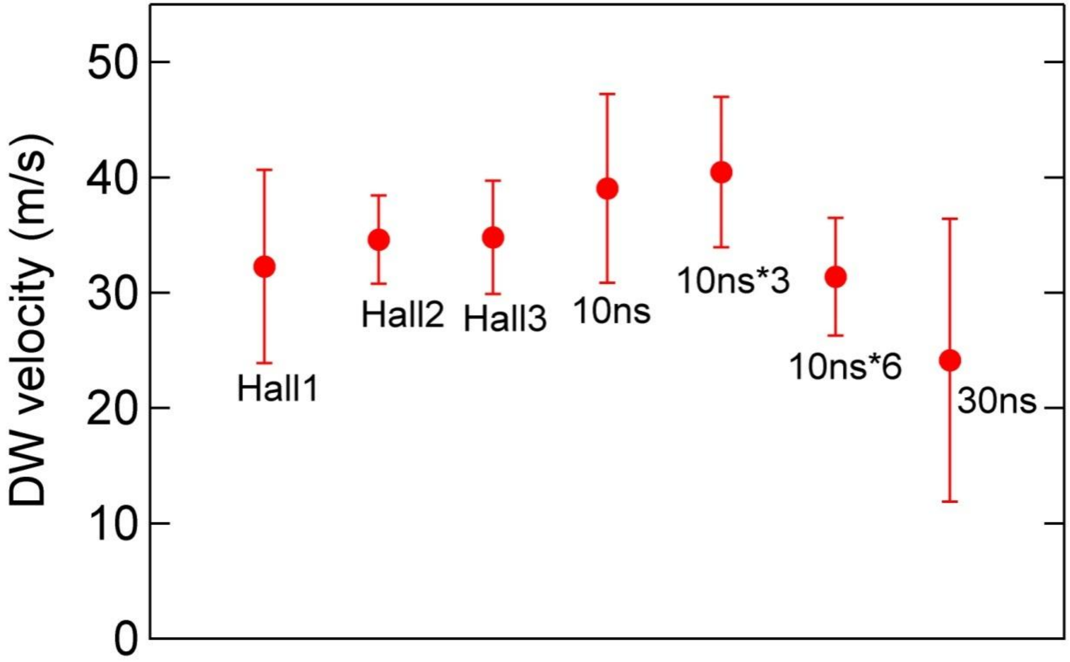
2.5×10^{12} A/m^2 (10 ns)



2.5×10^{12} A/m^2 (10 ns×3)



磁壁移動速度の見積もり
電気的測定と直接観察の比較



✓10 nsのパルスを印加した場合、磁壁移動速度は約30 ~ 40 m/sである。
✓10 nsパルスによる電気測定結果(Hall 1~3: 同一基板上の違う試料での結果)とPEEM測定結果は、ばらつきを含めておおよそ一致している。

放射光へ期待しています！

スピントロニクス素子は
　20nmルール・GHz動作

（1） nm分解能
（2） ps分解能
（3） 元素選択性
（4） one shot観察