Efficient Spin Injection and Absorption
Using CoFe-Based Alloys

Takashi KIMURA
Department of Physics
Kyushu University
Fukuoka, Japan
Main Contributors & Outline

Main Contributors

<table>
<thead>
<tr>
<th>Lab PD</th>
<th>SSP Lab D2</th>
<th>SSP Lab D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaojie Hu</td>
<td>Tatsuya Nomura</td>
<td>Kazuto Yamanoi</td>
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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: 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 current appears over the spin diffusion length.

Spin diffusion length ($\lambda$)

Non-equilibrium spin accumulation

$\exp(-x/\lambda)$
Spin reabsorption effect in F/N interface

Electrical spin injection

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

Highly polarized

Conventional

Backflow can be suppressed by high spin polarization.

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

NiFe: $P \sim 0.3$, CoFeAl: $P \sim 0.6$
Evaluation of electrical spin injection efficiency

- Py/Cu LSV
- CFA/Cu LSV

S. Hu et al. NPG asia mater. (2014)
Comparison between Py/Cu and CFA/Cu LSV

Distance dependence

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

<table>
<thead>
<tr>
<th>FM</th>
<th>( \rho_F \lambda_F )</th>
<th>( P_F )</th>
<th>( \eta )</th>
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</thead>
<tbody>
<tr>
<td>Py</td>
<td>0.5 f( \Omega )m(^2)</td>
<td>0.35</td>
<td>0.015</td>
</tr>
<tr>
<td>CFA</td>
<td>1.2 f( \Omega )m(^2)</td>
<td>0.67</td>
<td>0.10</td>
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S. Hu et al. NPG asia mater. (2014)

Transparent interface

Over 10 fold

\( \lambda_{\text{Cu}} = 500 \text{ nm} \)
1. Concept of Spin Current

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4. Spin current absorptions in hybrid systems
**Electrical and Thermal Spin Injection**

**Electrical Spin Injection**

- **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**

- **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**

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

\( \sigma_{\uparrow}, \sigma_{\downarrow} \): 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**

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

\( S_{\uparrow}, S_{\downarrow} \): Seebeck Coefficient

\[ P_S = (\sigma_{\uparrow} S_{\uparrow} + \sigma_{\downarrow} S_{\downarrow}) \nabla T \]

\[ P_S = (\sigma_{\uparrow} S_{\uparrow} - \sigma_{\downarrow} S_{\downarrow}) \nabla T \]

Thermal spin injection generation due to \( S_{\uparrow} \neq S_{\downarrow} \)
Thermal Spin Injection

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

→ Simplification of device structure

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

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

\( S_{\uparrow}, S_{\downarrow} \): Seebeck Coefficient

Spin current generation due to \( S_{\uparrow} \neq S_{\downarrow} \)
First demonstration of thermal spin injection using NiFe

NiFe/Cu lateral spin valve

Generated pure spin current can be injected into NM

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

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..

\[ S_{\uparrow,\downarrow} \propto -\frac{dD_{\uparrow,\downarrow}(E)}{dE} \bigg|_{E_F} \]

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**

High T

Low T

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

Temperature distribution under thermal spin injection
(COMSOL simulation)

\[ \nabla T \propto I^2 \]

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

\[ L = 200 \text{nm} \]

\[ \nabla T = 64 \text{ K} \mu \text{m}^{-1} \]
at \[ I = 0.78 \text{ mA} \]

Joule heating
Evaluation for thermal spin injection property

$V^{2f} = 0.873 \mu V$

$V^{2f}_{\uparrow \uparrow} \neq V^{2f}_{\downarrow \downarrow}$

Anomalous Nernst effect

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

\[ \lambda_F \approx 2 \text{nm}, \quad \nabla T_F \approx 64K/\mu m \quad \text{(at } I = 0.78mA) \]

\[ \lambda_{Cu} = 500 \text{ nm} \]

\[ S_S \approx -72.1 \mu V/K, \]

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

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

\[ S_\uparrow = -35.7 \mu V/K, \quad S_\downarrow = 36.4 \mu V/K \]

\[ \Delta V_s = \frac{P_F R_F R_{Cu} \lambda_F \nabla T_F S_s}{2R_F(R_F + R_{Cu})(\cosh(L/\lambda_{Cu}) + \sinh(L/\lambda_{Cu})) + R_N^2 \sinh(L/\lambda_{Cu})} \]
Comparison of thermal spin injection efficiency

NiFe/Cu
Slachter et al.
Nature Physics (2010)

CoFeAl/Cu
S. Hu et al.
NPG asia mater. (2014)

Spin current density
3.56×10^7 A/m²

@ RT

\[
S_s = -3.8 \mu V/K \quad P_S = \frac{S_s}{S_C} = 0.19
\]

Spin current density
7.46×10^8 A/m²

\[
S_s = -72.1 \mu V/K \quad P_S = \frac{S_s}{S_C} = 3.27
\]
Outline

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

• Without additional contact

Charge & spin currents  Pure spin current

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.

Spin current absorption

**Without middle wire**

Without a middle wire, the device shows a significant change in resistance ($\Delta R$) as a function of magnetic field ($H$). The graph illustrates a peak change in resistance of $0.2 \, \text{m} \Omega$ at a specific magnetic field.

**With middle wire**

With a middle wire, the change in resistance ($\Delta R$) is much smaller, approximately $0.05 \, \text{m} \Omega$. The magnetic field ($H$) range is shown to be from -800 to 800 Oe, and the resistance change is measured in milliohms ($\Delta V/I \, (\text{m} \Omega)$).
Spin current absorption into Superconductor

Nanopillar-based Lateral Spin Valve

Influence of Joule heating is perfectly removed.

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.

\[ \lambda_L \equiv \sqrt{2D_0 \tau_s f} \sim 5 \text{ nm} \]

\[ \lambda_T \equiv \sqrt{2\hbar D_0 / J} \sim 1 \text{ nm} \]

\[ R_A = \frac{1}{(1 - P^2)} \frac{2\lambda_L}{\sigma S} \]

\[ R_A = \frac{2\lambda_T}{\sigma S} \]

S. Nonoguchi et al. PRB (2012)
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
\[ \frac{\lambda_L}{\lambda_T} \cdot \rho_{FM3} \]
Nonlocal spin signal with Cu/CoFeAl channel

Spin signal shows the significant reduction but is still detectable.
Spin signal modulation due to anisotropic spin absorption

Modulation efficiency

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