KMS meeting

Efficient Spin Injection and Absorption Using CoFe-Based Alloys

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Main Contributors & Outline

Main Contributors

Lab PD	SSP Lab D2	SSP Lab D2
 Shaojie Hu	 Tatsuya Nomura	 Kazuto Yamanoi

Outline

1. Concept of Spin Current
2. Efficient electrical spin injection
3. Efficient thermal spin injection
4. Spin current absorptions in hybrid systems

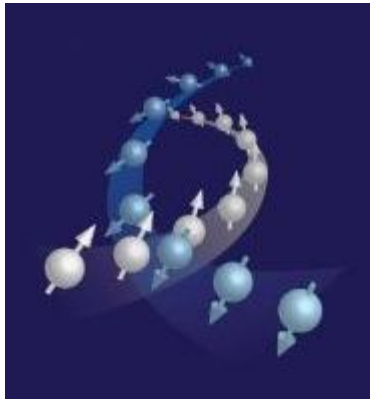
Concept of spin currents

Charge & Spin

Flow of Charge
→ Electric Current

Flow of Spin
→ Spin Current

Spin current : Flow of spin-angular momentum

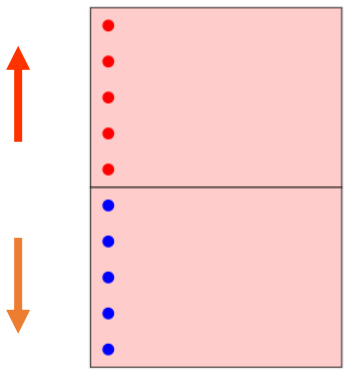


Two important innovations for development of spintronics

Manipulation of electric current ⟷ Spin current ⟷ Manipulation of magnetization

Conduction electrons in NM & FM

Nonmagnetic (N) metal



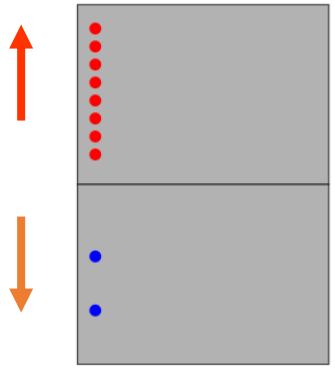
Charge current (Flow of charge)

$$j = j_{\uparrow} + j_{\downarrow}$$

Spin current (Flow of spin angular momentum)

$$j_S = j_{\uparrow} - j_{\downarrow} = 0$$

Ferromagnetic (F) metal



Charge current (Flow of charge)

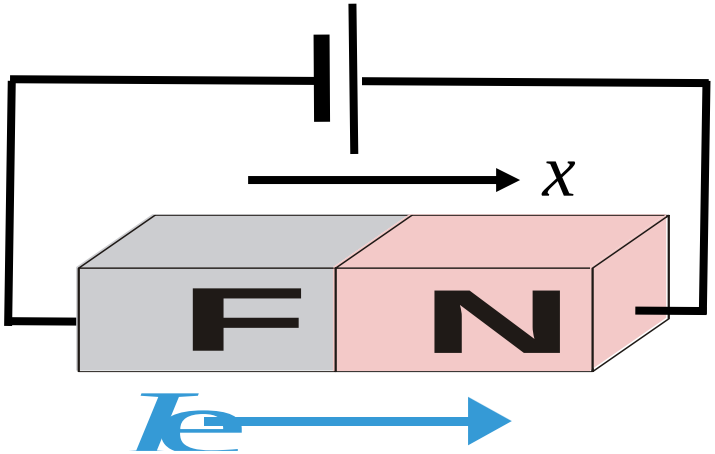
$$j = j_{\uparrow} + j_{\downarrow}$$

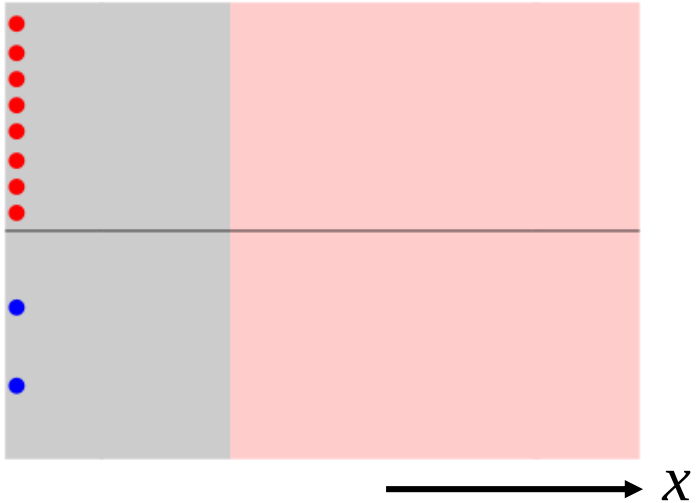
Spin current (Flow of spin angular momentum)

$$j_S = j_{\uparrow} - j_{\downarrow} \neq 0$$

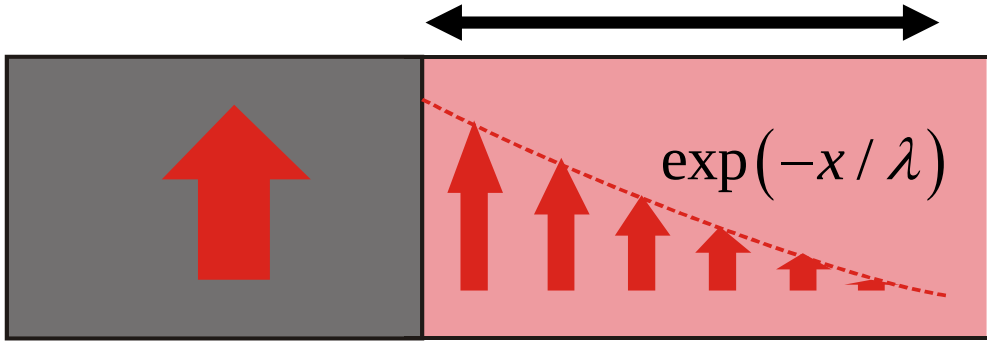
Electrical spin injection

Applying electric field across a F/N junction





Spin diffusion length (λ)

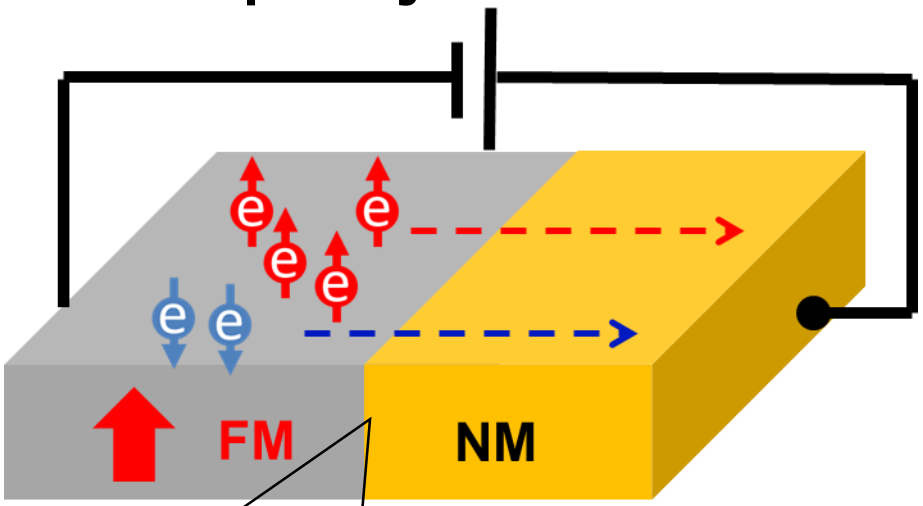


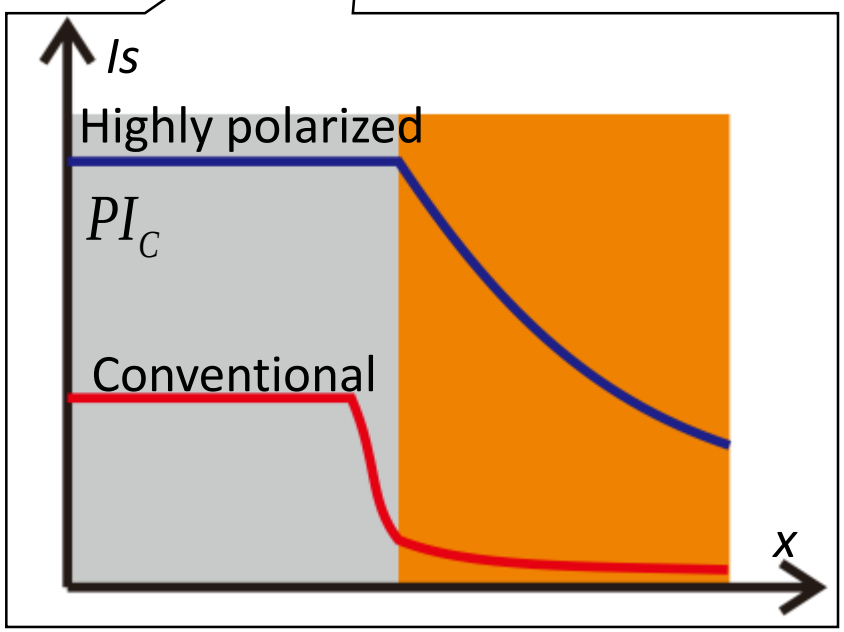
Non-equilibrium spin accumulation

Spin current appears over the spin diffusion length.

Spin reabsorption effect in F/N interface

Electrical spin injection





$$P \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$$I_{S0} = PI_C$$

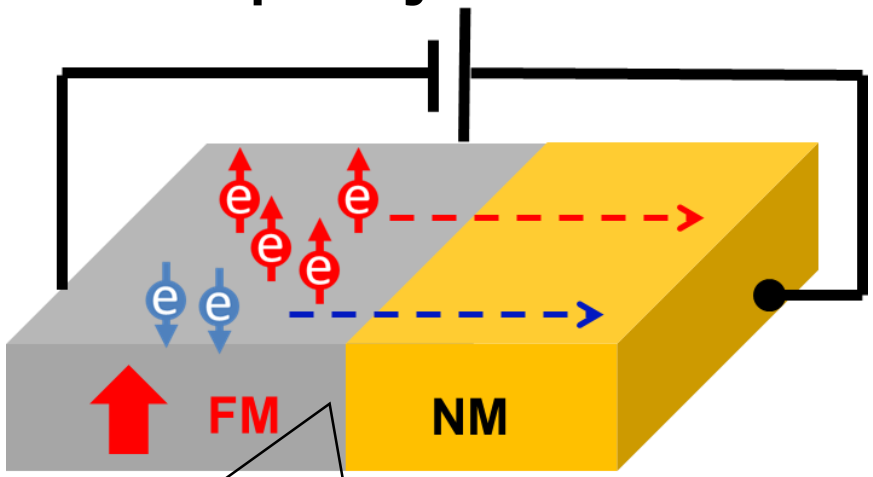
Original spin current is proportional to spin polarization.

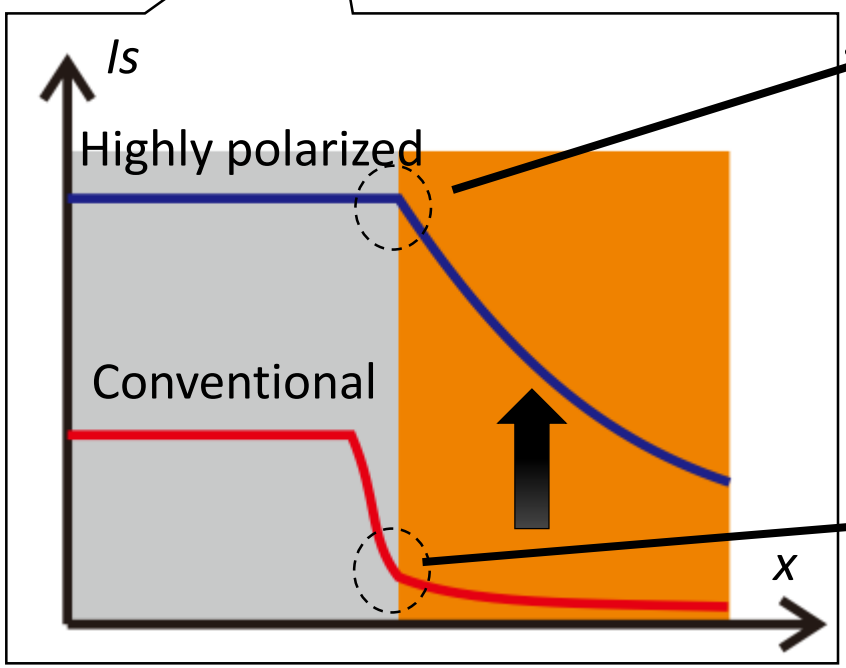
Spin polarization cannot maintain the original value.

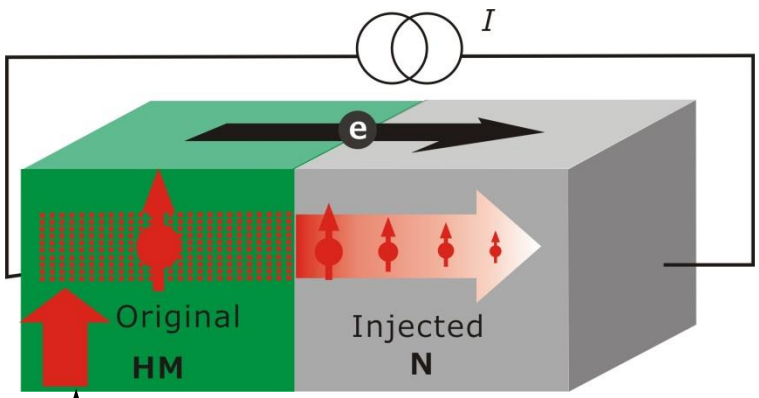
Spin reabsorption effect in F/N interface

Electrical spin injection

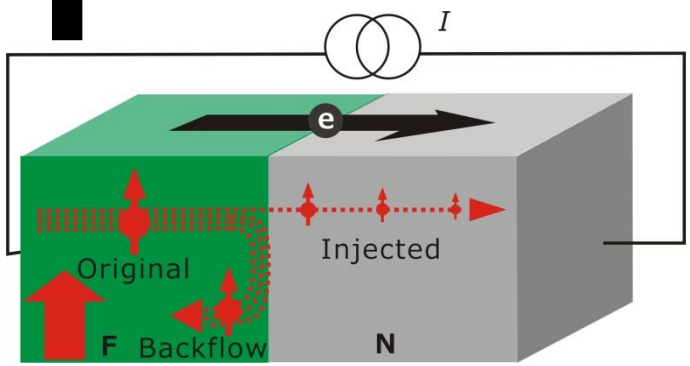
$$\eta_I = \frac{P}{\left(1-P^2\right)\frac{\rho_N \lambda_N}{\rho_F \lambda_F}+1}$$



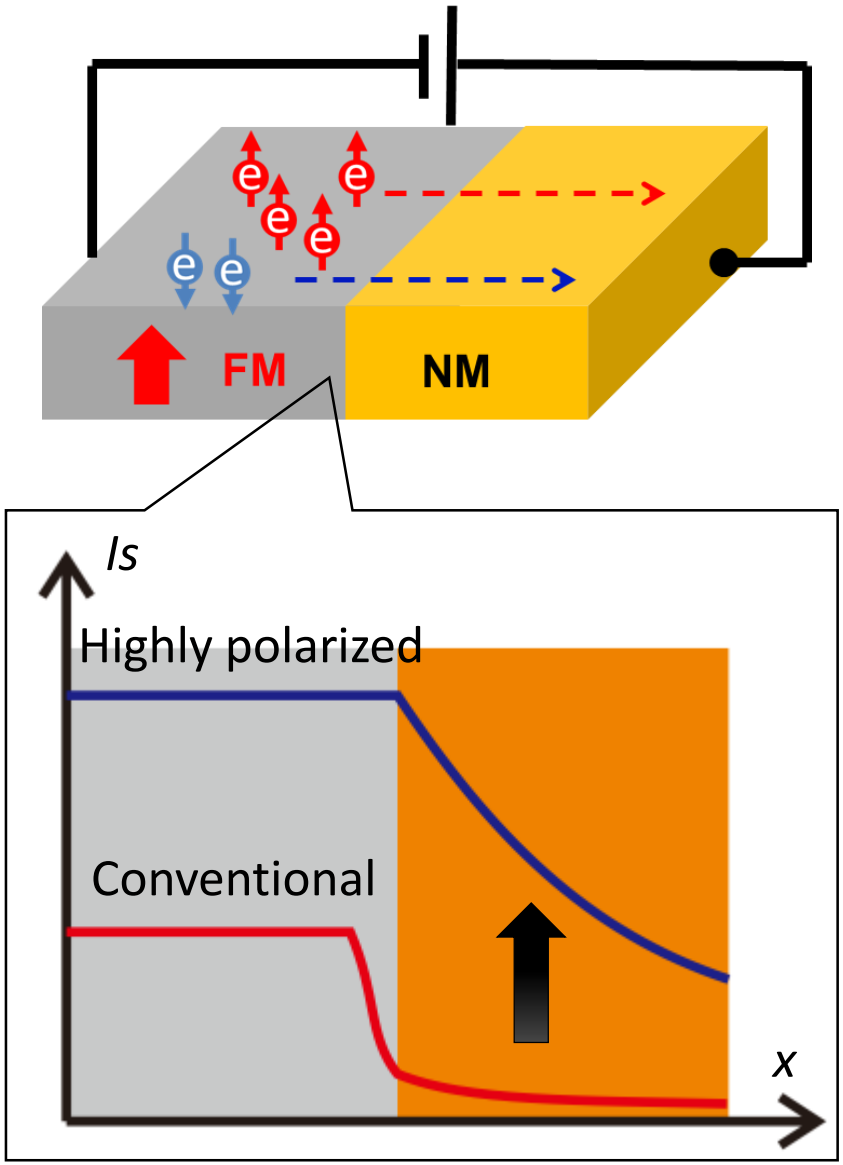


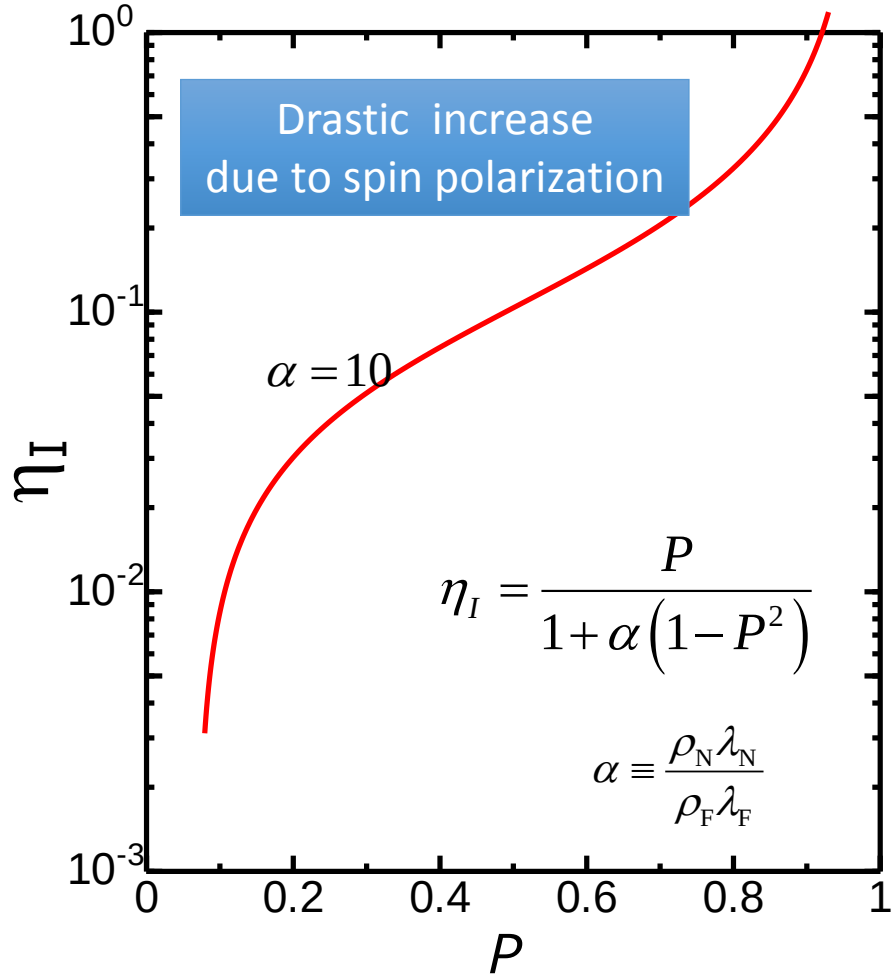


Backflow can be suppressed by high spin polarization.



Spin reabsorption effect in F/N interface



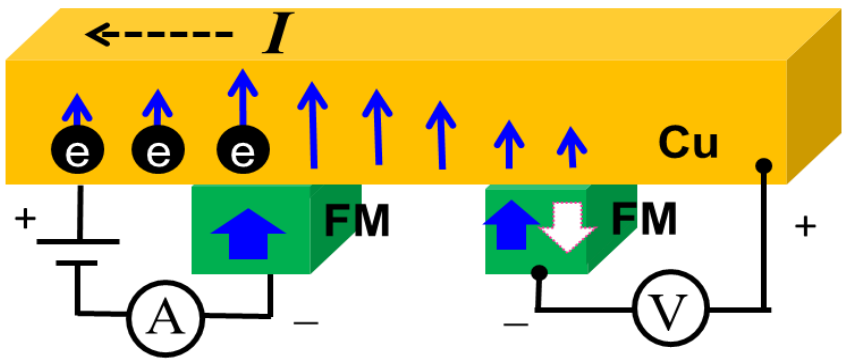


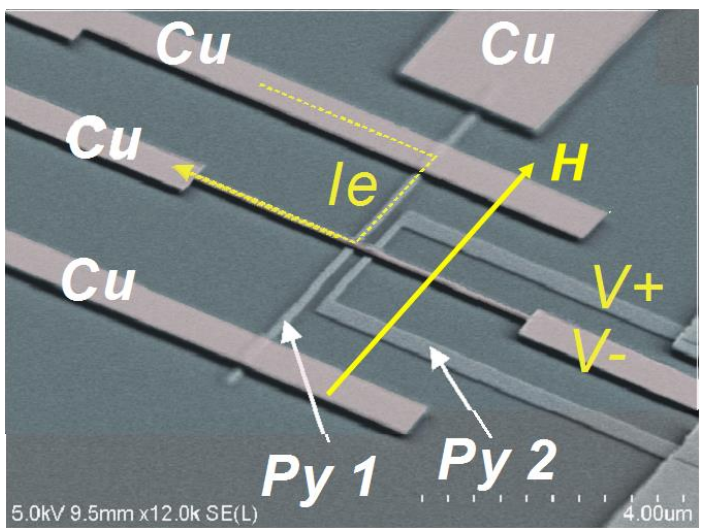
Spin polarization is key.

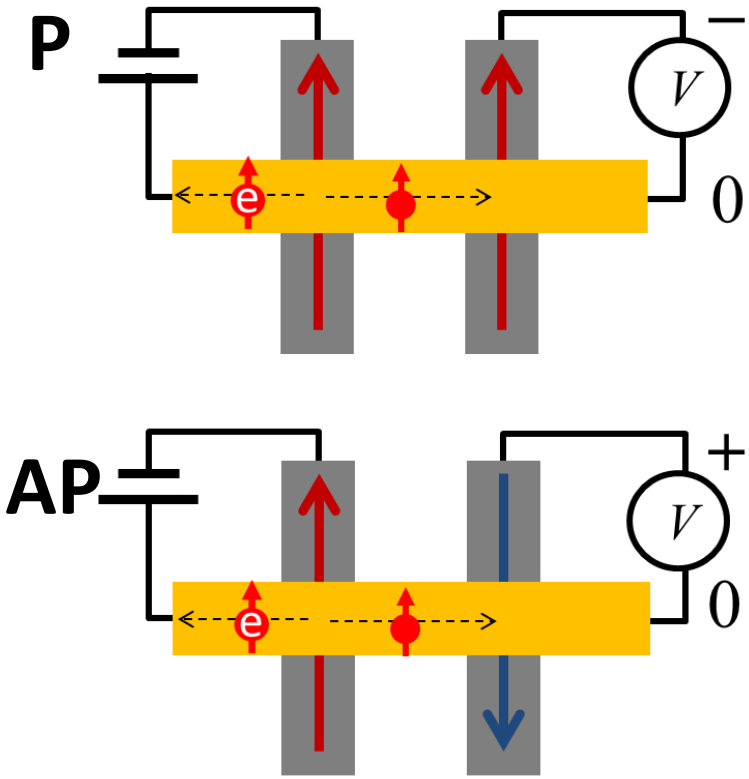
- Increase of original flow
- Suppression of backflow

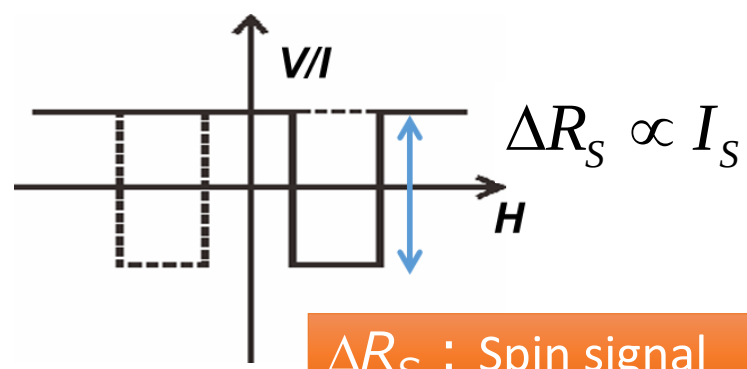
Evaluation of spin injection efficiency

Nonlocal spin valve









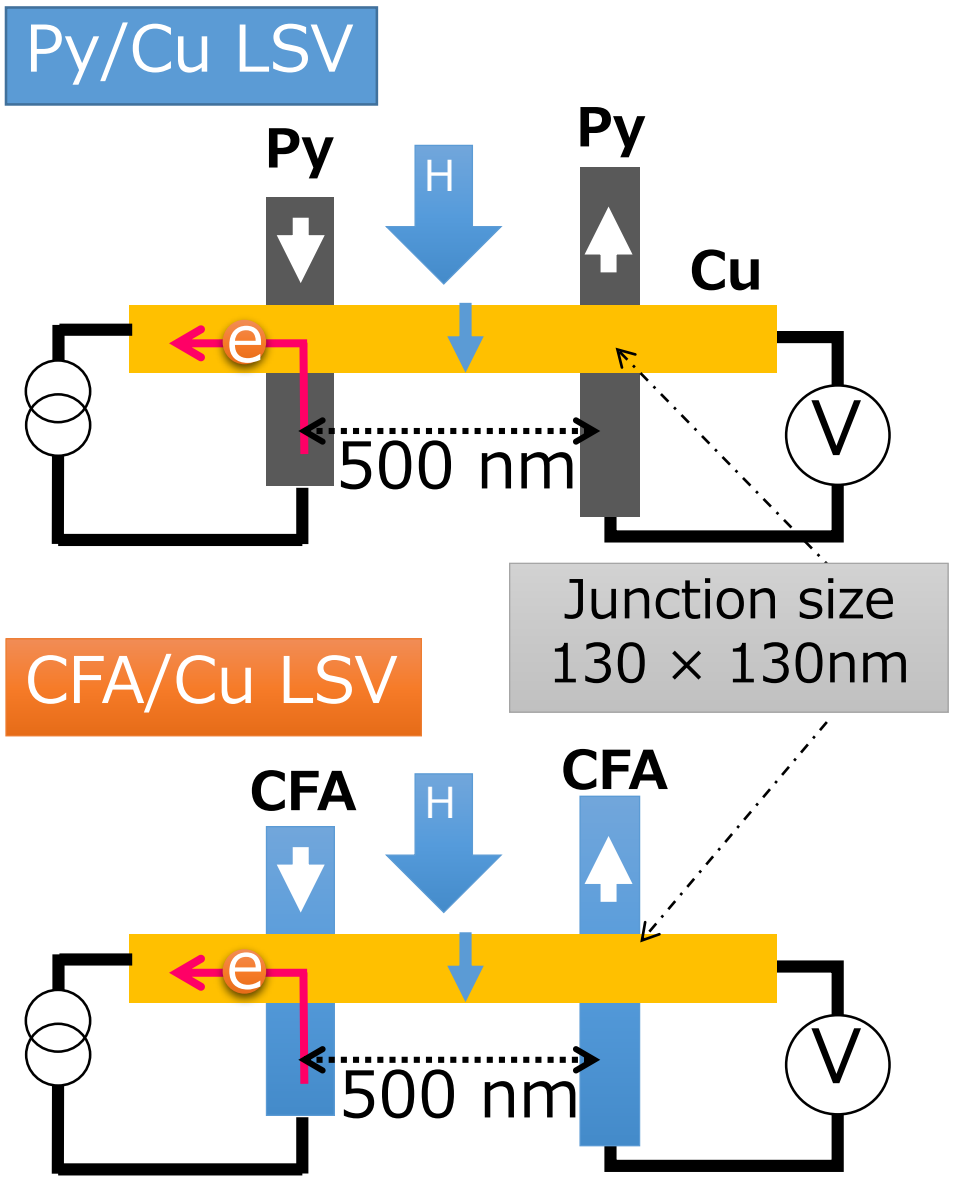
$\Delta R_S \propto I_S$

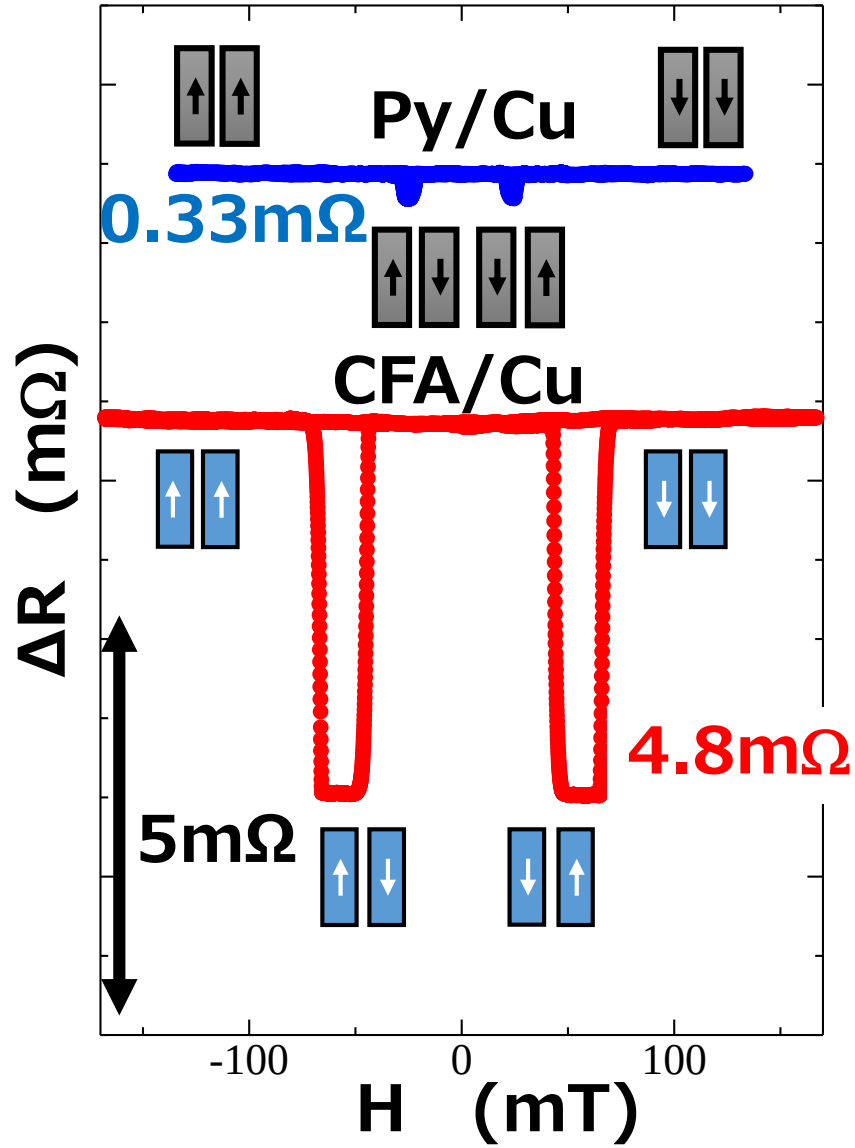
ΔR_S : Spin signal

NiFe : P~0.3, CoFeAl : P~ 0.6

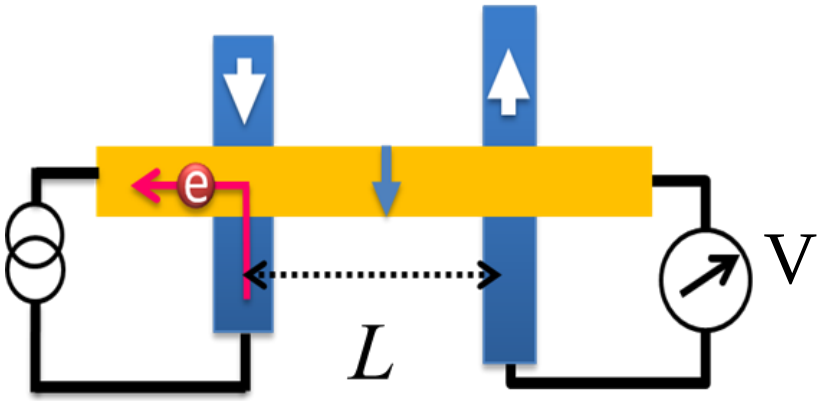
Evaluation of electrical spin injection efficiency

S. Hu et al. NPG asia mater. (2014)





Comparison between Py/Cu and CFA/Cu LSV



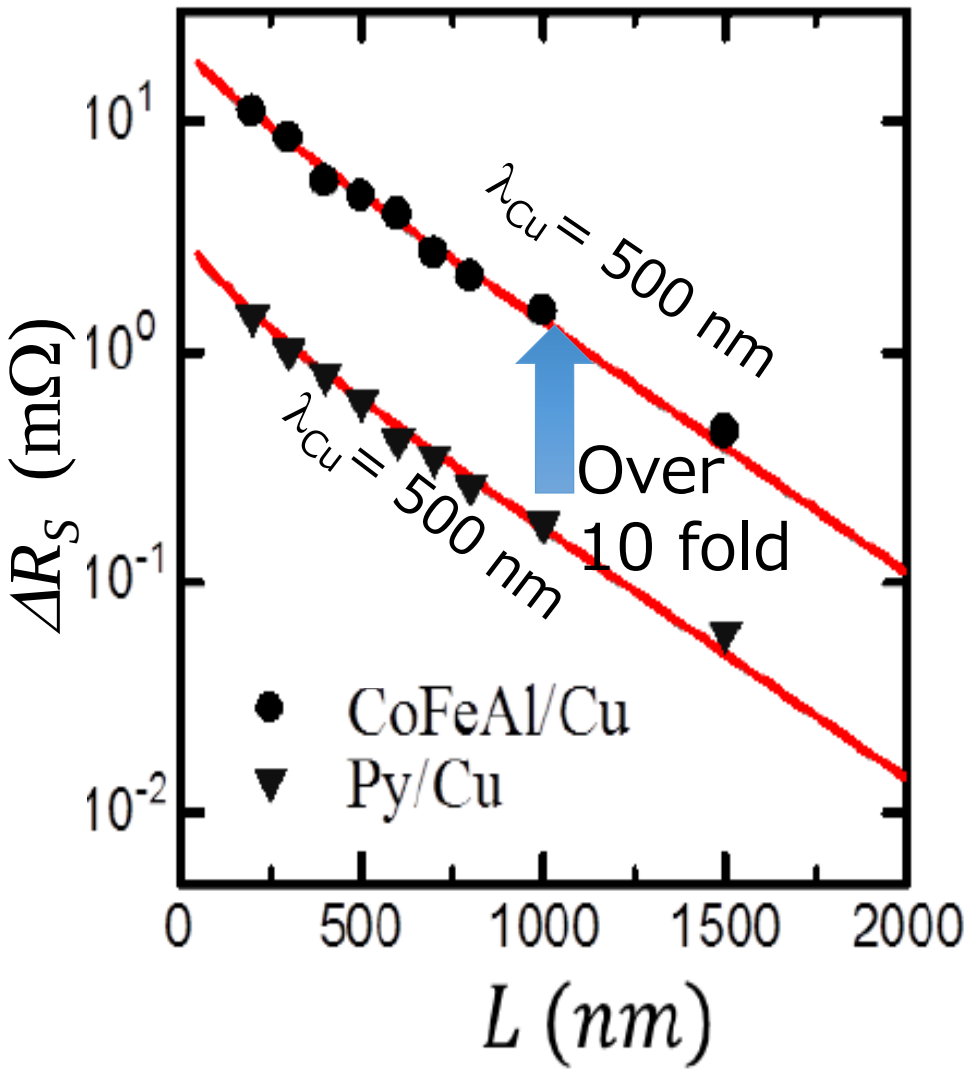
Transparent interface

$$\Delta R_S \approx \frac{S_N}{S_{inj} S_{det}} \frac{P_F^2}{(1-P_F^2)^2} \frac{\rho_F^2 \lambda_F^2}{\rho_N \lambda_N \sinh(d/\lambda_N)}$$

FM	$\rho_F \lambda_F$	P_F	η
Py	0.5 fΩm²	0.35	0.015
CFA	1.2 fΩm²	0.67	0.10

S. Hu et al. NPG asia mater. (2014)

Distance dependence

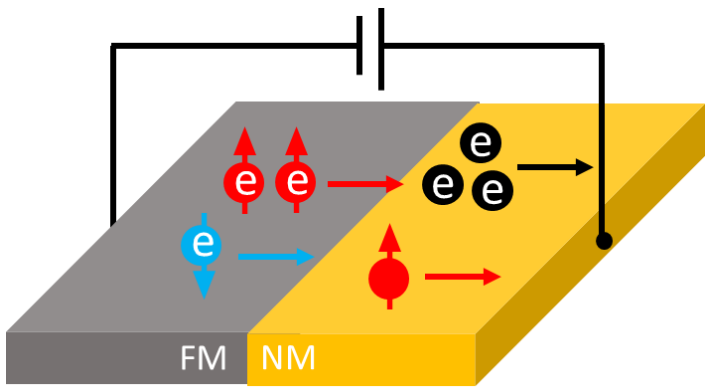


Outline

1. Concept of Spin Current
2. Efficient electrical spin injection
3. **Efficient thermal spin injection**
4. Spin current absorptions in hybrid systems

Electrical and Thermal Spin Injection

Electrical Spin Injection



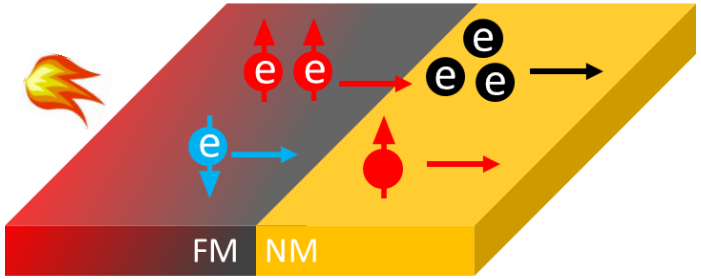
$\sigma_\uparrow$, $\sigma_\downarrow$: Electrical conductivity

Charge current $I_C = (\sigma_\uparrow + \sigma_\downarrow)\nabla V$

Spin current $I_S = (\sigma_\uparrow - \sigma_\downarrow)\nabla V$

Spin current generation due to $\sigma_\uparrow \neq \sigma_\downarrow$

Thermal spin injection



$S_\uparrow$, $S_\downarrow$: Seebeck Coefficient

Charge current $I_C = (\sigma_\uparrow S_\uparrow + \sigma_\downarrow S_\downarrow)\nabla T$

Spin current $I_S = (\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow)\nabla T$

Spin current generation due to $S_\uparrow \neq S_\downarrow$

Electrical and Thermal Spin Injection

Electrical Spin Injection

$\sigma_\uparrow$, $\sigma_\downarrow$: Electrical conductivity

$$P \equiv \frac{I_S}{I_C} = \frac{\sigma_\uparrow - \sigma_\uparrow}{\sigma_\uparrow + \sigma_\downarrow}$$

arge current $I_C = (\sigma_\uparrow + \sigma_\downarrow)\nabla V$

Spin current $I_S = (\sigma_\uparrow - \sigma_\downarrow)\nabla V$

Spin current generation due to $\sigma_\uparrow \neq \sigma_\downarrow$

Thermal spin injection

$S_\uparrow$, $S_\downarrow$: Seebeck Coefficient

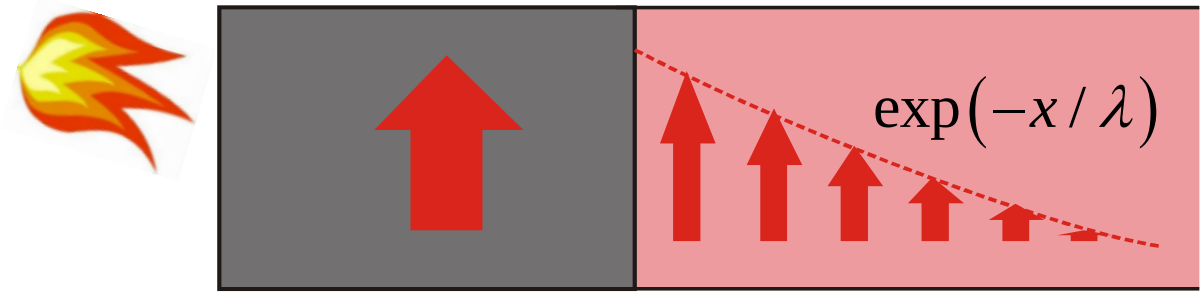
$$P_T \equiv \frac{I_S}{I_C} = \frac{P}{2}\frac{S_\uparrow - S_\uparrow}{S_0} = \frac{P}{2}P_S$$

$= (\sigma_\uparrow S_\uparrow + \sigma_\downarrow S_\downarrow)\nabla T$

$= (\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow)\nabla T$

generation due to $S_\uparrow \neq S_\downarrow$

Thermal Spin Injection

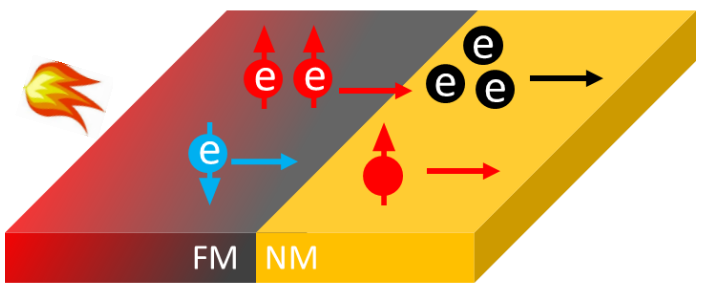


Spin current diminishes with the diffusion.

Spin current can be injected even at an open circuit condition !!

→ **Simplification of device structure**

Thermal spin injection



$S_\uparrow$, $S_\downarrow$: Seebeck Coefficient

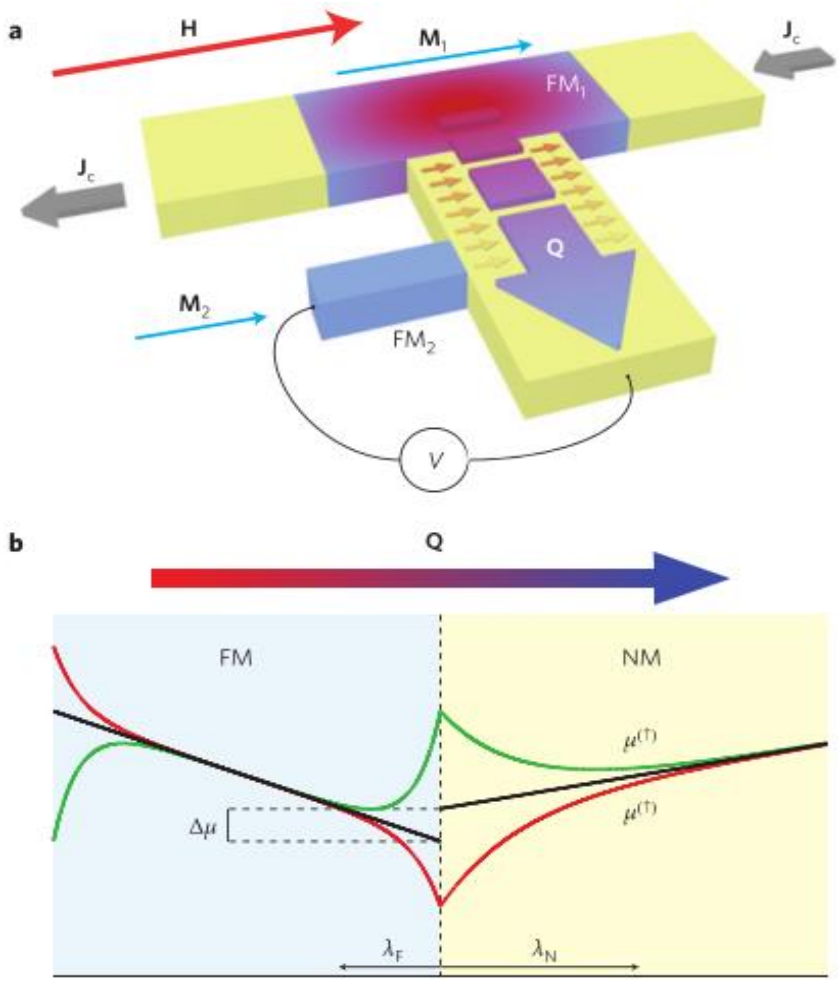
Charge current $I_C = (\sigma_\uparrow S_\uparrow + \sigma_\downarrow S_\downarrow)\nabla T$

Spin current $I_S = (\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow)\nabla T$

Spin current generation due to $S_\uparrow \neq S_\downarrow$

First demonstration of thermal spin injection using NiFe

NiFe/Cu lateral spin valve

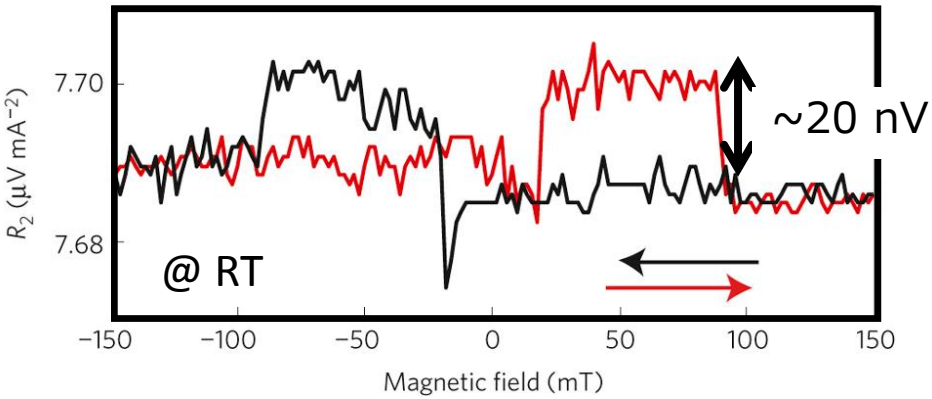


A. Slachter,et al, Nature Physics **6**, 879 (2010).

Seebeck coefficient in FM

$$S_{\uparrow} > S_{\downarrow}$$

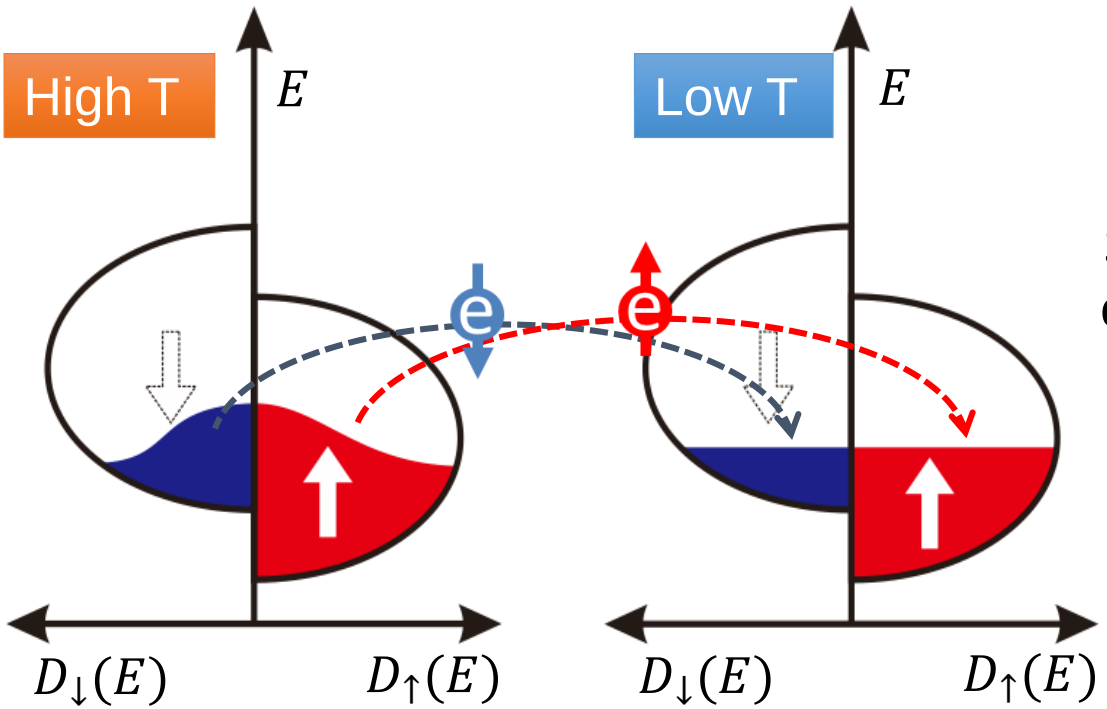
Generated pure spin current can be injected into NM

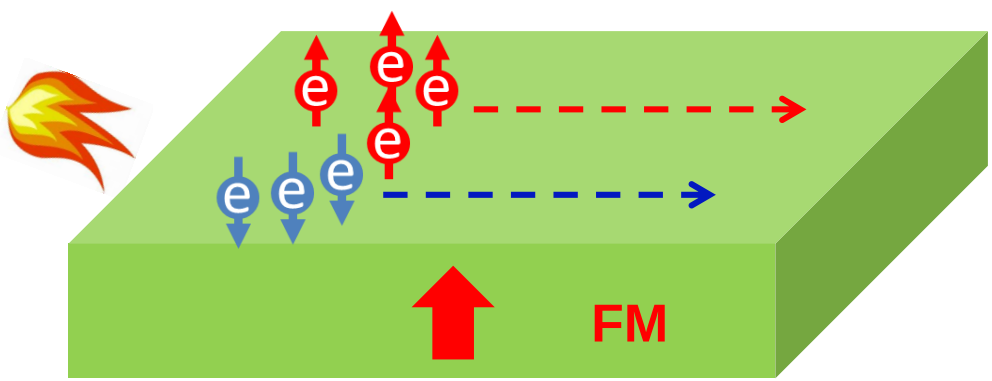


Generated spin current is very small because of the small difference in the Seebeck coefficients for NiFe.

Thermally driven spin current in conventional FM

Conventional FM such as NiFe, Ni, etc..





$$S_{\uparrow,\downarrow} \propto -\left.\frac{dD_{\uparrow,\downarrow}(E)}{dE}\right|_{E_F}$$

Small spin splitting yields a tiny difference between $S_\uparrow$ and $S_\downarrow$.

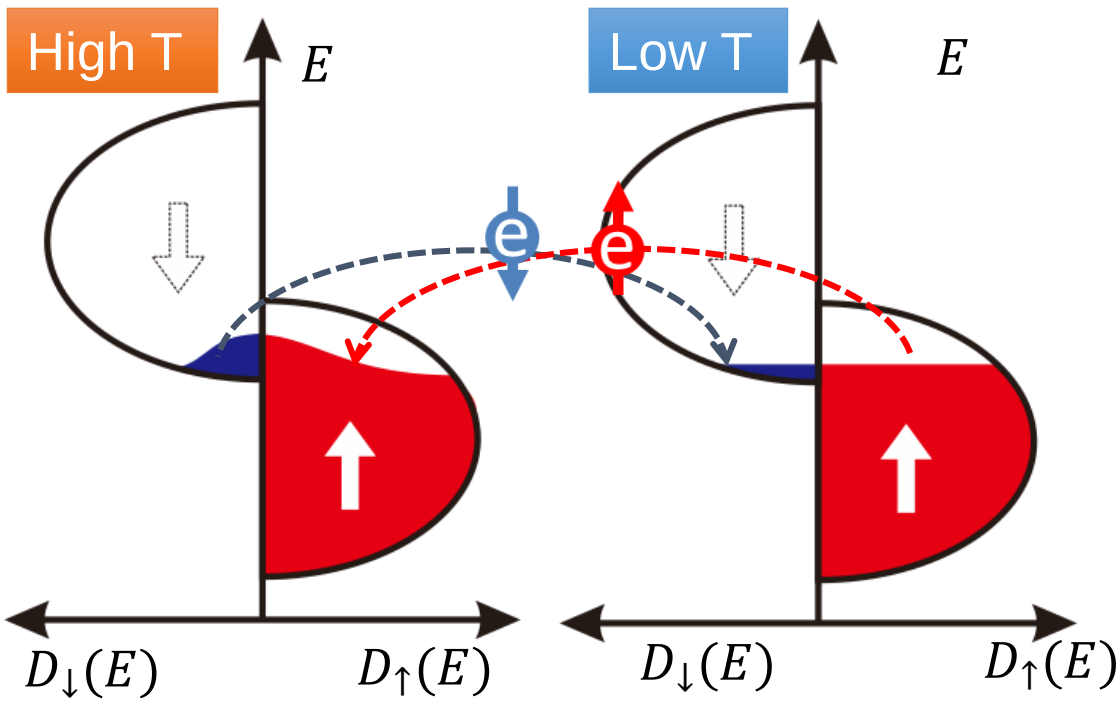
Small spin-dependent Seebeck coefficient

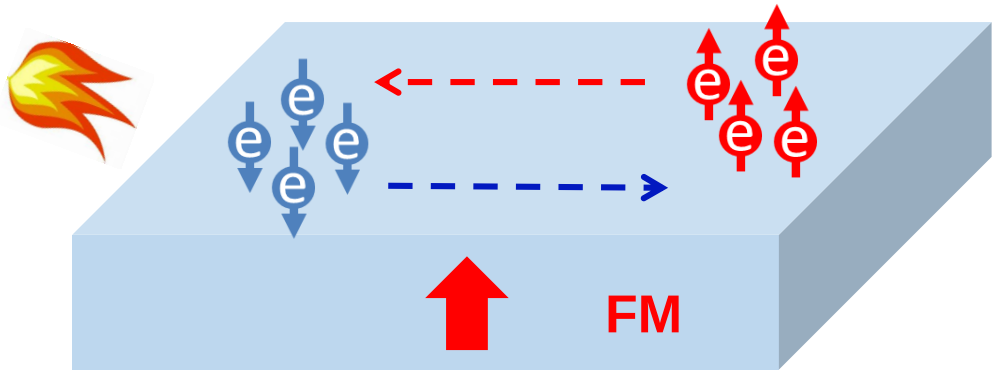
$$S_S = S_\uparrow - S_\downarrow \ll S_{\uparrow,\downarrow}$$

Inefficient situation for generating spin current

Thermally driven spin current in a favorable FM

FM with a large exchange splitting





$$S_{\uparrow,\downarrow} \propto -\left.\frac{dD_{\uparrow,\downarrow}(E)}{dE}\right|_{E_F}$$

Signs for $S_\uparrow$ and $S_\downarrow$ may be different each other

$$\boxed{S_\uparrow < 0,\ S_\downarrow > 0}$$

$$P_S \equiv \frac{S_\uparrow - S_\downarrow}{S_\uparrow + S_\downarrow} > 1$$

Highly efficient situation for generating spin current

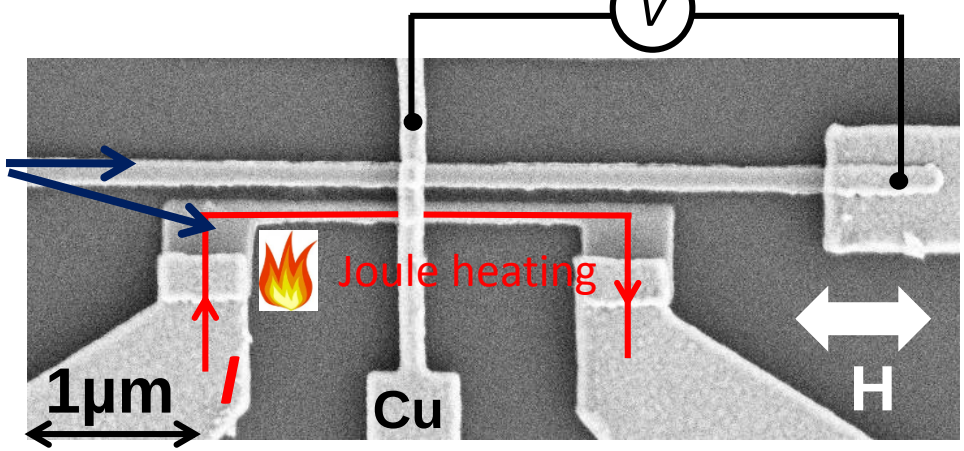
→ CoFe-based alloy

CoFeAl/Cu lateral spin valve for thermal spin injection

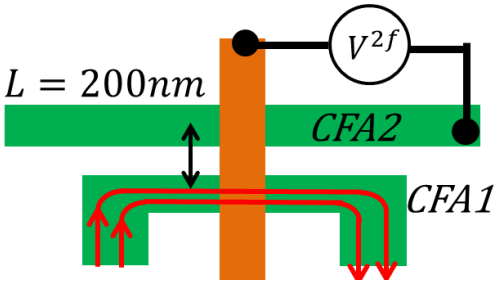
CoFeAl

43 wt% Co
54 wt% Fe
03 wt% Al

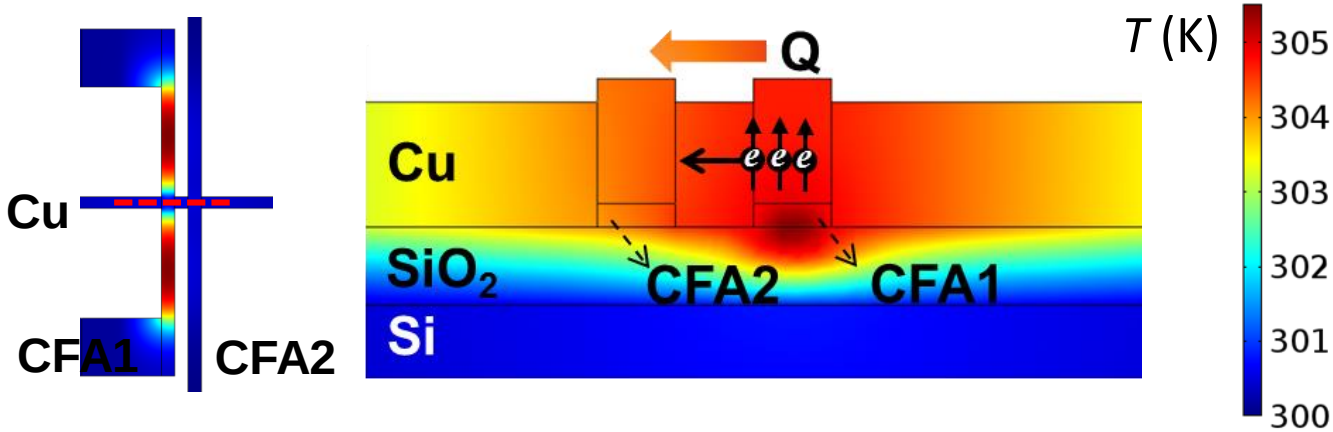
2nd harmonic detection $\nabla T \propto I^2$



$$V = R_1 I_{AC} sin\omega t + R_2 I_{AC}^2 sin^2\omega t + \cdots$$



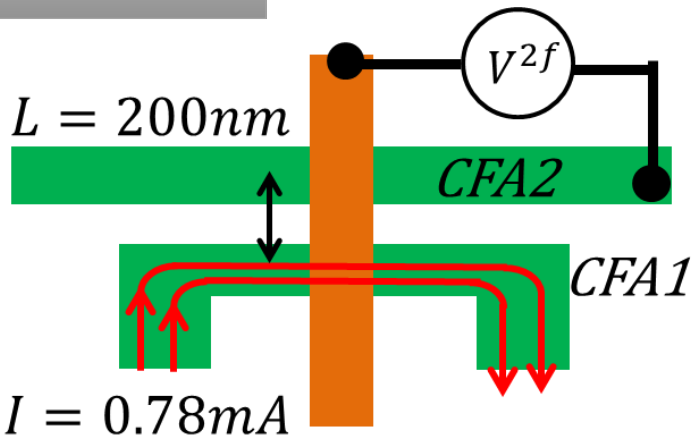
Temperature distribution under thermal spin injection (COMSOL simulation)

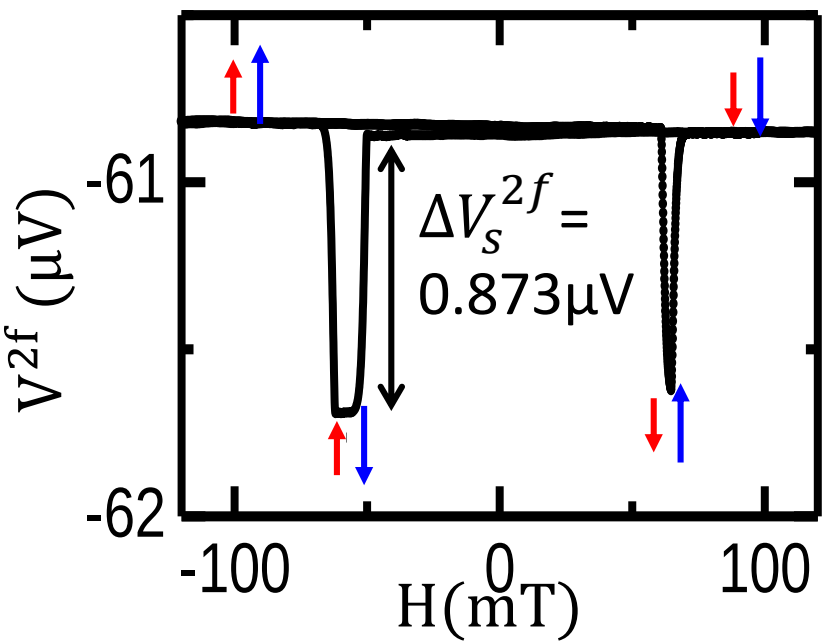


∇T=64 K μm^{-1}
at I=0.78 mA

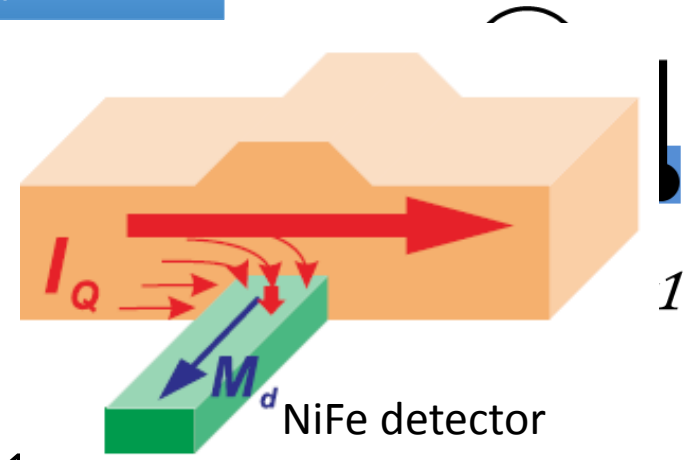
Evaluation for thermal spin injection property

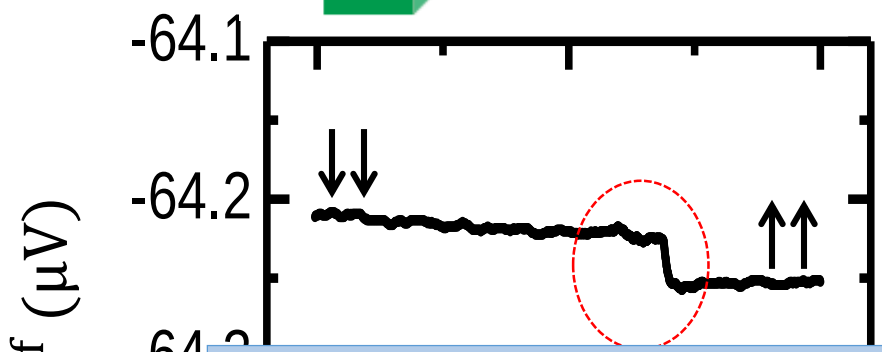
CoFeAl/Cu LSV





NiFe/Cu LSV





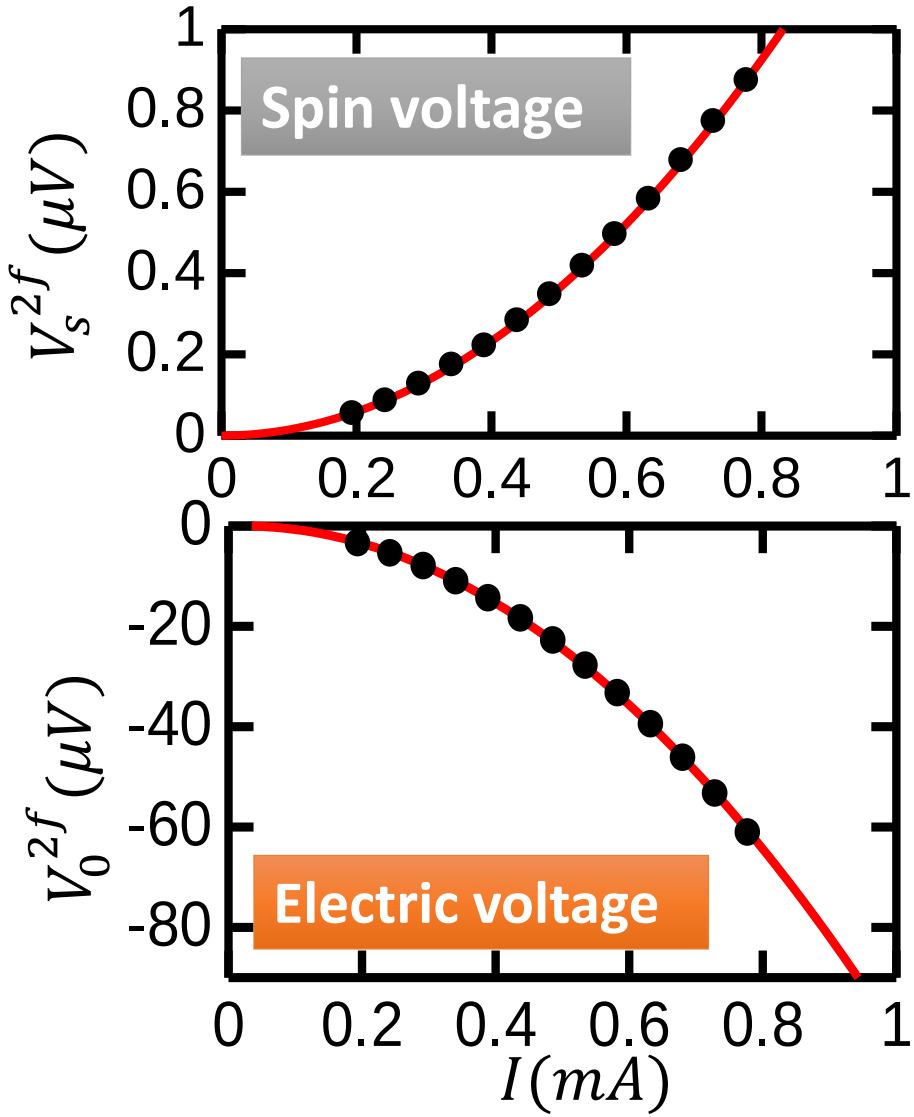
$V_{\uparrow\uparrow}^{2f} \neq V_{\downarrow\downarrow}^{2f}$

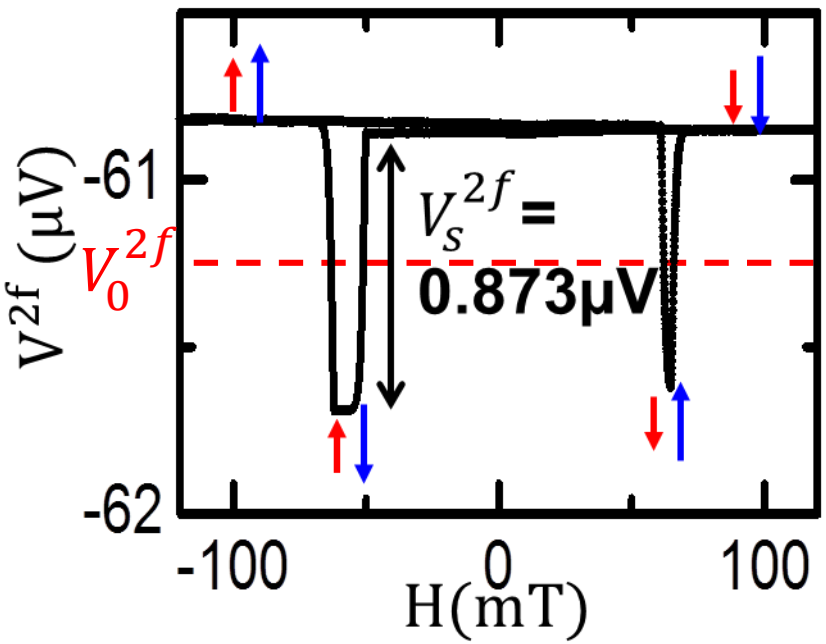
Anomalous Nernst effect

S. Hu and T. Kimura,
Phys. Rev. B **87**, 014424 (2013).

Confirmation of thermally excited spin current

Bias current dependence

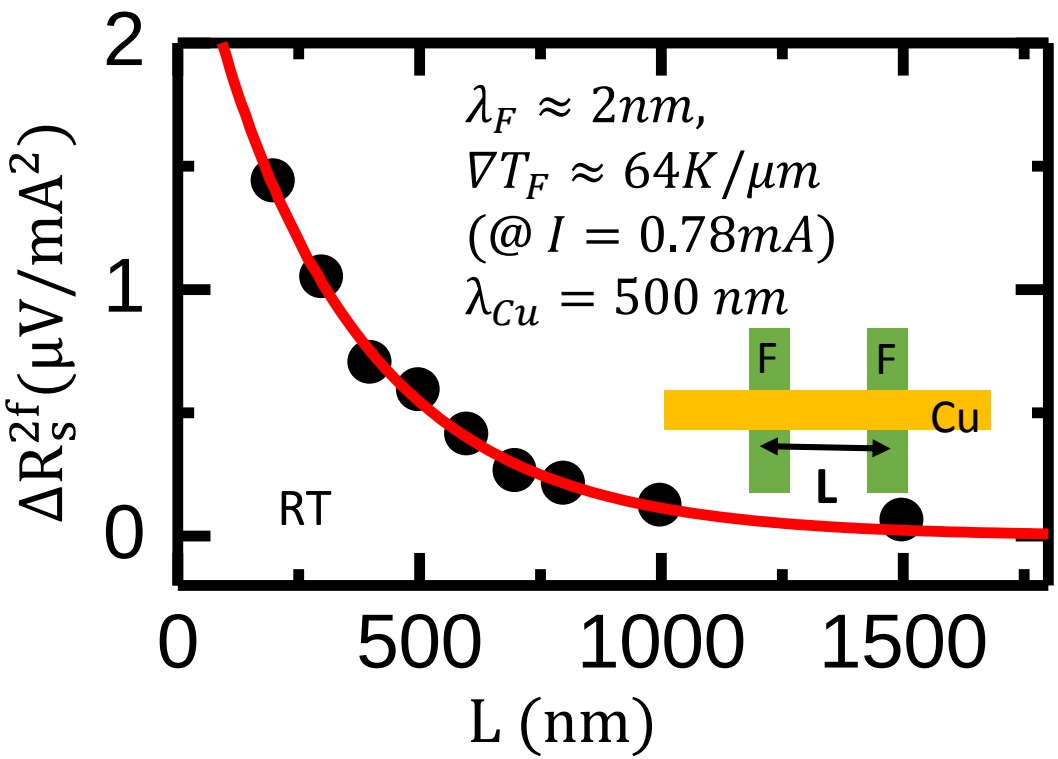




Both of V_s^{2f} and V_0^{2f} are well reproduced by the parabolic curves.

Clear evidence of thermal spin injection

Confirmation of thermally excited spin current



$$S_s \approx -72.1\mu V/K,$$

$$P = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = 0.62$$

$$S_0 = \frac{S_\uparrow \sigma_\uparrow + S_\downarrow \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -22\mu V/K$$

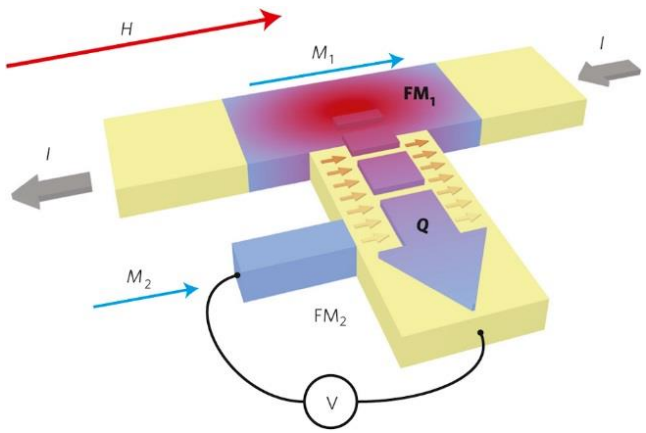
$$S_\uparrow = -35.7\mu V/K,$$
$$S_\downarrow = 36.4\mu V/K$$

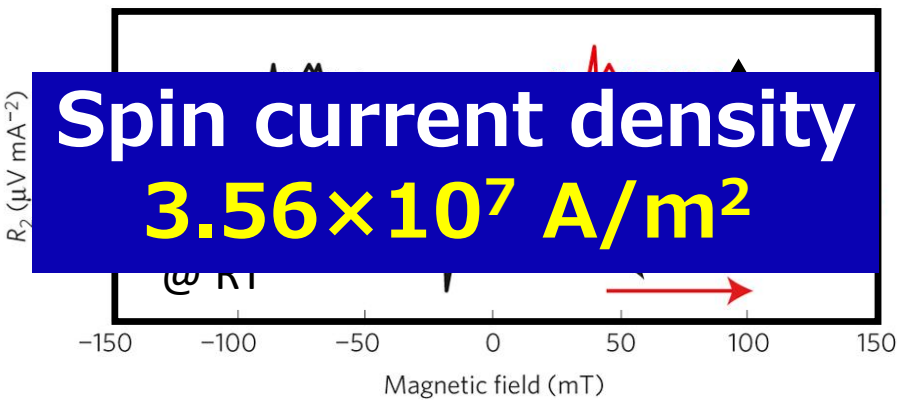
$$\Delta V_s = \frac{P_F R_F R_{Cu} \lambda_F \nabla T_F S_s}{2R_F(R_F + R_{Cu})(\cosh(L/\lambda_{Cu}) + \sinh(L/\lambda_{Cu})) + R_N^2 \sinh(L/\lambda_{Cu})}$$

Comparison of thermal spin injection efficiency

NiFe/Cu

Slachter et al.
Nature Physics (2010)



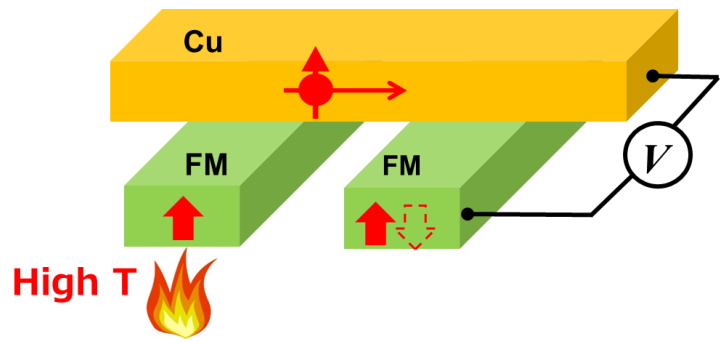


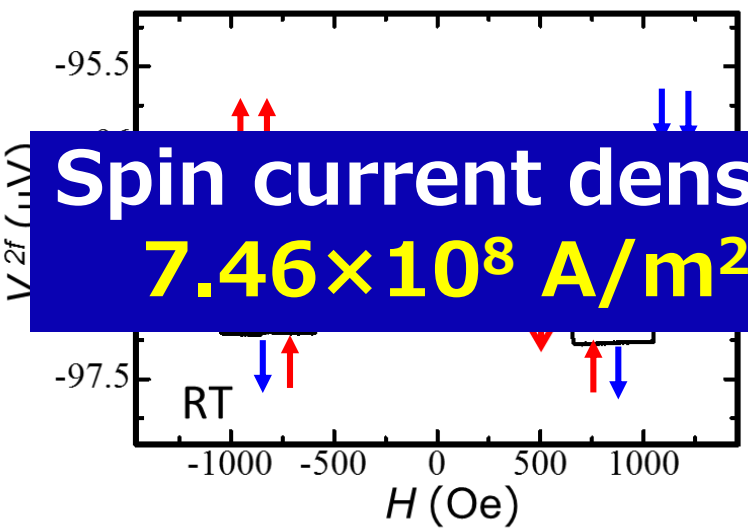
Spin current density
3.56×10^{7} A/m²

$$S_s = -3.8\ \mu V/K \qquad P_S = \frac{S_S}{S_C} = 0.19$$

CoFeAl/Cu

S. Hu et al.
NPG asia mater. (2014)





Spin current density
7.46×10^{8} A/m²

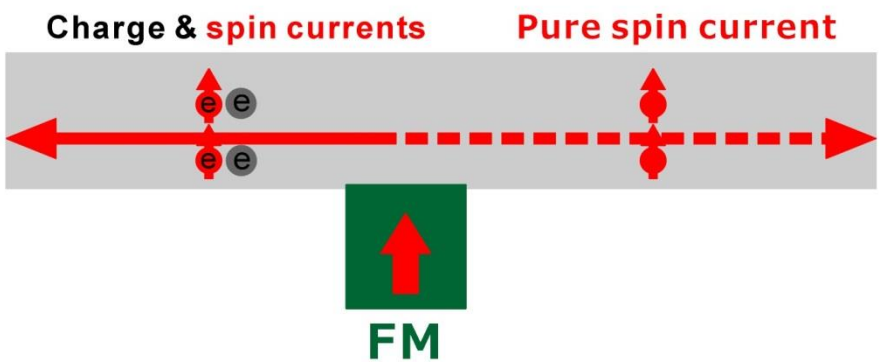
$$S_s = -72.1\ \mu V/K \qquad P_S = \frac{S_S}{S_C} = 3.27$$

Outline

1. Concept of Spin Current
2. Efficient electrical spin injection
3. Efficient thermal spin injection
4. **Spin current absorptions in hybrid systems**

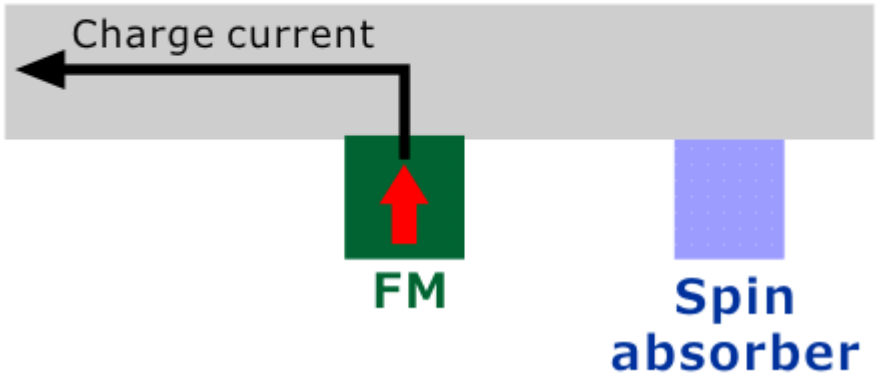
Spin current absorption

•**Without additional contact**



Symmetric flow with respect to the injecting junction

•**With spin current absorber**



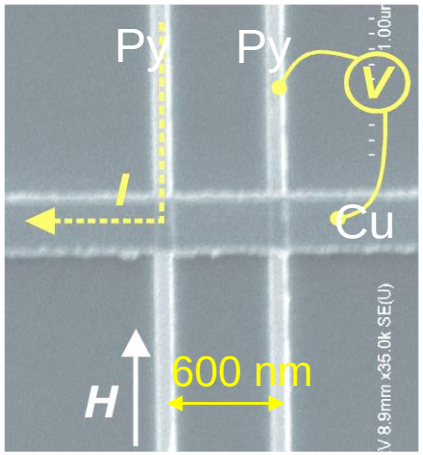
Spin current is preferably absorbed into spin absorber because of the strong spin relaxation.

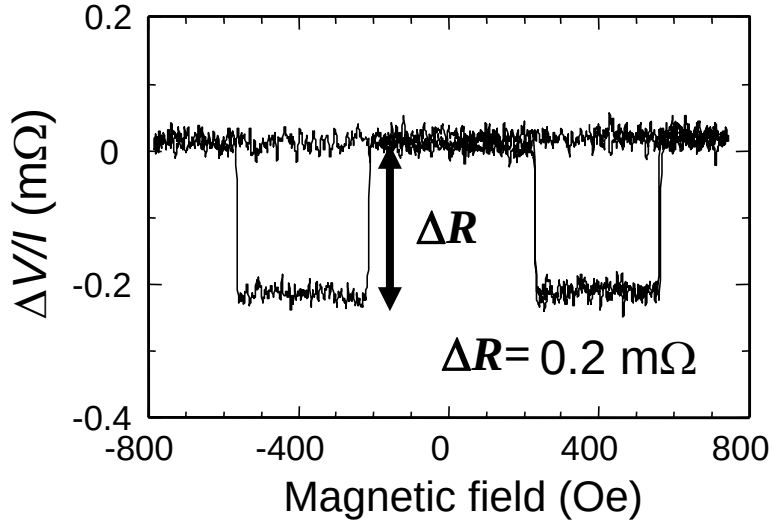
Phys. Rev. B 72, 014461 (2005)

Spin current absorption

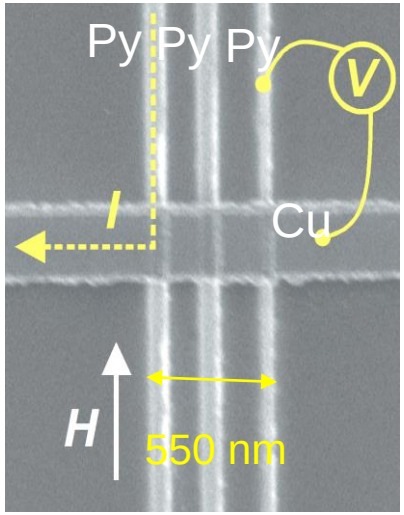
- **Without middle wire**

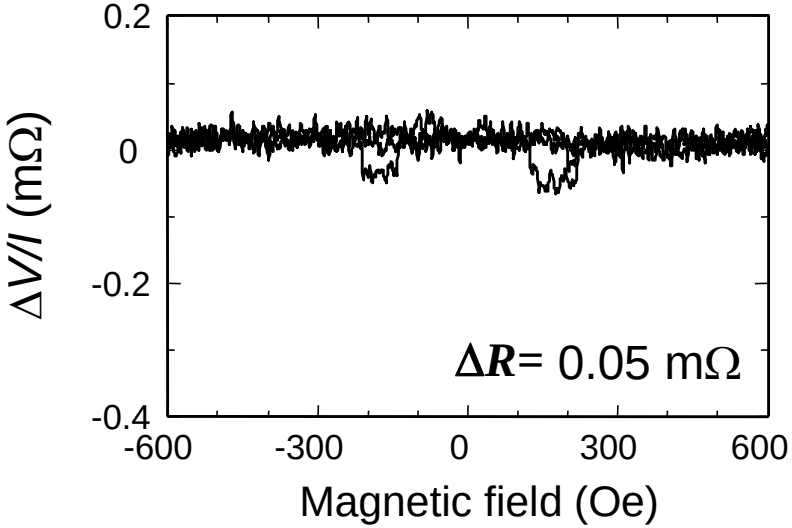
T. Kimura *et al*. Appl. Phys. Lett. 85, 3795 (2004)





- **With middle wire**



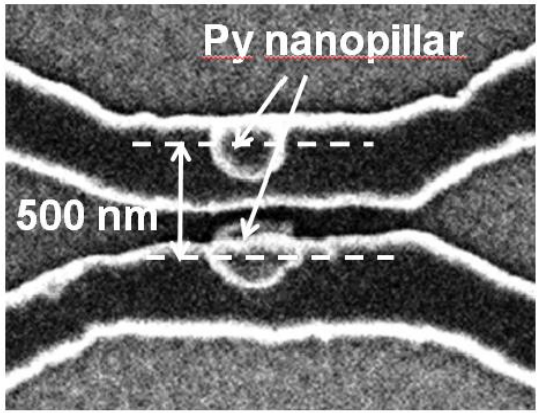


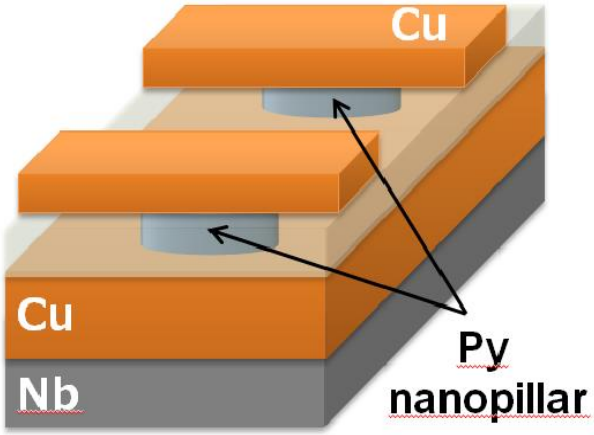
Spin current absorption into Superconductor

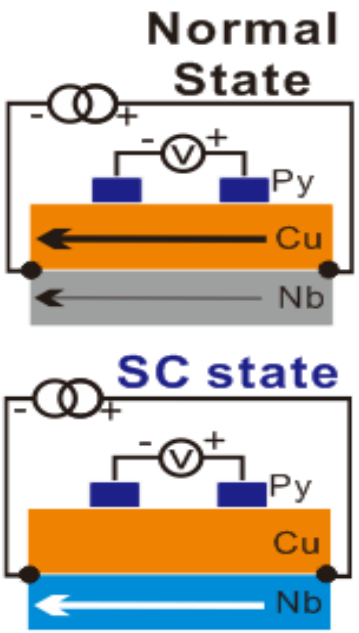
Nanopillar-based Lateral Spin Valve

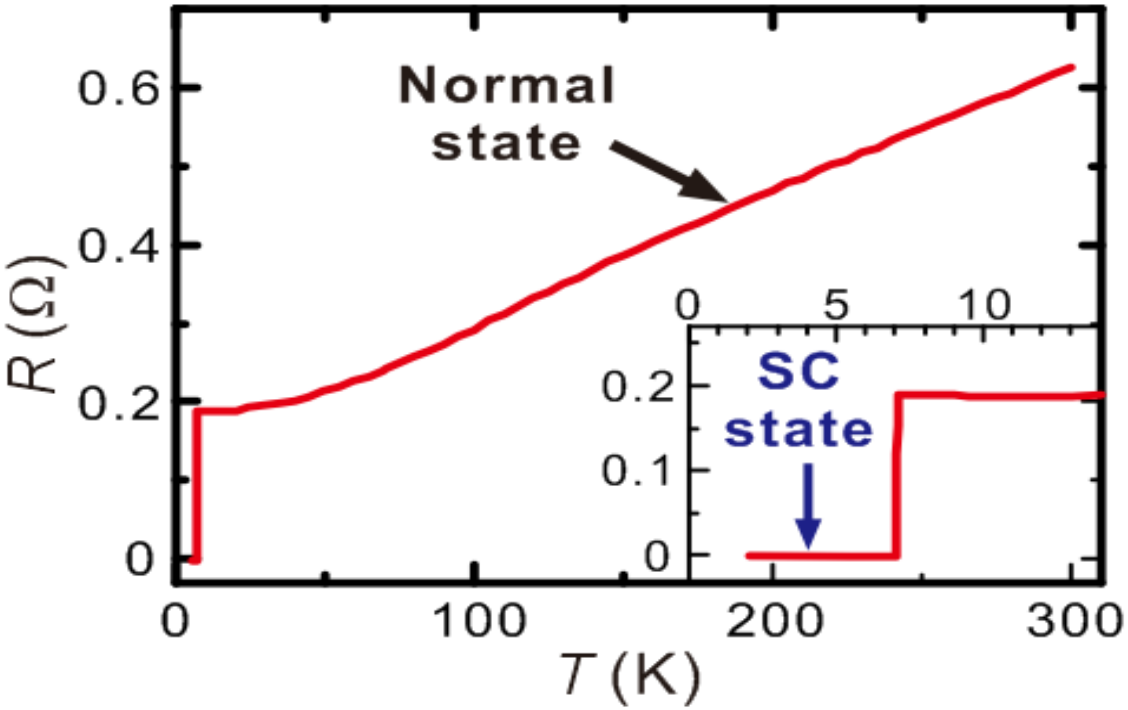
Influence of Joule heating is perfectly removed.

K. Ohnishi et al. Sci. Rep. (2014)

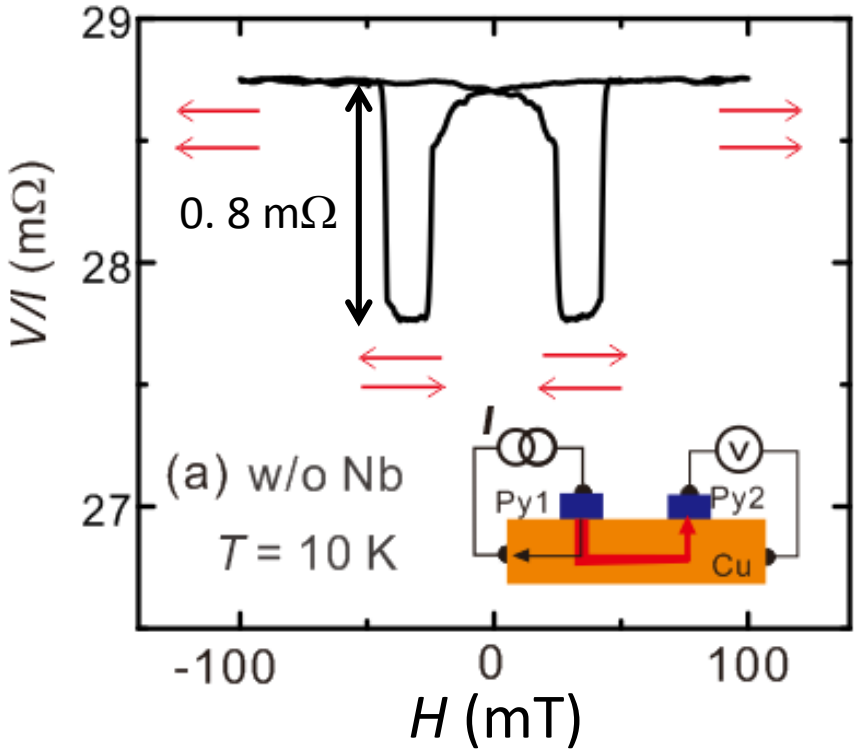


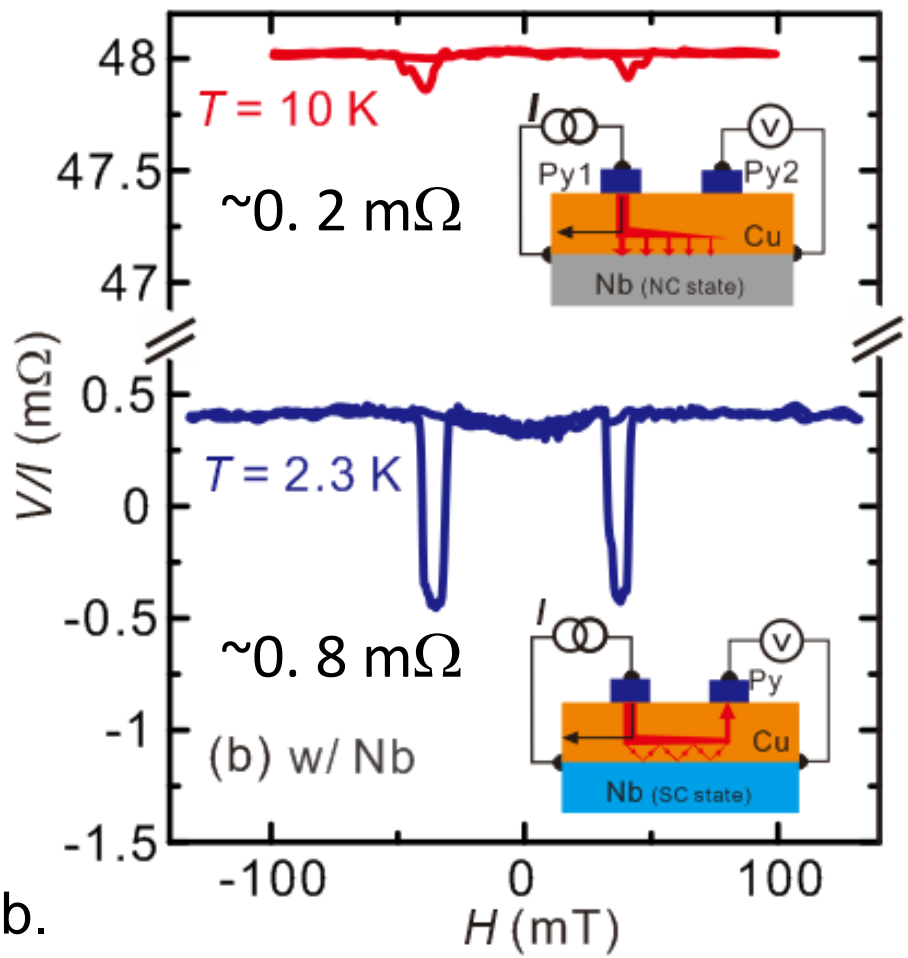






Spin transport in Cu/Nb bilayer





Spin signal at 10 K is strongly reduced by spin absorption into Nb.

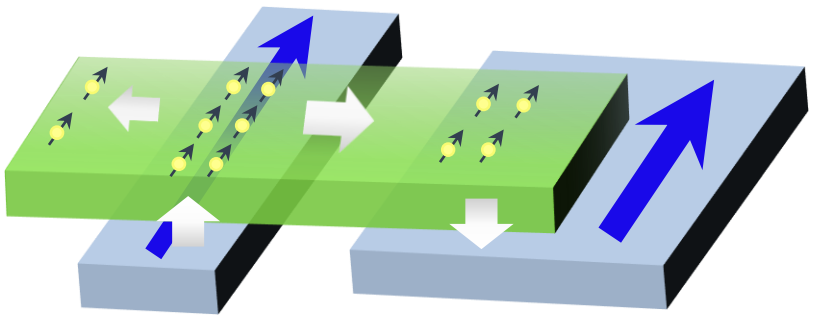
After the transition, it seems no spin absorption.

Longitudinal and transverse spin current absorptions

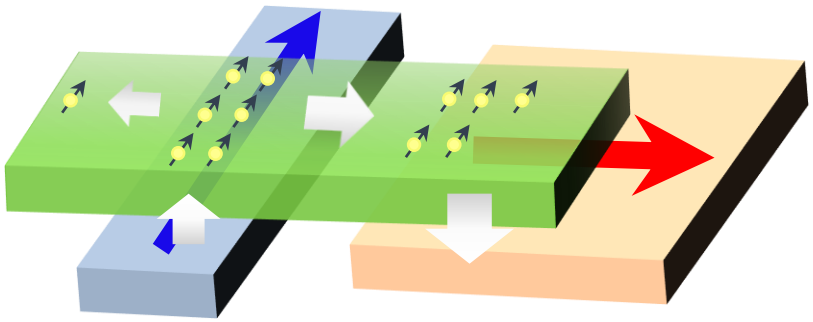
The absorption efficiency depends on the relative angle between the injecting spin and the localized magnetic moment.

S. Nonoguchi et al. PRB (2012)

Longitudinal spin current



Transverse spin current



Relaxation lengths for longitudinal spin

→ Spin diffusion length

$$\lambda_L \equiv \sqrt{2D_0\tau_{sf}} \sim 5\ \mathrm{nm}$$

Relaxation lengths for transverse spin

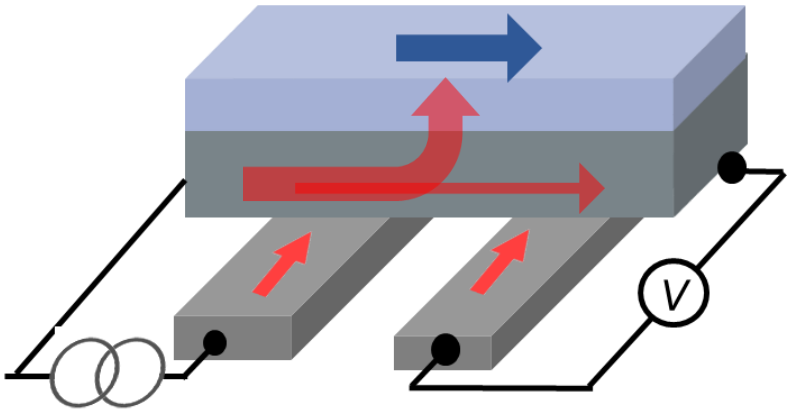
→ Spin penetration depth

$$\lambda_T \equiv \sqrt{2\hbar D_0 / J} \sim 1\ \mathrm{nm}$$

$$R_A = \frac{1}{\left(1-P^2\right)}\frac{2\lambda_L}{\sigma S} \quad > \quad R_A = \frac{2\lambda_T}{\sigma S}$$

Spin absorption into a FM/NM bilayer

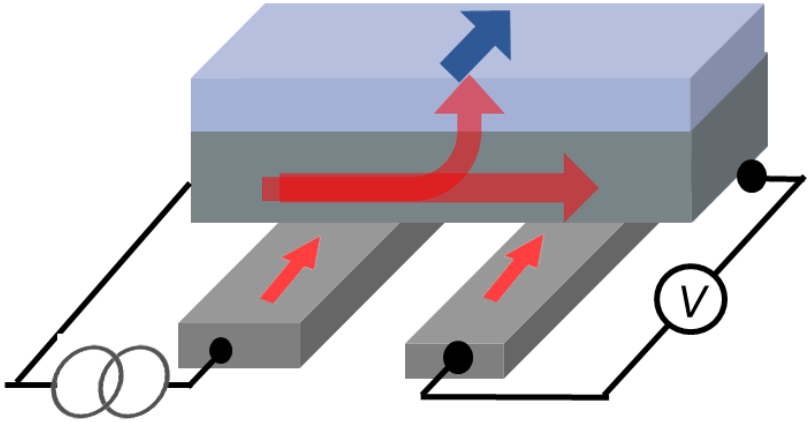
Transverse configuration



Spin current is strongly absorbed into the FM3.

By controlling these two states, the spin signal can be modulated.

Longitudinal configuration



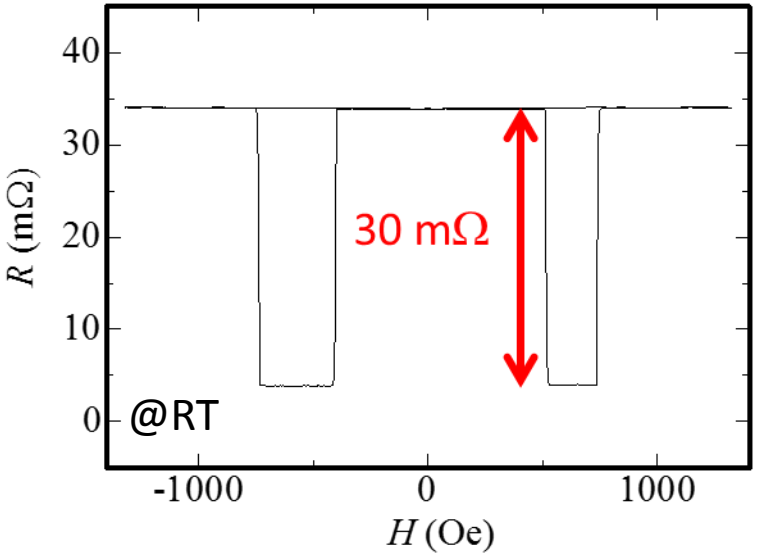
Spin current is moderately absorbed into the FM3.

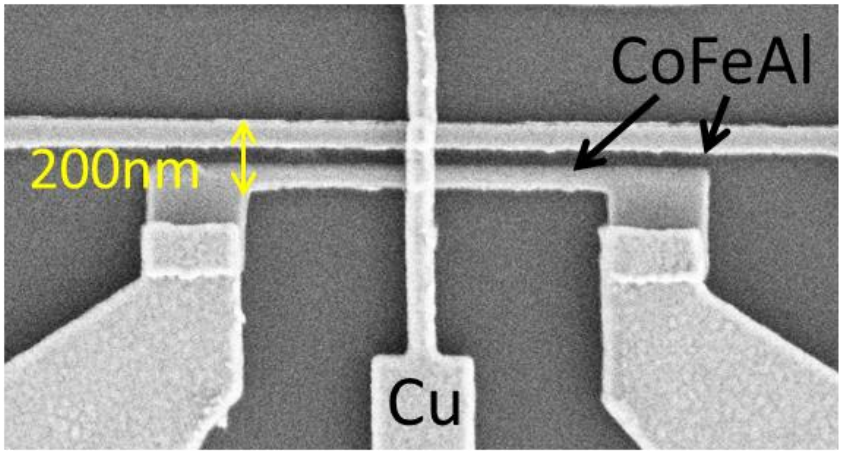
Modulation efficiency depends on

$$\lambda_L / \lambda_T \ \& \ P_{\mathrm{FM3}}$$

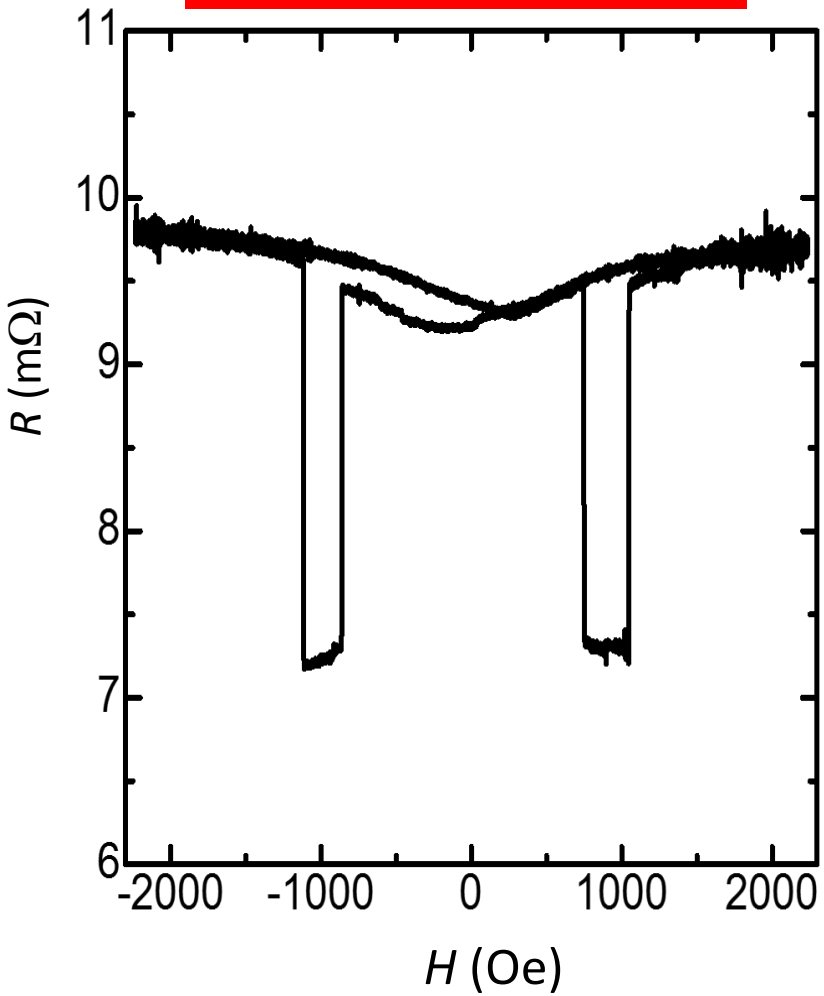
Nonlocal spin signal with Cu/CoFeAl channel

Cu channel



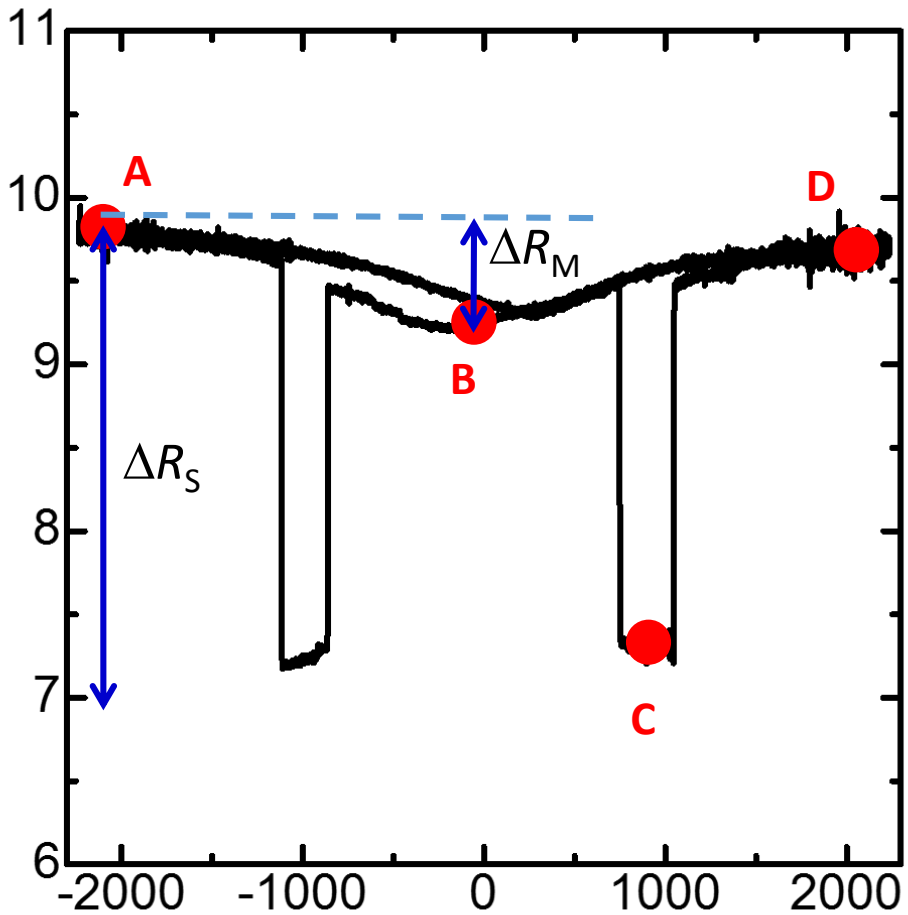


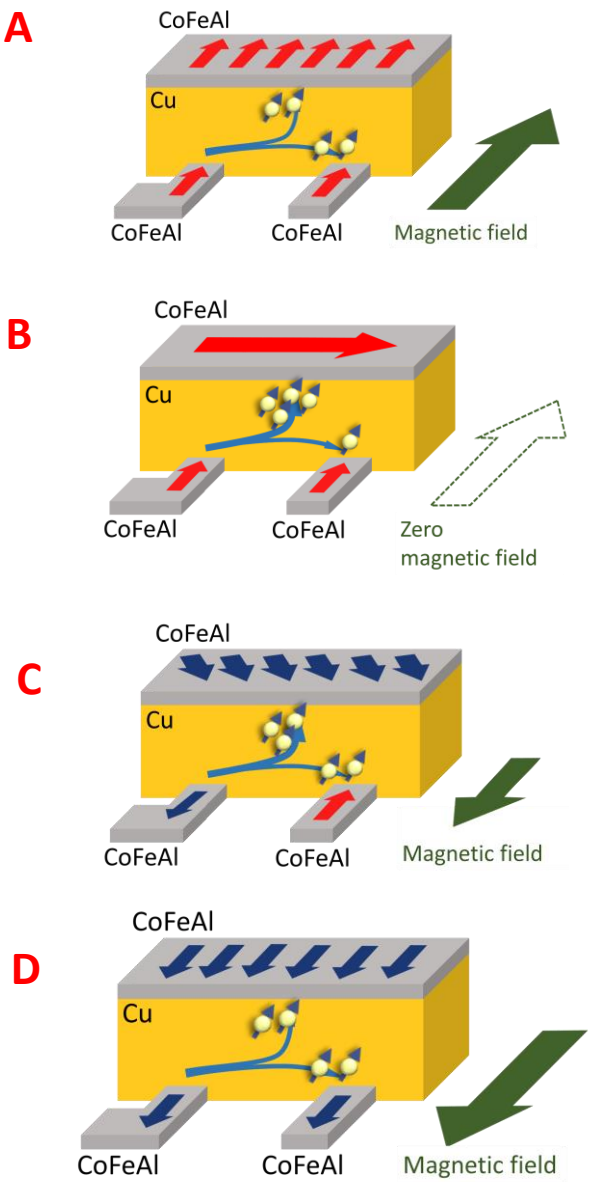
Cu/CoFeAl channel



Spin signal shows the significant reduction but is still detectable.

Spin signal modulation due to anisotropic spin absorption





Modulation efficiency

$$\frac{\Delta R_M}{\left(\frac{\Delta R_S}{2}\right)} \times 100 = 43.2\%$$

Summary

1. Spin polarization improves not only the generation efficiency but also the injection efficiency.
2. CoFe-based alloy is an excellent material for the electrical and thermal spin injection because of its favorable band structure.
3. Superconductor is found to be a insulator for spin current.
4. Anisotropic spin absorption has been demonstrated.