Surprises from the spin Hall effect
how the spin Hall effect and relativistic torques are opening new paths for information storage

Jairo Sinova
Johannes Gutenberg Universität Mainz

17th of September 2017
Magnetism: from fundamental to spin based technology
Bad Honnef, Germany
Surprises from the spin Hall effect
how the spin Hall effect and relativistic torques are opening new paths for information storage

I. Introduction

II. Spin-Orbit Torques in Ferromagnets:
   • SHE and Inverse spin galvanic effect phenomenology
   • Spin-Orbit Torques
     • Intrinsic SOT in GaMnAs
     • SOT in NiMnSb

III. Antiferromagnetic Spintronics: Neél SOTs
   • Active manipulation of Néel order by currents: Néel spin-orbit torque

IV. Topological Dirac Fermion + Antiferromagnets + Neel SOTs
Using charge and spin in information technology

The first spintronics revolution comes in information storage

**Transistors**

- Insulator
- Semiconductor
- Substrate

**Magnets**

- All electrons line up together

**HIGH tunability of electronic current**

Magnetism: from fundamentals to spin based technology; Bad Honnef School - Jairo Sinova
Evolution in World’s Storage Capacity

Digital: Hard-disks, DVDs,…

Analog: books, video/film, …

Hilbert et al. Science (2011)

Gutenberg (1400-1468)

Analog to Digital
Discovery of Giant Magneto Resistance

GMR first observed in 1988

From fundamental to practical

Stuart Parkin
2014 Humboldt Professor and 2014 Millennium Prize
What is next in memory storage?

**MRAM**
Magnetic Random Access Memory

**Spin-Transfer MRAM**
(2015)
Heating Problems

First generation did NOT combine charge and spin
Magnetization dynamics and Spin Transfer Torque

\[
\frac{d\hat{M}}{dt} = -\gamma \hat{M} \times \vec{H}_{eff} + \alpha \hat{M} \times \frac{d\hat{M}}{dt} + \frac{\hbar P J}{2e} (\hat{M} \times \hat{M}_0) \times \hat{M}
\]

(proposed by Slonczewski, Berger 1996)
Spin-Transfer-Torque MRAM

STT mechanism:

- excellent scaling
- lower power
- no crosstalk problem
- simpler fabrication

\[ \sim 30 \mu A \]
use **SPIN CURRENTS** instead of electric currents!

- Connects the motion of an electron to a spin dependent force

**Magnetism: from fundamentals to spin based technology; Bad Honnef School - Jairo Sinova**
spin-orbit coupling interaction

(one of the few echoes of relativistic physics in the solid state)

- "Impurity" potential $V(r)$ Produces an electric field $E = -\frac{1}{e} \nabla V(r)$

- Motion of an electron effective magnetic field in moving electron's rest frame $B_{eff} = \frac{\hbar k}{mc} \times E$

$H_{SO} = -\mu_B \cdot B_{eff}$
spin-orbit coupling interaction

(one of the few echoes of relativistic physics in the solid state)

• “Impurity” potential $V(r)$ \(\rightarrow\) \text{Produces an electric field} \[
\vec{E} = -\frac{1}{e} \nabla V(\vec{r})
\]

• Motion of an electron \(\rightarrow\) \text{effective magnetic field in moving electron’s rest frame} \[
\vec{B}_{eff} = -\frac{\hbar \vec{k}}{mc} \times \vec{E}
\]

Consequence #1: Spin or the band-structure Bloch states are linked to the momentum.

\[H_{SO} = -\vec{\mu}_B \cdot \vec{B}_{eff}\]
Spin-orbit coupling interaction

(one of the few echoes of relativistic physics in the solid state)

- "Impurity" potential $V(r)$ produces an electric field $\vec{E} = -\frac{1}{e} \nabla V(\vec{r})$
- Motion of an electron effective magnetic field in moving electron’s rest frame

$H_{SO} = -\vec{\mu}_B \cdot \vec{B}_{eff}$

Consequence #2
Mott scattering

$\vec{B}_{eff} = -\frac{\hbar \vec{k}}{mc} \times \vec{E}$
Spin-orbitronics

- Nano-transport
- Spin-orbit Torques
- New magnetic materials
- Caloritronics
- Spintronic Hall effects
- Topological transport effects
Anomalous Hall Effect: the basics

Spin dependent “force” deflects like-spin particles

Electrical measurement of spin polarization \((n_↑-n_↓)\)

\[
\rho_H = R_0 B \perp + 4\pi R_s M \perp
\]

\[
R_0 \ll R_s
\]

\[
\sigma_{xy}^{AH} \approx B + A\sigma_{xx}
\]

Nagaosa, JS, et al, Rev. Mod. Phys. 2010
Spin Hall effect

Transverse spin-current generation in paramagnets

**Intrinsic**
`Berry Phase’, interband coherence
[Murakami et al, Sinova et al 2003]

**Extrinsic**
`Skew Scattering’, Occupation # Response

Wunderlich, JS, PRL 05

Kato, et al Science Nov 04
Intrinsic spin-Hall effect: the Rashba SOC example

\[ H_R = \frac{\hbar^2 k^2}{2m} - \mu_B \vec{\sigma} \cdot \vec{B}_{\text{eff}}(\vec{k}) \]
\[ = \frac{\hbar^2 k^2}{2m} + \alpha_R (\sigma_x k_y - \sigma_y k_x) \]

\[ \Delta p \sim eEt \]
\[ \vec{B}_{\text{eff}}(\vec{k}) \propto \vec{s}_{eq} \]

Magnetism: from fundamentals to spin based technology; Bad Honnef School - Jairo Sinova
Current induced polarization

Inverse Spin Galvanic Effect or Edelstein Effect

\[ \delta S_y = 0 \]

\[ \delta S_y \neq 0 \]

\[ J || x \]

Anomalous/Spin Hall effects: more than meets the eye

**Anomalous Hall Effect**

- Spin Hall Effect
  - spin-current generator
- Inverse SHE
  - spin-current detector

**Topological Insulators**

- Mesoscopic Spin Hall Effect

**Intrinsic**

- Kane and Mele, 2005

**Extrinsic**

- SHE Transistor
- SHE/SOT MRAM

**Spin Hall Effect**


**Inverse SHE**


Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Spin-Transfer-Torque MRAM

- excellent scaling
- lower power
- no crosstalk problem
- simpler fabrication

STT mechanism:

~ 30 μA

probability distributions

voltage needed for read

voltage needed for write

breakdown voltage of MTJ

voltage
If switching can be done by an in-plane current then a key issue in STT-MRAM is resolved.
Experiments of in-plane current

Miron et al., Nature '11

Buhrman et al., Science '12

spin-orbit torque at PM/FM interface

Intrinsic SHE + STT

SHE as spin-current generator + STT

\[
\frac{d\hat{M}}{dt}_{SHE-\text{STT}} = PM \times (\hat{n} \times \hat{M})
\]

\[
H_{ex} = J_{ex} \vec{M} \cdot \delta \vec{s}
\]

\[
\frac{d\vec{M}}{dt} = \frac{J_{ex}}{\hbar} \hat{M} \times \delta \hat{s}
\]

\[
h_{SOT} \parallel z \times J
\]

Intrinsic SHE in paramagnet acts as the external polarizer
Experiments of in-plane current magnetic switching

spin-orbit torque at PM/FM interface

Miron et al., Nature ’11

SHE as spin-current generator + STT

Buhrman, et al., Science ’12

H_{ex} = J_{ex} \vec{M} \cdot \delta \vec{s}

h_{SOT} \parallel z \times J

(\frac{d\vec{M}}{dt})_{SOT} = \frac{J_{ex}}{h} \vec{M} \times \delta \vec{s}

(\frac{d\vec{M}}{dt})_{SHE-STT} = P\vec{M} \times (\hat{n} \times \vec{M})

Gordon Research Conference - Jairo Sinova
Spin-orbit Torques in Bilayer Systems

Make a ferromagnet behave like a cat:
SOC (broken bulk inversion)+ferromagnetism

Courtesy of P. Gambardella
Intrinsic (Berry phase) spin-orbit torque from Bloch eq.

Large exchange limit and Rashba SOC

\[ \Delta p \sim eEt \]

\[ \Delta B_{\text{eff}} \sim \Delta p \hat{y} \]

\[ B_{\text{eff}}^{\text{eq}} \sim -M \]

\[ \frac{d\hat{M}}{dt} \sim \hat{M} \times \delta s_z \hat{\hat{z}} \]

maximum \( \delta s_z \hat{\hat{z}} \) for \( \vec{M} \parallel \vec{E} \)

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Intrinsic (Berry phase) spin-orbit torque from Bloch eq.

Large exchange limit and Rashba SOC

\[ \Delta \rho \sim eEt \]

\[ \Delta B_{\text{eff}} \sim \Delta p\hat{y} \]

\[ \frac{d\hat{M}}{dt} \sim \hat{M} \times \delta s_z \hat{z} \]

anti-damping

\[ \delta s_z \hat{z} \sim (\vec{E} \times \hat{z}) \times \hat{M} \sim \cos(\theta_{\vec{M} \cdot \vec{E}}) \]

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Intrinsic (Berry phase) spin-orbit torque in GaMnAs

\[
\left( \frac{d\hat{M}}{dt} \right)_{SOT} = \hat{M} \times \delta s_z (\theta_{\hat{M} \cdot \hat{E}}) \hat{z}
\]

<table>
<thead>
<tr>
<th>current direction</th>
<th>Rashba: $\delta s_{z,\hat{M}} \sim$</th>
<th>Dresselhaus: $\delta s_{z,\hat{M}} \sim$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbf{E} \parallel [100]$</td>
<td>$\cos \theta_{\hat{M} \cdot \hat{E}}$</td>
<td>$\sin \theta_{\hat{M} \cdot \hat{E}}$</td>
</tr>
<tr>
<td>$\mathbf{E} \parallel [010]$</td>
<td>$\cos \theta_{\hat{M} \cdot \hat{E}}$</td>
<td>$- \sin \theta_{\hat{M} \cdot \hat{E}}$</td>
</tr>
<tr>
<td>$\mathbf{E} \parallel [110]$</td>
<td>$\cos \theta_{\hat{M} \cdot \hat{E}}$</td>
<td>$\cos \theta_{\hat{M} \cdot \hat{E}}$</td>
</tr>
<tr>
<td>$\mathbf{E} \parallel [1 - 10]$</td>
<td>$\cos \theta_{\hat{M} \cdot \hat{E}}$</td>
<td>$- \cos \theta_{\hat{M} \cdot \hat{E}}$</td>
</tr>
</tbody>
</table>

angle between $\mathbf{M}$ and current direction
Because $h_{so} = -J_{pd} \Delta s$
the V amplitudes contain spin-orbit fields information.
Torque types and line-shapes

\[ T_{\text{in-plane (or } h_z)} \]

\[ V_{\text{sym}} = C_1 \times h_z(\theta_{M-E}) \sin(2\theta_{M-E}) \]

Anti-damping torque

Fang et al., Nature Nanotech. (2011)

Sample:
18 or 25 nm-thick GaMnAs 4 mm-wide
The out-of-plane SO field

the out-of-plane field  ↔  the symmetric line-shape

\[ V_{\text{sym}}(\theta_{M-E}) \sim h_z(\theta_{M-E}) \sin (2\theta_{M-E}) \]

M-dependent \( h_z \)

\( \sin \theta \) symmetry for 100 direction.
Comparison to Theory

![Graph showing comparison to theory.](image_url)
Comparison to Theory

Dash line: Calculations replacing $H_{KL}$ with a parabolic model, i.e. no $(J.k)^2$ term
Discovery of anti-damping spin-orbit torques

Solid line: Calculations with $H_{KL}$ (captures higher harmonics)

$\mu_0 h_z [\mu T]$

$\theta_{M-J}$

SOT in metals: dominated by field like term

NiMnSb

Kubo Scattering Formalism

In Plane

Out of Plane

Magnetism: from fundamentals to spin based technology; Bad Honnef School - Jairo Sinova
Room-temperature SOT in NiMnSb


The driving field is linear in current: $B_{SO} \sim J$

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Surprises from the spin Hall effect
how the spin Hall effect and relativistic torques are opening new paths for information storage

I. Introduction

II. Spin-Orbit Torques in Ferromagnets:
   • SHE and Inverse spin galvanic effect phenomenology
   • Spin-Orbit Torques
     • Intrinsic SOT in GaMnAs
     • SOT in NiMnSb

III. Antiferromagnetic Spintronics: Neél SOTs
   • Active manipulation of Néel order by currents: Néel spin-orbit torque

IV. Topological Dirac Fermion + Antiferromagnets + Neel SOTs
### Why antiferromagnetic spintronics

<table>
<thead>
<tr>
<th>Ferromagnets: Spin-order with M</th>
<th>Antiferromagnets: Spin-order with M=0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magneto-electronics (spintronics): non-volatility, radiation-hardness, speed, energy,...</td>
<td></td>
</tr>
<tr>
<td>Allow for manipulation and detection by magnetic fields</td>
<td>Do not allow for direct manipulation and detection by magnetic fields</td>
</tr>
<tr>
<td>Magnetic fields not used in advanced ferromagnetic spintronics</td>
<td></td>
</tr>
<tr>
<td>Perturbed by &lt;Tesla Produce ~Tesla nearby stray fields</td>
<td>Insensitive to ~10-100 Tesla Produce no stray fields</td>
</tr>
<tr>
<td>Speed limited by FM dynamics timescales</td>
<td>Ultrafast due to AFM dynamics timescales</td>
</tr>
<tr>
<td>Difficult to realize in semiconductors</td>
<td>Many room-T semiconductors</td>
</tr>
</tbody>
</table>

---

X. Marti, et al., *arXiv:1303.4704*
Antiferromagnetic Spintronics

- Ordered spins
- Non-volatile
- Spin not charge based
- Radiation-hard
- No net moment
- Insensitive to magnetic fields, no fringing stray fields
- THz dynamics
  - Ultra-fast switching
- Multiple-stable domain configurations
  - Memory-logic bit cells
- Materials range
  - Insulators, semiconductors, semimetals, metals, superconductors

Last issue of the International Technological Roadmap for Semiconductors in 2016

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Antiferromagnetic AMR experiment: AFM memory

Negligible stray fields from the AFM

Antiferromagnetic AMR experiment: AFM memory

Transport experiment:
AFM-AMR memory read-out

Antiferromagnetic AMR experiment: AFM memory

AFM memory with no stray fields and insensitive to magnetic field (tested up to 9 T)

Comparable AMR to FM NiFeCo → comparable size and read-out-time scaling

Writing by spin-orbit torque in a single-layer ferromagnet

Magnet reversing itself: SOT

Writing by **spin-orbit torque** in a single-layer **ferromagnet**

*Magnet reversing itself: Rashba Spin-orbit Torque*

\[ H_{\text{SOT}} \parallel z \times J \]

\[ J \parallel x \]

Broken space-inversion symmetry (GaMnAs)
Writing by Néel spin-orbit torque in a single-layer antiferromagnet

Antiferromagnet with broken sublattice space-inversion symmetry: \((\text{Mn}_2\text{Au})\)

Zelezny, Gao, Jungwirth, JS
December PRL (2014)
Writing by Néel spin-orbit torque in a single-layer antiferromagnet

Antiferromagnet with broken sublattice space-inversion symmetry: (Mn₂Au)

Zelezny, Gao, Jungwirth, JS December PRL (2014)
How it works - kind of
Experimental Observation of Néel SOT in CuMnAs

Wadley, Jungwirth et al Science (2016)

Rashba field: $B_{\text{eff}} \approx \mathbf{z} \times \mathbf{E}$

$B \sim 3 \text{ mT per } 10^7 \text{ Acm}^{-2}$

\[ B_{\text{eff}} \approx \mathbf{z} \times \mathbf{E} \]

\[ B \sim 3 \text{ mT per } 10^7 \text{ Acm}^{-2} \]
From prediction, to observation, to device in 1 one year!!

Electrical read/write antiferromagnetic memory


Works like this but not done like this
Surprises from the spin Hall effect
how the spin Hall effect and relativistic torques are opening new paths for information storage

I. Introduction

II. Spin-Orbit Torques in Ferromagnets:
   • SHE and Inverse spin galvanic effect phenomenology
   • Spin-Orbit Torques
     • Intrinsic SOT in GaMnAs
     • SOT in NiMnSb

III. Antiferromagnetic Spintronics: Neél SOTs
   • Active manipulation of Néel order by currents: Néel spin-orbit torque

IV. Topological Dirac Fermion + Antiferromagnets + Neel SOTs
Magnetism: from fundamentals to spin based technology; Bad Honnef School - Jairo Sinova
Coexistence of Topological Dirac fermions and Néel SOT?

Magnetic order

Spin–orbit torque

Wan, PRB (2011)

Relativistic fermions

Topology

Γ X U

Γ X U

Néel spin-orbit torques

Smejkal, Zelezný, Sinova, Jungwirth PRL (2017)


Wadley, Science (2016)

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Relativistic physics, topological semimetals and spin-orbitronics effects
Dirac and Weyl fermions

Relativistic quantum field theory = spinor fields + Lorentz invariant building blocks

\[ \mathcal{L}_D = i \psi_D^{\dagger} \sigma^\mu \partial_\mu \psi_L + i \psi_R^{\dagger} \sigma^\mu \partial_\mu \psi_R - m (\psi_L^{\dagger} \psi_R + \psi_R^{\dagger} \psi_L) \]

\[ (\partial_0 - \sigma^i \partial_i) \psi_L = 0 \quad (i \slashed{\partial} - m) \Psi = 0 \]

\[ \bar{\psi}^{\mu} i \partial_\mu \psi_L = m \psi_R \]

\[ \sigma^\mu i \partial_\mu \psi_R = m \psi_L \]

\[ E = \sqrt{m^2 c^4 + p^2 c^2} \]

\[ v_F = 8 \times 10^5 \text{ m/s} \]
Dirac semimetals $\text{Na}_3\text{Bi}$ 2012/2013

\[ H = \nu_{ij} q_i \gamma_j \]

$^{13}$D Dirac semimetals
Young, Kane, Mele et al. PRL (2012)

$Liu \ et \ al. \ Science \ (2014)$

Weyl semimetal $Y_2\text{Ir}_2\text{O}_7$
Weyl semimetal TaAs

2011
2015

$cGGA+SOC$

$E_F$

$\text{Na}_3\text{Bi}$ candidate
Wang Na3Bi PRB (2012)
**Ab initio leading experiment: Topological Semimetal**

Dirac semimetals $\text{Na}_3\text{Bi}$ 2012/2013

Weyl semimetal $Y_2\text{Ir}_2\text{O}_7$ 2011

Weyl semimetal TaAs 2015

Symmetry breaking

Time reversal broken

$$H = \nu_{ij} q_i \sigma_j$$

Noncentrosymmetric

Pyrochlore iridates

Wan PRB (2011)

Can we control the relativistic fermions electrically?
Model of AFM topological semimetal

**DIRAC FERMIONS** + **AF SPINTRONICS**

**YES!**

**Overlap of symmetry conditions**

1. Two sites in unit cell
   - band crossing
   - inversion-partner sites → staggered field

2. $\mathcal{PT}$ symmetry
   - spin-degeneracy → Dirac point
   - $\mathcal{PT}$ symmetry
   - AF spin-sublattices at inversion partner sites → AF spin-orbitorque
Minimal lattice model: construction

\[ \mathcal{H}_{SOC}(r) = i \sum_{\langle\langle i,j \rangle\rangle,\langle k \rangle} \lambda_{ij} \hat{c}_i^\dagger \left( d_{ik}^1 \times d_{kj}^2 \right) \cdot \sigma \hat{c}_j \]

\[ \mathcal{H} = \sum_{\langle\langle i,j \rangle\rangle,\langle i,j \rangle} t_{ij} \hat{c}_i^\dagger \hat{c}_j + \sum_i J_i \hat{c}_i^\dagger \mathbf{n} \cdot \sigma \hat{c}_i \]

Kane-Mele spin-orbit coupling

Smejkal, Zelezny, Sinova, Jungwirth PRL (2017)
Minimal lattice model: local symmetries

Pseudovector/axial vector

\[ \rho T + A, B \text{ noncentrosymmetric} \]

Neel spin-orbit torque

Smejkal, Jungwirth, Sinova PSS (2017)
Symmetry protection of Dirac points

**Mirror**

**Translate**

at \( G_X \) invariant subspace

\[ (\pi, k_y, 0) \]

\[ m_x = -i, -i \]

\[ m_x = +i, +i \]

**nonsymmorphic symmetry** = point group + nontrivial translation
glide mirror plane \( G_X = \{ M_x / (1/2, 0, 0) \} \)

\[ M_x = i \sigma_x \tau_z \]
Quasi-2D effective model

\[
H = 2t\tau_x \cos \frac{k_x}{2} \cos \frac{k_y}{2} + t' \cos k_x \cos k_y + \lambda \tau_z (\sigma_y \sin k_x - \sigma_x \sin k_y) + \tau_z J_n \sigma \cdot n
\]

\[\text{Smejkal, Zelezny, Sinova, Jungwirth PRL (2017)}\]
Dirac fermions in antiferromagnets CuMnAs

Smejkal, Zelezny, Sinova, Jungwirth PRL (2017)

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Electrical control of Dirac fermions

Demonstration of inplane Field like torque manipulation

Demonstration of (001) \rightarrow inplane Field like torque

Nonsymmorphic symmetry: Screw axis+Glide plane

tetra.

ortho.
Topological metal-insulator transition

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Topological magnetotransport: AMR

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
SUMMARY

SHE and ISGE

JS, Valenzuela, Wunderlich, Back, Jungwirth RMP (2015)

Néel SOT in a single-layer antiferromagnet


SOT in a single-layer ferromagnet


SHE and ISGE


Neel SOT physics (ii)


Electrical control of Dirac fermions and topological phases

Topological Dirac Semi Metal+ AFM (i)

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
THANK YOU

Smejkal, Gayles, Zeledny, Gao, Masek, Kurebayashi, Fang, Irvine, Wunderlich, Zarbo, Vyborny, Ferguson, Gomonay, Abanov, and Jungwirth

Institute of Physics ASCR Prague
Charles Univ. Prague, Czech Rep.

Univ. of Nottingham, UK

Hitachi and Univ. of Cambridge, UK

JGU Mainz
Sign up to the youtube channel

Magnetism: from fundamentals to spin based technology; Bad Honnef School- Jairo Sinova
Sign up to the youtube channel

SPICE TALKS

SPICE - Spin Phenomena Interdisciplinary Center

Created playlists

Talks - SPICE Quantum Spintronics Workshop - Spin
Talks - SPICE SpinCaT Workshop - New Perspectives in Spin
Talks - SPICE Young Research Leaders Workshop 2016
Talks - SPICE Workshop - Quantum Acoustics - Surface
Talks - SPICE Workshop - Magnetic Adatoms as Building

Talks - SPICE Young Research Leaders Workshop 2015