Expecting the unexpected in the spin Hall effect: from fundamental to practical

JAIRO SINOWA
Texas A&M University
Institute of Physics ASCR

Institute of Physics ASCR
Tomas Jungwirth, Vít Novák, et al

Hitachi Cambridge
Joerg Wünderlich, A. Irvine, et al

U. of Wurzburg
Laurens Molenkamp, E. Hankiewicz, et al

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Research fueled by:
Expecting the unexpected in the spin Hall effect: from fundamental to practical

I. Introduction:
• Basics of AHE: SOC origins and mechanism
• SHE phenomenology

II. Spin Hall effect: the early days
• First proposals: from theory to experiment
• First observations of the extrinsic and intrinsic (optical)

III. Inverse spin Hall effect: SHE as a spin current detector
• Direct iSHE in metals
• Spin pumping and iSHE
• Intrinsic mesoscopic SHE

IV. SHE-FET: first steps towards practicality (but perhaps not)
• Spin Hall injection and spin precession manipulation
• iSHE device with spin-accumulation modulation

V. FMR measurement of SHE angle: giant and SHE as a spin current generator
• FMR and SHE angle
• Giant intrinsic SHE and STT: Future MRAM technology?

VI. Conclusion
Anomalous Hall Effect: the basics

Spin dependent “force” deflects like-spin particles

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

\[ R_0 \ll R_s \]

AHE is does NOT originate from any internal magnetic field created by \( M_\perp \); the field would have to be of the order of 100T!!

Simple electrical measurement of out of plane magnetization (or spin polarization \( \sim n_{\uparrow} - n_{\downarrow} \))

\[ \rho_{xy} = -\frac{\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2} \approx -\frac{\sigma_{xy}}{\sigma_{xx}^2} \approx -\sigma_{xy} \rho_{xx}^2 \approx -A \rho_{xx} - B \rho_{xx}^2 \]

\[ \sigma_{xy}^{\text{AH}} \approx B + A \sigma_{xx} \]
Nanoelectronics, spintronics, and materials control by spin-orbit coupling

Internal communication between spin and charge: spin-orbit coupling interaction

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

Classical explanation (in reality it arises from a second order expansion of Dirac equation around the non-relativistic limit)

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

- Motion of an electron
  In the rest frame of an electron the electric field generates an effective magnetic field
  \[ \vec{B}_{\text{eff}} = -\frac{\hbar k}{cm} \times \vec{E} \]

This gives an effective interaction with the electron’s magnetic moment

\[ H_{SO} = -\vec{\mu}_B \cdot \vec{B}_{\text{eff}} \]
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Consequence #1

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\[
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\]

Consequence #2
Mott scattering

\[
\vec{B}_{eff} = -\frac{\hbar k}{cm} \times \vec{E}
\]
Cartoon of the mechanisms contributing to AHE $\sigma_{xy}^{\text{AH}} \approx B + A \sigma_{xx}$

**Skew scattering** $A \sim 1/n_i$

Asymmetric scattering due to the spin-orbit coupling of the electron or the impurity. Known as Mott scattering.

**Intrinsic deflection** $B$

Electrons deflect to the right or to the left as they are accelerated by an electric field ONLY because of the spin-orbit coupling in the periodic potential (electronics structure).

$\dot{x}_c = \frac{\partial \varepsilon(k)}{\hbar \partial k} + \frac{e}{\hbar} \vec{E} \times \vec{\Omega}$

Electrons have an “anomalous” velocity perpendicular to the electric field related to their Berry’s phase curvature which is nonzero when they have spin-orbit coupling.

**Side jump scattering** $B$

independent of impurity density

Electrons deflect first to one side due to the field created by the impurity and deflect back when they leave the impurity since the field is opposite resulting in a side step. They however come out in a different band so this gives rise to an anomalous velocity through scattering rates times side jump.

$V_{\text{imp}}(r) (\Delta \text{so}>\hbar/\tau)$ or $\propto \lambda^* \nabla V_{\text{imp}}(r) (\Delta \text{so}<\hbar/\tau)$

$\Omega_z(\vec{k}, n) = 2 \text{Im} \left\langle \frac{\partial}{\partial y} n\vec{k} \right| \frac{\partial}{\partial x} n\vec{k} \right\rangle$
Spin Hall effect

Take now a PARAMAGNET instead of a FERROMAGNET: Spin-orbit coupling “force” deflects like-spin particles

Carriers with same charge but opposite spin are deflected by the spin-orbit coupling to opposite sides.

Transverse spin-current generation in paramagnets without external magnetic fields by spin-dependent deflection of electrons
Spin Hall Effect
(Dyaknov and Perel 1971)

Interband Coherent Response
\( \sim (E_F \tau)^0 \)

Occupation # Response
`Skew Scattering'
[Hirsch, S.F. Zhang]
2000

Intrinsic ‘Berry Phase'
[Murakami et al, Sinova et al]
2003

Influence of Disorder
[Inoue et al, Mischenko et al, Chalaev et al...]

Intrinsic
‘Berry Phase’
[Murakami et al, Sinova et al]
2003
First experimental observations at the end of 2004

Wunderlich, Kästner, Sinova, Jungwirth, cond-mat/0410295
PRL January 05

*Experimental observation of the spin-Hall effect in a two dimensional spin-orbit coupled semiconductor system*

Co-planar spin LED in GaAs 2D hole gas: ~1% polarization

Kato, Myars, Gossard, Awschalom, Science Nov 04

*Observation of the spin Hall effect bulk in semiconductors*

Local Kerr effect in n-type GaAs and InGaAs:
~0.03% polarization (weaker SO-coupling, stronger disorder)
extrinsic SHE detection by Kerr microscopy

The spin polarization is measured by magneto-optical Kerr effect.

Kato et al Science 2004
intrinsic SHE experiment in GaAs/AlGaAs 2DHG

- shows the basic SHE symmetries
- edge polarizations can be separated over large distances with no significant effect on the magnitude
- 1-2% polarization over detection length of ~100nm consistent with theory prediction (8% over 10nm accumulation length)
Completing the spin dependent Hall family: SHE\(^{-1}\)

- AHE
- Magnetic
  - \(M_z\) majority
  - \(M_z\) minority
- SHE
  - \(M_z = 0\)
- SHE\(^{-1}\)
  - \(M_z = 0\)
- Non-magnetic optical detection
- Non-magnetic

\(I_{\text{spin}}\)
\(I = 0\)
extrinsic SHE\(^{-1}\) in metals

Electrical non-local spin valve detection by FM and by iSHE

Valenzuela, S. O. & Tinkham, M, Nature‘06
SHE$^{-1}$ magnetoresistance measurement

Originally proposed by Shufeng Zhang 2000

Magnetoresistance signals from SHE and inverse SHE

$\theta_{SH} \sim 0.0037$


(SHE angle HIGHLHY underestimated)
The Cu shunts most of the charge current, so the charge current density in the Pt was much smaller than assumed.

Reason for the underestimate of $\theta_{SH}$ by Kimura et al.
Spin pumping and SHE\textsuperscript{-1}

Saitoh et al APL 06

Theory based on ref: Silsbee, Janossy, and Monod, PRB 19, 4382 (1979)
Mesoscopic intrinsic SHE$^{-1}$ in HgTe

Brune et al, Nature Physics

Sample layout
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From DD-FET to new paradigm using SO coupling

Problem: Rashba SO coupling in the Datta-Das SFET is used for manipulation of spin (precession) BUT it dephases the spin too quickly (DP mechanism).

1) Can we use SO coupling to manipulate spin AND increase spin-coherence?
   Use the persistent spin-Helix state or quasi-1D-spin channels and control of SO coupling strength (Bernevig et al 06, Weber et al 07, Wünderlich et al 09, Zarbo et al 10)

2) Can we detect the spin in a non-destructive way electrically?
   Use AHE to measure injected current polarization electrically (Wünderlich, et al Nature Physics. 09, PRL 04)

3) Can this effect be exploited to create a spin-FET logic device
iSHE transistor

Spin Hall effect transistor:
Wunderlich, Jungwirth, et al, Science 2010
SHE transistor AND gate

Spin-FET with two gates → logic AND function

Wunderlich et al., Science.'10
Electrical spin modulator

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SHE angle measurements in Pt Vary by a Factor of 20

T. Kimura et al.
PRL 98, 156601 (2007)
Magnetoresistance signals from SHE and inverse SHE
$\theta_{SH} \sim 0.0037$

K. Ando et al.
PRL 101, 036601 (2008)
Effect of inverse SHE on magnetic damping
$\theta_{SH} \sim 0.08$

O. Mosendz et al.
PRL 104, 046601 (2010), PRB 82, 214403 (2010)
Magnetically-excited Py precession produces voltage by inverse SHE
$\theta_{SH} \sim 0.013$
(assumes $\lambda_{SF} = 10$ nm in Pt)

Courtesy of D.C. Ralph
DC-Detected Spin-Transfer-Driven Ferromagnetic Resonance (ST-FMR)

Resonant resistance oscillations generate a DC voltage component by mixing

$$V(t) = I(t)R(t) \sim I_{RF} \cos(\omega t) \Delta R \cos(\omega t + \delta)$$

$$= \frac{1}{2} I_{RF} \Delta R [\cos(\delta) + \cos(2\omega t + \delta)]$$

$$V_{mix} \sim \frac{1}{2} I_{RF} \Delta R \cos(\delta) \propto \frac{d(Torque)}{dV}$$

Main source of signal at low bias:

Accurate measurement of SHE angle

FMR Peak Shape Analysis

If both Slonczewski and out-of-plane spin-torque components are present then the FMR response is a simple sum of two contributions.

Slonczewski torque: symmetric Lorentzian

Out-of-Plane torque: antisymmetric Lorentzian

\[ V_{\text{mix}} \propto A \frac{1}{1 + [(f - f_0)/\Delta_0]^2} \]

\[ V_{\text{mix}} \propto B \frac{(f - f_0)/\Delta_0}{1 + [(f - f_0)/\Delta_0]^2} \]


Courtesy of D.C. Ralph
Spin torque FMR measurement of the SHE

The two driving forces induce oscillations with 90° phase difference

DC readout of the FMR signal using the anisotropic magnetoresistance of Py

Spin current \( \rightarrow \) in plane torque \( \tau_{ST} \) \( \rightarrow \) symmetric peak

Oersted field \( \rightarrow \) perpendicular torque \( \tau_H \) \( \rightarrow \) antisymmetric peak

Courtesy of D.C. Ralph
**Spin torque FMR measurement of the SHE**

Pt(1.5-15 nm)/Py(2-15 nm), room temperature

Results: $\theta_{SH} = 0.068 \pm 0.005$ for Pt

This is big!

Luqiao Liu et al., PRL 106, 036601 (2011)

Courtesy of D.C. Ralph
Why is $J_S/J_C \sim 0.06$ is Big?

The spin Hall angle is a relationship between \textit{current densities}.

\[
\theta_{SH} = \frac{J_S/(\hbar/2)}{J/e}
\]

To calculate the efficiency of \textit{total spin current} generation, must take into account a difference in areas

\[
\frac{I_S/(\hbar/2)}{I/(e)} \text{ can be } >> 1 \text{ even with } \theta_{SH} \sim 0.06
\]

With the spin Hall effect, the traversal of one electron through the sample can transfer more than $\hbar/2$ angular momentum to a magnet!

Courtesy of D.C. Ralph
spin Hall effect in Ta

INTRINSIC spin Hall conductivity calculated for 4d, 5d elements


• ab initio calculation: $\theta_{\text{SH}}(\text{Ta})$ has opposite sign compared to $\theta_{\text{SH}}(\text{Pt})$
• for highly resistive case, $\theta_{\text{SH}}(\text{Ta})$ can be very large
ST-FMR induced by the SHE in Ta

- antisymmetric peak, same sign (Oersted field)
- symmetric peaks, opposite sign (spin torque)

CoFeB/Ta

\[ \frac{J_S}{J_C} = 0.15 \pm 0.04! \]

Narrower linewidth – less added damping from Ta compared to Pt

\[ f = 9 \text{ GHz} \]

- CoFeB (4nm)/Ta (8nm)

CoFeB/Pt

\[ f = 9 \text{ GHz} \]

- CoFeB (3 nm)/Pt (6 nm)


Courtesy of D.C. Ralph
SHE as a source for spin current

**Spin Hall Device**

- $J_S$ and $J_C$ travel perpendicular paths

**Conventional Magnetic Tunnel Junction**

- $J_S$ and $J_C$ travel the same path

What is

$$\theta_{SH} = \frac{J_S}{J_C}$$

in various metals?

Courtesy of D.C. Ralph
• Switch the magnetic moment using the SHE via an anti-damping mechanism
• Use a magnetic tunnel junction to read out the magnetic orientation

Ta strip 1 µm wide
MTJ 100×300 nm²
DC current in Ta strip to write
Resistance measurement across the MTJ to read

DC current induced switching

- Ramp-rate measurement of critical currents:
  \[ I_{c0} = 2.0 \text{ mA} \quad \text{and} \quad E_0 \sim 46 \, k_B T \]

\[ J_S/J_C \approx 0.12 \pm 0.03 \]

agrees with ST-FMR and perpendicular switching measurements

No barrier degradation, better read-out signal compared to conventional devices.

Switching currents well below 100 µA should be possible.

May 4th 2012

Courtesy of D.C. Ralph
Spin Hall Effect: from fundamentals to applications

- SOC Effects
  - AMR
  - AHE
- CIT
  - Current induced torque
- SHE
  - SHE
- SHE
  - SHE
- SHE
  - SHE
- Extrinsic
- Intrinsic
- Spin current detector
- Optical
- Electrical
- Spin Pumping
- FMR
- Spin current generator
- STT
- Spin Caoloritronics

Jungwirth, Wunderlich, Olejnik, Nat. Mat. 11,382 (2012)