Physics

Stewart E. Barnes

SERIES ON SEMICONDUCTOR SCIENCE AND TECHNOLOGY • 13

Nowadays information technology is based on semiconductor and ferromagnetic materials. Information processing and computation are based on electron charge in semiconductor transistors and integrated circuits, and information is stored on magnetic high-density hard disks based on the physics of the electron spins. Recently, a new branch of physics and nanotechnology, called magneto-electronics, spintronics, or spin electronics, has emerged, which aims at simultaneously exploiting both the charge and the spin of electrons in the same device. A broader goal is to develop new functionality that does not exist separately in a ferromagnet or a semiconductor. The aim of this book is to present new directions in the development of spin electronics in both the basic physics and the technology which will become the foundation of future electronics.

Sadamichi Maekawa is Honda Professor at the Institute for Materials Research, Tohoku University, Japan.

'Maekawa is a leading theorist in metal spin electronics... He has an excellent vision for this book.' L. J. Sham, University of California at San Diego

'. . . a very promising book, on subjects of interest to large numbers of researchers world-wide and across several disciplines.'
Kevin Edmonds, University of Nottingham

Cover image: Semiclassical picture of a spin-polarized electron interacting with a ferromagnetic thin film. The electron spin precesses as it travels through the magnet, due to the exchange field of the magnet. The changing angular momentum of the electron must be compensated by a corresponding change in angular momentum for the ferromagnet.

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Maekawa

Concepts in Spin Electronics

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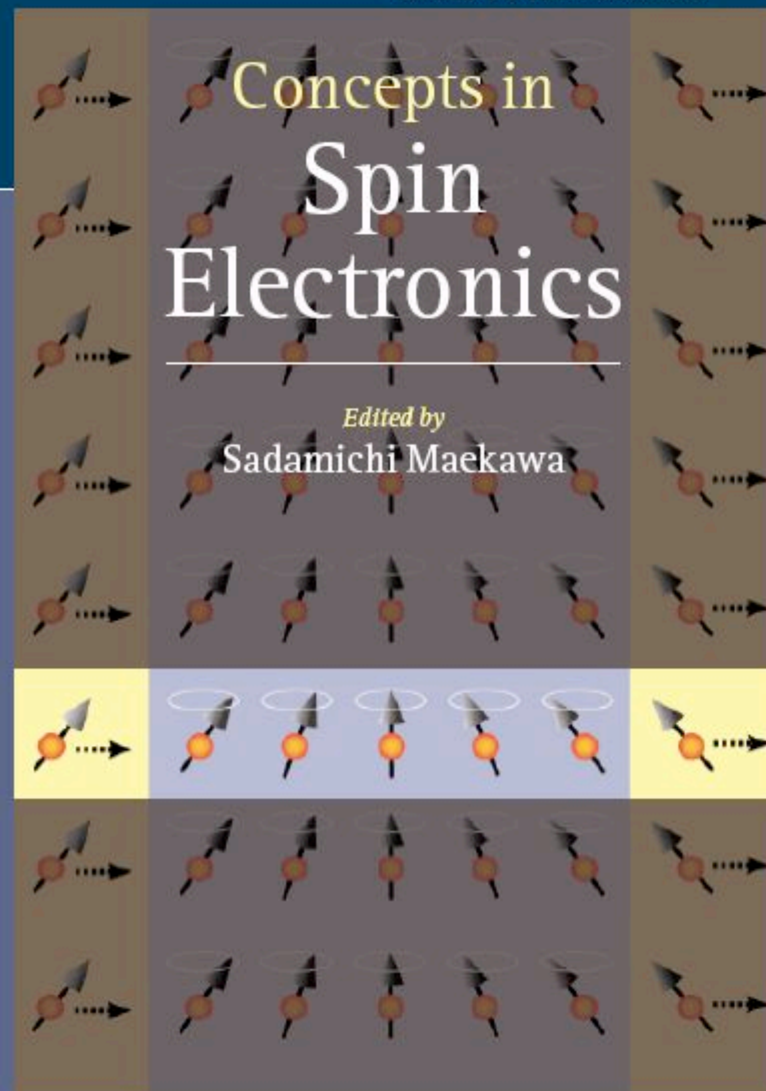
Concepts in Spin Electronics

Edited by
Sadamichi Maekawa



On the Dynamics of Domain Walls in Narrow Wires

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with S. Maekawa and J. Ieda, IMR Tohoku University, Japan

1. Background - experiment

2. A Domain wall in the Stoner model

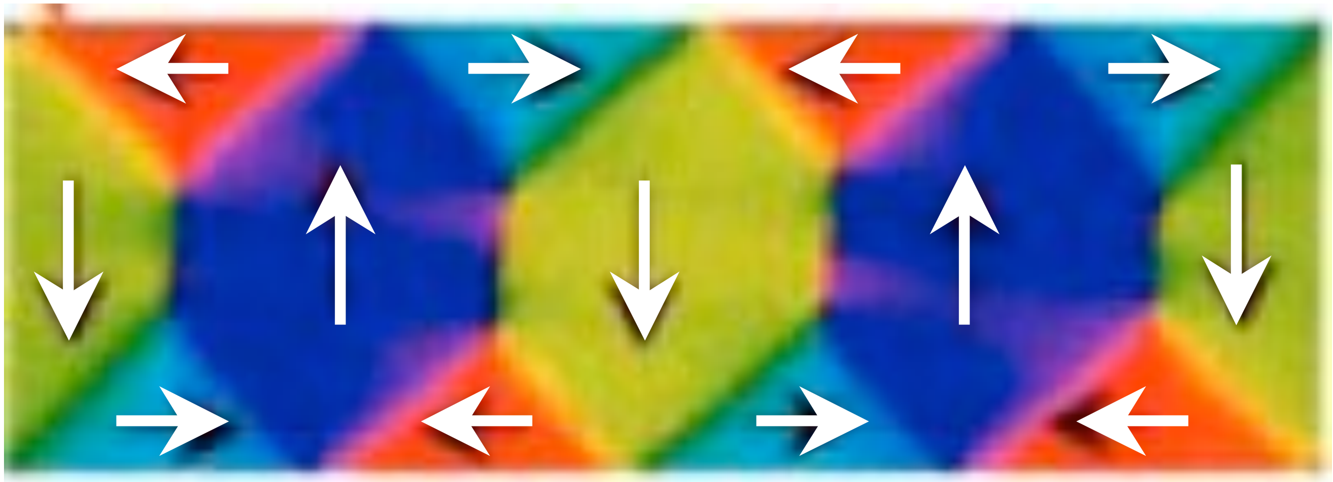
3. Torque transfer and emf's

4. Relaxation - Gilbert - 2nd law of thermo

5. Critical currents

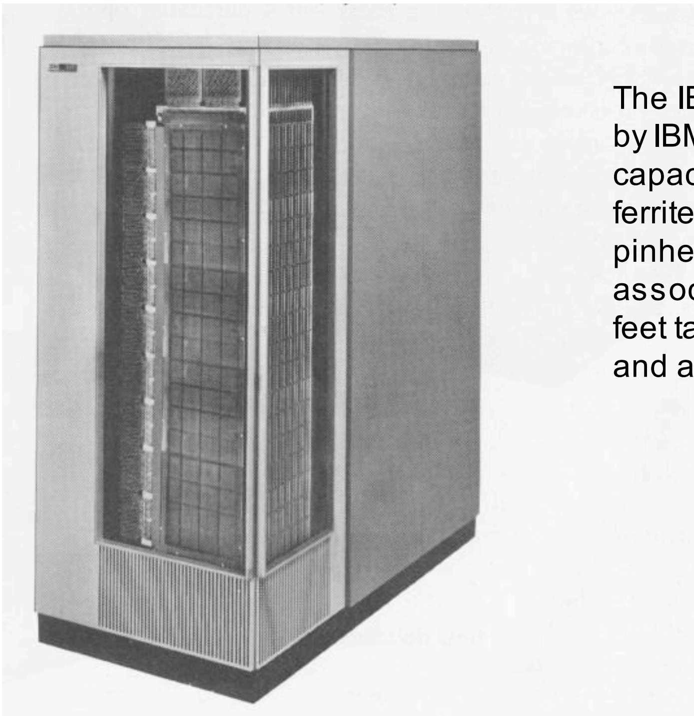
6. Spintronic devices

Domain structure in Fe:



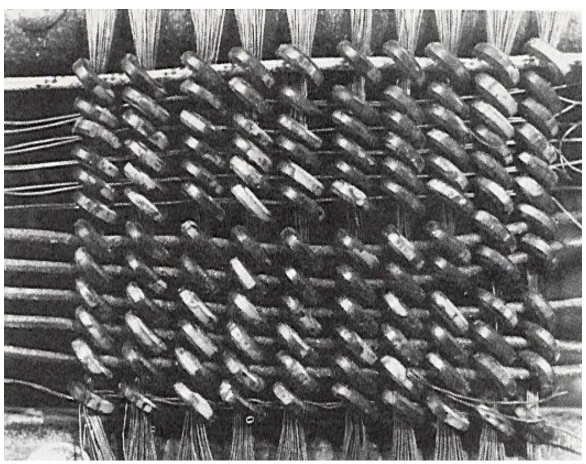
L. Thomas *et al*., Appl. Phys. Lett. **76**, 766 (2000).

c.f., P. Weiss: J. Phys. **6**, 661 (1907),
H. Barkhausen: Phys. Z. **20**, 401 (1919),
K. Honda & S. Kaya: Sci. Repts. Tohoku Imp. Univ. **15**, 721 (1926),
F. Bloch: Z. Phys. **74**, 295 (1932),
F. Bitter: Phys. Rev. **38**, 1903; **41**, 507 (1932).

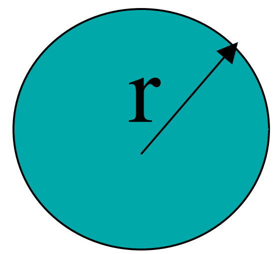


The IBM 2361 Core Storage Module housed 16K bytes of core memory.

The IBM 2361 Core Storage Unit was introduced in April 1964 and built by IBM's Poughkeepsie, N.Y., manufacturing facilities with 16 times the capacity of any previous IBM memory. In each 2361, almost 20 million ferrite cores -- tiny doughnut-shaped objects, each about the size of a pinhead -- were strung in two-wire networks and packaged, with associated circuitry, into a cabinet only five by 2 ½ feet and less than six feet tall. The 2361's design provided for storage of 524,000 36-bit words and a total cycle time of eight microseconds in each memory.



Why torque transfer?

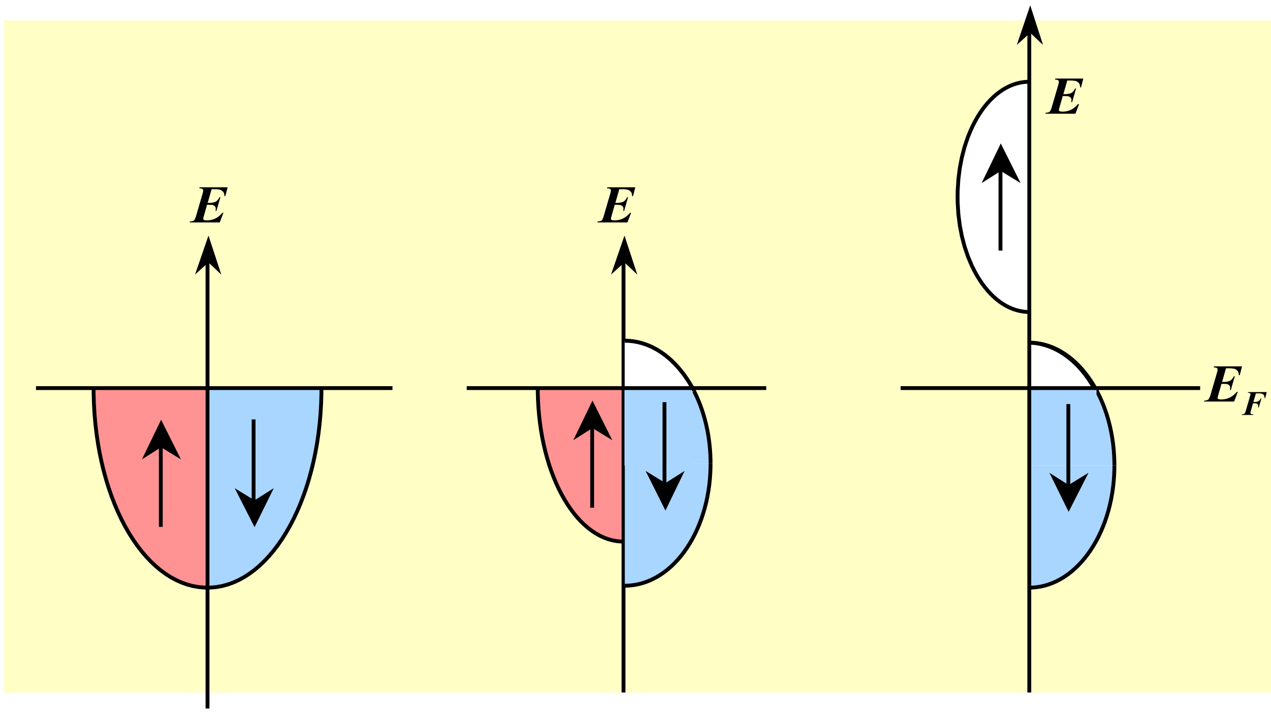


$B \sim r$

$\mathbf{M} \sim r^2$

$dL/dt \sim r^2$

What is a ferromagnet ?



Cu | **Fe,Co,Ni** | **$La_{1-x}Sr_xMnO_3$**

Electron number :	$N_\uparrow = N_\downarrow$	$N_\downarrow > N_\uparrow$	$N_\downarrow > N_\uparrow = 0$ **(half-metal)**
Atomic energy :	$\varepsilon_{i\uparrow} = \varepsilon_{i\downarrow}$	$\varepsilon_{i\downarrow} < \varepsilon_{i\uparrow}$	$\varepsilon_{i\downarrow} \ll \varepsilon_{i\uparrow}$

Electric current : $J_\uparrow \neq J_\downarrow$

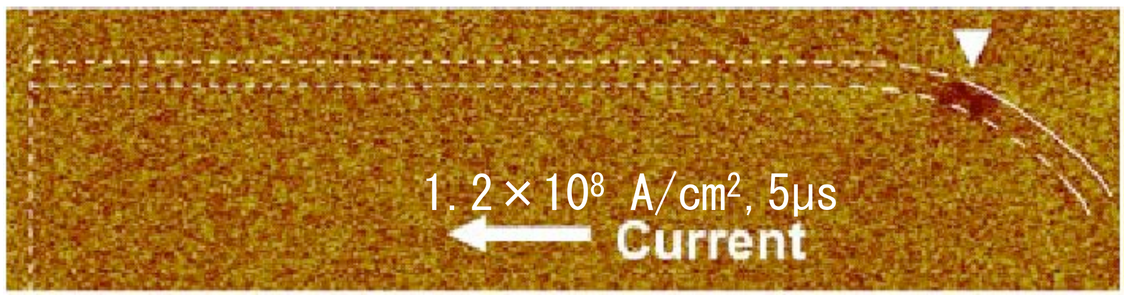
Magnetization : $\boldsymbol{M} = \mu_{\mathrm{B}} \left(N_\downarrow - N_\uparrow \right)$

charge current : $J_c = J_\uparrow + J_\downarrow$

spin current : $J_s = J_\uparrow - J_\downarrow$

小野輝男 大阪大学

Current-driven domain wall motion
(tail-to-tail domain wall)



Tail-to-tail DW also moves opposite to current direction.
No effect of Oersted field.

Polarisation of charge current:

ferromagnet

Conduction electron polarisation p

letters to nature

Nature **428**, 539 - 542 (01 April 2004); doi:10.1038/nature02441

Current-induced domain-wall switching in a ferromagnetic semiconductor structure

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[2] ERATO Semiconductor Spintronics Project, Japan Science and Technology Agency, Japan

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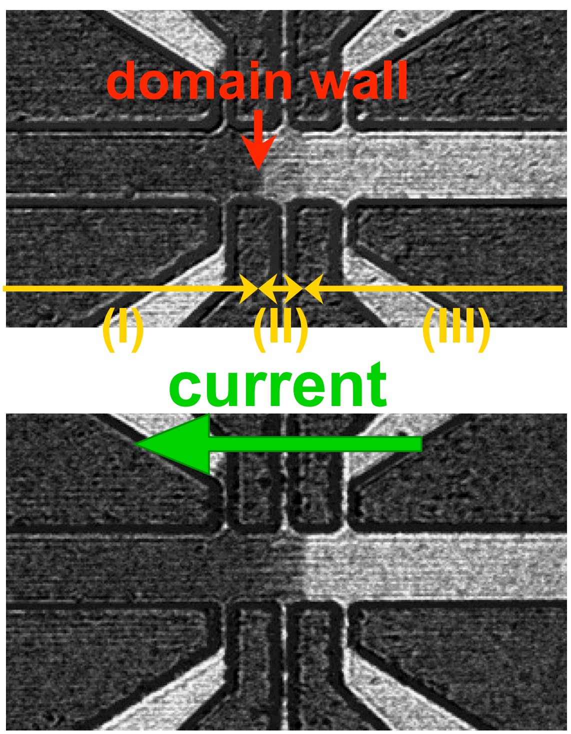
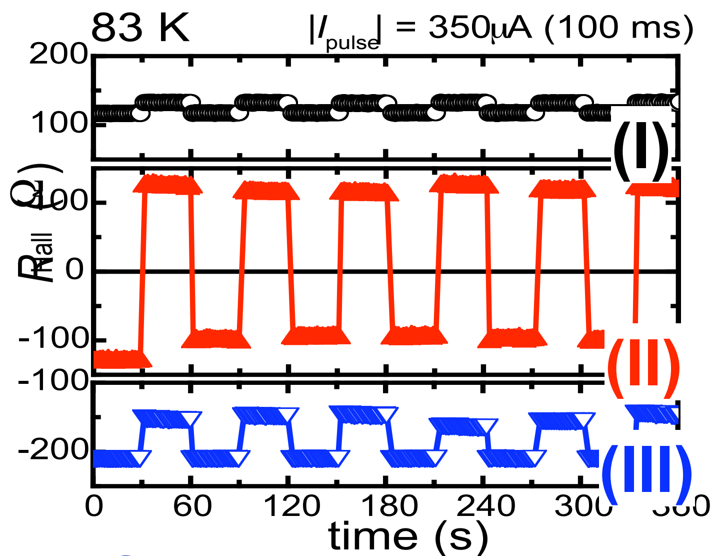
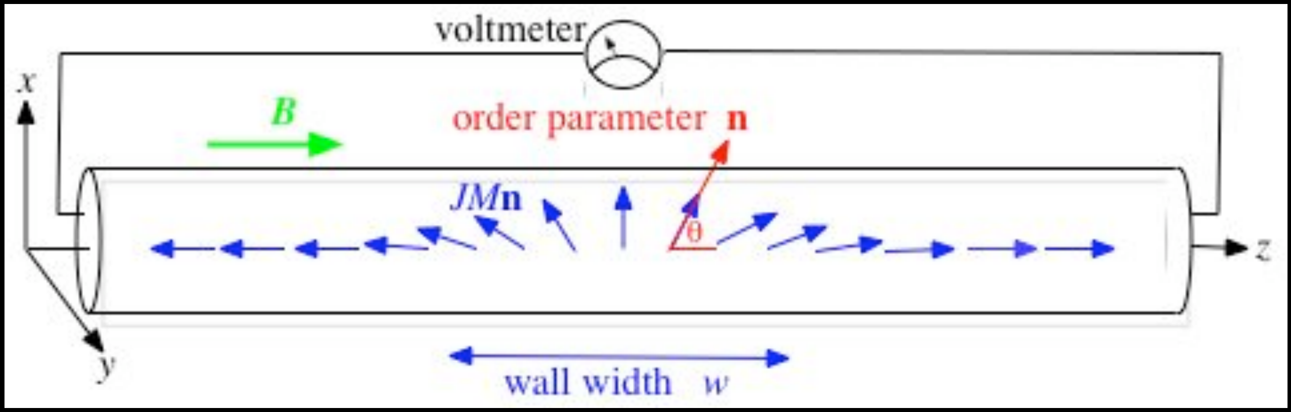




Sample A

~ 80 K

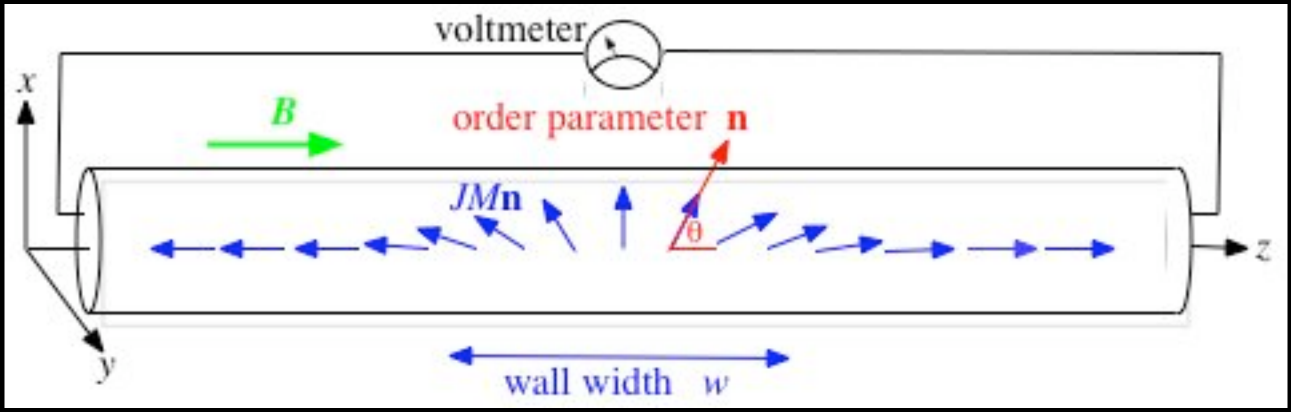
A domain wall :



The Stoner model:

$$i\hbar \frac{\partial \psi(\vec{r}, t)}{\partial t} = \left[\frac{p^2}{2m} + JM\vec{s} \cdot \hat{\mathbf{n}} + \frac{g\mu_B B_0}{\hbar} s_z \right] \psi(\vec{r}, t)$$

A domain wall :



The rotating frame :

$$U_\phi = e^{is_z\phi/\hbar}; \quad \hbar\dot{\phi} = \hbar\omega = g\mu_B B_0$$

$$U_\theta = e^{is_y\theta/\hbar}$$

$$\psi'(\vec{r},t) = U_\phi U_\theta \psi(\vec{r},t)$$

Schrodinger's equation in the rotating frame:

$$i\hbar \frac{\partial \psi'(\vec{r},t)}{\partial t} = \left[\frac{1}{2m} (\vec{p} - \frac{\hbar}{2} \vec{A}_s^t)^2 + JM s_z \right] \psi'(\vec{r},t)$$

$$\vec{A}_s^t = \frac{2}{\hbar} s_y \frac{\partial \theta}{\partial z} \hat{\mathbf{z}}$$

Wow - a non-abelian gauge theory!

Solve no wall Schrodinger's :

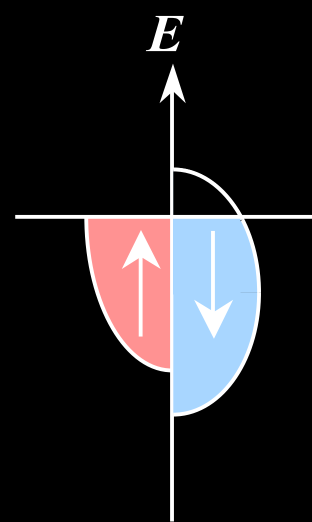
$$i\hbar \frac{\partial \psi'(\vec{r},t)}{\partial t} = \left[\frac{p^2}{2m} + JMs_z \right] \psi'(\vec{r},t)$$

$$\text{Solution :} \quad \psi'_{\vec{k}\pm}(\vec{r},t)$$

$$E_\pm = (\hbar^2 k^2/2m) \pm (\hbar/2)JM \qquad \vec{p} = \hbar\vec{k}$$

$$s_z = \mp\hbar/2 \quad \text{majority/minority}$$

Electronic structure :



Fe,Co,Ni

Laboratory frame :

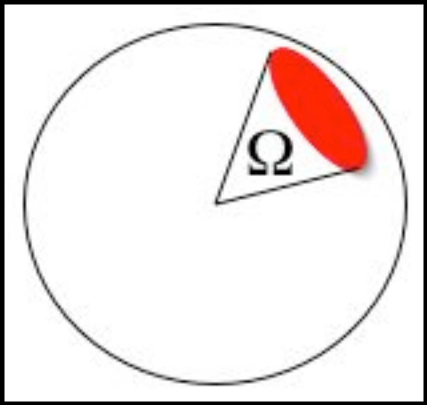
$$\psi_{\vec{k}\pm}(\vec{r},t) = U_{\theta}^{-1} U_{\phi}^{-1} \psi'_{\vec{k}\pm}(\vec{r},t)$$

Berry's phase :

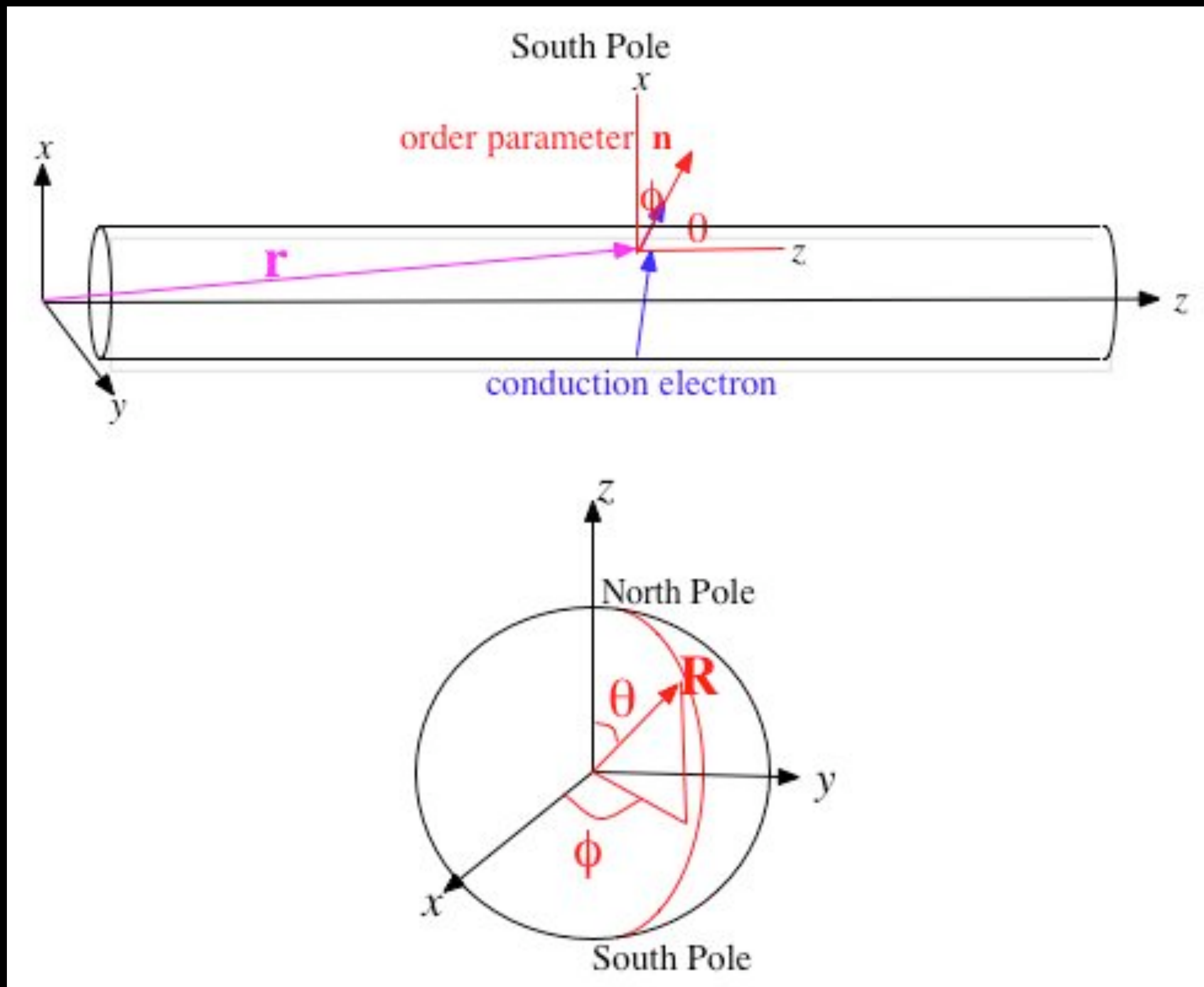
$$\gamma_s^{\pm} = i \int_{\vec{R}_0}^{\vec{R}} \langle \psi_{\vec{k}\pm} | \vec{\nabla}_{\vec{R}} \psi_{\vec{k}\pm} \rangle \cdot d\vec{R}$$

Spin Berry's phase :

$$\gamma_s = \mp \frac{\Omega}{2} \quad \text{as} \quad s_z = \pm \frac{\hbar}{2}$$



Spin Berry's phase :



Another vector potential

$$\gamma_s = \frac{1}{2}\int_{\vec{r}_0}^{\vec{r}} \vec{A}_s \cdot d\vec{r}$$

$$\vec{A}_s \equiv 2i\langle \psi_{\vec{k}\pm} | \vec{\nabla}_{\vec{r}} \psi_{\vec{k}\pm} \rangle$$

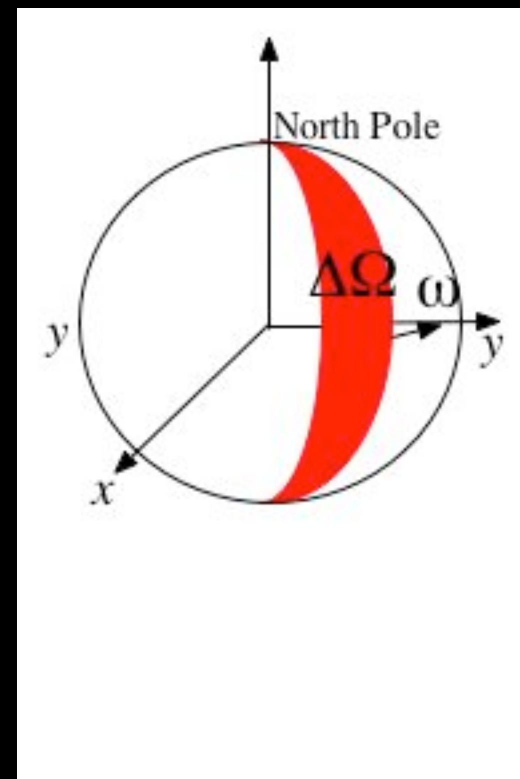
$$\boxed{\vec{f}_s^{\pm} = -(\hbar/2)(\partial \vec{A}_s^{\pm}/\partial t) = \mp \frac{1}{2} g \mu_B B_0 (\partial/\partial z) \cos\theta \, \hat{\mathbf{z}}}$$

Faraday's Law (maybe) :

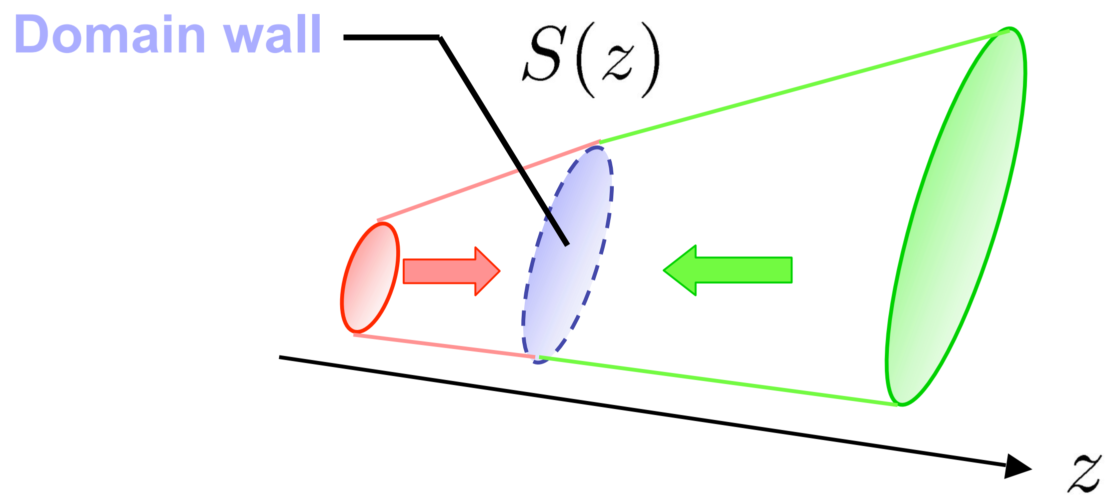
$$\mathcal{E} = -\frac{\hbar}{(-e)}\frac{d\gamma}{dt}$$

“Motional emf” :

$$\mathcal{E} = \frac{g\mu_B B_0}{e} = \frac{P_z v_c}{2eS}$$



Electromotive force due to DW



Magnetic energy stored in Domain wall

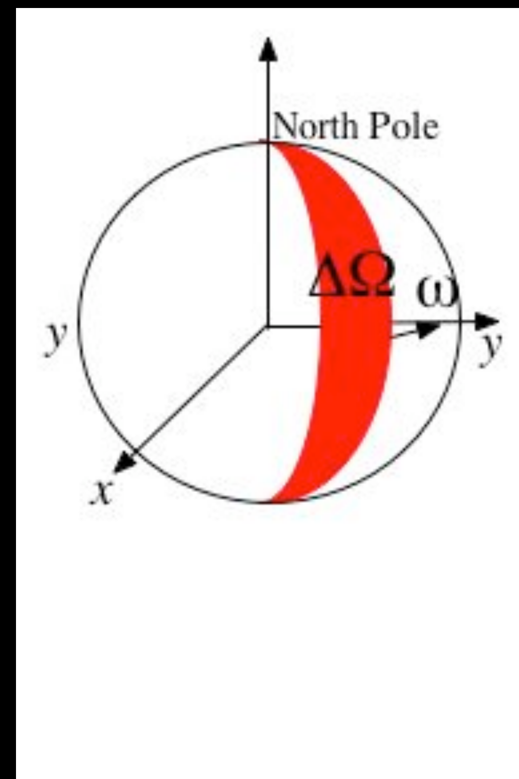
$$W(z) = \sigma_{\mathrm{DW}} S(z), \quad (\sigma_{\mathrm{DW}} = \sqrt{AK})$$

$$\mathcal{P}_z = -\frac{1}{S(z)} \frac{\partial W(z)}{\partial z}$$

$$\boxed{\mathcal{E} = p \frac{v_c}{2eM} \mathcal{P}_z}$$ Electromotive force

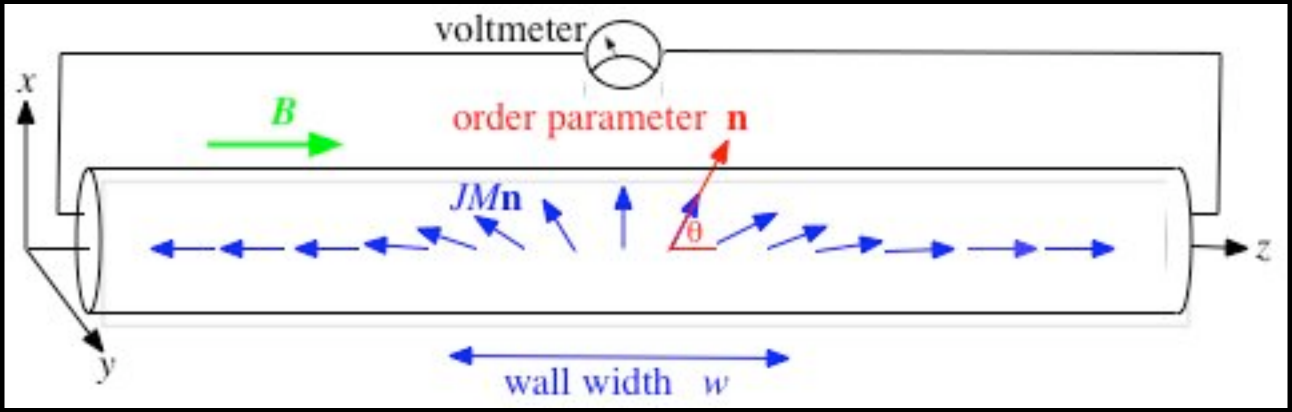
“Motional emf” :

$$\mathcal{E} = \frac{g\mu_B B_0}{e} = \frac{P_z v_c}{2eS}$$




Spin
Toshiba
battery
1.5V
LEAK PROOF
東芝乾電池

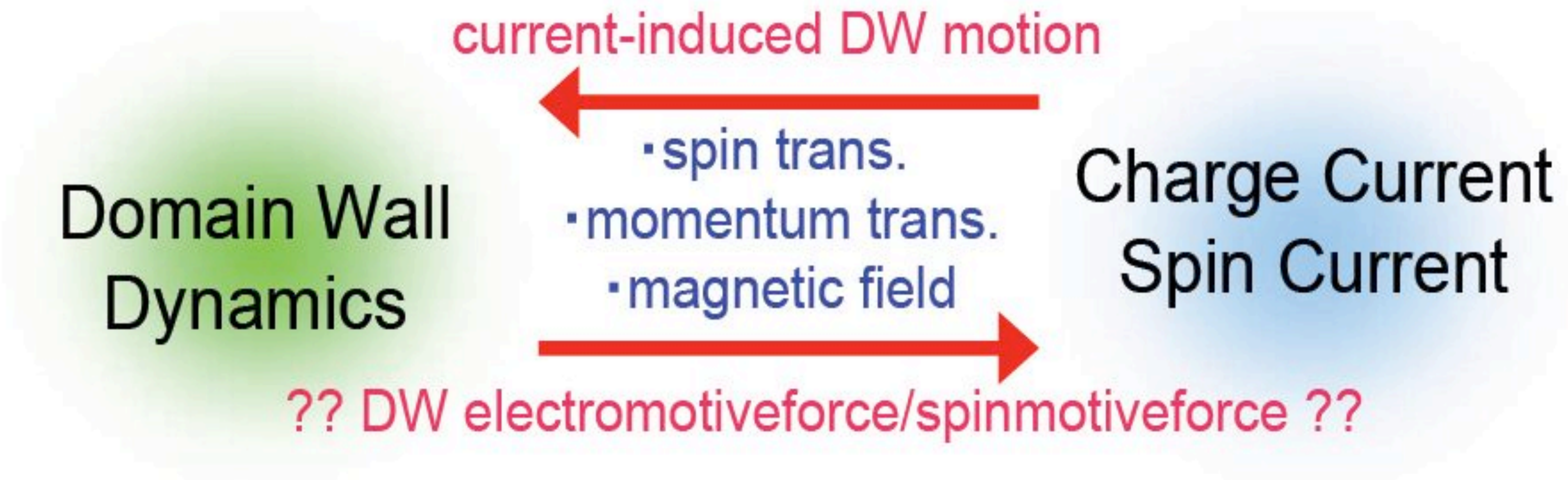
Measure voltage :



Saitoh

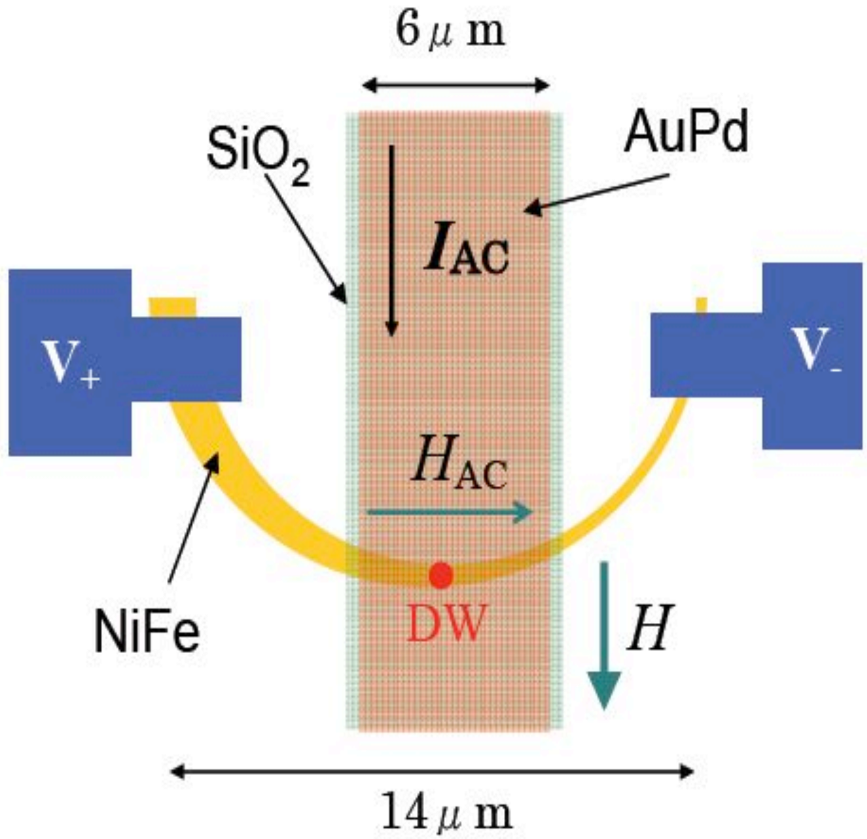
Electromotiveforce due to DW motion

- the reciprocity in current-DW coupling

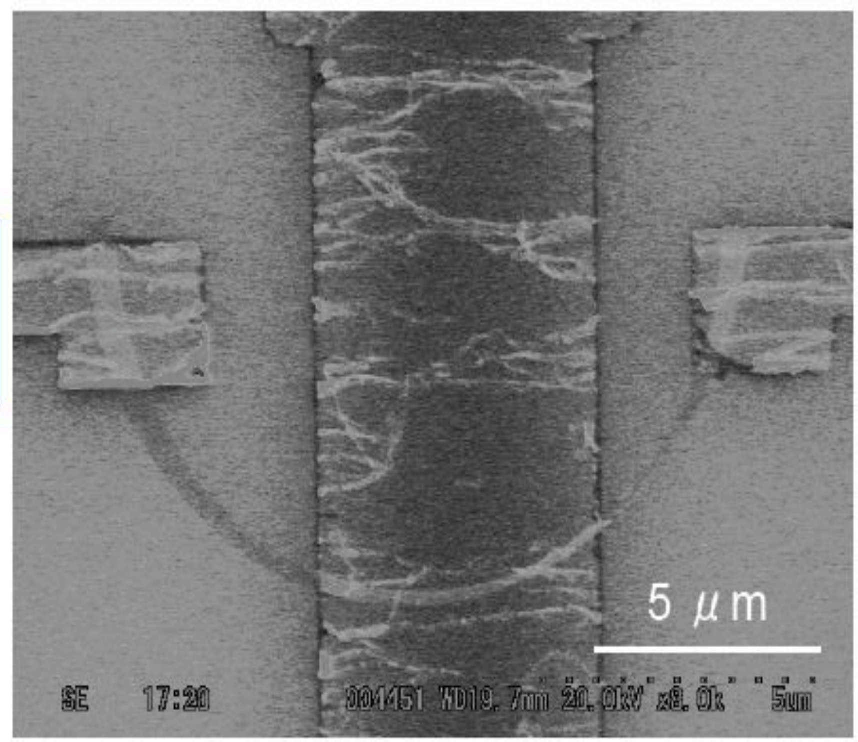


c.f. spin trans. , in Barnes & Maekawa (unpublished).

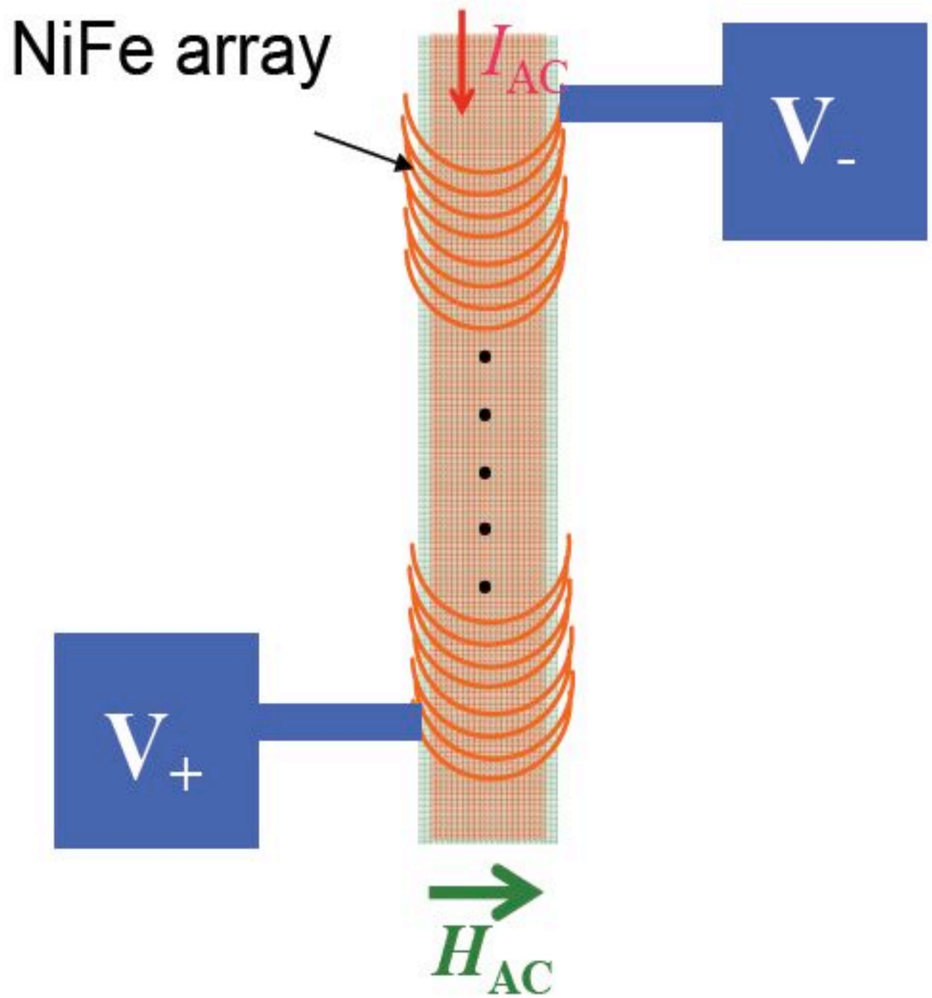
Sample for EMF measurement 1



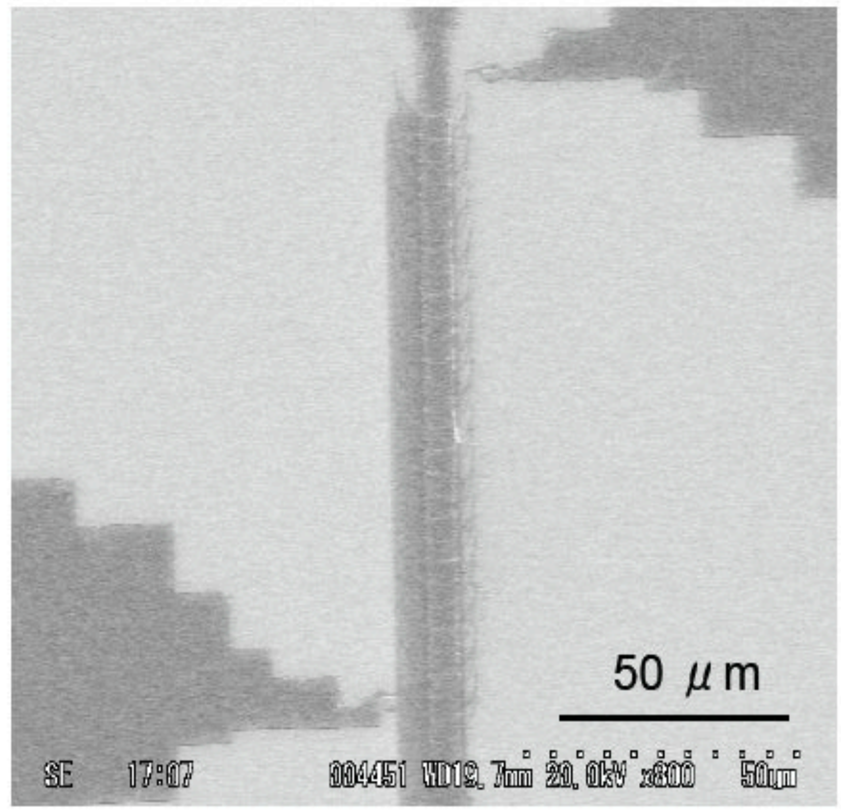
SEM image



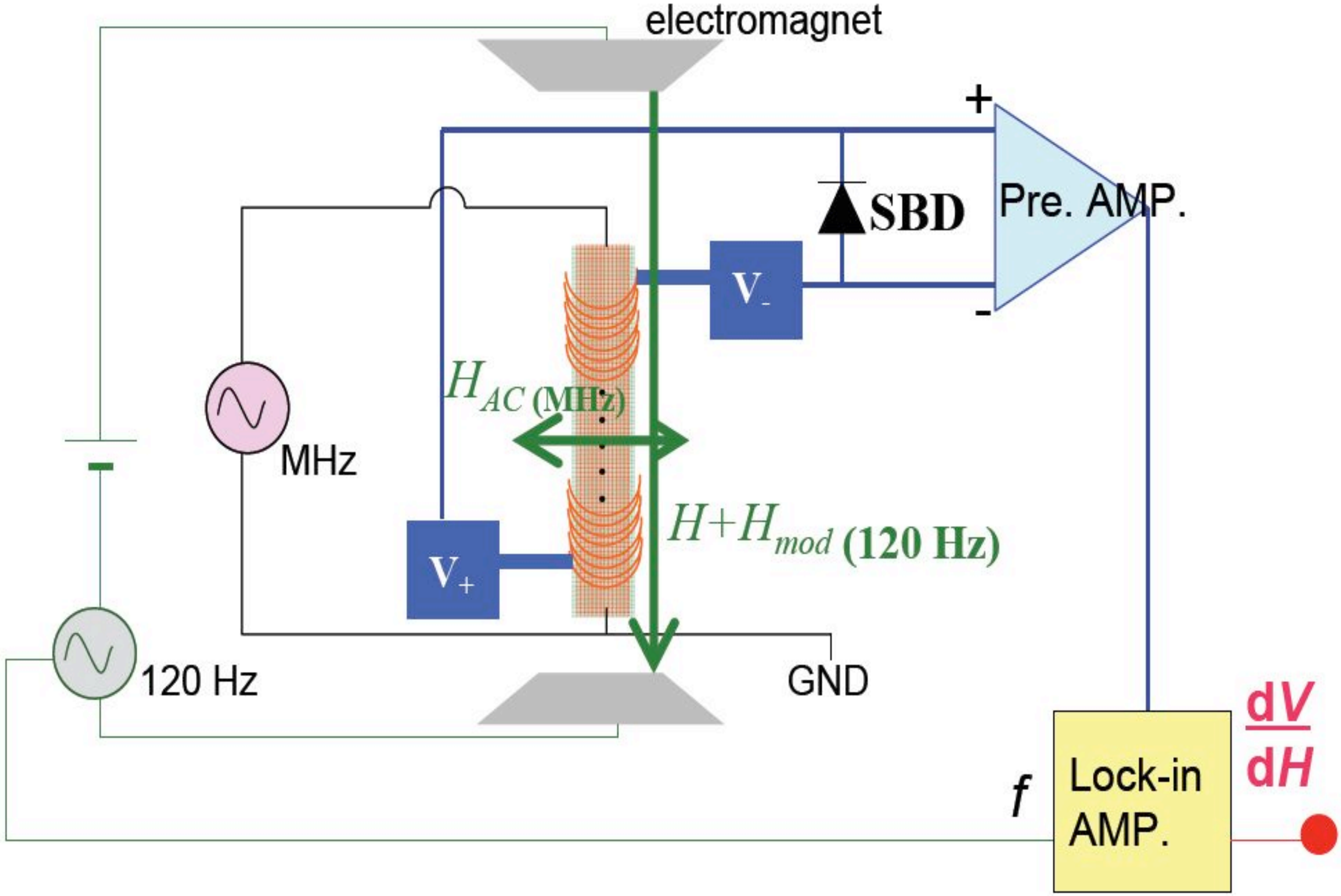
Sample for EMF measurement 2



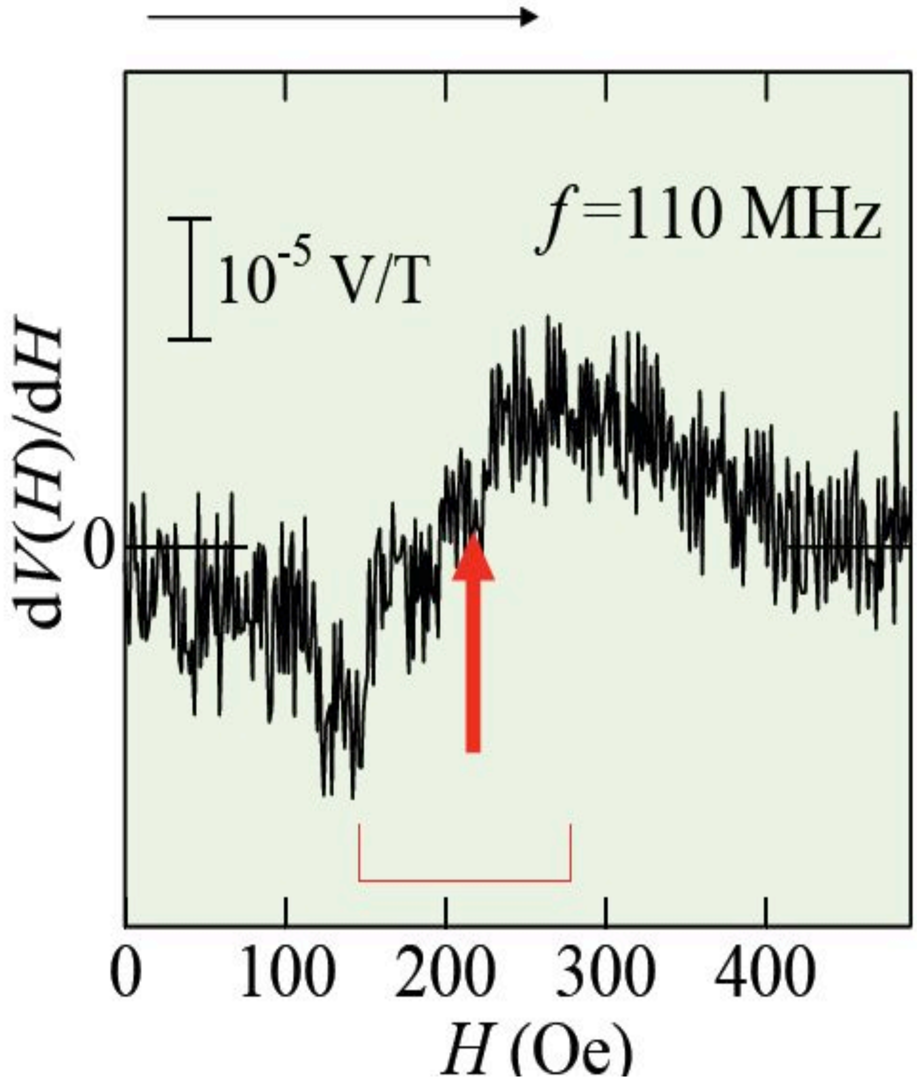
- SEM image



Measurement setup



Electromotiveforce from NiFe



….. *Dispersion-type signal appears*

$\int dH$

$\eta V_{peak} \sim 5 \cdot 10^{-8}$ V

η : rectifying efficiency at V_{EMI}

Questions :

1. Where does the energy come from?
2. And want about the conservation of angular momentum

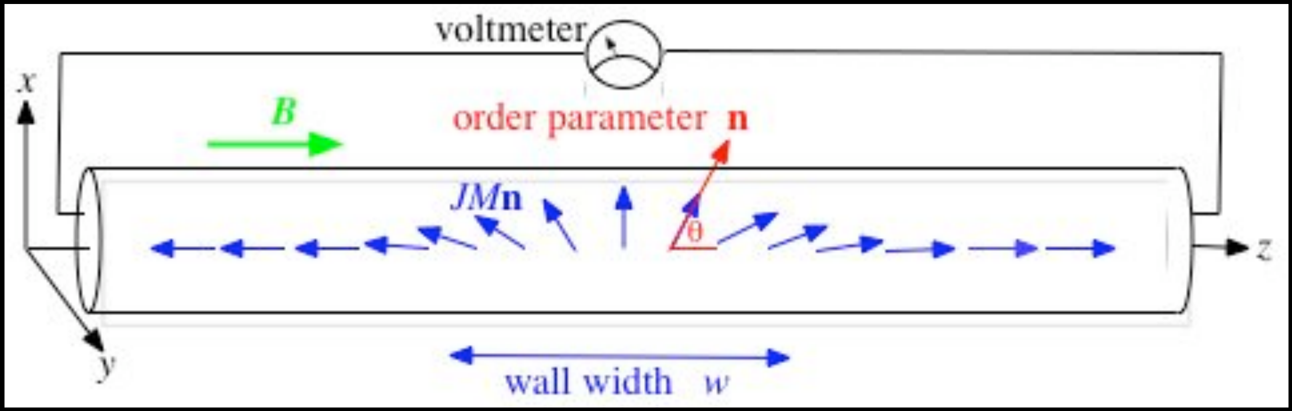
Schrodinger's equation in the rotating frame:

$$i\hbar \frac{\partial \psi'(\vec{r},t)}{\partial t} = \left[\frac{1}{2m} (\vec{p} - \frac{\hbar}{2} \vec{A}_s^t)^2 + J M s_z \right] \psi'(\vec{r},t)$$

$$\boxed{\vec{A}_s^t = \frac{2}{\hbar} s_y \frac{\partial \theta}{\partial z} \hat{\mathbf{z}}}$$

Beyond simple Stoner

Conservation



The wall position :

$$\hat{z}_0 \approx S_z/\hbar \mathcal{A} n$$

$n =$ number density $\quad \mathcal{A} =$ wire area

Small corrections Δz_0 due to $\vec{A}^t_s$ needed!

$$\psi'_{\vec{k}\pm}(\vec{r}) \Rightarrow e^{i(1/2)\int_{\vec{r}_0}^{\vec{r}} \vec{A}^t_s \cdot d\vec{r}'} \psi'_{\vec{k}\pm}(\vec{r}) \equiv U_a^{-1} \psi'_{\vec{k}\pm}(\vec{r})$$

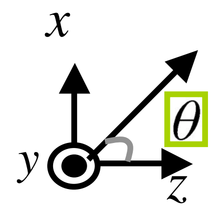
In *rotating frame*

$$z_0 \Rightarrow U_a U_\theta U_\phi \hat{z}_0 U_\phi^{-1} U_\theta^{-1} U_a^{-1}$$

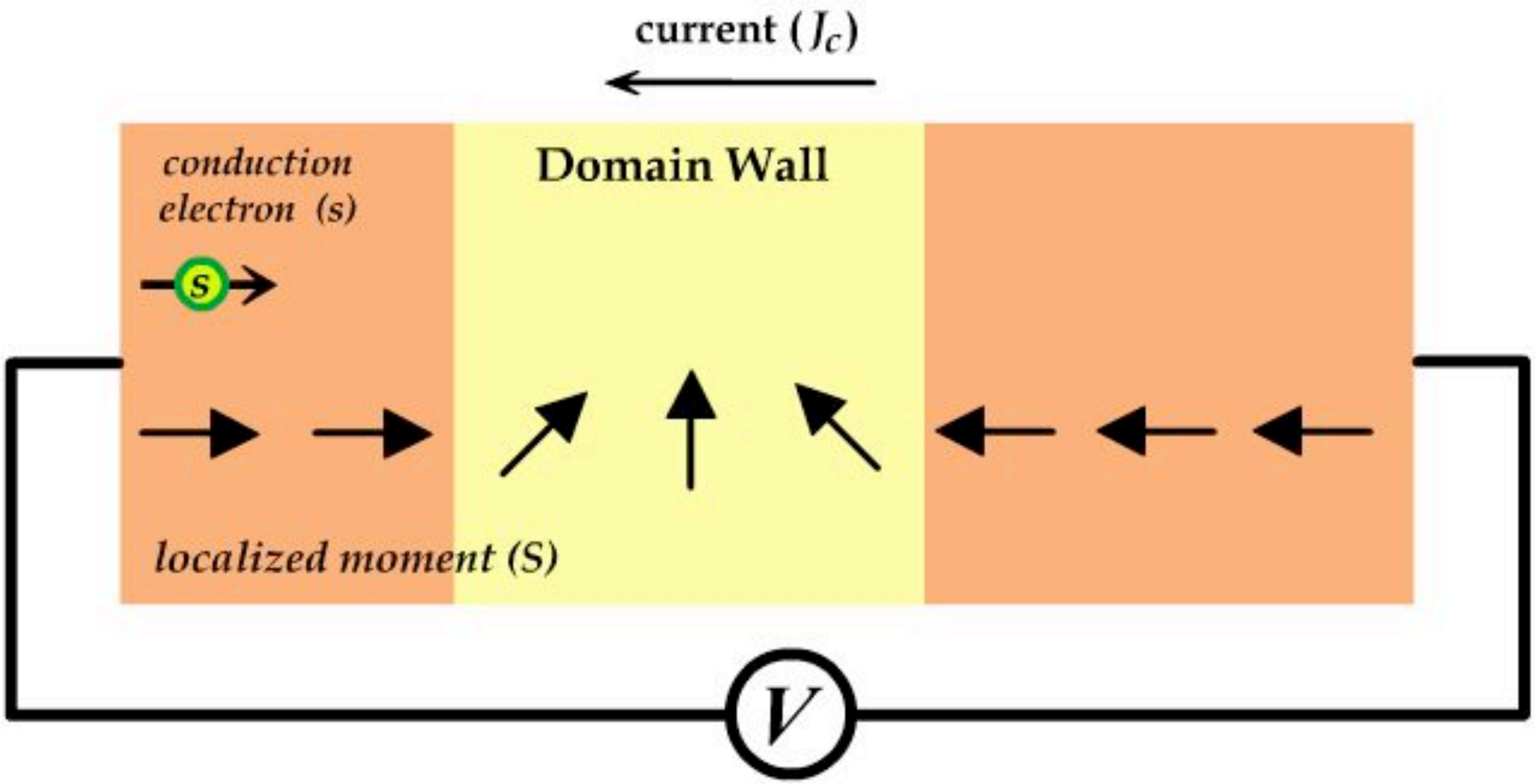
$$\Delta \hat{z}_0 = i(1/2)[U_\theta U_\phi (S_z/\hbar \mathcal{A}pn) U_\phi^{-1} U_\theta^{-1}, \int_{\vec{r}_0}^{\vec{r}} \vec{A}^t_s \cdot d\vec{r}']$$

$$\boxed{\Delta z_0^\pm = \mp \frac{1}{\mathcal{A}pn}(\cos\theta(\vec{r}_0) - \cos\theta(\vec{r}))}$$

Domain wall motion



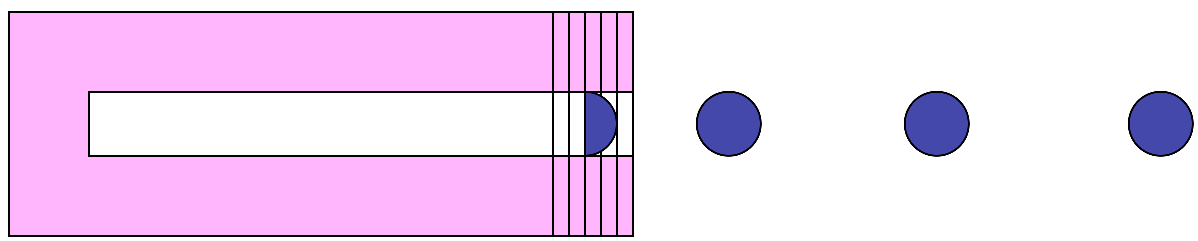
$$\boxed{\theta = 2\cot^{-1} e^{-(z-z_0)/w}}$$



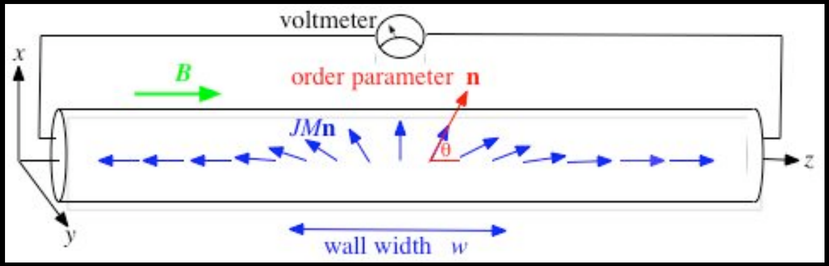
Current → torque on DW $\frac{\partial \theta}{\partial t} \neq 0, \quad \frac{\partial \phi}{\partial t} = 0$ ***Massless motion!!***

(Magnetic field → pressure on DW, $\frac{\partial \theta}{\partial t} \neq 0, \quad \frac{\partial \phi}{\partial t} \neq 0$ **)**

Recoil effect



Summary so far :



Distance moved per electron

$$\Delta z_0 = \frac{v_c}{2S},$$

implies velocity

$$\boxed{v_0 = \frac{v_c}{2eS} j,}$$

where j is the current density and S the spin per cell volume v_c.
Rate of doing work $(P_z \mathcal{A})v_0$ equals electrical power $\mathcal{E}(j\mathcal{A})$ to give emf

$$\boxed{\mathcal{E} = \frac{P_z v_c}{2eS}}$$

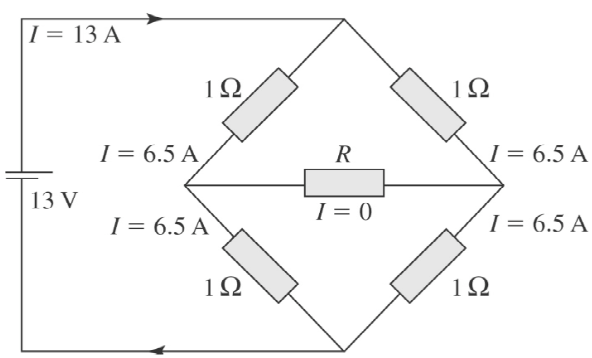
Boring plain old electronics:

Noether's Theorem

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \vec{J} = 0$$

$$\mathcal{E} = \frac{1}{e} \oint \vec{F} \cdot d\vec{s}$$

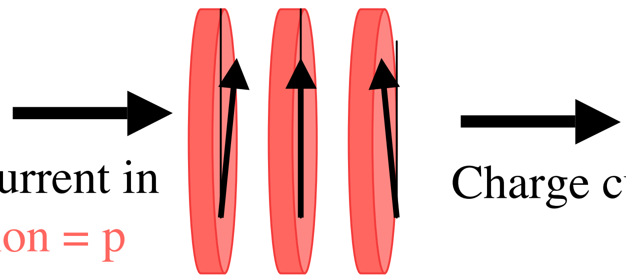
$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$$



Spintronics

$$\mathcal{E} = \frac{1}{e}\oint \vec{F}\cdot d\vec{s}$$

$$\vec{F} = e(\vec{E} + \vec{v}\times\vec{B}) + g\mu_B\frac{\partial}{\partial\vec{r}}(\vec{s}\cdot\vec{B})$$



Charge current in

polarisation = p

Charge current out

$$\frac{\partial\rho}{\partial t} + \vec{\nabla}\cdot\vec{J} = 0$$

$$\frac{\partial\vec{M}}{\partial t} + \vec{\nabla}\cdot\vec{\vec{j}} = 0$$

$$\vec{B}(t) = -\frac{\delta\mathcal{V}}{\delta\vec{M}}$$

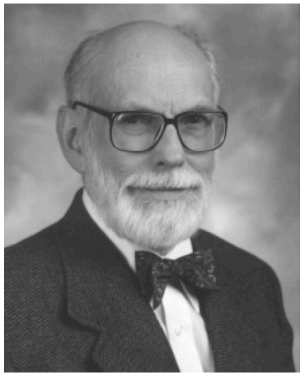
Total energy

$$\vec{\nabla}\cdot\vec{\vec{j}} \equiv \begin{pmatrix} \frac{\partial j_x^x}{\partial x} + \frac{\partial j_y^x}{\partial y} + \frac{\partial j_z^x}{\partial z} \\ \frac{\partial j_x^y}{\partial x} + \frac{\partial j_y^y}{\partial y} + \frac{\partial j_z^y}{\partial z} \\ \frac{\partial j_x^z}{\partial x} + \frac{\partial j_y^z}{\partial y} + \frac{\partial j_z^z}{\partial z} \end{pmatrix}$$

Relaxation - Gilbert, Landau

$$\boxed{\frac{\alpha}{M}\vec{M} \times \frac{\partial \vec{M}}{\partial t}}$$

Gilbert



$$\boxed{\frac{\alpha}{M}\frac{g\mu_B}{\hbar}\vec{M} \times \left(\vec{M} \times \vec{B}\right)}$$

Landau

No divergence

$$\boxed{\frac{\partial \vec{M}}{\partial t} = -\frac{g\mu_B}{\hbar}\vec{M}\times\vec{B} - \frac{\alpha}{M}\vec{M}\times\frac{\partial \vec{M}}{\partial t}}$$

$$\frac{\partial \vec{M}}{\partial t} = -\frac{g\mu_B}{\hbar}\vec{M}\times\vec{B} + \frac{g\mu_B}{\hbar}\frac{\alpha}{M}\vec{M}\times(\vec{M}\times\vec{B}) + \left(\frac{g\mu_B}{\hbar}\right)\left(\frac{\alpha}{M}\right)^2\vec{M}\times(\vec{M}\times\frac{\partial \vec{M}}{\partial t})$$

$$\vec{M}\times(\vec{M}\times\frac{\partial \vec{M}}{\partial t}) = [\vec{M}(\vec{M}\cdot\frac{\partial \vec{M}}{\partial t}) - \frac{\partial \vec{M}}{\partial t}M^2]$$

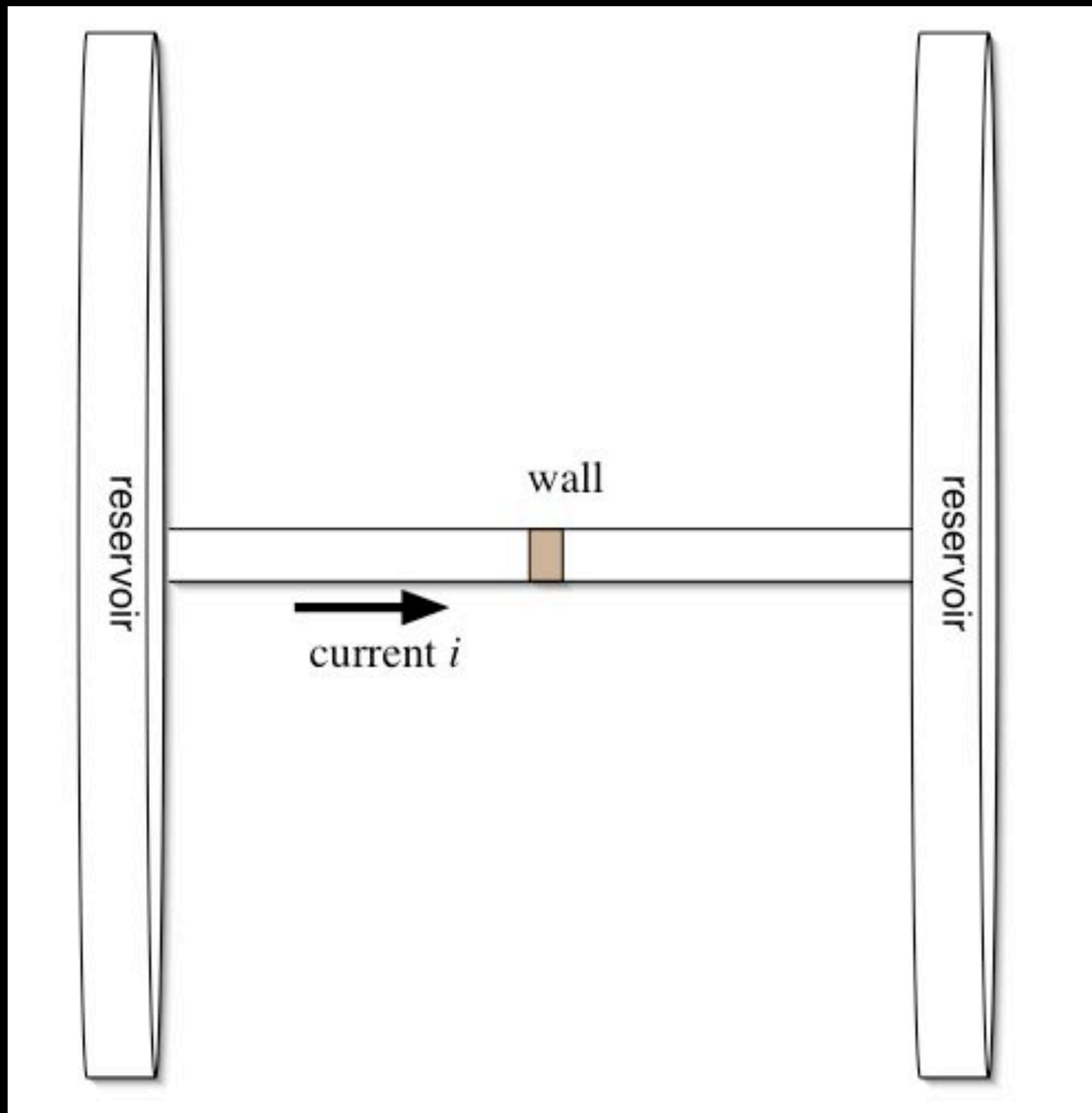
$$\boxed{(\vec{M}\cdot\frac{\partial \vec{M}}{\partial t}) = 0}$$

Rigid order parameter

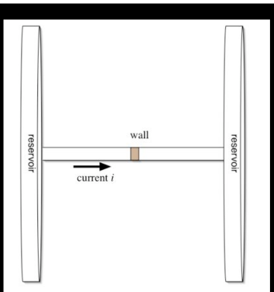
$$\boxed{\frac{\partial \vec{M}}{\partial t} = -\frac{1}{1+\left(\frac{g\mu_B}{\hbar}\right)\left(\frac{\alpha}{M}\right)^2}\frac{g\mu_B}{\hbar}\vec{M}\times\vec{B} + \frac{g\mu_B}{\hbar\left(1+\left(\frac{g\mu_B}{\hbar}\right)\left(\frac{\alpha}{M}\right)^2\right)}\frac{\alpha}{M}\vec{M}\times(\vec{M}\times\vec{B})}$$

Gilbert = Landau

Closed system with relaxation :



Closed system with relaxation :



$$\boxed{L = -X\dot{\phi} - \dot{q}\phi - U(q) - \frac{1}{2}k\phi^2}$$

$$H = \frac{k}{2}\phi^2 + U(q)$$

Rayleigh dissipation function :

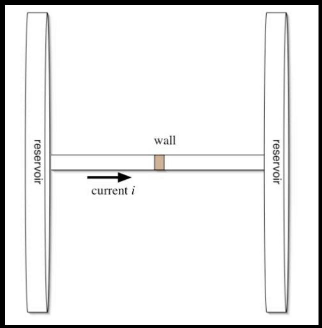
$$\mathcal{F} = \alpha(\dot{X}^2 + \dot{\phi}^2)$$

Equations of motion :

$$\dot{\phi} + \alpha \dot{X} = 0$$

$$\dot{X} - \alpha \dot{\phi} = \dot{q} + k\phi$$

$$\dot{\phi} = \frac{\partial U}{\partial q} \equiv \mathcal{E}$$



No relaxation :

$$\dot{\phi} = 0$$

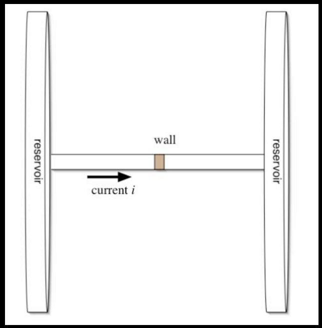
$$\dot{X} = \dot{q} + k\phi$$

$$\dot{\phi} = \frac{\partial U}{\partial q} \to 0 \quad : \quad U \approx \frac{q^2}{2C} \quad : \quad C \to \infty$$

Initial motion
“turning on”
relaxation :

$$H = \frac{k}{2}\phi^2 + U(q)$$

$$\mathcal{F} = \alpha(\dot{X}^2 + \dot{\phi}^2)$$



$$U_i = 0 \quad \frac{dU}{dt} = \frac{dU}{dq}\dot{q} = \mathcal{E}\dot{q} > 0 \quad \dot{q} > 0 \rightarrow \mathcal{E} > 0$$

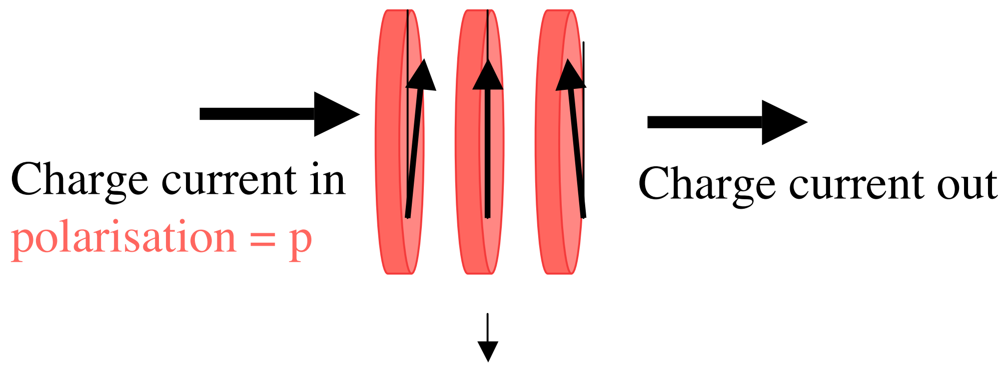
$$\phi_i = 0 \quad \dot{X} \approx \dot{q} > 0$$

$$\dot{\phi} = \mathcal{E} > 0$$

$$\alpha = -\frac{\dot{\phi}}{\dot{X}} < 0$$

$$\frac{dH}{dt} = -2\mathcal{F} > 0$$

Spin current divergence



spin direction changes

$$\boxed{\frac{D\vec{M}}{Dt} = \frac{\partial \vec{M}}{\partial t} + \vec{\nabla} \cdot \vec{j}_s = g\mu_B \vec{M} \times \vec{B} - \frac{\alpha}{M} \vec{M} \times \frac{D\vec{M}}{Dt}}$$

Charge current constant but finite divergence of spin current!

$$\boxed{\frac{D\vec{M}}{Dt} \equiv \frac{\partial \vec{M}}{\partial t} + \vec{\nabla} \cdot \vec{j}_s}$$

Particle Derivative - follows a spin direction as wall moves

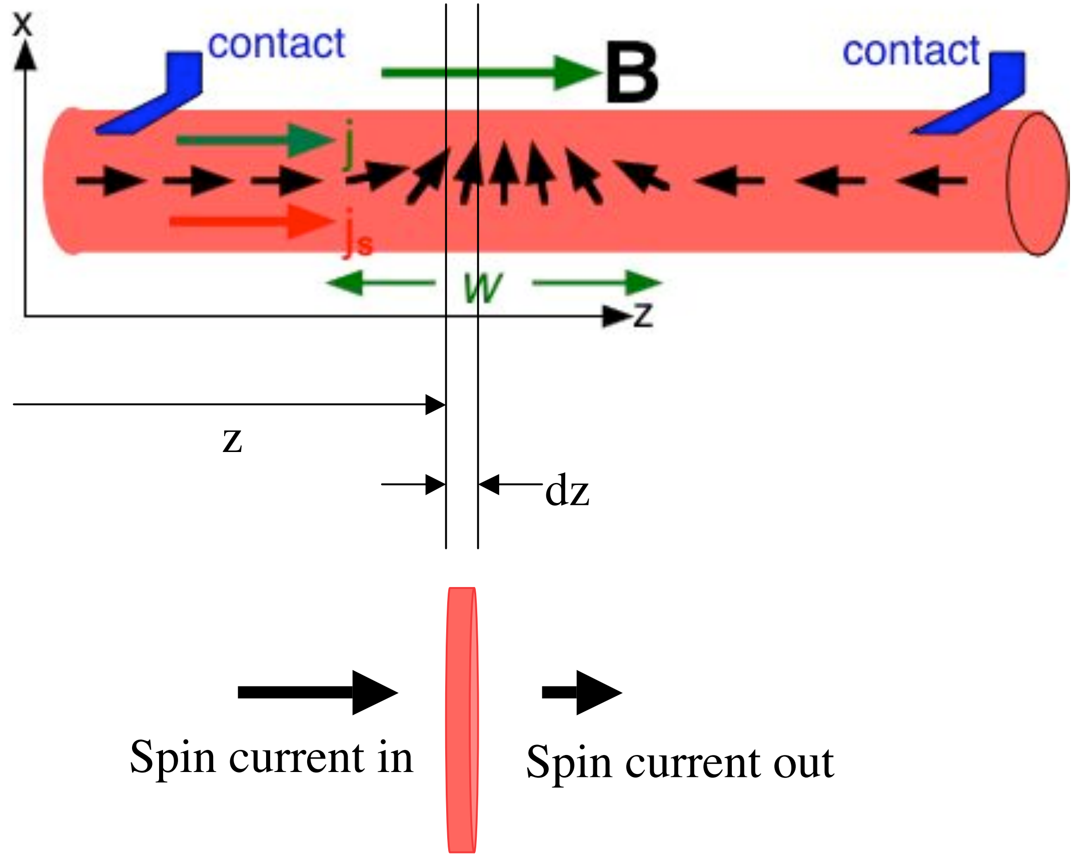
Comparison with other attempts

Zhang-Li: PRL93 127204 (cond-mat/0407174)
Thiaville et al.: Eurphys.Lett.69_990 (cond-mat/0407628)

$$\frac{\partial \vec{m}}{\partial t} = -\gamma\, \vec{m} \times \vec{B} - \mathrm{v}_0 \frac{\partial \vec{m}}{\partial z} + \underline{\alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t} + \beta \mathrm{v}_0 \vec{m} \times \frac{\partial \vec{m}}{\partial z}}$$

Nothing but the modified Gilbert term!

(here β as a phenomelogical parameter)



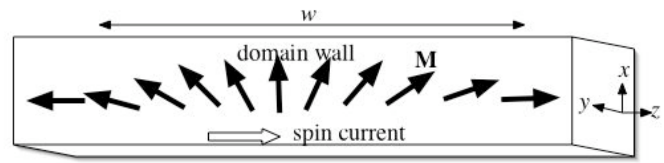
$$\boxed{\frac{\partial \vec{M}}{\partial t} + \vec{\nabla} \cdot \vec{\vec{j}}_s = 0}$$

Usual equation

$$\boxed{\frac{\partial \vec{M}}{\partial t} - v_0 \frac{\partial \vec{M}}{\partial z} = 0}$$

Result from gauge theory

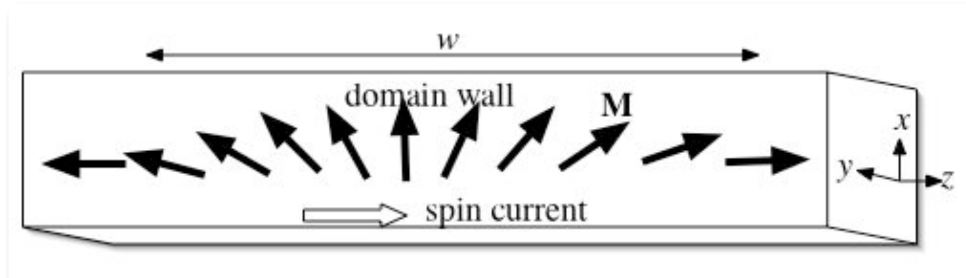
Add modified Gilbert's Relaxation



$$\frac{D\vec{M}}{Dt} \equiv \frac{\partial \vec{M}}{\partial t} - v_0 \frac{\partial \vec{M}}{\partial z}$$

$$\frac{D\vec{M}}{Dt} = g\mu_B \vec{M} \times \vec{B} - \frac{\alpha}{M}\vec{M} \times \frac{D\vec{M}}{Dt}$$

Moving ground state



$$\boxed{\text{Zero field, i.e., B=0}}$$

$$\boxed{\frac{D\vec{M}}{Dt} = 0}$$

No intrinsic pinning, cf. last talk

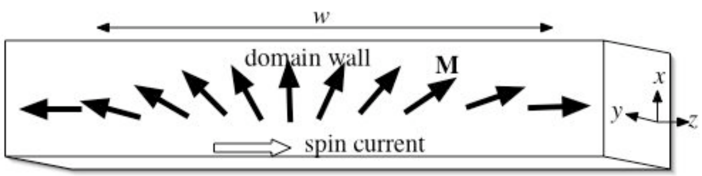
$$\boxed{\frac{\partial \vec{M}}{\partial t} - v_0 \frac{\partial \vec{M}}{\partial z} = 0}$$

$$\boxed{v_0 = \frac{j_s a^3}{2eM}}$$

Relaxation by the pinning potential

$$\boxed{\frac{\partial \phi_0}{\partial t} = \frac{a}{\mathcal{A}\hbar m} P_z \qquad \frac{\partial z_0}{\partial t} = \frac{1}{2m_D} \sin\left(2\frac{\partial \phi_0}{\partial t} t\right)}$$

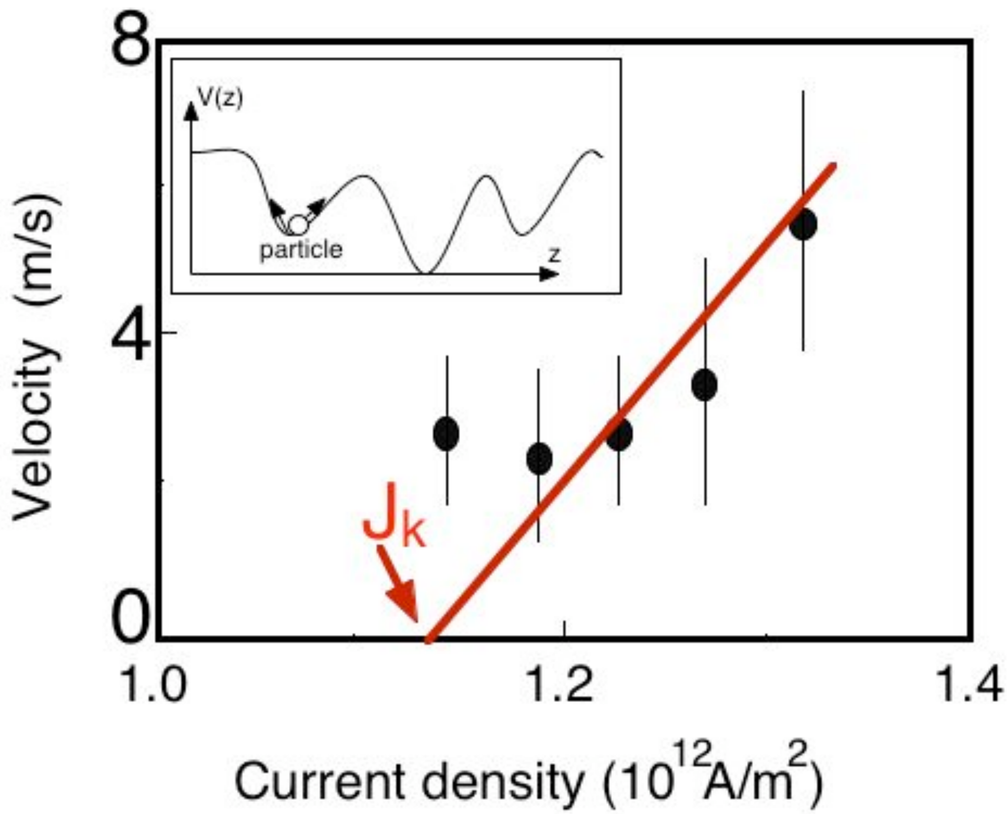
$$\boxed{p = \frac{2\mathcal{HAM}\hbar}{a^3}\phi}$$

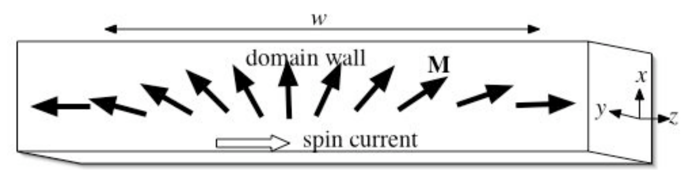


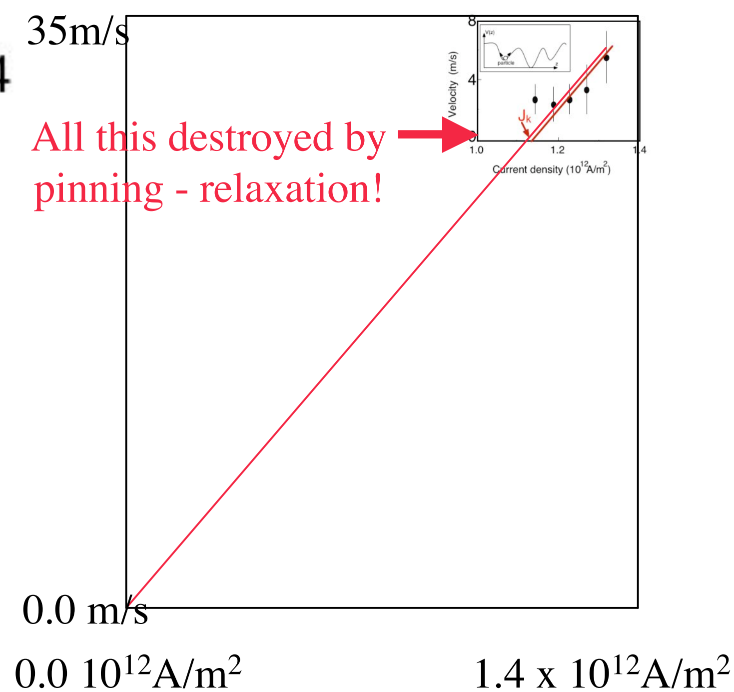
$$\boxed{\frac{\partial z}{\partial t} - v_0 = \frac{1}{m_D} p - \alpha' \frac{a^3}{2\hbar} P_z}$$

$$\boxed{\frac{\partial z}{\partial t} - (v_0 - v_r) = \frac{1}{m_D} p}$$

$$\boxed{v_r = \alpha \frac{a^3}{2} \langle P_z \rangle}$$







$$v = pC(j - j_k); \qquad C \equiv \frac{a^3}{2eM}$$

Velocity of domain-wall motion induced by electrical current in a ferromagnetic semiconductor (Ga,Mn)As

M. Yamanouchi,[1] D. Chiba,[2,1] F. Matsukura,[1,2] T. Dietl,[3,1,2] and H. Ohno[1,2]

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[2] *ERATO Semiconductor Spintronics Project, Japan Science and Technology Agency, Japan*

[3] *Institute of Physics, Polish Academy of Sciences, PL-02668 Warszawa, Poland; Institute of Theoretical Physics, Warsaw University, Poland*

(Dated: January 24, 2006)

$$\boxed{j_{\mathrm{C}} = 2eK\delta_W/\pi\hbar P}$$

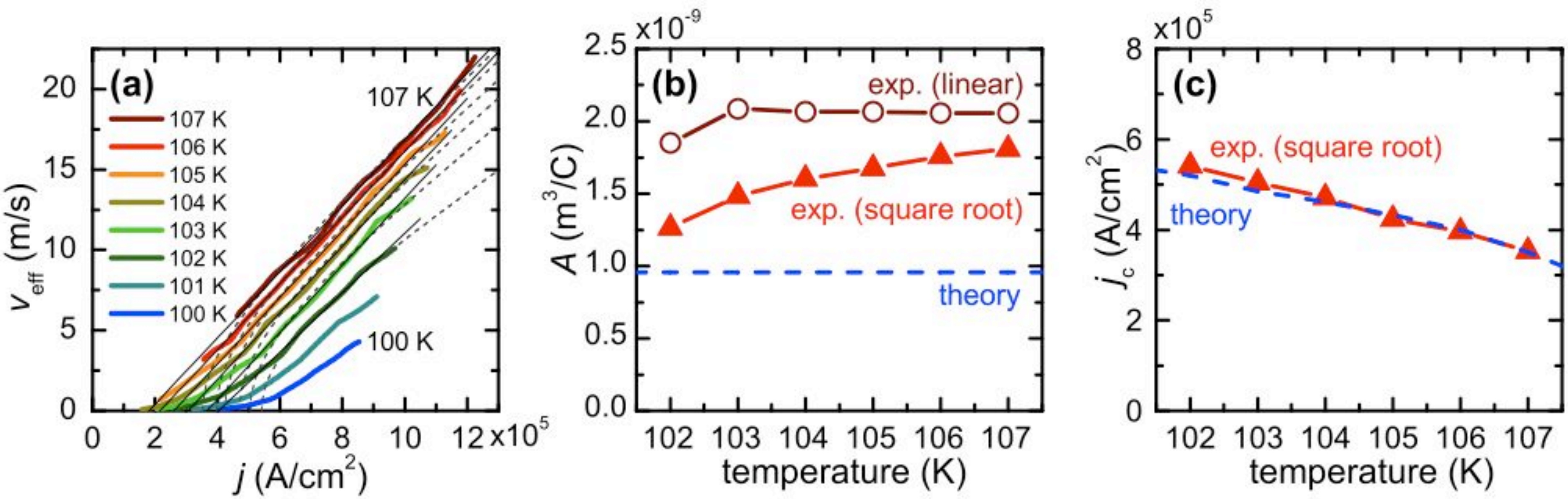
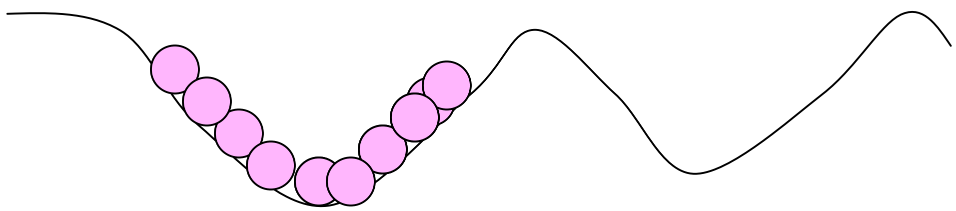


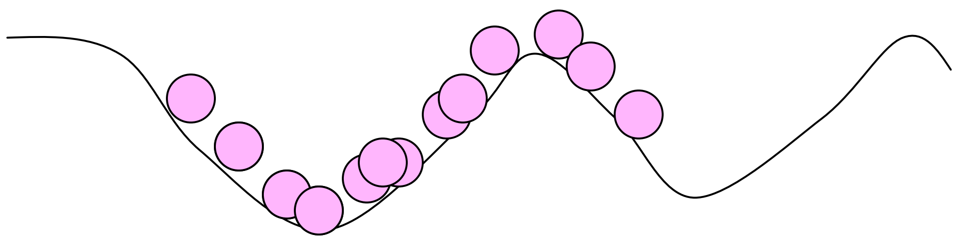
FIG. 2: [Color online] (a) DW velocity as a function of current at various device temperatures. Thin line and broken thin line show fitted linear and square root dependencies of velocity on current, respectively. Efficiency factor A (b) and critical current density j_{C} (c) resulting from these two fits (empty and full symbols, respectively). Broken lines are theoretically calculated assuming that spin current polarization is equal to thermodynamic spin polarization.

The characteristic current j_c and pinning

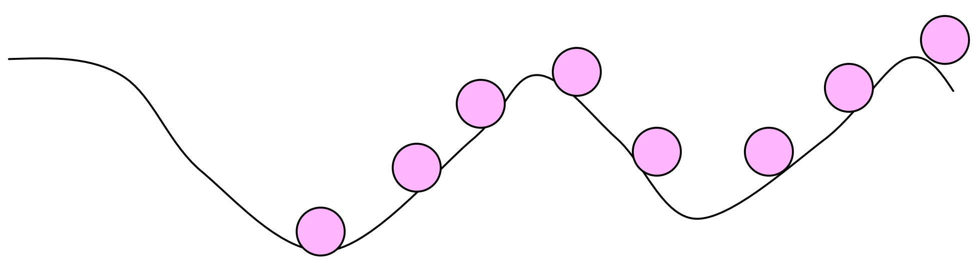


$j < j_p$

$$\boxed{j_{\mathrm{C}} = 2eK\delta_W/\pi\hbar P}$$



$j_p < j < j_c$



$j > j_c$

iv) New devices:

a) Current only read-write memory:

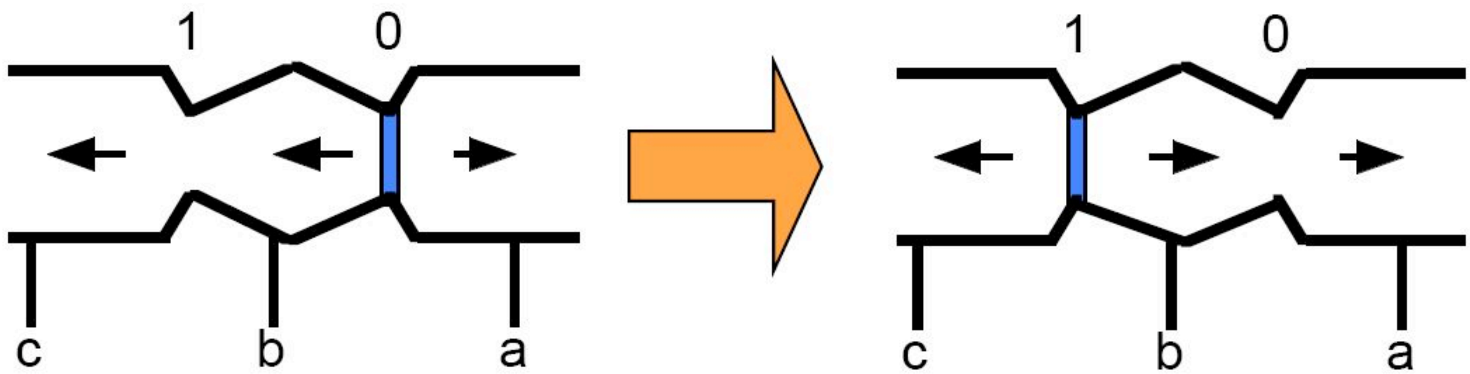
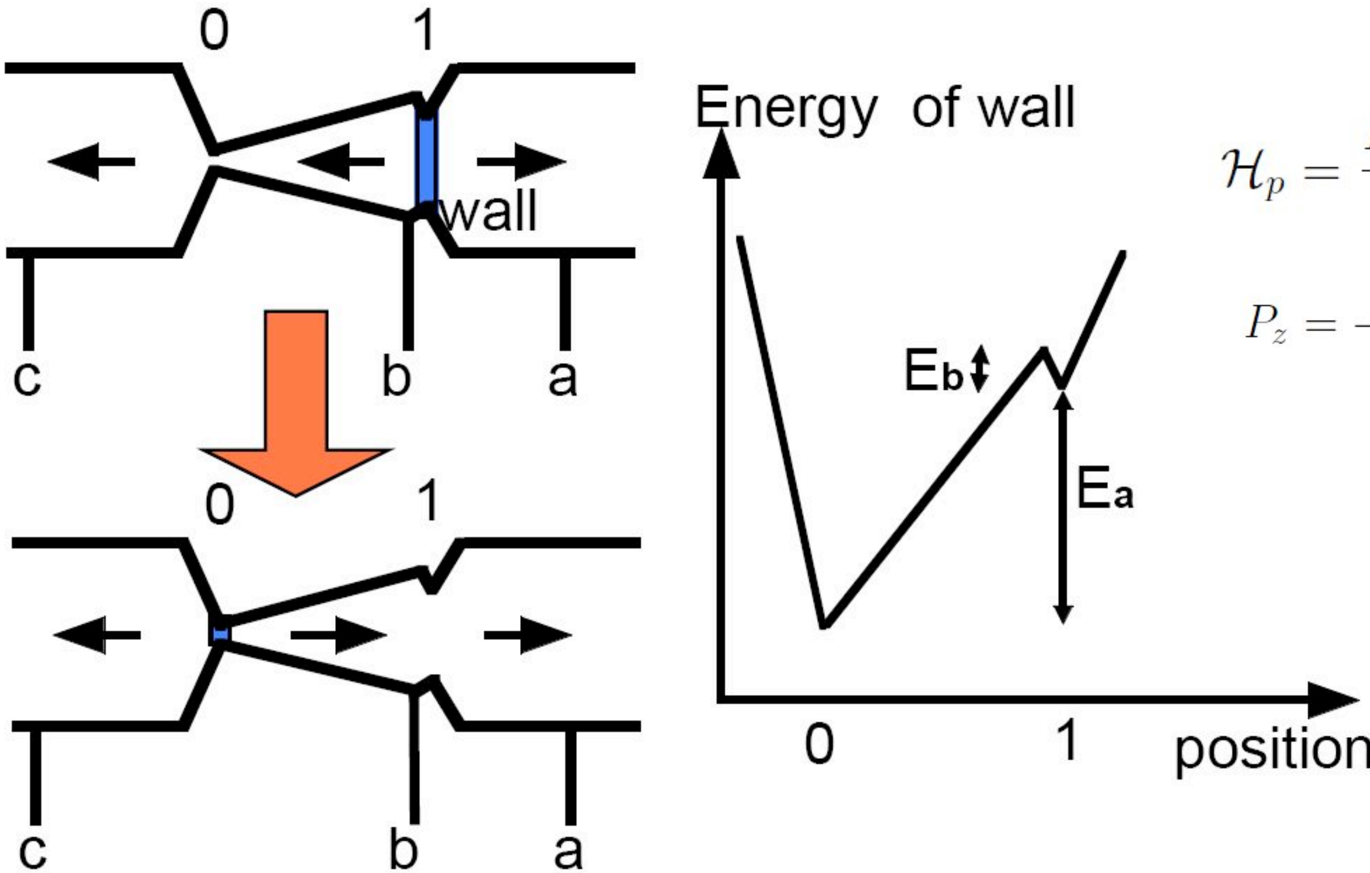


Figure 2: A current only read-write memory element. To the left the system is in the 0-state. A current between a and b will carry the wall past the unstable equilibrium point. As it moves towards 1-state under the force P_z implicit in the device shape it will produce an output emf between b and c. No emf occurs if the system is in the 1-state. The system can be switched between 0 and 1 by a passing a current from a to c.

Magnetic force (P_z) $\longrightarrow$ *emf*

b) A power amplifier:



$$\mathcal{H}_p = \frac{P_z v_c}{a}\hat{z}_0,$$

$$P_z = -\frac{a}{v_c}\frac{\partial \mathcal{V}}{\partial z_0}$$

Figure 3: An power amplifier. Starting with the initial state, top left, a pulse between a and b moves the wall from 1 to b, i.e., a point at which there is a F_x to the left. There is an emf between b and c as the wall moves between b and 0. The final state is shown at the bottom left. To the right is shown the energy profile of the device, see text.

Conclusions :

1. Angular momentum (torque) transfer reflects the divergence of the spin current.

2. Energy conservation implies an emf/smf proportional to P_z. (Berry phase Faraday's law.)

3. Gilbert relaxation involves dM/dt.

4. Critical currents are extrinsic reflecting α.