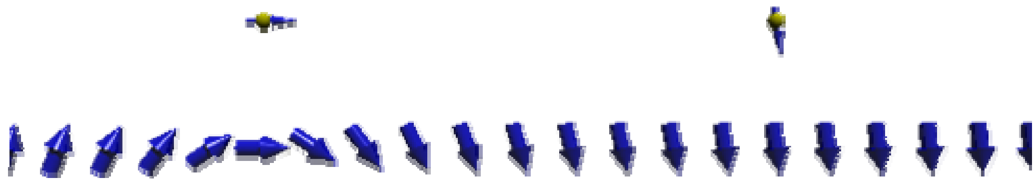
Threshold Current of Domain Wall Motion
based on rigid wall description



Tokyo Metropolitan Univ.
首都大学東京 都市教養学部

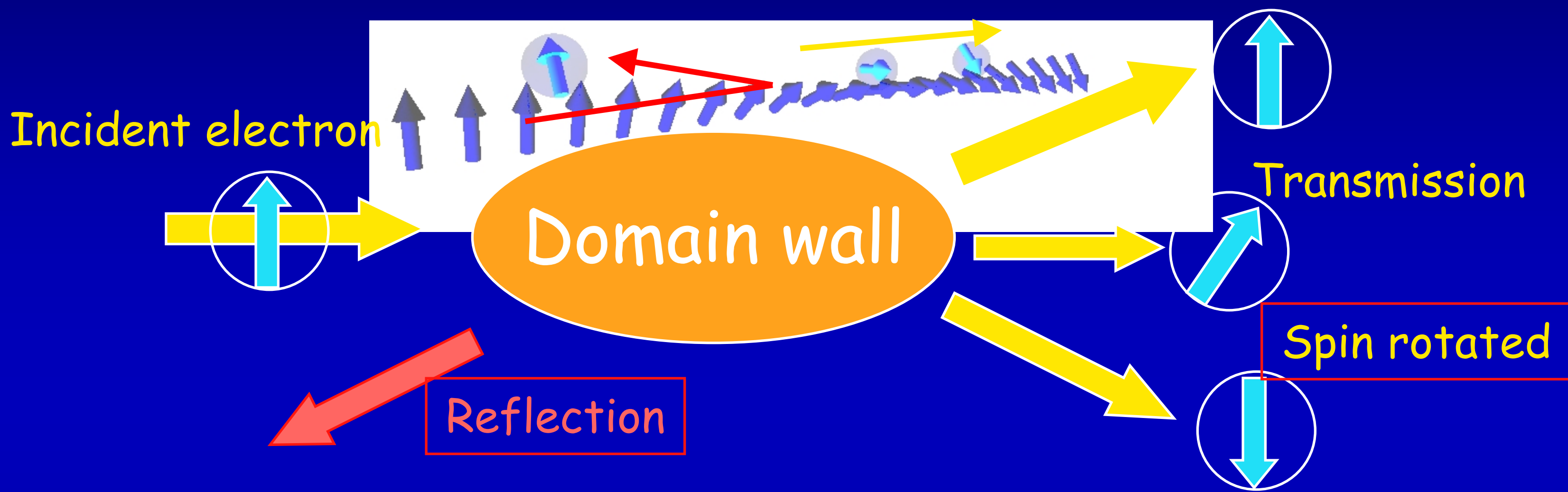
多々良源
Tatara, Gen

H. Kohno (Osaka Univ.)
J. Shibata (RIKEN)
J. Ferre, N. Vernier (Univ. Paris)
T. Takayama (TMU)
Y. Nakatani (Univ. Elec. Comm.)
H. Fukuyama (IFCAM)

•Domain wall and electron transport

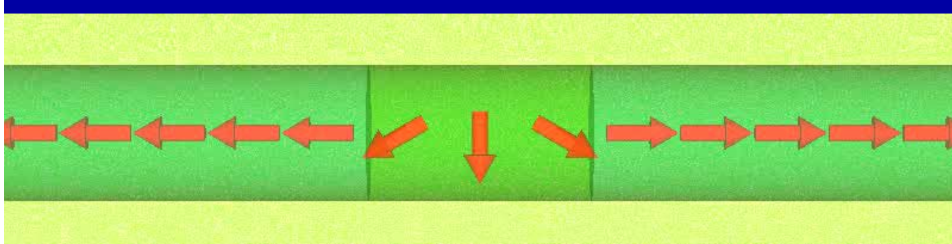
Berger ('84,'92)
GT& Kohno (2004)

- •Charge scatterer
- •Spin rotator SU(2)



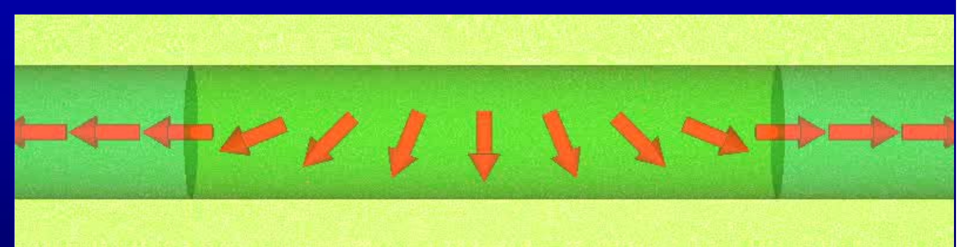
2 different driving mechanisms of DW

Momentum transfer to DW (Force)



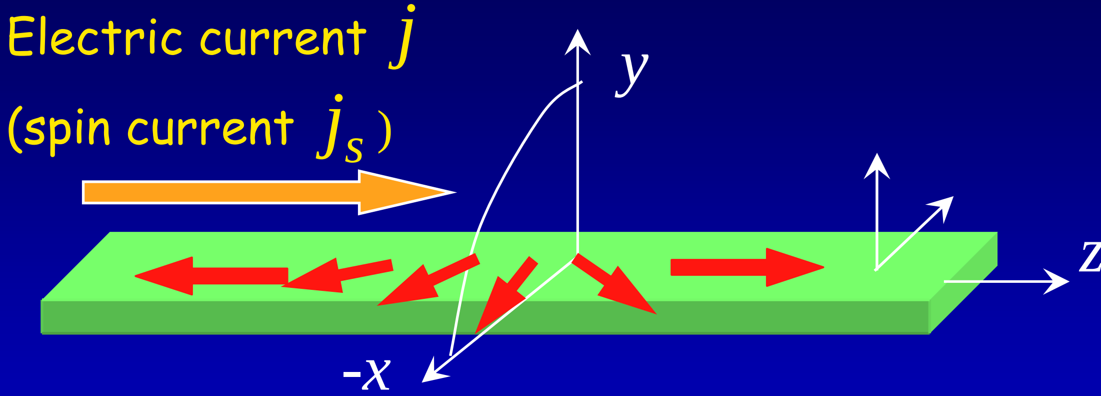
Thin wall

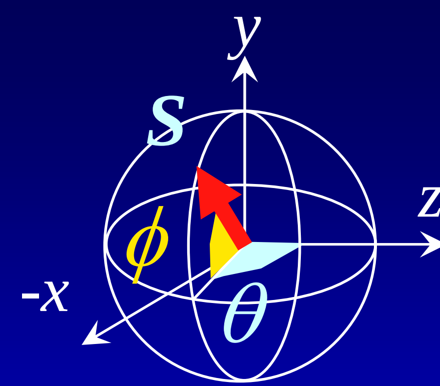
Spin transfer (Spin Torque)



Thick wall

•Domain wall in nanowires





θ: angle in easy (xz) plane
ϕ: angle from easy plane

•Lagrangian

$$L = \sum_x \left(-\hbar S \dot{\phi}(1-\cos\theta) - H_S - \Delta \vec{S}\cdot\vec{\sigma} + L_e \right)$$

Spin Hamiltonian

$$H_S = \sum_x \tfrac{1}{2}\left(J(\nabla S)^2 - K S_z{}^2 + K_\perp S_y{}^2 \right)$$

Rigidness of DW

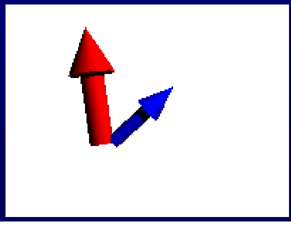
Out of plane Energy (dynamics)

Electron part

$$H_e = \sum_{k\sigma} \varepsilon_k c^+_{k\sigma} c_{k\sigma}$$

· Exchange interaction

$$H_{ex} = \Delta \int dz \vec{S}(z)\cdot\vec{\sigma}$$



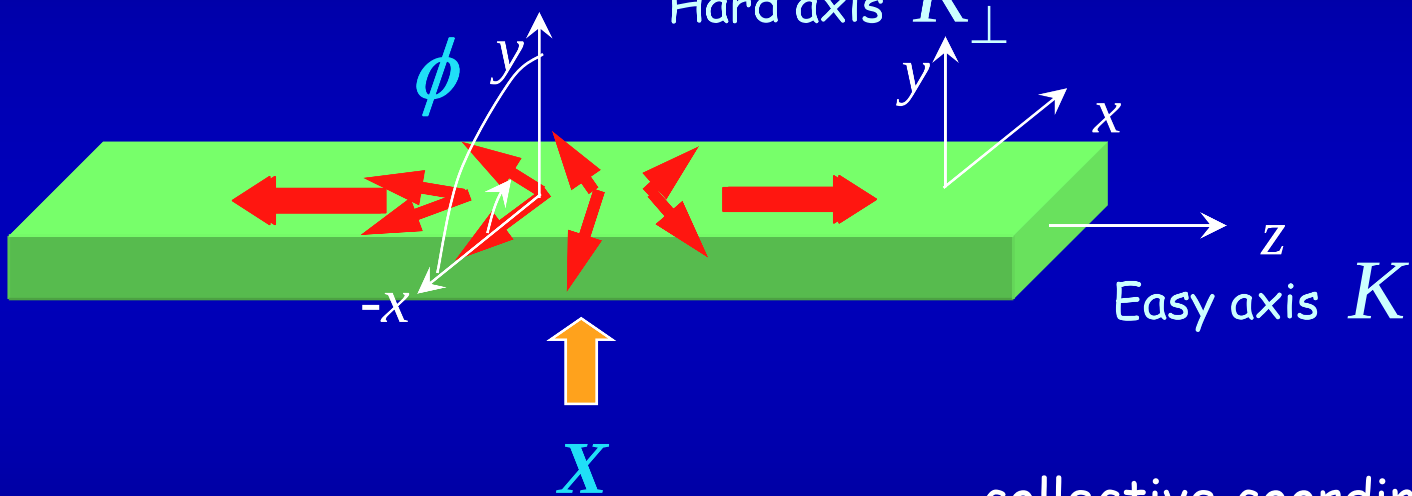
•Rigid 1D wall description

Slonczewski ('72)
Berger ('78-93)
Braun & Loss ('96)
Takagi & GT ('96)

Assumption Large K : deformation negligible (except ϕ)

$L_\perp \ll \lambda$: planar (1D) DW

λ: wall width



collective coordinates

Low energy dynamics of DW is described by X and ϕ

Deformation is high-energy mode

•Free DW Lagrangian

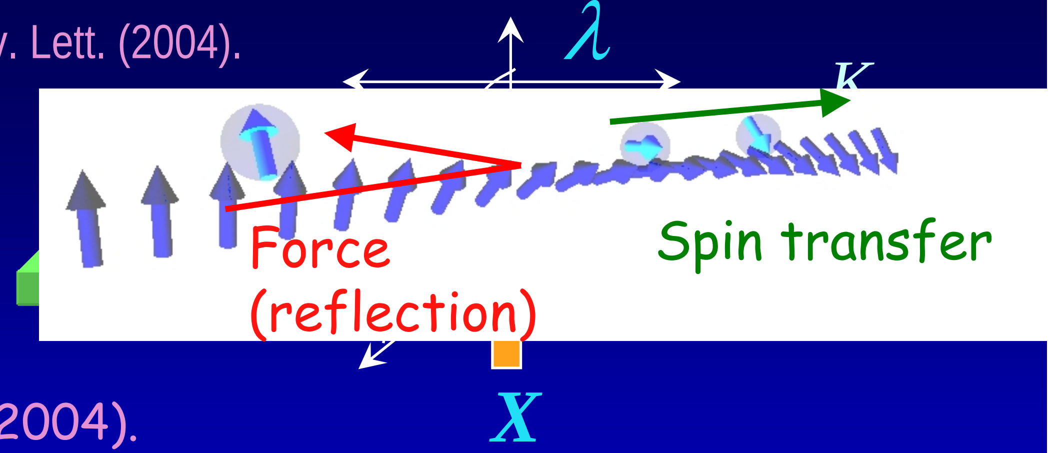
$$L = \frac{\hbar S N}{\lambda} \dot{X} \phi - \frac{N S^2}{2} K_\perp \sin^2 \phi$$

$N = 2\lambda L_\perp^2 / a^3$
number of spins in DW

$K_\perp$: Hard axis anisotropy

Formulation

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



- Equation of motion

  collective coordinates X, ϕ

  Berger ('84), GT & Kohno (2004).

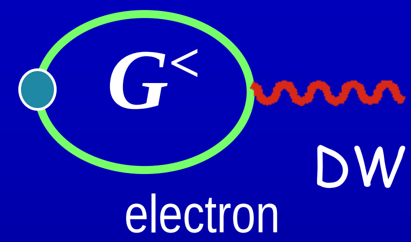
$$\frac{\hbar SN}{\lambda}\left(\dot{\phi}+\alpha\frac{\dot{X}}{\lambda}\right)= eN\rho_w j$$

$$\frac{\hbar SN}{\lambda}\left(\dot{X}-\alpha\lambda\dot{\phi}\right)=-\frac{NS^2K_\perp}{2}\sin 2\phi-\frac{\hbar NS}{\lambda}\frac{a^3}{2Se}j_s$$

j: charge current

ρ_w: resisitivity due to DW

j_s: spin current



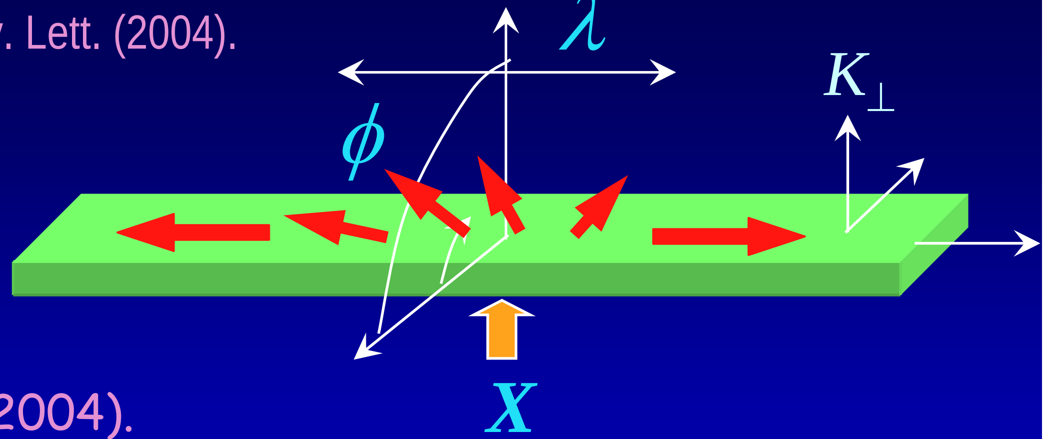
Simple equation

But describes fairly well (compared with simulation)

Deformation is high-energy mode

Formulation

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



- Equation of motion
  collective coordinates X, ϕ
  Berger ('84), GT & Kohno (2004).

$$\dot{\phi} + \alpha\frac{\dot{X}}{\lambda} = -\frac{\hbar SN}{\lambda} e N \rho_w j$$

$$\dot{X} - \alpha\lambda\dot{\phi} = -\frac{SK_\perp\lambda}{2\hbar}\sin 2\phi + \frac{Pa^3}{2Se} j_s$$

Force on DW

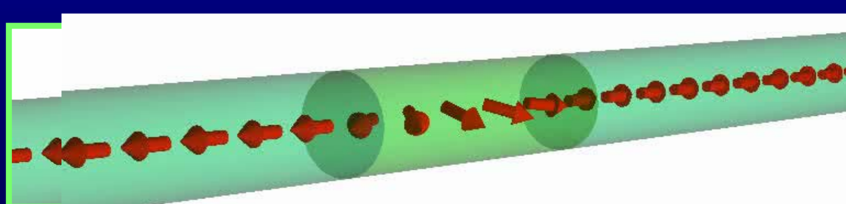
Angular momentum conservation

j: charge current

j_s: spin current

ρ_w: resisitivity due to DW

α : damping



$$\dot{X} \to \frac{Pa^3}{2eS} j \quad (j \to \infty)$$

100% Angular momentum transfer

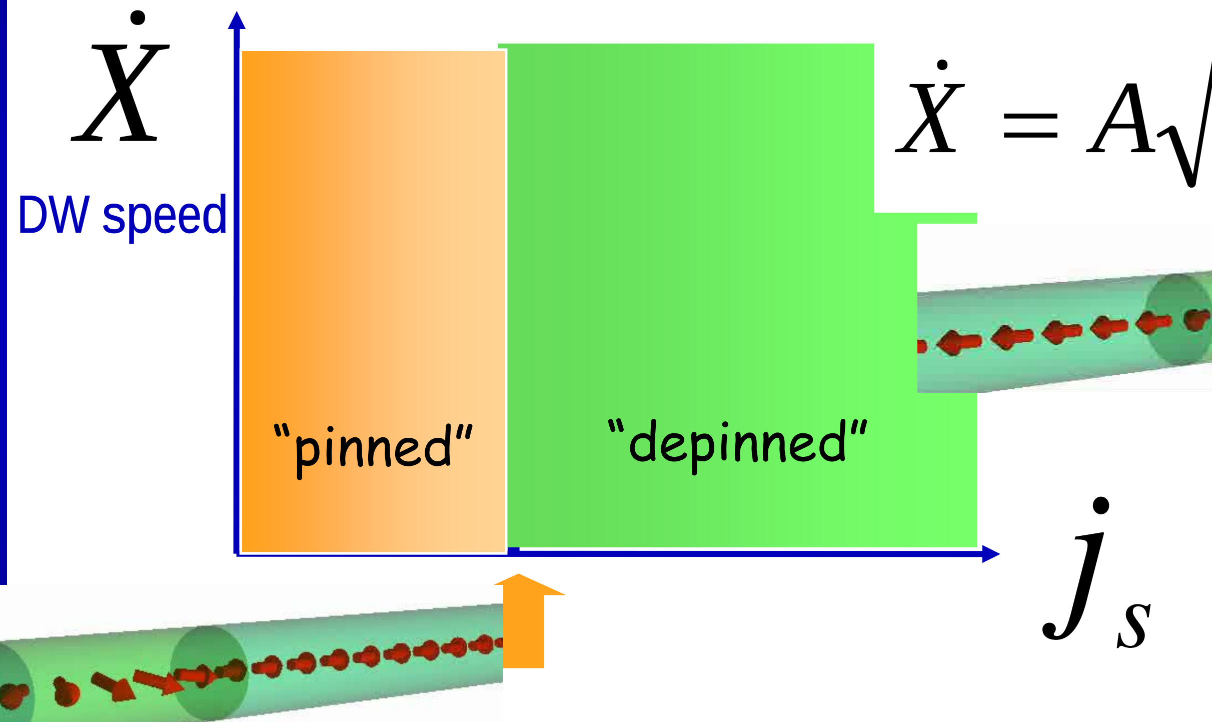
Intrinsic pinning of DW (if no force)

Tatara & Kohno (2004).

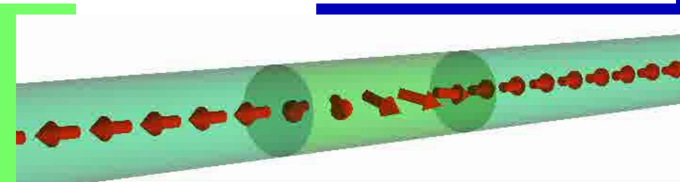
$$\dot{X} - \alpha\lambda\dot{\phi} = \frac{\hbar S}{2} K_{\perp}\lambda \sin 2\phi + \frac{1}{2S}\frac{a^3}{e} Pj$$

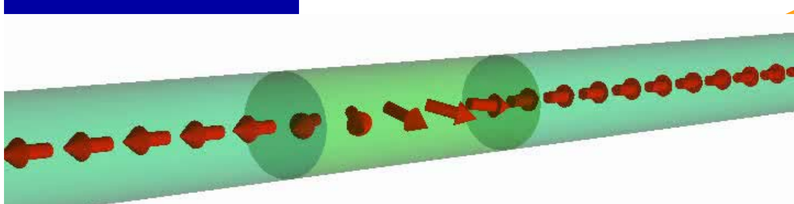
$$\dot{\phi} + \alpha\frac{\dot{X}}{\lambda} = \quad 0$$

(spin torque only)



$$\dot{X} = A\sqrt{j^2 - j_c{}^2}$$





j_c Threshold current $j_c \propto K_{\perp}\lambda S^2$

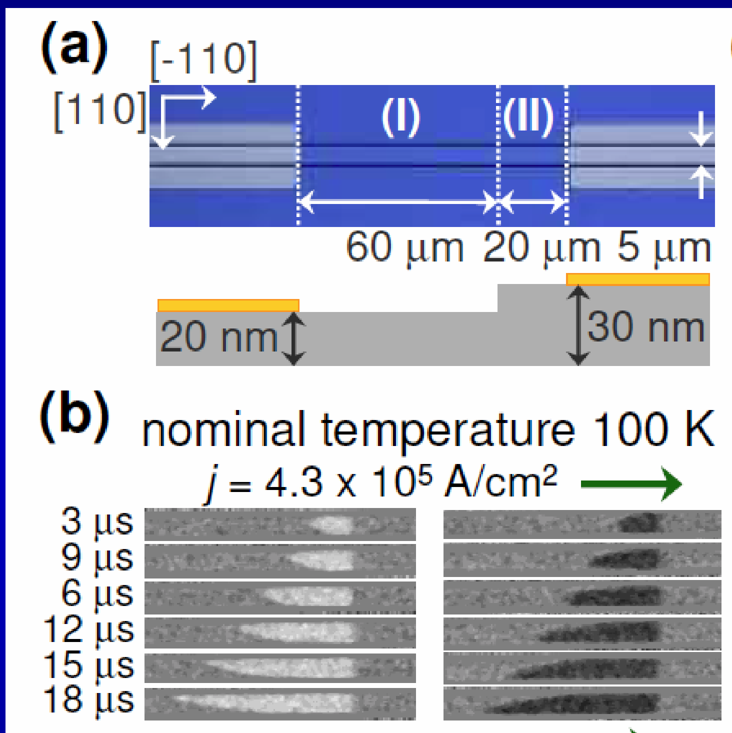
Controllable by sample geometry

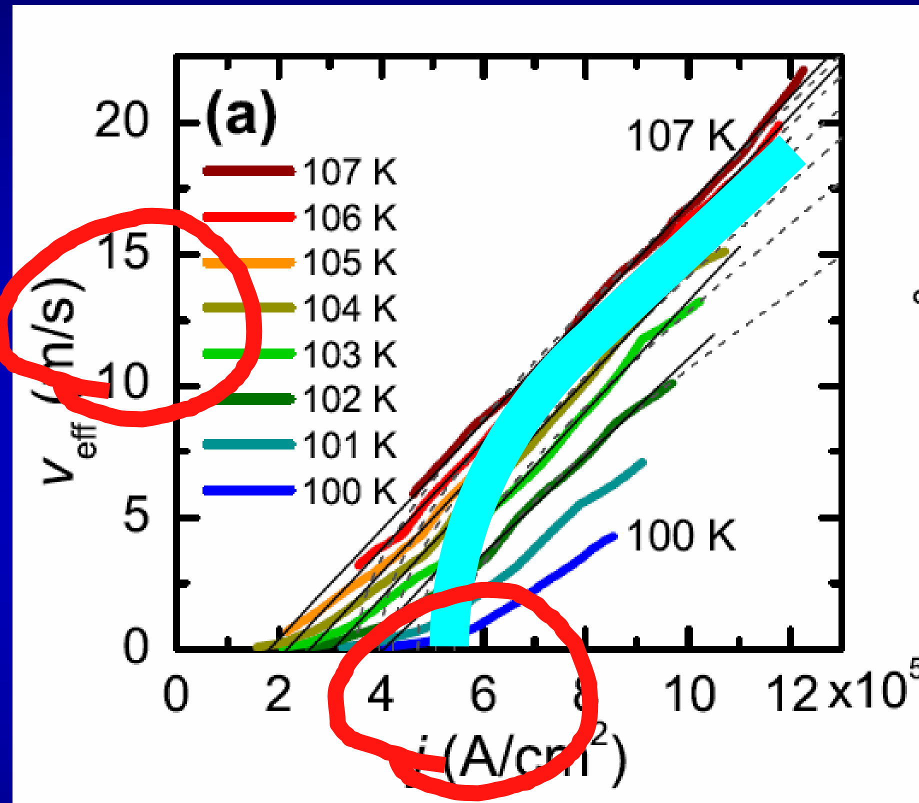
Threshold : Not affected by extrinsic pinning

Experiment (Magnetic semiconductor)

GaMnAs

Yamanouchi, Chiba, Matsukura, Dietl & Ohno, PRL (2006)



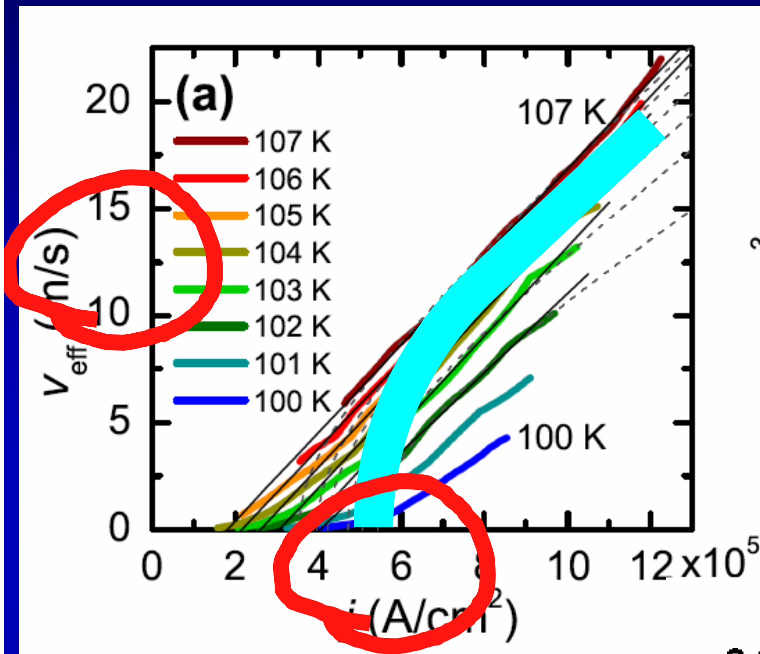


- Low current operation
- v=20m/s

Experiment

GaMnAs

Yamanouchi, Chiba, Matsukura, Dietl & Ohno, PRL (2006)



$$\dot{X} = A\sqrt{j^2 - j_c^{\,2}}$$

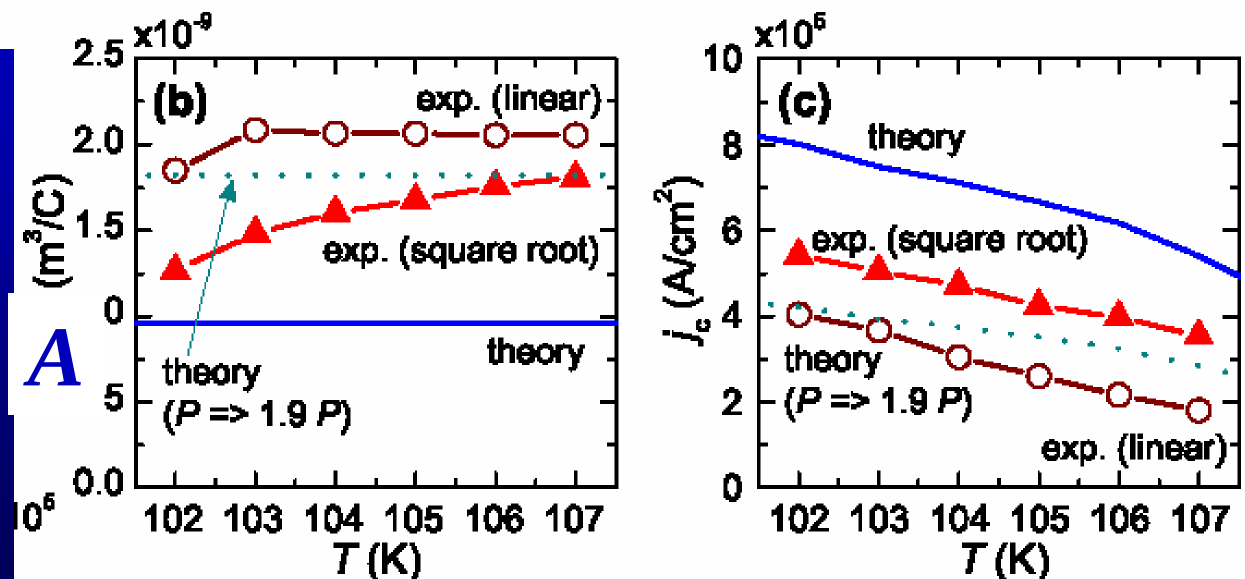
$$j_c = \frac{eS^2}{a^3\hbar P} K_\perp \lambda$$

$$A = \frac{Pa^3}{2eS}$$

GT & Kohno ('04)

Angular momentum conservation

Agreement within factor of 2

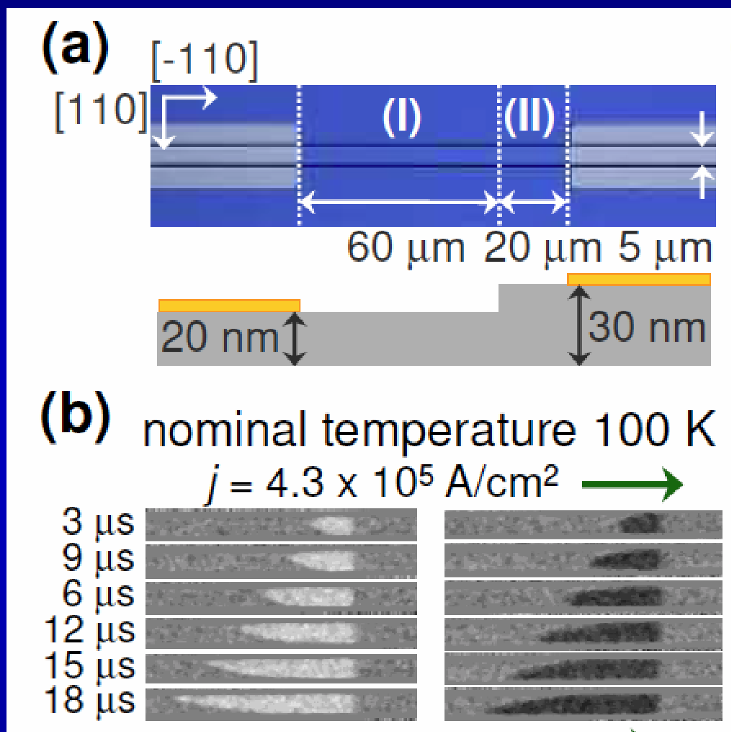


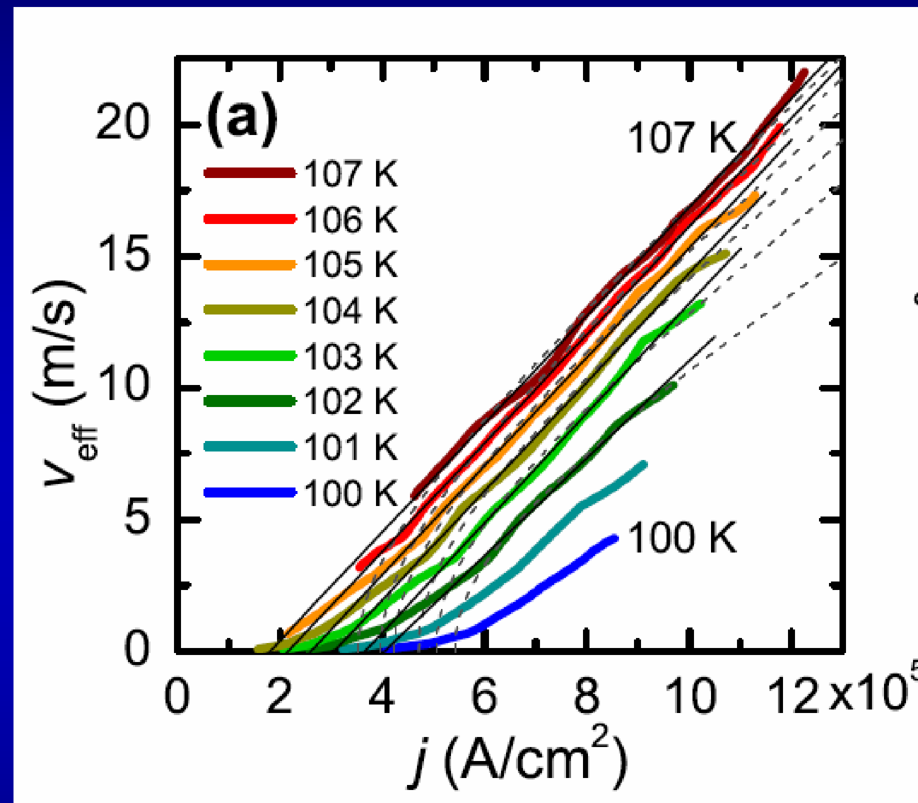
Yamanouchi et al.

Experiment (Magnetic semiconductor)

GaMnAs

Yamanouchi, Chiba, Matsukura, Dietl & Ohno, PRL (2006)





Threshold, velocity:

Consistent with Intrinsic pinning

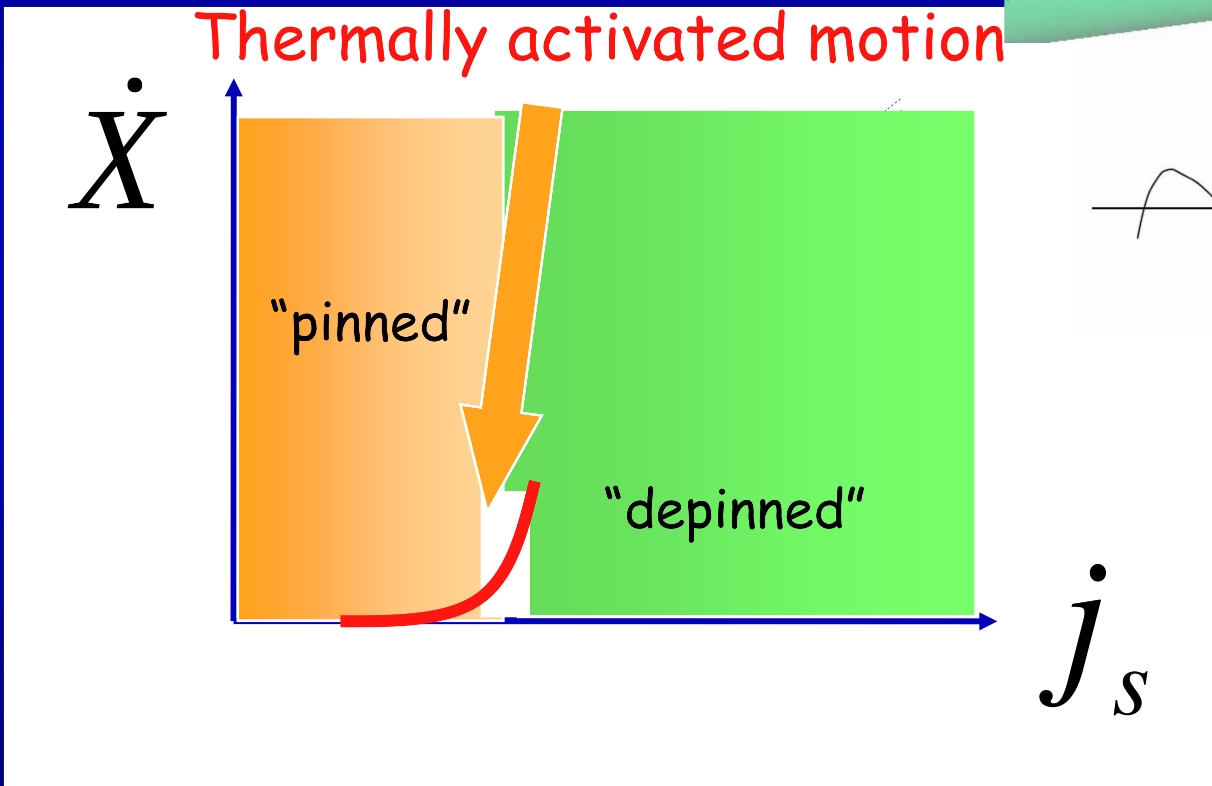
Thermal effect ?

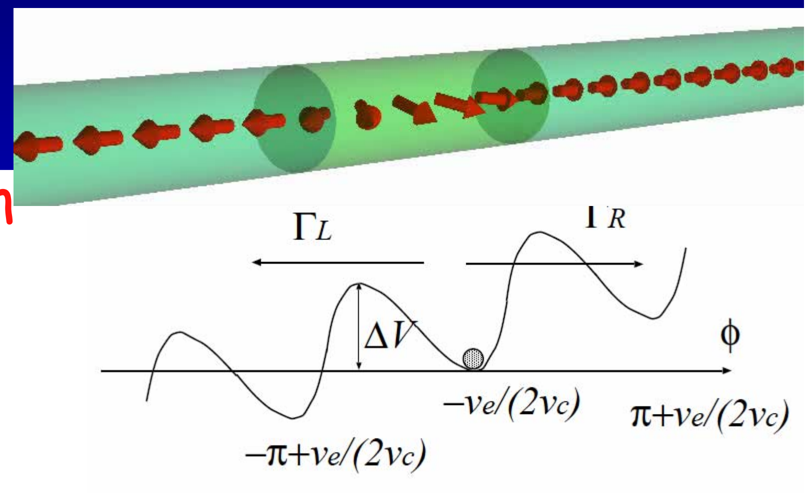
$$\ln v \approx -(T - T_c)^2 j^{-1/2}$$

• Thermally activated motion by spin torque below threshold

Tatara, Vernier & Ferre, Appl. Phys. Lett. (2005)

finite temperature





Energy barrier

= const + I_s

$$\ln v \approx \frac{\pi\hbar I_s}{2ek_BT}$$

Universal

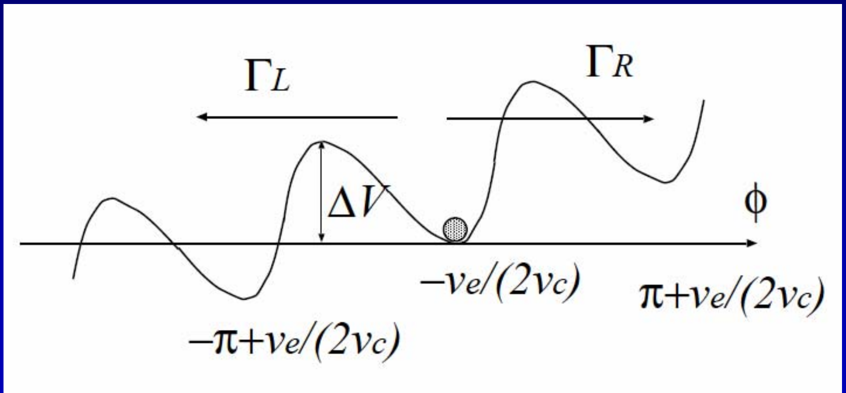
Dependence on I_s / T

• Thermally activated motion by spin torque below threshold

Tatara, Vernier & Ferre, Appl. Phys. Lett. (2005)

• Pinned wall

• Potential for ϕ



$$V_\phi = \frac{NS^2K_\perp}{2}\sin^2\phi + \frac{\hbar}{e} I_s$$

Universal dependence on spin current I_s

• velocity of ϕ

$$\langle\dot\phi\rangle \propto e^{-NS^2K_\perp/(2k_BT)} \sinh\frac{\pi\hbar I_s}{2ek_BT}$$

$$v \equiv \langle\dot X\rangle = -\frac{\lambda}{\alpha}\langle\dot\phi\rangle$$

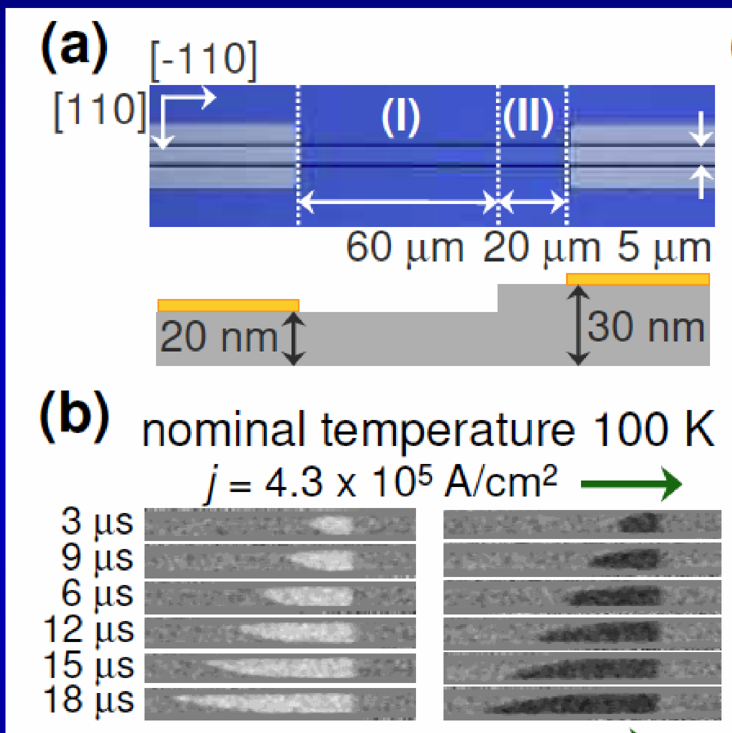
$$\ln v \approx \ln\sinh\frac{\pi\hbar I_s}{2ek_BT} \approx \frac{\pi\hbar I_s}{2ek_BT}$$

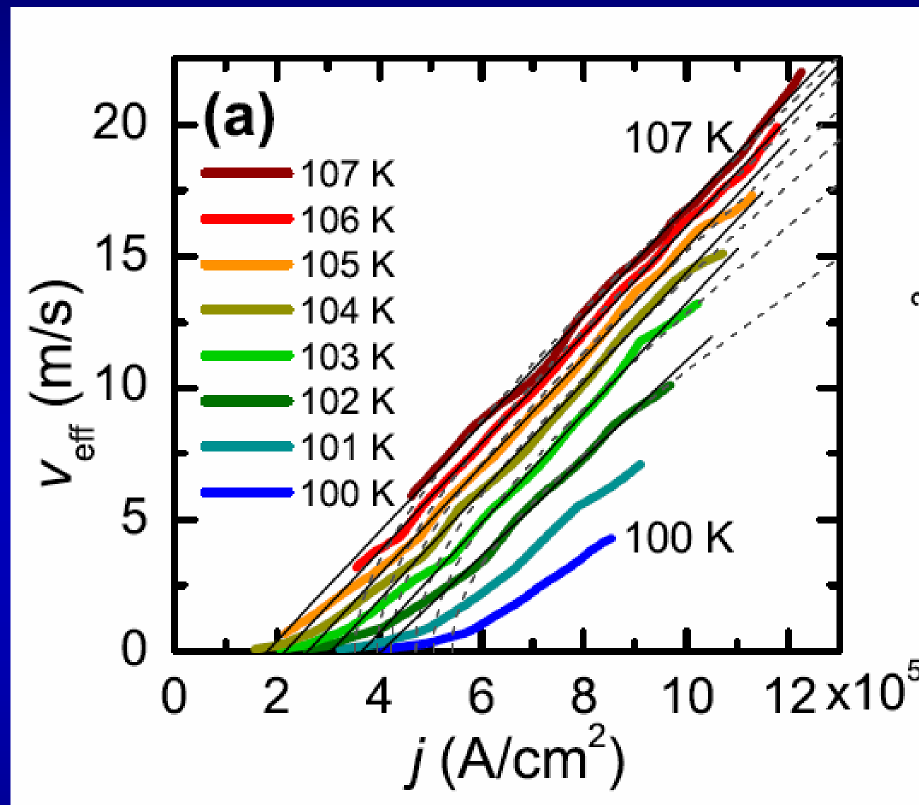
Experiment

GaMnAs

Magnetic semiconductor

Yamanouchi, Chiba, Matsukura, Dietl & Ohno, PRL (2006)





Threshold, velocity:

Consistent with Intrinsic pinning

Thermal effect

Rigid wall theory

Tatara, Vernier & Ferre

$$\ln v \approx j/T$$

$$\ln v \approx -(T-T_c)^2 j^{-1/2}$$

Randomness and creep?
(Nakatani)

Experimemt (**metals**)

$Ni_{81}Fe_{19}$ wire 100-300nm width

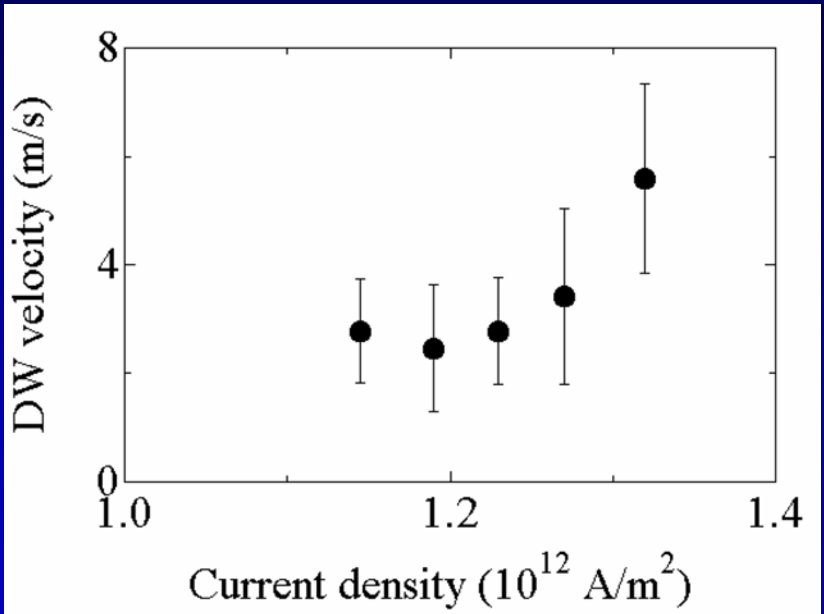
$\lambda \sim$ 500nm   Adiabatic limit

Yamaguchi, Ono, *et al.* (2004)

- $j_c \sim 10^{12}$ A/m^2

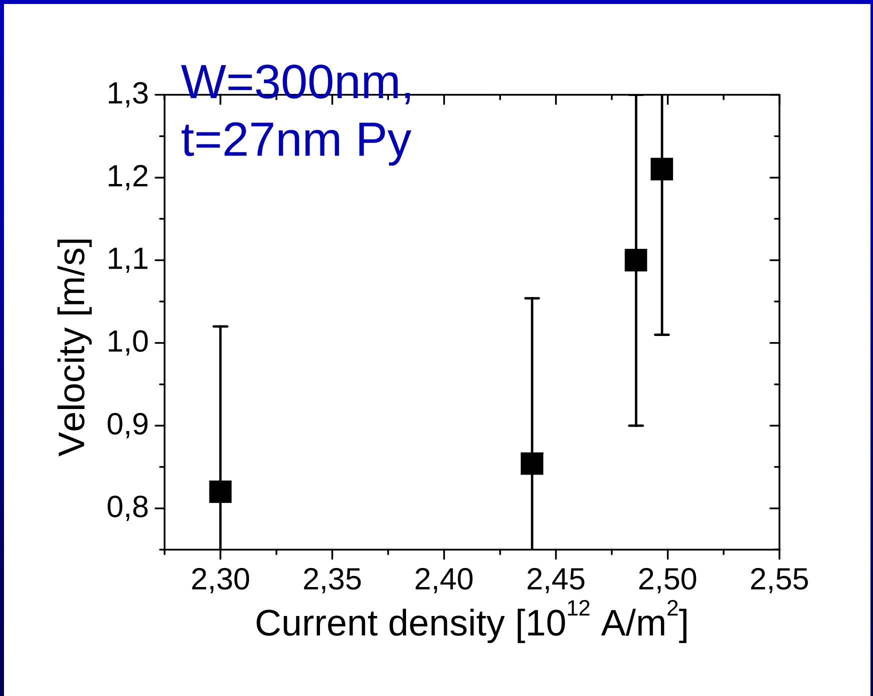
$K_\perp \sim$ 1K ➡ $j_s^{cr} \sim 2.5 \times 10^{13}$[A/m^2]

- $v \sim$ 3 m/s (~30m/s If full spin transfer)



Klaui *et al.* (2005)

- $j_c \sim 2 \times 10^{12}$A/m^2
- $v \sim$ 1 m/s



•Origin of threshold?
•Velocity is too small

j_c may not be of intrinsic origin

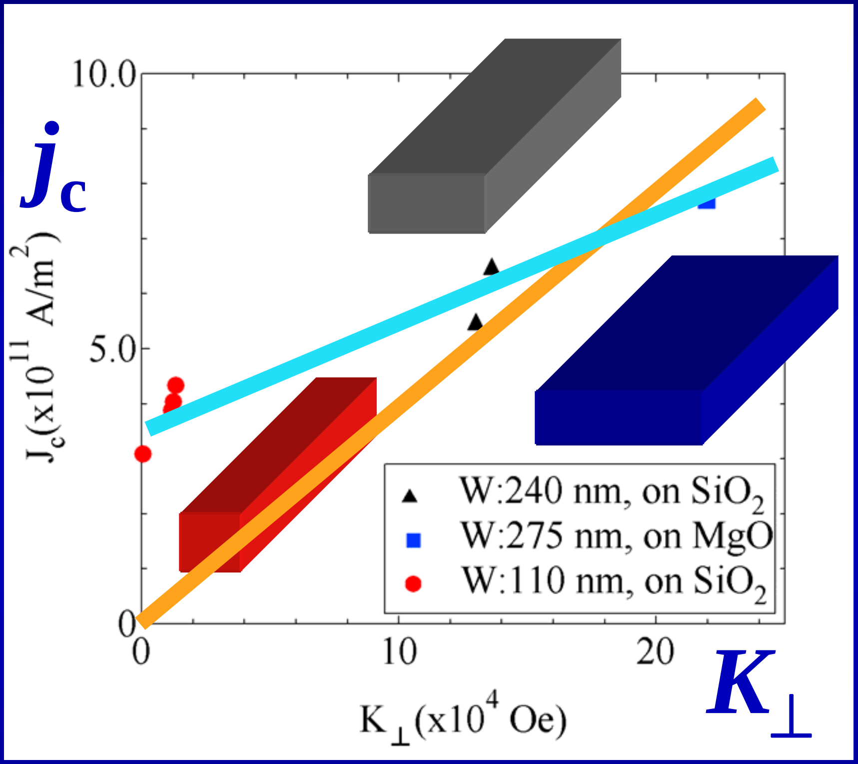
Behavior of threshold (metals)

$$j_c = \frac{eS^2}{a^3 \hbar P} K_\perp \lambda$$ TK04

- Yamaguchi, Ono

J_c depends on geometry ($K_\perp$)
(but weakly)

Not intrinsic pinning ??
(another possibility : see below)



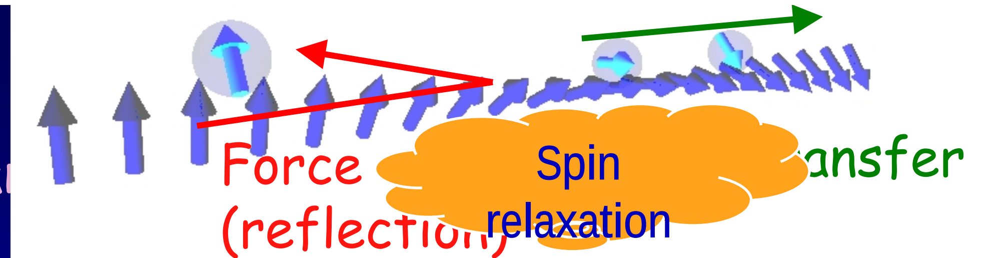
- Parkin

Threshold : Not affected by extrinsic pinning

intrinsic pinning ..? But jc may be too low

Correction terms

•Non-adiabaticity, β-term a



$$\dot{X} - \alpha\lambda\dot{\phi} = \frac{\hbar S}{2} K_{\perp} \lambda \sin 2\phi + \frac{1}{2S}\frac{a^3}{e} P\, j$$

$$\dot{\phi} + \alpha\frac{\dot{X}}{\lambda} = (\gamma R_w + \beta_0)\, j - \frac{1}{2}\Omega^2 X \theta(\lambda - |X|)$$

R_w : resistance b

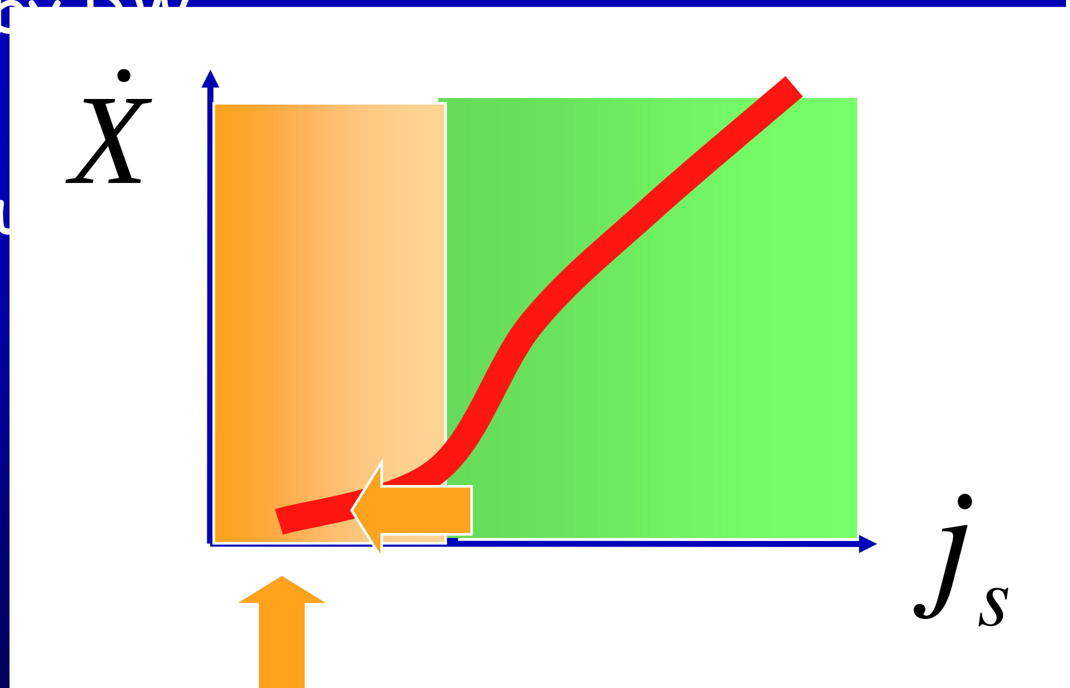
β_0 : Electron spin

Ω : pinning frequ

➡

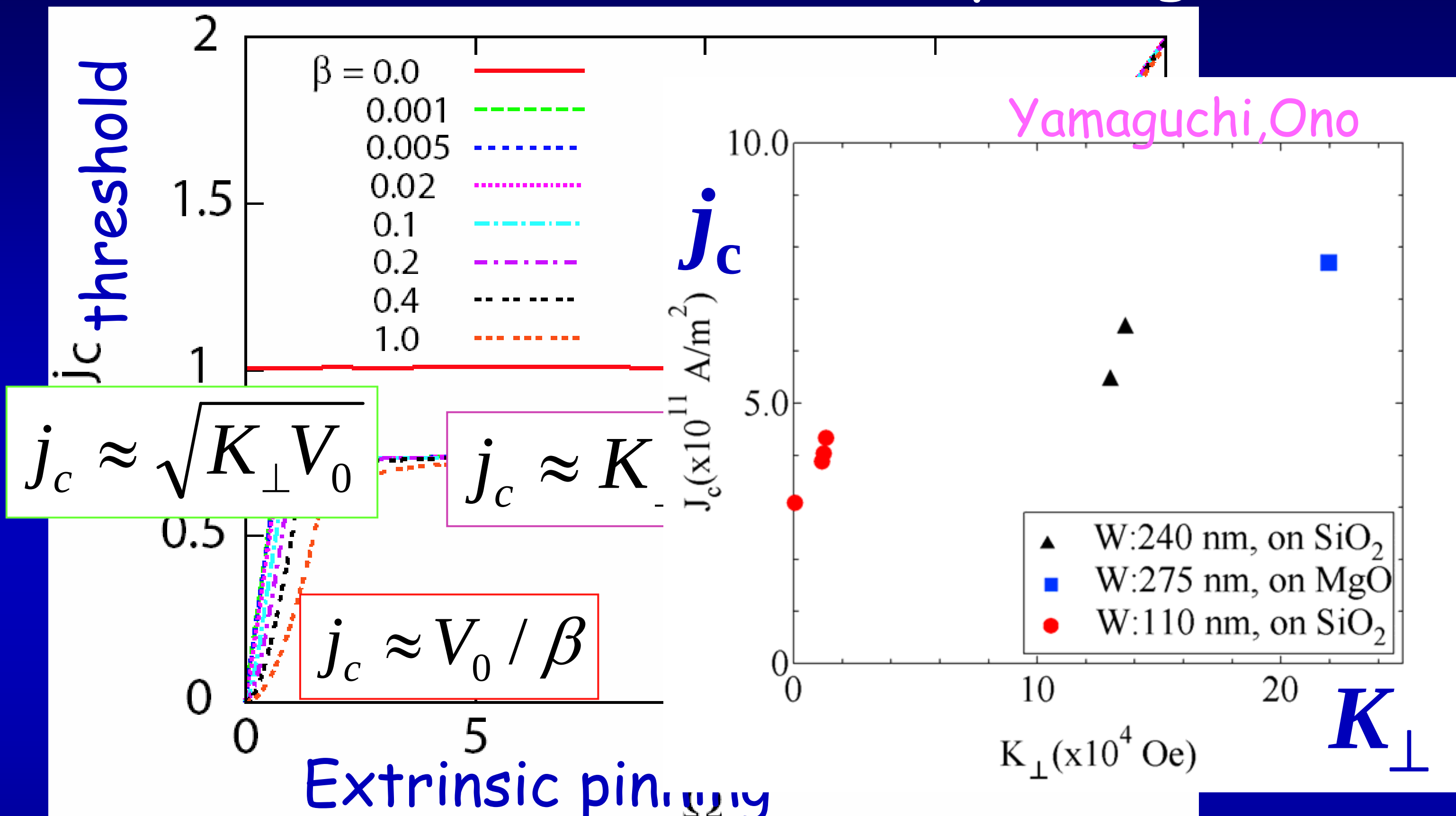
Intrinsic threshold disappears

Even if β is small



j_c determined by Extrinsic pinning

Threshold under β-term and extrinsic pinning



Extrinsic pinning	I-a	$j_c \propto \sqrt{K_\perp V_0}$	Geometry and Pinning
	I-b	$j_c \propto V_0/\beta'$	β' and Pinning
Intrinsic pinning	II	$j_c \propto K_\perp$	Geometry
Extrinsic pinning	III	$j_c \propto V_0/\alpha$	Pinning

Yamaguchi,Ono (?)

Yamanouchi,Ohno

Parkin (?)

Himeno,Ono

Correction terms

- Non-adiabaticity, β-term a

$$\dot{X} - \alpha\lambda\dot{\phi} = \frac{\hbar S}{2} K_{\perp} \lambda \sin 2\phi + \frac{1}{2S}\frac{a^3}{e} P\, j$$

$$\dot{\phi} + \alpha \frac{\dot{X}}{\lambda} = (\gamma R_w + \beta_0)\, j - \frac{1}{2}\Omega^2 X \theta(\lambda - |X|)$$

$$\dot{S} = B \times S + \frac{1}{S}\alpha S \times \dot{S} - \frac{1}{2eS}(j_s \cdot \nabla) S - \frac{1}{eS}\beta_0 S \times (j \cdot \nabla) S$$

Landau-Lifshitz-Gilbert eq.

Origin of β

R_w : resistance by DW   Saitoh et al '04

β_0 : Electron spin relaxation
Zhang & Li '04, Thiaville et al '04, Tserkovnyak et al '05
Kohno GT Shibata '06

Modification of damping by current

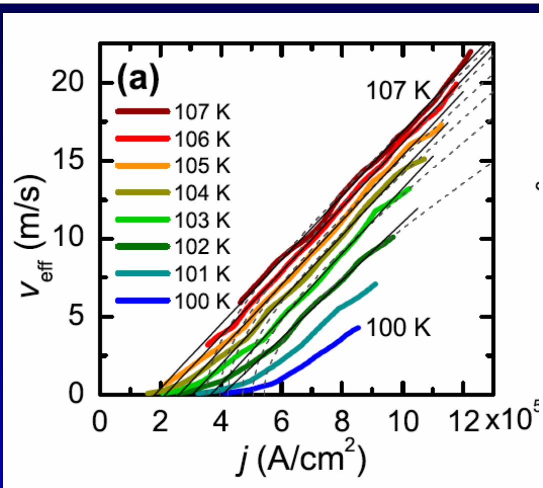
Barnes & Maekawa '05, Tserkovnyak et al $\beta_0 = \alpha$

Stiles, MacDonald...

Different model -> diffrerent results   Still controversial

Summary

Various behavior of J_c



Experiments

- semiconductors

Yamanouchi, Ohno

- Intrinsic pinning appears roughly O.K.
- Thermal activation
  collective creep under random pinning, deformation

- metals
  - Origin of threshold still controversial

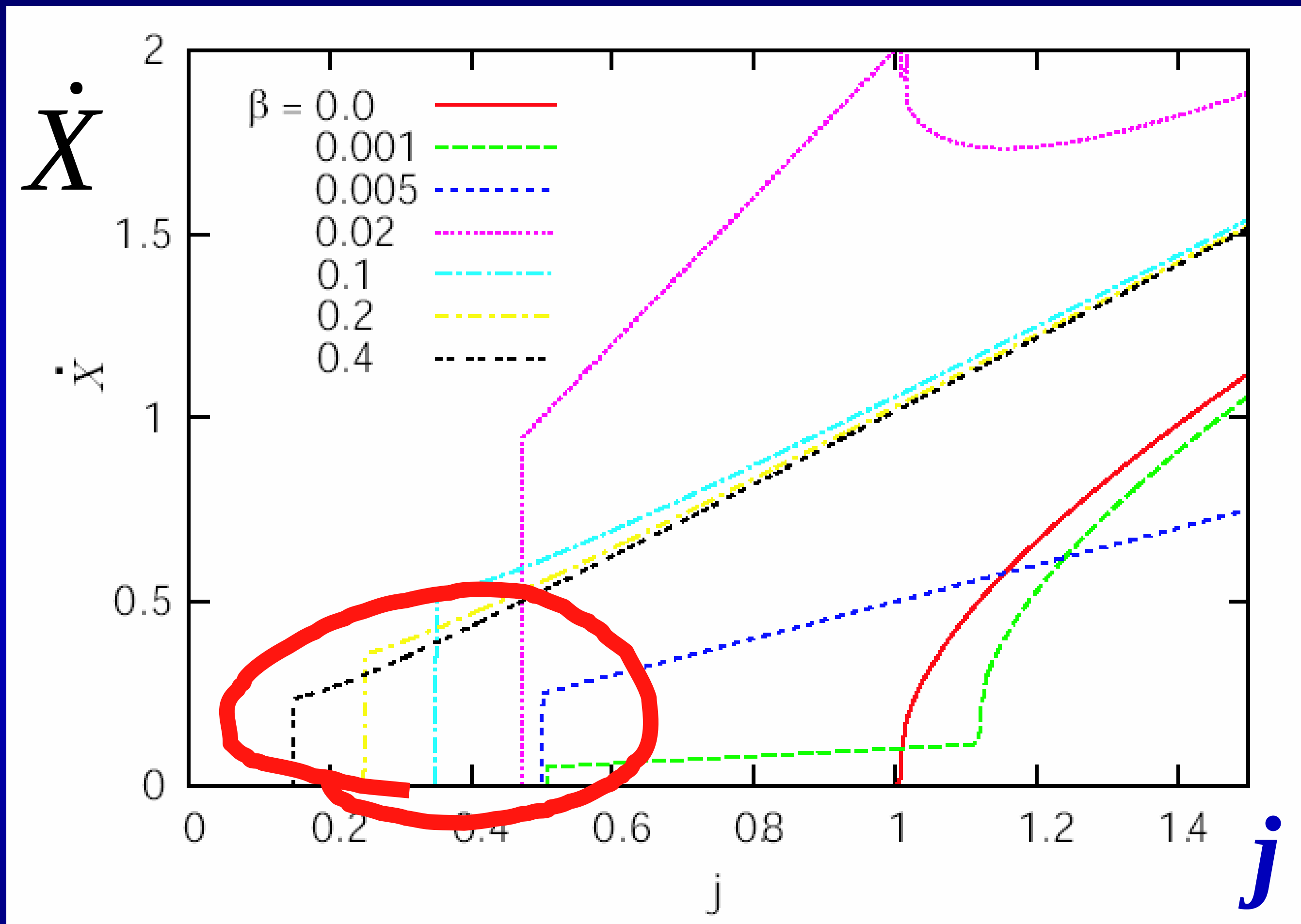
Theory

Role of spin relaxation, single band or s-d?,...

- 3 controllable parameters
  $K_\perp$. V_0, β → Lower J_c !

DW speed

Under extrinsic pinning (fixed)



- Threshold j_c is extrinsic
- Discontinuity at j_c (T=0)

$$v = (\beta / \alpha) j$$

Below threshold

•Non-adiabaticity, β-term and extrinsic pinning

Experiments on metals

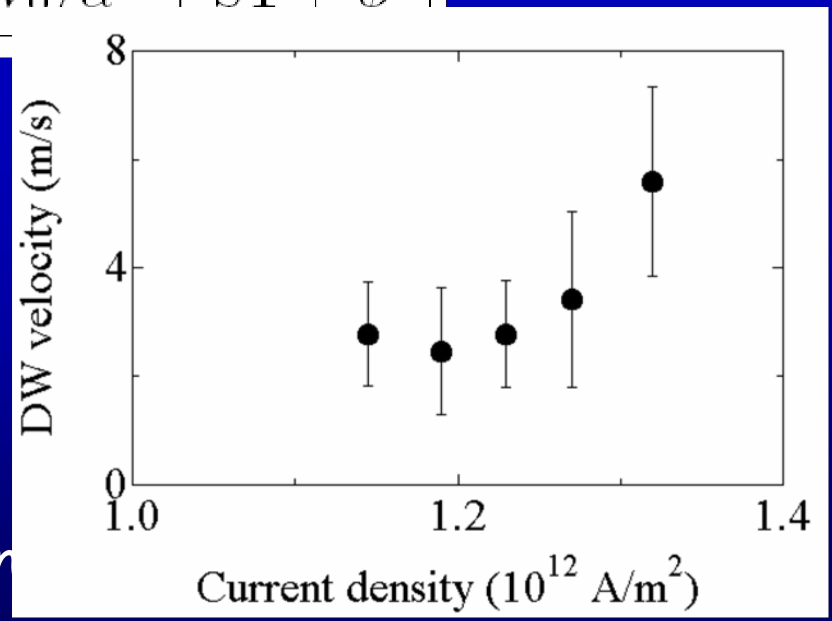
Weak pinning	I-a	$j_c \propto \sqrt{K_\perp V_0}$	ST	X
Weak pinning	I-b	$j_c \propto V_0/\beta'$	β'	X
Intermediate pinning	II	$j_c \propto K_\perp$	ST	ϕ
Strong pinning	III	$j_c \propto V_0/\alpha$	ST	ϕ

Yamaguchi et al

$j_c \sim 10^{12}$ [A/m^2] << $K_\perp$

$v \sim 3$ [m/s]

$H_c \sim 10\text{-}100$ [Oe]



Experimen

Thermally smeared out pinning potential ?

•Non-adiabaticity, β-term and extrinsic pinning

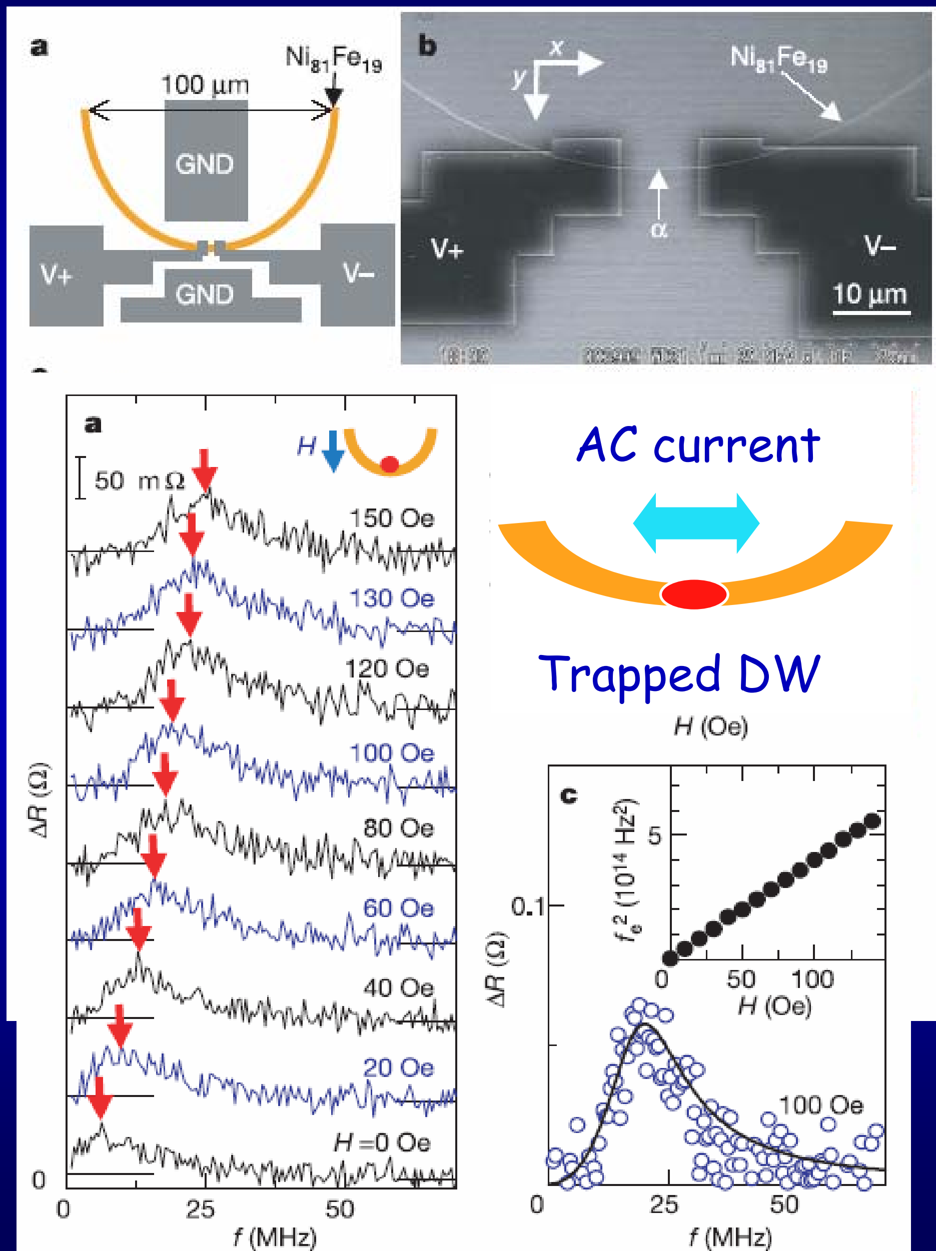
Extrinsic pinning	I-a	$j_c \propto \sqrt{K_\perp V_0}$	Geometry and Pinning
	I-b	$j_c \propto V_0/\beta'$	β' and Pinning
Intrinsic pinning	II	$j_c \propto K_\perp$	Geometry
Extrinsic pinning	III	$j_c \propto V_0/\alpha$	Pinning

To lower threshold

- Sample quality (extrinsic pinning V_0)
- Spin-orbit (β) : heavy impurities
- Sample geometry (intrinsic pinning $K_\perp$)

•Manipulation by AC current

•Spin transfer or Momentum transfer? - driving mechanism



•E. Saitoh, Miyajima, Yamaoka & Tatara, Nature 432, 203 (2004)

•DW motion by use of resonance

•Momentum transfer dominates

•Determination of DW character

$m=6.6\times10^{-23}$ kg
$\tau=10^{-8}$ s ($\alpha=0.01$)
$R_w=10^{-4}\ \Omega$

•Low-current operation

$j\approx10^{10}[\mathrm{A/m^2}]\quad \Delta X\approx10\mu\mathrm{m}$

Resonance

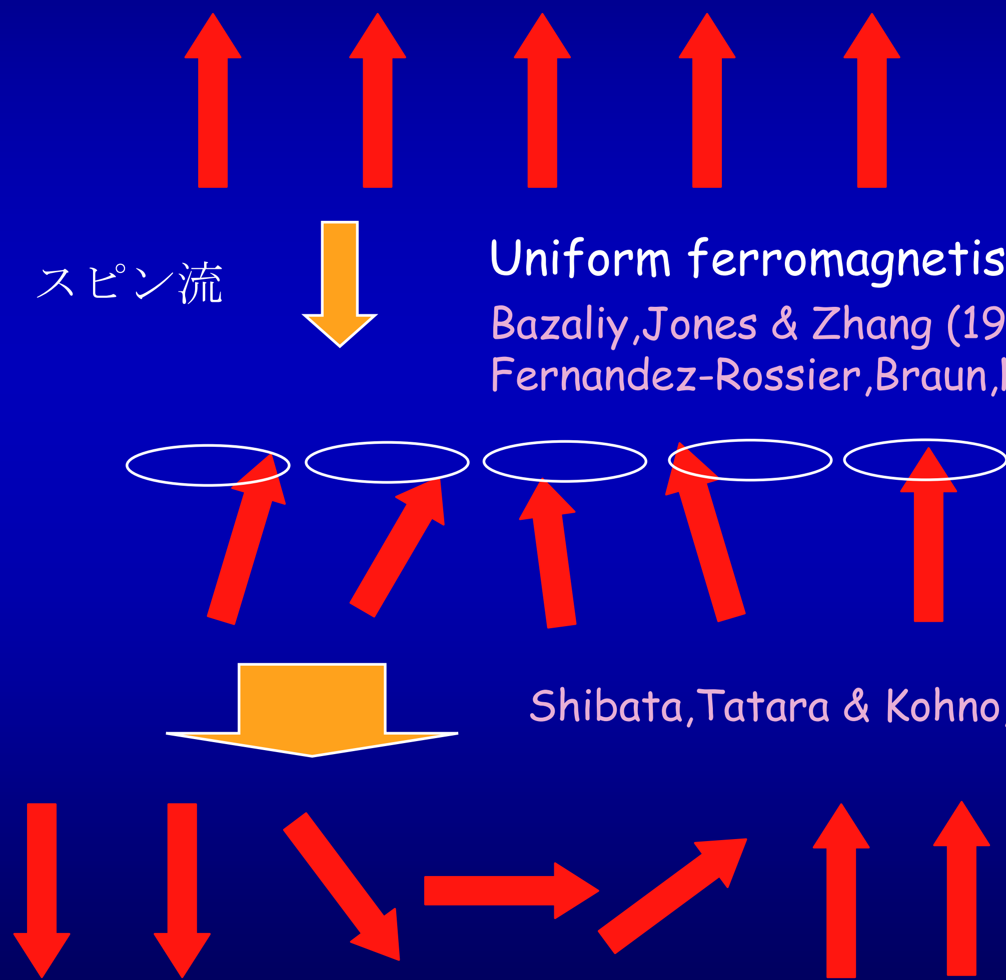
"Domain wall electronics"

Nature, News and Views

20MHzでの動作

- 電流による書き込み
  - スピン流による磁壁生成

一様強磁性状態



Uniform ferromagnetism unstable

Bazaliy,Jones & Zhang (1998)
Fernandez-Rossier,Braun,Nunez &MacDonald (2004)

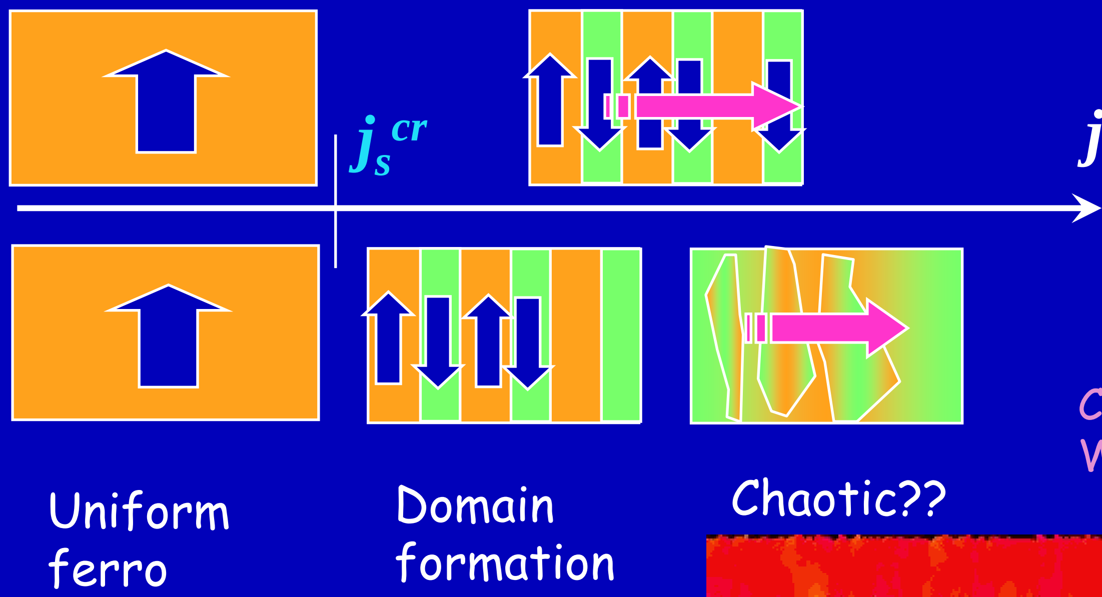
Shibata,Tatara & Kohno, Phys. Rev. Lett. (2005)

磁壁生成

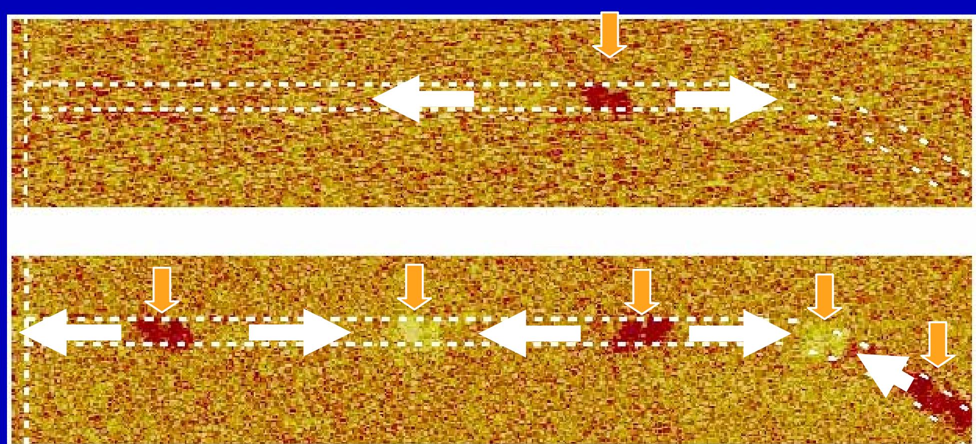
情報書き込み

- Domain nucleation by spin current

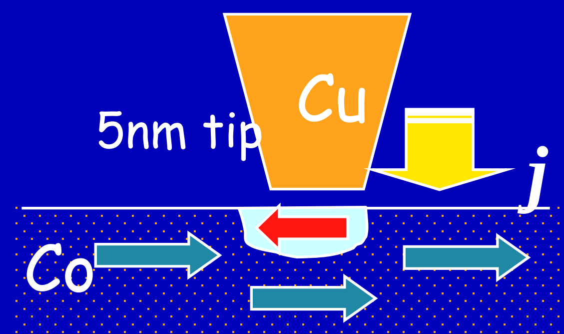
$j_s^{cr} \sim 10^{12\text{-}13}[A/m^2]$



Cf. Thieville, Nakatani, Miltat
Wegrowe, Ansermat (1999)



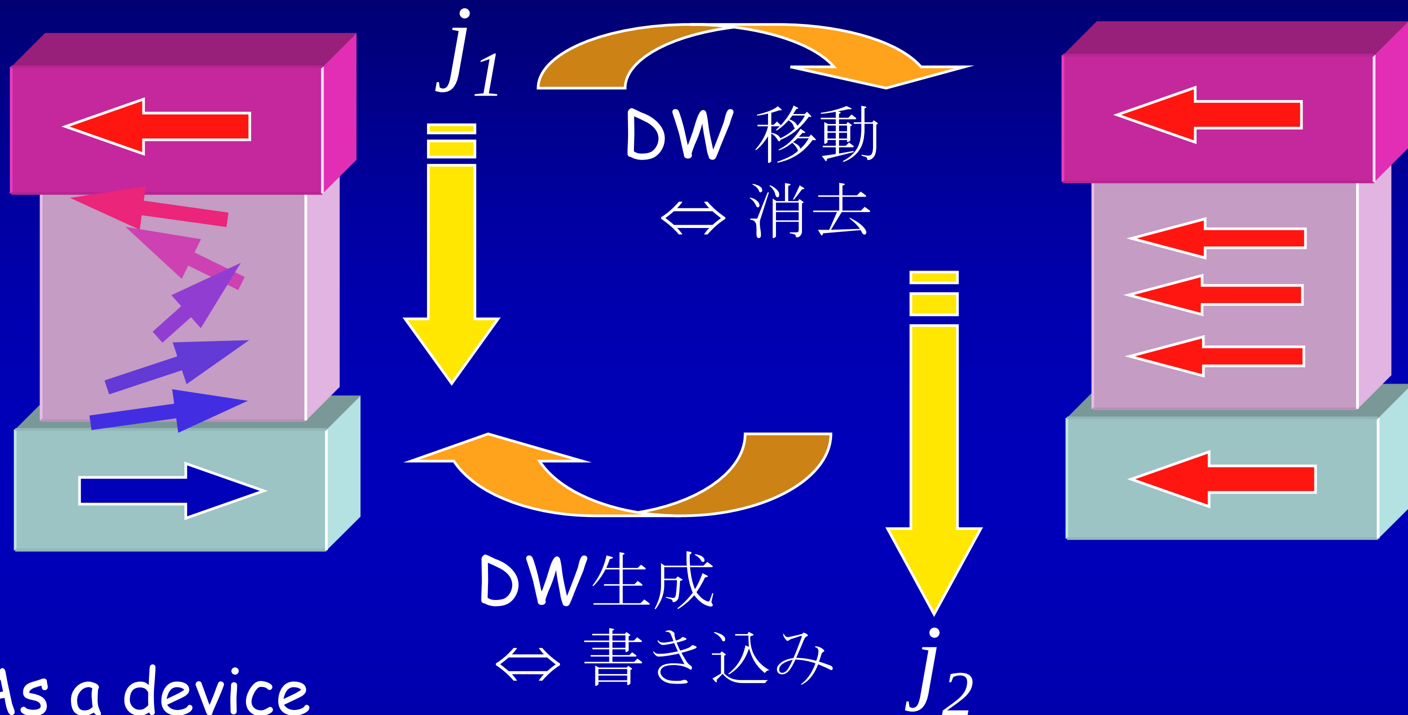
- Ono et al (2004)



- Chen, Ji, Chien and Stiles (2004)

制御すれば電流による書き込み

•磁壁の電流による制御（ここまでの結果）



As a device

✓ •Erase information

✓ •Operation speed : 20MHz range

✓ •Write in : domain wall nucleation