Charge, Spin, and Heat Transport in the Proximity of Metal/Ferromagnet Interface

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Outline

- Introduction
- 1G and 2G Spintronic devices
- Spin current
- Spin Hall effect
- Spin Seebeck Effect (SSE)
  - Entangled with anomalous Nernst effect (ANE)
  - Intrinsic spin-dependent thermal transport
  - Entangled with magnetic proximity effect (MPE)
  - Intrinsic Spin Seebeck effect
- New MR by MPE (or Spin Hall MR)
- Summary

Power Consumption of Information Technology

G-W-h

Refreshing in "off" state

5% of total electrical power

Monumental problem

In the beginning, there was only electronics.......
**Spintronic GMR and TMR Devices**

**GMR**
- Metal 1
- Metal 2
- Insulator
- Spin-dependent scattering

**TMR**
- Metal 1
- Insulator
- Metal 2
- Spin-selective tunneling

**P**
- Free
- Storage
- Reference

**AP**
- "0"
- "1"

**Field Sensing & Non-Volatile Storage**

- Low R
- High R

**Spin transfer torque**

- Electrical current affects magnetic configurations
- Incident electron
- Reflected
- Transmitted

- \( \text{torque} \sim \sin \theta \)

- Large M: spin polarizer
- Small M: M can be rotated

**Non-Volatile Storage: Magnetic Random Access Memory (MRAM)**

- Magnetic Tunnel Junction (MTJ)
- Magnetic field
- Write
- Read

- "0"
- "1"

- Advantages:
  - Non-volatile memory
  - Short access time
  - Low power consumption

- Key Challenges:
  - High density
  - Eliminate field writing

- Universal memory: speed as SRAM, density as DRAM, rewritability as flash

**1G and 2G Spintronic Devices**

- Field Sensing & Non-Volatile Storage
- "0"
- "1"
- \( I > I_C \)

- (1G) Field Devices
- (2G) Current (STT) Devices

- Requires very large \( I \)
- What are new Spintronic Effects for 3G devices?

**Various Hall effects**

- Ordinary Hall effect (E. H. Hall, 1879)
- Anomalous Hall effect (E. H. Hall, 1880)
- Integer quantum Hall effect (von Klitzing, Nobel 1985)
- Fractional quantum Hall effect
  - (Stormer, Tsui, Laughlin, Nobel 1998)
- Spin Hall effect
- Inverse spin Hall effect
- Magnon Hall effect
- Topological Hall effect
- maybe more...

**Charge, Spin, Thermal Transport in thin films**

- \( \nabla T_x \) : Hall Effect
- \( \nabla T_x \) : Nernst Effect

- Edwin Hall (1879, 1880)
- Walther Nernst (1879, 1880)

- Axon of Henry Rowland @ JHU

- \( E \propto V \times B \)
- \( E_{ANE} \propto V_x T \times m \)
Spin-Orbit Coupling

Lorentz Force

Ordinary Hall effect with magnetic field H Hall voltage but no spin accumulation
Anomalous Hall effect with magnetic field H and spin polarization Hall voltage and spin accumulation
(Pure) spin Hall effect no magnetic field necessary but spin accumulation

Spin-Orbit Coupling

Only Charge
Detect by voltage

F = q (E + VxB)

Charge + Spin
Detect by voltage

AHE can be either sign

Definite Axis but Not Definite Sign

Only Spin

Detect by voltage

SHE can be either sign

Definite Axis but Not Definite Sign

(Definite Axis but Not Definite Sign)

Spin Hall effect

Detection by voltage

Definite Axis but Not Definite Sign

Charge + Spin
Detect by voltage

AHE can be either sign

Definite Axis but Not Definite Sign

Spin Caloritronics

Electronics

Spin

Pure spin current

Spin-polarized charge current

Charge

Thermal conductivity

Spintronics

Spin-Seebeck effect

Pure spin current

Spin-polarized charge current

Spin Caloritronics

Spin Seebeck effect

Heat

Spin

Metals, insulators, or semiconductors

Ferromagnetic metals

Optical observation SHE in semiconductors


Spin Hall effect

Direct vs. Inverse effects

ISHE in Pt detects pure spin current

Direct Spin Hall

Charge Current

Transverse Spin Dependent Scattering

Spin Imbalance

(measured by what?)

How to detect?

Inverse Spin Hall

Spin Current

Transverse Charge Imbalance

(measured by side voltage)

How to detect?

Spin Seebeck Effect

Thermal activity

Thermoelectric

Spin Hall effect

j_s = j_T - j_s = (\sigma_s S_T - \sigma_T S_s) (-VT)


Spin Hall effect

Electron frame “sees” B field with gradient

Electron frame

The mechanism of SHE

F = q (E + VxB)

Definite Sign q

Definite Axis but Not Definite Sign

AHE can be either sign

SHE can be either sign

(Nagaosa et. al.)

Hall effect

Anomalous Hall effect

Spin Hall effect

Spin-Orbit Coupling

Electron frame “sees” B field with gradient

Electron frame

Spin Hall effect

Electron frame “sees” B field with gradient

Electron frame

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Electron frame “sees” B field with gradient

Electron frame
Detection of Spin Current by Inverse Spin Hall Effect

\( E_y = E_{\text{SHE}} = D_{\text{SHE}} I_y \times \mathbf{S} \)

Asymmetric in \( H \)

Sign change

Proportional to \( \Delta T \)


Spin Seebeck effect in broken FM semiconductors

\[ E_s(\theta) = G(\theta) T - T \theta \mathrm{v} \mathrm{s} \exp \frac{1}{T} \mathrm{c} \mathrm{c} \mathrm{h} \mathrm{i} \mathrm{n} \mathrm{i} \mathrm{g} \mathrm{n} \mathrm{e} \mathrm{v} \mathrm{i} \mathrm{t \text{ intrinsic} SSE} \]

Revision 2: magnon-phonon drag through substrate

Where is intrinsic SSE?

Adachi et al., APL 97, 252506 (2010)


Jaworski et al., PRL 106, 186601 (2011)

Pt strip and in-plane temperature gradient \( \nabla \perp T \) indicated

Pt strip detects \( j_s \)

In-plane \( \nabla \perp T \)

Intrinsic caloritronic effect (not substrate dominated)?

Intrinsic spin Seebeck effect?

Intrinsic spin-dependent thermal transport?

Create in-plane gradient $\nabla_z T$

- Higher $T$ to Lower $T$
- Heat flow $H$
- Py

Consistent, Robust, but Strange $\Delta V_{th}(H, \theta)$ Results

- Asymmetric in $H$
- Py/Si $\Delta V \propto \sin \theta$
- But this is physically impossible!
  - e.g., opposite signals at $\theta = 90^\circ$ and $\theta = 270^\circ$.

Reversed $\nabla T$, Same $\Delta V \parallel$

- $\nabla_z T$ must be out-of-plane!

Out-of-plane $\nabla_z T$

- Sign change
- No sign change
- This is anomalous Nernst effect
  - with perpendicular $\nabla_z T$
  - Transverse geometry, $V_y$

Only $\nabla_z T \parallel$

- Uniform Heating from substrate
- Same ANE sign and value everywhere
- In the transverse configuration ($\nabla_z T$): where does $\nabla_z T$ come from?

Thin film on substrate: in-plane and out-of-plane gradient

- Anomalous Nernst effect: sensitive detector of $\Delta T_z$ and $\nabla_z T$
- $E_{ANE} \propto \nabla_z T \times m$
- $\nabla_z T$ due to substrate
What causes out-of-plane gradient $V_zT$?

- Thin film thickness: $10^3$~$10^5$ nm
- Substrate thickness: $5\times10^5$ nm

Thermal conduction through substrate overwhelms!

<table>
<thead>
<tr>
<th>Resitivity (Ωcm)</th>
<th>Si</th>
<th>GaAs</th>
<th>PPy</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1</td>
<td>&gt;1</td>
<td>$5\times10^{-4}$</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

| Thermal conductivity (W/m-K) | 125 | 56 | 30 | 80 |

What causes out-of-plane gradient $V_zT$?

- Electrically Insulating
- Not thermally Insulating

Electric Current vs. Heat Current

- Electrical Current exclusively in-plane
- Heat Current NOT exclusively in-plane

Removal of out-of-plane gradient ($V_zT$)

- Substrate-Free sample ($V_zT$ only)
- Thermal AMR (Longitudinal)
- Planar Nernst Effect (Transverse)

Spin Seebeck effects with in-plane $V_xT$ and out-of-plane $V_zT$

SSE in FM Metal

Substrate-free limit

No strong evidence of SSE

In transverse configuration: SSE and ANE are entangled

$V_{ANE}$ and ($E_{SSE})_{||} \propto j_x \times m$

Both along $y$  

$E_{ANE} \propto V_zT \times m$

$V_{ANE}$ and ($E_{SSE})_{||}$ additive, both are asymmetric in $m$ (or $H$)

Symmetric in $H$ by using a substrate free sample

Necessary Signatures of FM film with in-plane $V_xT$!
Thickness dependence of AMR in Py/YIG & Pt/YIG

Pt/YIG and Py has opposite t dependence

Anomalous Hall Effect in Pt/YIG

Ferromagnetic Insulator: YIG (Y_3Fe_5O_12)  

AMR vs. New MR

New MR increases at small t

Thermal voltages in Pt/YIG and Pt/Si (Hall samples)
**Thickeneses dependence of thermal voltage**

\[ \Delta V_{th}(T) = \frac{\alpha T}{1 + \Delta V_{th}/V_{th}(0)} \]

- **Pt/YIG**
- **Py/YIG** similarly large

**Induced magnetic moments in Pt/YIG**

- 7 Pt layers
- Assuming all Pt have same moment
- Pt(2.5nm)/YIG

**X-ray Magnetic Circular Dichroism (XMCD)**

- **Py(10nm)/YIG**
- **Pt(2.5nm)/YIG**

**Comparison of Pt/YIG and Au/YIG**

- **Spin Seebeck**
  - 50x larger
- **New MR**
  - Yes
  - No
- **Anomalous Hall**
  - Yes
  - No
- **Moment (Theory)**
  - Yes
  - No
- **Moment (XMCD)**
  - Yes
  - Not observed

**Anisotropic MR vs. New MR**

- **AMR** \( I_x(s) \& M_y \)
- **New MR**

\[ \rho(x) > \rho(y) \]
\[ \rho_x \text{ scan} = \rho_y \text{ scan} = \text{constant} \]
Spin Hall Magnetoresistance (SMR)

Spin Hall MR in Pt/YIG: charge/spin current conversion (Nakayama et al.)
SOC metals/NO magnetic moment

The reflection $J_z$ depends on STT $\sigma_{yz}=\sigma_{yz}^p+\sigma_{yz}^f=\sigma_{yz}^p+\sigma_{yz}^f$

SMR:
- SOC metals on YIG
- No magnetic moment
- Spin current
- $\sigma_{yz}$ axis (independent of H)

Pt is not an ideal spin current detector
Au is better spin current detector

New MR observed in cases with induced moments
Pt/YIG, Py/YIG, Pt/Py/YIG and Au/Py

New MR observed by magnetic proximity effect

Magnetic Proximity can be detected in FM metal from XMCD and NEW MR

Summary

- Transverse Spin Seebeck ($\mathbf{P}_T$) (metals, semiconductors, insulators):
  Entanglement with anomalous Nernst ($\mathbf{V}_N$)
  Intrinsic spin-dependent thermal transport on substrate free sample
- Longitudinal Spin Seebeck Effect (ferromagnetic insulators):
  Complicated Magnetic proximity effects in Pt
  Entanglement of SSE and AME
- New MR in FM metals and Insulator
  * new MR in Pt/YIG, Py/YIG, Pt/YIG/ins, and Pt/Py
  * No new MR in Au/YIG and Au/Py

New MR by magnetic proximity effect or Spin Hall MR ?
Pt is not an ideal spin current detector (magnetic proximity effects)
Au is better spin current detector

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Pt/Py vs. Spin Hall MR

New MR vs. Spin Hall MR

Experimental observation
Induced Moment ? (AHE, XMCD)
Spin Hall MR Prediction ?

Pt/YIG New MR Yes Yes
Pt/Py AMR + New MR Yes ?
Pt/YIG/BB New MR Yes ?
Au/Py AMR No ?
Au/YIG No new MR No ?

New MR observed in cases with induced moments
Magnetic proximity effect accounts for all cases