MANIPULATION OF SPIN CURRENT & SPIN HALL EFFECTS IN METALLIC SYSTEMS

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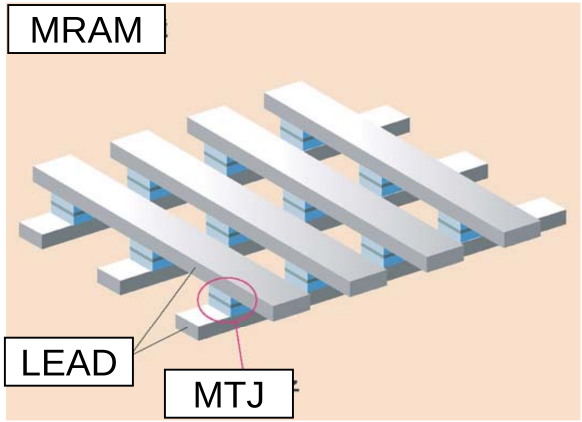
Contents

1. **Nonlocal spin injection**
   - **Planar F/N hybrid structure**
   - **Electrical detection of spin accumulation**
   - **Spin absorption effect**

2. **Spin Hall effect**
   - **Electrical detection of SHE by spin absorption**
   - **Possible origins for SHE**
   - **SHEs for various transition metals**

Advantage of planar spintronic devices

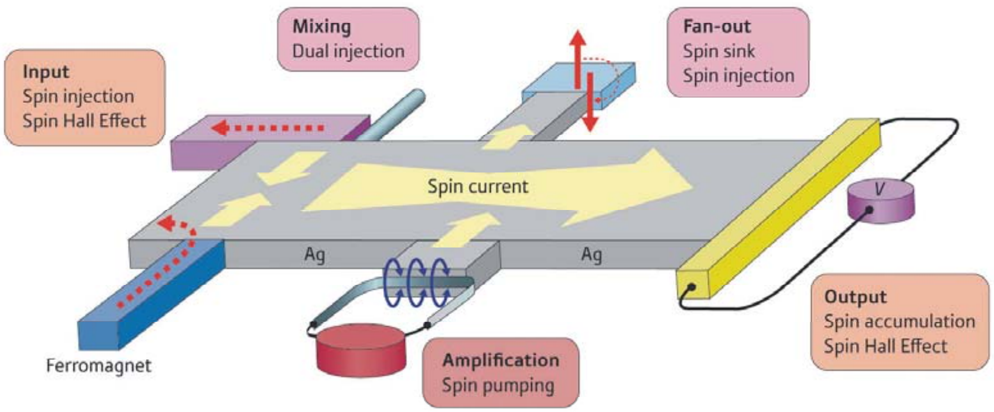
Conventional



Mainly two terminal structure

Difficult to make
multi-terminal devices

Planar structures



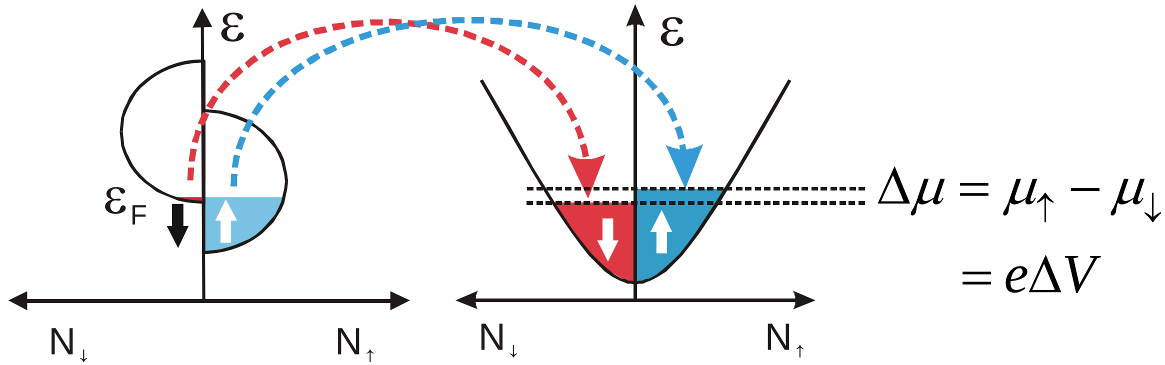
Easily expand to multi-terminal and functional devices

- **Detailed study of spin current diffusion in F/N hybrid structures**
- **Development of novel spintronic devices.**

Optimizing structures for efficient operation

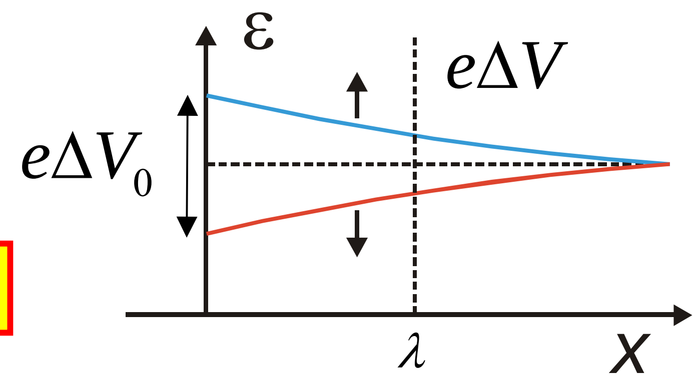
Spin injection from F to N

Electric currents are injected from F into N.



Spin accumulation

Accumulated spins diffuse with spin-flip scattering.



Spin diffusion length

Diffusion equation

$$\frac{\partial \Delta V}{\partial t} = D\frac{\partial^2 \Delta V}{\partial x^2} - \frac{\Delta V}{\tau_S}$$

$$\longrightarrow 0 = D\frac{\partial^2 \Delta V}{\partial x^2} - \frac{\Delta V}{\tau_S}$$

General solution

$$\Delta V = V_+ \exp\left(\frac{x}{\lambda}\right) - V_- \exp\left(-\frac{x}{\lambda}\right)$$

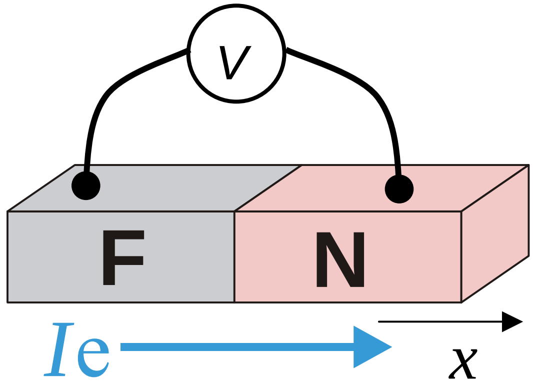
$$\lambda = \sqrt{D\tau_S}$$

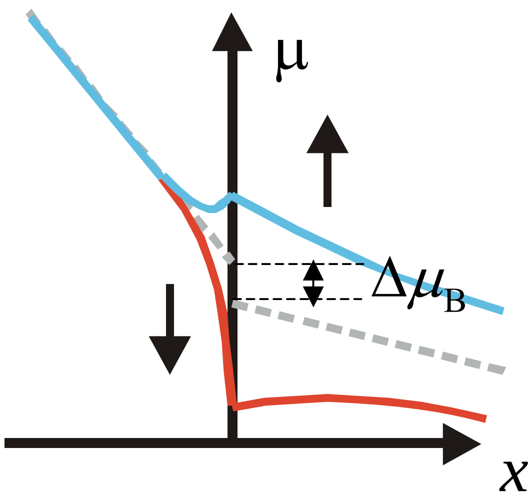
D: Diffusion constant

τ_S : Spin life time

Boundary resistance due to spin accumulation

van Son, Phys. Rev. Lett. (1987)





~~$R = R_F + R_N$~~

$$R = R_F + R_N + R_B$$

1. Conservation of spin current at the interface

$$I_{\uparrow F} = I_{\uparrow N} \qquad I_{\downarrow F} = I_{\downarrow N}$$

2. Continuity of the electrochemical potential

$$\mu_{\downarrow F} = \mu_{\downarrow N} \qquad \mu_{\uparrow F} = \mu_{\uparrow N}$$

$$\longrightarrow \Delta\mu_B = \frac{P\lambda_F\lambda_N}{(1-P^2)\lambda_N\sigma_F + \lambda_F\sigma_N}\frac{I}{S}$$

$$R_B \equiv \frac{\Delta\mu_B}{I} = \frac{PR_{SF}R_{SN}}{R_{SF} + R_{SN}}$$

Spin resistance

$$R_S \equiv \frac{2\lambda}{\sigma S(1-P^2)}$$

λ : Spin diffusion length

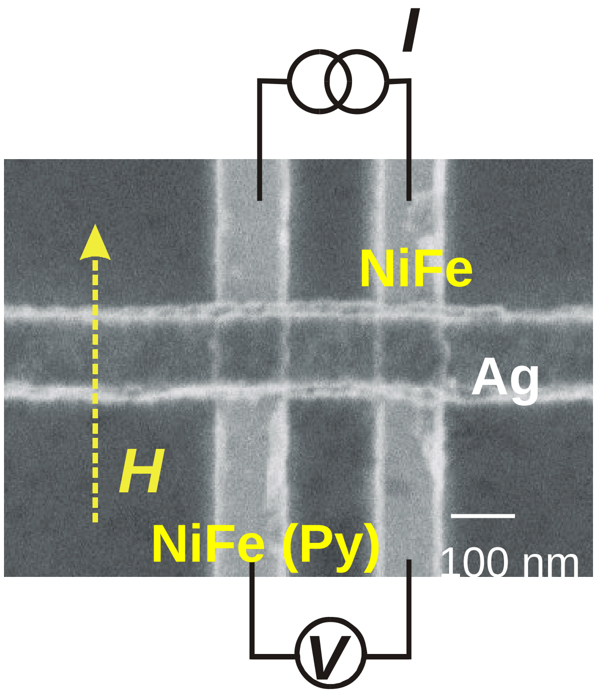
S : Cross section

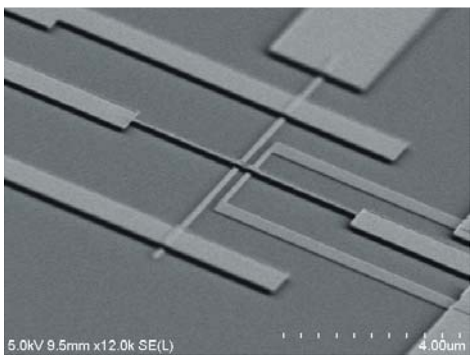
P : Spin polarization

$$R_B \ll R_F,\ R_N$$

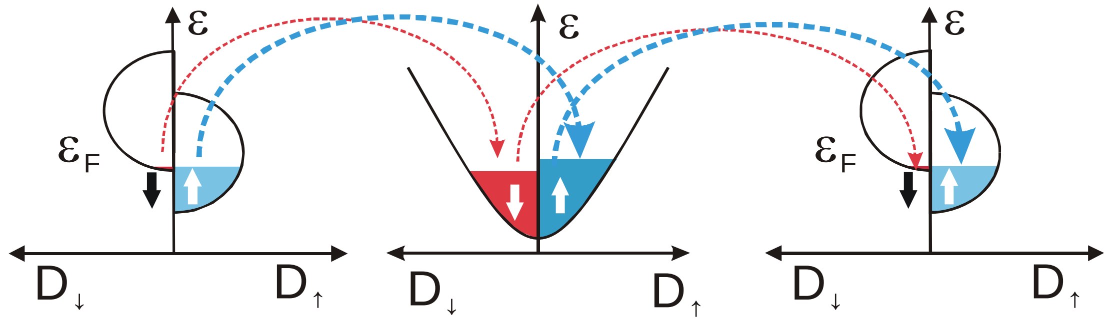
Resistance change is too small.

Detection of spin accumulation





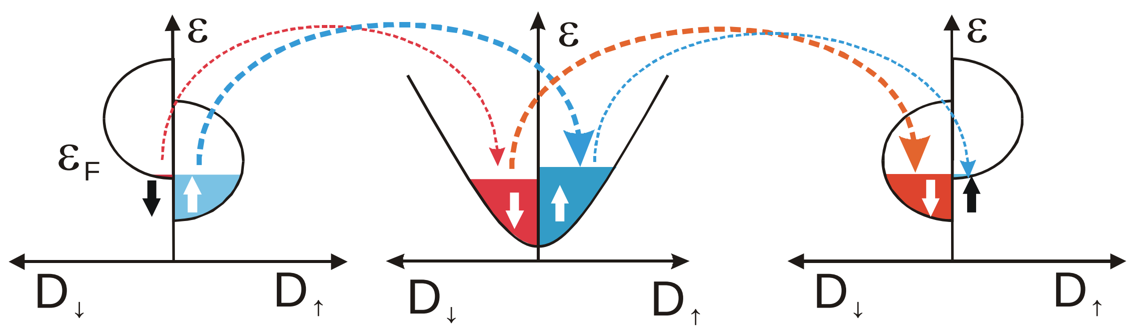
Two Fs are in parallel



Small spin accumulation in N

Smooth current flow → **Low resistance**

Two Fs are in anti-parallel



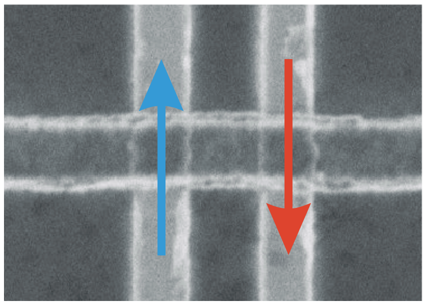
Large spin accumulation in N

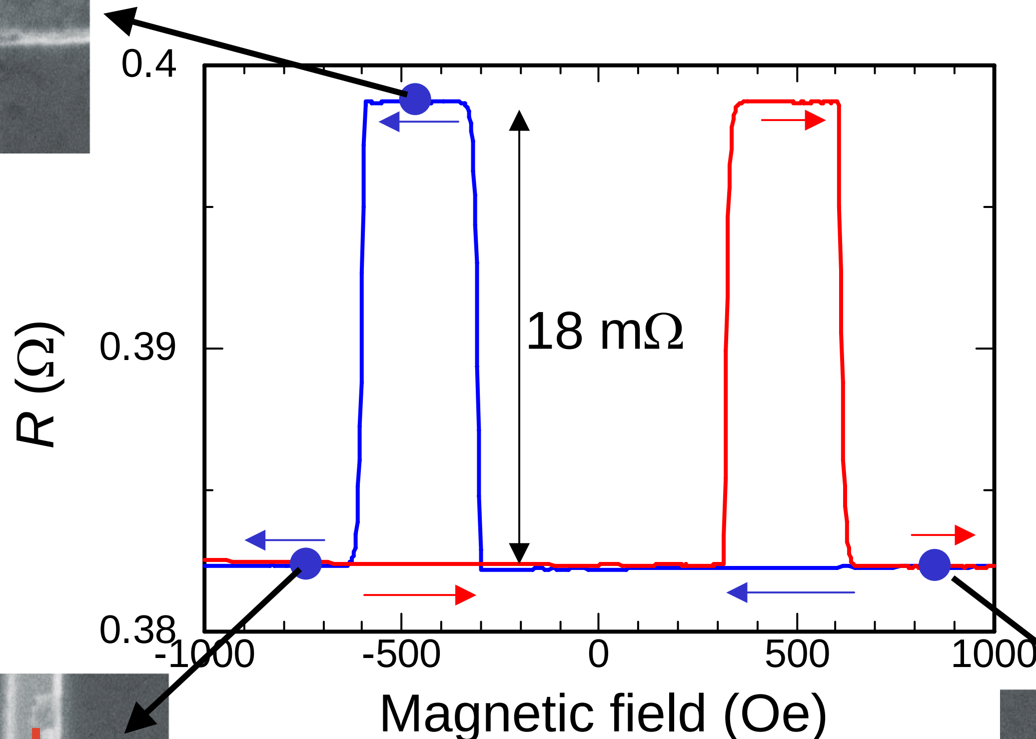
→ **High resistance**

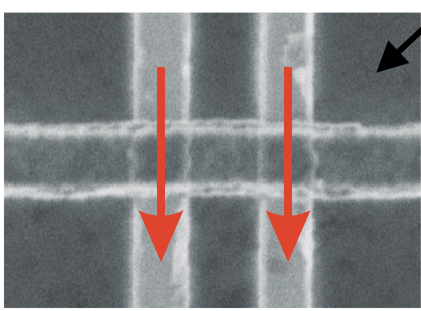
Magnetoresistance due to spin accumulation

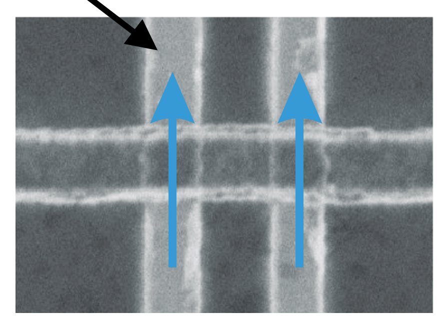
T. Kimura et al. Appl. Phys. Lett 85, 3501 (2004)

$$2\frac{\Delta\mu_{\mathrm{BAP}}-\Delta\mu_{\mathrm{BP}}}{eI}=18\ \mathrm{m}\Omega$$



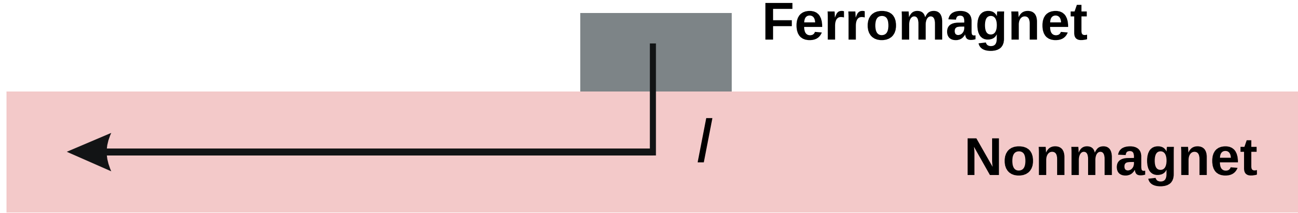


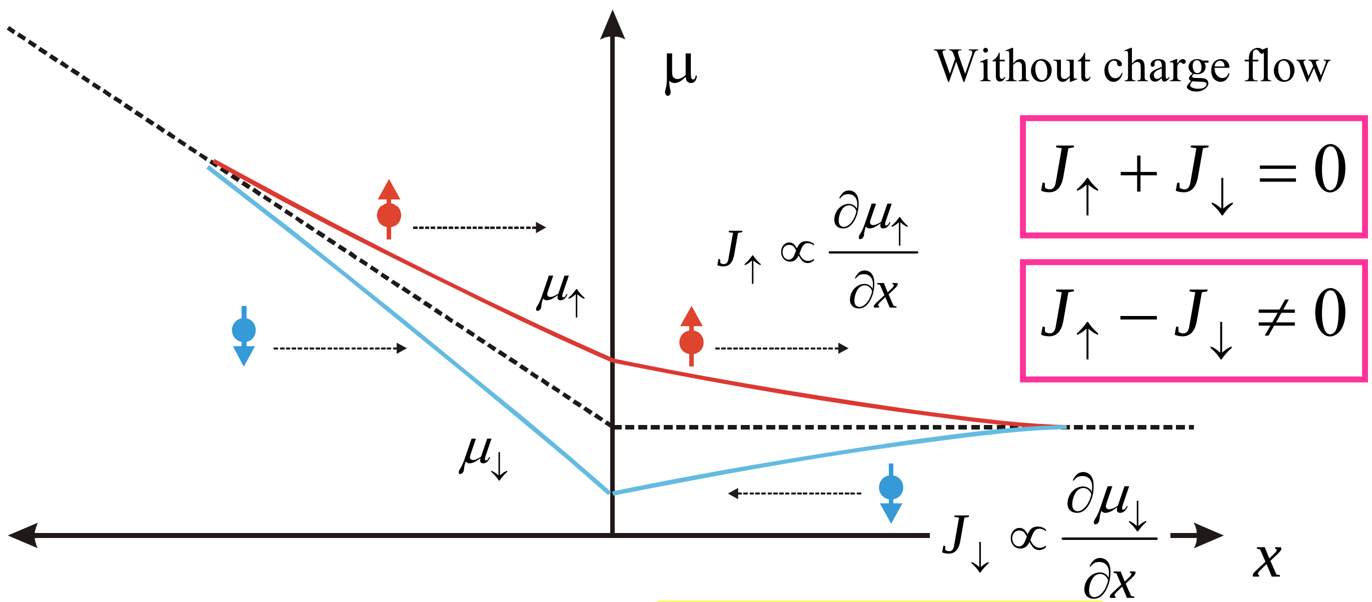




Nonlocal spin injection and pure spin current

M. Johnson, B. J. van Wees

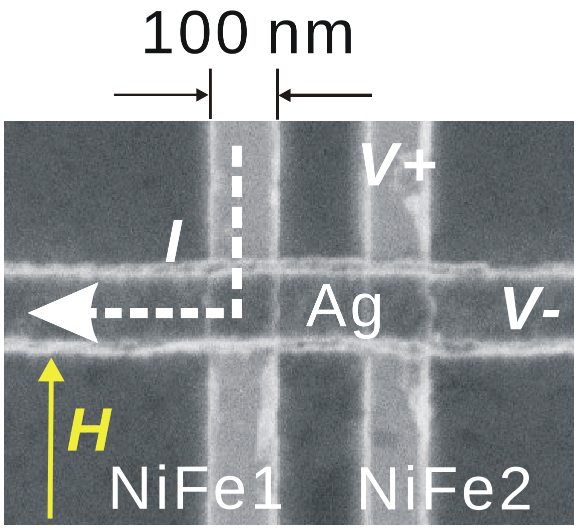


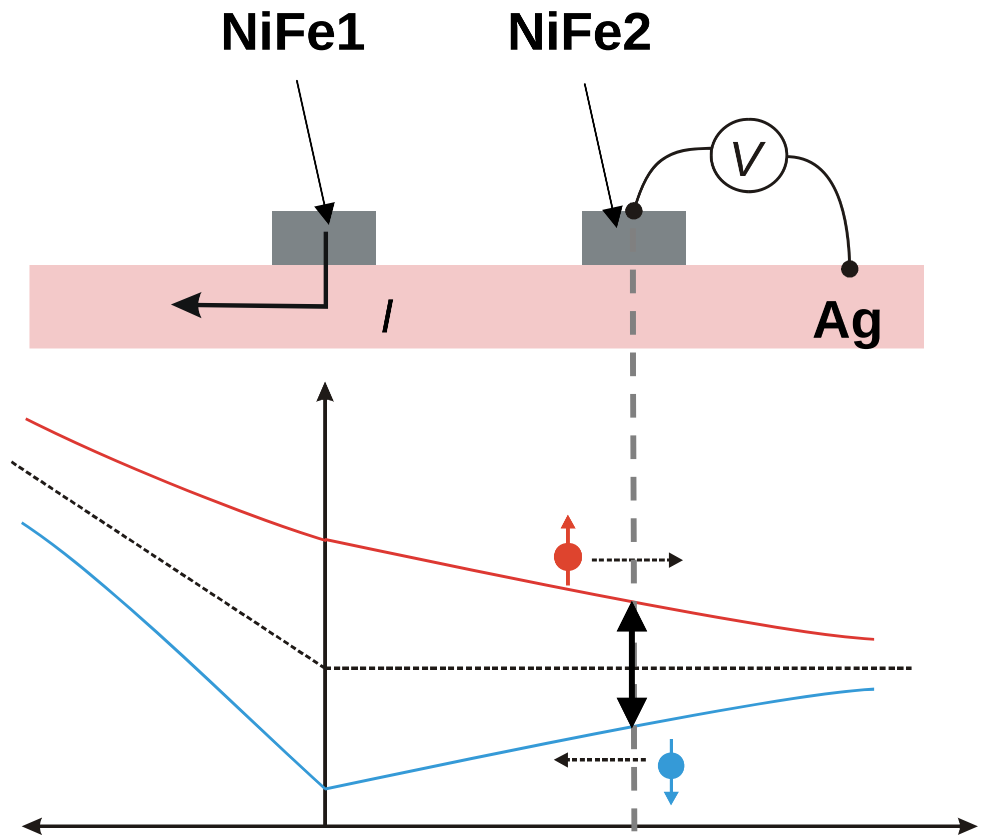


Spin-polarized current **Only spin current**

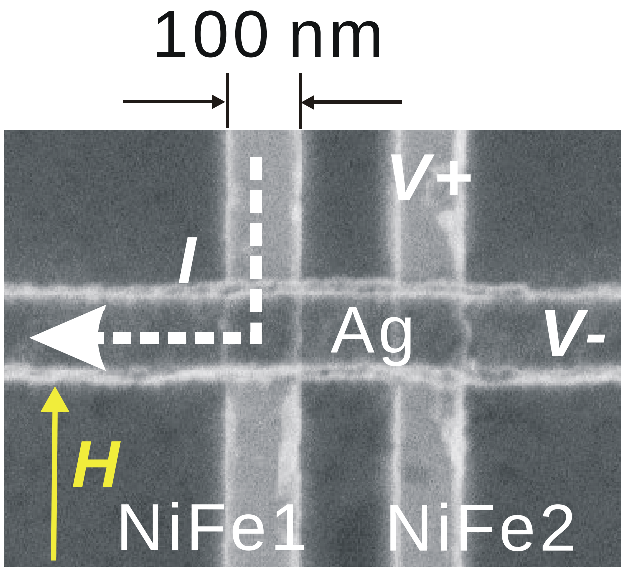
Driving force for spins is the diffusion into the equilibrium state.

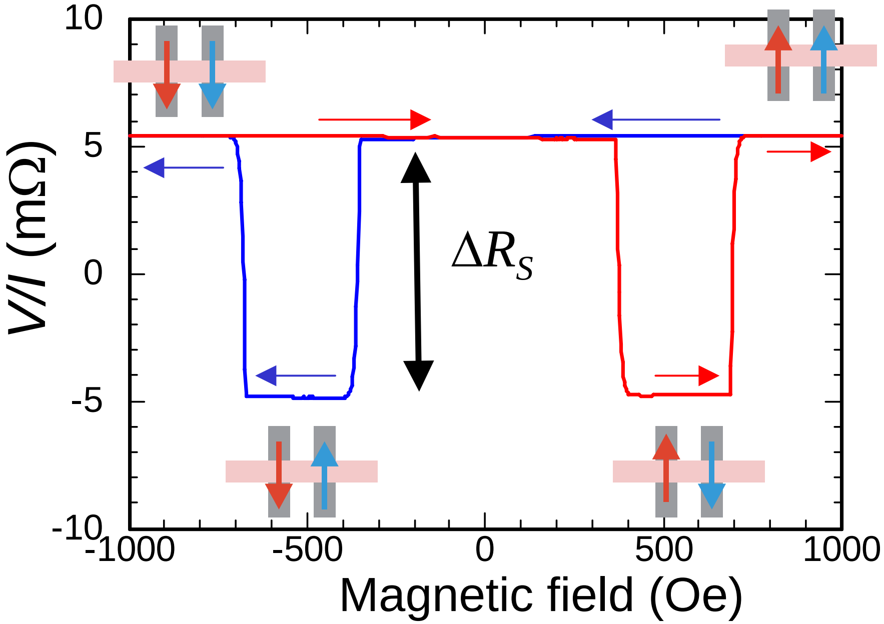
Nonlocal spin valve measurement

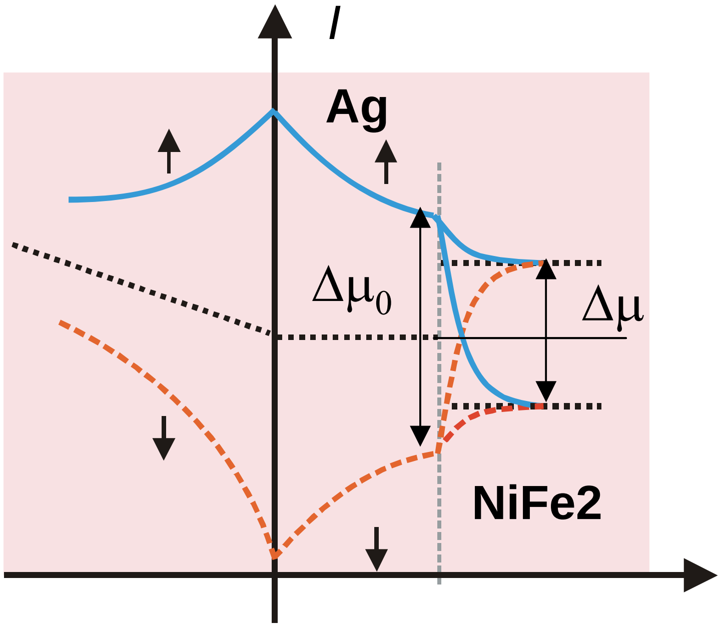




Nonlocal spin valve measurement







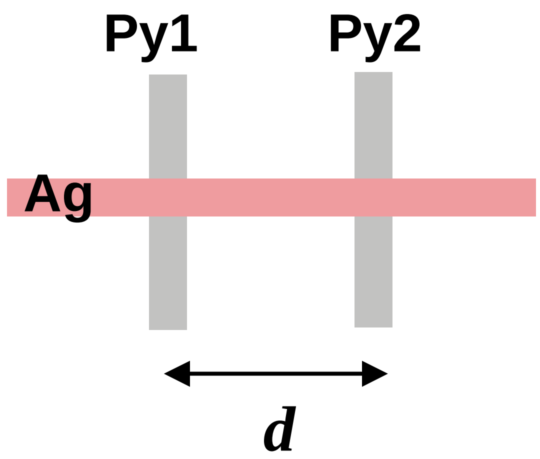
$$\Delta\mu = P\Delta\mu_0$$

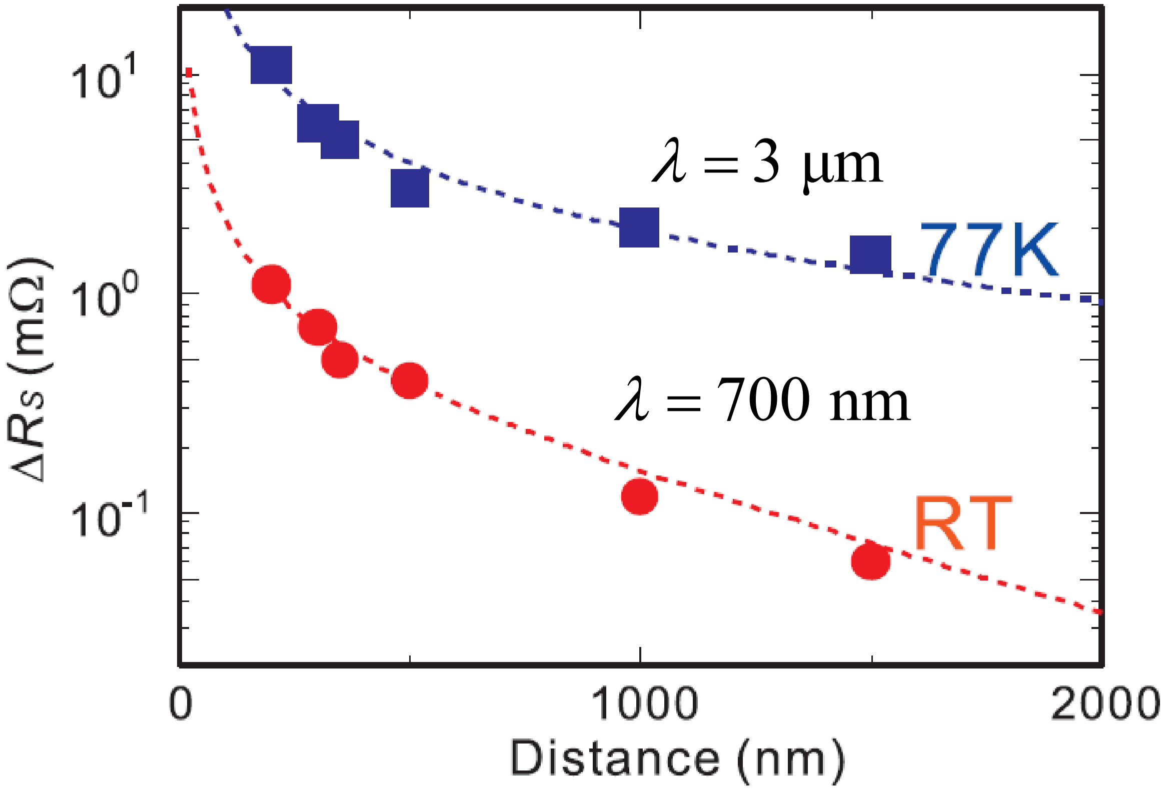
Voltage does not include any back ground signal.

→ Sensitive detection of spin information

Spin diffusion length of Ag wire

T. Kimura & Y. Otani. Phys. Rev. Lett. 99, 196604 (2007)





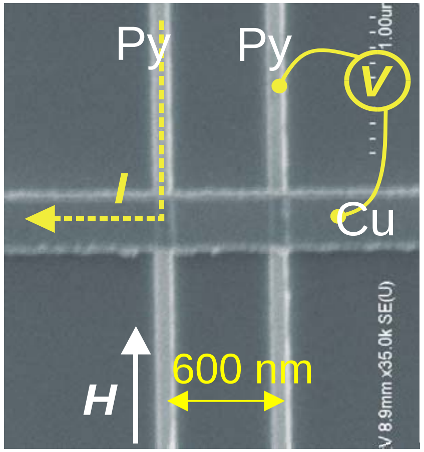
$P_{\mathrm{I}} = 0.17$ @ RT

0.26 @ 77K

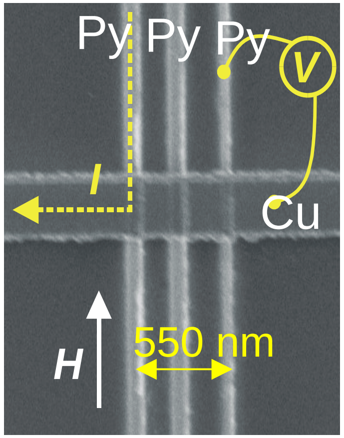
$$\frac{\Delta V}{I} \approx \frac{P_{\mathrm{I}}^2 R_{\mathrm{SI}}^2 + P_{\mathrm{F}}^2 R_{\mathrm{SF}}^2}{R_{\mathrm{SN}} \sinh\left(d/\lambda_{\mathrm{N}}\right)}$$

Spin current absorption into Py wire

Without middle wire



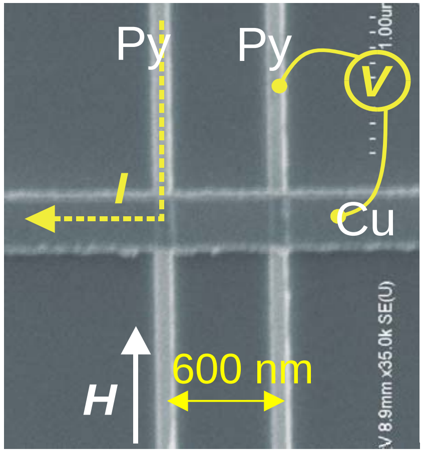
With middle wire

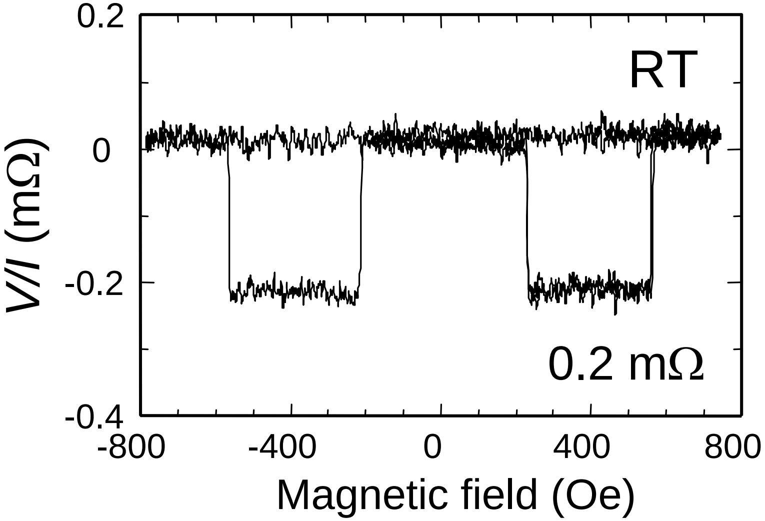


Spin current absorption into Py wire

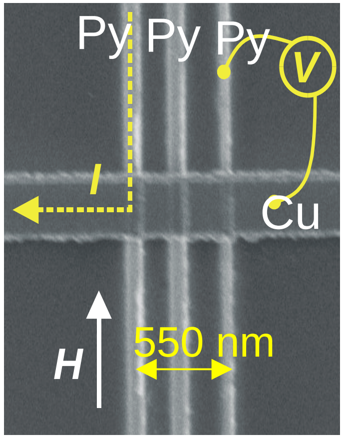
T. Kimura et al. APL (2004)

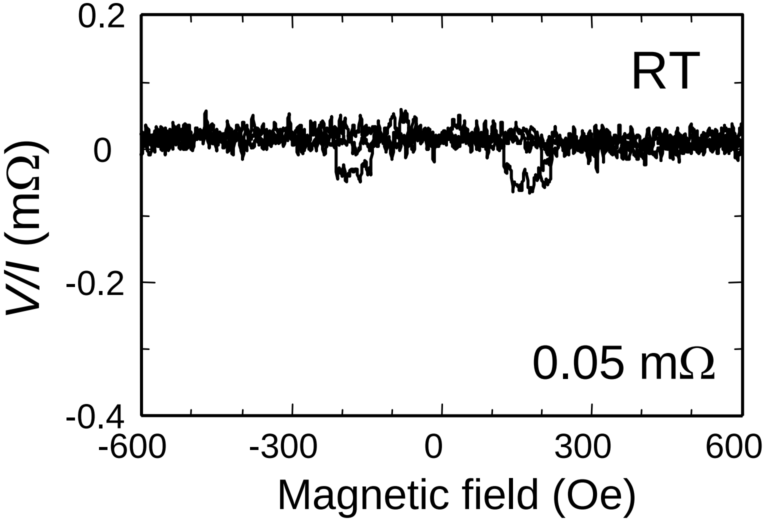
Without middle wire





With middle wire





Drastic reduction of the spin signal due to the middle Py insertion

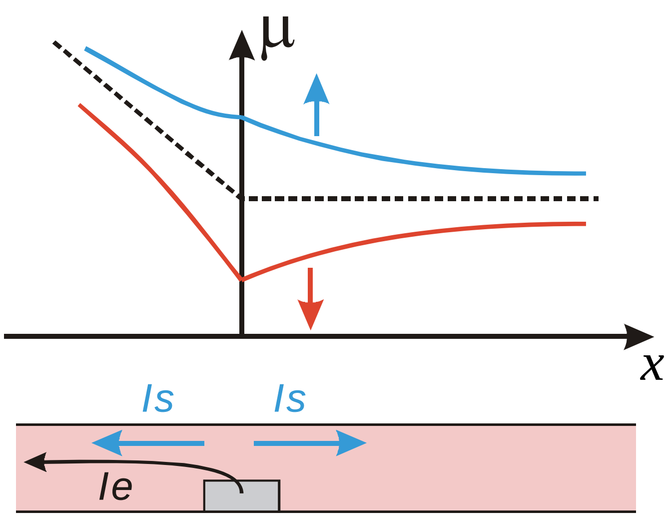
Influence of additional contact

$$\Delta\mu = \frac{1}{\lambda^2}\frac{\partial^2 \Delta\mu}{\partial x^2}$$

General solution

$$\Delta\mu = \mu_- \exp(-x/\lambda) + \mu_+ \exp(x/\lambda)$$

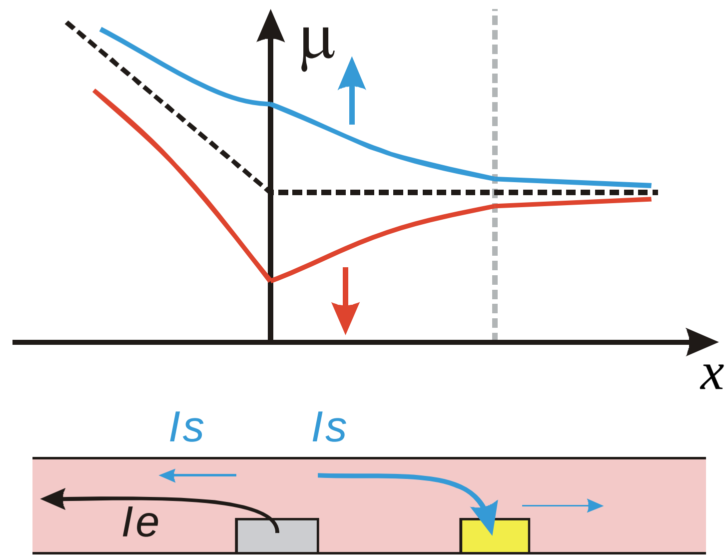
In single F/N junction



$$\Delta\mu = \mu_- \exp(-|x|/\lambda)$$

Spin accumulation simply expressed by the exponential decay.

With additional contact

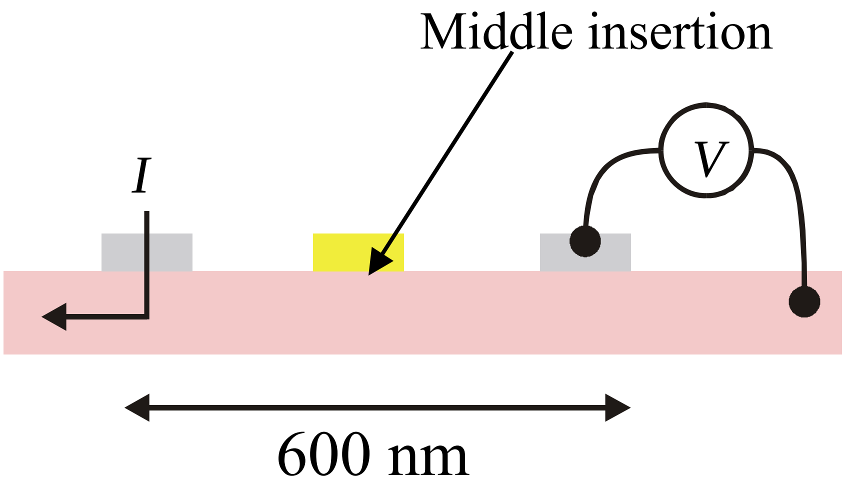


$$\Delta\mu = \mu_- \exp(-x/\lambda) - \mu_+ \exp(x/\lambda)$$

$(x > 0)$

Taking into account the spin diffusion into additional contact

Spin signals with insertion for various materials



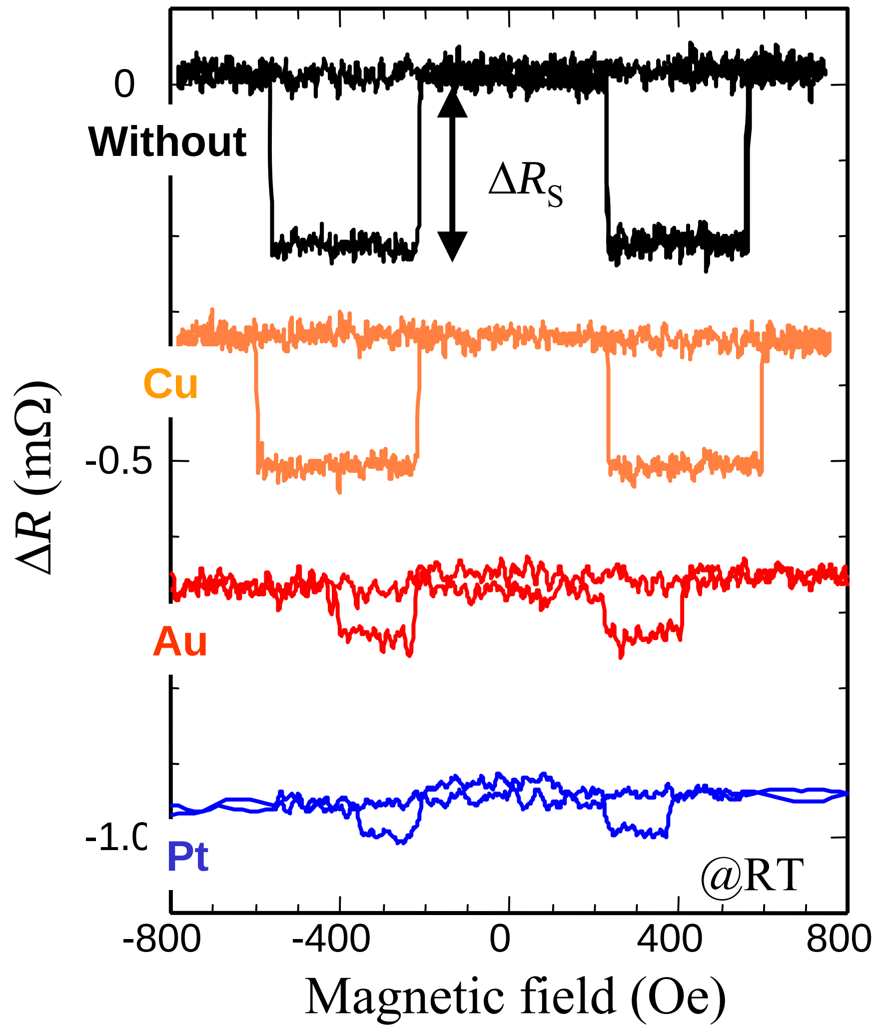
Spin resistance

$$R_S \equiv \frac{2\lambda}{\sigma S(1-P^2)}$$

λ : Spin diffusion length

S : Cross section

P : Spin polarization



Magnitude of the spin signal strongly depends on the spin resistance of the middle insertion, but is not related to whether ferromagnet or nonmagnet.

Spin resistances for several metals

Spin resistance

$$R_S \equiv \frac{2\lambda}{\sigma S(1-P^2)}$$

λ : Spin diffusion length

S : Effective cross section for spin current

P : Spin polarization

Material	ρ (μΩcm)	λ (nm)	P	R_S (Ω)
Cu	2.1	500	0	1.25
Py	15.4	3	0.2	0.15
Au	5.24	60	0	0.31
Co	24	20	0.2	0.46
Pt	15.6	10	0	0.15

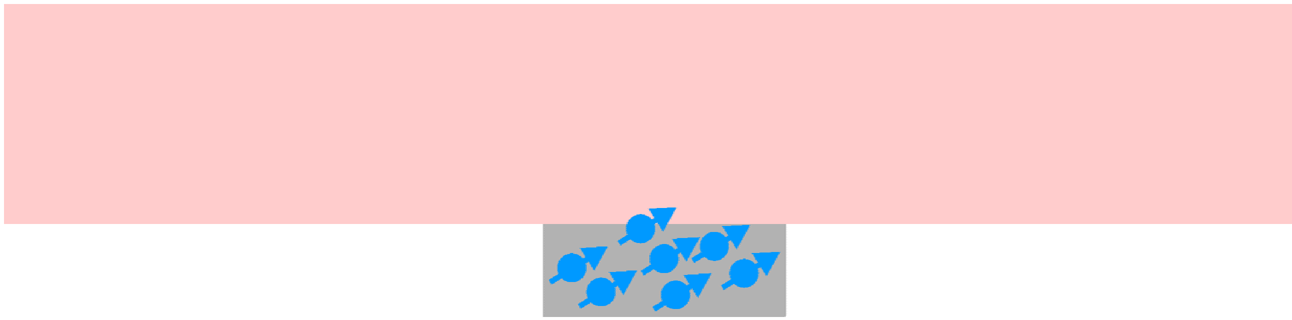
$S=(100\text{ nm})^2$

T. Kimura et al. PRB (2005)

Spin sink effect

Single interface

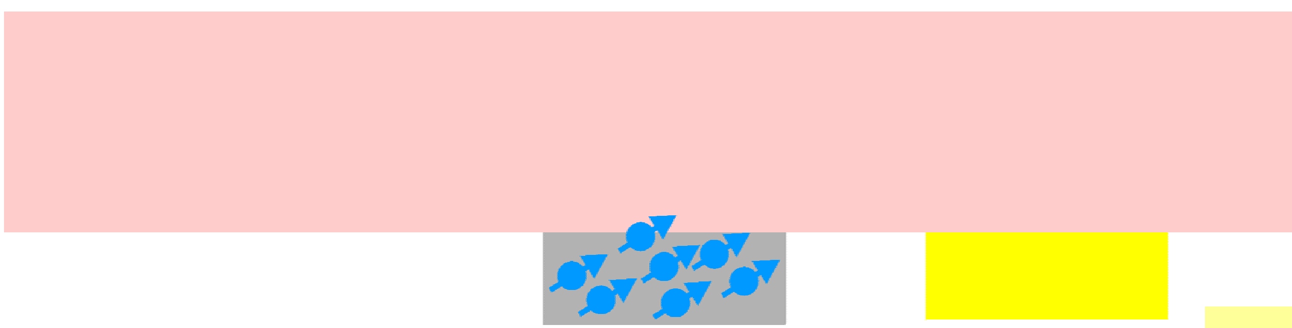
Spin currents diffuse isotropically.



Spin injector

Additional contact

When the spin resistance for the additional contact is small, spin currents are preferably absorbed into the contact.



Spin injector

Additional contact

$R_{SN} >> R_{SC}$

Summary 01

1. **Nonlocal spin injection can generate pure spin current.**

2. **Spin accumulation in N can be detected by using a F voltage probe.**

3. **An additional ohmic contact with a small spin resistance strongly modify the distributions of the spin current and spin accumulation. (Spin sink effect)**

Contents

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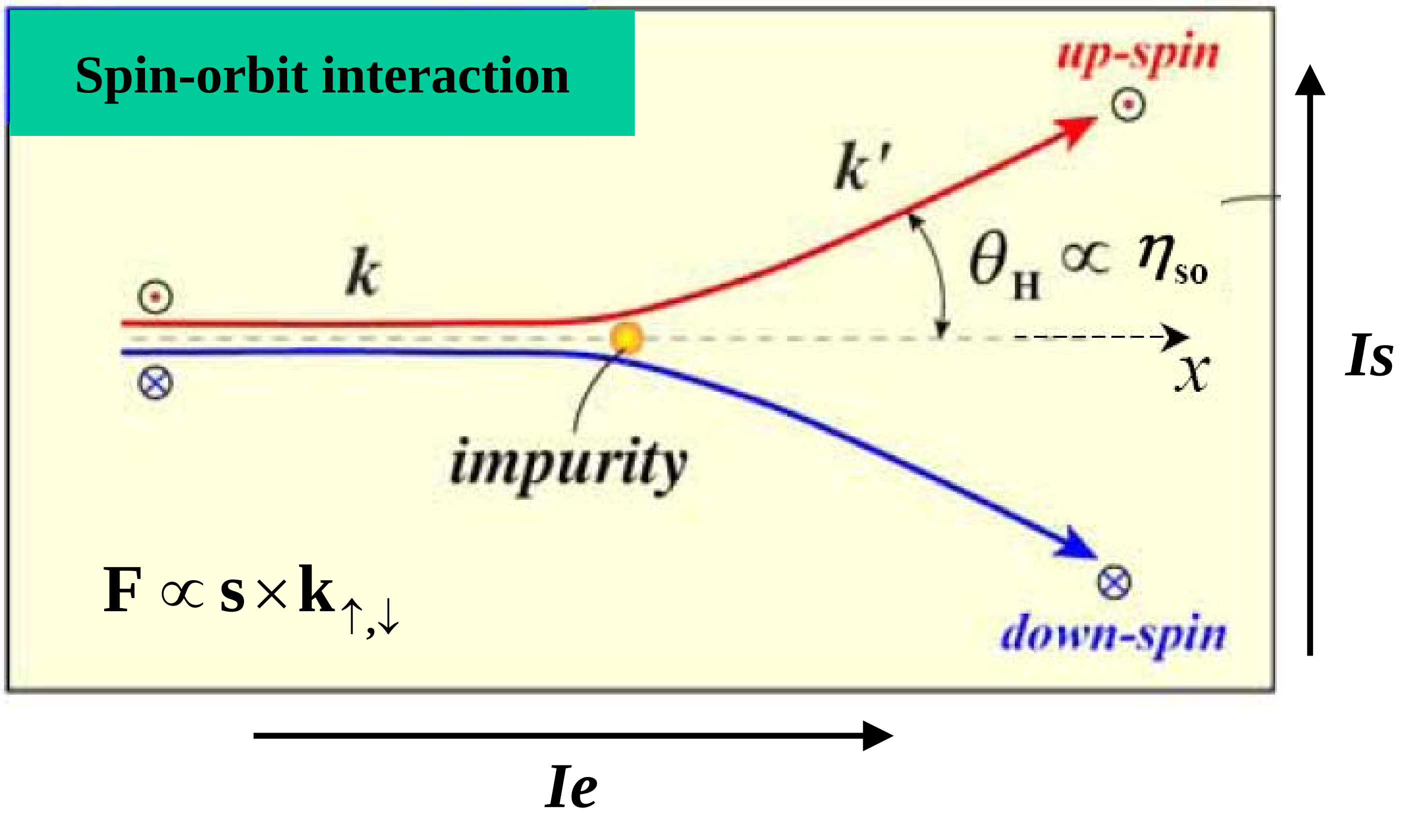
   - Planar F/N hybrid structure
   - Electrical detection of spin accumulation
   - Spin absorption effect

2. Spin Hall effect
   - Electrical detection of SHE by spin absorption
   - Possible origins for SHE
   - SHEs for various transition metals

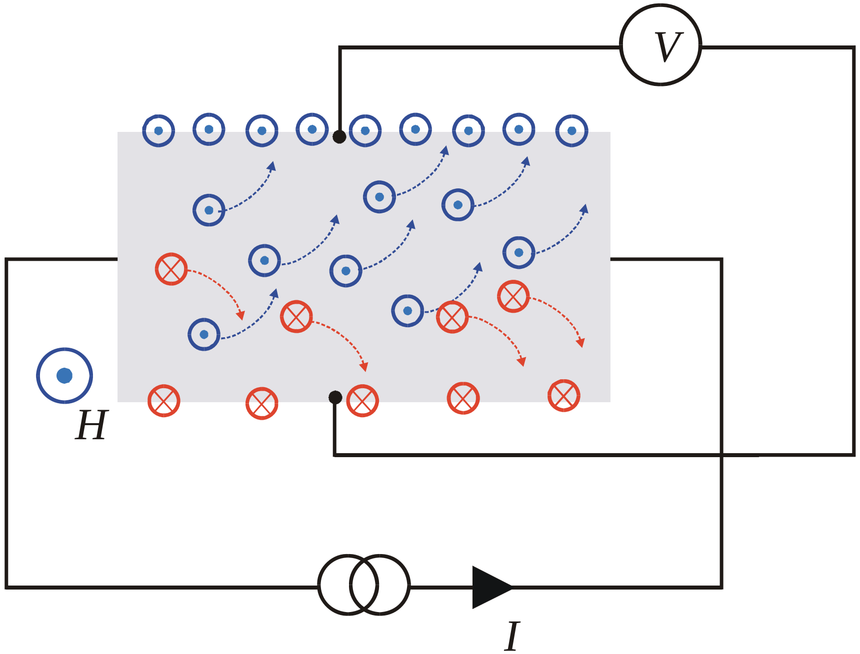
Spin Hall effect



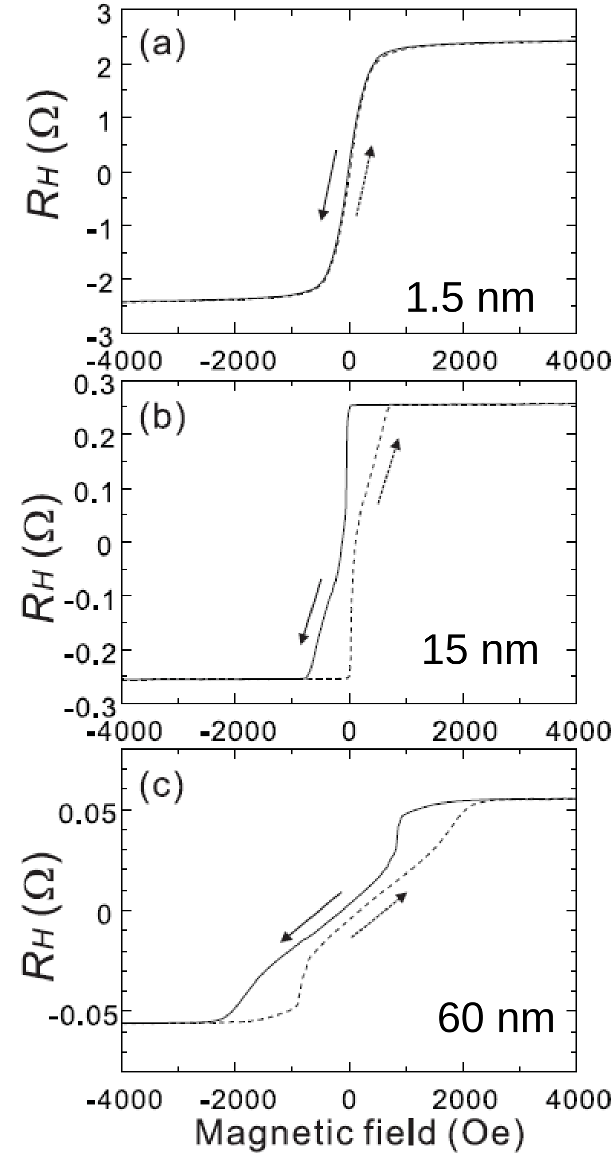
Trajectories of electrons are affected by spin-orbit interaction. Scattering direction depends on the spin.

→ **Transverse spin current is induced.**

Anomalous Hall effect in ferromagnet

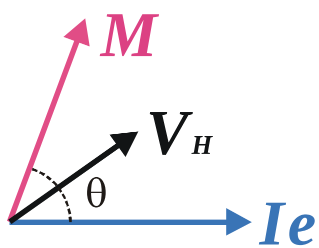


AHE in Ni film



Spin-orbit interaction

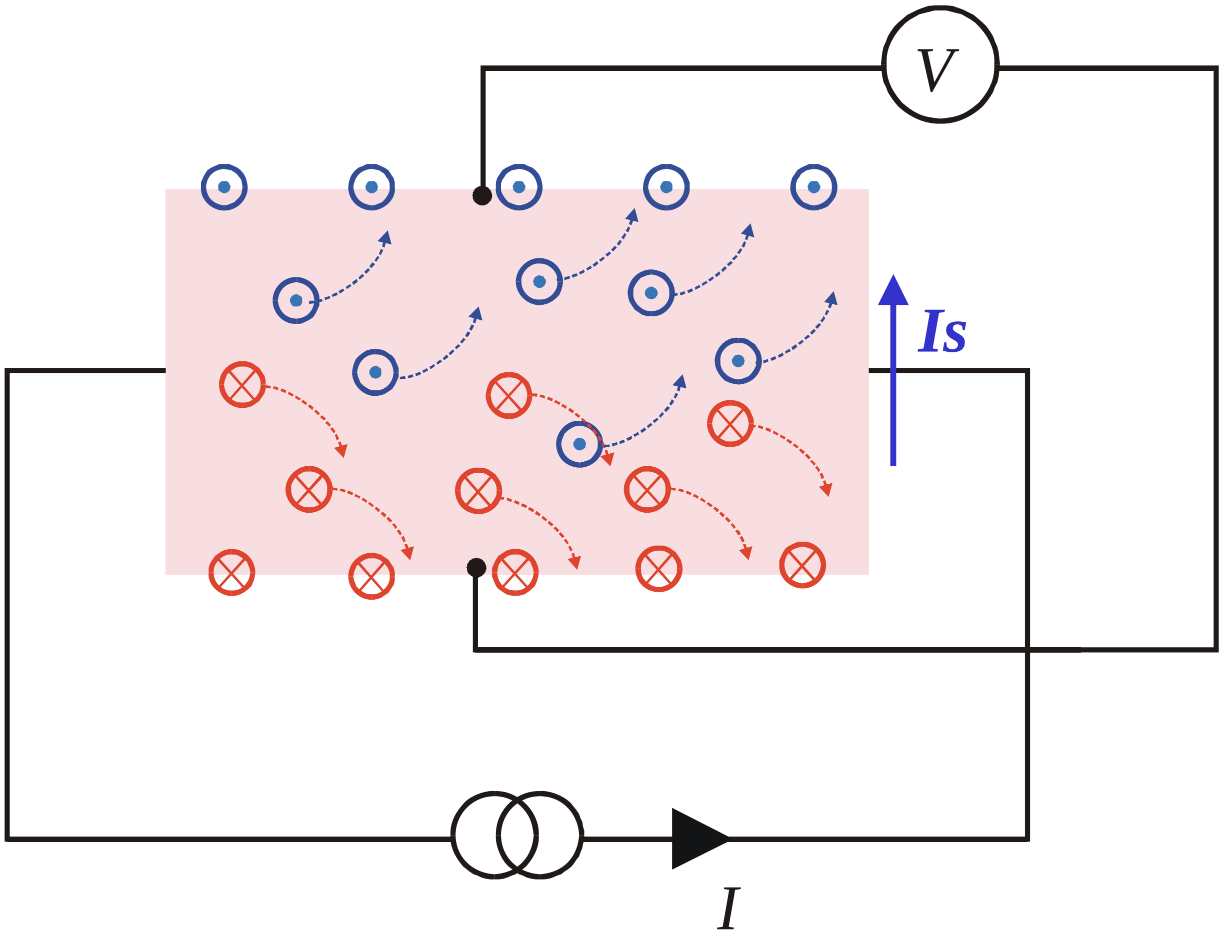
$$\mathbf{F} \propto \mathbf{s} \times \mathbf{k}_{\uparrow,\downarrow}$$



$$\frac{V_H}{I} \propto \sin\theta$$

Both of the spin and charge are accumulated at the side edge.
→ Voltage generation due to charge accumulation

Anomalous (Spin) Hall effect in nonmagnet

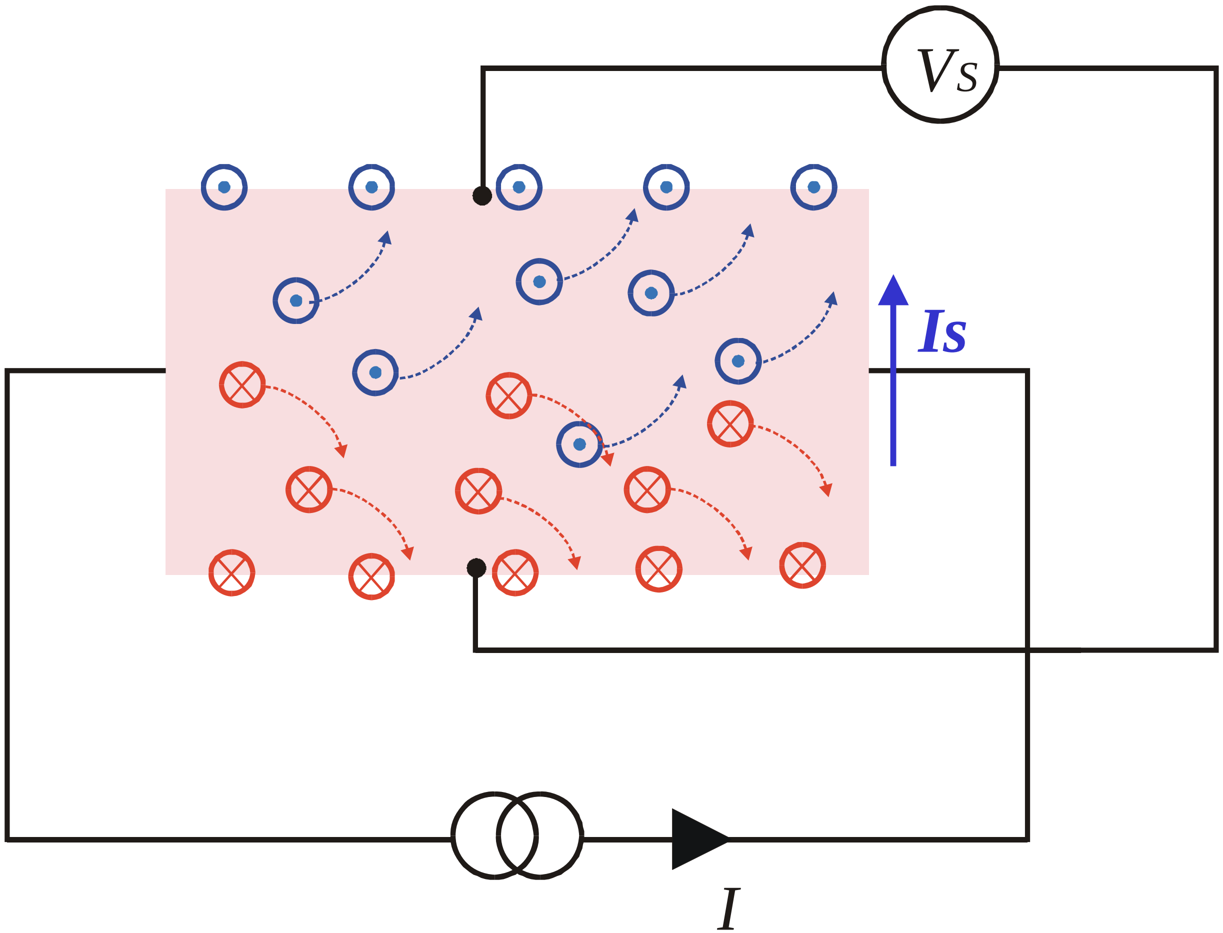


Spin orbit interaction induces spin-dependent scattering.

→ No charge accumulation

→ Electrical detection is impossible ?

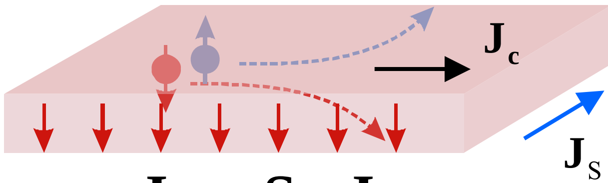
Anomalous (Spin) Hall effect in nonmagnet



Spin accumulation can be detected electrically by using ferromagnetic voltage probe.

Spin Hall effect & inverse spin Hall effect

- **Novel way for generation & manipulation of spin current**

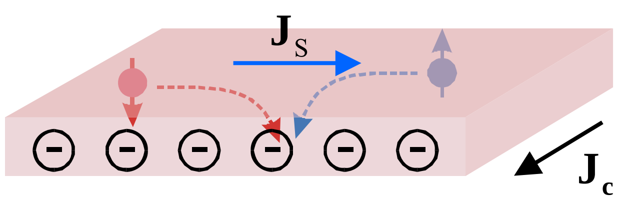


$$\mathbf{J}_S \propto \mathbf{S} \times \mathbf{J}_c$$

→ Unpolarized charge current induces transverse spin current.

Direct SHE : Transformation from charge to spin currents

- **Inverse SHE (Reciprocal SHE)**



$$\mathbf{J}_c \propto \mathbf{S} \times \mathbf{J}_S$$

→ Spin current induces transverse charge current.

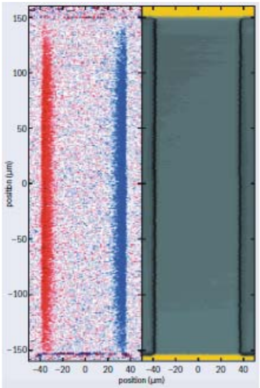
Transformation from spin to charge currents

Novel technique for manipulating spin current

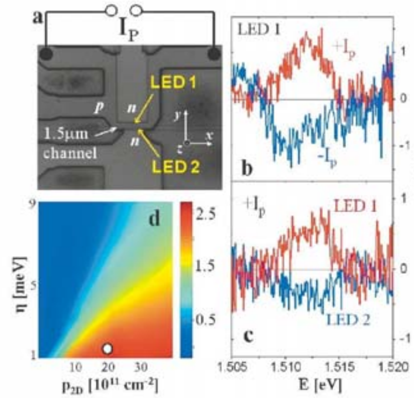
Spintronics without ferromagnets

Experimental study of Spin Hall effect

- **Optical detection in semiconductor**

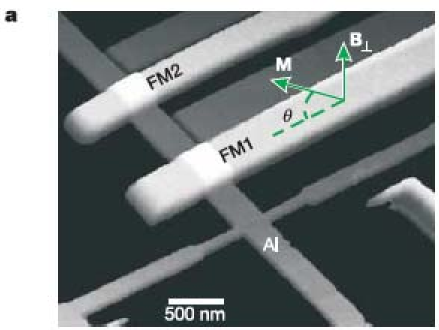


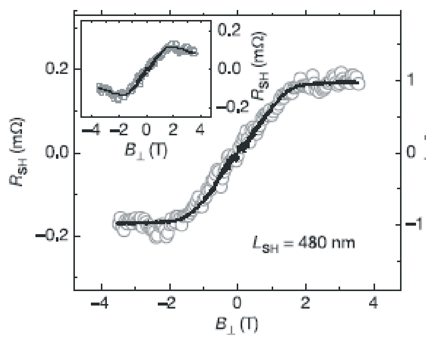
Y. K. Kato et al.
Science (2004)



J. Wunderlich et al.
Phys. Rev. Lett. (2005)

- **Electrical detection using a Hall cross in metallic systems**





CoFe/Al hybrid structure

Valenzuela & Tinkham, Nature (2006)

T. Seki *et al* (FeMn/Au, Nature mat. 2008)

Limited materials (λ > 100 nm)
Weak SO interaction

- **Using spin pumping**

E. Saitoh et al. APL (2006)

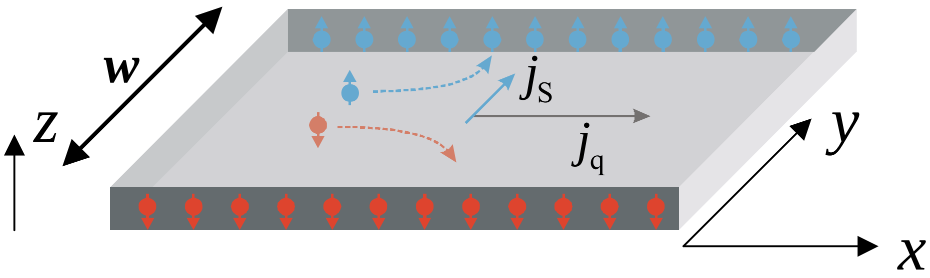
Qualitative analysis

Quantitative study of large SHE in materials with large SO interaction
(Transition metals : Pt, Pd, ….)

Spin current & spin accumulation with SO interaction

- Spin accumulation in x-z plane

Electron with z spin axis



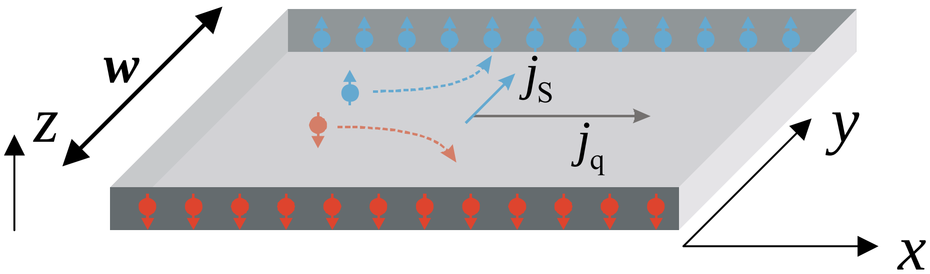
$$j_{Sy} = \frac{\sigma_{xy}}{\sigma_{xx}} j_{qx}$$

Transverse spin current
due to SHE.

Spin current & spin accumulation with SO interaction

- Spin accumulation in x-z plane

Electron with z spin axis



$$j_{Sy} = \frac{\sigma_{xy}}{\sigma_{xx}} j_{qx} + \frac{\sigma_{yy}}{e} \frac{\partial}{\partial y} \left(\delta\mu_{\uparrow} - \delta\mu_{\downarrow} \right)$$

Transverse spin current due to SHE.

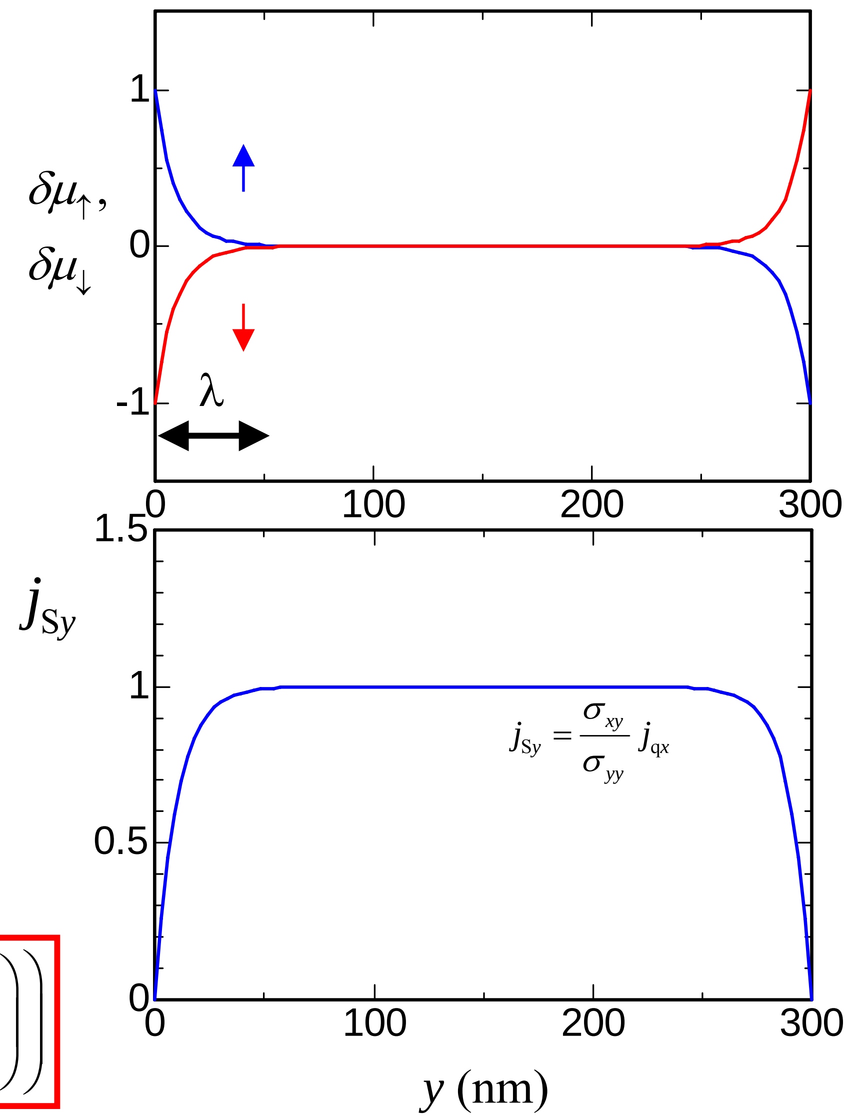
spin current due to spin accumulation

Using boundary conditions in steady state :

$$\boldsymbol{J_{Sy} = 0 \quad @\ y=0\ \&\ w}$$

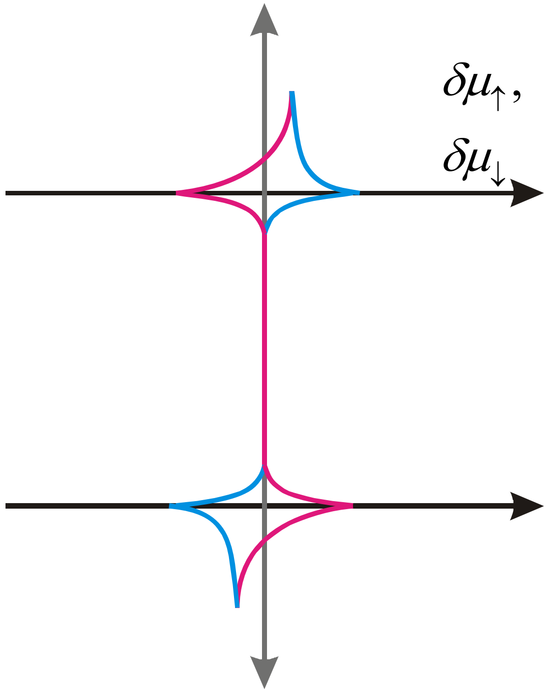
$$j_{Sy} = \frac{\sigma_{xy}}{\sigma_{xx}} j_q \left(1 - \left(\frac{e^{w/\lambda} - 1}{e^{w/\lambda} - e^{-w/\lambda}} \mathrm{e}^{-\frac{y}{\lambda}} + \frac{1 - e^{-w/\lambda}}{e^{w/\lambda} - e^{-w/\lambda}} \mathrm{e}^{\frac{y}{\lambda}} \right) \right)$$

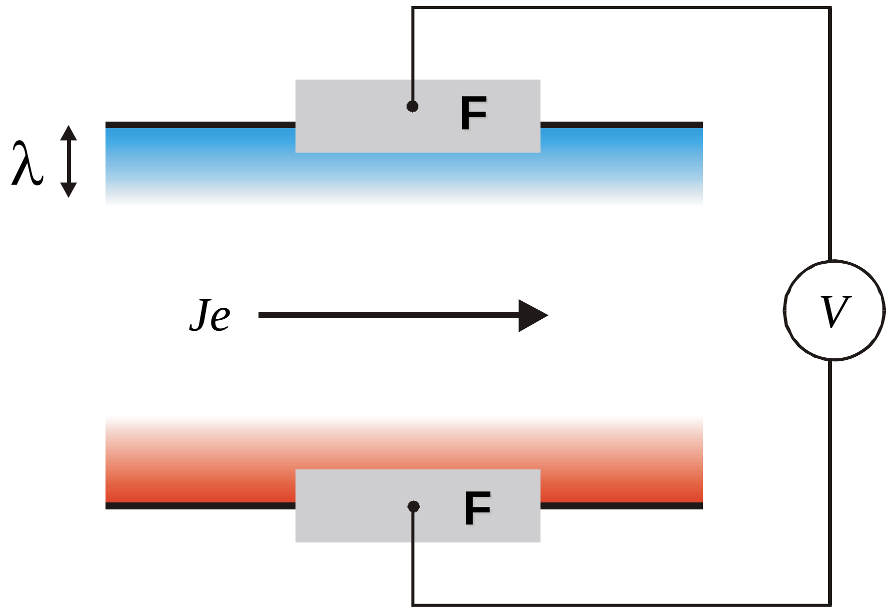
Pt wire with λ=10 nm, w = 300 nm



Structure for electrical detection of SHE

Spin accumulation appears only in the vicinity of the edges.



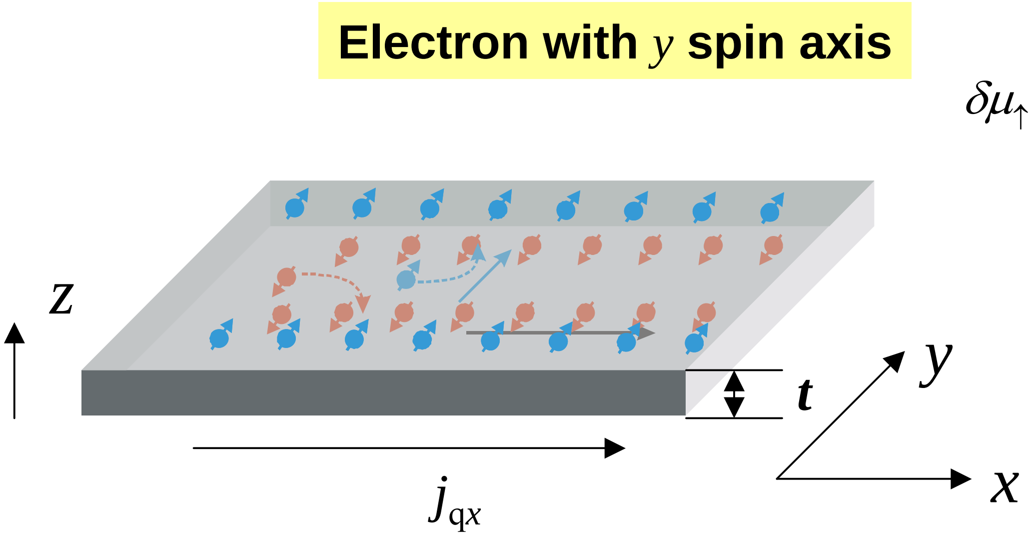


Junction size is less than the spin diffusion length (< 10 nm).

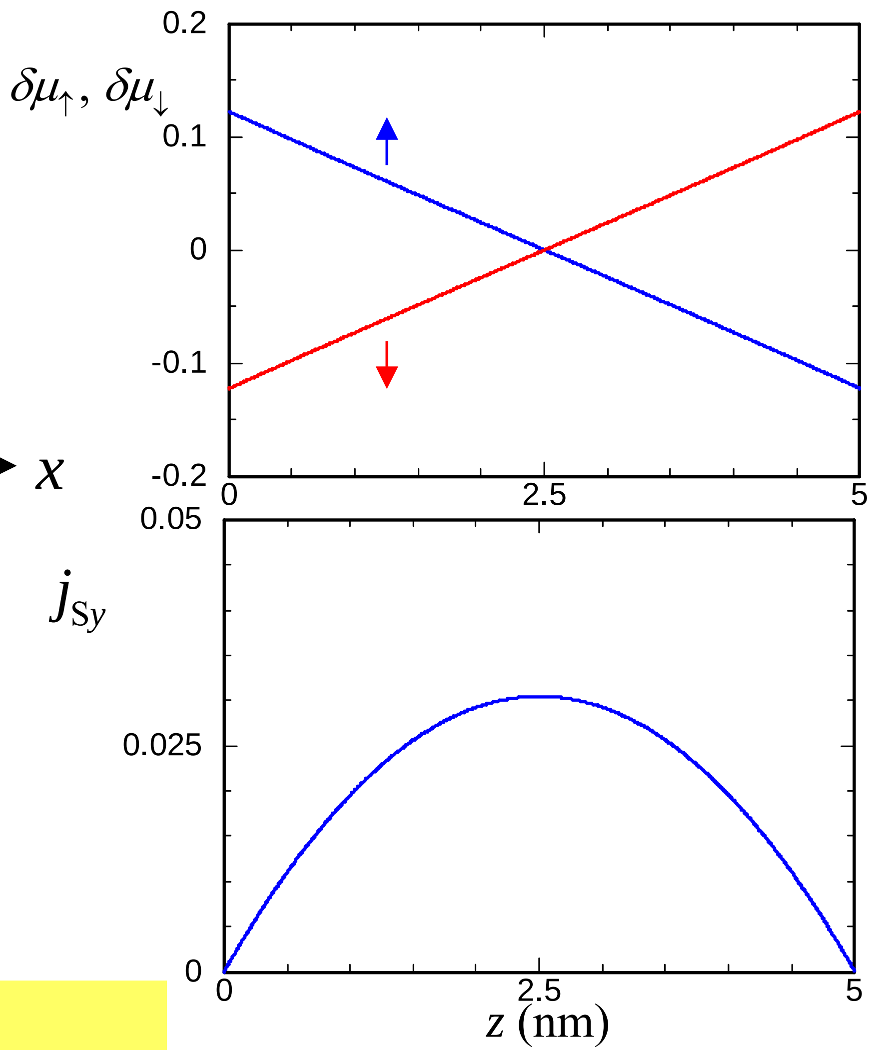
Structure fabrication is very difficult.

Spin current & spin accumulation with SO interaction

- Spin accumulation in x-y plane



λ=10 nm, t = 5 nm



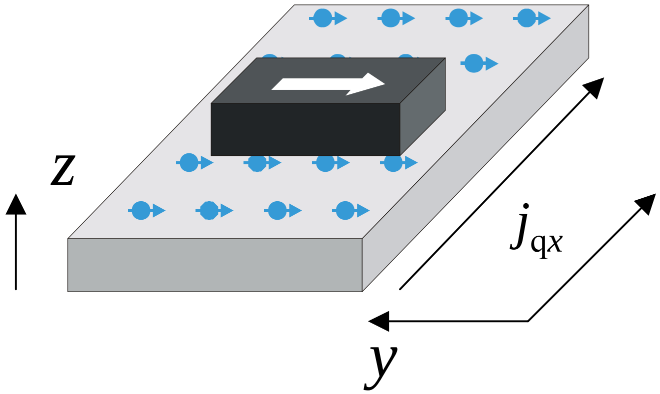
$$j_{Sz} = \frac{\sigma_{xz}}{\sigma_{xx}} j_{qx} + \frac{\sigma_{zz}}{e}\frac{\partial}{\partial z}\left(\delta\mu_\uparrow - \delta\mu_\downarrow\right)$$

Using boundary conditions in steady state :

$$J_{Sz} = 0 \quad @\ z=0\ \&\ t$$

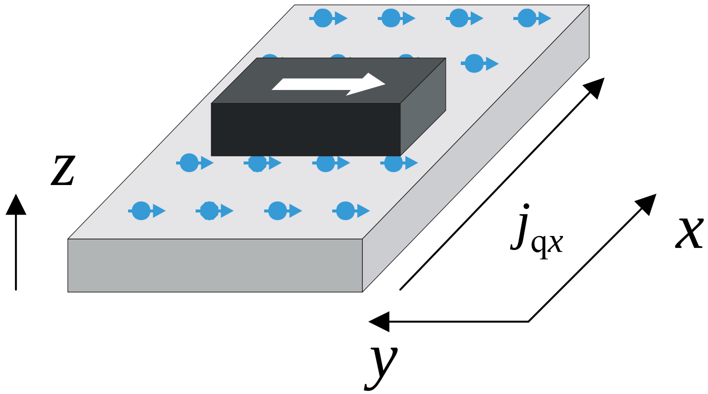
Surface spin accumulation in x-y plane can be detected by putting a ferromagnetic probe on the surface.

Influence of additional contact



$$j_{Sz} = \frac{\sigma_{xz}}{\sigma_{xx}} j_{qx} + \frac{\sigma_{zz}}{e} \frac{\partial}{\partial z} \left(\delta\mu_{\uparrow} - \delta\mu_{\downarrow} \right)$$

Influence of additional contact



$$j_{Sz} = \frac{\sigma_{xz}}{\sigma_{xx}} j_{qx} + \frac{\sigma_{zz}}{e} \frac{\partial}{\partial z} \left(\delta\mu_{\uparrow} - \delta\mu_{\downarrow} \right)$$

Taking into account the absorption of the spin current into additional contact.

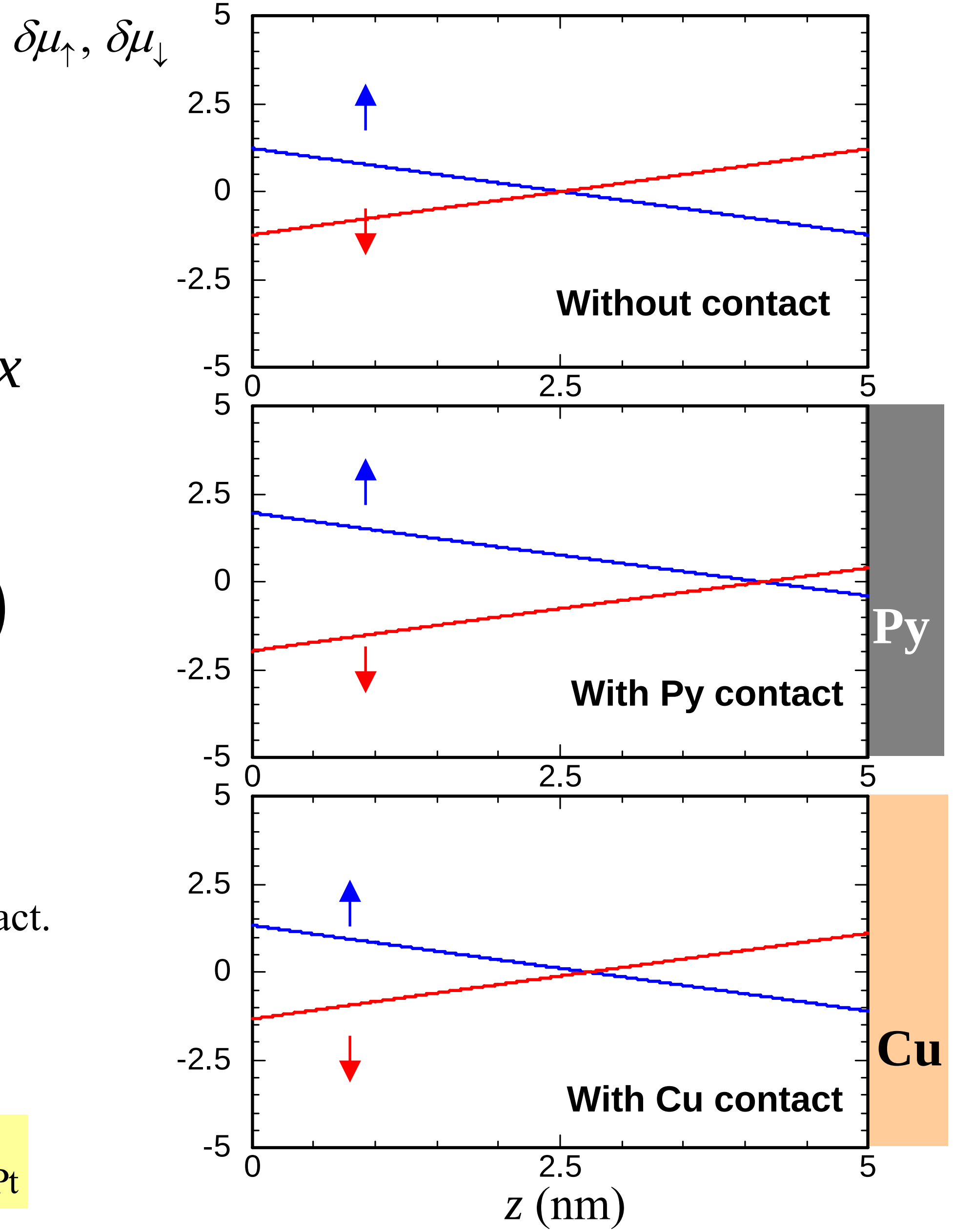
- Spin accumulation is suppressed by the Py contact.

$$R_{SPy} \approx R_{SPt}$$

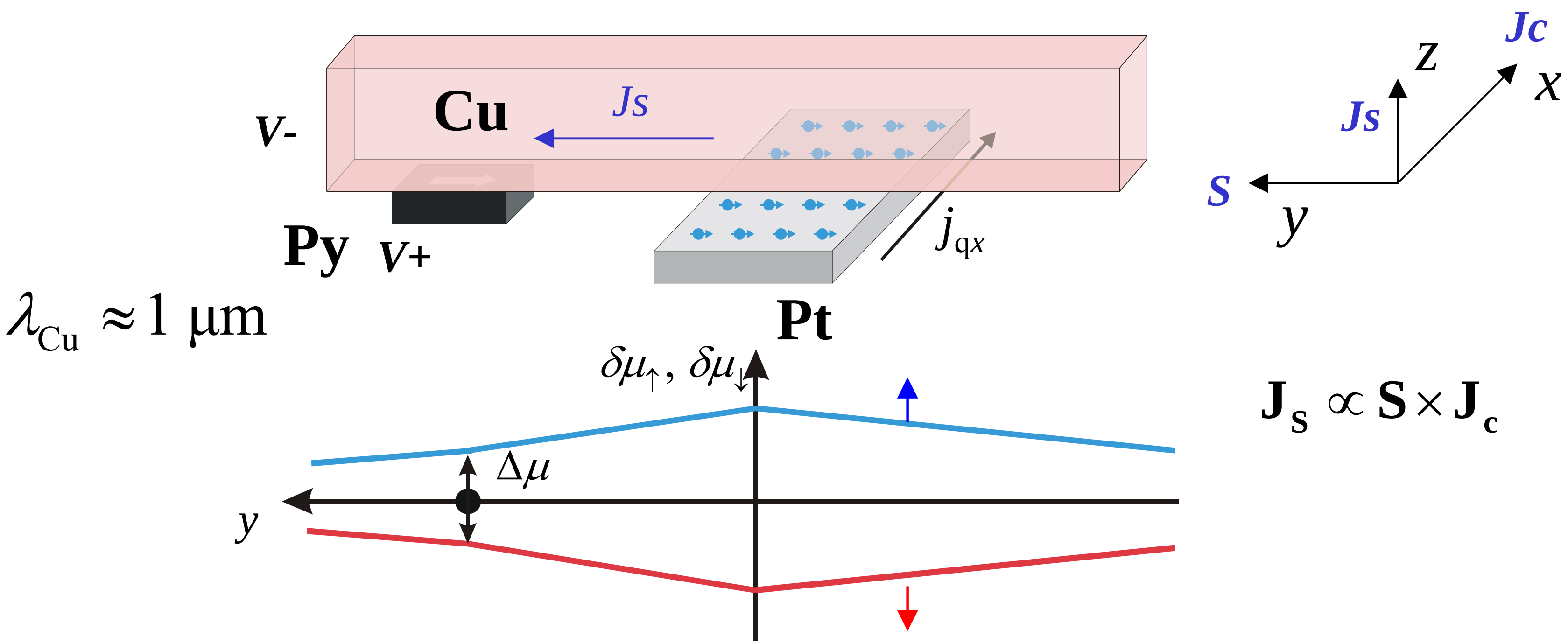
- Spin accumulation is not modified by the Cu contact so much.

$$R_{SCu} >> R_{SPt}$$

Spin accumulation in Pt

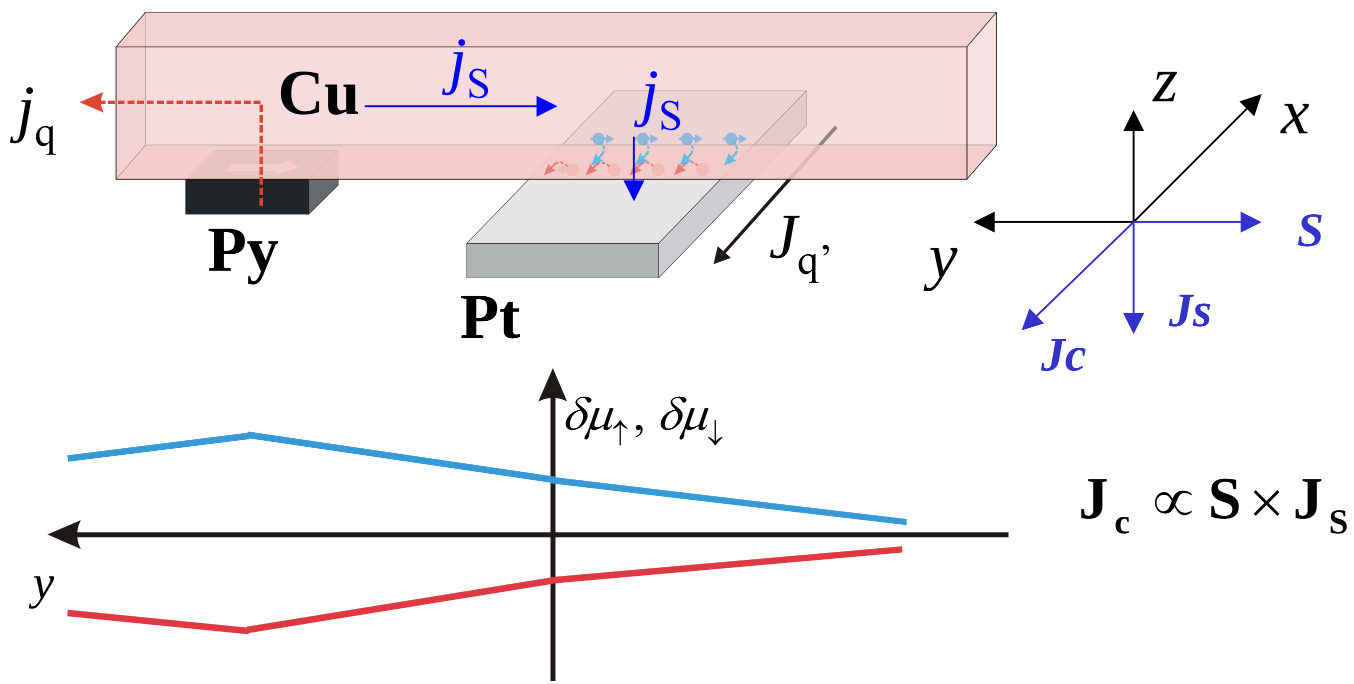


Detection of spin accumulation in *x*-*y* plane



- Spin accumulation due to SHE is extracted by Cu wire without disturbing the spin distribution.
- Spin accumulation in the Cu wire is measured by ferromagnetic probe.

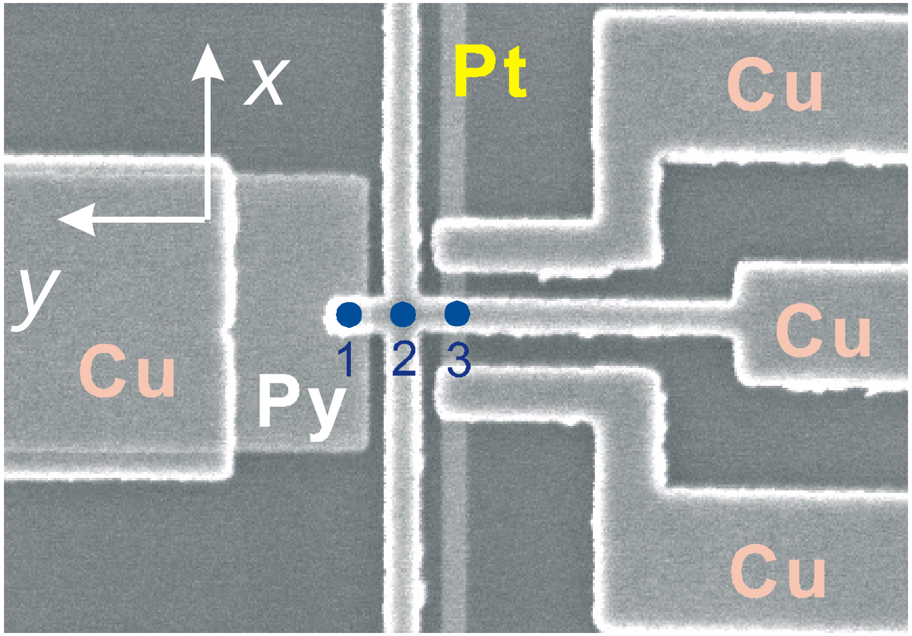
Detection of charge accumulation along *x* axis



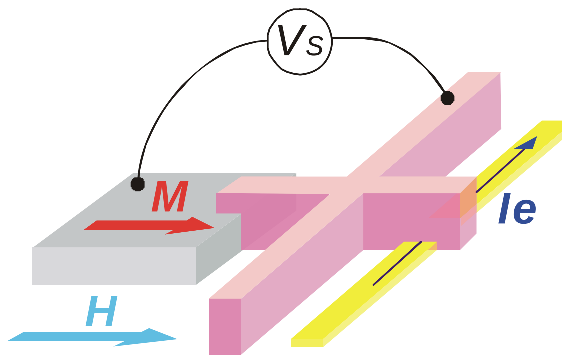
- Induced spin current is preferably absorbed into the Pt wire.
- Direction of the spin current in the Pt wire is perpendicular to the junction (along z axis). $\mathbf{J}_s \propto \nabla \mu$
- Injected spin current is transferred to the charge current along the Pt wire.

Sample structure for electrical detection of SHE

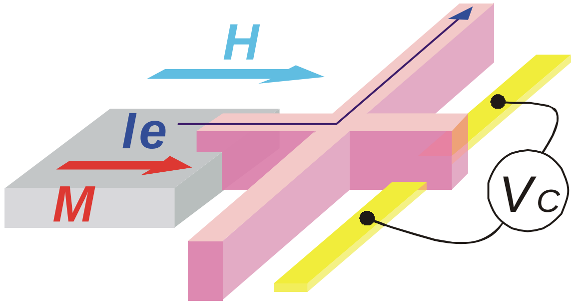
T. Kimura, Y. Otani et al. PRL (2007)



Direct SHE



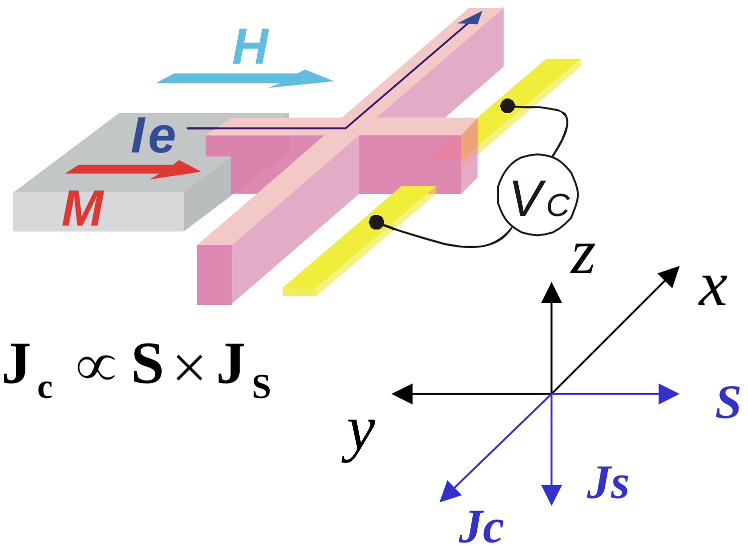
Inverse SHE



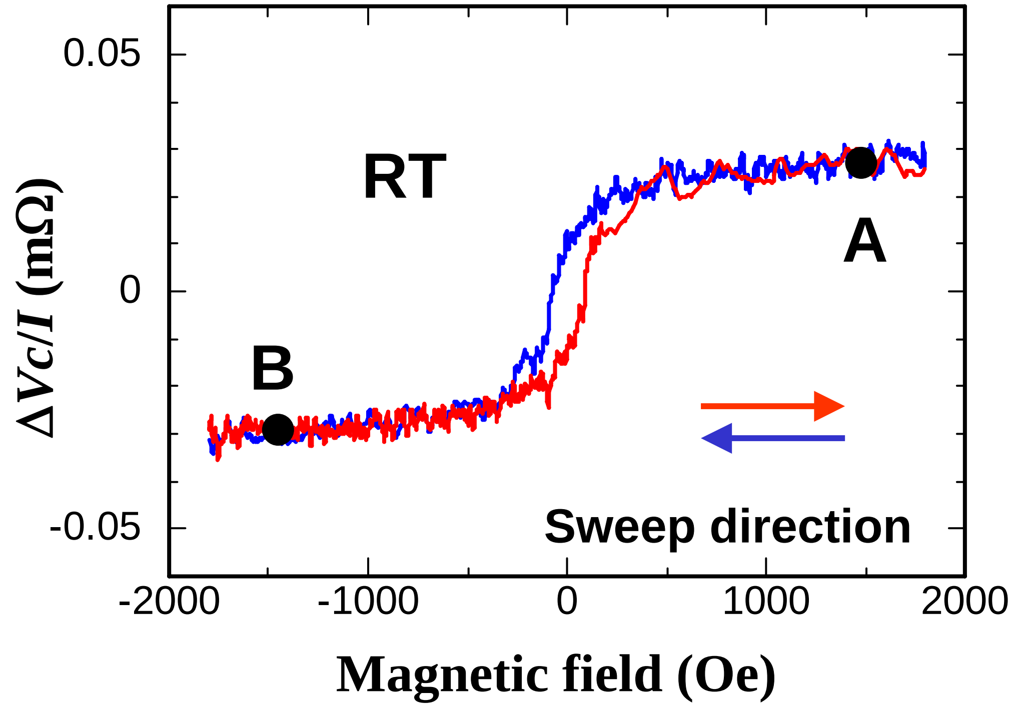
Sample dimension

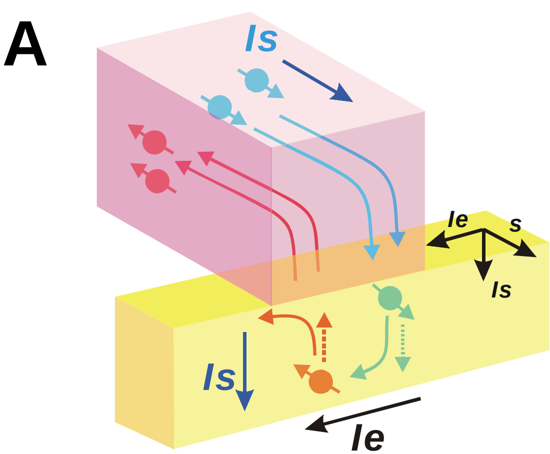
Pt : 80 nm wide, 4 nm thick
Py : 1 μm wide, 30 nm thick
Cu : 100 nm wide, 80 nm thick

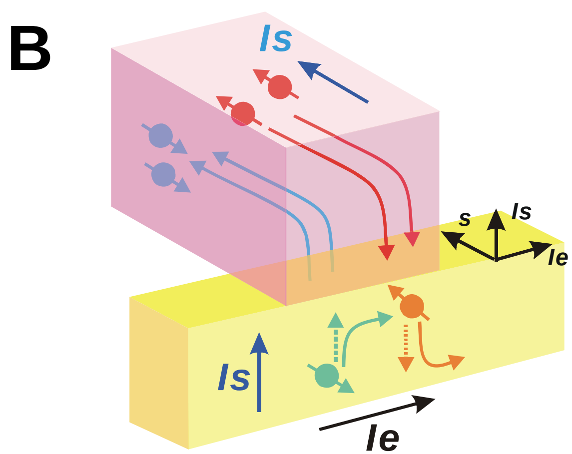
Observation of inverse SHE



$$\mathbf{J}_c \propto \mathbf{S} \times \mathbf{J}_S$$

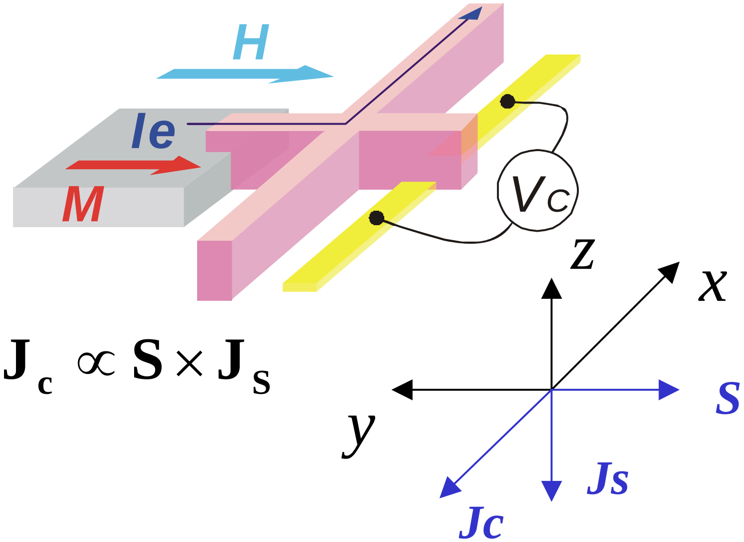




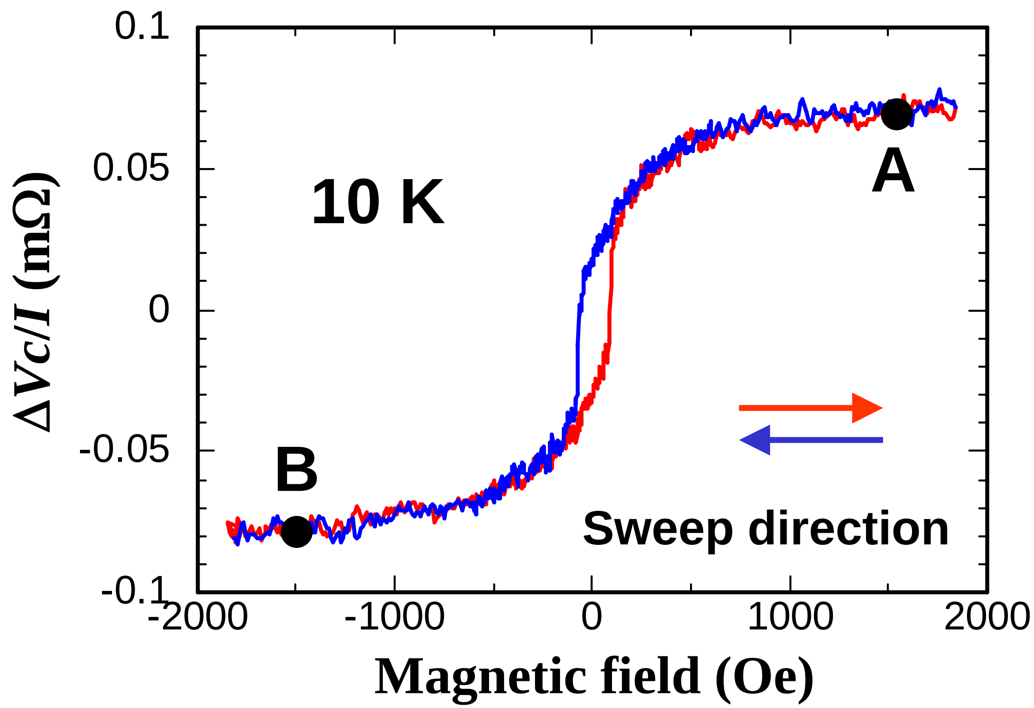


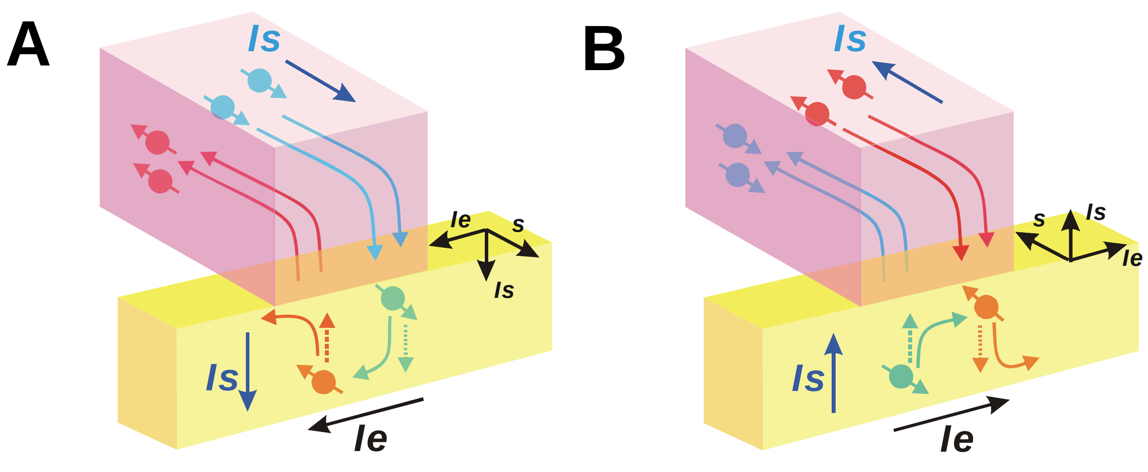
Direction of the spin axis of generating spin current is reversed by the magnetic field.

Observation of inverse SHE



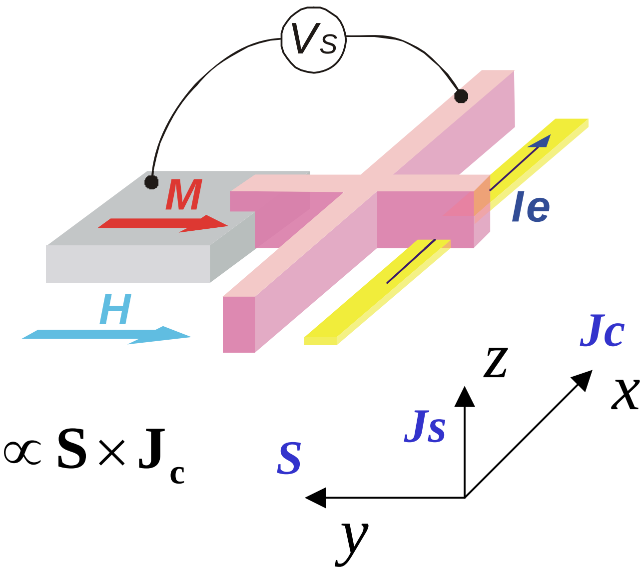
$$\mathbf{J}_c \propto \mathbf{S} \times \mathbf{J}_S$$



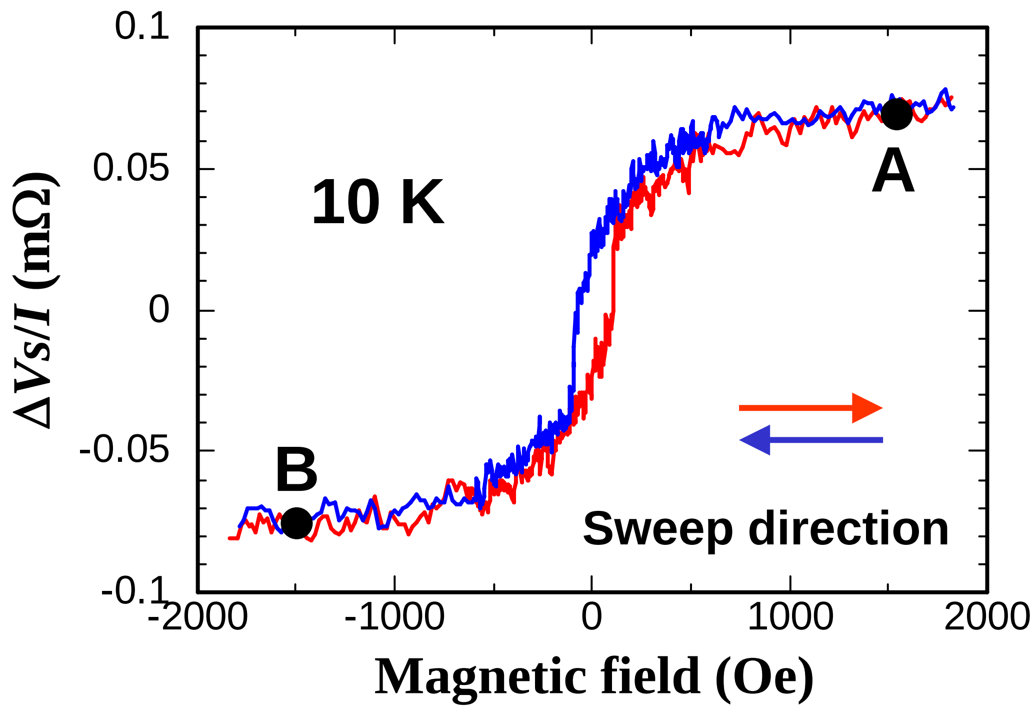


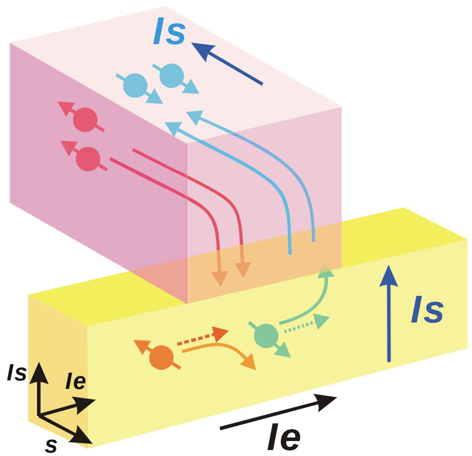
Direction of the spin axis of generating spin current is reversed by the magnetic field.

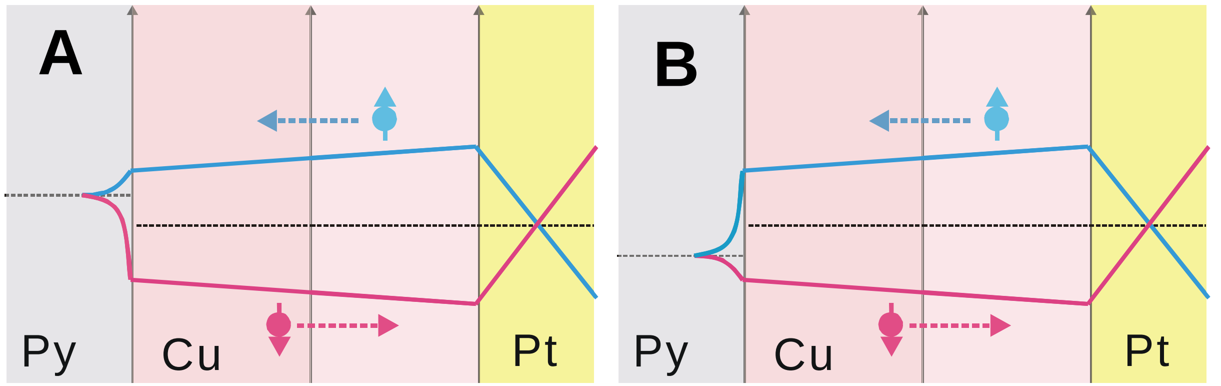
Observation of direct SHE



$$J_s \propto S \times J_c$$







Positive voltage appears. Negative voltage appears.

Estimation of spin Hall conductivity

$$J_{c,y} = \sigma E_y + \sigma_{\mathrm{SHE}} \nabla_Z \delta\mu / e$$

$$J_{\mathrm{S}y} = 0 \quad @\, y{=}0 \;\&\; t$$

$$\Rightarrow \quad \sigma_{\mathrm{SHE}} = w\sigma^2 \left(\frac{I_{\mathrm{C}}}{I_{\mathrm{S}}}\right) \Delta R_{\mathrm{SHE}}$$

$$\frac{I_{\mathrm{S}}}{I_{\mathrm{C}}} \approx \frac{P_{\mathrm{Py}} R_{\mathrm{Py}}}{\left(R_{\mathrm{Py}} + R_{\mathrm{Pt}}\right)\cosh\left(\dfrac{d}{\lambda_{\mathrm{Cu}}}\right) + \left(R_{\mathrm{Cu}} + R_{\mathrm{Py}} + R_{\mathrm{Pt}}\right)\sinh\left(\dfrac{d}{\lambda_{\mathrm{Cu}}}\right)}$$

- Spin Hall conductivity

$$\sigma_{\mathrm{SHE}} \approx 2.4 \times 10^4 \ (\Omega\mathrm{m})^{-1} \quad \text{for Pt at RT}$$

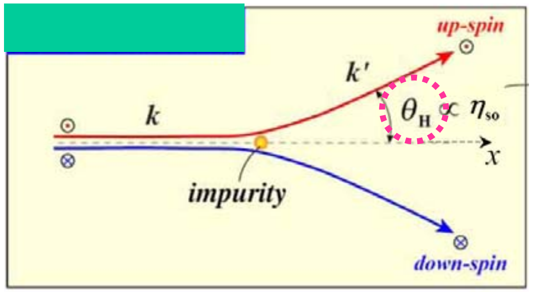
$10 \sim 10^4$ times larger than previously reported values
(Al at 4.1 K, GaAs at 20 K, ZnSe at RT)

- Spin Hall angle

$$\alpha \equiv \frac{\sigma_{\mathrm{SHE}}}{\sigma}$$

$$\alpha_{\mathrm{Pt}} = 3.7 \times 10^{-3}$$

Larger than previously reported values

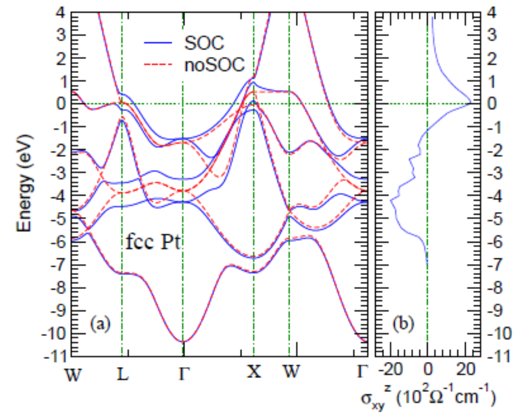


Possible mechanism of SHE

- **Intrinsic SHE in Pt**

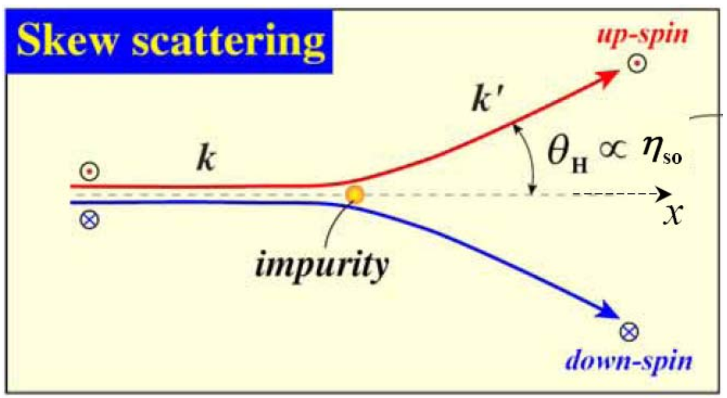
G. Y. Guo et al. PRL (2008)

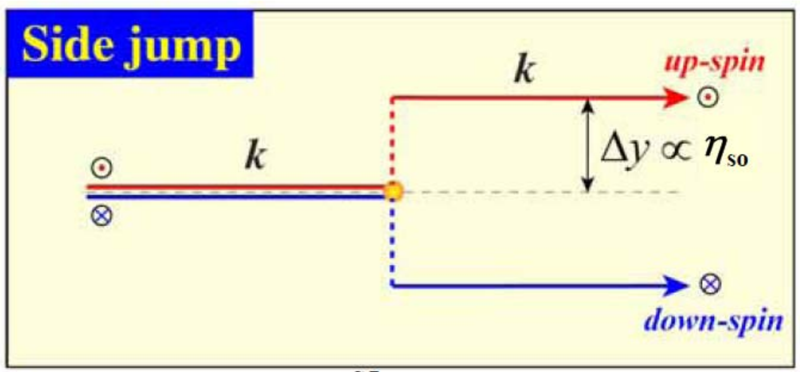
Band structure & Berry phase



The present Pt wire is polycrystalline.
→ Extrinsic SHE

- **Extrinsic SHE in Pt**





J. Smit (1956)

$$\rho_{SHE} \propto \rho$$

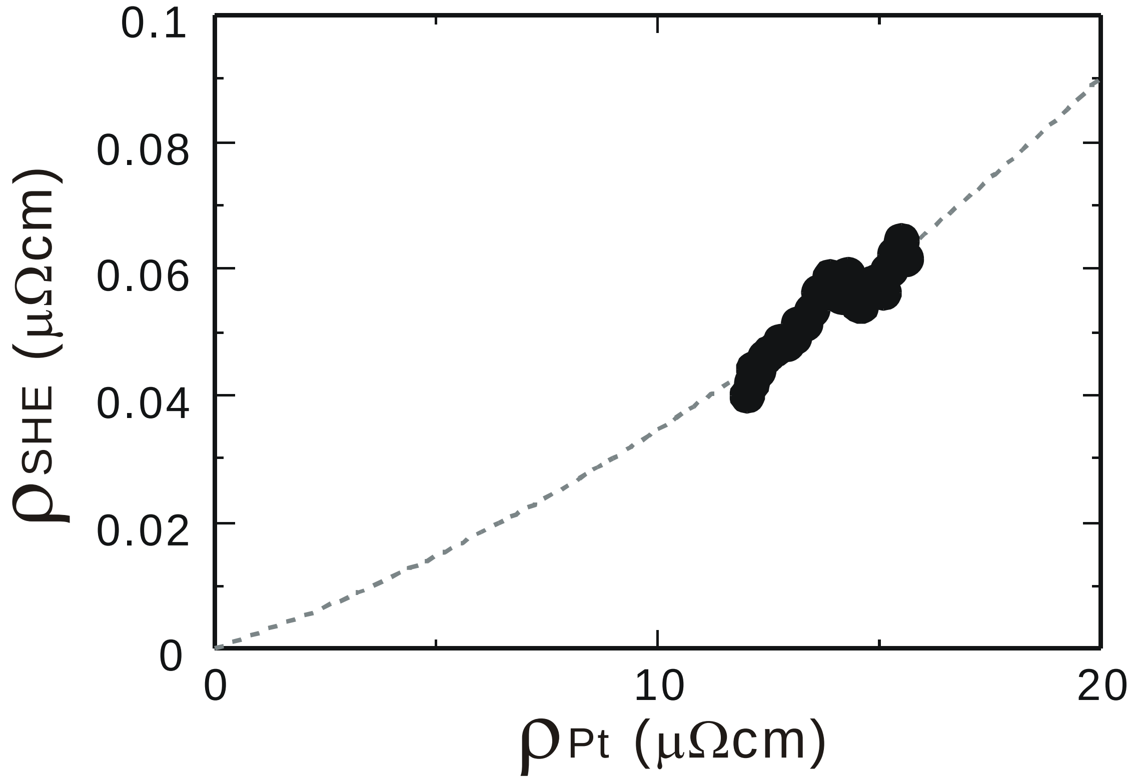
L. Berger (1970)

$$\rho_{SHE} \propto \rho^2$$

Relation between ρ_{SHE} & ρ

$$\sigma_{SHE} = w\sigma^2 \left(\frac{I_C}{I_S}\right) \Delta R_{SHE}$$

$$\rho_{SHE} \approx \rho^2 \sigma_{SHE}$$



$$\rho_{xy} = a\rho_{xx} + b\rho_{xx}^{\ 2}$$

$$a = 1.0 \times 10^{-3}$$

$$b = 2.4 \times 10^{-4}$$ (μΩcm)$^{-1}$

$\rho_{xx} > 10\ \mu\Omega\mathrm{cm}$

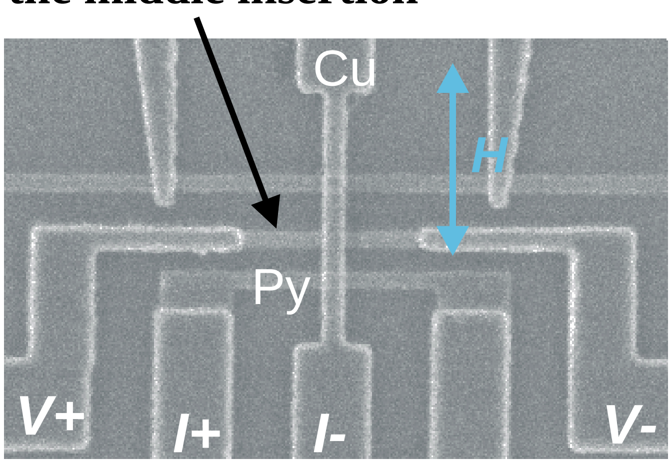
Quadratic term is dominant.

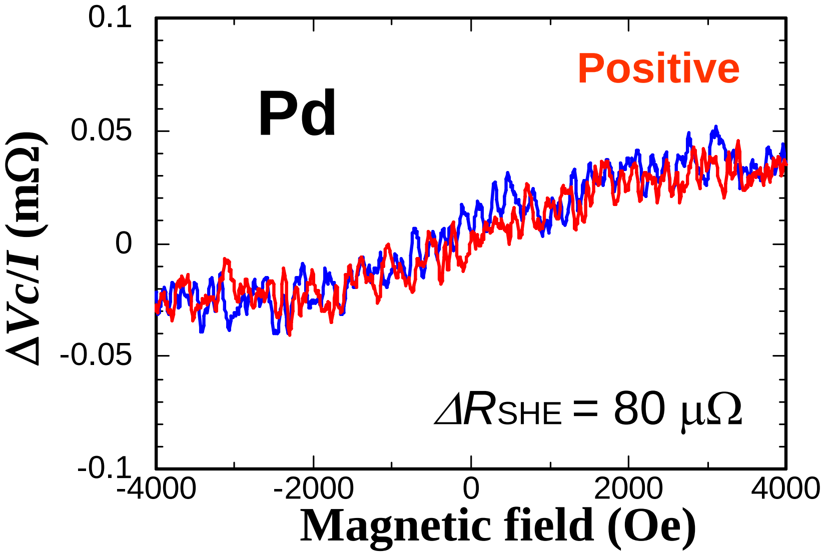
→ **Side jump (?)**

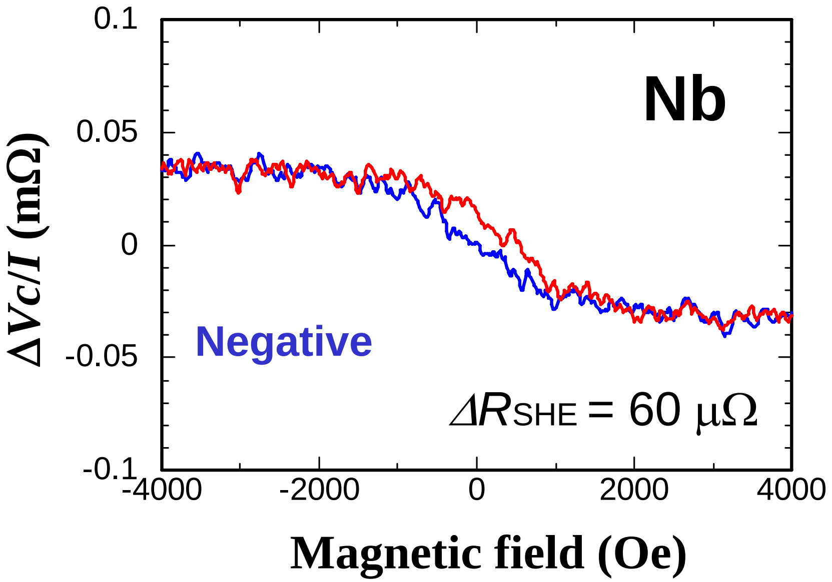
Intrinsic contribution is also proportional to ρ^2

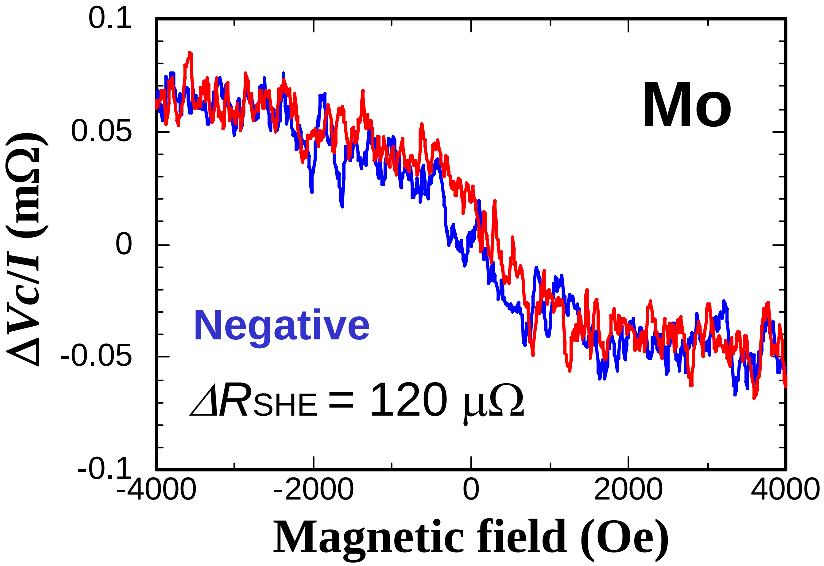
Inverse SHEs for various materials

Changing the material of the middle insertion







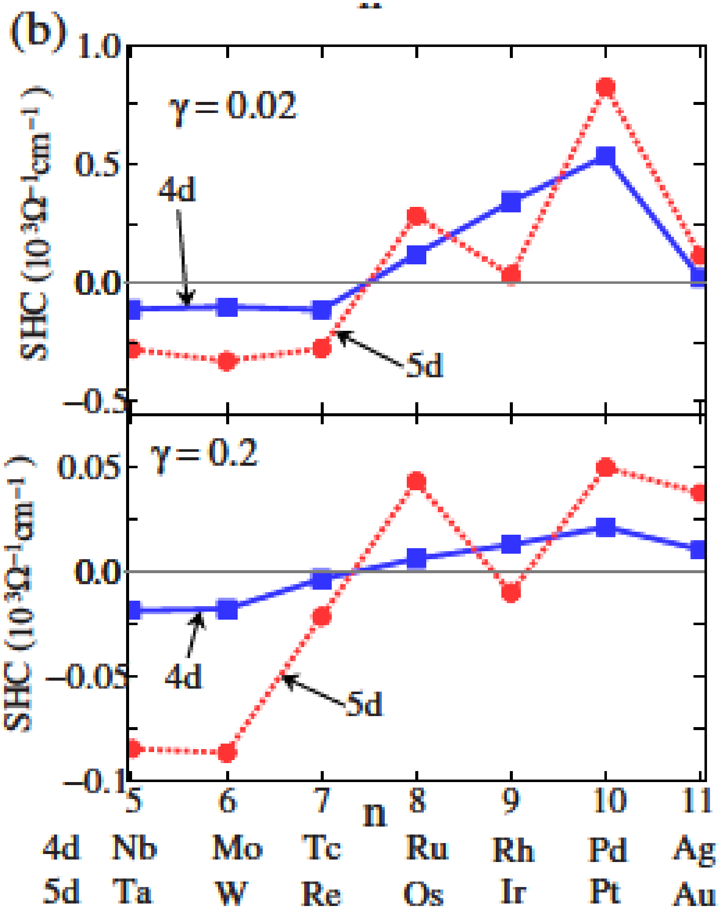


SH conductivity for various materials

Material	$\sigma\ (\Omega m)^{-1}$	$\sigma_{SHE}\ (\Omega m)^{-1}$	σ_{SHE}/σ
Pt (10K)	8.0×10^{6}	3.3×10^{4}	4.1×10^{-3}
Pd (10 K)	2.2×10^{6}	1.1×10^{3}	0.5×10^{-3}
Au (10 K)	2.0×10^{7}	2.0×10^{4}	1.0×10^{-3}
Cu (10 K)	5.0×10^{7}	2.0×10^{3}	0.4×10^{-3}
Nb (10 K)	2.7×10^{6}	-2.0×10^{3}	-0.7×10^{-3}
Mo (10 K)	2.8×10^{6}	-1.4×10^{3}	-0.5×10^{-3}

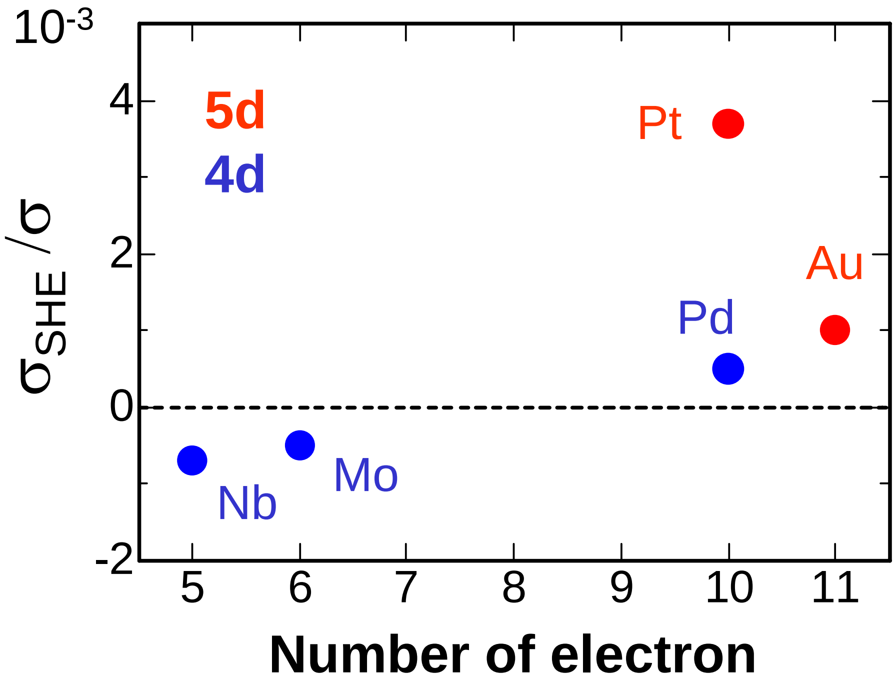
Origin of SHE

Numerical calculation intrinsic SHE



H. Tanaka *et al*. PRB (2008)

Experimentally obtained Hall angle



The experimental results seem to reproduce the numerical results.

Summary 02

1. **Spin Hall effects in transition metals are efficiently detected by means of spin current absorption.**

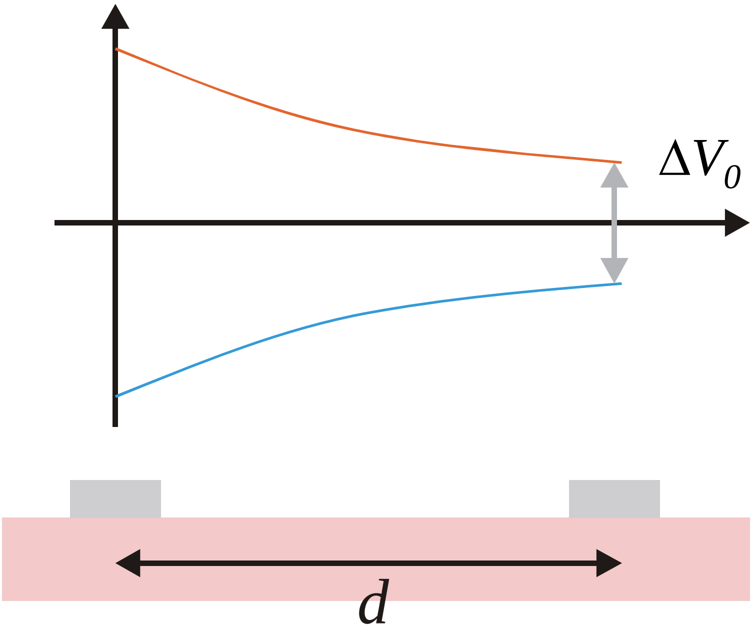
2. **Pt was found to have a large SH conductivity and Hall angle.**

3. **Temperature dependence of SHE in Pt suggests the relationship "$\rho \propto \rho_{SHE}^2$".**

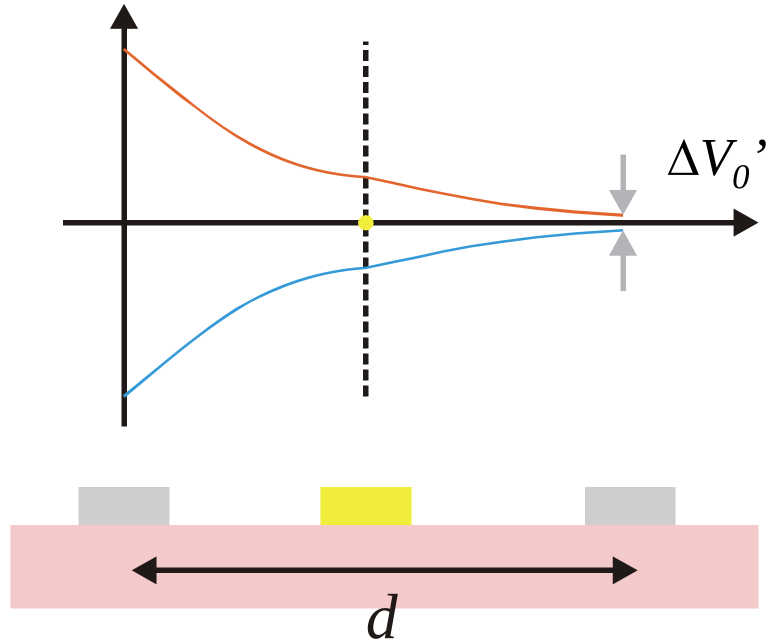
4. **SHEs for other metals shows suggest the intrinsic origin.**

Influence of additional contact

In single F/N junction



With additional contact

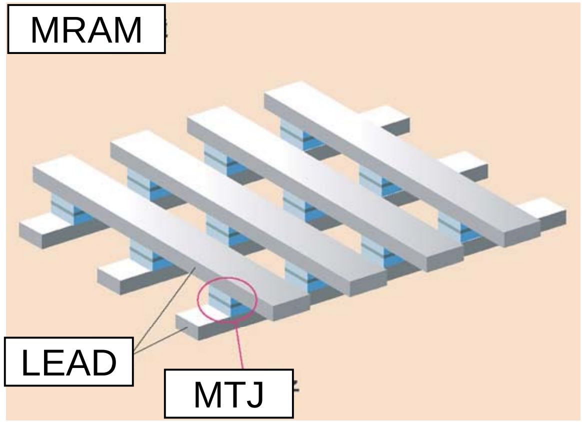


$$\Delta V_0 \gg \Delta V_0'$$

An additional contact with a small spin resistance is strongly modify the spin accumulation and spin current.

Advantage of planar spintronic devices

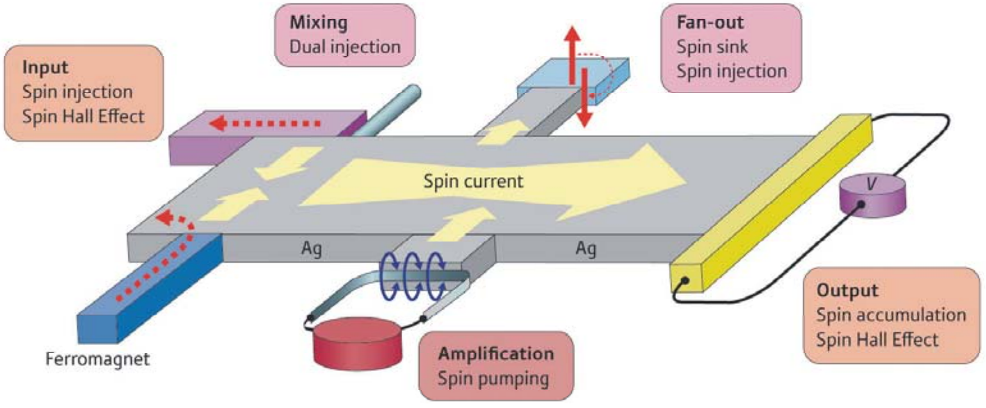
Conventional



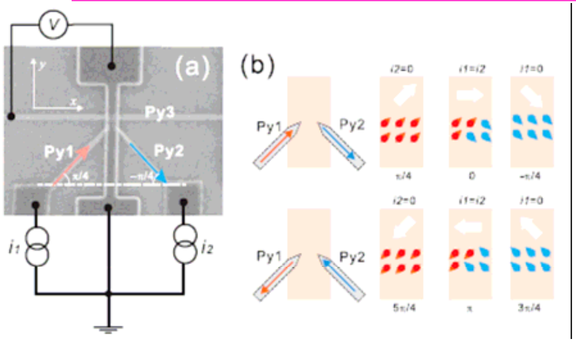
Mainly two terminal structure

Difficult to make multi-terminal devices

Planar structures



Easily expand to multi-terminal devices



Dual spin injection
(T. Kimura, Y. Otani & P. Levy, PRL 2007)

- **Development of novel functional spintronic devices.**
- **Detailed study of spin current diffusion in F/N hybrid structures**

Difficult to detect spin informations. → Optimization of the structure

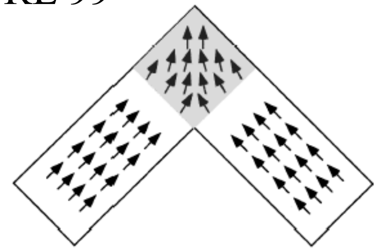
SHE with zigzag spin injector

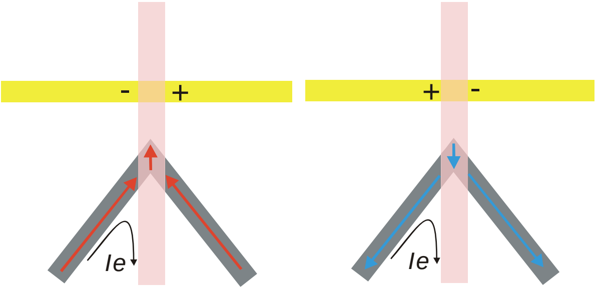
Taniyama et al. PRL 99

$$\mathbf{J}_c \propto \mathbf{S} \times \mathbf{J}_s$$

$\mathbf{J}_s$: Perpendicular to the junction

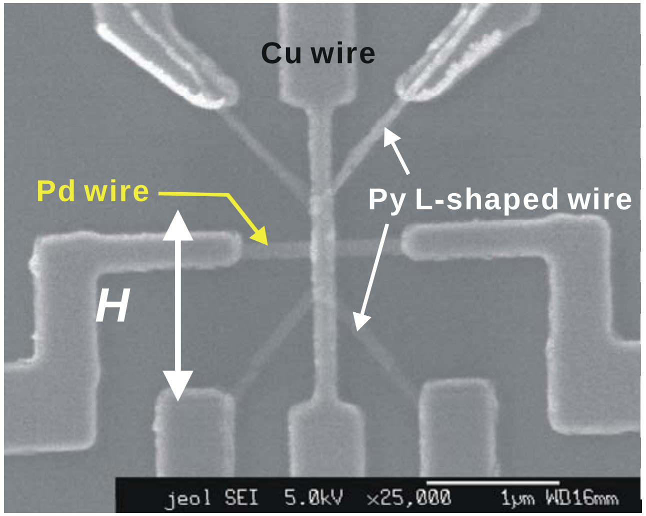
$\mathbf{S}$: should be parallel to the Cu wire.

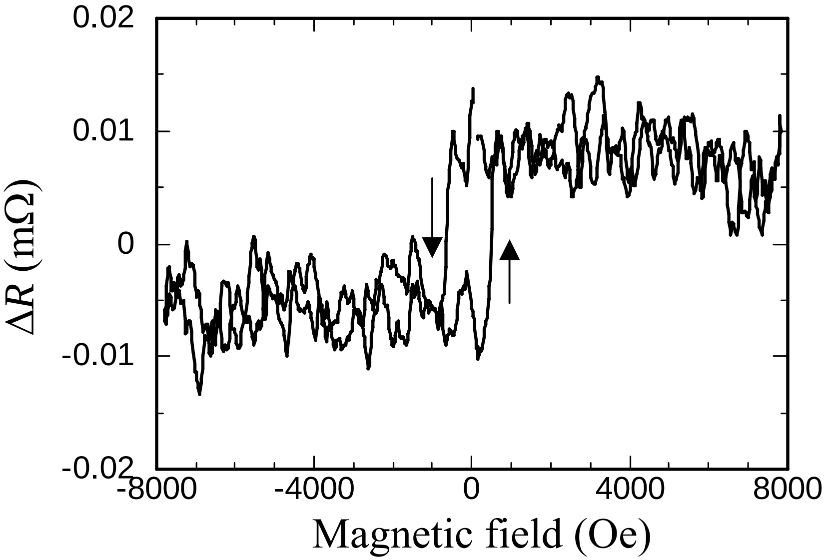




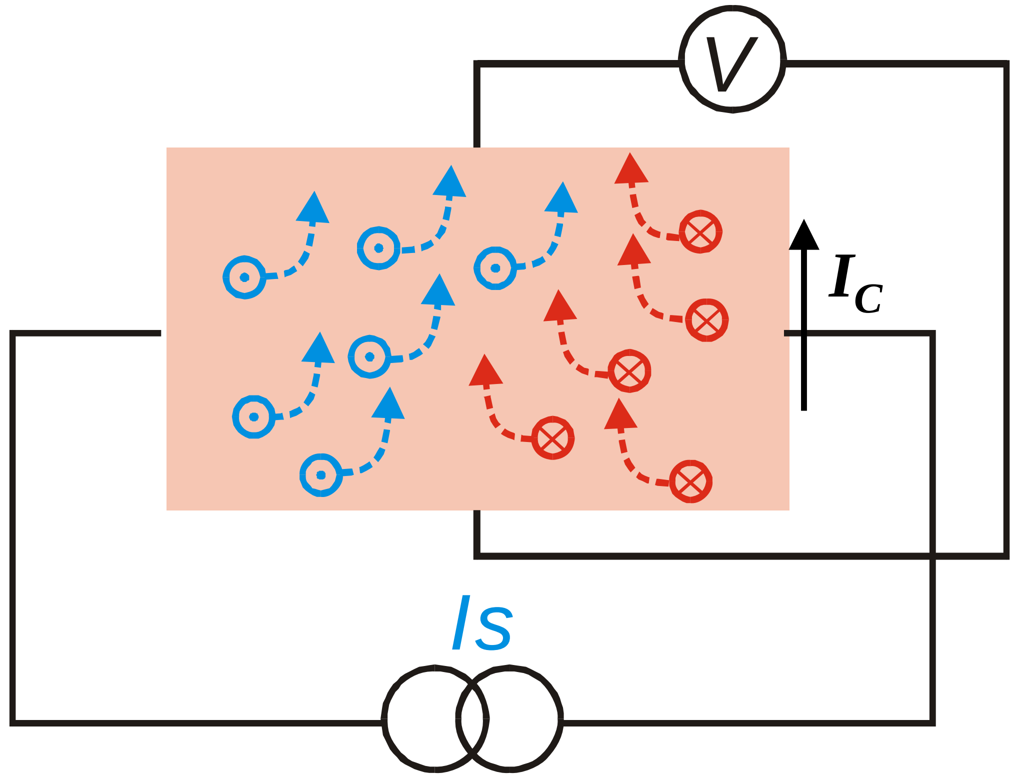
The magnetizations at the corner easily align with the transverse (y) direction.

→ **Spin Hall voltage will be induced even at the remanent state.**
Bi-stable spin Hall signal will appear.





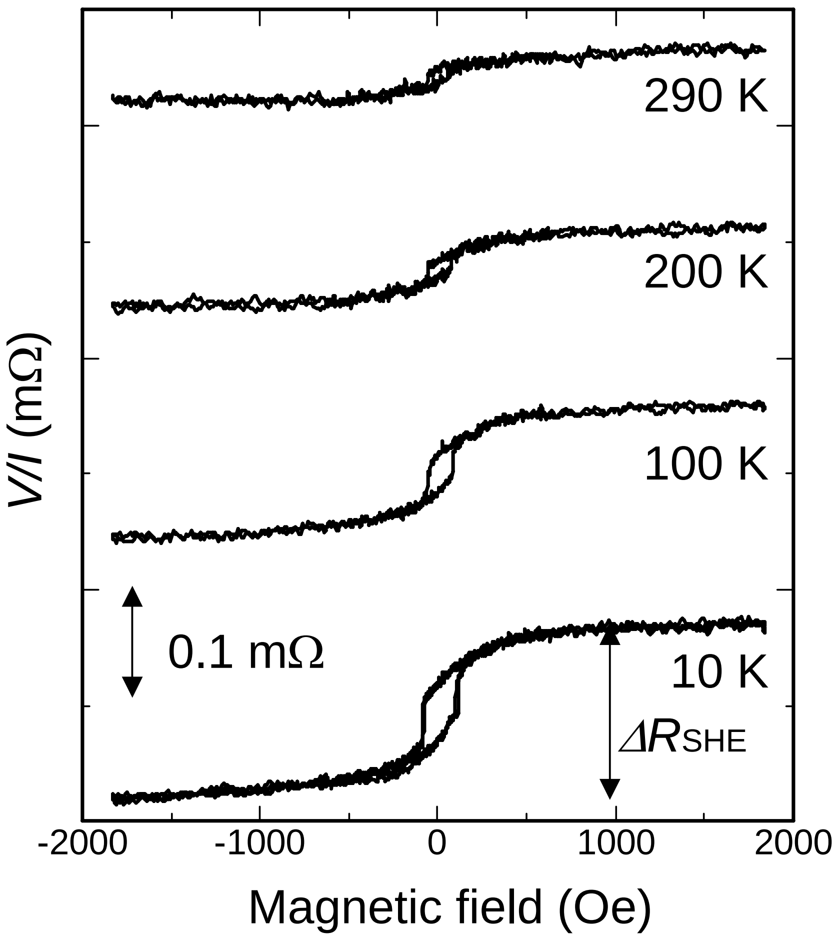
Spin-current-induced Hall effect in nonmagnet

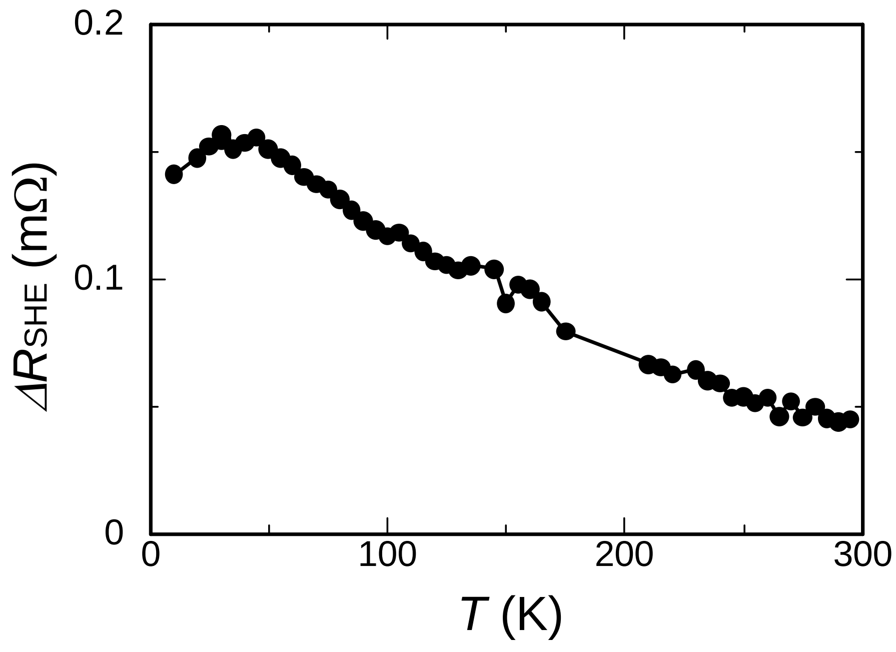


Spin current induces charge accumulation,
which can be detected by the conventional voltmeter.

Spin current can be injected by spin current absorption.

Temperature dependence of inverse SHE for Pt wire

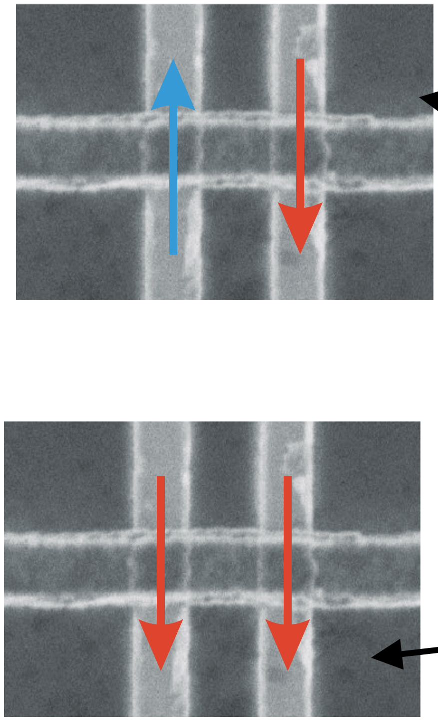


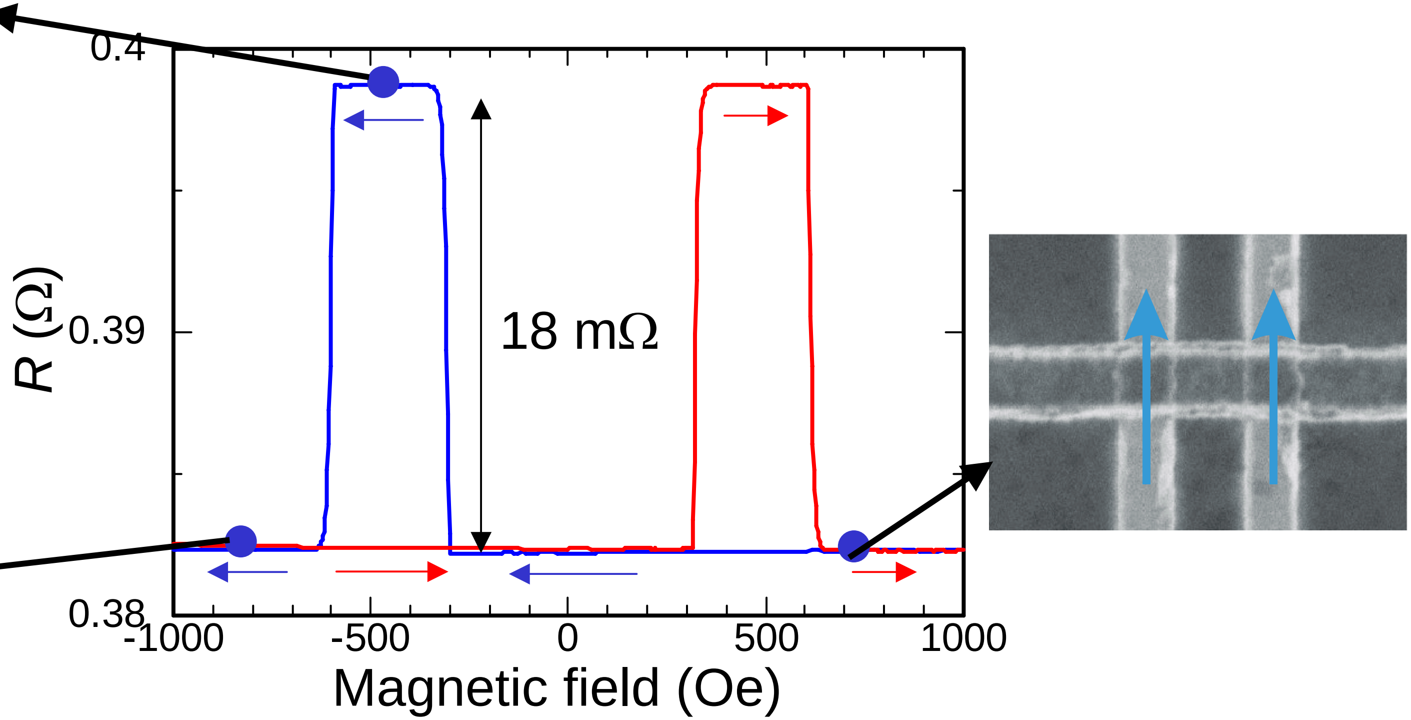


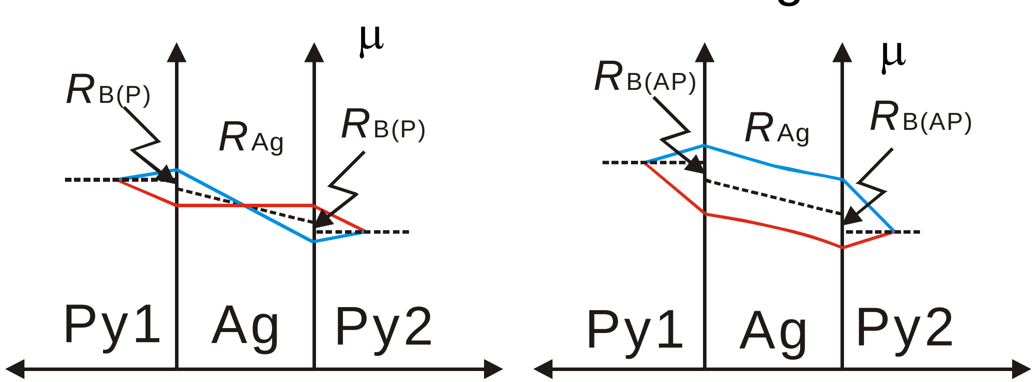
ΔR_{SHE} increases as the temperature declines. This is because the spin diffusion length of the Cu wire increases with decreasing the temperature, leading to the increment of the injected spin current.

Magnetoresistance due to spin accumulation

T. Kimura et al. Appl. Phys. Lett 85, 3501 (2004)

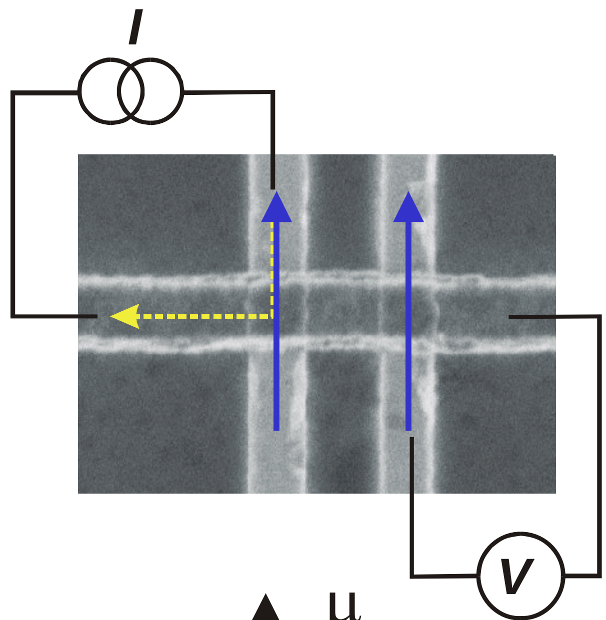


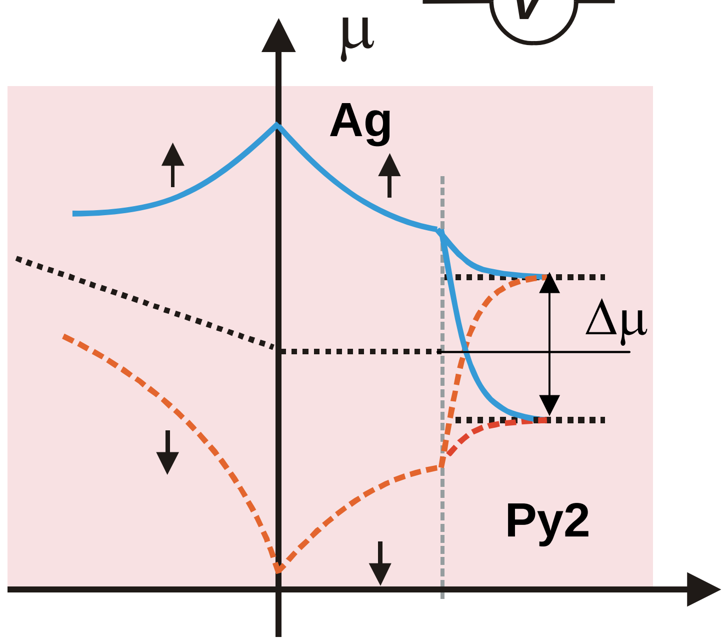


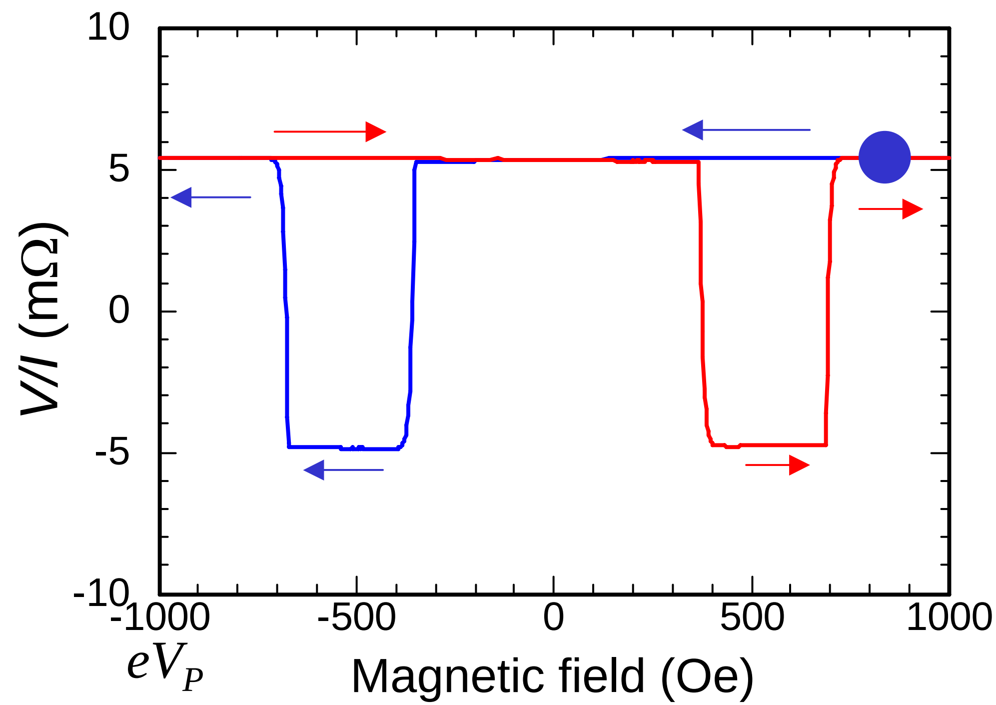


$$R_{B(AP)} - R_{B(P)} = 18\ \text{m}\Omega$$

Nonlocal spin valve measurement







eV_P

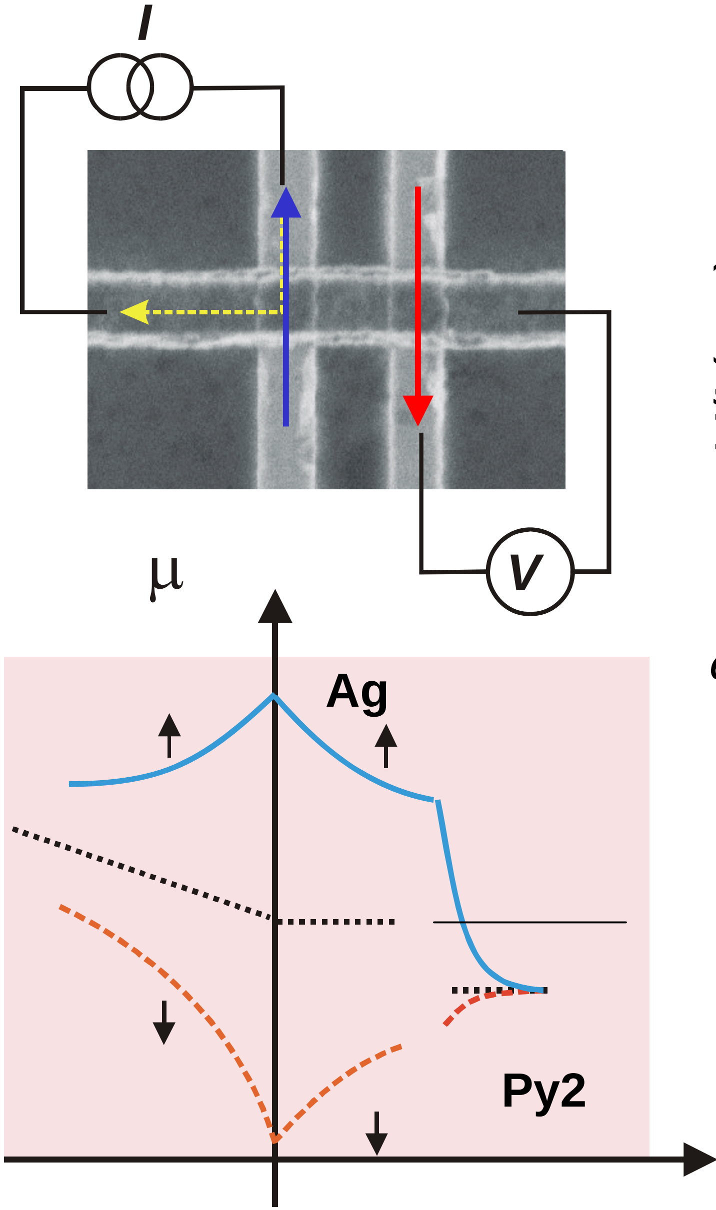
$$\mu_{\uparrow} \propto \frac{1}{\sigma_{\uparrow}} \exp\left(-\frac{x-d}{\lambda_{\mathrm{Py}}}\right) \qquad \mu_{\downarrow} \propto -\frac{1}{\sigma_{\downarrow}} \exp\left(-\frac{x-d}{\lambda_{\mathrm{Py}}}\right)$$

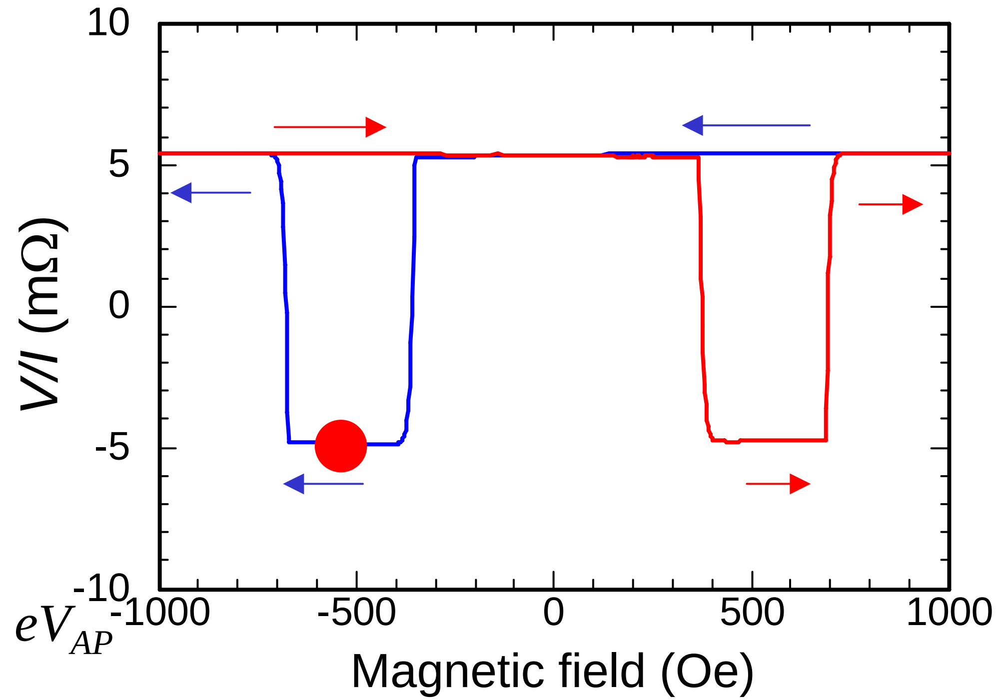
$$\sigma_{\uparrow} > \sigma_{\downarrow} \qquad I_{\uparrow} + I_{\downarrow} = 0$$

Charge neutral point shifts upward.

Positive voltage appears

Nonlocal spin valve measurement





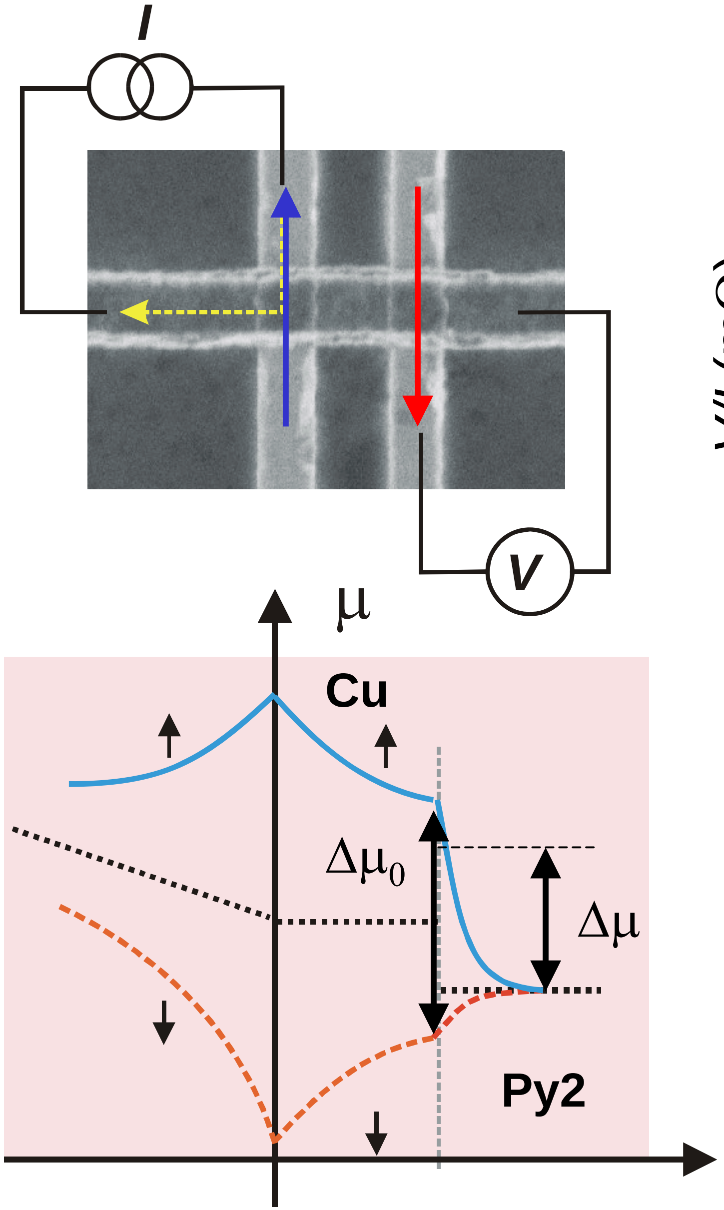
$$\mu_{\uparrow} \propto \frac{1}{\sigma_{\uparrow}} \exp\left(-\frac{x-d}{\lambda_{Py}}\right) \quad \mu_{\downarrow} \propto -\frac{1}{\sigma_{\downarrow}} \exp\left(-\frac{x-d}{\lambda_{Py}}\right)$$

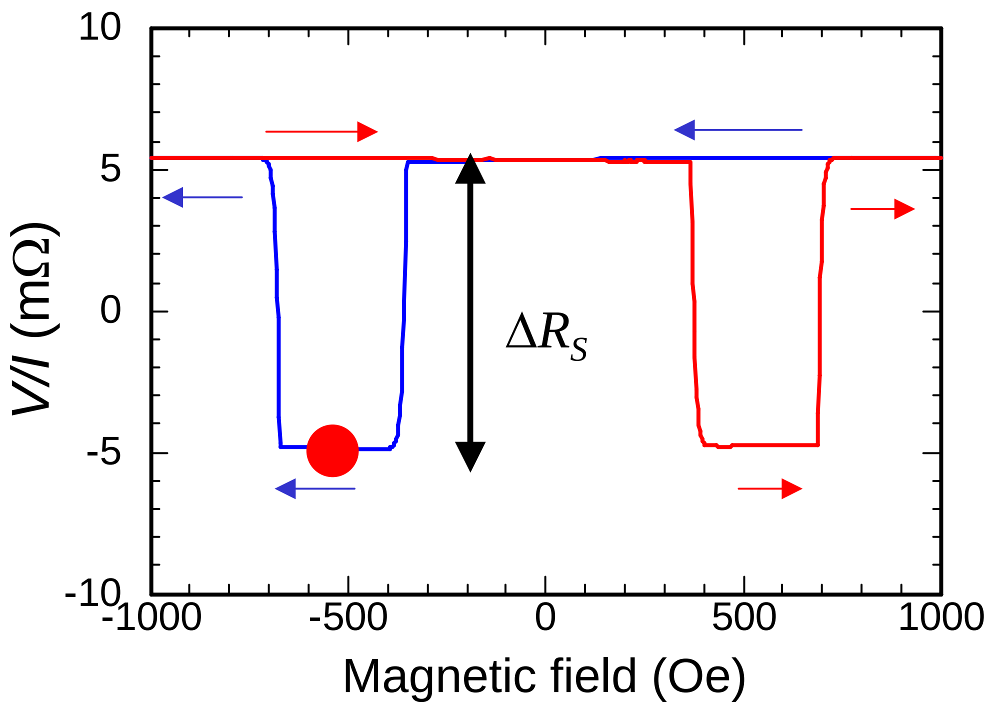
$$\sigma_{\uparrow} < \sigma_{\downarrow} \qquad I_{\uparrow} + I_{\downarrow} = 0$$

Charge neutral point shifts downward.

Negative voltage appears

Nonlocal spin valve measurement



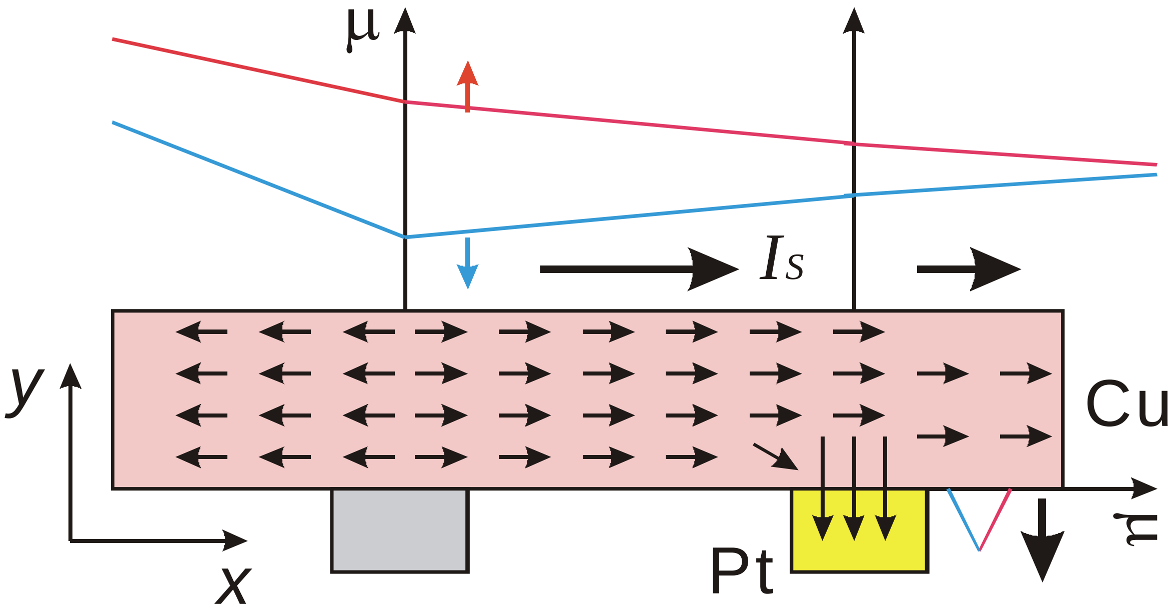


$$\Delta\mu = P\Delta\mu_0$$

Voltage does not include any back ground signal.

→ Sensitive detection of spin information

Flow of spin currents in Cu & Pt wires



In Cu wire,

Spin currents flow along the Cu wire. **$\mathbf{I_S}$ □ x**

In Pt wire,

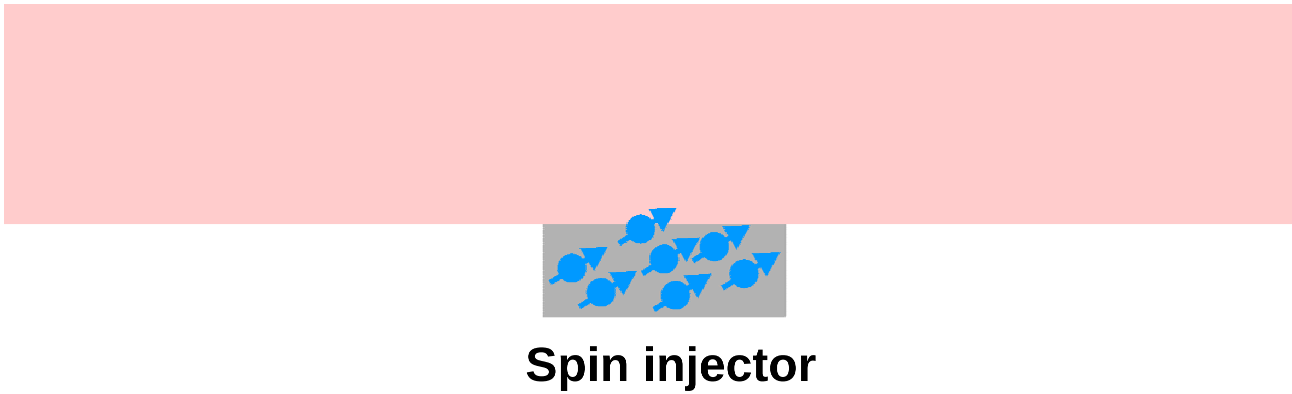
Spin currents are sucked into the Pt wire because of the short spin diffusion length. **$\mathbf{I_S}$ □ y**

When **S □ x** $\mathbf{I_C \propto S \times I_S}$ **SHE will be induced.**

Spin sink effect

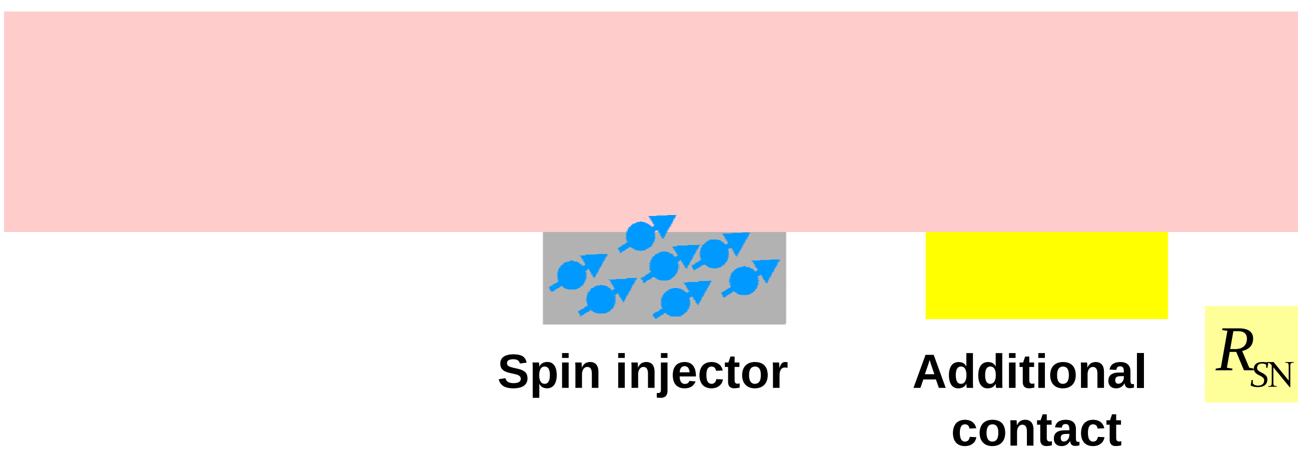
Single interface

Spin currents diffuse isotropically.



Additional contact

When the spin resistance for the additional contact is small, spin currents are preferably absorbed into the contact.



$R_{SN} >> R_{SC}$

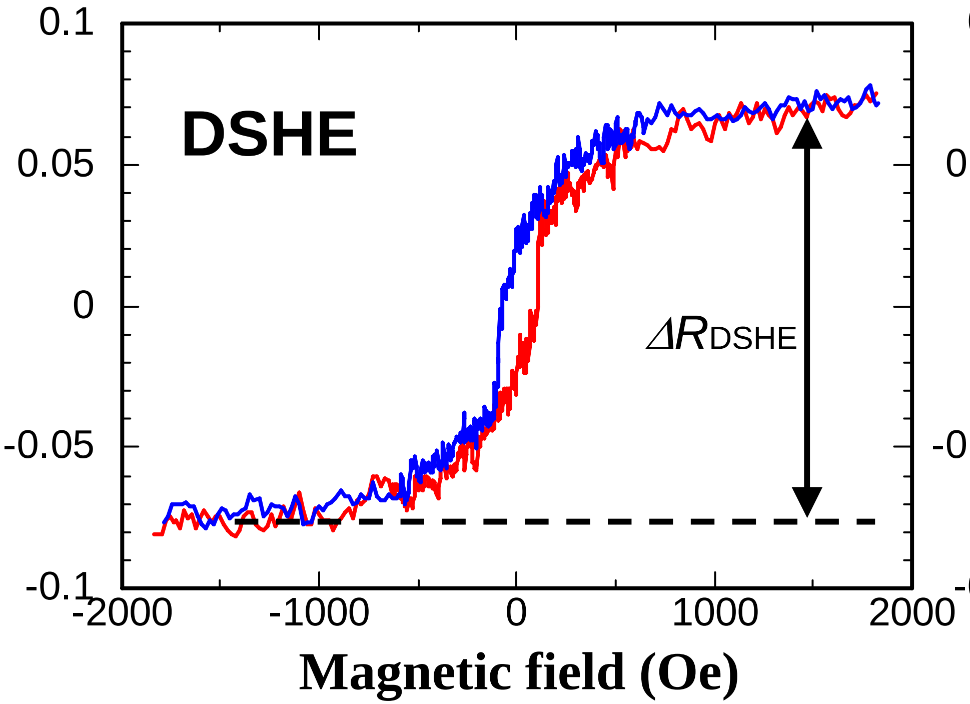
Basic transport formulation with SHE

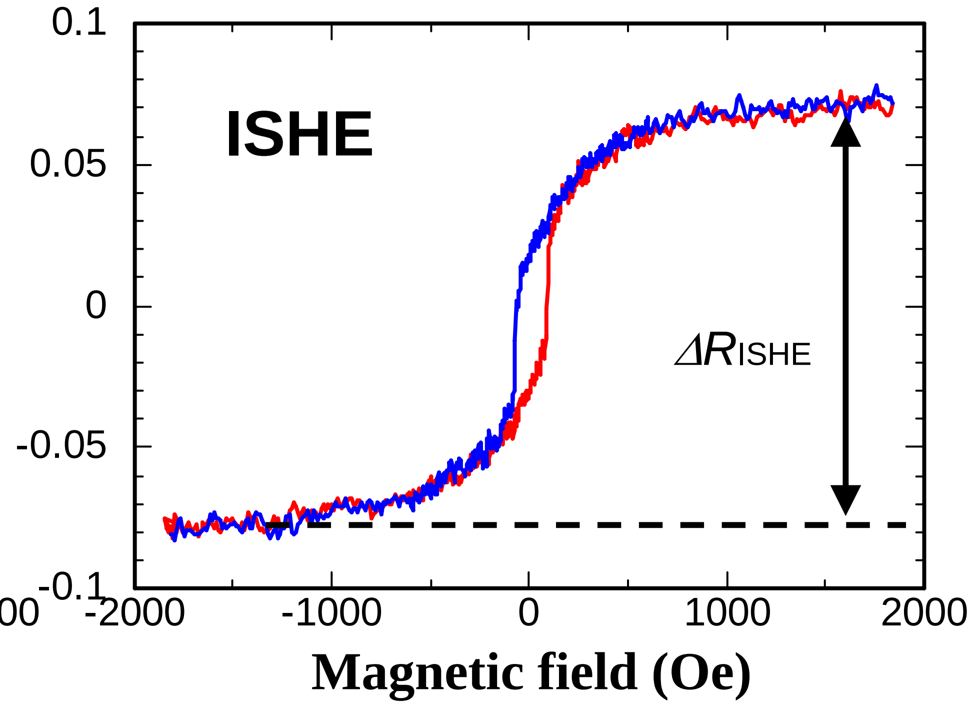
$$\begin{pmatrix} J_{c,y} \\ J_{s,z} \end{pmatrix} = \begin{pmatrix} \sigma & -\sigma_{\mathrm{SHE}} \\ \sigma'_{\mathrm{SHE}} & \sigma \end{pmatrix} \begin{pmatrix} E_y \\ -\nabla_z \delta\mu_{\mathrm{N}} / e \end{pmatrix}$$

σ_{SHE} : Charge-Hall conductivity for the spin current

σ'_{SHE} : Spin-Hall conductivity for the charge current

Reciprocal relation between spin & charge currents





$$\Delta R_{\mathrm{DSHE}} \approx \frac{R_{S\,\mathrm{Py}}}{R_{S\,\mathrm{Cu}}} \frac{P_{\mathrm{Py}} \sigma_{\mathrm{SHE}}}{w \sigma^2} \sinh^{-1}\left(\frac{d}{\lambda_{\mathrm{Cu}}}\right)$$

σ_{SHE} : Spin-Hall conductivity for the charge current

$$\Delta R_{\mathrm{ISHE}} \approx \frac{R_{S\,\mathrm{Py}}}{R_{S\,\mathrm{Cu}}} \frac{P_{\mathrm{Py}} \sigma'_{\mathrm{SHE}}}{w \sigma^2} \sinh^{-1}\left(\frac{d}{\lambda_{\mathrm{Cu}}}\right)$$

σ'_{SHE} : Charge-Hall conductivity for the spin current

$$\Delta R_{\mathrm{DSHE}} = \Delta R_{\mathrm{ISHE}}$$

means $\sigma_{\mathrm{SHE}} = \sigma'_{\mathrm{SHE}}$

Experimental demonstration of Onsager reciprocal relation