YKIS2007 (November 20 ,2007)

Spin Current vs. Charge Current
in Magnetic Nanostructures

S. Maekawa
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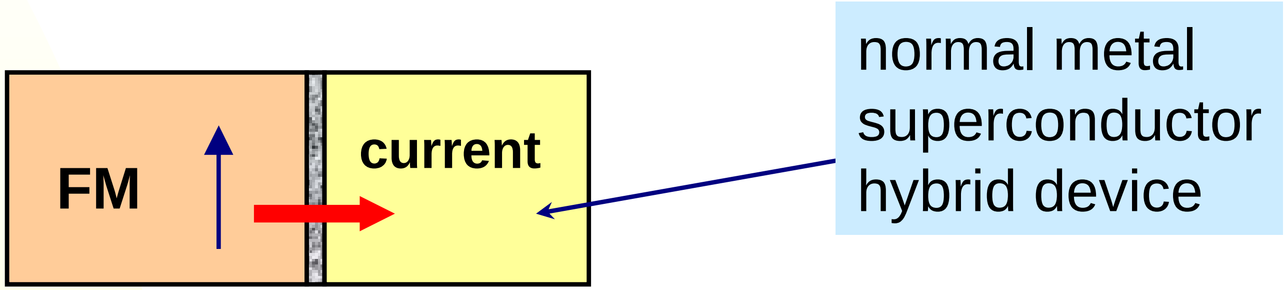
Contents:
- **(i)** ***Spin current,***
- ***(ii) Spin accumulation,***
- **(iii)** ***Spin Hall effect,***
- **(iv)** ***Spin current pumping.***

(Charge current ⟺ Spin Current)



normal metal
superconductor
hybrid device

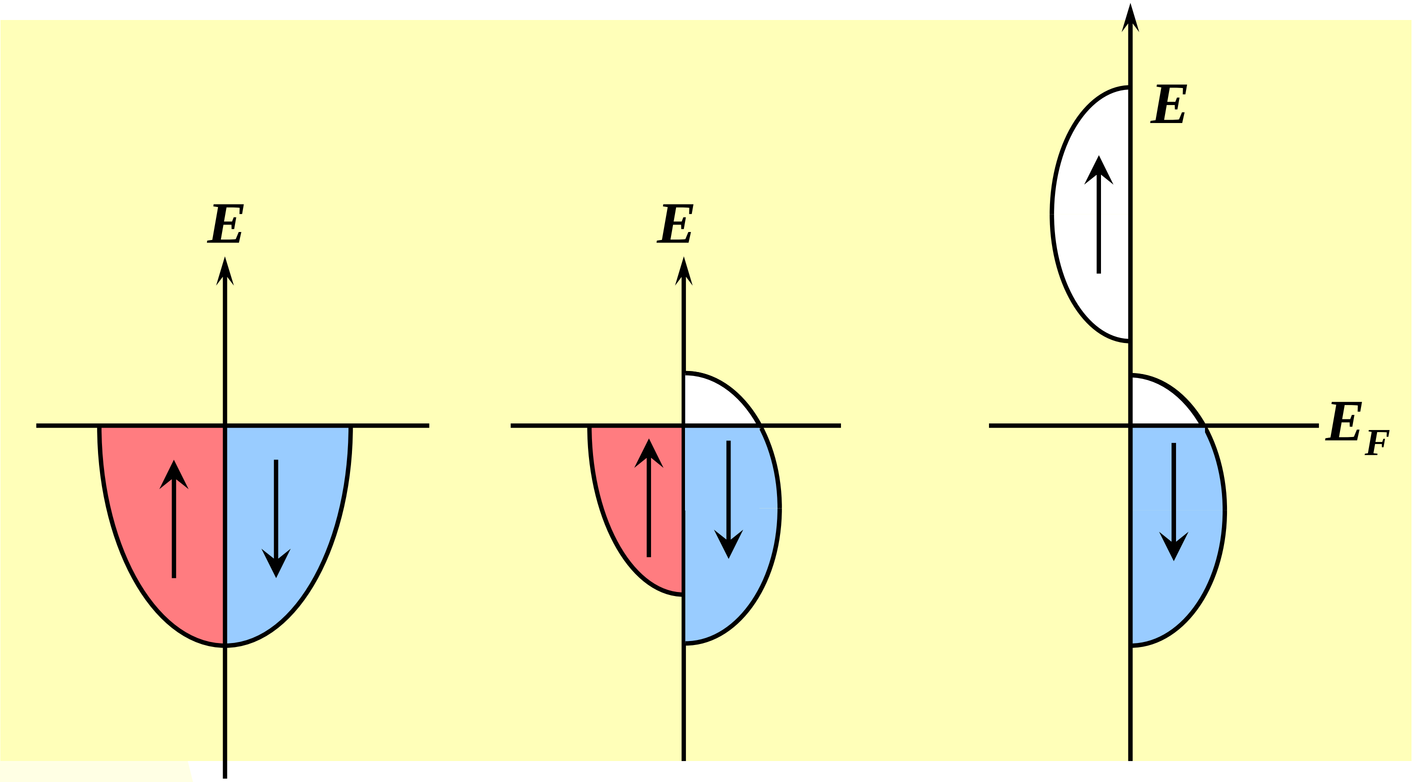
charge current : $J_c = J_\uparrow + J_\downarrow$

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

Contents:

- **(i)** ***Spin accumulation,***
- ***(ii) Spin current,***
- **(iii)** ***Spin Hall effect,***
- **(iv)** ***Spin current pumping.***

What is a ferromagnet ?



Cu

Fe,Co,Ni

$La_{1-x}Sr_xMnO_3$
CrO_2

	Cu	Fe,Co,Ni	$La_{1-x}Sr_xMnO_3$, CrO_2
Electron number :	$N_\uparrow = N_\downarrow$	$N_\downarrow > N_\uparrow$	$N_\downarrow > N_\uparrow = 0$ **(half-metal)**
Atomic energy :	$\varepsilon_{i\uparrow} = \varepsilon_{i\downarrow}$	$\varepsilon_{i\downarrow} < \varepsilon_{i\uparrow}$	$\varepsilon_{i\downarrow} = \varepsilon_{i\uparrow}$

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

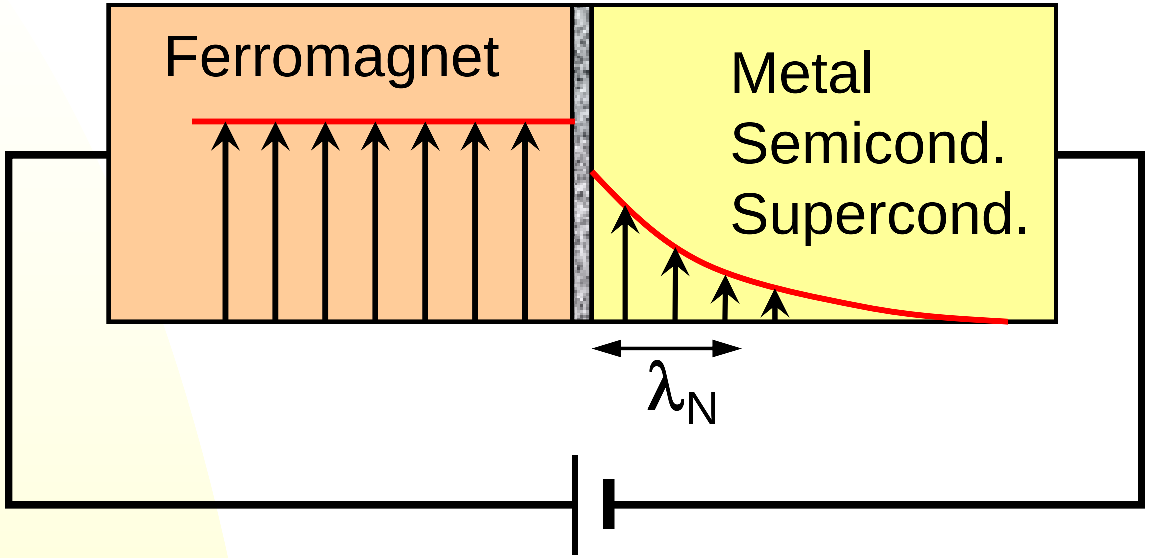
$J_c = J_\uparrow + J_\downarrow$

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

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

Spin diffusion length (λ_N)

10 nm ~ 1 μm

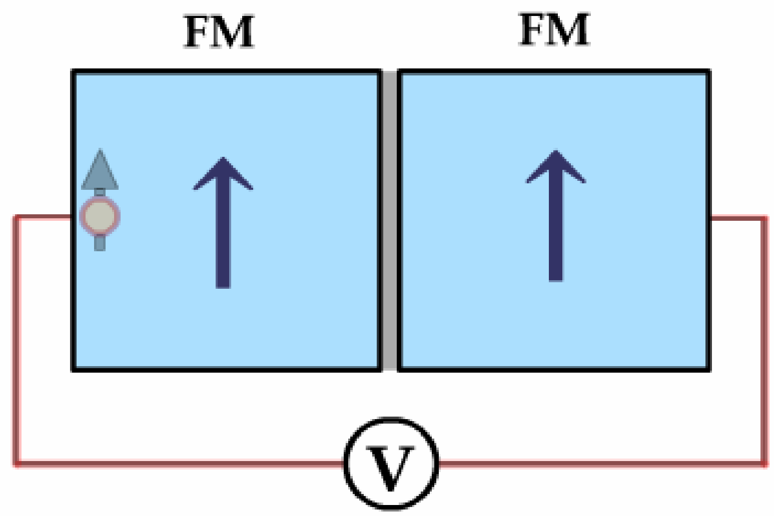


Device size < λ_N

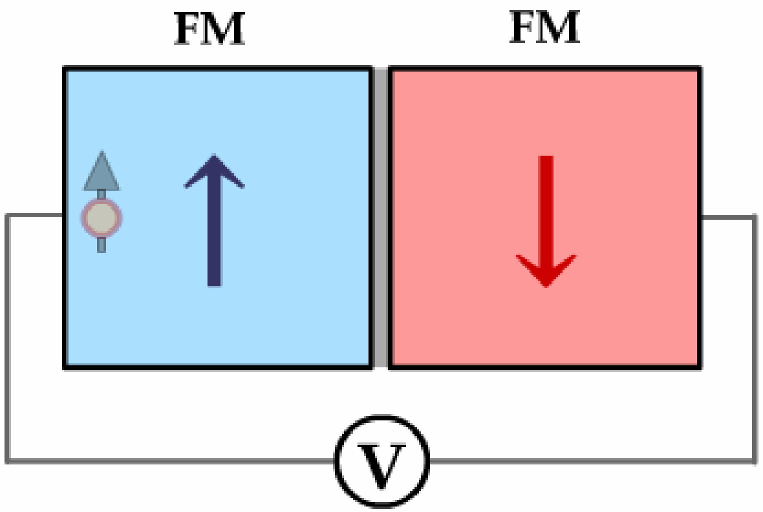
→ Spin Electronics Device !

(Charge current → usual electronics)

Tunnel magnetoresistance (TMR)



Parallel alignment



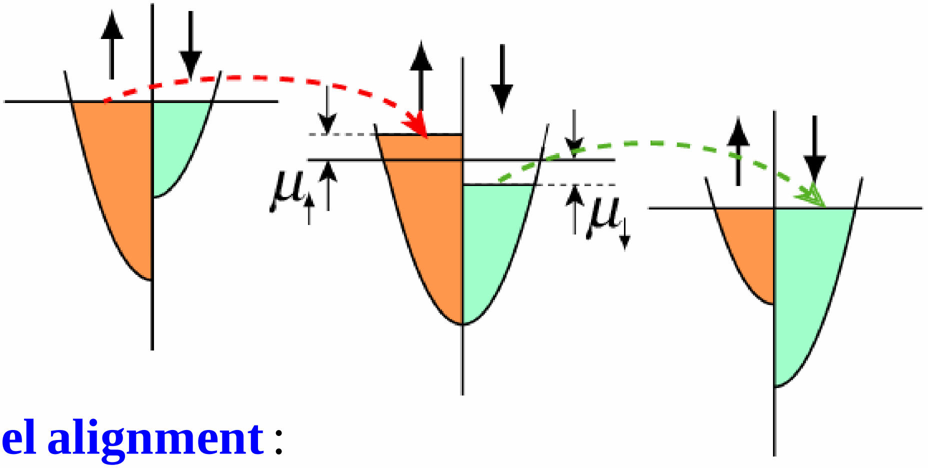
Antiparallel alignment

(S. Maekawa and U. Gafvert: IEEE Mag. ***18****, 707 (1982))*

Spin accumulation :

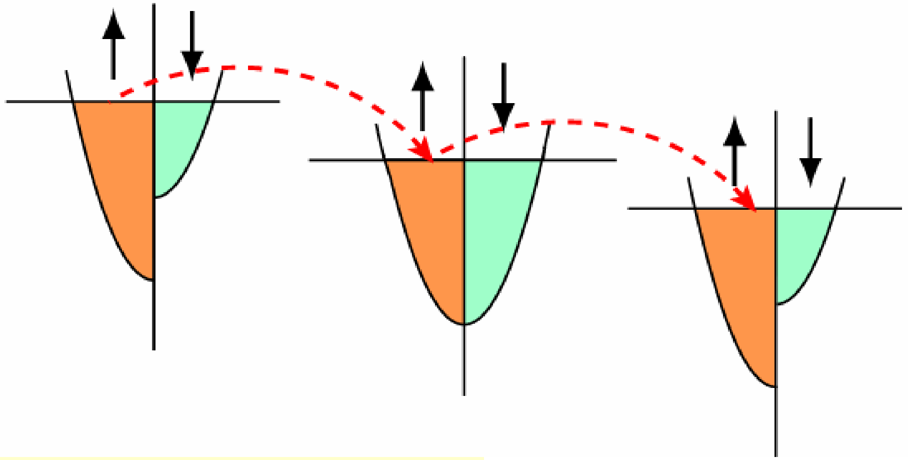
Antiparallel alignment :

$(\uparrow\downarrow)$

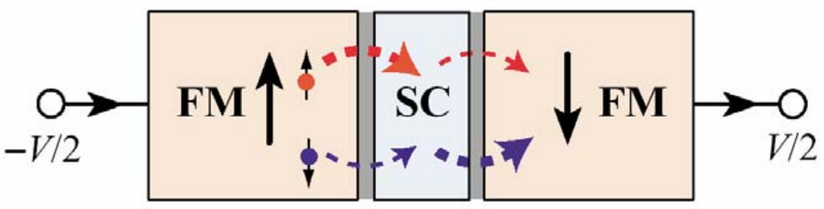


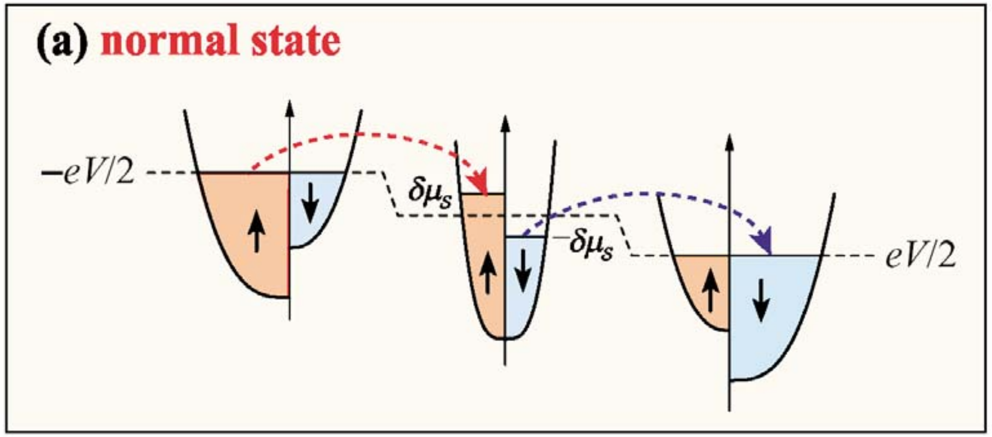
Parallel alignment :

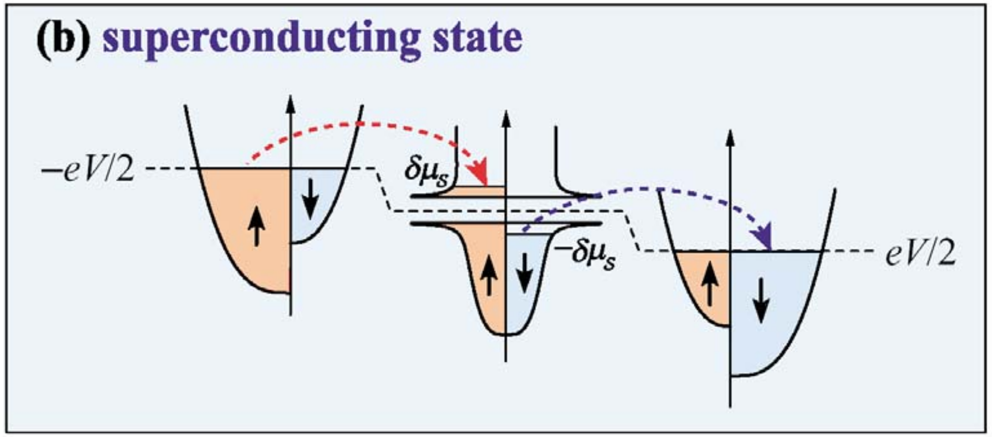
$(\uparrow\uparrow)$



Antiparallel alignment

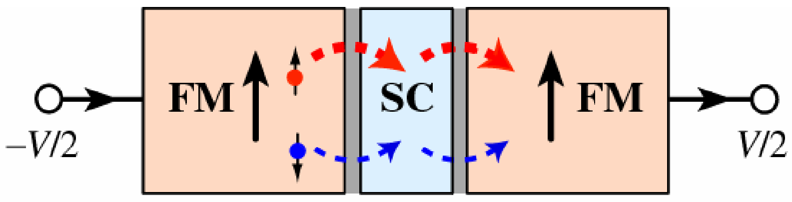


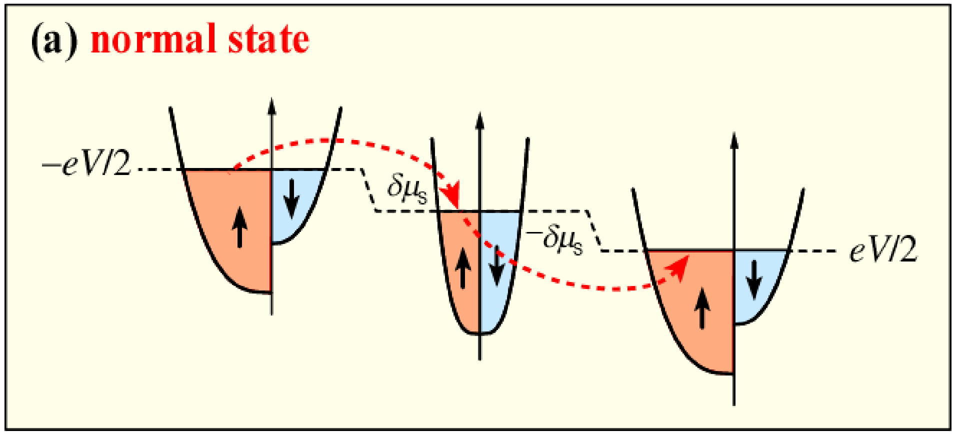

(a) normal state

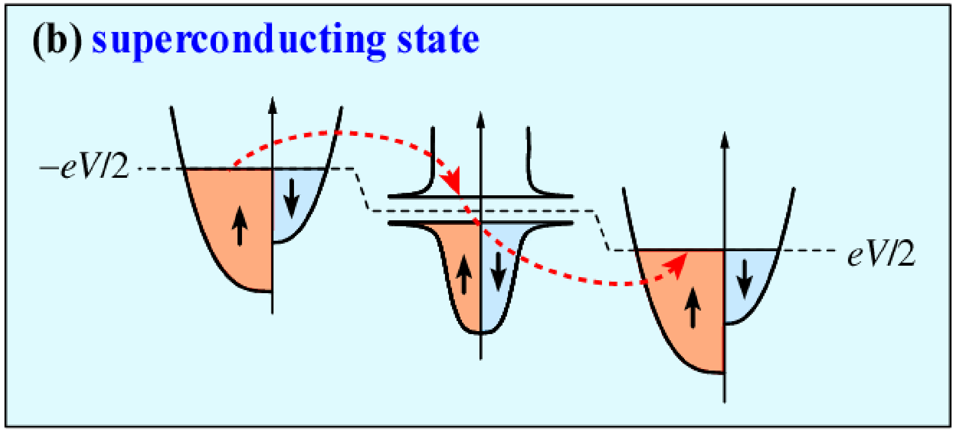

(b) superconducting state

"Spin accumulation"

Parallel alignment

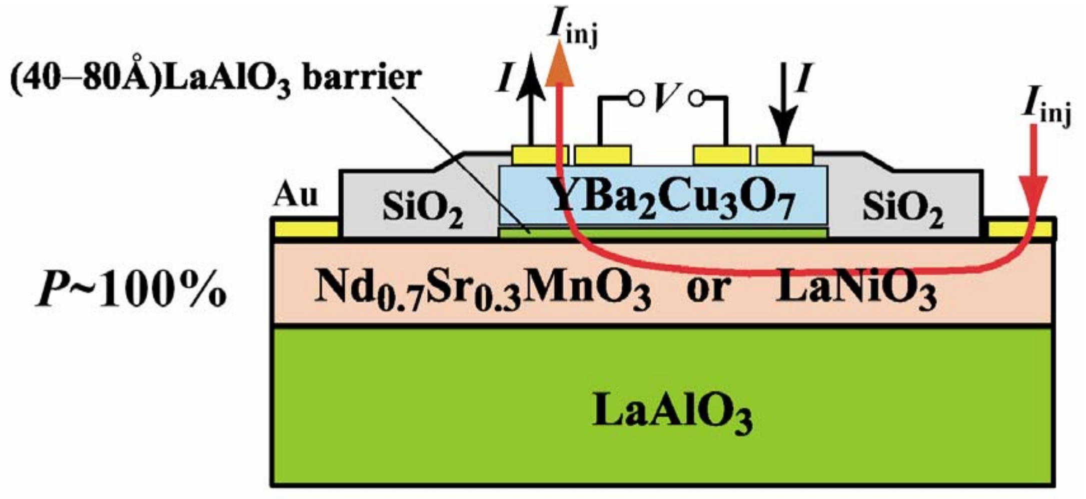


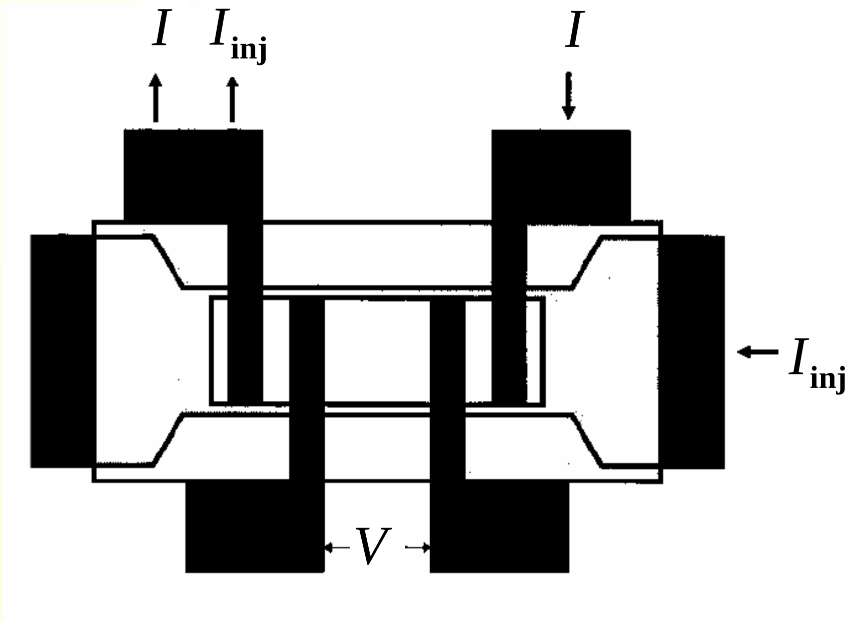

(a) normal state


(b) superconducting state

"Spin current"

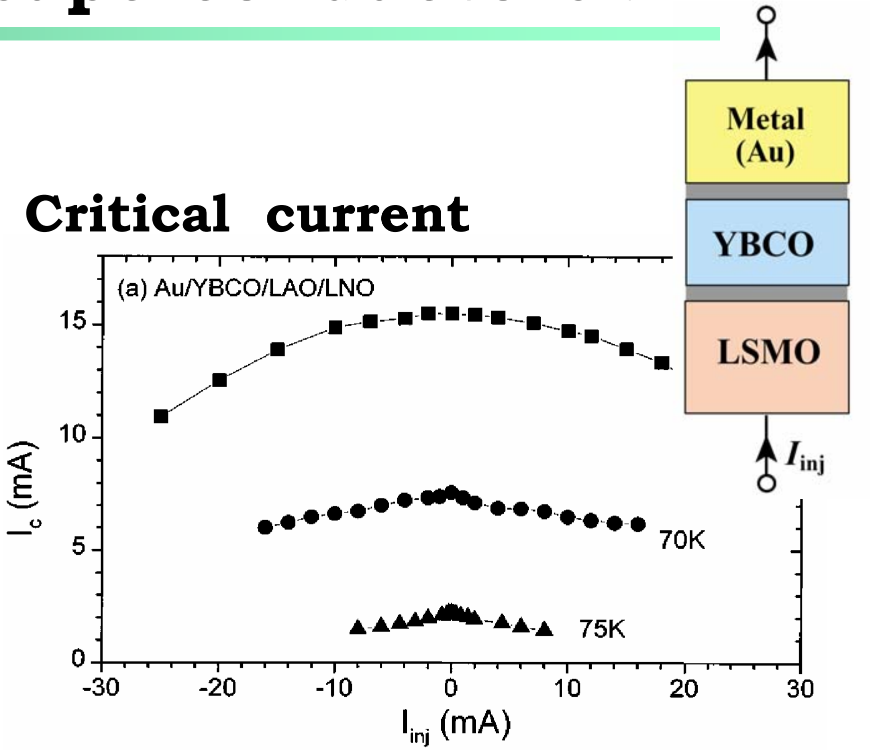
Spin accumulation in High-T_c superconductors :

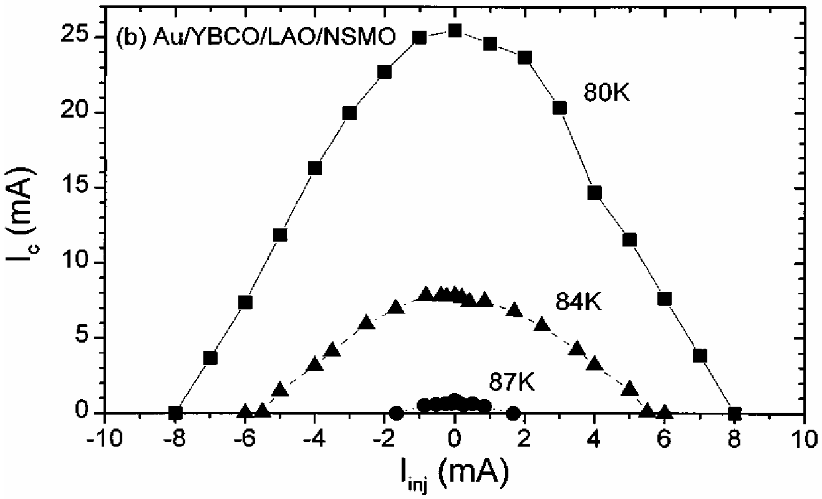




Top view (not in scale)

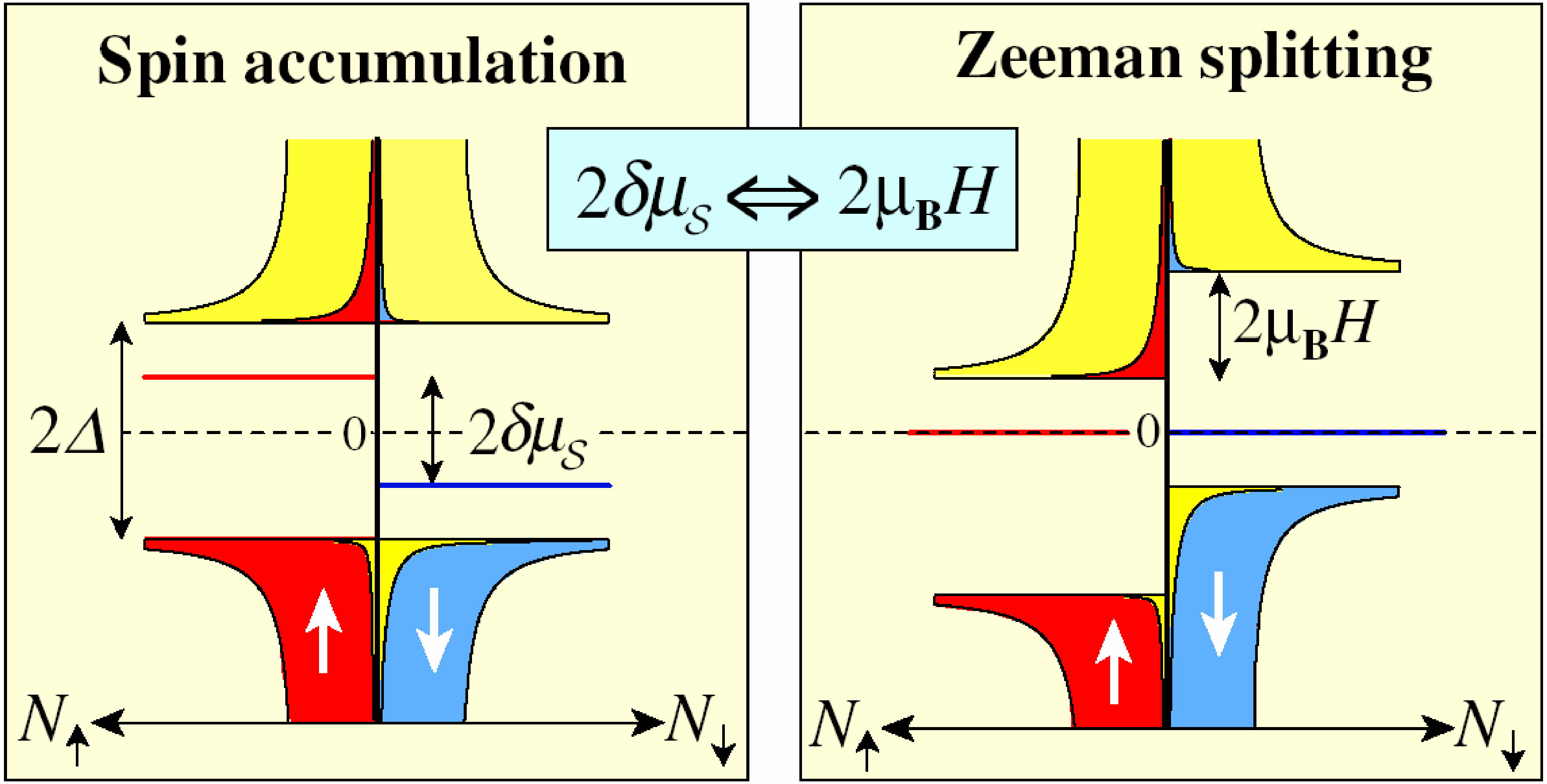
Critical current





Injection current

(Z.W. Dong *et al.*: *APL* **71**, 1718 (1997))



Spin accumulation

Zeeman splitting

$2\delta\mu_S \Leftrightarrow 2\mu_B H$

$2\Delta_0 \approx PeV$

Magnetization

$M = \mu_B \left(n_\uparrow - n_\downarrow \right)$

Pair breaking :

$2\Delta_0 \approx \mu_B H$

For **Al,**

$$\Delta_0^{\mathbf{Al}} \sim 0.4\ \mathrm{meV}$$

$$H \sim O(1\ \mathrm{T})$$

$$V_b \sim O(10^{-3}\ \mathrm{V}) \qquad (P \sim 1)$$

$$M : \mu_{\mathrm{B}} N(0) PeV \rightarrow B_{\mathrm{S}}^{\mathrm{Al}} = 4\pi M^{\mathrm{Al}} : O(1\mathrm{Oe})$$

For **YBCO,**

$$\Delta_0^{\mathbf{YBCO}} : 100\,\Delta_0^{\mathbf{Al}}$$

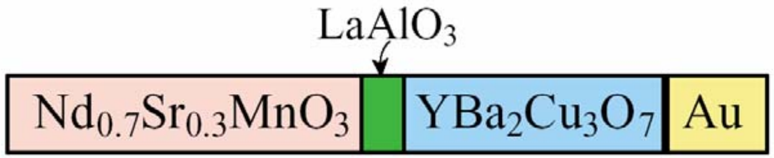
$$H : O(10^2\ \mathrm{T})$$

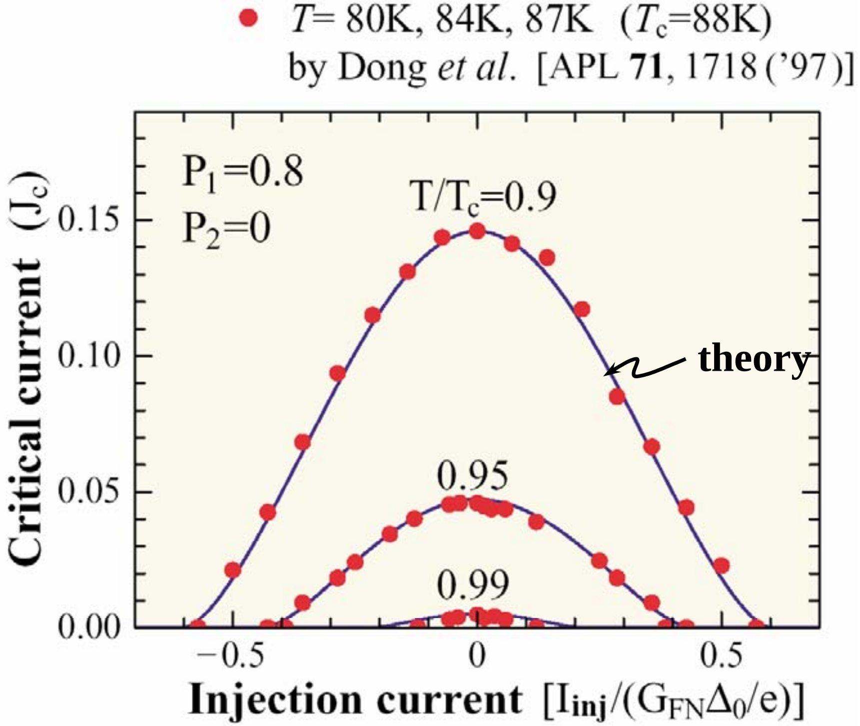
$$V_b : O(10^{-1}\ \mathrm{V})$$

$$B_S^{\mathbf{YBCO}} : O(10^4\,\mathrm{Oe}) \quad \left[N^{\mathbf{YBCO}}(0) : 10^2 N^{\mathbf{Al}}(0) \right]$$

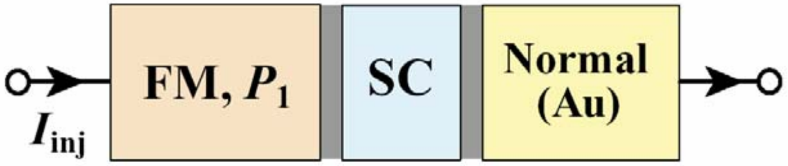
Spin accumulation >> Zeeman effect

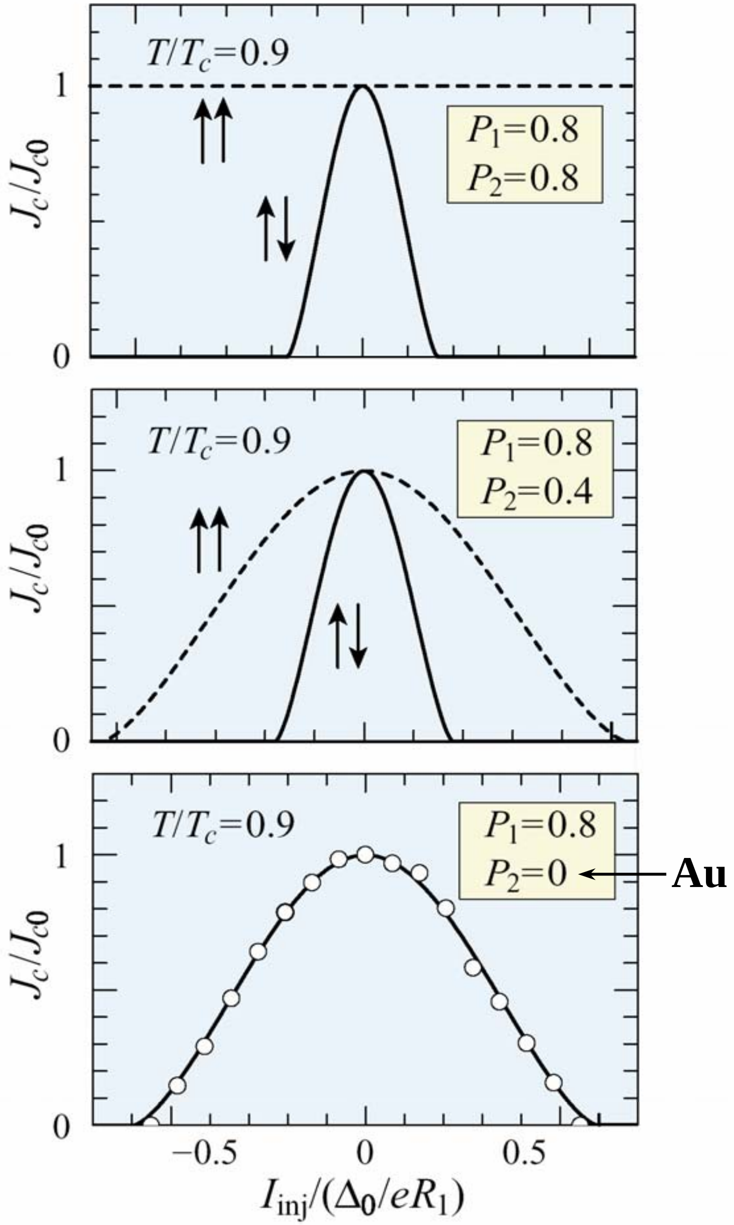
- **Suppression of Critical Current by Spin Injection**

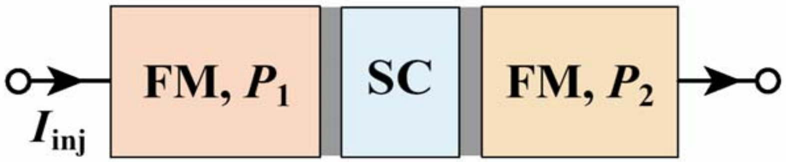




$$J_c \propto n_S v_c \propto \Delta^3$$





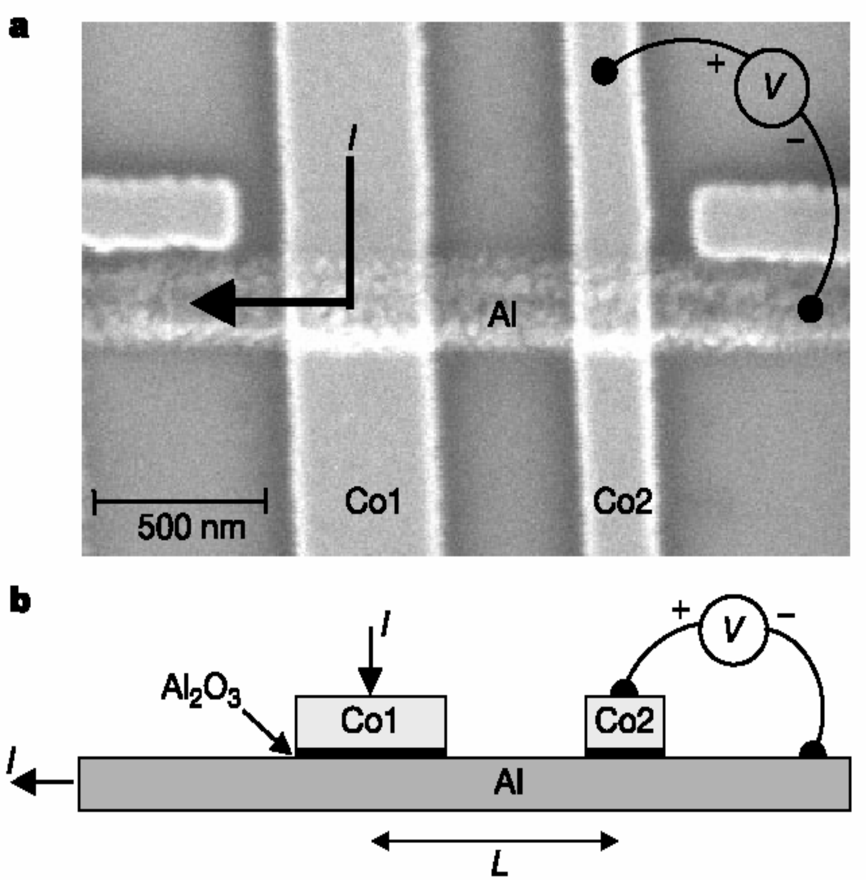


(S. Takahashi, H. Imamura, S.M., *PRL*. **82**, 3911 (1999))

Non-Local Spin Accumulation Device,

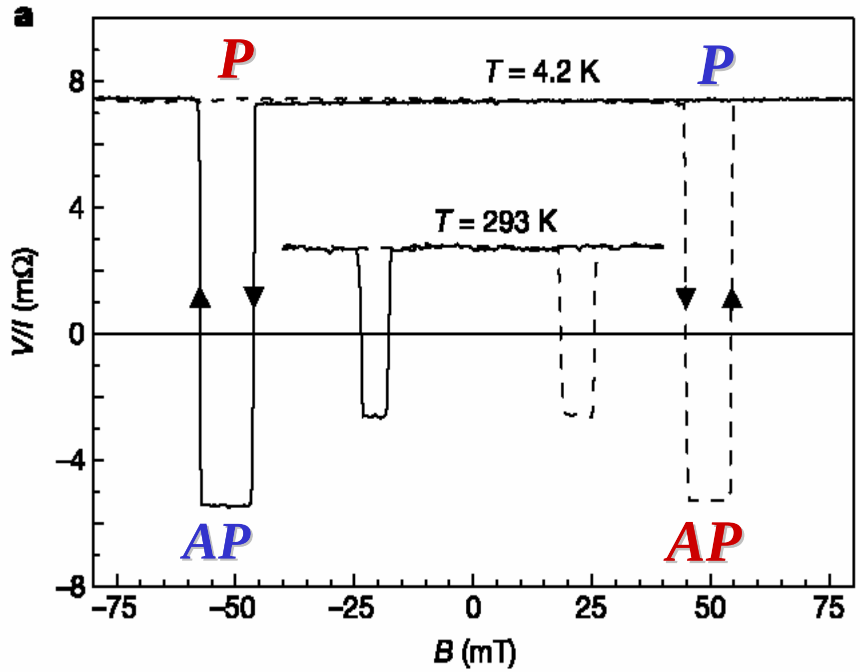
F. J. Jedema *et. al.*, ***Nature* 416,** 713 (2002)

Co-Al-Co



Spin accumulation signal:

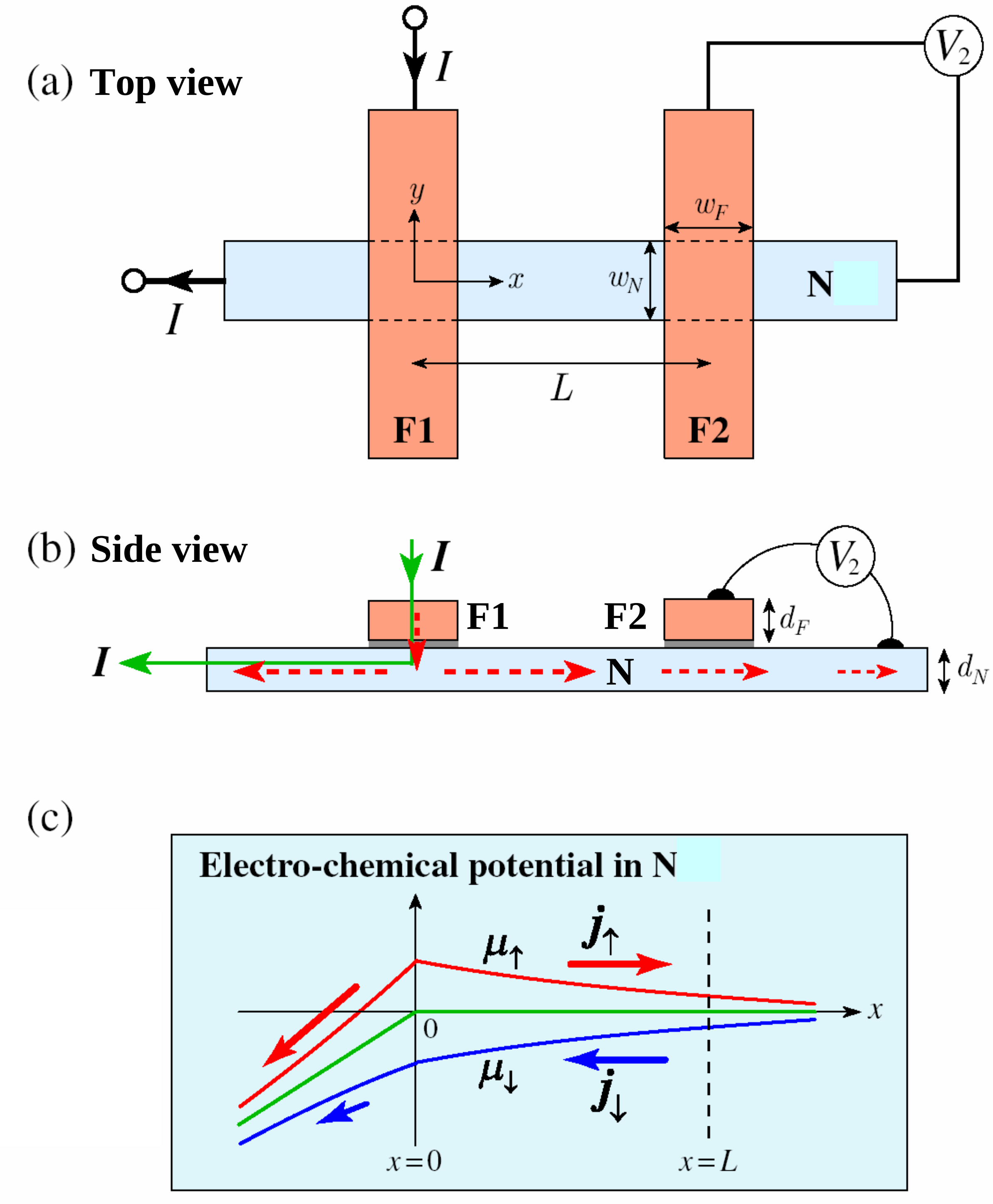
$$R_S = (V_P - V_{AP}) / I$$

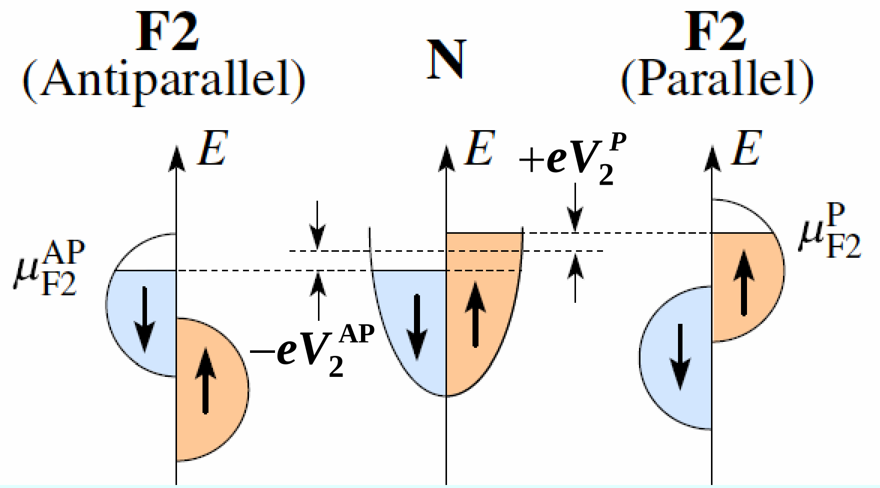


$$L = 650 \text{ nm}$$

$$R_S = 10 \text{ m}\Omega$$

Non-local geometry for measurement





Spin accumulation signal:

$$R_S = \frac{V_2^P - V_2^{AP}}{I} = \frac{2\delta\mu_N/e}{I}$$

Spin accumulation:

$$\delta\mu_N(x) = \mu_\uparrow - \mu_\downarrow$$

Charge and Spin currents:

$$\begin{cases} j = j_\uparrow + j_\downarrow \\ j_{\text{spin}} = j_\uparrow - j_\downarrow \end{cases}$$

Spin-dependent currents:

$$\boldsymbol{j}_{\uparrow} = -\frac{\sigma_{\uparrow}}{e}\nabla\mu_{\uparrow}, \quad \boldsymbol{j}_{\downarrow} = -\frac{\sigma_{\downarrow}}{e}\nabla\mu_{\downarrow}$$

$$\mathbf{N:}\ \ \sigma_{\mathrm{N}}^{\uparrow} = \sigma_{\mathrm{N}}^{\downarrow} = \frac{1}{2}\sigma_{\mathrm{N}},$$

$$\mathbf{F:}\ \ \sigma_{\mathrm{F}}^{\uparrow} \neq \sigma_{\mathrm{F}}^{\downarrow} \quad (\sigma_{\mathrm{F}} = \sigma_{\mathrm{F}}^{\uparrow} + \sigma_{\mathrm{F}}^{\downarrow})$$

Bulk spin polarization of F:

$$p_{\mathrm{F}} = \frac{\sigma_{\mathrm{F}}^{\uparrow} - \sigma_{\mathrm{F}}^{\downarrow}}{\sigma_{\mathrm{F}}^{\uparrow} + \sigma_{\mathrm{F}}^{\downarrow}}$$

$p_{\mathrm{F}} = 50:\ 70\%$*

Basic equations for *Electro-chemical potential*:

$$\nabla^2(\sigma_{\uparrow}\mu_{\uparrow} + \sigma_{\downarrow}\mu_{\downarrow}) = 0 \quad \leftarrow$$ **Charge conservation**

$$\nabla^2(\mu_{\uparrow} - \mu_{\downarrow}) = \frac{1}{\lambda_{\mathrm{s}}^2}(\mu_{\uparrow} - \mu_{\downarrow}) \quad \leftarrow$$ **Spin diffusion**

$$\mu_{\uparrow} - \mu_{\downarrow} \propto \exp(-x/\lambda_{\mathrm{s}})$$

λ_{s} **: spin diffusion length**

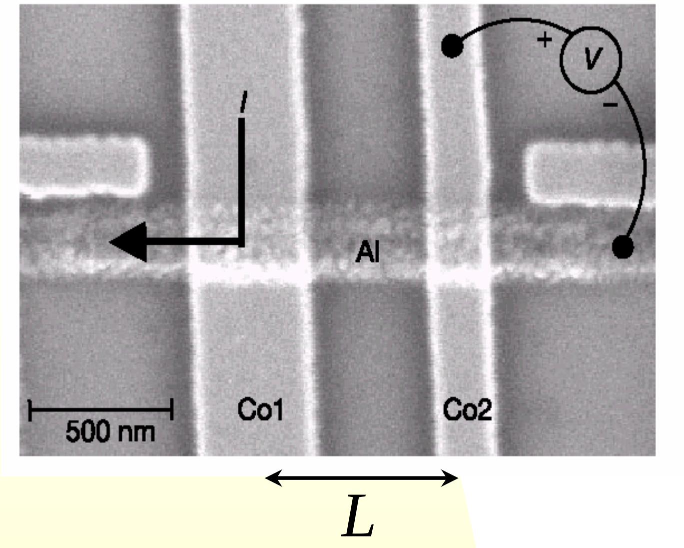
Jedema *et al.* $T = 4.2\mathrm{K}$

	λ_S	ρ
Cu	1000 nm	1.4 μΩcm
Al	650 nm	6 μΩcm
Py	5 nm*	8 μΩcm
Co	50 nm*	14 μΩcm

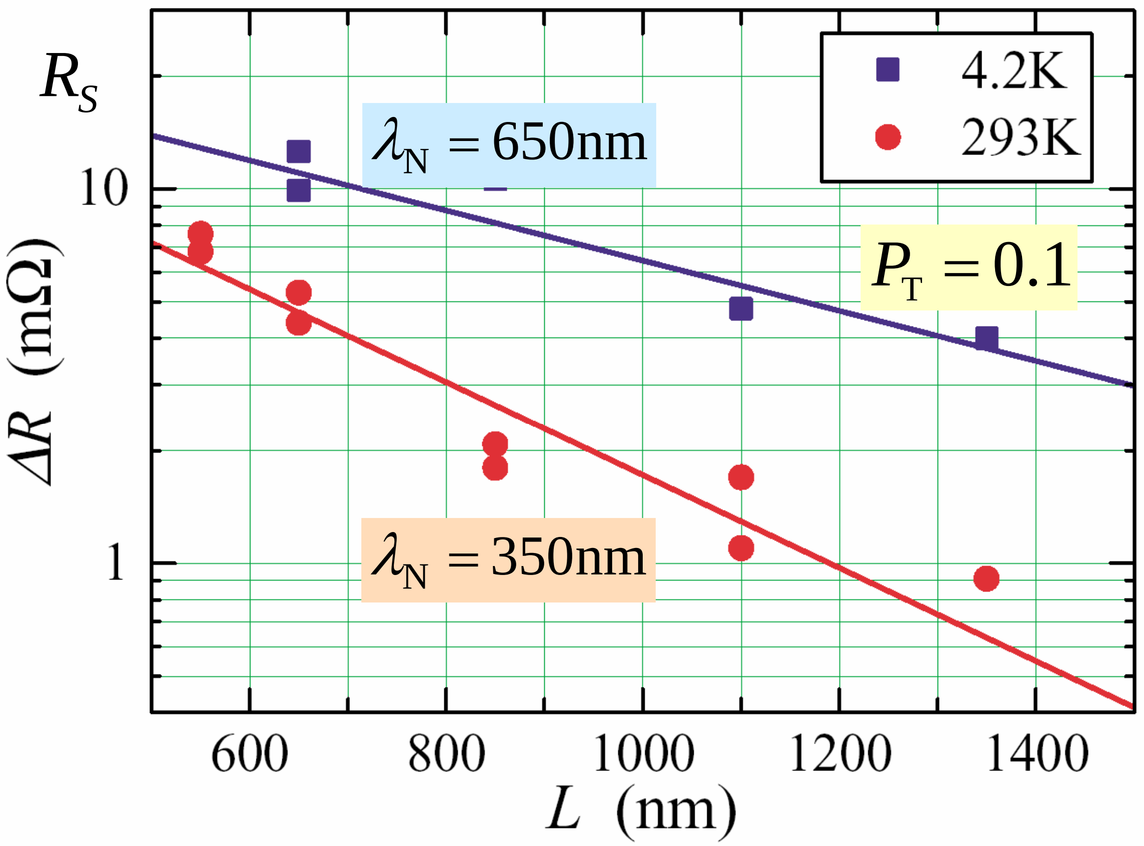
(Py: $\mathrm{Ni_{80}Fe_{20}}$) ***Bass and Pratt**

Co-Al-Co tunnel device

$$\begin{cases} R_1 = 600\Omega, \quad R_2 = 1200\Omega, \quad I = 100\mu\text{A} \\ \rho_\text{N} = 6\ \mu\Omega\text{cm} \\ A_\text{N} = w_\text{N} d_\text{N} = 250\text{nm} \times 50\text{nm} \end{cases}$$



Fitting parameter: P, λ_N

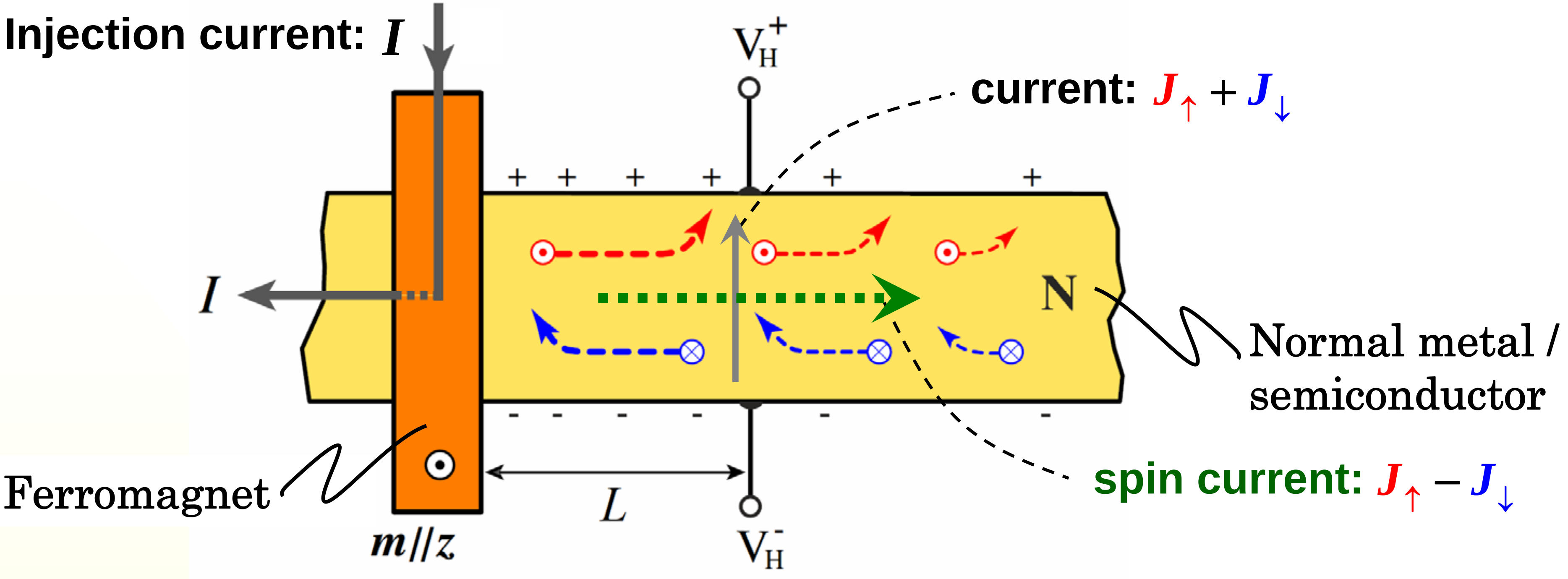


$$R_S = \frac{V_\text{P} - V_\text{AP}}{I} = P_\text{T}^2 R_\text{N} e^{-L/\lambda_\text{N}}$$

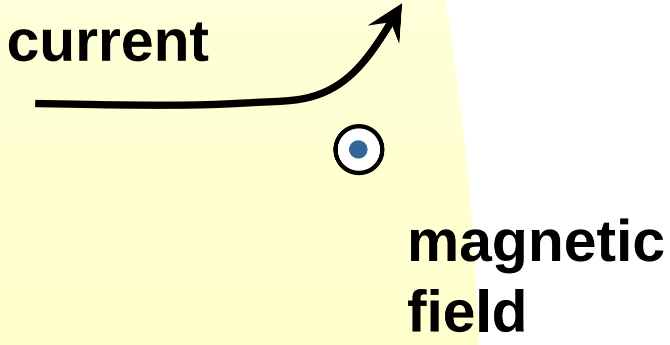
$$\delta\mu_\text{N}(x) = \underbrace{\frac{1}{2} P e R_\text{N} I}_{15\mu\text{eV}} \cdot e^{-x/\lambda_\text{N}}$$

$$R_\text{N} = \frac{\rho_\text{N} \lambda_\text{N}}{A_\text{N}} = 3\Omega$$

(F. J. Jedema *et al.*, ***Nature*** **416**, 713 (2002)
S. Takahashi and S.M., ***PRB*** **67,** 052409 (2003))



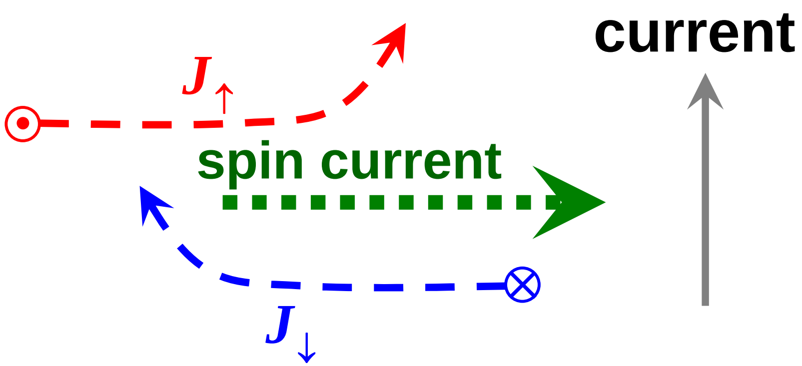
Hall effect



Spin Hall effect

(Anomalous Hall effect)

Spin current $(J_\uparrow - J_\downarrow)$



Spin Hall effect :

- **Intrinsic Spin Hall Effect:**

Spin-Orbit Coupling in the Band Structure

→ Ballistic transport

- **Extrinsic Spin Hall Effect:**

Spin-Orbit Scattering of Electrons

→ Diffusive transport

↑

metallic systems

Experiments:

Valenzuela & Tinkham, ***Nature*** 442, 176 (2006).
Saitoh *et al*., ***APL*** 88, 182509 (2006)
Kimura *et al*., ***PRL*** 98,156601(2007),

⬆

Anomalous Hall effect in ferromagnets

Boltzman equation for AHE (Anomalous Hall Effect):

Hamiltonian:

$$\mathcal{H} = \sum_{k\sigma} \xi_k a^\dagger_{k\sigma} a_{k\sigma} + \sum_{k,k'} \sum_{\sigma,\sigma'} U^{\sigma\sigma'}_{kk'} a^\dagger_{k'\sigma'} a_{k\sigma}$$

Impurity potential:

$$U^{\sigma\sigma'}_{kk'} = u_{\text{imp}} \left[\delta_{\sigma\sigma'} + \underbrace{i\lambda_{\text{so}} \boldsymbol{\sigma}_{\sigma\sigma'} \cdot \left(\hat{\boldsymbol{k}} \times \hat{\boldsymbol{k}}' \right)}_{\text{spin-orbit scatt.}} \right] \sum_j e^{i(\boldsymbol{k}-\boldsymbol{k}')\cdot \boldsymbol{r}_j}$$

Current density with spin σ: $\hat{\boldsymbol{j}}_\sigma = e \sum_{k\sigma} \left[\frac{\hbar \boldsymbol{k}}{m} + \boldsymbol{\omega}^\sigma_k \right] a^\dagger_{k\sigma} a_{k\sigma}$

Anomalous velocity: $\boxed{\boldsymbol{\omega}^\sigma_k = \frac{\lambda_{\text{so}}}{k_{\text{F}} \tau_{\text{imp}}} \left[\boldsymbol{\sigma}_{\sigma\sigma} \times \hat{\boldsymbol{k}} \right]}$ → **side jump**

Fermi distribution function:

$$\boxed{f_{k\sigma} = f^0_{k\sigma} - \tau_{\text{imp}} \boldsymbol{v}_k \cdot \nabla f^0_{k\sigma} + \alpha_{\text{SS}} \tau_{\text{imp}} \left[\boldsymbol{\sigma}_{\sigma\sigma} \times \frac{\hbar \boldsymbol{k}}{m} \right] \cdot \nabla f^0_{k\sigma}}$$

→ **skew scattering**

$$\alpha_{\text{SS}} = (2\pi/3) \lambda_{\text{so}} N(0) u_{\text{imp}}$$

Spin Hall conductivity:

$$\begin{cases} J_q = j_q + \alpha_H \left[x \times j_s \right] \\ J_s = j_s + \alpha_H \left[x \times j_q \right] \end{cases}$$

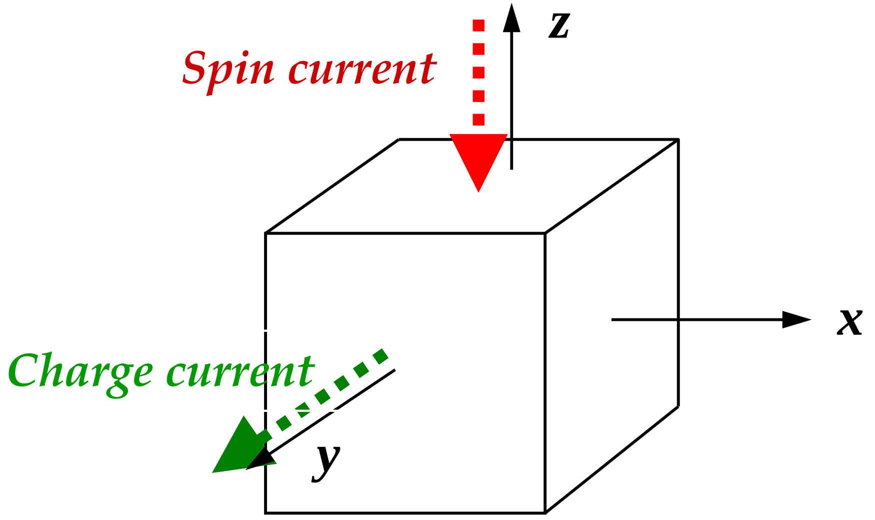
spin // *x*

$$\begin{cases} j_q = \sigma_N E \\ j_s = -\sigma_N \nabla \left(\delta\mu_N / e \right) \end{cases}$$

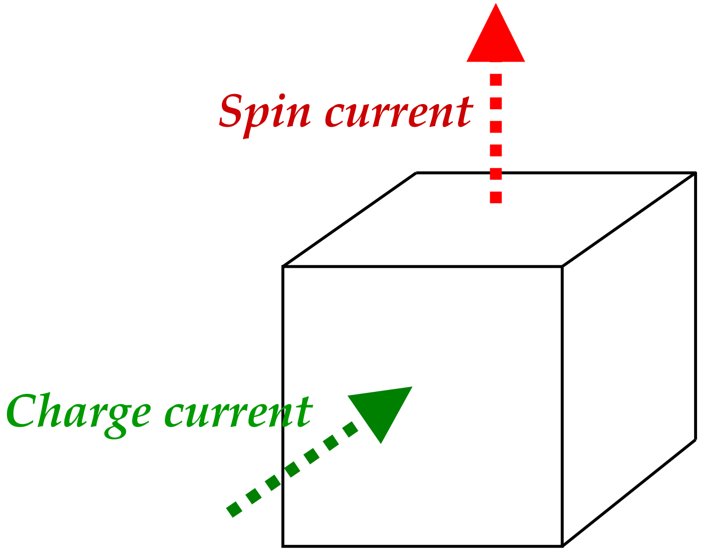
$$\begin{bmatrix} J_{q,x} \\ J_{s,y} \end{bmatrix} = \begin{bmatrix} \sigma_N & -\sigma_{SH} \\ \sigma_{SH} & \sigma_N \end{bmatrix} \begin{bmatrix} E_x \\ -\nabla_y \delta\mu_N / e \end{bmatrix}$$

$$\begin{bmatrix} J_{s,x} \\ J_{q,y} \end{bmatrix} = \begin{bmatrix} \sigma_N & -\sigma_{SH} \\ \sigma_{SH} & \sigma_N \end{bmatrix} \begin{bmatrix} -\nabla_x \delta\mu_N / e \\ E_y \end{bmatrix}$$

$$\sigma_{SH} = \sigma_{SH}^{\mathrm{SS}} + \sigma_{SH}^{\mathrm{SJ}}$$



$$j_q^y = \sigma_{\mathrm{N}} E_y + \alpha_{\mathrm{H}} \left[x \times j_{\mathrm{spin}}^z \right]$$



$$J_s^z = -\frac{\sigma_N}{e} \frac{\partial}{\partial z} \delta\mu_{\mathrm{N}} + \alpha_{\mathrm{H}} \left[x \times \frac{I}{A_{\mathrm{Pt}}} \right]$$

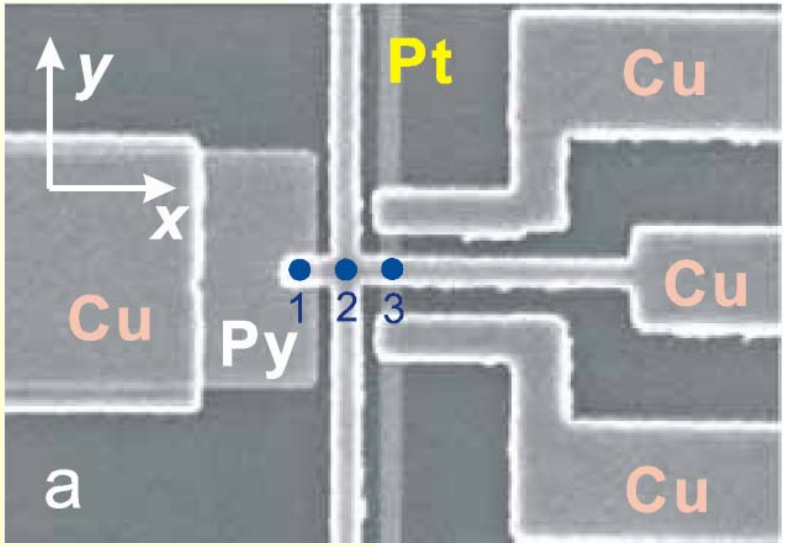
Room Temperature Spin Hall Effect

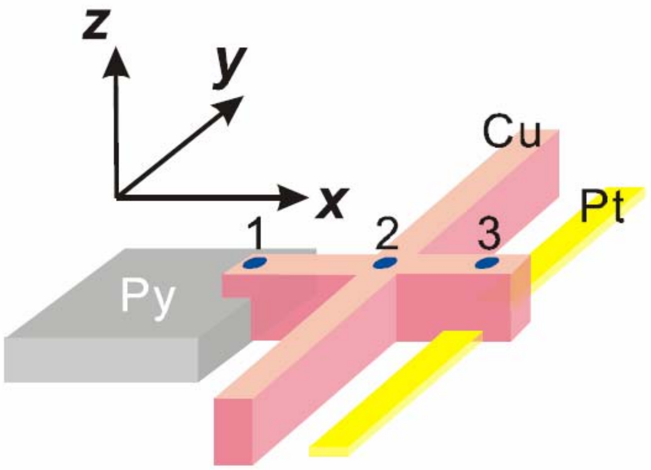
T. Kimura (*ISSP*, *RIKEN*), Y. Otani (*ISSP*, *RIKEN*), T. Sato (*ISSP*)
S. Takahashi (*IMR*, *CREST*), S. Maekawa (*IMR*, *CREST*)

(Phys. Rev. Lett. ***98,*** *156601(2007))*

``Conversion between charge-current and spin-current’’

Nonlocal Spin Hall device

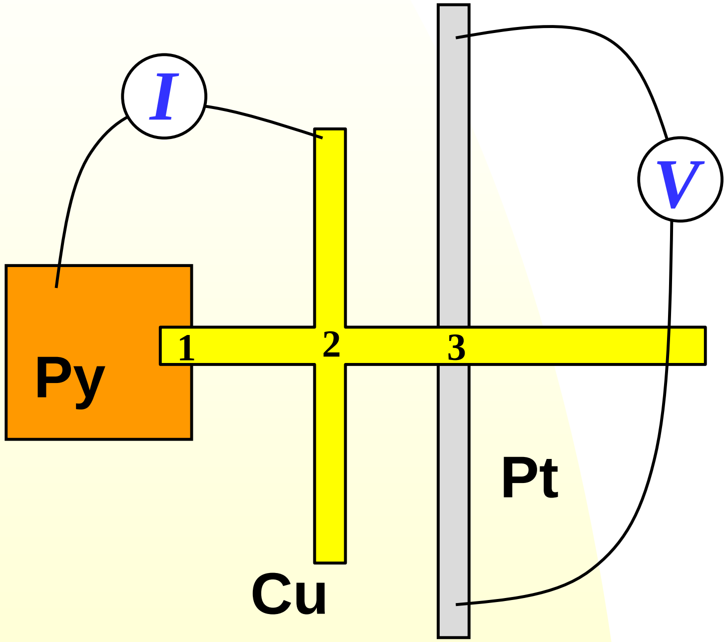


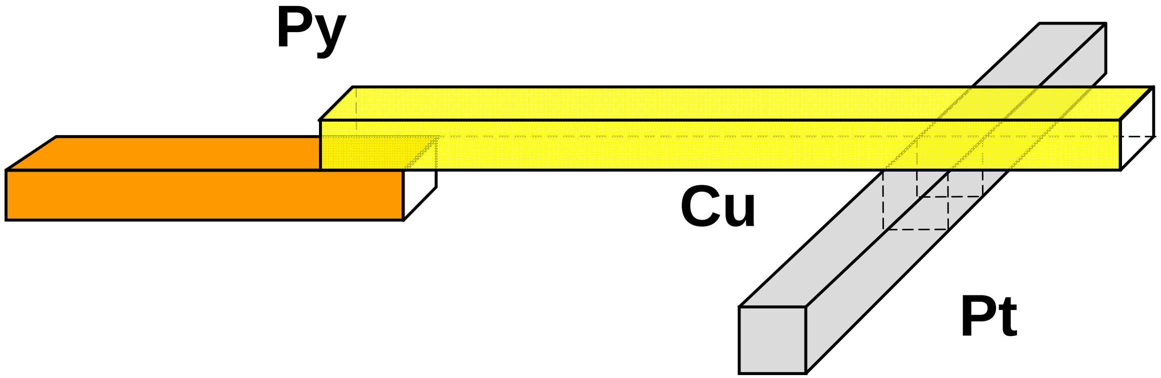


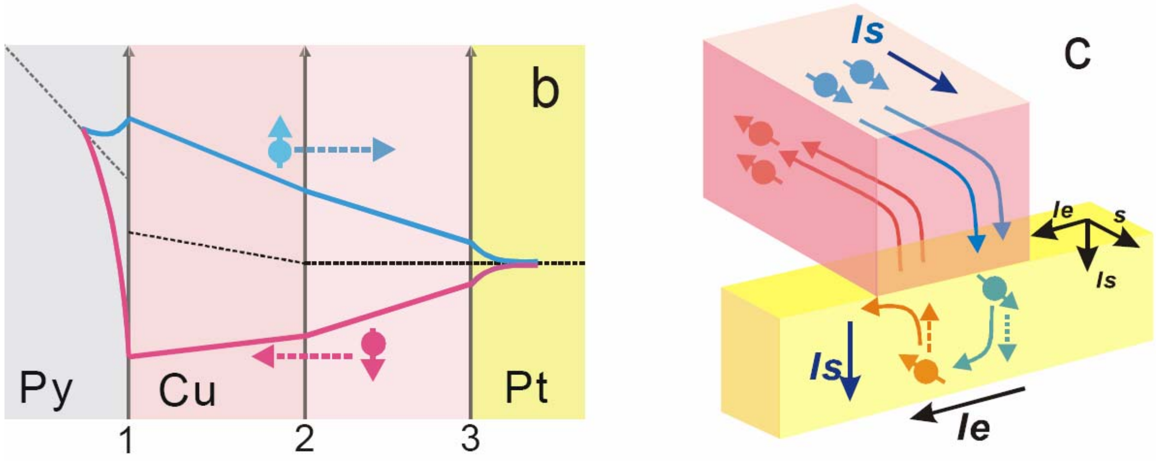
Spin-current induced Spin Hall effect

(Kimura *et al.*)

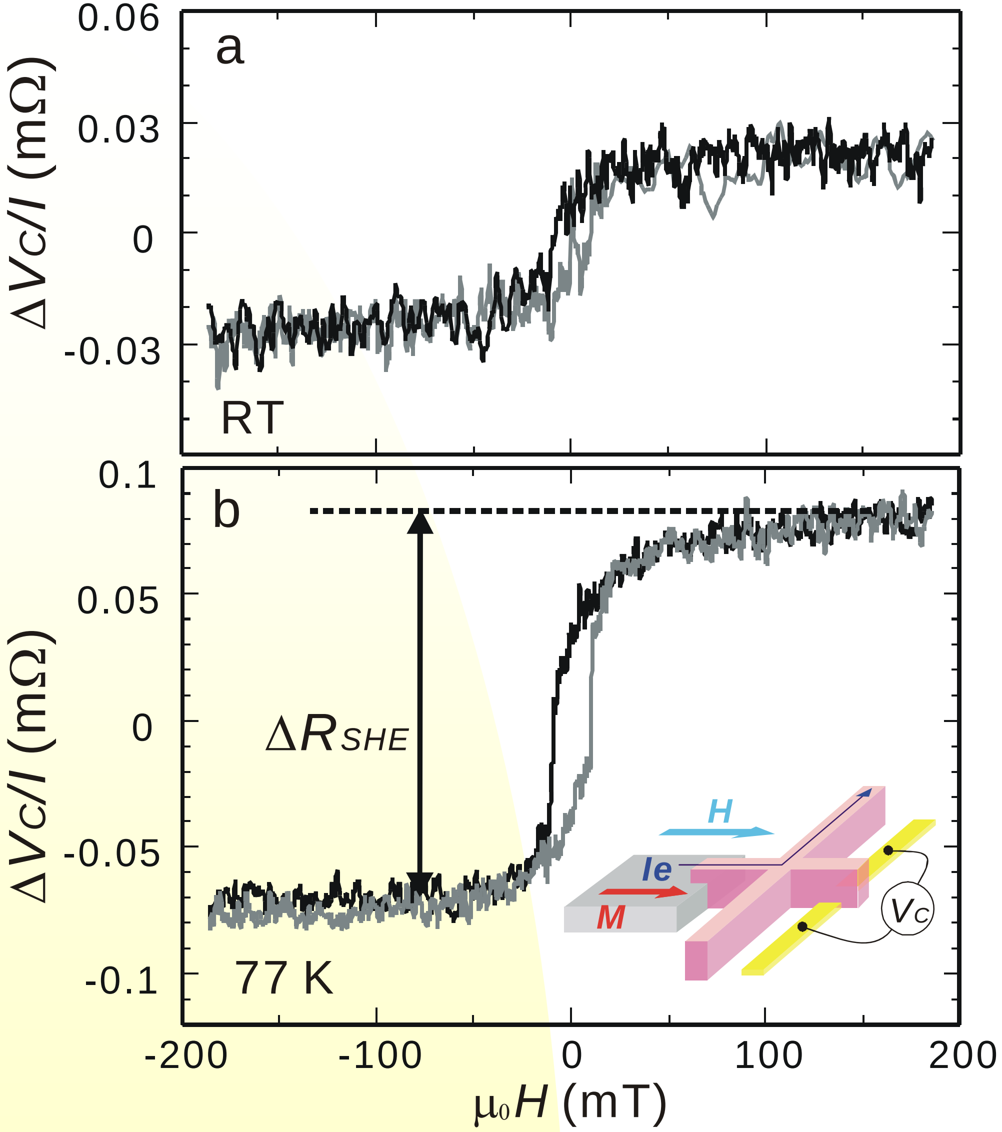
$$[R_{\mathrm{H}}]_{S\rightarrow Q}=\frac{\Delta V}{I}$$

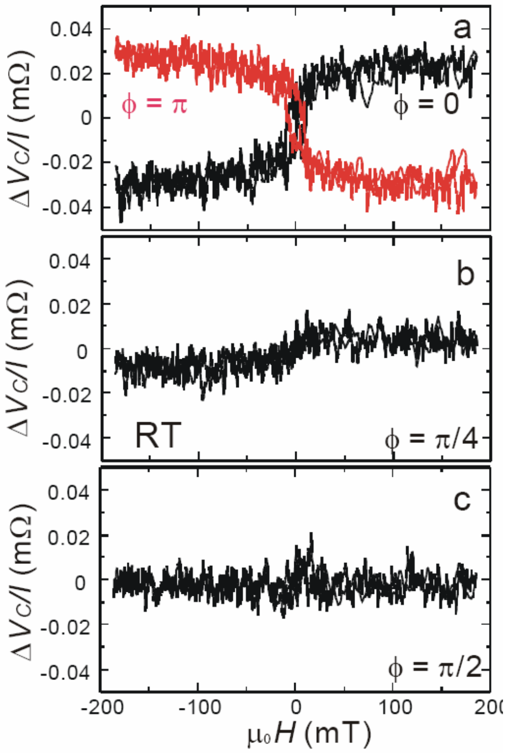


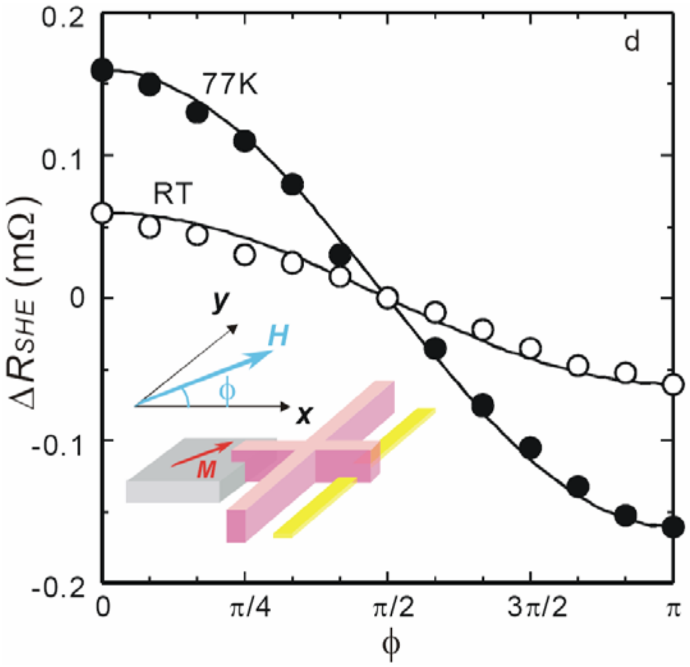




Nonlocal Spin Hall resistivity

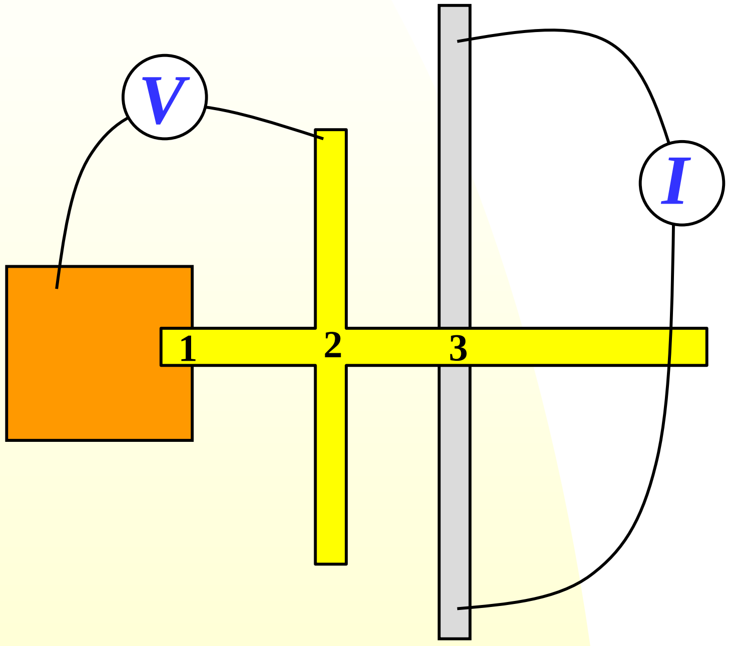


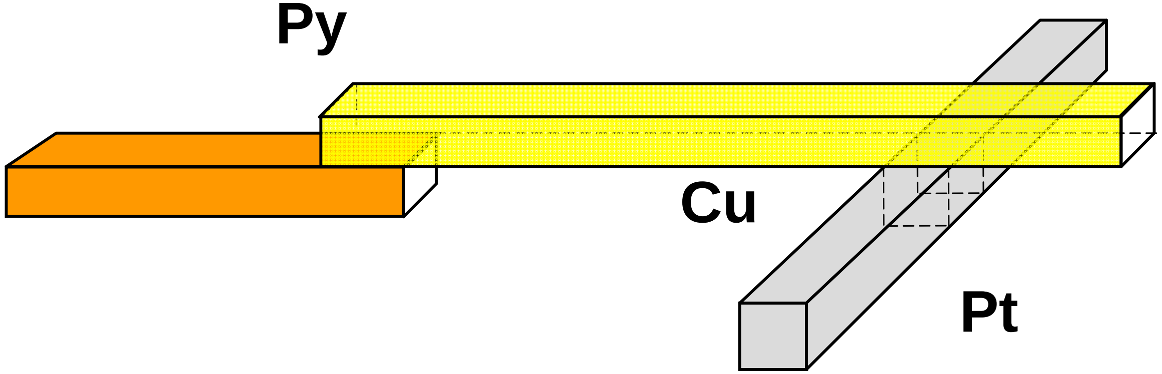


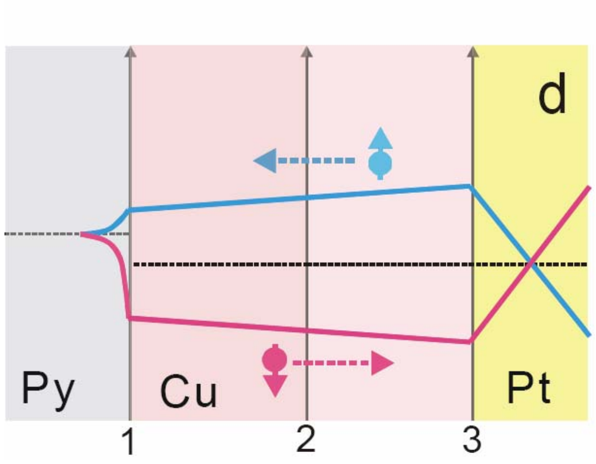


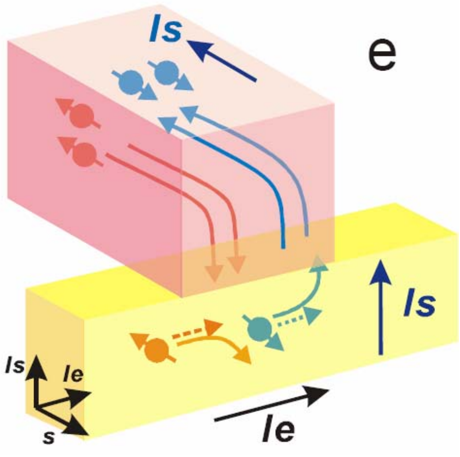
Charge-current induced Spin Hall effect

$$\left[R_{\mathrm{SH}}\right]_{Q\rightarrow S}=\frac{\Delta V}{I}$$

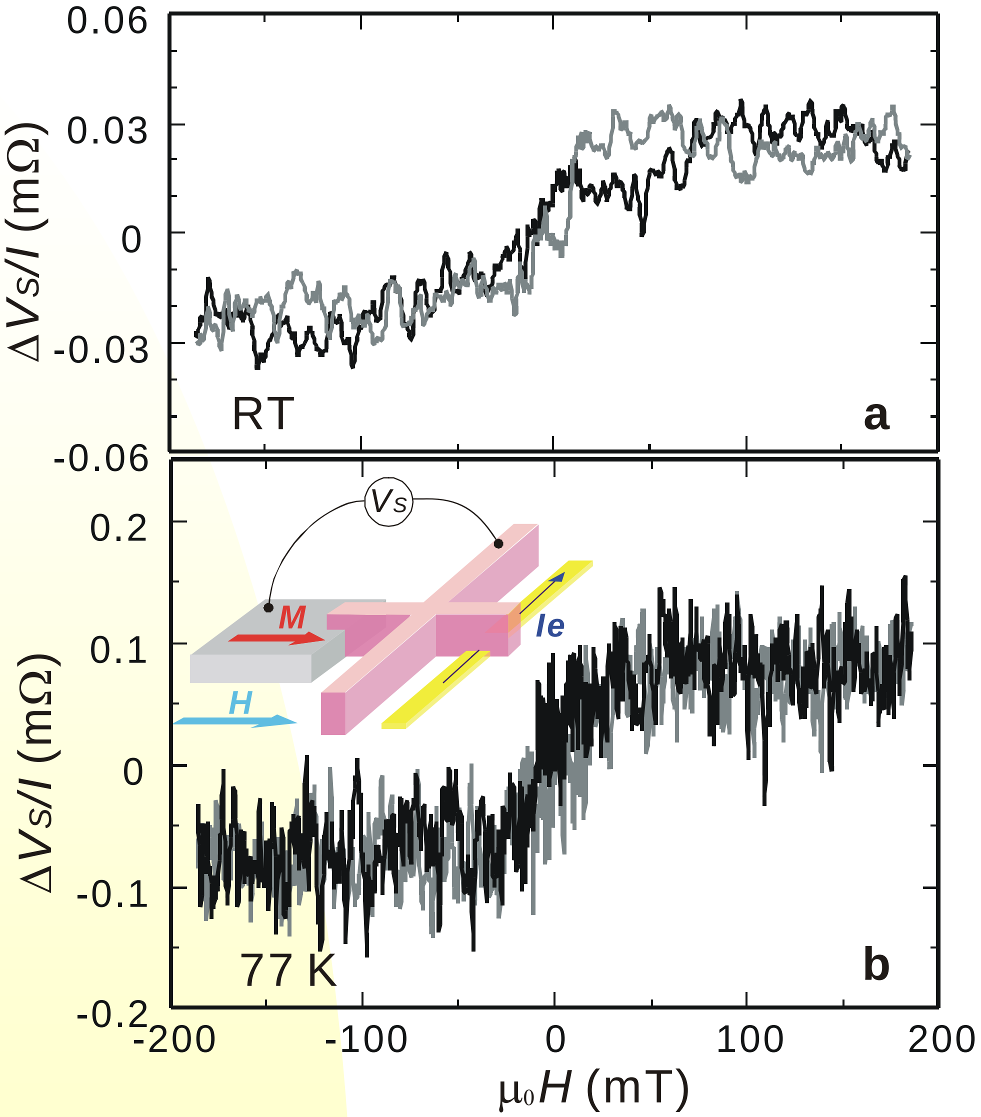






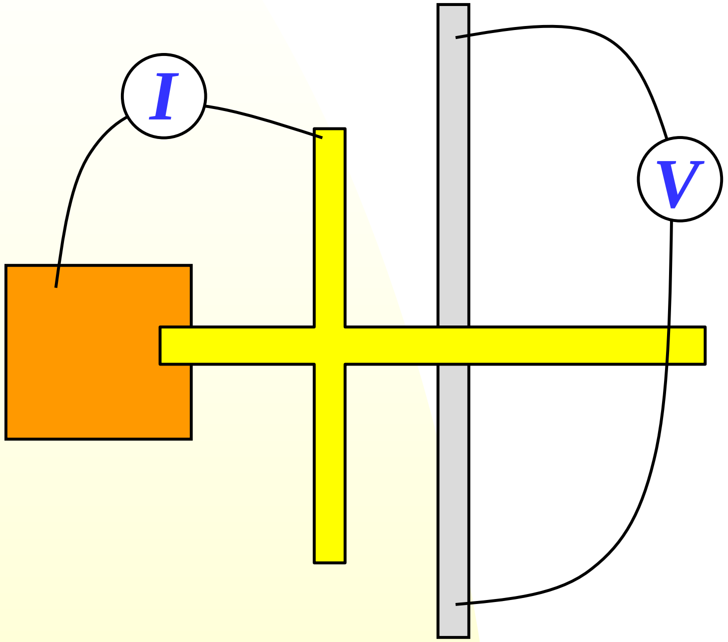


Nonlocal Spin Hall resistivity



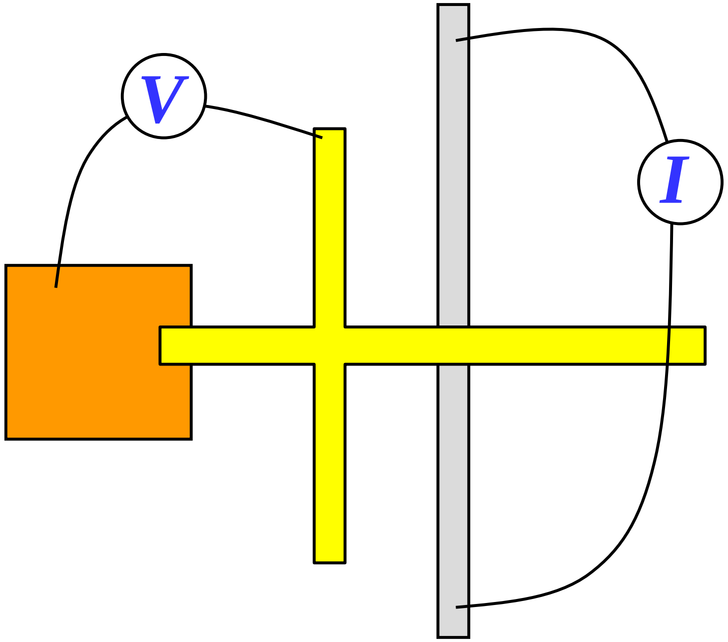
Spin-current induced SHE

$$\left[R_{\mathrm{SH}}\right]_{S\rightarrow Q}=\frac{\Delta V}{I}$$



Charge-current induced SHE

$$\left[R_{\mathrm{SH}}\right]_{Q\rightarrow S}=\frac{\Delta V}{I}$$



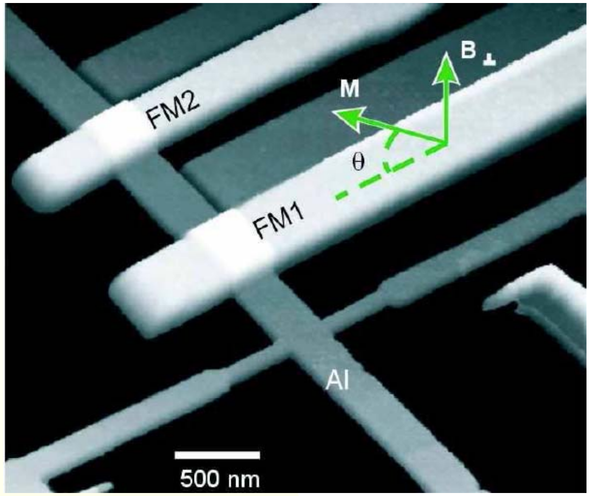
Onsager Reciprocal Relation!!

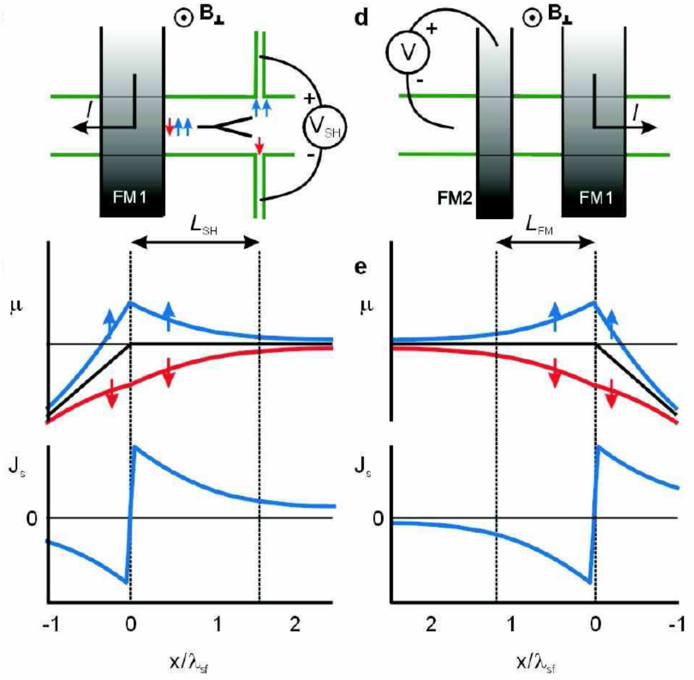
Charge-current ↔ ***Spin-current***

Spin-current induced Spin Hall effect:

Valenzuela & Tinkham:

(***Nature*** ***442***, 176 (2006))





k_F=1. 5 ×10^8 cm^{-1} (Au)

	λ_N	ρ_N	$\rho_N\lambda_N$	τ_{sf} / τ	λ_{so}
Al^{b2}	**705 nm**	**5.88 μΩcm**	**4.15 ×10^{-10} Ωcm^2**	**1.8 ×10^4**	**0.011**

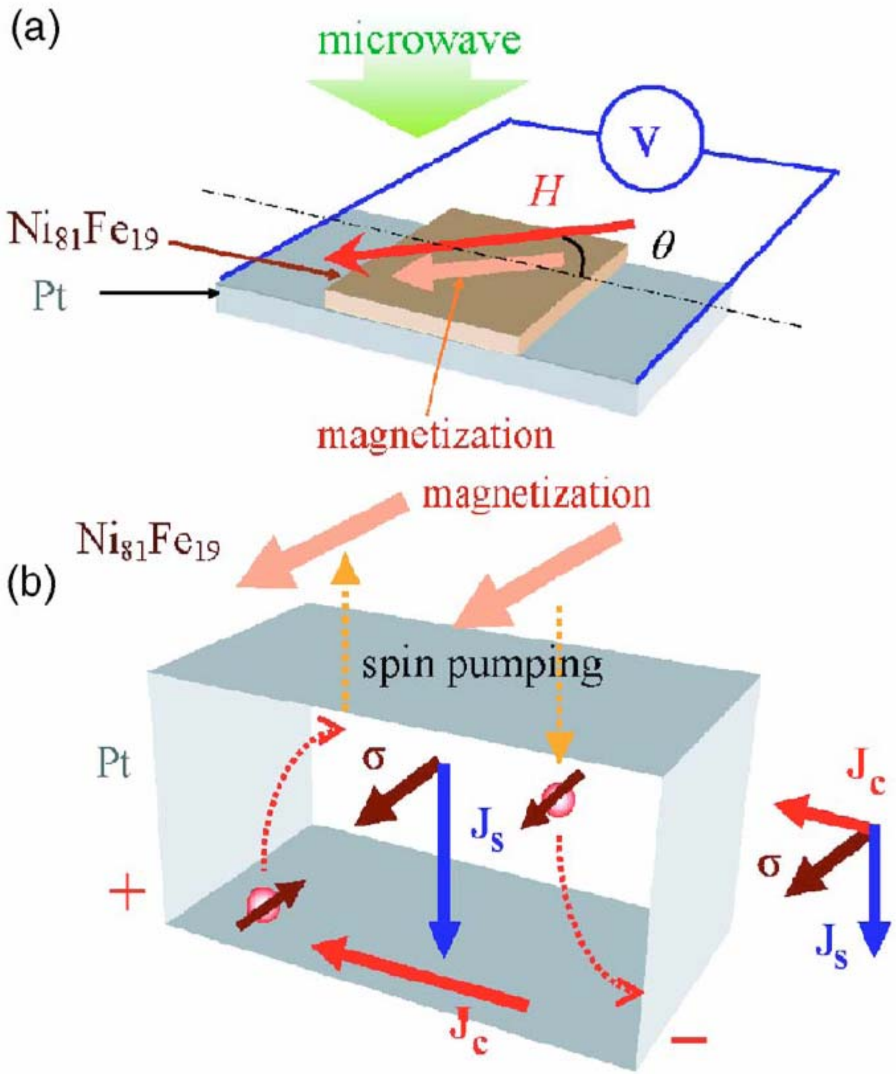
◎ Side jump analysis:

$$\begin{cases} \alpha_H^{SJ} = \dfrac{\sigma_{SH}^{SJ}}{\sigma_N} = \dfrac{\lambda_{so}}{k_F l_{imp}} : \; 1\times10^{-4} \\ \lambda_{so} : \; 0.011 \end{cases}$$

$$\Longrightarrow \quad k_F l_{imp} : \; 110 \qquad \left(l_{imp} = \lambda_{so} \right)$$

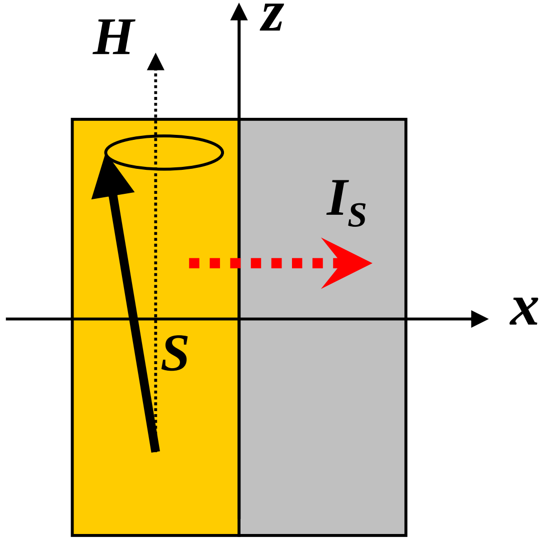
Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect

E. Saitoh *et al.*, ***APL*88** (2006)



Spin pumping:

$$[\boldsymbol{I}_s]_j^\alpha \propto \left(\boldsymbol{S}\times\frac{\partial \boldsymbol{S}}{\partial \boldsymbol{t}}\right)_\alpha$$



Spin-orbit coupling : λ_{so}

$$\left.\begin{aligned} \lambda_{\mathrm{N}} &= \sqrt{D\tau_{\mathrm{sf}}} \\ \rho_{\mathrm{N}} &= \frac{m}{ne^2\tau} \end{aligned}\right\} \Rightarrow \boxed{\rho_{\mathrm{N}}\lambda_{\mathrm{N}} = \frac{\sqrt{3}\pi}{2k_{\mathrm{F}}^2}\frac{h}{e^2}\sqrt{\frac{\tau_{\mathrm{sf}}}{\tau}}} \Rightarrow \boxed{\lambda_{\mathrm{so}} \approx 4\left(\frac{R_{\mathrm{K}}}{k_{\mathrm{F}}^2}\right)\frac{1}{\rho_{\mathrm{N}}\lambda_{\mathrm{N}}}}$$

$$\boxed{\frac{\tau}{\tau_{\mathrm{sf}}} = \frac{4}{9}\lambda_{\mathrm{so}}^2}$$

$$R_{\mathrm{K}} = h/e^2 \approx 25.8\ \mathrm{k\Omega}$$

T=4.2K

$k_{\mathrm{F}}=1.5\times10^{8}\ \mathrm{cm}^{-1}$

	λ_{N}	ρ_{N}	$\rho_{\mathrm{N}}\lambda_{\mathrm{N}}$	τ_{sf}/τ	λ_{so}
Al[c]	705 nm	5.88 μΩcm	$41.5\times10^{-11}\ \Omega\mathrm{cm}^2$	18000	**0.011**
Cu[a]	1000 nm	1.43 μΩcm	$14.3\times10^{-11}\ \Omega\mathrm{cm}^2$	2100	**0.033**
Cu[b]	1500 nm	1.00 μΩcm	$15.0\times10^{-11}\ \Omega\mathrm{cm}^2$	2300	**0.031**
Ag[d]	195 nm	3.50 μΩcm	$6.8\times10^{-11}\ \Omega\mathrm{cm}^2$	475	**0.07**
Au[e]	90 nm	2.45 μΩcm	$2.2\times10^{-11}\ \Omega\mathrm{cm}^2$	50	**0.21**
Pt[f]	14 nm	12.8 μΩcm	$1.8\times10^{-11}\ \Omega\mathrm{cm}^2$	33	**0.26**

a) Jedema *et. al.*, b) Kimura *et. al.*(77K), c) Valenzuela&Tinkham, d) Godfrey&Johnson
e) Seki *et al.*.(RT), f) Kurt *et. al.*

$$\frac{\alpha_{\mathrm{H}}(\mathbf{Pt})}{\alpha_{\mathrm{H}}(\mathbf{Al})} = 30, \qquad \frac{\lambda_{\mathbf{so}}(\mathbf{Pt})}{\lambda_{\mathbf{so}}(\mathbf{Al})} = 30,$$

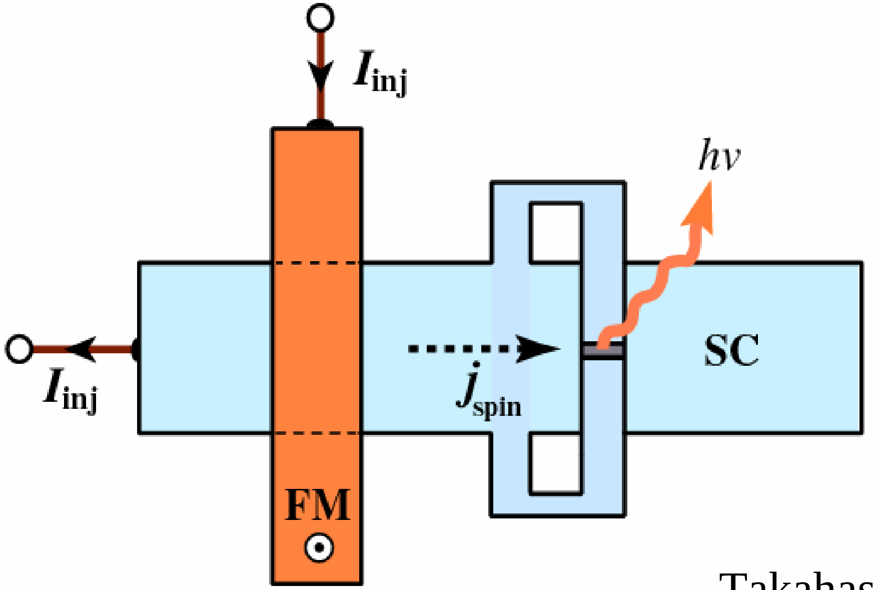
Spin-orbit interaction strength in Pt and Au is about 30 times larger than that in Al.

Pt, Au: ***Strong spin-orbit material***

- **Spin absorber**
- **Spin generator**

- **Spin-injection Hall device with a Josephson junction.**
  - **Hall voltage V_H generates ac Josephson effect.**

$$(h\nu = 2eV_H \sim 10^7 \mathrm{Hz})$$



Takahashi, Maekawa
***PRL*88**, 116601 (2002)

Spin Current vs. Charge Current

in Magnetic Nanostructures

S. Maekawa
(*IMR, Tohoku University*)

Contents:

(i) *Spin current,*
(ii) Spin accumulation,
(iii) *Spin Hall effect,*
(iv) *Spin current pumping.*

(Charge current ⟺ Spin Current)