Mesoscopic Spintronics

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Lecture 2
Today’s Topics

• 2.1 Anomalous Hall effect and spin Hall effect
• 2.2 Spin Hall effect measurements
• 2.3 Interface effects
Anomalous Hall effect and spin Hall Effect

**Anomalous Hall Effect (AHE)**

Conventional Hall effect

If the materials is a ferromagnet with magnetization $\mathbf{M}$, what happens?

Empirical relation between Hall resistivity $\rho_{xy}$ and $\mathbf{M}$:

$$\rho_{xy} = R_0 H_z + R_s M_z$$

$R_s$: Anomalous Hall coefficient
Anomalous Hall effect and spin Hall Effect

Early experiments

Two years after the momentous discovery of the “Hall effect” by Hall in 1879 with gold, he found that the Hall effect becomes dramatically large (10 times) for ferromagnetic iron.

Empirical relation

$$\rho_{xy} = R_0 H_z + R_s M_z$$

If you look at the right figure, the shape of the transverse resistance versus magnetic field is quite different from ordinary ones, and it is characterized with the steep increase of resistance for smaller magnetic field range entailing shallow slope for higher field range.

Hall effect of Ni, measured by Smith (1910).
Anomalous Hall effect and spin Hall Effect

What is the mechanism of the AHE?

Key ingredients:
Magnetization + spin-orbit interaction

Mechanisms

Intrinsic mechanism (band origin)

Extrinsic mechanisms

- Skew scattering
- Side jump

Extrinsic effect

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry’s phase curvature.

\[ \frac{d\langle \vec{r} \rangle}{dt} = \frac{iE}{\hbar} + \frac{e}{\hbar} [E \times \vec{b}] \]

The electron velocity is deflected in opposite directions by the opposite electric fields experienced upon approaching and leaving an impurity. The time-integrated velocity deflection is the side jump.

Asymmetric scattering due to the effective spin-orbit coupling of the electron or the impurity.

N. Nagaosa, Rev. Mod. Phys. 82, 1539 (2010).
Anomalous Hall effect and spin Hall Effect

**Anomalous Hall Effect (AHE)**

**Intrinsic mechanism**

- Band origin does not depend on $\tau$

The effect of the Berry curvature

$$\dot{x} = \frac{1}{\hbar} \frac{\partial \varepsilon_n(k)}{\partial k} - \k \times \Omega_n(k)$$

Anomalous velocity (normal to the electric field)

where $\Omega_n$ is the Berry curvature defined as

$$\Omega_n(k) = -\text{Im} \langle \nabla_k u_{nk} | \times | \nabla_k u_{nk} \rangle$$

Defines “how much the band bends”
Anomalous Hall effect and spin Hall Effect

**Anomalous Hall Effect (AHE)**

**Intrinsic mechanism**

\[
\dot{x} = \frac{1}{\hbar} \frac{\partial \varepsilon_n(k)}{\partial k} - \mathbf{k} \times \Omega_n(k)
\]

When the electron moves, it feels the bending of the band.

Electron ➔ Wave packet

**Effect of the Berry curvature**

The center of the wave packet is determined by the interference of the waves close to a certain wave number \( k \). When the Berry curvature is not zero, it affects the interference during the motion of the electron and causes the shift of the center of the wave packet.
Anomalous Hall effect and spin Hall Effect

**Anomalous Hall Effect (AHE)**

**Intrinsic mechanism**

Transverse conductivity can be calculated using the sum of Berry curvatures over the occupied bands:

$$
\sigma_{xy} = -\frac{e^2}{\hbar} \int_{BZ} \frac{d^3 k}{(2\pi)^3} \Omega^z(k)
$$

where

$$
\Omega(k) = \sum_n f_n \Omega_n(k) \quad \Omega_n(k) = -\sum_{n' \neq n} \frac{2\text{Im} \langle \psi_{n'k} | v_x | \psi_{n'k} \rangle \langle \psi_{n'k} | v_y | \psi_{n'k} \rangle}{(\omega_{n'} - \omega_n)^2}
$$

Becomes larger for nearly degenerate points
Anomalous Hall effect and spin Hall Effect

**Anomalous Hall Effect (AHE)**

**Extrinsic mechanism**

**Skew scattering**

Electrons with different spin direction are scattered to different direction by impurities with strong spin-orbit coupling.

**Side-jump effect**

Electric potential induced by impurities with strong spin-orbit coupling pushes electron with different spin orientation to different direction.

→ Small effect ($\sim \frac{\varepsilon_{SO}}{E_F}$, Onoda 2006)

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N. Nagaosa, Rev. Mod. Phys. 82, 1539 (2010).
Anomalous Hall effect and spin Hall Effect

How to distinguish a dominant mechanism?

Skew scattering: \( \rho_{xy} \propto \rho \)

- Side-jump
- In intrinsic:
  \[ \rho_{xy} \propto \rho^2 \]

Clean system (small \( \rho \))

- Skew scattering effect should be dominant

Dirty system (small \( \rho \))

- Intrinsic effect should be dominant
  (SJ effect is small)

N. Nagaosa, Rev. Mod. Phys. 82, 1539 (2010).
Anomalous Hall effect and spin Hall Effect

Theoretical expectations

A. High conductivity regime ($\sigma_{xx} > 10^6 \, (\Omega \, \text{cm})^{-1}$)

- Skew scattering contribution is dominant $\sigma_{xy} \propto \sigma_{xx}$

B. Good metal regime ($10^4 < \sigma_{xx} < 10^6 \, (\Omega \, \text{cm})^{-1}$)

- Intrinsic contribution is dominant $\sigma_{xy} \sim \text{const.}$

C. Bad hopping regime ($\sigma_{xx} < 10^4 \, (\Omega \, \text{cm})^{-1}$)

- $\sigma_{xy} \propto \sigma_{xx}^{1.6}$
  (Close to the normal Hall effect in the hopping regime)
Anomalous Hall effect and spin Hall Effect

*Experimental examples*

Anomalous Hall effect for epitaxially grown Fe on MgO

Different thickness \(\rightarrow\) Control of resistivity

Anomalous Hall effect and spin Hall Effect

Experimental examples

The values of $R_s$ is much larger than $R_0$.

Crossover between different limit as a function of $\sigma_{xx}$ is observed ($n \sim 1.6$).

$$\rho_{xy} = R_0 H_z + R_s M_z$$

Anomalous Hall Effect (AHE) and Spin Hall Effect (SHE)

Anomalous Hall Effect

- Magnetic materials (broken time-reversal symmetry)

Spin Hall Effect

- Non-magnetic materials (time-reversal symmetric)

Spin Hall effect

Inverse spin Hall effect
Anomalous Hall Effect (AHE) and Spin Hall Effect (SHE)

Anomalous Hall effect ➔ In ferromagnets (spin polarized currents)

Different number of charges accumulated at each edge parallel to the direction of charge currents

⇒ Hall voltage is measurable

Spin Hall effect ➔ In nonmagnets (spin unpolarized currents)

Same number of charges accumulated at each edge parallel to the direction of charge currents

⇒ No voltage is measurable

How can we detect the spin Hall effect?
Spin Hall effect measurement techniques

First measurement
By optical Kerr microscope (Kato et al., 2004).

Static technique
Lateral spin valve structure + Spin absorption

Dynamic techniques
Spin pumping

Modulation of magnetization damping by the spin Hall effect

Spin-Transfer-Torque ferromagnetic resonance (STT-FMR)
Spin Hall effect measurement techniques

First measurement
By optical Kerr microscope (Kato et al., 2004).

Static technique
Lateral spin valve structure + Spin absorption

Dynamic techniques
Spin pumping
Modulation of magnetization damping by the spin Hall effect
Spin-Transfer-Torque ferromagnetic resonance (STT-FMR)
Anisotropic magnetoresistance (AMR)

When magnetization is in-plane, resistance also changes depending on the relative angle between the direction of currents and the magnetization.

When currents are in the $x$ direction with the angle of $\phi_M$ to the magnetization,

\[
\rho_x = \frac{1}{2} (\rho_{||} + \rho_{\perp}) + \frac{1}{2} (\rho_{||} - \rho_{\perp}) \cos 2\varphi_M
\]

\[
\rho_y = \frac{1}{2} (\rho_{||} - \rho_{\perp}) \sin 2\varphi_M,
\]

Mechanism

Electrons feel magnetization direction via spin-orbit interaction, and this changes trajectories of electrons and also scattering rates.
Spin Absorption Technique and SHE

*SHE in various metals measured by the spin absorption technique*

Spin valve structure with a middle wire shows smaller signals than that of the structure without middle wire (marked as Ref).

Spin currents are absorbed into materials with strong spin-orbit interaction (=strong spin relaxation).

Spin Absorption Technique and SHE

**Inverse spin Hall effect signals**

Spin currents injected into strong SO materials are converted into charge currents

Accumulated charges at the edges of the middle wire generate electrical voltage

If you look at the figure, the sign of the gradient of the slopes are different for Nb and Pt for example.

\[ J_C \propto J_s \times s \]

Spin Absorption Technique and SHE

Hund’s rule

1) For a given electron configuration, the lowest energy state is the state with the largest $S$ ($S$ is the sum of spin angular momentum for each electron).

2) If there are multiple states with the same largest $S$, the lowest energy state is the state with the largest $L$ ($L$ is the sum of the orbital angular momentum for each electron).

e.g. 3d electrons

\[
\begin{array}{ccccc}
\text{m}_z & 2 & 1 & 0 & -1 & -2 \\
\text{Spin}\downarrow\downarrow & \uparrow\uparrow & \uparrow\downarrow & \uparrow\downarrow & \uparrow\downarrow
\end{array}
\]

Spin-orbit coupling

\[
\mathcal{H}_{SO} = \xi \sum_i l_i \cdot s_i
\]
Spin Absorption Technique and SHE

Spin-orbit coupling
\[ \mathcal{H}_{SO} = \xi \sum_i \vec{l}_i \cdot \vec{s}_i \]

When the total electron number \( n \) is smaller than \( 2l+1 \), \( \vec{s}_i = \frac{\vec{S}}{n} \). Therefore
\[ \mathcal{H}_{SO} = \frac{\xi}{n} \vec{S} \cdot \sum_i \vec{l}_i = \frac{\xi}{n} \vec{L} \cdot \vec{S} = \lambda \vec{L} \cdot \vec{S}. \quad (\lambda = \xi/n) \]

When the total electron number \( n \) is larger than \( 2l+1 \),
\[ \mathcal{H}_{SO} = \xi \sum_{i=1}^{2(2l+1)} \vec{l}_i \cdot \vec{s}_i - \xi \sum_{i=1}^{2(2l+1)-n} \vec{l}_i \cdot \vec{s}_i \rightarrow \mathcal{H}_{SO} = -\xi \sum_{i=1}^{m} \vec{l}_i \cdot \vec{s}_i \]
\[ \mathcal{H}_{SO} = -\xi \sum_{i=1}^{m} \vec{l}_i \cdot \vec{s}_i = -\frac{\xi}{m} \vec{S} \cdot \sum_{i=1}^{m} \vec{l}_i = -\frac{\xi}{m} \vec{L} \cdot \vec{S} = \lambda \vec{L} \cdot \vec{S}. \quad (\lambda = -\xi/m) \]

Spin-orbit coupling constant changes sign depending on the # of electrons in \( d \) orbitals.
Spin Absorption Technique and SHE

Different sign of spin-orbit coupling for $d$-electrons is reflected as a different sign of spin Hall angle.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda_{TM}$ (nm)</th>
<th>$\sigma_{TM}$ ($10^3 \Omega^{-1} \text{cm}^{-1}$)</th>
<th>$\sigma_{SHE}$ ($10^3 \Omega^{-1} \text{cm}^{-1}$)</th>
<th>$\alpha_h$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>5.9 $\pm$ 0.3</td>
<td>11</td>
<td>$-(0.10 \pm 0.02)$</td>
<td>$-(0.87 \pm 0.20)$</td>
</tr>
<tr>
<td>Ta</td>
<td>2.7 $\pm$ 0.4</td>
<td>3</td>
<td>$-(0.011 \pm 0.003)$</td>
<td>$-(0.37 \pm 0.11)$</td>
</tr>
<tr>
<td>Mo</td>
<td>8.6 $\pm$ 1.3</td>
<td>28</td>
<td>$-(0.23 \pm 0.05)$</td>
<td>$-(0.80 \pm 0.18)$</td>
</tr>
<tr>
<td>Pd</td>
<td>13 $\pm$ 2</td>
<td>22</td>
<td>0.27 $\pm$ 0.09</td>
<td>1.2 $\pm$ 0.4</td>
</tr>
<tr>
<td>Pt</td>
<td>11 $\pm$ 2</td>
<td>81</td>
<td>1.7 $\pm$ 0.4</td>
<td>2.1 $\pm$ 0.5</td>
</tr>
</tbody>
</table>

Spin Absorption Technique and SHE

How to determine the dominant mechanism of SHE?

Spin Hall effect in CuIr alloys

Modulation of Ir doping level

Modulation of spin Hall angle and resistivity

Spin Hall effect

Which mechanism is dominant?

\[ \rho_{\text{SHE}} = a \rho_{xx} + b \rho_{xx}^2 \]

- Skew scattering
- Side-jump & Intrinsic

Spin Hall angle \( \alpha = \frac{\rho_{\text{SHE}}}{\rho_{xx}} \)

If \( \alpha \) is constant for \( T \), skew scattering contribution should be dominant.

Spin Hall effect measurement techniques

First measurement
By optical Kerr microscope (Kato et al., 2004).

Static technique
Lateral spin valve structure + Spin absorption

Dynamic techniques
Spin pumping
Modulation of magnetization damping by the spin Hall effect
Spin-Transfer-Torque ferromagnetic resonance (STT-FMR)
Spin Hall effect measurement techniques

First measurement
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Dynamic techniques
- Spin pumping
- Modulation of magnetization damping by the spin Hall effect
- Spin-Transfer-Torque ferromagnetic resonance (STT-FMR)
**Ferromagnetic resonance**

**Basics of ferromagnetic resonance (FMR)**

Magnetization ($\mathbf{M}$) under a magnetic field ($\mathbf{H}$) precesses around ($\mathbf{H}$) as described in the LLG equation:

$$\dot{\mathbf{M}} = -\gamma_g \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \dot{\mathbf{M}}$$

- **Damping term**
- **Energy loss**

**Damping $\rightarrow$ Energy loss**

When rf microwave with frequency $\omega$ is applied to $\mathbf{M}$, the microwave is resonantly absorbed when $\omega$ fulfills the resonant condition expressed as (Kittel formula);

$$\left(\frac{\omega_f}{\gamma_g}\right)^2 = H_{dc}(H_{dc} + 4\pi M_s)$$

- **Saturation magnetization**

The linewidth $\Delta H$ is directly connected to the relaxation processes.
Spin pumping

\[ \dot{\mathbf{M}} = -\gamma g \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \dot{\mathbf{M}} \]

Landau-Lifshitz-Gilbert (LLG) equation

Ferromagnetic metal in contact with (especially with strong spin-orbit) nonmagnetic metal

Enhanced Gilbert damping

This can be considered that spin angular momentum (= spin current) is leaked into the nonmagnetic metal.

The pumped spin currents can be expressed as

\[ j_{s,\text{pump}}(t) = \frac{\hbar}{4\pi} A_r \dot{\mathbf{m}} \times \frac{d\mathbf{m}}{dt} \]

\( A_r \): Interface parameter


Spin injection efficiency depends on materials’ combination.

This can be expressed as “spin-mixing conductance” at the interface, derived from the scattering matrix at the interface.

\[ g_{\text{eff}}^{\uparrow\downarrow} = \frac{4\pi\gamma g M_s t_{\text{Py}}}{g\mu_B\omega_f} (\Delta H_{\text{Py}|N} - \Delta H_{\text{Py}}) \]

Injected spin currents diffuse in the N based on the diffusion equation;

\[ i\omega \tilde{\mu}_N = D \frac{\partial^2 \tilde{\mu}_N}{\partial z^2} - \frac{1}{\tau_{sf}} \tilde{\mu}_N \]

If spin relaxation in N is weak, spin accumulates inside N due to backflow and spin currents are not efficiently injected. On the other hand, if N is a material with strong spin relaxation, N is a “good spin sink”.

Spin pumping

**Systematic study of the spin pumping with coplanar waveguides**

**Measurement principle**

- RF currents flow through the waveguide
- Oscillating Oersted field \( h_{rf} \) is generated around the RF currents

Magnetic moment precesses around externally applied static field \( H_{dc} \), and ferromagnetic resonance occurs at a certain condition with \( h_{rf} \).

Pumped spin into the normal metal is converted into charge currents via the inverse spin Hall effect, resulting in a measurable voltage.

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Spin pumping

But you have to also consider...

Waveguide and the bilayer (Py/N) are electrically disconnected by an insulator layer (MgO). But for RF currents, there is a **capacitive coupling**.

- AMR effect can be contributed to the measured voltage

Observed voltage: Voltage generated by the ISHE + AMR effect

**Measurement with Py/Pt bilayer**

Broadening of FMR spectra is observed for Py/Pt structure compared with that of a simple Py layer (right figure).

Spin pumping

**Measurement with Py/Pt bilayer**

Measured voltage:
Symmetric to the resonant field for Py
- AMR effect

Complicated structure for Py/Pt bilayer
- AMR effect + ISHE effect

**Why are AMR signals asymmetric to the resonant field?**

When the RF current is expressed as \( I(t) = I_{RF} \sin(\omega t) \), the oscillating magnetization is written as

\[
M(t) = M_{RF} \sin(\omega t + \delta)
\]

where \( \delta \) is the phase lag between the RF field and magnetization precession.

Spin pumping

*Measurement with Py/Pt bilayer*

Resistance due to AMR oscillates in the same way as $\mathbf{M}$, thus the measured voltage should be

$$V(t) = I(t)R(t) = I_{RF}\sin(\omega t)(R_0 + \Delta R_{AMR}\sin(\omega t + \delta))$$

Change due to AMR

$$= I_{RF} \Delta R_{AMR} \cos(\delta)/2 + I_{RF} R_0 \sin(\omega t) - I_{RF} \Delta R_{AMR} \cos(2\omega t + \delta)/2$$

DC component

DC component of AMR is sensitive to the phase lag, and the phase lag of magnetization becomes $\pi/2$ at the resonant field.

Asymmetric to the resonant field, and the AMR contribution should be zero at the resonant field.

\[ Y. \text{ Guan et al., J. Magn. Mag. Mater. 312, 374 (2007).} \]
Spin pumping

**Measurement with Py/Pt bilayer**

ISHE voltage is symmetric to the resonant field

Spin currents generated by the ISHE are written as

\[ J_{s,dc}^{0,circ} = \frac{\hbar \omega_f}{4\pi} \text{Re} \ g_{eff}^\dagger \sin^2 \theta \]

\( \theta \): Cone angle

Spin currents only depend on \( \theta \), and \( \theta \) is symmetric to the resonant field \( (H_r) \). (see the right figure)

\[ \rightarrow \text{ISHE voltage is symmetric to } H_r \]


Spin pumping

**Measured voltages**

Voltage due to the AMR (asymmetric to $H_r$) + Voltage due to the ISHE (symmetric to $H_r$)

$$V_{AMR} = I_{rf}^m \frac{R_{wg}}{R_s} \Delta R_{AMR} \frac{\sin(2\theta) \sin(2\alpha)}{2} \cos \varphi_0$$

$$V_{ISH} = -\frac{\gamma eLP \omega_f \lambda_{sd} g_{eff}^\uparrow \downarrow \sin \alpha \sin^2 \theta}{2\pi(\sigma_N t_N + \sigma_{Py} t_{Py})} \tanh \left( \frac{t_N}{2\lambda_{sd}} \right)$$

$R_{wg}$: Resistance of the waveguide
$R_s$: Resistance of the sample
$P$: Correction factor for the cone angle
$\alpha$: angle between $H_{dc}$ and $I_{rf}$

Spin Hall angle $\gamma \sim 1.3 \pm 0.2\%$ for Pt

Spin pumping

*Measurement with different normal metals*

Spin pumping into metals (Pd, Au and Mo)

Different asymmetric signal amplitude and also sign (consistent with previous studies)

<table>
<thead>
<tr>
<th>Normal metal</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt</td>
<td>$0.013 \pm 0.002$</td>
</tr>
<tr>
<td>Pd</td>
<td>$0.0064 \pm 0.001$</td>
</tr>
<tr>
<td>Au</td>
<td>$0.0035 \pm 0.0003$</td>
</tr>
<tr>
<td>Mo</td>
<td>$-0.0005 \pm 0.0001$</td>
</tr>
</tbody>
</table>

Spin Hall effect modulation of magnetization damping

DC current flowing through a Pt layer in a Py/Pt bilayer structure

- Spin currents are generated via the spin Hall effect
- Generated spin currents exert a torque to precessing magnetization

**LLG equation**

\[
\frac{dM}{dt} = -\gamma M \times H_{\text{eff}} + (\alpha_0/M_s)M \times \frac{dM}{dt} - (\gamma J_s^{\text{SHE}}/M_s^2V_F)M \times (M \times \sigma)
\]

Spin transfer torque (STT) term

Spin Hall effect modulation of magnetization damping

Depending on the direction of the DC current, the direction of STT is parallel or antiparallel to the Gilbert damping torque when $\theta$ is 90°.

Modulation of magnetization damping

$$\Delta \alpha_{\text{SHE}} \approx \left( \frac{\hbar \gamma \eta \theta_{\text{SHE}}}{2 \pi f M_s e A_N d_F} \right) J_c$$

Spin-transfer-torque ferromagnetic resonance (STT-FMR)

**Measurement principle**

RF current flowing through a Pt layer in a Py/Pt bilayer structure generates RF spin currents that exert the STT on the magnetization of Py, and also RF Oersted field.

**LLG equation**

\[
\frac{d\hat{m}}{dt} = -\gamma \hat{m} \times \tilde{H}_{\text{eff}} + \alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma \frac{\hat{h}}{2e\mu_0M_{\text{St}}} \times J_{S,\text{rf}}(\hat{m} \times \hat{\sigma} \times \hat{m}) - \gamma \hat{m} \times \tilde{H}_{\text{rf}}.
\]

STT

RF Field torque

Precessing magnetization + RF current leads to AMR, thus DC voltage signal is measurable.

Spin-transfer-torque ferromagnetic resonance (STT-FMR)

Note: AMR induced by field torque is again asymmetric to the resonant field

\[
\frac{d\hat{m}}{dt} = -\gamma \hat{m} \times \hat{H}_{\text{eff}} + \alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma \frac{\hbar}{2e\mu_0 M_s} J_{S,\text{rf}}(\hat{m} \times \hat{\sigma} \times \hat{m}) - \gamma \hat{m} \times \hat{H}_{\text{rf}}. 
\]

On the other hand, AMR due to STT is symmetric to the resonant field

\[ \rightarrow \] Contribution from magnetic field and STT can be distinguished by the symmetry difference

Measured voltage can be written as a sum of symmetric and asymmetric terms to the resonant field.

\[
V_{\text{mix}} = -\frac{1}{4} \frac{dR}{d\theta} \left. \frac{\gamma I_{\text{rf}} \cos\theta}{\Delta 2\pi (df/dH)|_{H_{\text{ext}}=H_0}} \right[ SF_S(H_{\text{ext}}) + AF_A(H_{\text{ext}}) \right]
\]

Spin-transfer-torque ferromagnetic resonance (STT-FMR)

“Symmetric” and “Asymmetric” contributions

\[ V_{\text{mix}} = - \frac{1}{4} \frac{dR}{d\theta} \frac{\gamma I_{\text{rf}} \cos \theta}{\Delta 2\pi (df/dH)|_{H_{\text{ext}} = H_0}} \left[ SF_S(H_{\text{ext}}) + AF_A(H_{\text{ext}}) \right] \]

Symmetric components

\[ F_S(H_{\text{ext}}) = \frac{\Delta^2}{[\Delta^2 + (H_{\text{ext}} - H_0)^2]} \]

\[ S = \hbar J_{S,\text{rf}} / (2e\mu_0 M_s t) \]

Symmetric Lorentzian peak is proportional to \( J_s \)

Asymmetric components

\[ F_A(H_{\text{ext}}) = F_S(H_{\text{ext}})(H_{\text{ext}} - H_0)/\Delta \]

\[ A = H_{\text{rf}}[1 + (4\pi M_{\text{eff}}/H_{\text{ext}})]^{1/2} \]

\[ \frac{J_{S,\text{rf}}}{J_{C,\text{rf}}} = \frac{S}{A} \frac{e\mu_0 M_s t d}{\hbar} \left[ 1 + (4\pi M_{\text{eff}}/H_{\text{ext}}) \right]^{1/2} \]

Spin Hall angle of Pt = 7.6 %
Magnetization switching by spin-orbit torques

**STT-FMR measurement for Ta/CoFeB bilayer**

Large spin Hall effect is theoretically expected for Ta

Spin Hall angle of \(-15 \pm 3\%\) is observed by STT-FMR measurements (Figure B).

Note: the sign of the spin Hall angle is opposite for Ta and Pt (Figure B and C)

If large spin currents are generated by Ta, is it possible to switch the magnetization by torque of the spin currents (spin-orbit torque)?

Magnetization switching by spin-orbit torques

Important point for magnetization switching by SOT

- Gilbert damping should be smaller (small spin-pumping effect)
- Large spin Hall angle of the normal metal
  ➡️ CoFeB/Ta is a good candidate

TMR signal as a function of external magnetic field (Figure B)

Similar parallel-antiparallel magnetization switching is also observed as a function of currents through Ta!

Spin-orbit torque magnetization switching

Spin Hall effect measurements, how qualitatively reliable?

Important quantities to evaluate “spintronic” properties of materials:

- Spin Hall angle ($\alpha_{\text{SH}}$) and spin diffusion length ($\lambda_{\text{sf}}$).
- Vary a lot depending on measurement techniques etc.

<table>
<thead>
<tr>
<th>Material</th>
<th>$T$ (K)</th>
<th>$\lambda_{\text{sd}}$ (nm)</th>
<th>$\sigma_{\text{Hall}}$ ($\mu$S/m)</th>
<th>$\alpha_{\text{SH}}$ (%)</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>4.2</td>
<td>455 ± 15</td>
<td>10.5</td>
<td>0.032 ± 0.006</td>
<td>NL (12-nm-thick films)</td>
<td>Valenzuela and Tinkham (2006, 2007)</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>705 ± 30</td>
<td>17</td>
<td>0.016 ± 0.004</td>
<td>NL (25-nm-thick films)</td>
<td>Valenzuela and Tinkham (2006, 2007)</td>
</tr>
<tr>
<td>Au</td>
<td>295</td>
<td>86 ± 10</td>
<td>37</td>
<td>11.3</td>
<td>NL (10-nm-thick films)</td>
<td>Seki et al. (2008, 2010)</td>
</tr>
<tr>
<td></td>
<td>295</td>
<td>80</td>
<td>37</td>
<td>11.3</td>
<td>NL (20-nm-thick films)</td>
<td>Seki et al. (2008, 2010)</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>65°</td>
<td>48.3</td>
<td>&lt;2.3</td>
<td>NL (SHE-ISHE)</td>
<td>Mihajlovic et al. (2009)</td>
</tr>
<tr>
<td></td>
<td>295</td>
<td>36°</td>
<td>25.7</td>
<td>7.0 ± 0.1</td>
<td>NL (SHE-ISHE)</td>
<td>Mihajlovic et al. (2009)</td>
</tr>
<tr>
<td></td>
<td>295</td>
<td>35 ± 4</td>
<td>28</td>
<td>7.0 ± 0.3</td>
<td>NL (0.95 at 0 Fe)</td>
<td>Sugis, Mitani, and Takahashi (2010)</td>
</tr>
<tr>
<td></td>
<td>295</td>
<td>27 ± 3</td>
<td>14</td>
<td>7.0 ± 0.3</td>
<td>NL (0.95 at 0 Fe)</td>
<td>Sugis, Mitani, and Takahashi (2010)</td>
</tr>
<tr>
<td></td>
<td>295</td>
<td>25 ± 3</td>
<td>14.5</td>
<td>12 ± 4</td>
<td>NL (1.4 at % Pt, 10nm-thick films)</td>
<td>Gu et al. (2010)</td>
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<td>50 ± 8</td>
<td>6.7</td>
<td>8.0 ± 0.2</td>
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<tr>
<td>&lt;10</td>
<td>40 ± 16</td>
<td>25</td>
<td>14.0</td>
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<td>Niiiri et al. (2014)</td>
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<tr>
<td></td>
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<td>35 ± 4°</td>
<td>25.2</td>
<td>0.35 ± 0.03</td>
<td>NL</td>
<td>Moosbrugger, Pearson et al. (2010)</td>
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<td>20</td>
<td>0.25 ± 0.1</td>
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<td>Niiiri et al. (2014)</td>
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<td>5.25</td>
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<td>Niiiri et al. (2014)</td>
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<td>7</td>
<td>0.335 ± 0.006</td>
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<td>1.1 ± 0.3</td>
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<td></td>
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<td>60</td>
<td>20.4</td>
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<td>AuW</td>
<td>295</td>
<td>1.9</td>
<td>1.75</td>
<td>&lt;10</td>
<td>NL and SP (7 at. % W concentration in Au host, 10 K)</td>
<td>Lueckow et al. (2014)</td>
</tr>
<tr>
<td>Ag</td>
<td>295</td>
<td>700</td>
<td>15</td>
<td>0.7 ± 0.1</td>
<td>SP</td>
<td>Wang, Puyac, and Manceno (2014)</td>
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<tr>
<td>Bi</td>
<td>3</td>
<td>0.3 ± 0.1</td>
<td>-3.1</td>
<td>-0.3</td>
<td>Local, signal decreases with $d_H$</td>
<td>Fan and Eom (2008)</td>
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<tr>
<td></td>
<td>295</td>
<td>2.4 ± 0.3</td>
<td>-7.1 (0.1)(l)</td>
<td>-7.1 (0.1)(l)</td>
<td>SP as a function of</td>
<td>Hou et al. (2012)</td>
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<td>Cu</td>
<td>295</td>
<td>50 - 12V</td>
<td>1.9 ± 0.2V</td>
<td>0.32 ± 0.03</td>
<td>SP</td>
<td>Wang, Puyac, and Manceno (2014)</td>
</tr>
<tr>
<td>CuInTe2</td>
<td>10</td>
<td>5 - 30</td>
<td>2.1 ± 0.5</td>
<td>NL (Ir concentrations from 0% to 12%)</td>
<td>Niiiri et al. (2011)</td>
<td></td>
</tr>
<tr>
<td>MnSb</td>
<td>135Å</td>
<td>1.5 (5b)</td>
<td>0.7(1)A, 2.6(1)B</td>
<td>T = L = T, Br, Au, Sn [γ = (1 - 2) x 10^12]</td>
<td>Fert, Friederich, and Hamaji (1981)</td>
<td></td>
</tr>
<tr>
<td>CuBi</td>
<td>10</td>
<td>~100 - 30</td>
<td>~11</td>
<td>Note a factor of 2 in the definition of $\alpha_{\text{SH}}$</td>
<td>Ref. [15] in Fert and Levy (2011)</td>
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<td>$n$-GaAs</td>
<td>4.2</td>
<td>2290</td>
<td>0.9096</td>
<td>0.15</td>
<td>NL, $n = 0^{10^7}$ cm$^{-3}$</td>
<td>Oeztük et al. (2012)</td>
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<td></td>
<td>4.2</td>
<td>8500</td>
<td>0.0137</td>
<td>0.08</td>
<td>LSA, $n = 0^{10^7}$ cm$^{-3}$</td>
<td>Ehret et al. (2012)</td>
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<td></td>
<td>3.0</td>
<td>9006</td>
<td>0.083</td>
<td>0.08</td>
<td>LSA, $n = 3 - 5 \times 10^{12}$ cm$^{-3}$</td>
<td>Garud et al. (2010)</td>
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<tr>
<td></td>
<td>295</td>
<td>0.27</td>
<td>0.00044; 0.0001</td>
<td>8.0 $\times 10^{10}$ cm$^{-3}$</td>
<td>MR, $\sigma_{\text{Hall}}$ T-dependent, sign change at 10 K</td>
<td>Charalambidis and Solomon (1972)</td>
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<tr>
<td>GaSb</td>
<td>0.3</td>
<td>295</td>
<td>0.000 ± 0.002</td>
<td>1.1 ± 0.25; 0.38</td>
<td>LSA, $x = 0.03 \times 0.05 \times 0.06, n = 3 - 5 \times 10^{12}$ cm$^{-3}$</td>
<td>Charalambidis and Solomon (1972)</td>
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<tr>
<td>InSb</td>
<td>1.3</td>
<td>0.028 ± 0.005</td>
<td>MR, $n = 0^{10^12}$ cm$^{-3}$, $\mu = 2.2 \times 10^5$ cm$^2$/Vs</td>
<td>Garud et al. (2010)</td>
<td></td>
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<td>IrO$_2$</td>
<td>300</td>
<td>3.8(1)P</td>
<td>0.55(0) 18A</td>
<td>4P(0) 6.5A</td>
<td>NL polycrystalline (P), amorphous (A)</td>
<td>Fujishara et al. (2013)</td>
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</table>
Spin Hall effect measurements, how qualitatively reliable?

Spin Hall angle: How much currents are converted into spin currents.

Defined as $\rho_{yx}/\rho_{xx}$ or $J_s/J_c$

<table>
<thead>
<tr>
<th>Material</th>
<th>$T$ (K)</th>
<th>$\lambda_d$ (nm)</th>
<th>$\alpha_{SH}$ (10$^9$ S/m)</th>
<th>$\alpha_{SH}$ (%)</th>
<th>Comment</th>
<th>Reference</th>
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<tr>
<td>Mo</td>
<td>10</td>
<td>10</td>
<td>3.01</td>
<td>$-0.20$</td>
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<td></td>
<td>10</td>
<td>8.6 ± 1.3</td>
<td>2.8</td>
<td>$-(0.8 \pm 0.18)$</td>
<td>NL</td>
<td>Morota et al. (2011)</td>
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<tr>
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<td>295</td>
<td>35 ± 3</td>
<td>4.66</td>
<td>$-(0.05 \pm 0.01)$</td>
<td>SP</td>
<td>Mosenz, Pearson et al. (2010)</td>
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<td>Nb</td>
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<td>5.9 ± 0.3</td>
<td>1.1</td>
<td>$(0.87 \pm 0.20)$</td>
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<td>Pd</td>
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<td>13 ± 2</td>
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<td>$1.2 \pm 0.4$</td>
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<td>1.97</td>
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<td>Ando et al. (2010)</td>
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<td>$1.2 \pm 0.3$</td>
<td>SP</td>
<td>Mosenz, Pearson et al. (2010)</td>
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<tr>
<td></td>
<td>295</td>
<td>5.5 ± 0.5</td>
<td>3</td>
<td>$(0.8 \pm 0.20)$</td>
<td>STT + SHE</td>
<td>Vlaminik et al. (2013)</td>
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<td>295</td>
<td>7.0 ± 0.1</td>
<td>3.7</td>
<td>$(0.8 \pm 0.20)$</td>
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<td>Kondou et al. (2012)</td>
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<td>Pt</td>
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<td>10</td>
<td>11 ± 2</td>
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<td>2.1 ± 0.5</td>
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<td>$1.3 \pm 0.2$</td>
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<td>Ando et al. (2008)</td>
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<td>295</td>
<td>10`</td>
<td>2</td>
<td>4.0</td>
<td>SP</td>
<td>Mosenz, Pearson et al. (2010)</td>
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<td>8.3 ± 0.9</td>
<td>4.3 ± 0.2</td>
<td>1.2 ± 0.2</td>
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<td>Ando, Takahashi, Iida, Kajiwara (2011)</td>
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<td>7.7 ± 0.7</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>SP</td>
<td>Azevedo et al. (2011)</td>
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<td>1.5 - 10`</td>
<td>2.45 ± 0.1</td>
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<td>SP</td>
<td>Hahn et al. (2013)</td>
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<td>2.7 ± 0.5</td>
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<td>Hahn et al. (2013)</td>
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<td>8.1 ± 1</td>
<td>1.02</td>
<td>2.012 ± 0.003</td>
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<td>Hahn et al. (2013)</td>
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<td>Zhai et al. (2013)</td>
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<td>2.7 ± 0.4</td>
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<td>Ohsbourn et al. (2014)</td>
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<td>Rojas-Sánchez et al. (2014)</td>
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<td>Wang, Payac, and Manchon (2014)</td>
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<td>STT + SHE</td>
<td>Liu et al. (2011)</td>
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<td>Gargulj et al. (2014)</td>
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<td>3.6</td>
<td>8.5 ± 0.6</td>
<td>STT + SHE, modulation of damping</td>
<td>Gargulj et al. (2014)</td>
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<td>~4</td>
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<td>Althammer et al. (2013)</td>
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<td>p-Si</td>
<td>295</td>
<td>0.1</td>
<td>0.01</td>
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<td>SP, $\tau_s \sim 10$ ps $\alpha \sim 2 \times 10^{-3}$ cm$^{-3}$</td>
<td>Ando and Saitoh (2012)</td>
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<td>Ta</td>
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<td>0.5</td>
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<td>Morota et al. (2011)</td>
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<td>0.34</td>
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<td>Hahn et al. (2013)</td>
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<td>1.8 ± 0.7</td>
<td>0.08-0.75</td>
<td>$(2 \times 10^{-3})$</td>
<td>SP, spin Hall magnetoresistance (variable Ta thickness)</td>
<td>Morota et al. (2014)</td>
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<td>0.53</td>
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<td>Liu et al. (2012)</td>
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<tr>
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<td>1.5 ± 0.5</td>
<td>0.5</td>
<td>$(3 \pm 1)$</td>
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<td>0.38 ± 0.06</td>
<td>$(33 \pm 6)$</td>
<td>0.8 ± 0.1</td>
<td>STT + SHE</td>
<td>Pal et al. (2012)</td>
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</table>
Brief summary

Spin Hall effect (SHE) is an essential phenomenon for spintronics. SHE and the inverse spin Hall effect (ISHE) enable interconversion between change and spin currents.

For detection of the SHE, static technique (lateral spin valve + spin absorption) and dynamical techniques (spin pumping, modulation of magnetization damping by the spin Hall effect and STT-FMR) can be exploited.

Magnetization switching is even possible by spin-orbit torques generated by the SHE.

Important quantity for the SHE is spin Hall angles. However, values of spin Hall angles differ depending on measurement techniques.
Interface Effects

*Spin Hall Magnetoresistance (SMR)*

Spin Hall effect  ➔ Conversion from change to spin
Inverse spin Hall effect  ➔ Conversion from spin to charge

Is it possible to observe these two effects simultaneously?

—— Yes! You can see that as the SMR effect!

*Concept of the SMR effect*

Pt/Y$_3$F$_5$O$_{12}$ (YIG) bilayer structure

YIG ➔ Ferrimagnetic insulator

Charge currents in Pt generates spin currents ➔ Spin currents go to the interface with YIG, and scattered depending on the magnetization direction of YIG (spin transfer to YIG).

Interface Effects

**Concept of the SMR effect**

Spin currents diminish depending on the direction of the magnetization ($\mathbf{M}$).

Then they are reflected back and converted into charge currents.

- Measured voltages generated by the charge currents reflect the direction of the magnetization of YIG.

The largest spin scattering occurs when the direction of spin of spin currents ($\sigma$) is perpendicular to that of $\mathbf{M}$ and smallest when $\sigma$ and $\mathbf{M}$ are colinear.

Because $\sigma \perp \mathbf{J}_e$, conductivity enhances when $\mathbf{M}$ is parallel to $\mathbf{J}_e$.

Interface Effects

**Spin Hall Magnetoresistance (SMR)**

Magnetism might be induced in Pt by YIG...

⇒ No. Even with Cu as a spacer, the SMR effect is observable. (spin currents flow through Cu and reflected at Cu/YIG interface)

With SiO$_2$ as a spacer layer, no SMR is observed. (because SiO$_2$ is an insulator and spin currents cannot transmit)

With Cu on top of YIG, no SMR is observed.

⇒ Spin-orbit interaction is essential to observe the effect.

**Crucial role of spin currents and spin-orbit interaction for the effect support the SMR scenario!**

Interface Effects

**Rashba Effect**

Spin-orbit Hamiltonian

$$H_{SO} = \frac{e\hbar}{2m^2c^2} \mathbf{s} \cdot (\mathbf{p} \times \mathbf{E}) = \frac{\hbar}{4m^2c^2} \mathbf{\sigma} \cdot (\mathbf{p} \times \nabla U)$$

Potential gradient induces spin-orbit interaction

Two dimensional electron gas (e.g. in a quantum well or at an interface) feels an electric potential generated by inversion asymmetry. This electric potential induces a net spin-orbit interaction written as

$$H_{RSO} = \frac{\alpha}{\hbar} \mathbf{\sigma} \cdot (\mathbf{p} \times \hat{z}) = \frac{\alpha}{\hbar} (p_y \sigma_x - p_x \sigma_y)$$

Spin-orbit interaction expressed as this equation is called Rashba interaction.
Interface Effects

**Rashba Effect**

\[
H_{\text{RSO}} = \frac{\alpha}{\hbar} \sigma \cdot (p \times \hat{z}) = \frac{\alpha}{\hbar} (p_y \sigma_x - p_x \sigma_y)
\]

After diagonalizing the Hamiltonian, the spin-split bands appears.

When you look at the vector inner product of the \( H_{\text{RSO}} \), you can find that

**Spin-momentum locking occurs!**

Recently it has been found that the Rashba effect is also important for metallic interfaces.

Giant Rashba effect induced by surface alloying is observed by ARPES measurements at Bi/Ag(111) surface.


Interface Effects

Rashba-Edelstein effect

- Charge-to-spin conversion via the Rashba effect at the interface

Inverse Rashba-Edelstein effect

- Spin-to-charge conversion via the Rashba effect at the interface

Experimental measurements

Concept

Spin currents are pumped into Ag from NiFe (Py), and then transferred through Ag and converted into charge currents via Rashba SOI at the Ag/Bi interface.

Interface Effects

**Rashba-Edelstein Effect**

Large charge currents are observed around the resonance field of the Py for Ag/Bi.

Evidence for the Rashba-Edelstein effect

Quantity to evaluate the strength of Rashba Edelstein effect: $\lambda_{\text{IREE}}$

\[ j_C = \lambda_{\text{IREE}} j_S \]

\[ \lambda_{\text{IREE}} = \alpha_R \tau_S / \hbar \]

$\lambda_{\text{IREE}} \sim 0.2 \text{ nm}$

J. C. Rojas Sanchez et al., Nat. Comm. 4, 2944 (2013). $t_{\text{Ag}}$ (nm)
Brief summary

Intriguing phenomena such as spin angular momentum transfer or Rashba effect occurs at the interface of two different materials.

The former gives the spin Hall magnetoresistance (SMR) at ferromagnetic insulator (YIG)/normal metal interface.

The latter gives the Rashba-Edelstein effect, thereby efficient charge-spin conversion becomes possible.