ECE 492
Future Electronic Devices from Condensed Matter Physics Topics

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Lecture 7: Pure spin currents & topological spintronics
Spintronics Timeline

1990
- Giant MR (GMR)
- Magnetic Tunnel Junctions (MTJ)
- Tunneling MR (TMR)

2000
- Spin Transfer Torque (STT)
- STT Magnetic Switching
- STT-MRAM

2010
- Spin Torque Nano-oscillators
- Spin Hall Effect
- Magnonics
- Spin Seebeck Effect

Present
- Spin Injection & Diffusion
- Spin Pumping
- Spin Hall Nano-oscillators
- Topological SOT
- SOT-MRAM
- Pre-spintronics
- Spin Orbit Torques (SOT)
Spintronics without charge?

Remove $I^2R$ Joule heating by removing charge -> near dissipationless spin transport

In conducting systems:

<table>
<thead>
<tr>
<th>Spin-polarized current</th>
<th>Charge current</th>
<th>Spin current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure spin current</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

In insulating systems:

Magnon

Magnon spin currents
Pure spin based electronics

Spin Hall effect (SHE):
Transverse spin current generated for longitudinal charge current in conductors

Spin Hall effect (SHE):
Spin current generation

Inverse spin Hall effect (ISHE):
Spin current detection
Magnons (Spin waves)

Quasiparticle collective magnetic excitation

- **a**  Ground state

- **b**  Excited state
  - High energy

- **c**  Excited state
  - Low energy
  - Side view
  - Top view

Mediated through magnetic exchange interaction
Magnonics

Using magnons to carry spin information (typically magnetic insulators)

This picture uses SHE and ISHE to generate and detect magnons but other methods exist
Spin Caloritronics

Spin Seebeck effect (SSE)

Conventional Seebeck Effect:
Charge current from $\nabla T$

Spin Seebeck Effect:
Spin current from $\nabla T$

Spin Hall Effect & other Hall Effects

**Ordinary Hall effect**
with magnetic field $H$
Hall voltage but no spin accumulation

**Anomalous Hall effect**
with magnetization $M$
(carrier spin polarization)
Hall voltage and spin accumulation

**(Pure) spin Hall effect**
no magnetic field necessary
No Hall voltage but spin accumulation
Spin Hall Effect Prediction and Discovery

Predicted in 1971...

CURRENT-INDUCED SPIN ORIENTATION OF ELECTRONS IN SEMICONDUCTORS

M.I. DYAKONOV and V.I. PEREL
A.F. Ioffe Physico-Technical Institute of the Academy of Sciences of the USSR, Leningrad, USSR

Received 12 June 1971

An electrical current in a semiconductor induces spin orientation in a thin layer near the surface of the sample due to spin-orbit effects in scattering of electrons. A weak magnetic field parallel to the current destroys this orientation.

Signs of inverse spin hall effect discovered in 1986 (Sov. Phys. JETP Lett. 44, 59 (1986))

Repredicted in 1999

Spin Hall Effect

J.E. Hirsch
Department of Physics, University of California, San Diego, La Jolla, California 92093-0319
(Received 24 February 1999)

It is proposed that when a charge current circulates in a paramagnetic metal a transverse spin imbalance will be generated, giving rise to a "spin Hall voltage." Similarly, it is proposed that when a spin current circulates a transverse charge imbalance will be generated, giving rise to a Hall voltage, in the absence of charge current and magnetic field. Based on these principles we propose an experiment to generate and detect a spin current in a paramagnetic metal.
Spin Hall Effect Prediction and Discovery

Experimental observation of direct spin Hall effect in late 2004

Wunderlich (2005)

Optically measured spin Hall effect induced spin accumulation

Spin Hall Effect Experiments

Soon followed all-electric SHE measurements

Inject spin current, detect using ISHE

Source: Valenzuela (2006)
Magnitude of SHE & Spin orbit coupling

Phenomenologically characterize spin Hall effect with spin Hall angle

$$\Theta_{SH} = \frac{\sigma_{xy}^s}{\sigma_{xx}^c} \frac{e}{\hbar}$$

<table>
<thead>
<tr>
<th>Material</th>
<th>$T$ (K)</th>
<th>$\sigma_{xx}^c$ (10^6 eV/τm)</th>
<th>$\sigma_{xy}^s$ (ħ 10^3 eV/τm)</th>
<th>$\Theta_{SH}$ (%)</th>
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</thead>
<tbody>
<tr>
<td>Al</td>
<td>4.2</td>
<td>17</td>
<td>2.7±6</td>
<td>0.02 ±0.01</td>
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<td>Au</td>
<td>4.5</td>
<td>48.3</td>
<td>&lt;1110</td>
<td>&lt;2.3</td>
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<td></td>
<td>293</td>
<td>25.2</td>
<td>88±8</td>
<td>0.35 ±0.03</td>
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<td>293</td>
<td>5.3</td>
<td>84±5</td>
<td>1.6 ±0.1</td>
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<td>293</td>
<td>7.0</td>
<td>23.4±0.4</td>
<td>0.335±0.006</td>
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<td>293</td>
<td>20</td>
<td>50±10</td>
<td>0.25 ±0.05</td>
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<td></td>
<td>295</td>
<td>37</td>
<td>≈4200</td>
<td>≈11</td>
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<td>25.7</td>
<td>&lt;694</td>
<td>&lt;2.7</td>
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<td>Bi</td>
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<td>&gt;0.198</td>
<td>&gt;0.8</td>
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<td>Cu_{99.5}Bi_{0.5}</td>
<td>10</td>
<td>8.8</td>
<td>≈−970</td>
<td>−1.10 ±4.0</td>
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<td>10</td>
<td>2</td>
<td>43</td>
<td>2.1 ±0.6</td>
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<td>Mo</td>
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<td>−23±5</td>
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<td>4.0</td>
<td>26±4</td>
<td>0.64 ±0.1</td>
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<td>293</td>
<td>1.97</td>
<td>≈20</td>
<td>≈1</td>
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<td>293</td>
<td>3.7</td>
<td>30±7</td>
<td>0.8 ±0.2</td>
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<td>2.4</td>
<td>29±5</td>
<td>1.2 ±0.2</td>
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<td>Pt</td>
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<td>170±40</td>
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<td>6.4</td>
<td>≈510</td>
<td>≈8</td>
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<td>31±5</td>
<td>1.3 ±0.2</td>
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<td>≈80</td>
<td>≈4</td>
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<td>5</td>
<td>340±30</td>
<td>6.8 ±0.5</td>
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<td>2.42</td>
<td>97±12</td>
<td>4.0 ±0.5</td>
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<td>51.6±3</td>
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<td>293</td>
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<td>76±14</td>
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<td>1.02</td>
<td>20.51±0.03</td>
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<td>≈47</td>
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<td>293</td>
<td>2.45</td>
<td>74±100</td>
<td>3. ±4.</td>
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<tr>
<td></td>
<td>293</td>
<td>4</td>
<td>110±10</td>
<td>2.7 ±0.3</td>
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<tr>
<td></td>
<td>300</td>
<td>3.05</td>
<td>330±240</td>
<td>11. ±8.</td>
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<td>Ta</td>
<td>10</td>
<td>0.3</td>
<td>−1.1±0.3</td>
<td>−0.37 ±0.11</td>
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<td></td>
<td>293</td>
<td>0.53</td>
<td>≈−63</td>
<td>−12. ±4.</td>
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<tr>
<td></td>
<td>293</td>
<td>0.08</td>
<td>−1.6±1.2</td>
<td>−2. ±1.5</td>
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<tr>
<td>W</td>
<td>293</td>
<td>0.38</td>
<td>−127±23</td>
<td>−33. ±6.</td>
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</tbody>
</table>

Large variation due to different experimental methods

Generally scales with spin-orbit interaction

Larger Z means larger $L \cdot S$
Spin Hall Effect Magnetic Switching

We can switch magnetization in MTJ’s using spin Hall effect

Source: Liu (2012)
Spin Orbitronics

More efficient generation of spin current through spin-orbit torques (SHE, etc.)

\[ \frac{I^s}{I^c} = \frac{A^s}{A^c} \frac{j^s}{j^c} = \frac{l}{t} \Theta^{SH} \]

I/t can be large by design

Source: Hoffmann
Other ways to generate spin current

**Rashba effect**

Spin band splitting due to interface inversion asymmetry and spin-orbit coupling

A normal metal

Spin degeneracy = no spintronic applications

At certain interfaces

Separation of the spins
Rashba Effect

“Inverse spin Hall like” voltage from Rashba interface

Inverse Rashba-Edelstein Effect

Source: Rojas-Sanchez (2013)
Control of Rashba effect with E field

Source: Lesne (2016)
Topological Insulators

Can we do even better with topological insulators?

Topological materials winner of 2016 Nobel Prize
Topology in band structure

“Same” if can be deformed without singularity (pinch, poke, ...)

Source: D. Vanderbilt
Topology in band structure

Topological invariants in electronic band structure

Replace geometric curvature for Berry curvature in materials

Source: D. Vanderbilt
Topology in band structure

Topological invariants exist in electronic band structure

Edge states exist at the boundary where two topologically inequivalent states meet

Considered “topologically protected” due to symmetries of material

Source: D. Vanderbilt, J. Moore
Relation to QHE

Magnetic field induced protected edge states

Can be understood as a boundary between two topologically nonequivalent materials

Topological order: Describes much larger class of materials than just QHE
Quantum Hall Effects

Replace magnetic field with spin-orbit coupling: Two copies of QHE

Quantum spin Hall effect or 2D topological insulator

Topological invariant: Chern Parity
Quantum Hall Effects
2D Ti: Properties and Experiments

HgTe Quantum Wells

Trivial Insulator

Topological Insulator

Source: Physics Today
3D TI: Properties and Experiments

Graphene-like dirac states with spin momentum locking

$\text{Bi}_2\text{Se}_3$
Topological spin currents

Directly generate and detect spin current by passing current through TI

Source: Li (2016)
Topological Magnetization Switching

Claim spin Hall angle of 140-425
Pure spin current summary

- New field of spin-orbitronics promise MTJ magnetization switching that may be more efficient than traditional STT
- Currently exploring various mechanisms to generate pure spin current & various ways to control
- More topological materials with more unique spin textures are being discovered
Next time: Functional complex oxides