Spin-Torques and Spin Hall Effect in ferromagnets and antiferromagnets

Jairo Sinova
Johannes Gutenberg Universität Mainz

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Nanoscience and Quantum Transport
Kiev, Ukraine
Spin-Torques and Spin Hall Effect in ferromagnets and antiferromagnets

I. Spin-Transfer Torque
   • Phenomenology
   • Anatomy of STT (no spin-orbit)
     • Complex anatomy of STT with spin-orbit coupling
II. SHE and Inverse spin galvanic effect
   • SHE and Inverse spin galvanic effect phenomenology
III. Spin-Orbit Torques in Ferromagnets:
   • Spin-Orbit Torques:
     • Bilayer geometry: SOT vs SHE+STTT
     • Intrinsic and Field like SOTs in ferromagnets
IV. Antiferromagnetic Spin-orbitronics: Neel SOTs
   • Active manipulation of Néel order by currents: Néel spin-orbit torque
V. Antiferromagnetic Spintronics + Dirac Physics
VI. SPICE
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Sign up to the youtube channel
The Spin Phenomena Interdisciplinary Center aims to bring together scientists from diverse disciplines and of varying backgrounds to break down scientific barriers and foster emergent areas of research that combine the strengths of different fields.

INVITED SPEAKERS:

Arne Brataas (Trondheim Univ.)
Rombert Dürre (Utrecht Univ.)
Richard Campion (Univ. Nottingham)
Rang Cheng (Cambridge M. Univ.)
Claudia Cococcioni (Univ. Cambridge)
Claudia Felser (MPI Dresden)
Mathias Kohl (JGU Mainz)
Manfred Fleeg (ETH Zürich)
Brian Gallagher (Nottingham Univ.)
Helen Gomonay (JGU Mainz)
Sebastian Gonnenwein (Munich)
Hardy Gross (MPI Halle)
Avri Hoffman (ANL Chicago)
Dominik Kleppner (Charite Univ.)
Sebastian Loffi (MPI Hamburg)
Auraiari Martonov (KAZET)
Hideo Ohno (Sendai)
Skiel Mélit (Prague)
Yuri Mekrousov (Prague)
Ulrich Neel (Univ. Konstanz)
Stuart Parkin (MPI Halle)
Theo Rasing (Hamburg Univ.)
Dae Rahn (Cornell Univ.)
Ulrich Roessler (MPI Dresden)
Oleg Tretiakov (Sendai)
Yediste Tserkovnyak (UCLA)
Sergej Uhradil (Emory Univ.)
Michel Viret (CEA)
Peter Wadley (Univ. Nottingham)
Roland Wiesendanger (Hamburg)
Michel Wunderlich (Prague/Cambridge)
http://www.spice.uni-mainz.de/
SPICE Visitor Program

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Magnetization dynamics and Spin Transfer Torque

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

(proposed by Slonczewski, Berger 1996)
sd exchange interaction between itinerant and local electrons

\[ H_{sd} = -J_{sd} \vec{m} \cdot \vec{M} \]

\[ J_{sd} \quad \text{exchange coupling constant [energy]} \]

Effective exchange field acting on \( \vec{m} \):
\[ \vec{B} = \frac{J_{sd}}{m} \vec{M} \rightarrow \text{Torque:} \quad \vec{T} = J_{sd} \vec{m} \times \vec{M} \]

Effective exchange field acting on \( \vec{M} \):
\[ \vec{B} = \frac{J_{sd}}{M} \vec{m} \rightarrow \text{Torque:} \quad \vec{T} = J_{sd} \vec{M} \times \vec{m} \]

Changes of \( \vec{m} \) and \( \vec{M} \) are related by:
\[ \frac{d\vec{m}}{dt} = -\frac{d\vec{M}}{dt} \quad \text{Action = Reaction!} \]

Conservation of angular momentum

Note: This is exact if spin relaxation and spin-orbit coupling are neglected, i.e., assuming weak spin-lattice interactions compared to electron-electron interactions

Courtesy of P. Gambardella
Torques due to non-equilibrium spin accumulation

\[
T = J_{sd} \vec{M} \times \hat{m}
\]
Torque on \( M \) due to the \( sd \) exchange interaction

\[
m = m_0 + \delta m
\]
\( m_0 \) equilibrium magnetization of conduction electrons, \( m_0 \parallel M \)

\[
\delta m = -DOS(E_F)\mu_B \mu_s
\]
nonequilibrium magnetization

Assuming \( |M| = \text{const.} \), the only component of \( m \) that gives a torque is \( \delta m_\perp \)

\[
\delta m_\perp = a_j M \times m + b_j (M \times m) \times M
\]
\( a_j, b_j \) parameters that depend on the current, magnetization, NM/FM geometry and materials

\[
T \sim M \times \delta m_\perp = a_j M \times (M \times m) + b_j M \times m
\]

"In-plane torque"
"Spin transfer torque"
"Slonczewski torque"
"Antidamping torque"

"Out-of-plane torque"
"Perpendicular torque"
"Effective field"
"Field-like torque"


Courtesy of P. Gambardella
Anatomy of spin-transfer torque: general case

1. **Spin filter effect:** spin-dependent reflection and transmission at NM/FM interface, reduces the transverse spin components of reflected and transmitted electrons.

2. **The spin rotates upon reflection:** $r_\uparrow r_\downarrow^* = |r_\uparrow r_\downarrow^*|e^{i\Delta \phi}$. The relative phase $\Delta \phi$ of the reflected transverse components varies significantly over the Fermi surface. The reflected transverse spin averages out when summing over the electron distribution (classical dephasing).

3. **Spatial precession of the transmitted spins in the FM.** Spin-up and spin-down components have the same total energy $E_f$, but different kinetic energy $\Rightarrow k_\uparrow \neq k_\downarrow$, leading to a space-dependent phase difference $e^{i(k_\uparrow-k_\downarrow)z}$ as the electron penetrates into the FM. The precession frequency is different for electrons from different portions of the Fermi surface, hence complete cancellation of the transverse spin occurs after propagation into the FM by a few lattice constants.

Courtesy of P. Gambardella
Anatomy of spin-transfer torque: circuit theory

- Generalization of the two-channel series resistor model to multilayer structures and noncollinear magnetization
- Similar to drift-diffusion theory but neglects the spatial dependence of the chemical potential within the layers (nodes).
- Practical for treating interface effects and complex device structures.


\[ j_s = (j_\uparrow - j_\downarrow) \hat{M} - \frac{2}{e} \text{Re}\{G_{\uparrow\downarrow}\} \hat{M} \times (\hat{M} \times \mu_s) - \frac{2}{e} \text{Im}\{G_{\uparrow\downarrow}\} \hat{M} \times \mu_s \]

Spin current absorbed by the ferromagnet

\[ G_{\uparrow\downarrow} = \frac{e^2}{\hbar} \sum_{n \in NM} \left[ 1 - \sum_{m \in NM} r_\uparrow^{nm}(r_\downarrow^{nm})^* \right] \]

- Spin mixing conductance: relevant for transport at interfaces when the spin accumulation \( m \) and magnetization \( \hat{M} \) are not collinear

Courtesy of P. Gambardella
Anatomy of spin-transfer torque: 1D toy model

\[ G_{\uparrow} = \frac{e^2}{h} \sum_{n \in NM} \sum_{m \in FM} |t_{n}^{nm}|^2 \]

\[ G_{\downarrow} = \frac{e^2}{h} \sum_{n \in NM} \sum_{m \in FM} |t_{\downarrow}^{nm}|^2 \]

Majority and minority conductances describe electrons going from one material to another.

\[ G_{\uparrow \downarrow} = \frac{e^2}{h} \sum_{n \in NM} \left[ 1 - \sum_{m \in NM} r_{n}^{nm}(r_{m}^{nm})^* \right] \]

Describes a spin current absorbed by the FM, hence the behavior of the spins in the NM that are perpendicular to the magnetization of the FM.

\[ \text{Re}\{G_{\uparrow \downarrow}\} \quad \text{Spin current aligned with the transverse part of } \mu_s \text{ in the NM} \]

\[ \text{Im}\{G_{\uparrow \downarrow}\} \quad \text{Spin current perpendicular to both } \mu_s \text{ and } M \]

Both spin current components \( \text{Re}\{G_{\uparrow \downarrow}\} \) and \( \text{Im}\{G_{\uparrow \downarrow}\} \) are absorbed in the FM, leading to the spin torque

\[ \tau_{ST} = \frac{\hbar}{2e} j_{s}^{abs} = \frac{\hbar}{e^2} \left[ \text{Re}\{G_{\uparrow \downarrow}\} \hat{M} \times (\hat{M} \times \mu_s) + \text{Im}\{G_{\uparrow \downarrow}\} \hat{M} \times \mu_s \right] \]

\[ \text{[torque / unit area]} \]


Courtesy of P. Gambardella
Anatomy of SOT in Bilayers: revisiting $G_{\uparrow\downarrow}$

“Anatomy” of Spin-Orbit Torque in Bilayers

Spin transport with interfacial spin-orbit coupling

- Interfacial spin-orbit scattering creates a non-equilibrium spin polarization and spin currents!
- Interfacial spin current sources also determine ratio of damping-like and field-like torques
- Magneto-electric circuit theory (Arne Brataas, et al. PRL 84, 11, 2000) must be generalized!

Amin, et al. PRB 94, 104419 (2016)
Amin, et al. PRB 94, 104420 (2016)

Interfacial spin-orbit scattering

\[ j_{\alpha} = G_{i\alpha\beta} \mu_{\beta} + \sigma_{i\alpha} E \]
Magnetization dynamics and Spin Transfer Torque

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\]

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

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

STT mechanism:

~ 30 μA

MTJ

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.
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Spin Hall effect

Transverse spin-current generation in paramagnets

Sinova et al RMP 87, 1213 (2015)

**Intrinsic**

`Berry Phase’, interband coherence

[Murakami et al, Sinova et al 2003]

**Extrinsic**

`Skew Scattering’, Occupation # Response


Wunderlich, PRL 05

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

\[ H_R = \frac{\hbar^2 k^2}{2m} - \mu_B \vec{\sigma} \cdot \vec{B}_{eff}(\vec{k}) \]

\[ = \frac{\hbar^2 k^2}{2m} + \alpha_R (\sigma_x k_y - \sigma_y k_x) \]

\[ \Delta p \sim eEt \]

\[ \Delta B_{eff} \sim \Delta p \hat{y} \]
Completing the spin dependent Hall family: SHE\(^{-1}\)

- AHE
  - magnetic \(M_z \neq 0\)

- SHE
  - non-magnetic \(M_z = 0\)

- SHE\(^{-1}\)
  - non-magnetic \(M_z = 0\)

Valenzuela & Tinkham Nature’06

optical detection

electrical detection

I=0
Anomalous/Spin Hall effects: more than meets the eye

Anomalous Hall Effect

Spin Hall Effect

Intrinsic

Extrinsic

Intrinsic

Extrinsic

Topological Insulators

Mesoscopic Spin Hall Effect

SHE Transistor

SHE/SOT MRAM

Kane and Mele
PRL 05

Brune, JS, Molenkamp, et al
Nature Physics 2010

Wunderlich, Irvine, JS,
Jungwirth, et al, Nature Physics
09, Science 2011

Buhrow, et al., Science 2012
Another way to create current induced polarization

Inverse Spin Galvanic Effect or Edelstein Effect
(Reverse process of circular photo-galvanic effect, Ganichev et al., 2001)

Spin Hall Effect in p-GaAs

Effective fields $\sim$ 1-10 T
Spin polarizations $\sim$ 1-10%

$\delta S \neq 0$

$\mathbf{J} \parallel \mathbf{x}$
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V. SPICE
First works: current-induced SO effective fields

Effective spin-orbit (SO) field by dc current

✓ Hysteresis observed in the planar Hall effect

AlOx/Co/Pt: interface broken symmetry, Miron, Nature Mater. 9, 230 (2010)

✓ DW nucleation difference in the perpendicularly magnetised system
Experiments of in-plane current switching in bilayers

Miron et al., Nature '11

Liu et al., Science '12

Spin-orbit torque at PM/FM interface

Intrinsic SHE + STT

Intrinsic SHE in paramagnet acts as the external polarizer

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

\[ \hbar_{SOT} \parallel z \times \vec{J} \]

\[ \left( \frac{d\vec{M}}{dt} \right)_{SOT} = \frac{J_{ex}}{\hbar} \vec{M} \times \delta \vec{s} \]

Intrinsic SHE + STT

\[ \left( \frac{d\vec{M}}{dt} \right)_{SHE-STT} = P \hat{M} \times (\hat{n} \times \vec{M}) \]
Spin-orbit induced spin accumulation in bilayer systems

Spin Hall

Rashba

Courtesy of P. Gambardella
Spin-orbit Torques in Bilayer Systems

\[ T_{FL} = M \times m \]

\[ T_{AD} = M \times (M \times m) \]

Courtesy of P. Gambardella
“You like potato and I like potato . . .

\[ T_{AD} = M \times (M \times m) \]
\[ T_{FL} = M \times m \]

“Spin Hall torque”
“Spin transfer torque”
“Slonczewski torque”
“Spin orbit torque”
“Spin orbit field”
“Rashba torque”

Antidamping and field-like spin-orbit torques (SOT)

Courtesy of P. Gambardella
Boltzmann theory: non-equilibrium distribution function and equilibrium states

Extrinsic (skew-scattering) SHE

\[ \delta \vec{j}_s = \frac{1}{V} \sum_{\vec{k}} \vec{j}_s(\vec{k}) g_{\vec{k}} \]

Dyakonov and Perel 1971
Hirsch PRL'99
Kato et al., Science '04

Field-like SOT

\[ \delta \vec{s} = \frac{1}{V} \sum_{\vec{k}} \vec{s}(\vec{k}) g_{\vec{k}} \]

\[ \left( \frac{d \vec{M}}{dt} \right)_{SOT} = \frac{J_{ex}}{h} \vec{M} \times \delta \vec{s} \]
Perturbation theory: equilibrium distribution function and non-equilibrium states

Intrinsic SHE from linear response II

\[ j_{\parallel} = \sum_{\vec{k}} \langle \psi_{\vec{k}}^-(t) | \hat{j}_{\parallel} | \psi_{\vec{k}}^- \rangle f_0(E_{\vec{k}}) \]

\[ |\psi_{\vec{k}}^-\rangle = |\vec{k}\rangle e^{-iE_{\vec{k}}t} + \frac{e}{i\omega} \sum_{\vec{k}n \neq \vec{k}n'} \frac{\langle \vec{k}n' | \vec{E} \cdot \vec{v} | \vec{k}n \rangle}{E_{\vec{k}n} - E_{\vec{k}n'} + i\omega} e^{-i(E_{\vec{k}n} + \omega)t} + \ldots \]

\[
\begin{align*}
\mathcal{J}_{\text{int}} & = \frac{e\hbar}{V} \sum_{\vec{k}, n \neq n'} \left( f_0^{\vec{k}, n} - f_0^{\vec{k}, n'} \right) \frac{\text{Im}[\langle \vec{k}, n' | j_{\parallel}^\ast | \vec{k}, n \rangle \langle \vec{k}, n' | \vec{v} \cdot \vec{E} | \vec{k}, n \rangle]}{(E_{\vec{k}, n'} - E_{\vec{k}, n})^2} \\
\end{align*}
\]

Scattering-independent anti-damping SOT from linear response II.

\[
\begin{align*}
\mathcal{S}_{z}^{\text{int}} & = \frac{e\hbar}{V} \sum_{\vec{k}, n \neq n'} \left( f_0^{\vec{k}, n} - f_0^{\vec{k}, n'} \right) \frac{\text{Im}[\langle \vec{k}, n' | s_{z} | \vec{k}, n \rangle \langle \vec{k}, n' | \vec{v} \cdot \vec{E} | \vec{k}, n \rangle]}{(E_{\vec{k}, n'} - E_{\vec{k}, n})^2} \\
\end{align*}
\]

Murakami, et al, Science’03
Sinova, et al, PRL’04

Wunderlich et al. Phys. Rev. Lett. ’05
Werake et al., PRL’11
Intrinsic (Berry phase) spin-orbit torque from Bloch eq.

Large exchange limit and Rashba SOC

\[ \Delta p \sim eEt \]

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

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

maximum \( \delta s_z \hat{z} \) for \( \hat{M} \parallel \hat{E} \)
Intrinsic (Berry phase) spin-orbit torque from Bloch eq.

Large exchange limit and Rashba SOC

$\Delta p \sim eEt$

$\Delta B_{\text{eff}} \sim \Delta p \hat{y}$

$M \quad B_{\text{eff}}^{\text{eq}} \sim -M$

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

anti-damping

$\delta s_z \hat{z} \sim (\vec{E} \times \hat{z}) \times \hat{M} \sim \cos(\theta_{\vec{M} - \vec{E}})$

\[ \]
Intrinsic (Berry phase) spin-orbit torque in GaMnAs

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

angle between \( \mathbf{M} \) and current direction

<table>
<thead>
<tr>
<th>current direction</th>
<th>Rashba: ( \delta s_{z, \mathbf{M}} \sim )</th>
<th>Dresselhaus: ( \delta s_{z, \mathbf{M}} \sim )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbf{E} \parallel [100] )</td>
<td>( \cos \theta_{\mathbf{M}-\mathbf{E}} )</td>
<td>( \sin \theta_{\mathbf{M}-\mathbf{E}} )</td>
</tr>
<tr>
<td>( \mathbf{E} \parallel [010] )</td>
<td>( \cos \theta_{\mathbf{M}-\mathbf{E}} )</td>
<td>( -\sin \theta_{\mathbf{M}-\mathbf{E}} )</td>
</tr>
<tr>
<td>( \mathbf{E} \parallel [110] )</td>
<td>( \cos \theta_{\mathbf{M}-\mathbf{E}} )</td>
<td>( \cos \theta_{\mathbf{M}-\mathbf{E}} )</td>
</tr>
<tr>
<td>( \mathbf{E} \parallel [1 - 10] )</td>
<td>( \cos \theta_{\mathbf{M}-\mathbf{E}} )</td>
<td>( -\cos \theta_{\mathbf{M}-\mathbf{E}} )</td>
</tr>
</tbody>
</table>
Measuring spin-orbit fields: electrical induced/detected FMR

**Landau-Lifshitz-Gilbert equation**

\[
\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{tot}} + \frac{\alpha}{M_s} \left( \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right) - \gamma \mathbf{M} \times \mathbf{h}_{\text{so}}
\]

Because \( h_{\text{so}} = -J_{pd} \Delta s \)

the V amplitudes contain spin-orbit fields information.
Torque types and line-shapes

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

\[ T_{\text{out-of-plane}} \text{ (} h_x \text{ & } h_y) \]
\[ V_{\text{asy}} = C_2 \times \sin(2\theta_{M-E}) \times (-h_x(\theta_{M-E})\sin(\theta_{M-E}) + h_y(\theta_{M-E})\cos(\theta_{M-E})) \]

Fang et al., Nature Nanotech. (2011)

Sample:
18 or 25 nm-thick GaMnAs 4 mm-wide
Comparison of Experiment - Theory

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

Other Materials: Half Heuslers

NiMnSb

<table>
<thead>
<tr>
<th>point group</th>
<th>field-like $\chi$</th>
<th>point group</th>
<th>field-like $\chi$</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>$\begin{pmatrix} x_{11} &amp; 0 &amp; x_{13} \ 0 &amp; x_{22} &amp; 0 \ x_{21} &amp; 0 &amp; x_{33} \end{pmatrix}$</td>
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<tr>
<td>m</td>
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<td>-6</td>
<td>$\begin{pmatrix} 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{pmatrix}$</td>
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<tr>
<td>4</td>
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<tr>
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<td>-6m2</td>
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<td>23</td>
<td>$\begin{pmatrix} x_{21} &amp; 0 &amp; 0 \ x_{21} &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{pmatrix}$</td>
</tr>
<tr>
<td>-42m</td>
<td>$\begin{pmatrix} -x_{21} &amp; x_{21} &amp; 0 \ x_{11} &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{pmatrix}$</td>
<td>432</td>
<td>$\begin{pmatrix} x_{11} &amp; 0 &amp; 0 \ 0 &amp; x_{11} &amp; 0 \ 0 &amp; 0 &amp; 0 \end{pmatrix}$</td>
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<tr>
<td>3</td>
<td>$\begin{pmatrix} x_{11} &amp; -x_{21} &amp; 0 \ x_{21} &amp; x_{11} &amp; 0 \ 0 &amp; 0 &amp; x_{33} \end{pmatrix}$</td>
<td>-43m</td>
<td>$\begin{pmatrix} 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{pmatrix}$</td>
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</table>

$T_c = 730$ K in bulk
Room-temperature SOT in NiMnSb


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

$V^{[1-10]}_{\text{asy}}(\theta) \propto -B_x \sin 2\theta \sin \theta + B_y \sin 2\theta \cos \theta$

$V^{[110]}_{\text{asy}}(\theta) \propto -B_x \sin 2\theta \sin \theta - B_y \sin 2\theta \cos \theta$

$V_{\text{dc}}(\mu V)$

$\phi$ (deg)

[1-10]

[110]
Measurement Techniques

Magnetization switching:

Spin-torque FMR:
(Resonant ACcurrent excitation AMR readout)

Domain wall motion

ACHall voltage and AMR modulation

Pi et al., APL 2010;  
Garello et al., Nat. Nanotech. 2013;  
Kim et al., Nat. Mater. 2013

Liu et al., PRL 2011  
Fang et al., Nat. Nanotech. 2011  

Emori et al., Nat. Mater. 2013  
Ryu et al., Nat. Nanotech. 2013  
Haazen et al., Nat. Mater. 2013

 Courtesy of P. Gambardella
Spin Hall Effect and Spin-Orbit Torques in ferromagnets and antiferromagnets

I. Spin-Transfer Torque
- Phenomenology
- Anatomy of STT (no spin-orbit)
- Complex anatomy of STT with spin-orbit coupling

II. SHE and Inverse spin galvanic effect
- SHE and Inverse spin galvanic effect phenomenology

III. Spin-Orbit Torques in Ferromagnets:
- Spin-Orbit Torques:
  - Bilayer geometry: SOT vs SHE + STTT
  - Intrinsic and Field-like SOTs in ferromagnets

IV. Antiferromagnetic Spin-orbitronics: Neel SOTs
- Active manipulation of Néel order by currents: Néel spin-orbit torque

V. Antiferromagnetic Spintronics + Dirac Physics

VI. SPICE
Antiferromagnetic Spin-orbittronics

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

*Magnet reversing itself: SOT*

What type of current-induced polarisation can we generate?

Néel spin-orbit torque in a single-layer antiferromagnet

\[ \mathbf{H}_{\text{SOT}} \parallel \mathbf{z} \times \mathbf{J} \]  
\[ \mathbf{H}_{\text{SOT}} \parallel -\mathbf{z} \times \mathbf{J} \]


Antiferromagnet with broken sublattice space-inversion symmetry: \((\text{Mn}_2\text{Au})\)
Néel spin-orbit torque in a single-layer antiferromagnet

Antiferromagnet with broken sublattice space-inversion symmetry: (Mn$_2$Au)

Zelezny, Gao, Jungwirth, PRL (2014)
How it works - kind of

Frank Freimuth
## Classification of torques

<table>
<thead>
<tr>
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<th>Field-like, $M \times p$</th>
<th>Antidamping-like, $M \times p \times M$</th>
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<td><strong>Non staggered</strong> $p_1 = p_2$</td>
<td>$\sqrt{H_{an} H_{ex}}$</td>
<td>$\alpha_G \sqrt{H_{an} H_{ex}}$</td>
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| **Staggered** $p_1 = -p_2$ | $H_{an}$ | $\alpha_G H_{ex}$ |
| $H_{eff}$ | $H_{eff}$ | $H_{eff}$ | $H_{eff}$ | $H_{eff}$ |
Staggering antiferromagnetic domain wall velocity in a staggered spin-orbit field

O. Gomonay,†, 1, 2 T. Jungwirth,† 3, 4 and J. Sinova†, 3

1 Institut für Physik, Johannes Gutenberg Universität Mainz, D-55099 Mainz, Germany
2 National Technical University of Ukraine “KPI”, 03056, Kyiv, Ukraine
3 Institute of Physics ASCR, v.v.i., Cukrovarnicka 10, 162 53 Praha 6 Czech Republic
4 School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom

Gomonay, Jungwirth, JS PRL (2016)
Classification of torques

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Writing by Néel spin-orbit torque in a single-layer antiferromagnet

2D Antiferromagnet with Rashba SOC
intrinsic Néel SOT can be much larger than FM SOTs!!

extrinsic/Rashba Néel SOT=0

BUT intrinsic Néel SOT≠0

Antiferromagnet with broken global space-inversion symmetry: 2D-AFM+Rashba
Writing by Néel spin-orbit torque in a single-layer antiferromagnet

2D Antiferromagnet with Rashba SOC

intrinsic Néel SOT can be much larger than FM SOTs!!

Antiferromagnet with broken global space-inversion symmetry: 2D-AFM+Rashba
Experimental discovery of Néel SOT in CuMnAs

Wadley et al, Science 2016

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

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

Works like this but not done like this

**Electrical read/write antiferromagnetic memory**

Antiferromagnetic recording & spin-orbit torque

- Spin; not charge based
- Radiation-hard
- Ordered spins
- Non-volatile
- No net moment, no dipolar fields
- Insensitive, invisible to magnetic fields, no magnetic cross-talk
- THz dynamics
- Ultra-fast switching

Tested up to 12 T and down to 250 ps

Wadley et al. Science ‘16, Schuler et al arXiv ‘16
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Dirac/Weyl semimetals

3D TI

2003

2D TI

graphene

2016

Néel SOT

SOT

QSHE

SHE
Antiferromagnetic spintronics and Dirac metals

Dirac fermions in graphene → topological insulators, semimetals, superconductors …

Inverse spin galvanic (Edelstein) torque
Local inversion asymmetry & antiferromagnet

Serendipitous overlap of symmetry conditions:
- Two sites in unit cell
- $\mathcal{PT}$ symmetry

Electric control of Dirac semimetal/semiconductor via AF

Novoselov, Geim et al. 2004

Máca et al. JMMM ‘12
Šmejkal et al. DPG Regensburg ‘16
Tang et al. Nature Phys. ‘16

$\vec{T}_A \sim \vec{M}_A \times \vec{\sigma}_A$

$\vec{T}_B \sim \vec{M}_B \times \vec{\sigma}_B$

Šmejkal et al. DPG Regensburg ‘16
Electrical control of Dirac fermions

Demonstration of inplane Field like torque manipulation

Demonstration of (001) → inplane Field like torque

Nonsymmorphic symmetry: Screw axis+Glide plane
Electrical control of phases

Dirac semimetal
SOC (001)

Semiconductor
SOC (101)

\[ X^{(0)} \]
SUMMARY

SHE and ISGE

Néel SOT in a single-layer antiferromagnet

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


Wadley, Jungwirth et al Science (2016)

SOTs in ferromagnet: field and damping like


SHE and ISGE

Electrical control of Dirac fermions and topological phases

Topological Dirac Semi Metal + AFM (i)

Neel SOT physics (ii)