IEEE DL lecture, Western Digital
June 7, 2016

Spin dynamics
in inhomogeneously magnetized systems

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- **IEEE Magnetics Society Home Page:** ***www.ieeemagnetics.org***
  - **3000 full members**
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- **The Society**
  - **Conference organization (INTERMAG, MMM, TMRC, etc.)**
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  - ***IEEE Magnetics Letters***
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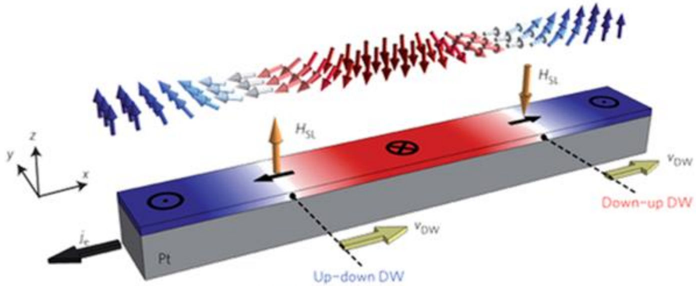
  - **IEEE student membership** **IEEE full membership**

Inhomogeneously magnetized systems

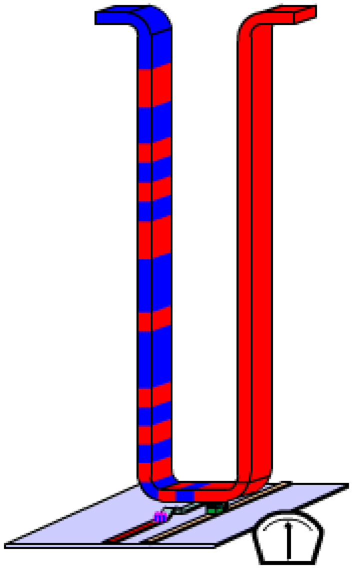
Domain wall



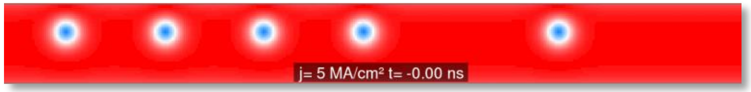
Nat. Mat. 12, 611 (2013)

Skyrmion

Race-track memory



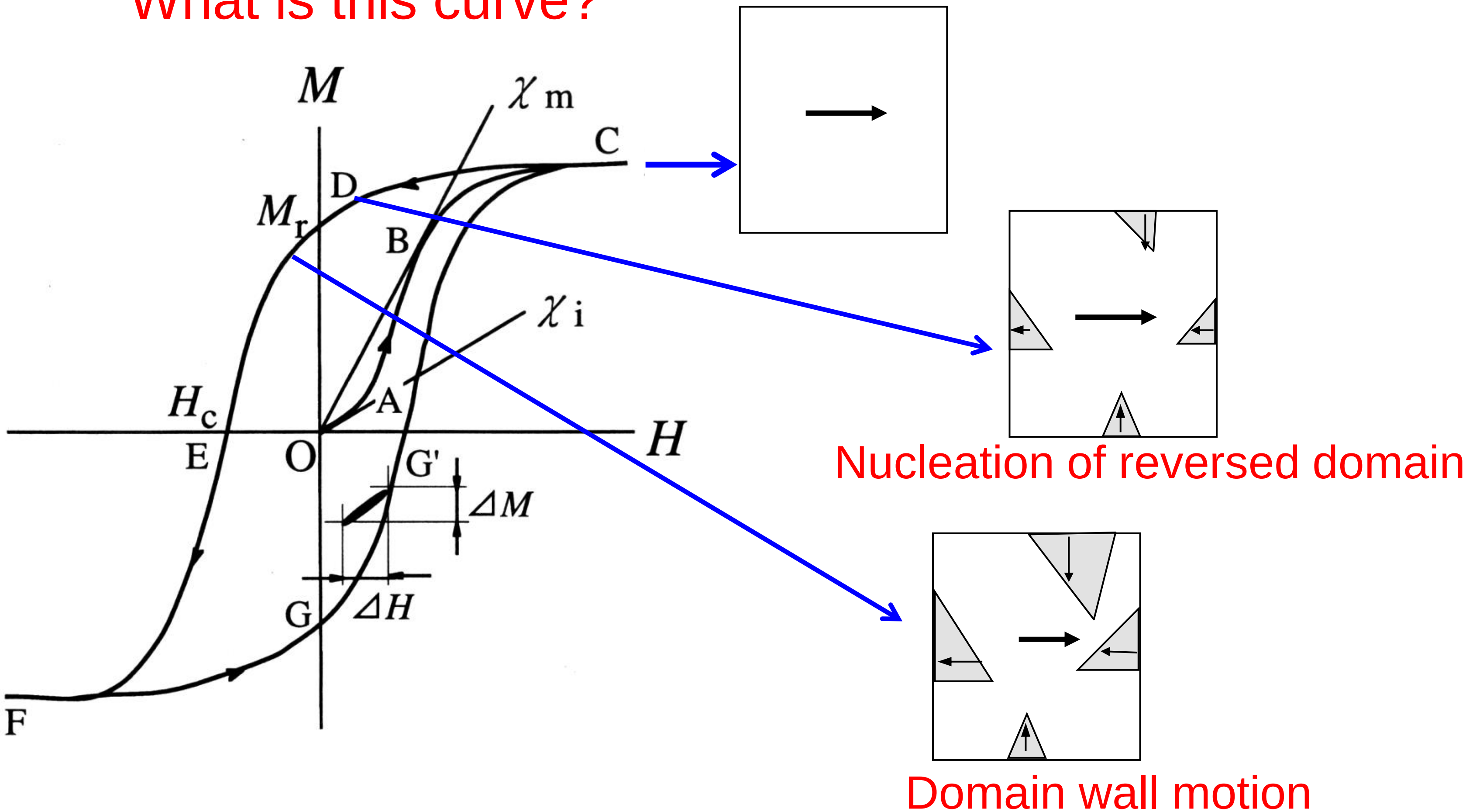
Skyrmion race-track



Low power consumption, High density memory

My motivation

What is this curve?



Magnetization process is so complicated to understand for me…

I want to see

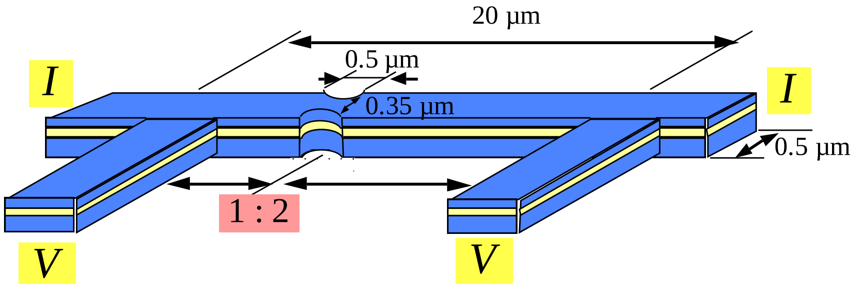
Nucleation of a single domain & motion of a single DW !

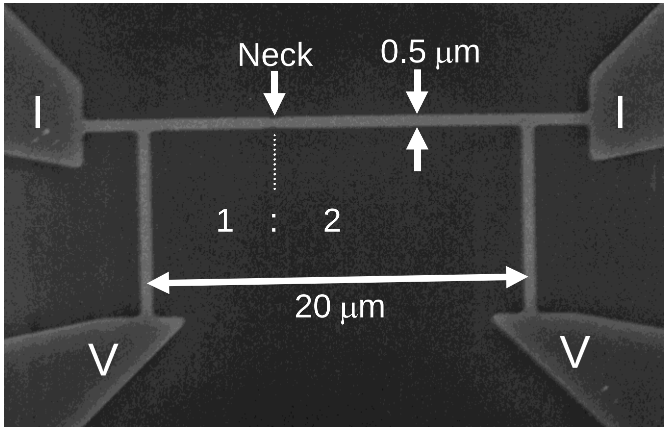
Observation of nucleation & motion of single domain wall

--- Sample --- GMR film

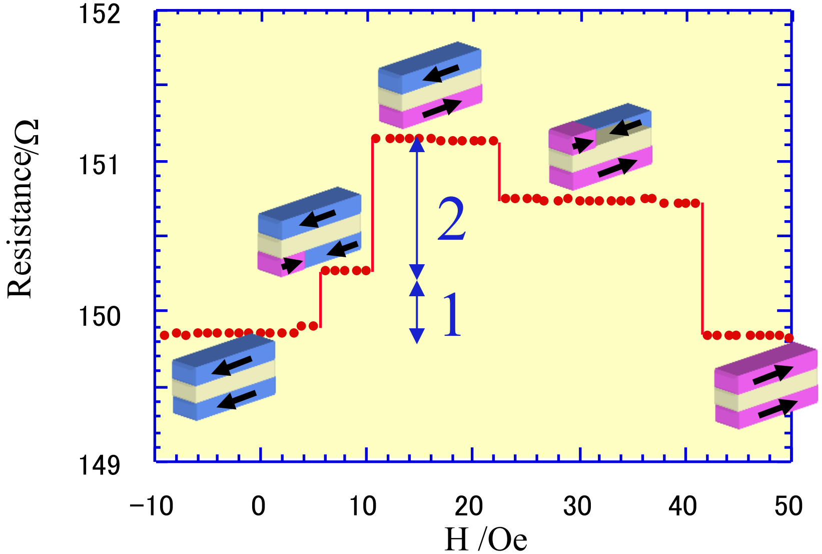
NiFe(20nm)/Cu(10nm)/NiFe(5nm)

0.5 μm in width, 20 μm in length





SEM image



Domain wall is pinned by artificial neck.
Single DW nucleation & motion!

Appl. Phys. Lett. **72** (1998) 1116.

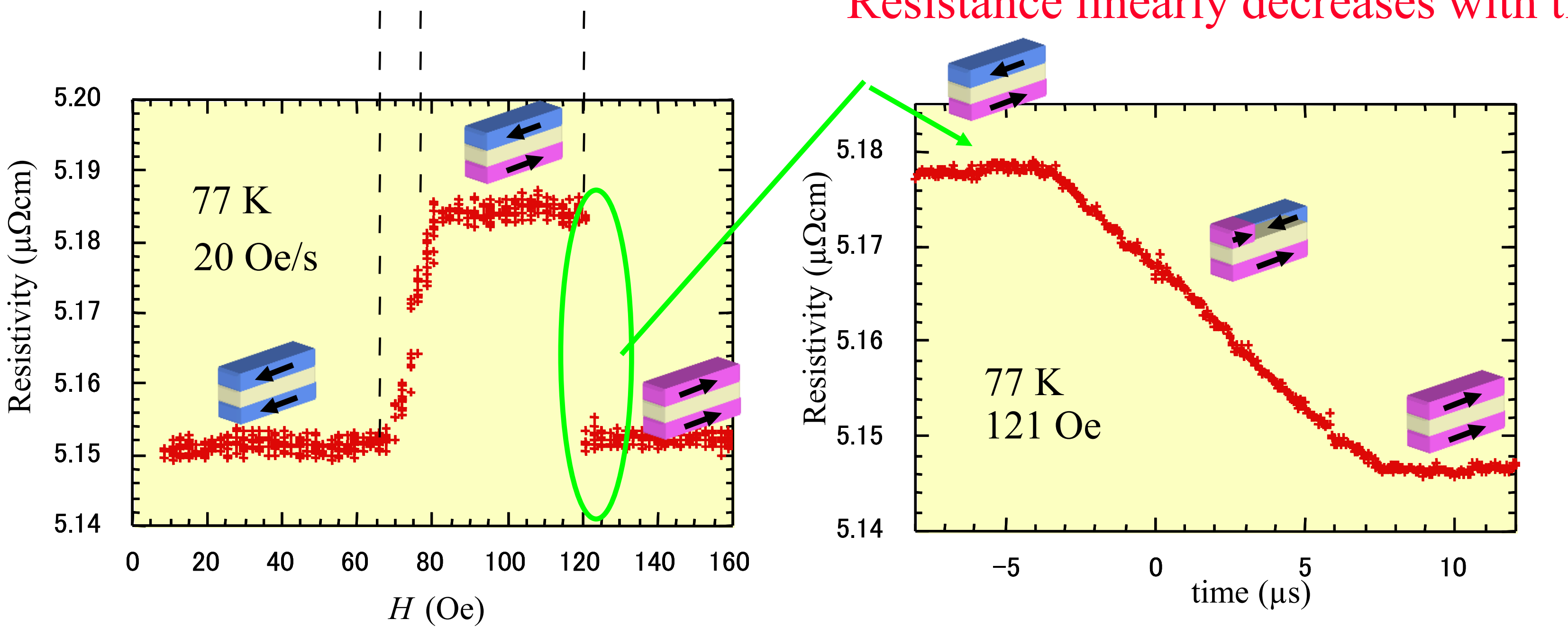
Real-time observation of single DW motion

--- Sample ---

$Ni_{81}Fe_{19}$(40nm)/Cu(20nm)/ $Ni_{81}Fe_{19}$(5nm)

0.5 μm in width, 2 mm in length

Resistance linearly decreases with time.



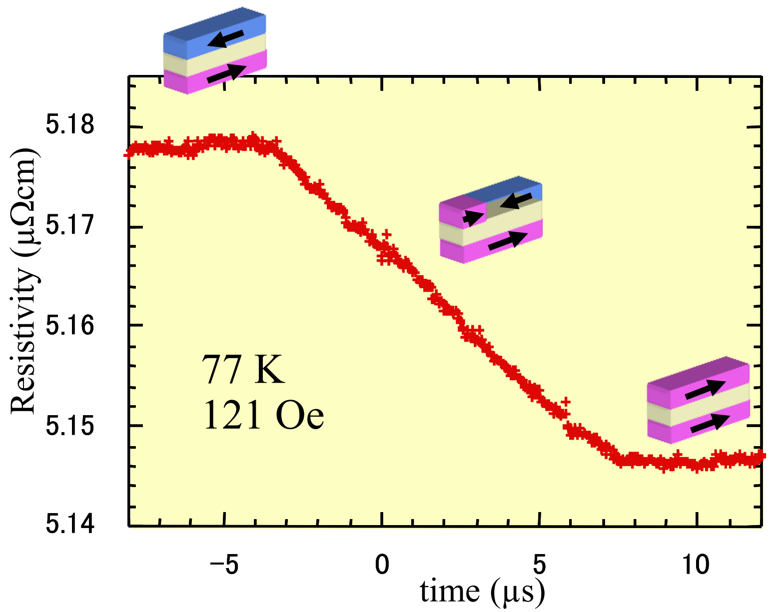
v = 2 mm /11 μs = 182 m/s = 655 km/h

H = 121 Oe

Science **284** (1999) 468.

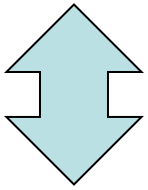
DW runs faster than Shinkansen!

Interaction between DW & current ?



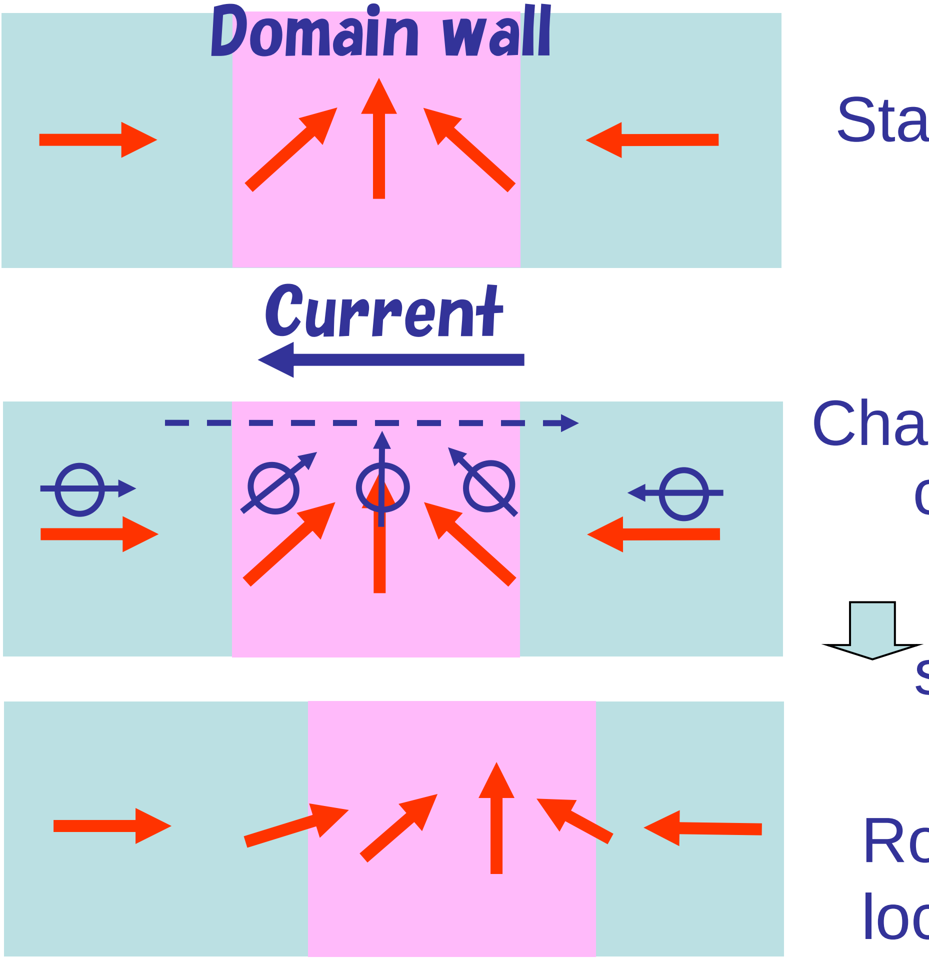
Science **284** (1999) 468.

DW motion can be detected by resistance measurement.



Can we manipulate DW motion by electric current?

Prediction of current-induced domain wall motion



Static domain wall

Change in spin direction of conduction electron

Conservation of spin angular momentum

Rotation of local magnetic moment

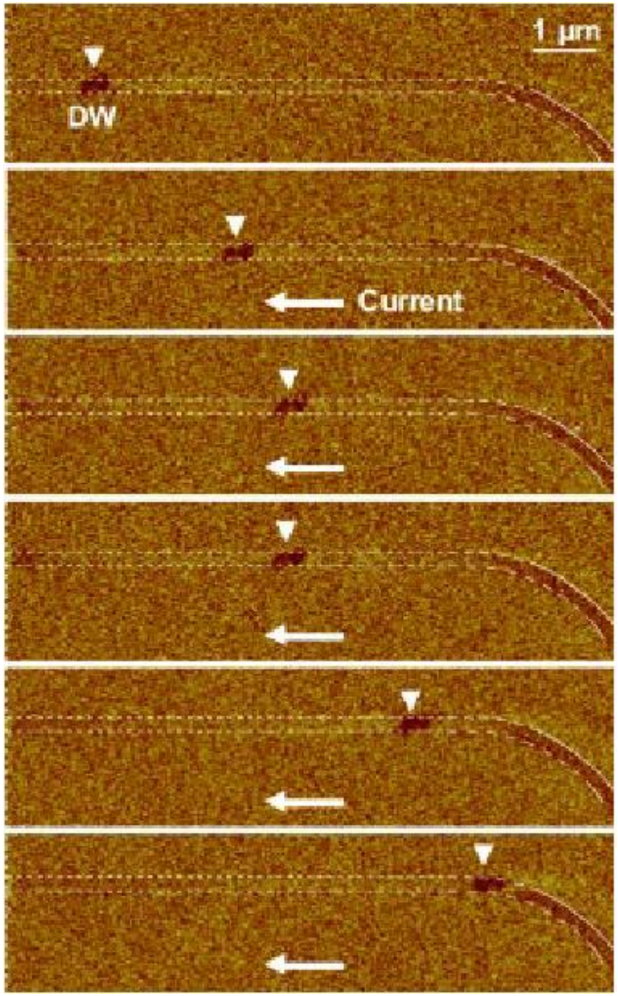
DW motion along electron flow

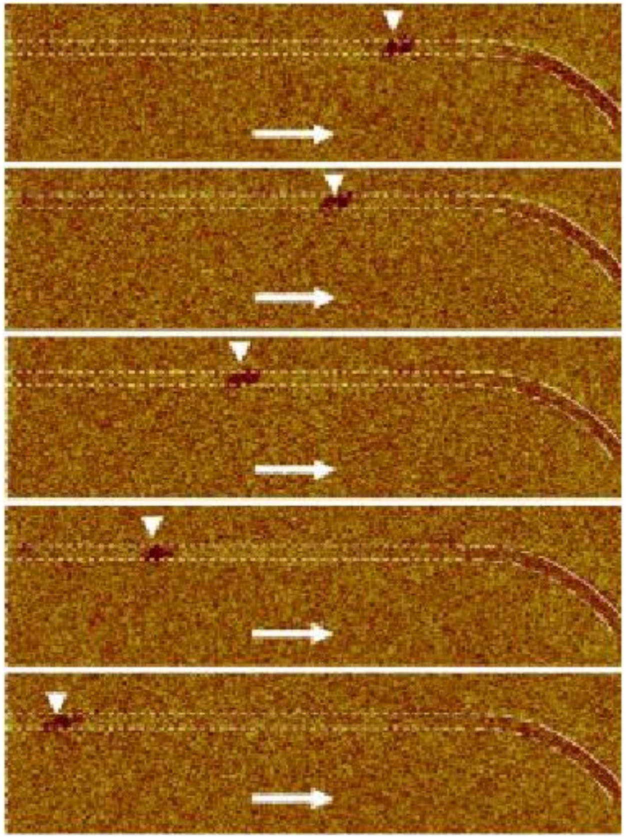
$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t} - u_j \frac{\partial \vec{m}}{\partial x} \qquad u_j = \frac{g\mu_B}{2eM_s} jP$$

Adiabatic spin transfer torque

Successive MFM images of DW motion by current injection

(7×10^{11} A/m^2, 0.5 μs)





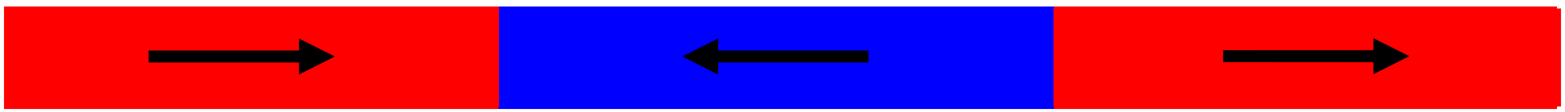
NiFe, w = 240nm, t = 10nm

Phys. Rev. Lett., 92 (2004) 077205.

DW position can be controlled by current pulsed.

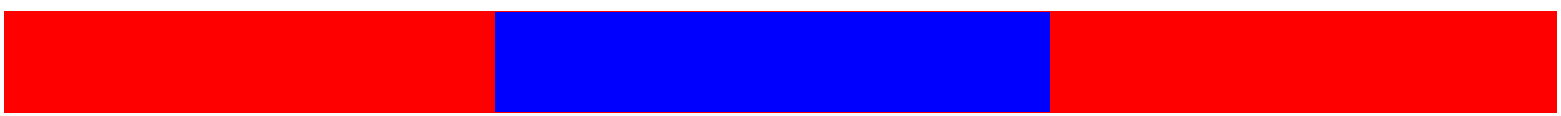
Field-driven v.s. Current-driven DW motion

Magnetic field-driven DW motion



DWs annihilate each other….

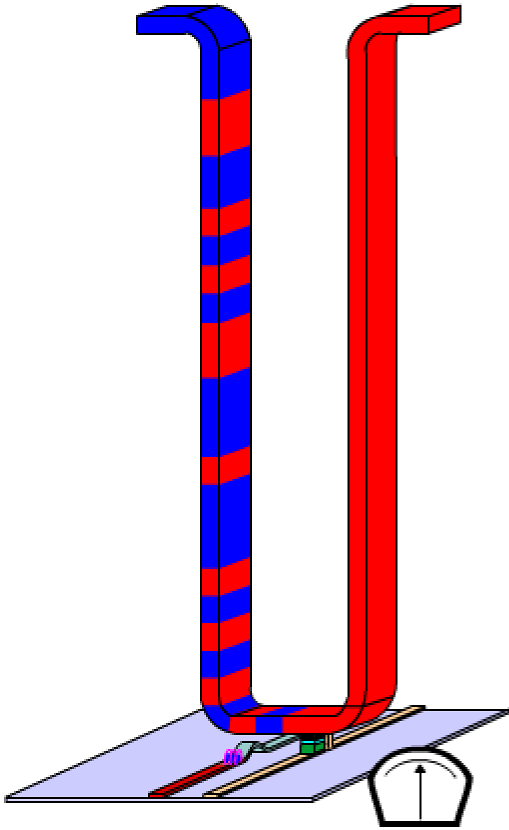
Electric current-driven DW motion



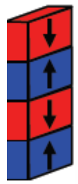
DWs are moving together to the same direction.

We can shift the information (DW)!

Magnetic Racetrack Memory proposed by IBM



A novel three-dimensional spintronic storage memory

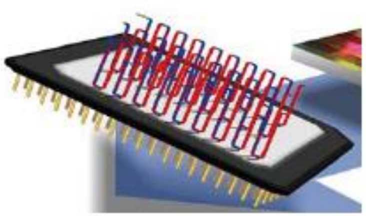


Magnetic nanowires:

Information stored in the domain

-Capacity of a hard disk drive

-Reliability and performance of solid state memory (DRAM, FLASH, SRAM...)



=

DRAM

(Samsung)

+

FLASH

(TDK)

or

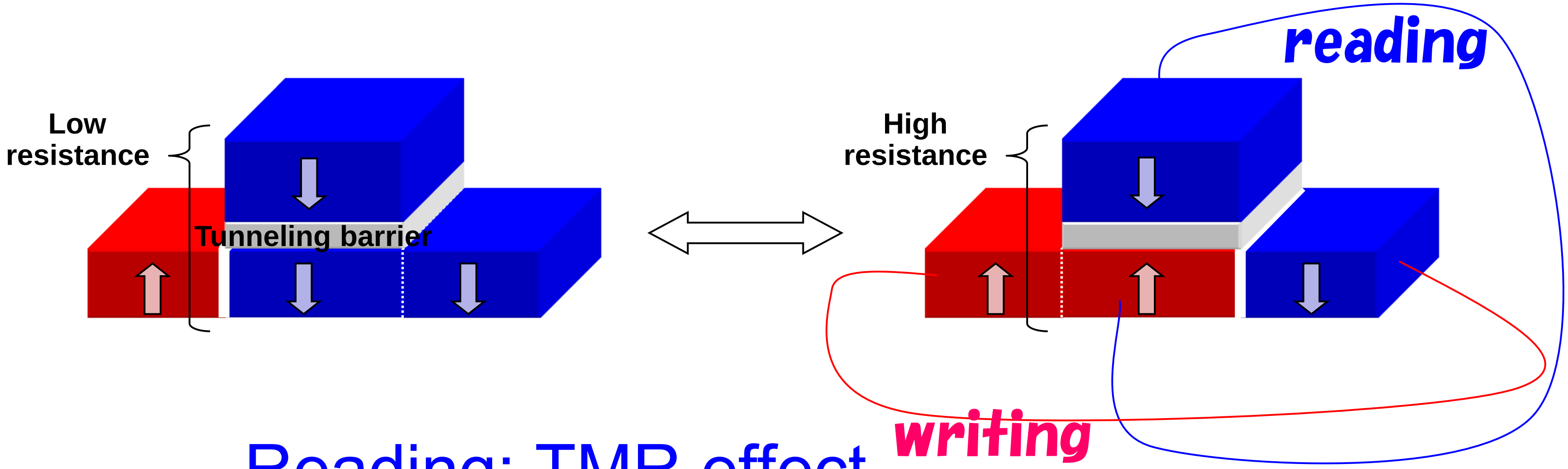
HDD

(Toshiba)

Courtesy of Stuart Parkin (IBM)

CIDW-MRAM proposed by NEC

S. Fukami et al., 52nd Conference on MMM Abstracts FE-06 (2007).



Reading: TMR effect

Writing: Current-induced DW motion

Independent circuits for reading and writing

Fast operation

Replace SRAM

Requirements for practical applications

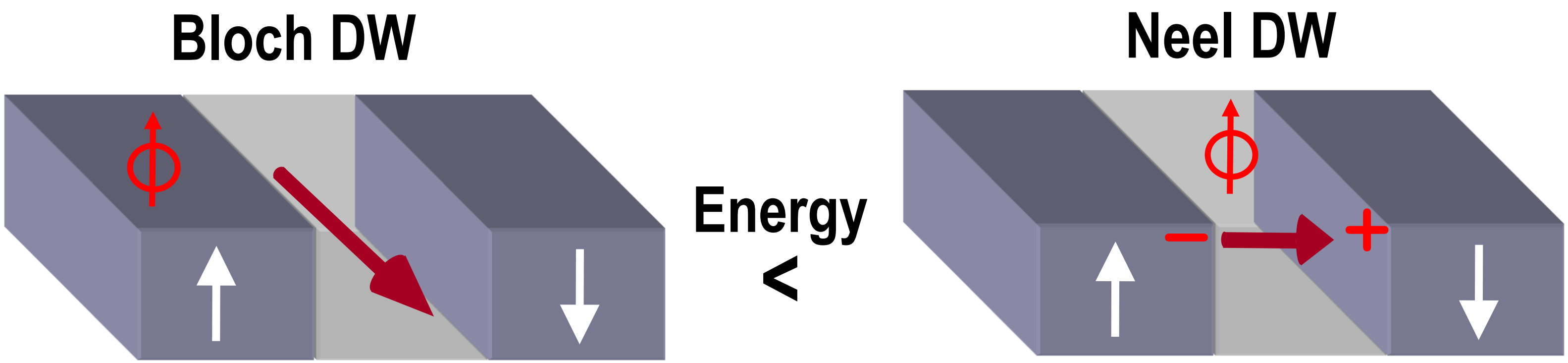
(1) High thermal stability $> 60\ k_B T$

(2) Low threshold current $< 10^{11}\ A/m^2$

(3) High DW velocity > 100 m/s

- **Elucidation of mechanism**
- **Exploration of new material**

DWM by adiabatic spin torque &Intrinsic pinning for DW motion



To drive a DW by current,
spin torque has to overcome the barrier of Neel wall!

- DW moves with precessional motion.
- Direction of DW motion is along electron flow.
- J_{th} is given by

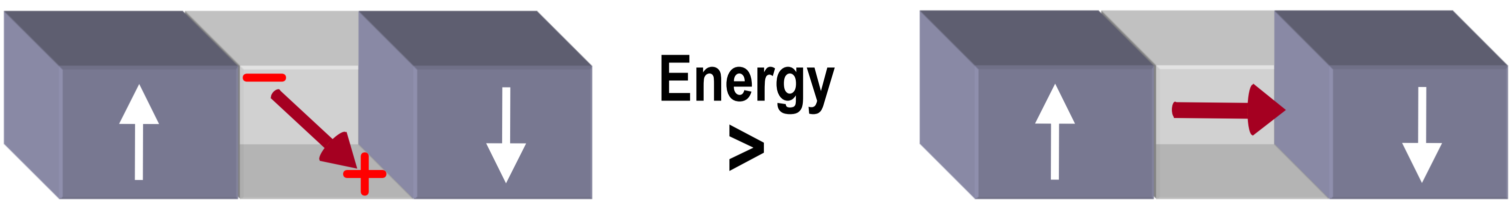
$$J_{\mathrm{th}} = \frac{e\gamma\lambda K_{\perp}}{2\mu_{\mathrm{B}}P}$$

Tatara and Kohno, Phys. Rev. Lett. (2004).

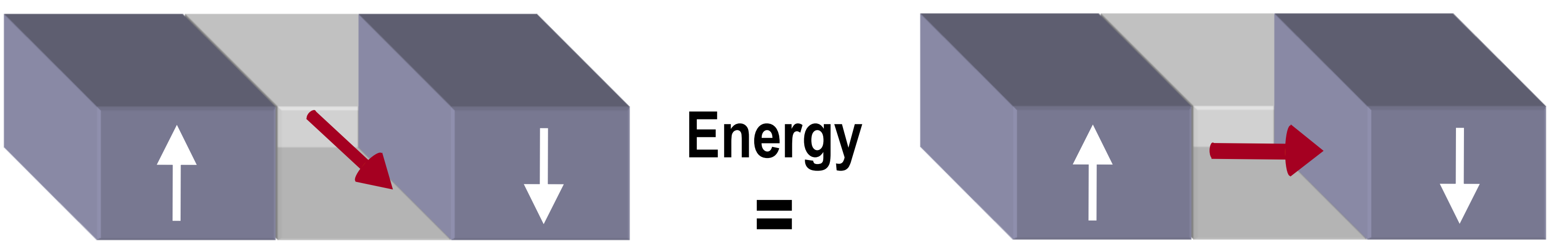
How to prove the intrinsic pinning?

By changing wire width,
(1) Existence of minimum of J_{th} for DW motion
(2) Change of DW structure from Bloch to Neel

Spin torque has to overcome the barrier of Neel wall!

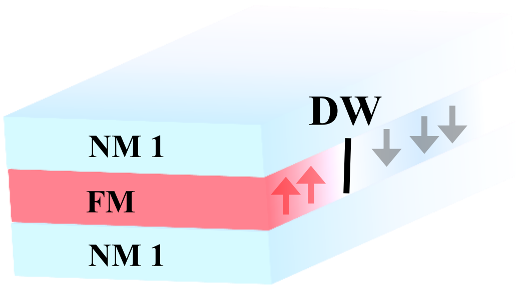


Spin torque has to overcome the barrier of Bloch wall!



Resulting in J_{th} minimum

CIDWM in symmetric nanowires



Si/Ta(3)/Pt(1.6)[Co(0.2)/Ni(0.6)]$_4$Co(0.2)/Pt(1.6)/Ta(3nm)

- ✓ Eliminate the effect of current-induced magnetic field
- ✓ Cancel the interfacial effect (Rashba, DMI, spin Hall etc.)

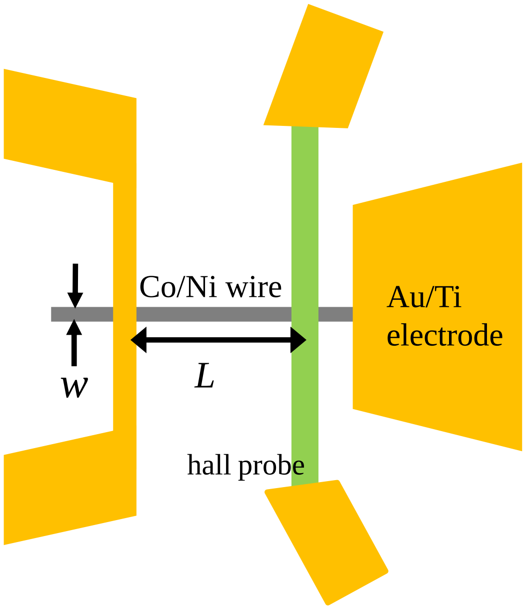
Ideal system to investigate DW motion by

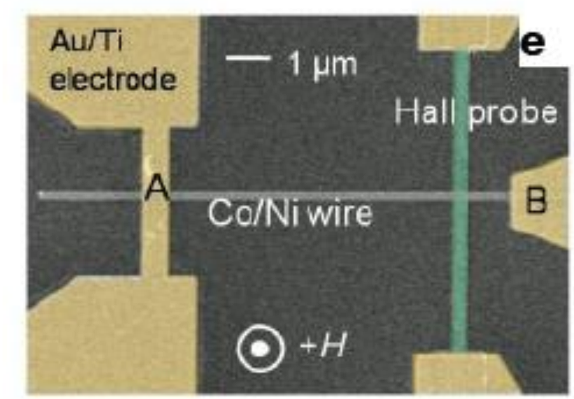
Bulk adiabatic spin transfer torque

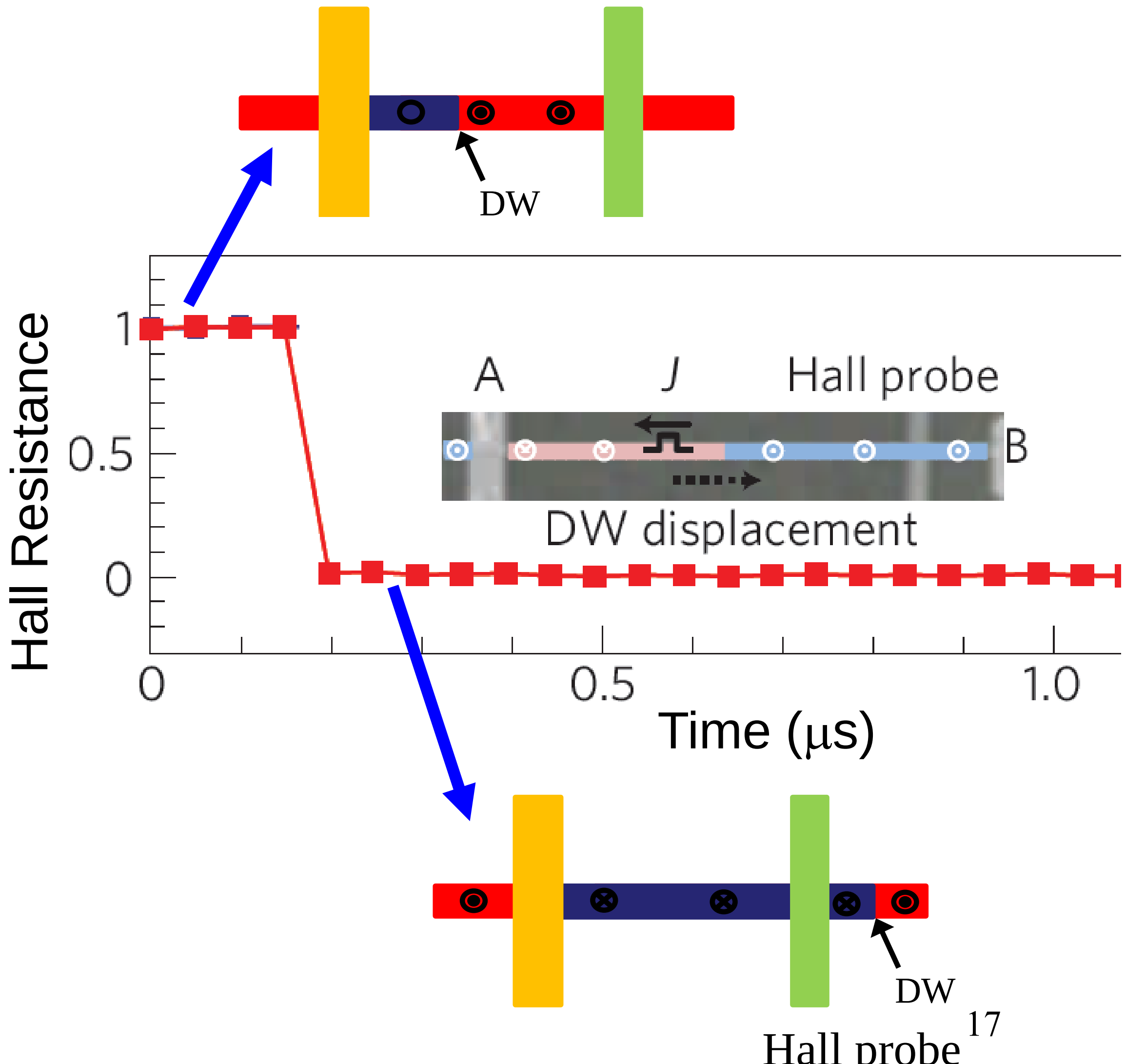
Nature Materials 10 (2011) 194.
Nature Nanotechnology 7 (2012) 635.
Nature Communications 4 (2013) 2011.

Device & DW motion detection method

Si/Ta(3)/Pt(1.6)[Co(0.2)/Ni(0.6)]$_4$Co(0.2)/Pt(1.6)/Ta(3nm)

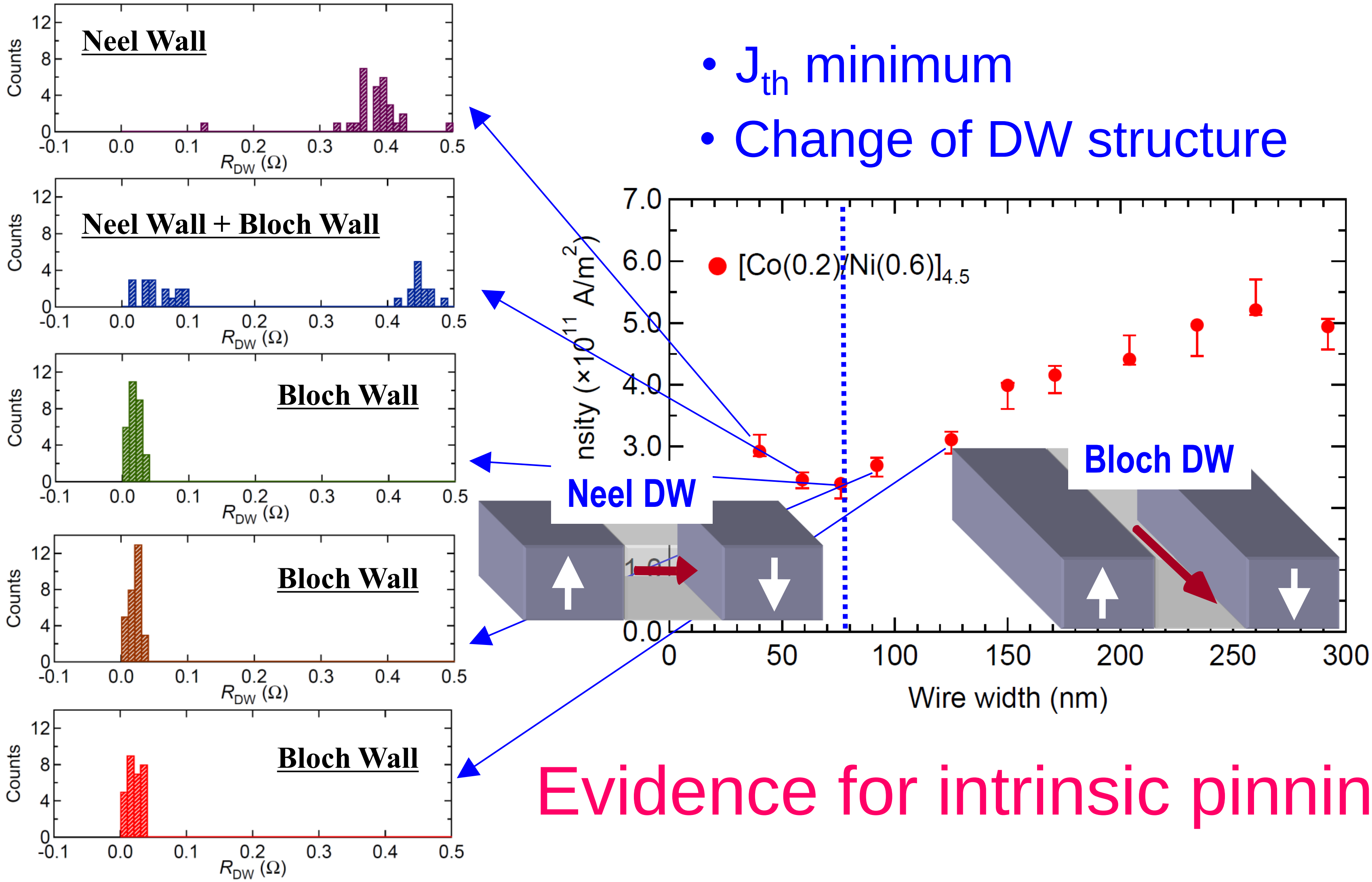






J_{th} & DW resistance v.s. wire width

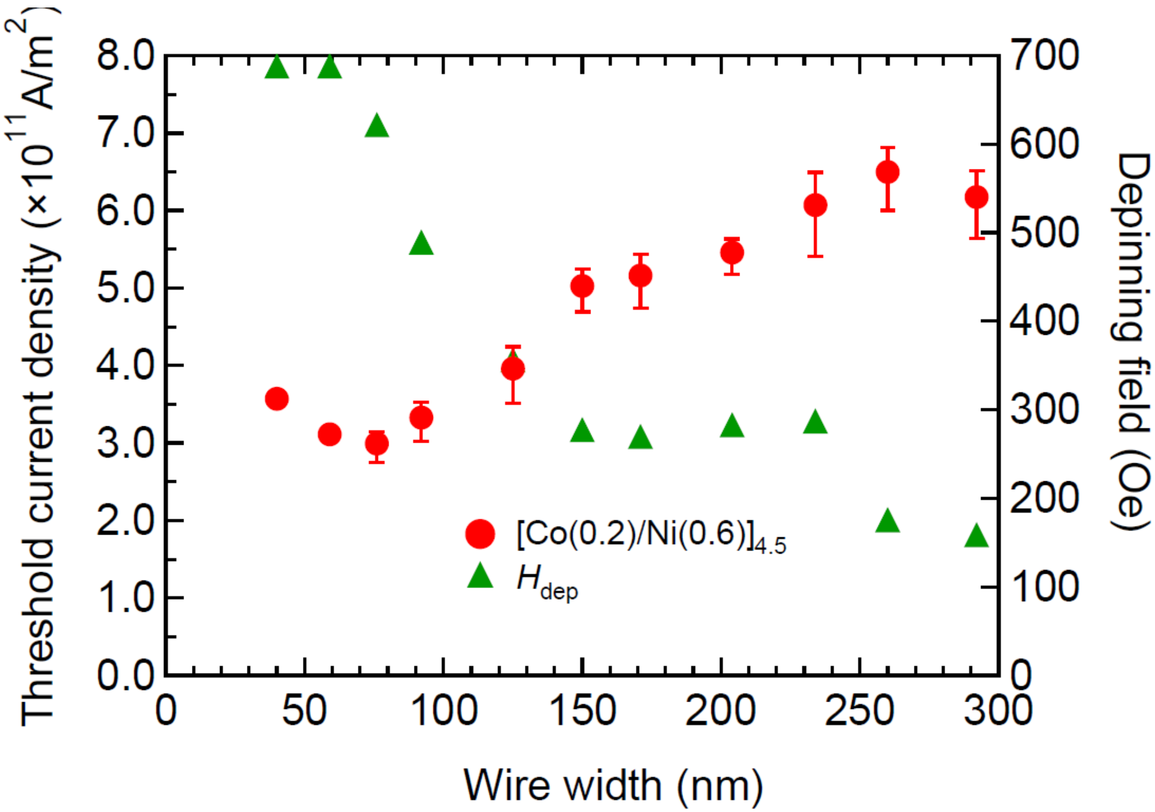
- J_{th} minimum
- Change of DW structure



Evidence for intrinsic pinning!

Nature Materials 10 (2011) 194.

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



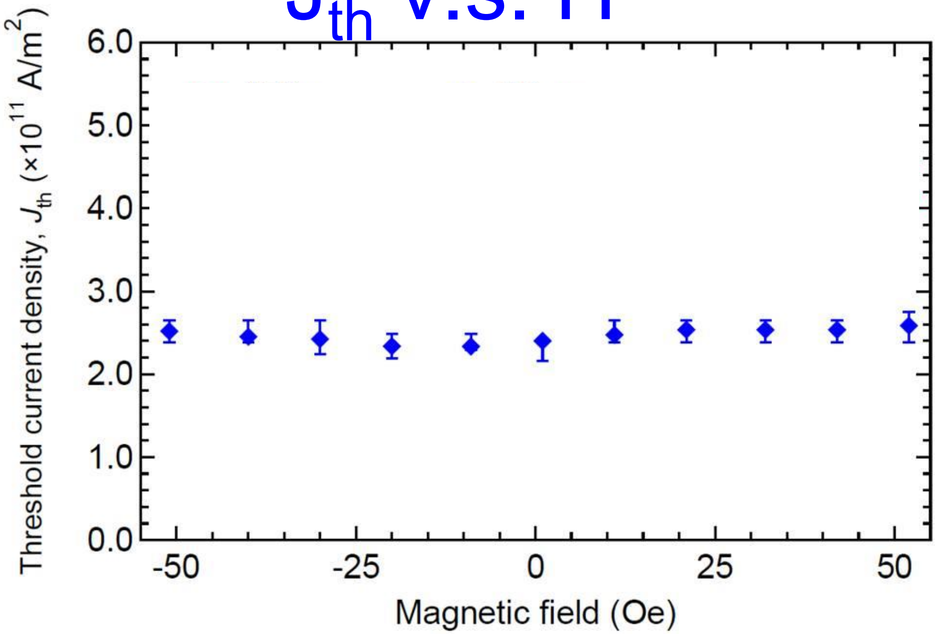
No correlation between J_{th} & depinning field.

Compatibility of low power operation & high stability !

Nature materials 10 (2011) 194.

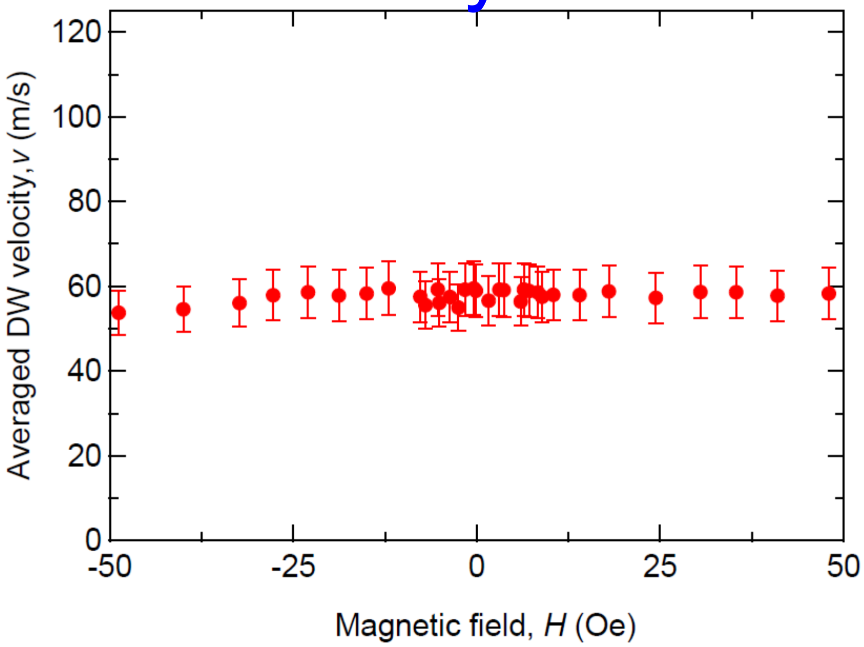
In the case of DW motion by adiabatic torque, J_{th} & DW velocity are insensitive to H

J_{th} v.s. H



T. Koyama, *et al.*, Nat. Mater. 10, 194 (2011).

velocity v.s. H



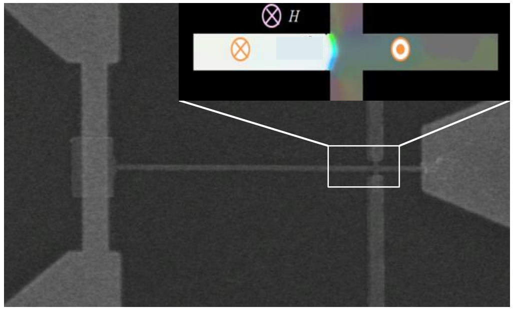
T. Koyama, *et al.*, Appl. Phys. Lett. 98, 192509 (2011)

Good for application!

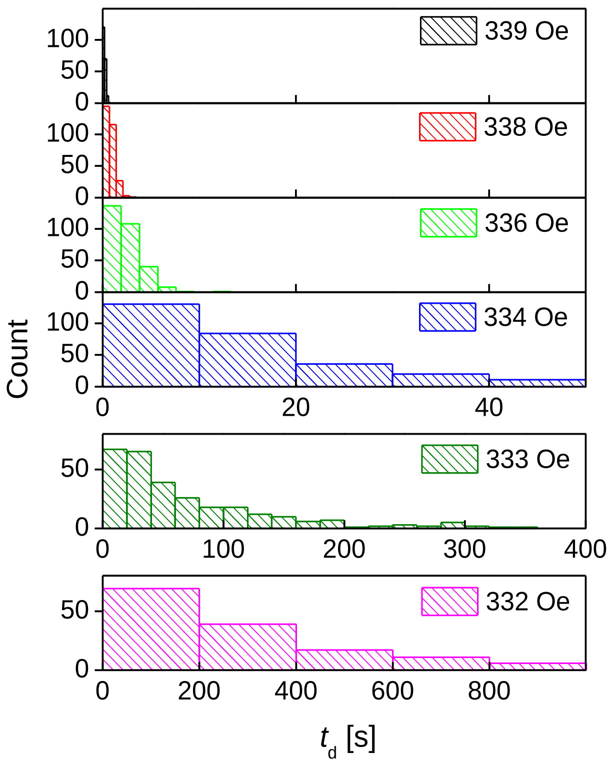
Thermal stability of DW

Determination of the barrier by magnetic field

Thermally activated DW depinning

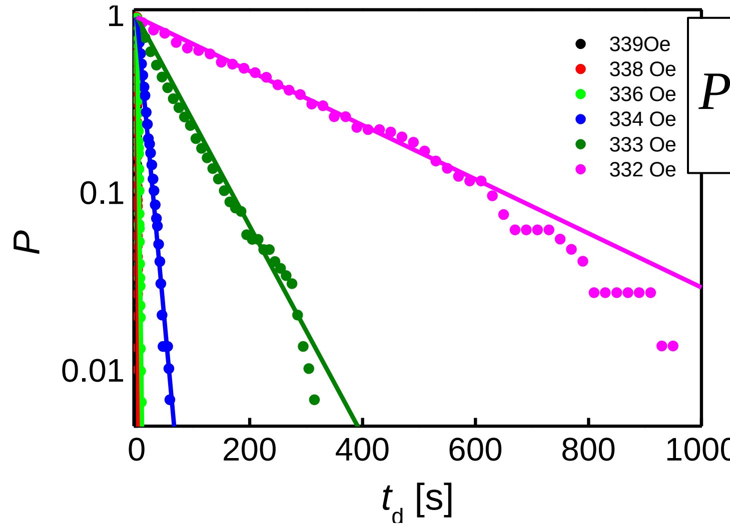


Depinning # for each time span



300 repeated measurements

Depinning probability as a function of time

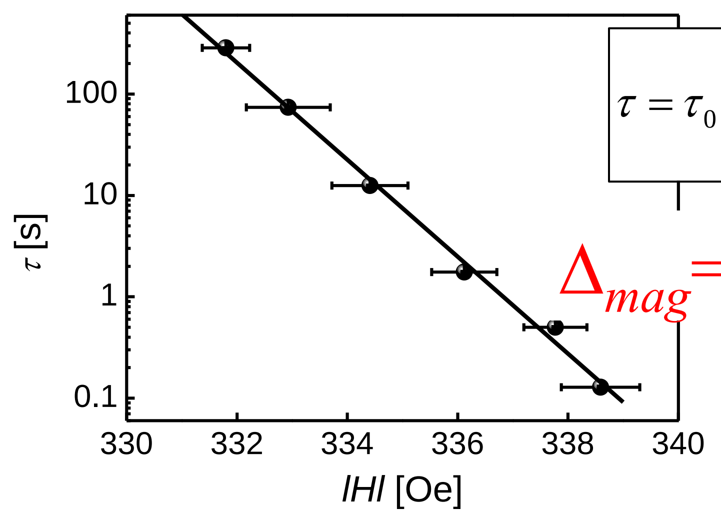


$$P(t_d) = 1 - \exp\left(-\frac{t_d}{\tau}\right)$$

Single exponential

Single barrier

τ as a function of *H*



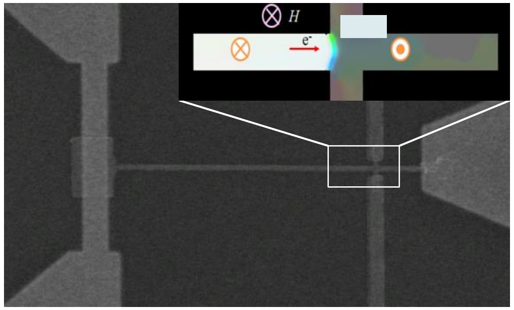
$$\tau = \tau_0 \exp\left\{\frac{\Delta_{mag}^{thermal}}{k_B T}\left(1 - \frac{H}{H_I}\right)\right\}$$

$\Delta_{mag} = 392 \pm 13\ k_B T$

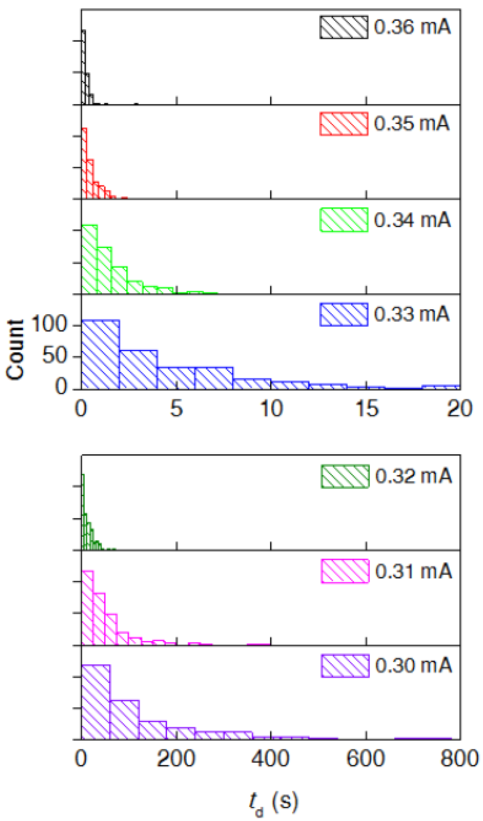
Nature Communication 4 (2013) 2011.

Determination of the barrier by current

Thermally activated DW depinning

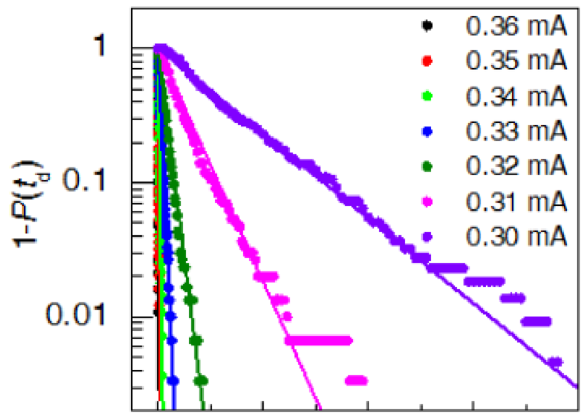


Depinning # for each time span



300 repeated measurements

Depinning probability as a function of time



$$P(t_d) = 1 - \exp\left(-\frac{t_d}{\tau}\right)$$

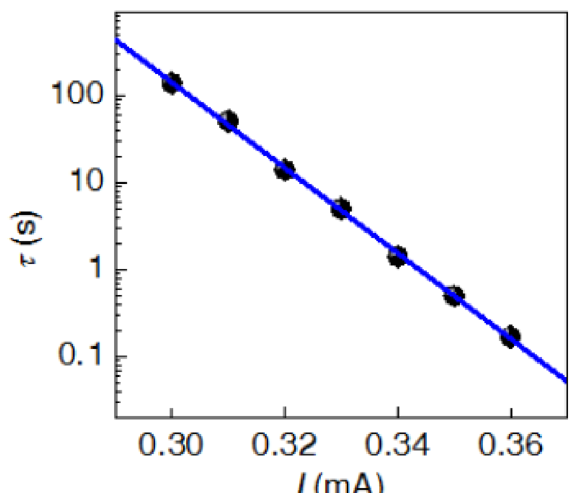
Single exponential

Single barrier

Δ_{mag}=392±13 k_BT

Δ_{curr}=60±3 k_BT

τ as a function of *I*



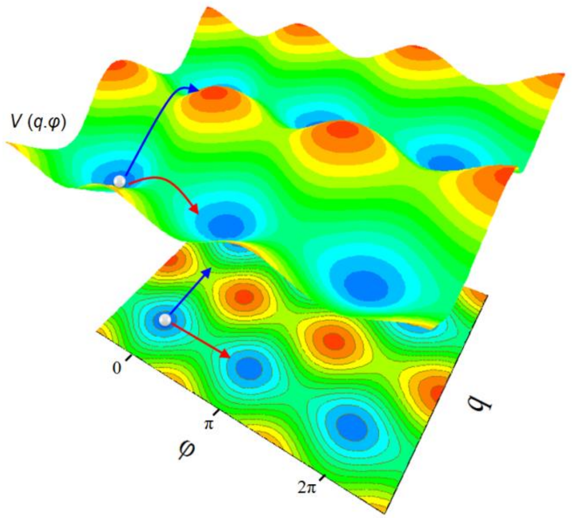
$$\tau = \tau_0 \exp\left\{\frac{\Delta_{curr}^{thermal}}{k_BT}\left(1 - \frac{I}{I_c}\right)\right\}$$

Δ_{curr}=60±3 k_BT

Two barriers and device properties

Thermal stability

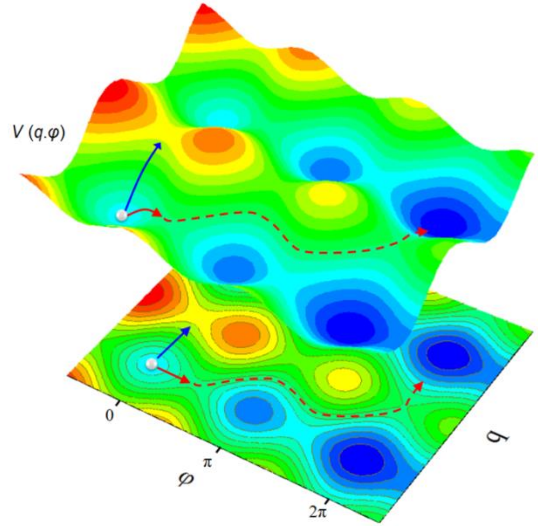
Defined *without* the d.c. current



d.c. current induces
the tilting along φ axis

Threshold current

Defined *with* the d.c. current



Thermal energy larger than intrinsic barrier induces not the position change of DW but the random precession of ϕ.

Thermal stability of position is governed by extrinsic pinning

Intrinsic energy barrier can induce the position change of DW due to the tilting of energy slope.

Threshold current is domintated by intrinsic pinning

Two barrier stability allows us the low threshold current with high thermal stability.

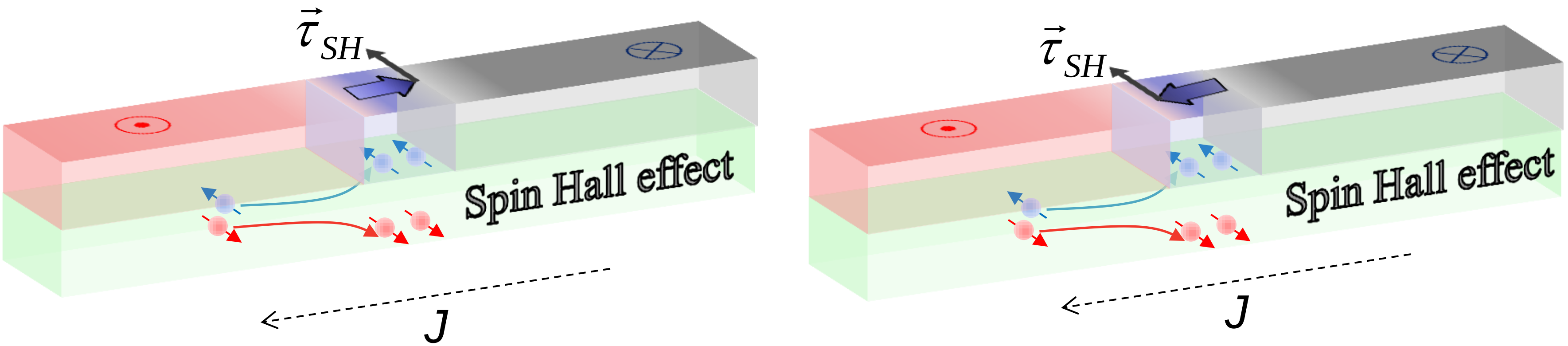
Recent progress on DW motion

DW motion induced by spin Hall torque

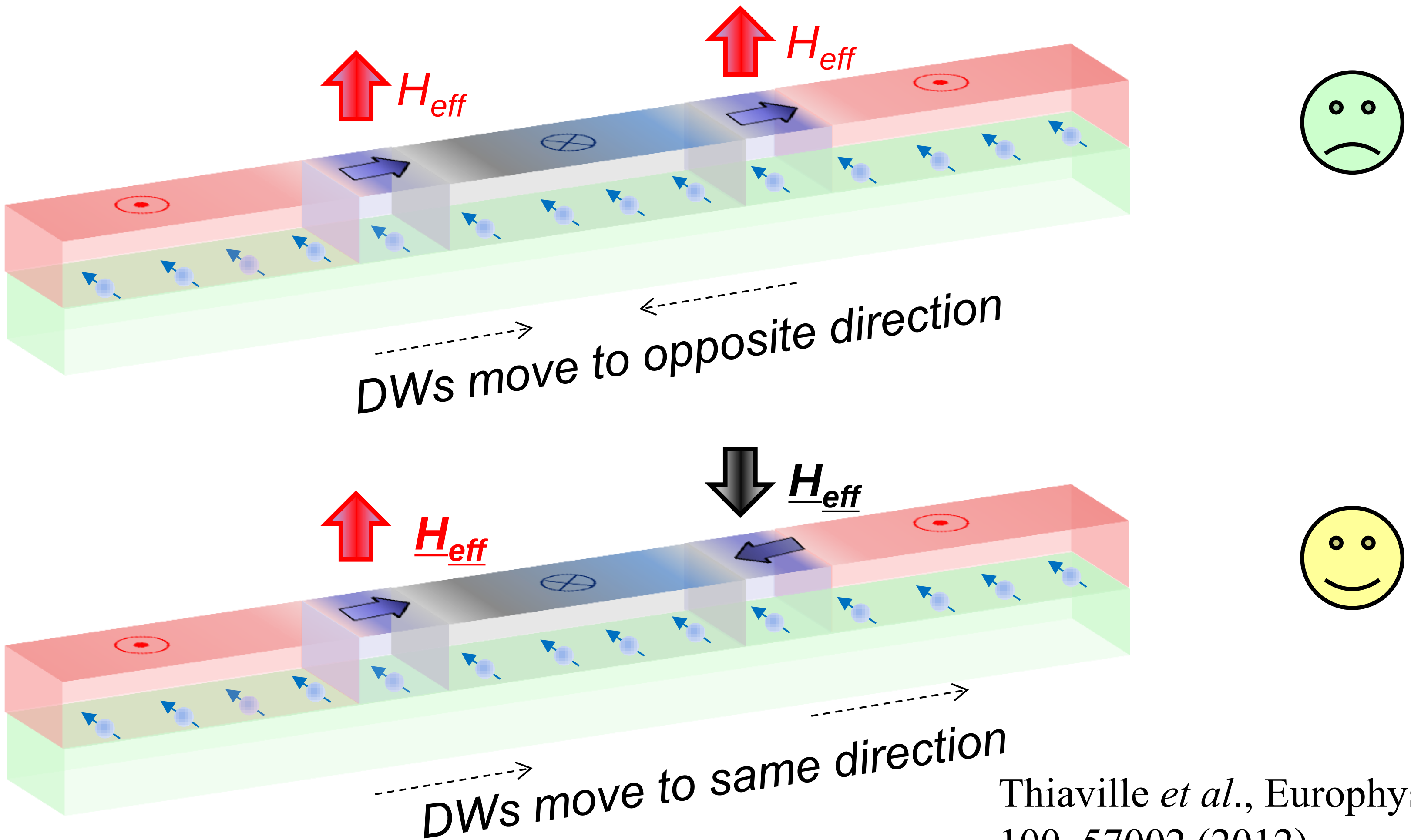
&

Dzyaloshinskii-Moriya Interaction

New mechanism for DW motion
-Spin Hall torque on Neel DW-



spin Hall torque on Neel wall!
→ DW motion…



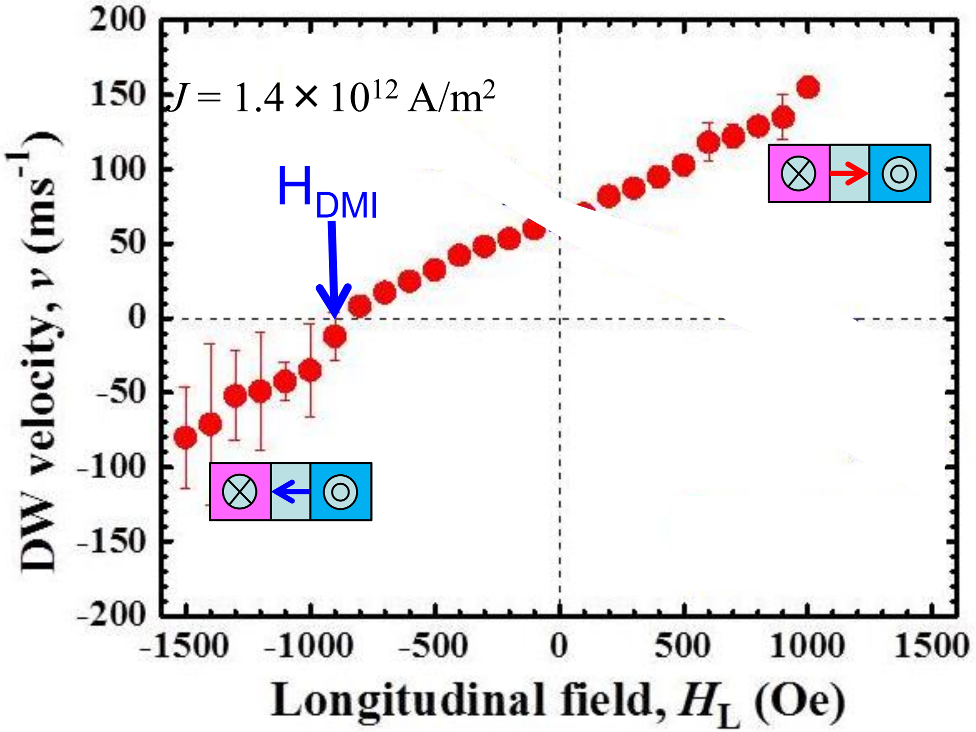
Thiaville *et al*., Europhys. Lett. 100, 57002 (2012).

Chiral Neel wall stabilized DMI wall is necessary!

How to confirm? → Experiments under H_L!

DW velocity under in-plane field

Ta(3nm)/Pt(2nm)/MgO(1nm)/Co(0.3nm)/Ni(0.6nm)/Co(0.3nm)/Pt(2nm)/Ta(3nm)/Si sub.



Appl. Phys. Express 7 (2014) 053006.

Emori *et al*., Nat. Mater. (2013), Ryu *et al*., Nat. Nanotech. (2013)

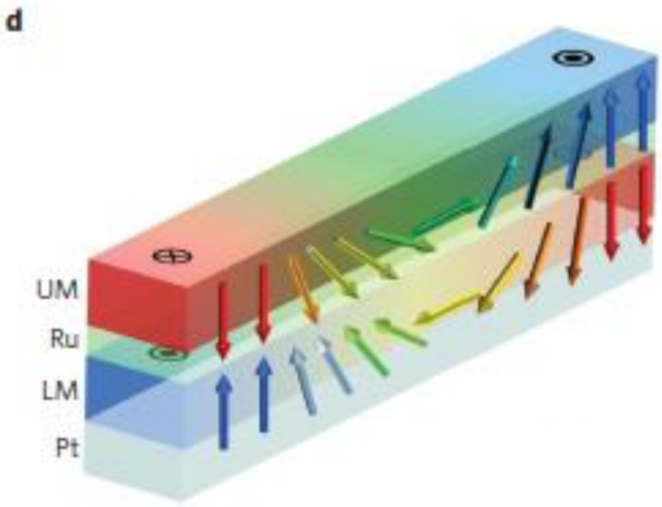
Field-induced chirality change of DW results in change of DWM direction.

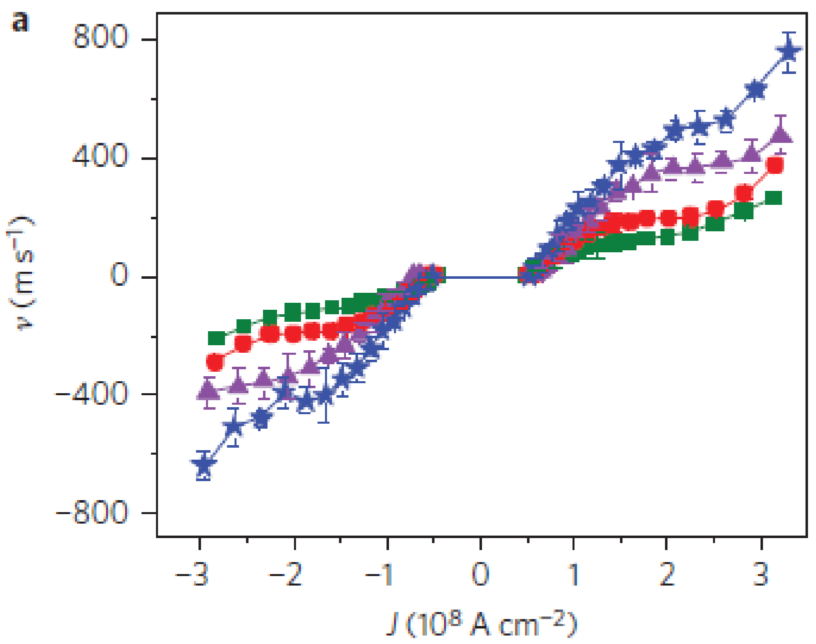
Chiral Neel wall + spin Hall torque

nature nanotechnology
FOCUS | LETTERS
PUBLISHED ONLINE: 23 FEBRUARY 2015 | DOI: 10.1038/NNANO.2014.324

Domain-wall velocities of up to 750 m s^{-1} driven by exchange-coupling torque in synthetic antiferromagnets

See-Hun Yang†, Kwang-Su Ryu† and Stuart Parkin*

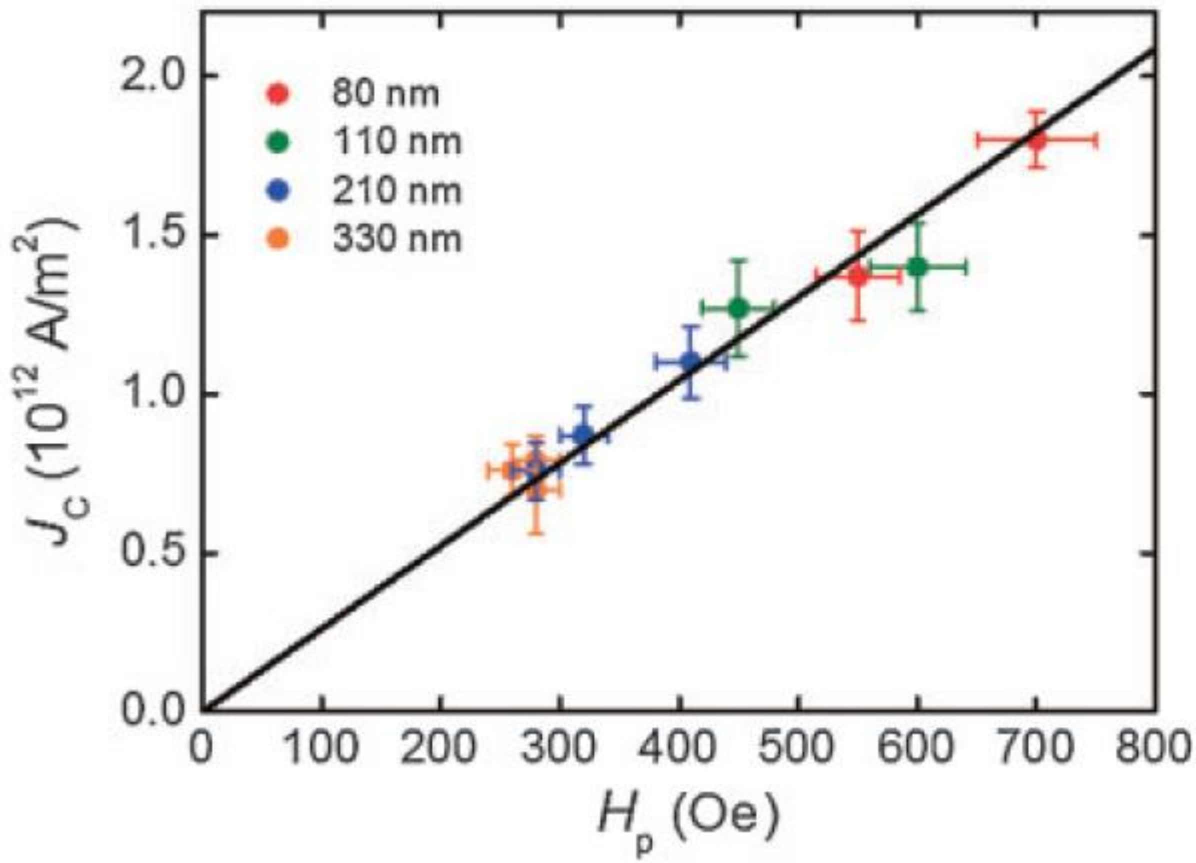




Very good news, but…

J_c v.s. H_p for spin Hall torque DW motion

Ta(4nm)/Pt(2nm)/MgO(1nm)/Co(0.3nm)/Ni(0.6nm)/Co(0.3nm)/Pt(2nm)/Ta(4nm)/Si substrate



J_c is proportional to H_p.

High thermal stability leads to high Jc.

Appl. Phys. Express 7 (2014) 053003.

Summary

Spin dynamics in inhomogeneously magnetized systems

(1) Magnetic domain wall

(1-1) DW motion by adiabatic spin transfer torque

- Existence of intrinsic pinning
- DW motion is insensitive to external field and defects.

(1-2) DW motion by spin Hall torque

- Need for chiral DW induced by DMI.
- DW motion is sensitive to external field and defects.

(1-3) Correlation between DMI and orbital moment.

(2) Magnetic vortex

(2-1) Current-induced dynamics magnetic vortex core

- Current-induced vortex core switching
- Vortex core memory

(2-2) Spin motive force due to a gyrating magnetic vortex