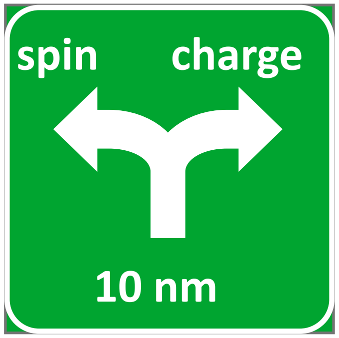
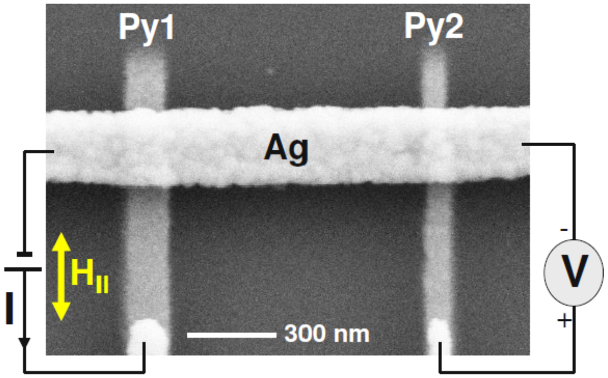
Pure Spin Currents: Discharging Spintronics

IEEE Magnetics Society Distinguished Lecture



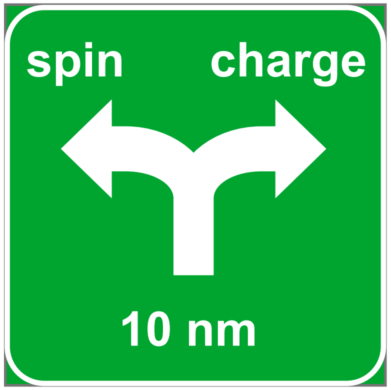


Axel Hoffmann

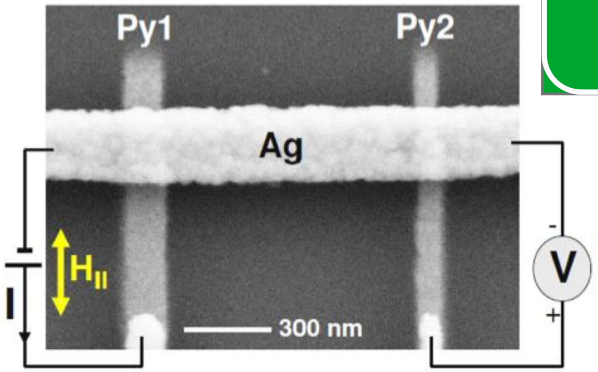
Materials Science Division
Argonne National Laboratory
hoffmann@anl.gov

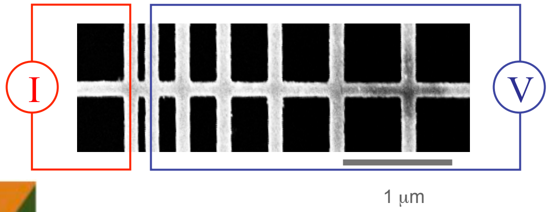
Presented November 15, 2011
IEEE
Santa Clara Valley Magnetics Society

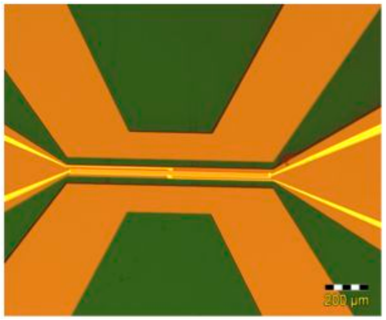
Outline



- Why Pure Spin Currents?
- Electrical Injection
- Spin Hall Effect
- Spin Pumping
- Conclusions







IEEE Magnetics Society

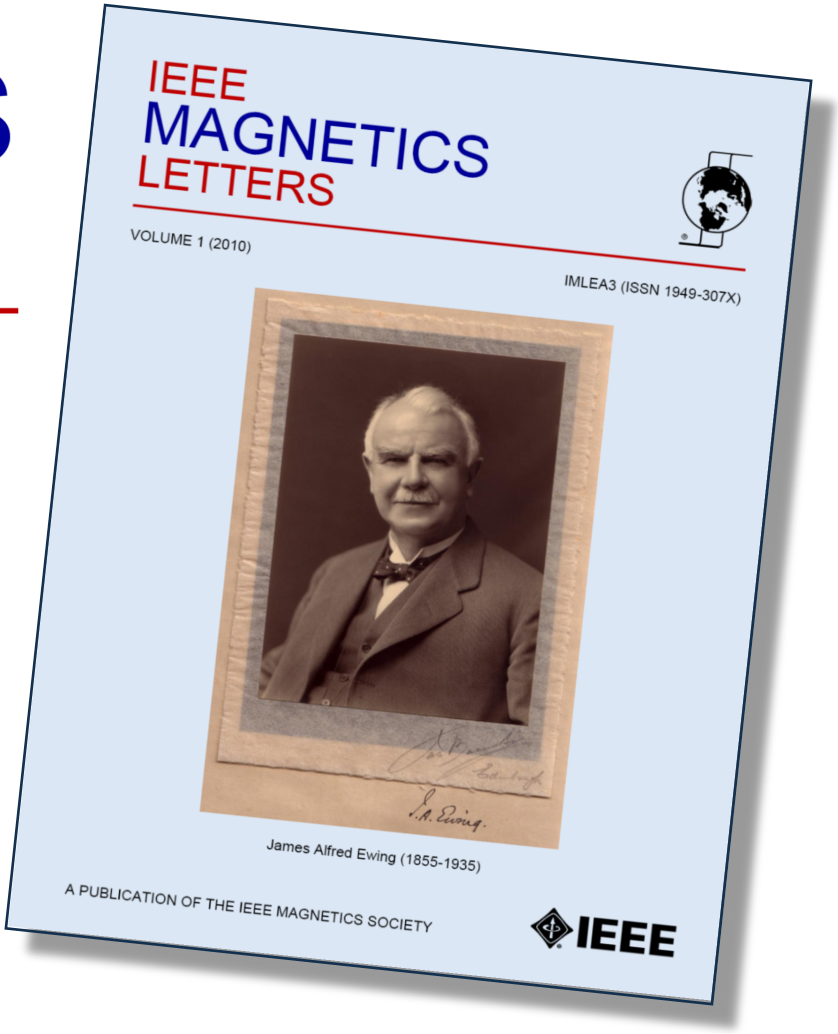
IEEE

- **IEEE Magnetics Society Home Page: *www.ieeemagnetics.org***
  - 3500 full members
  - 300 student members
- **The Society**
  - Conference organization (INTERMAG, MMM, TMRC, etc.)
  - Student support for conferences and magnetism summer school
  - Large conference discounts for members
  - Local chapter activities
  - Distinguished lectures
  - Society awards
- ***IEEE Transactions on Magnetics***
  - ~2000 peer reviewed pages each year
  - Electronic access to all *IEEE Transactions on Magnetics* papers
- **Since 2010 *IEEE Magnetics Letters*;** a rapid-publication, primarily electronic, peer-reviewed journal dedicated exclusively to magnetics articles of substantial current interest. (See MagSoc Homepage)
- **Online applications for IEEE membership: *www.ieee.org/join***
  - 360,000 members
  - IEEE student membership $30
  - IEEE full membership $150

IEEE
MAGNETICS
LETTERS

The Journal of Your Field

- Peer reviewed
- Rapid publication
- IEEE Xplore archive
- Four-page articles
- No page charges



IEEE
MAGNETICS
LETTERS

VOLUME 1 (2010)

IMLEA3 (ISSN 1949-307X)

James Alfred Ewing (1855-1935)

A PUBLICATION OF THE IEEE MAGNETICS SOCIETY

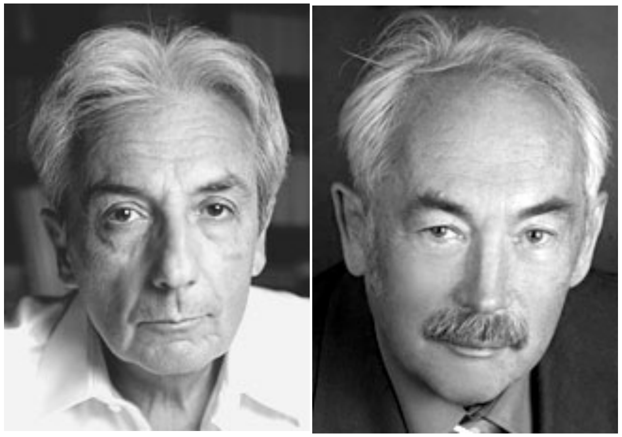
IEEE

On line at ieeexplore.ieee.org
Submit manuscripts at mc.manuscriptcentral.com/maglet-ieee

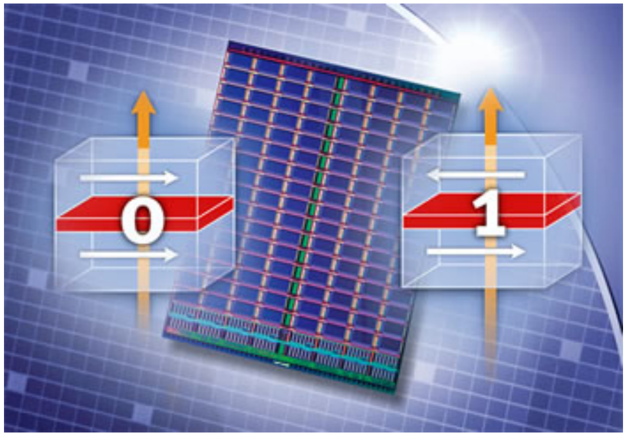
Spintronics

Putting

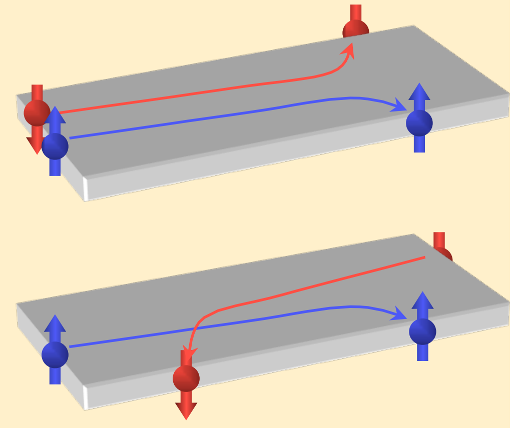
into Electronics



Nobel Prize



Novel Devices

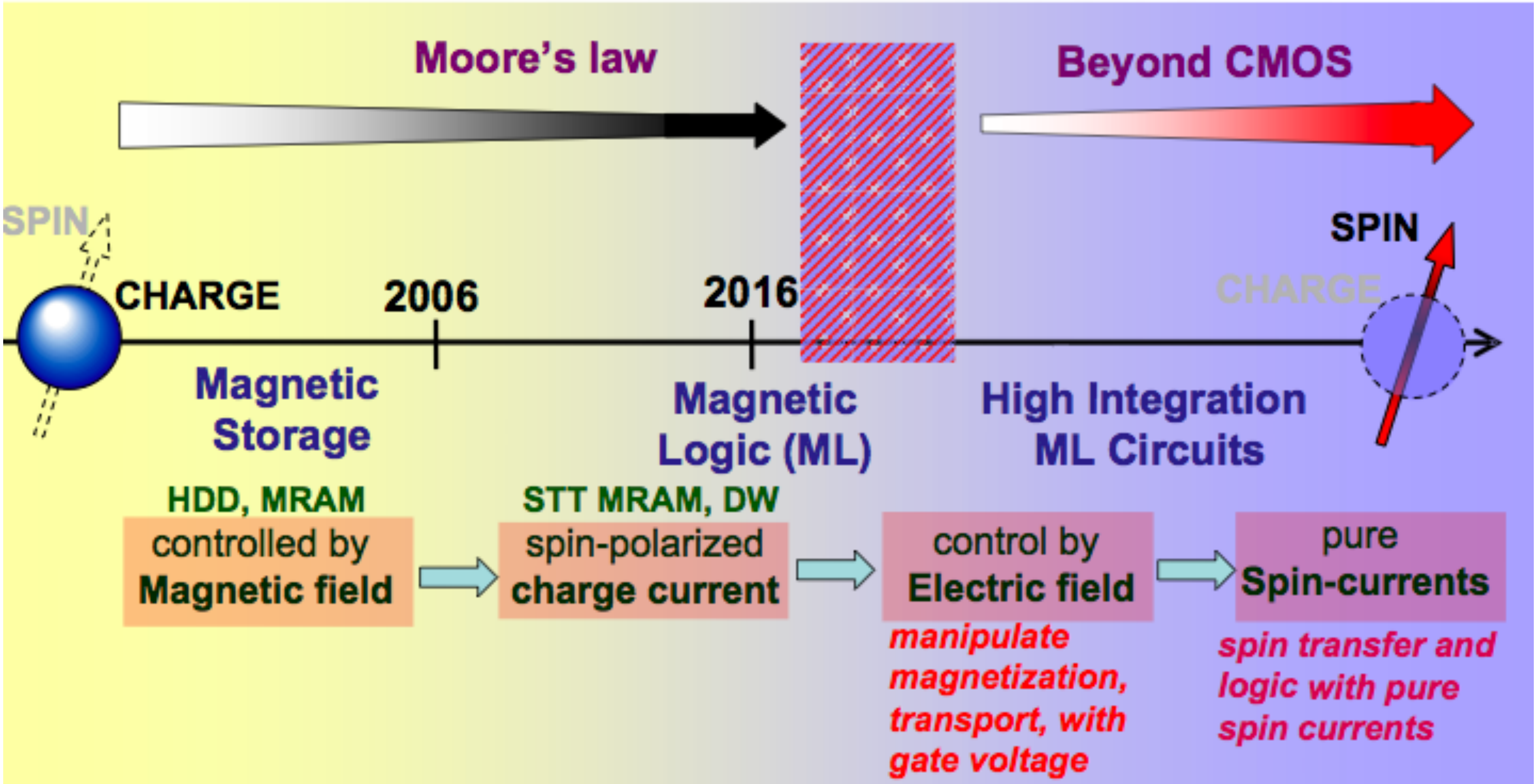


New Physics

Recent Review: S. D. Bader and S. S. P. Parkin, Annu. Rev. Cond. Matter Phys. **1**, 71 (2010)

Tentative roadmap

Courtesy Claude Chappert, Université Paris Sud



Moore's law

Beyond CMOS

Magnetic Storage

Magnetic Logic (ML)

High Integration ML Circuits

HDD, MRAM

controlled by **Magnetic field** →

STT MRAM, DW

spin-polarized **charge current** →

control by **Electric field** →

manipulate magnetization, transport, with gate voltage

pure **Spin-currents**

spin transfer and logic with pure spin currents

increase in anisotropy "effective" field to maintain non volatility → increase in precession frequency → speed will increase !!!!

Charge vs. Spin Currents

Charge

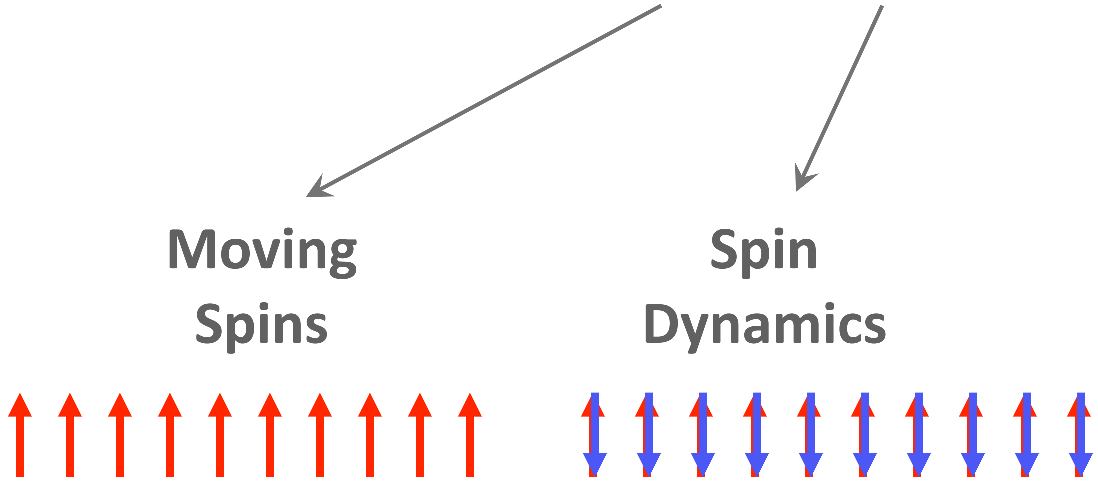
$$\vec{j}_e = \tfrac{d}{dt}\left(q\vec{r}\right)$$

$$\vec{j}_e = q\vec{v}$$

Spin

$$\vec{j}_s = \tfrac{d}{dt}\left(\sigma\vec{r}\right)$$

$$\vec{j}_s = \sigma\vec{v} + \dot{\sigma}\vec{r}$$



Moving Spins

Spin Dynamics

No Need for Moving Spin:
Potential for Low Power Dissipation!

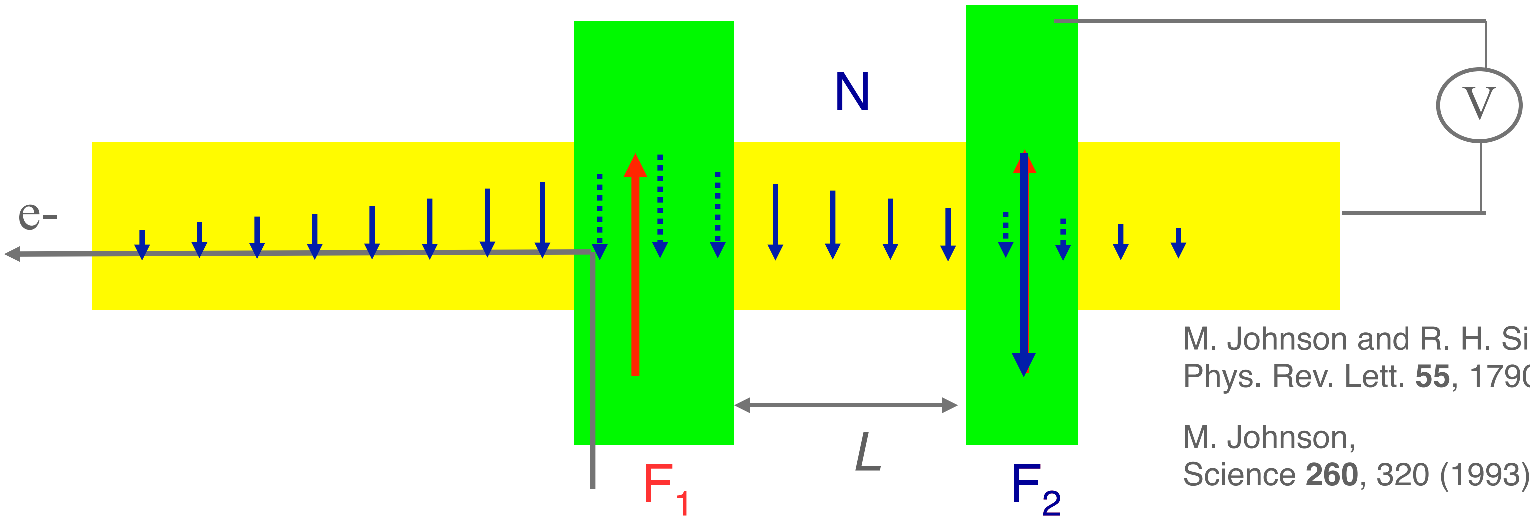
J. Shi, *et al.*, Phys. Rev. Lett. **96**, 076604 (2006).

Can we generate pure spin currents in paramagnetic materials?

YES !!!

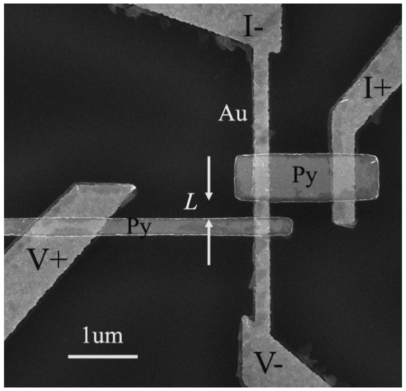
- Non-local geometries
- Spin-dependent scattering (Spin-Hall)
- Spin pumping

Pure Spin Currents: Non-Local Spin Valves

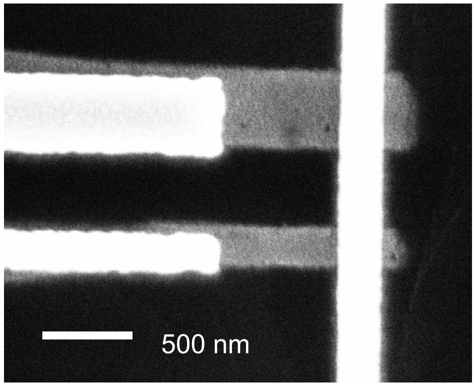


M. Johnson and R. H. Silsbee,
Phys. Rev. Lett. **55**, 1790 (1985)

M. Johnson,
Science **260**, 320 (1993)



Our Early Work



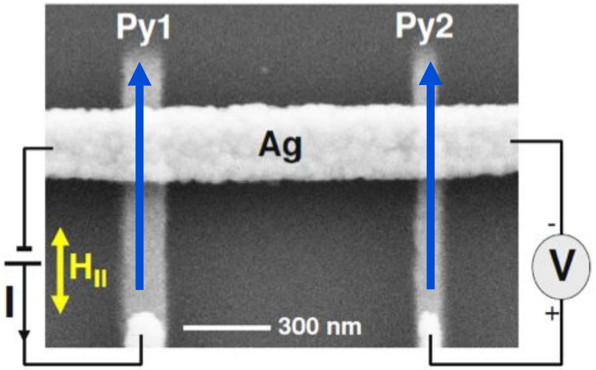
Au: λ_s = 63±15 nm (10 K)

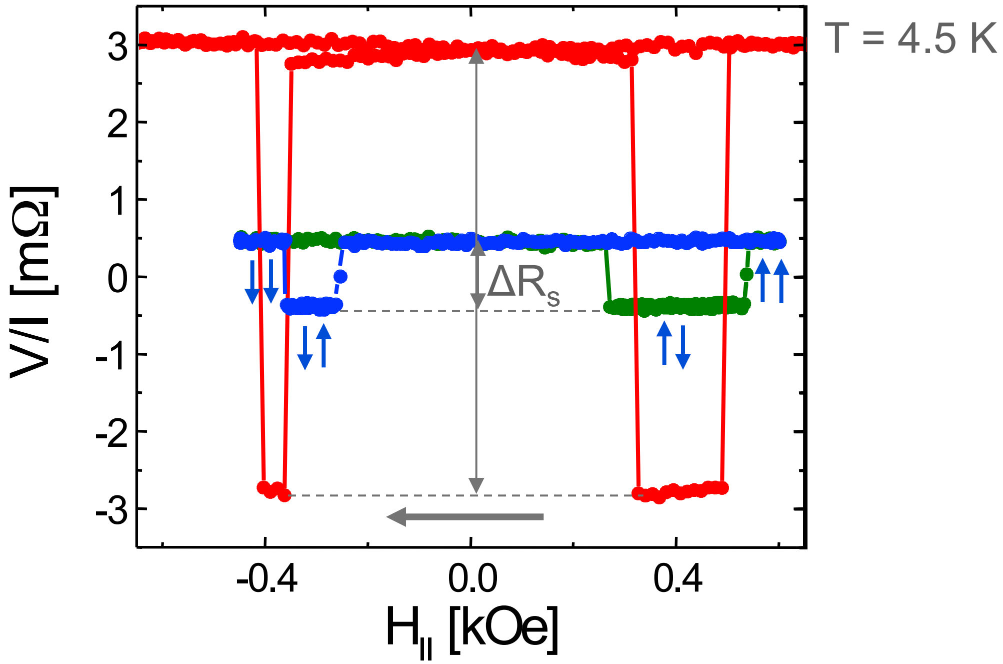
Y. Ji *et al.,* Appl. Phys. Lett. **85**, 6218 (2004)

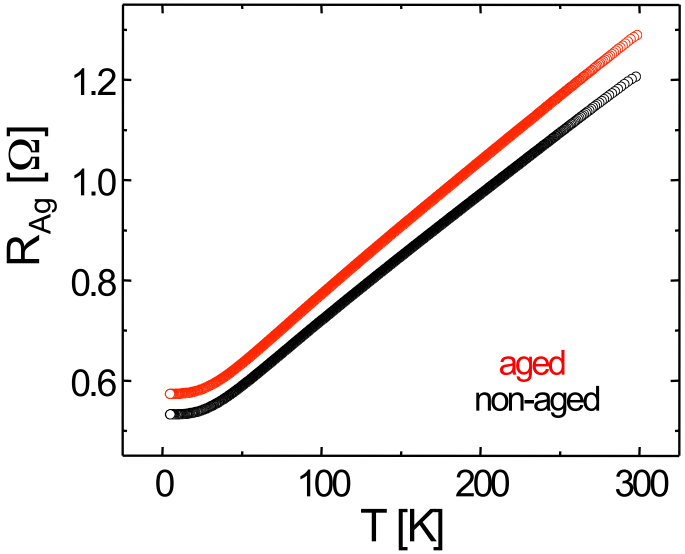
Cu: λ_s = 200 ±20 nm (10 K)

Y. Ji *et al.,* Appl. Phys. Lett. **88**, 052509 (2006)

Py/Ag Non-Local Spin Valve







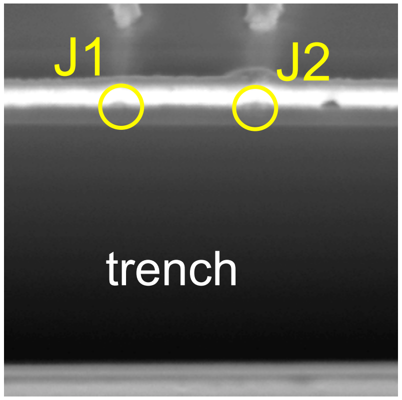
$$\Delta R_s = 0.9\ \text{m}\Omega \xrightarrow[\text{in air}]{\text{after 2 weeks}} \Delta R_s = 5.9\ \text{m}\Omega$$

$$\boxed{\Delta R_s = \frac{P^2 \rho \lambda_s}{A} \exp\left(-\frac{L}{\lambda_s}\right)}$$

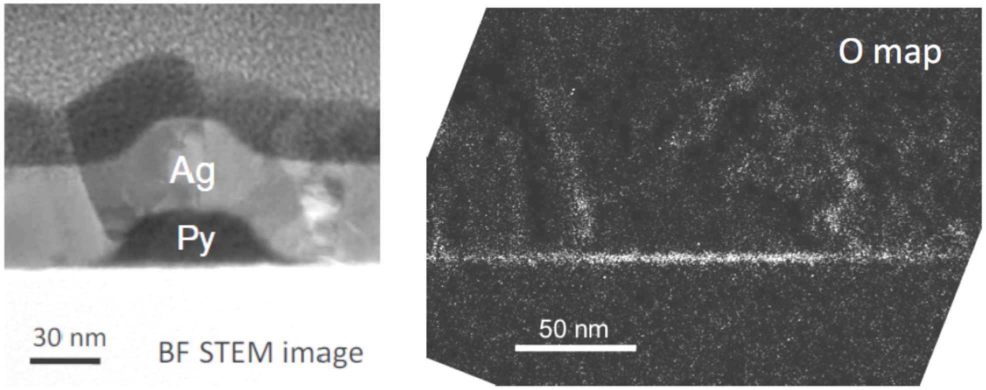
G. Mihajlović *et al.*, Appl. Phys. Lett. **97**, 112502 (2010)

Origin of Enhanced ΔR_s

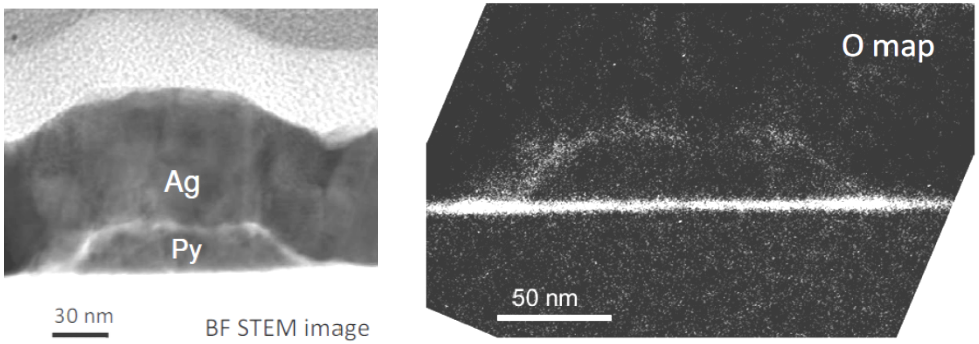
FIB sliced LSV



TEM of a non-aged sample



TEM of an aged sample

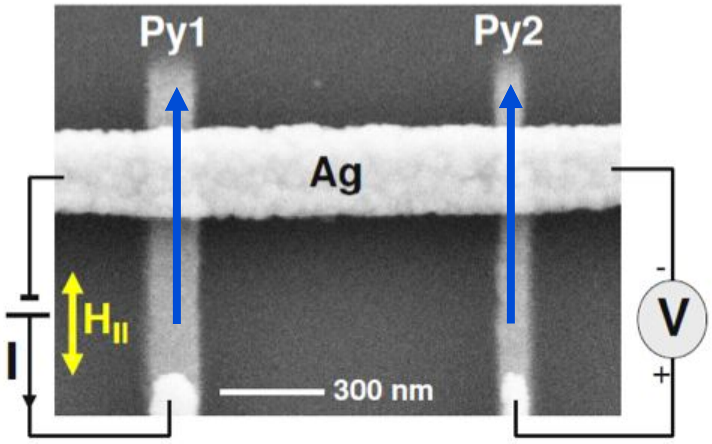


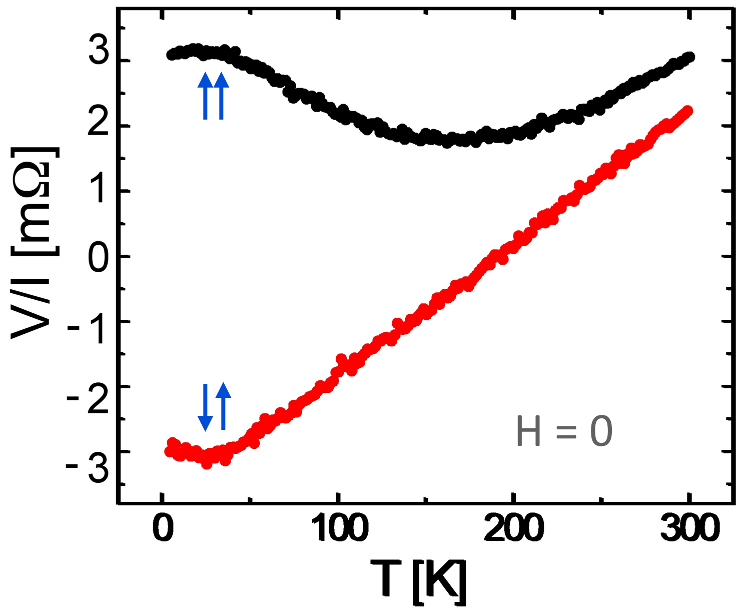
Thin layer of O-rich compound observed at Py-Ag interface in aged samples

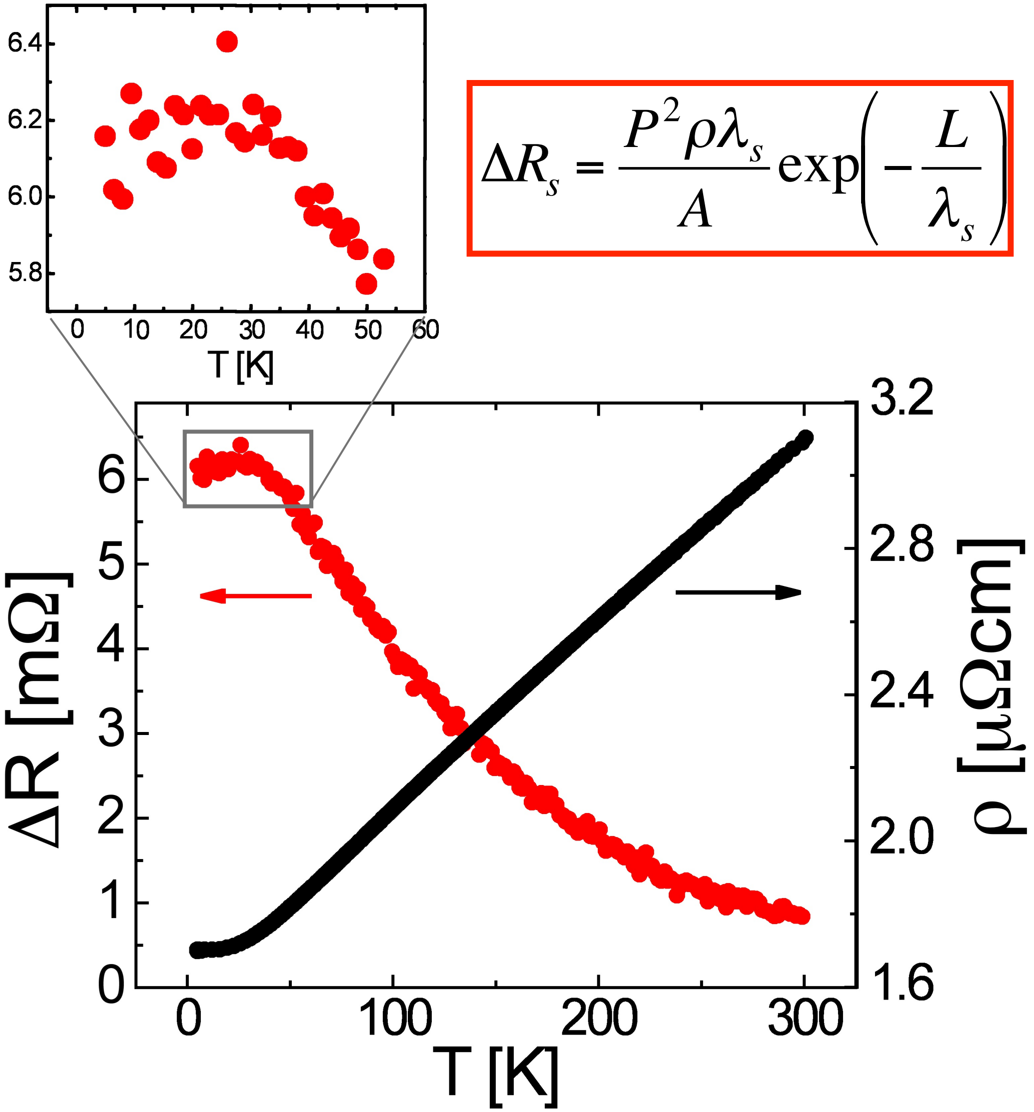
Higher interface resistance ➡ Better spin injection efficiency

G. Mihajlović *et al.*, Appl. Phys. Lett. **97**, 112502 (2010)

Temperature Dependence of Spin Signal



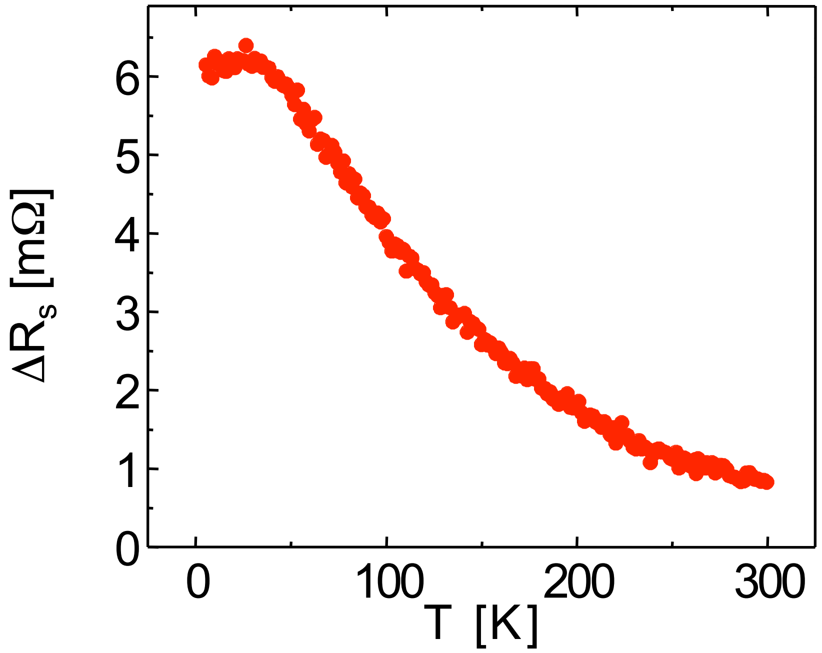


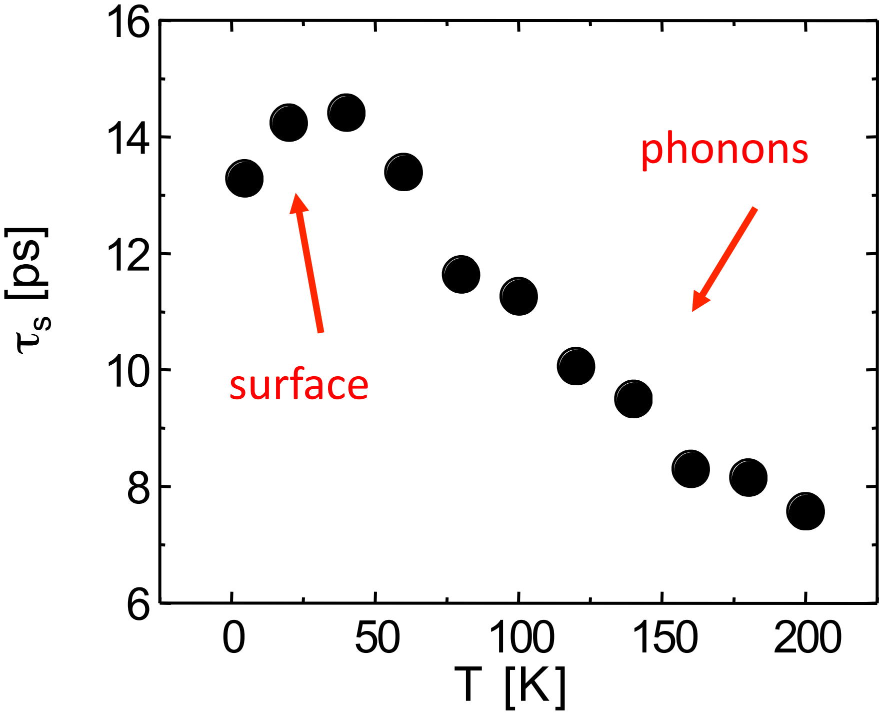


$$\Delta R_s = \frac{P^2 \rho \lambda_s}{A} \exp\left(-\frac{L}{\lambda_s}\right)$$

G. Mihajlović *et al.*,
Phys. Rev. Lett. **104**, 237202 (2010)

T-Dependence of Spin Relaxation Time





phonons

surface

$$\lambda_s = \sqrt{D\tau_s}$$

$$\boxed{\Delta R_s = \frac{P^2 \rho \lambda_s}{A} \exp\left(-\frac{L}{\lambda_s}\right)}$$

ΔR_s decreases

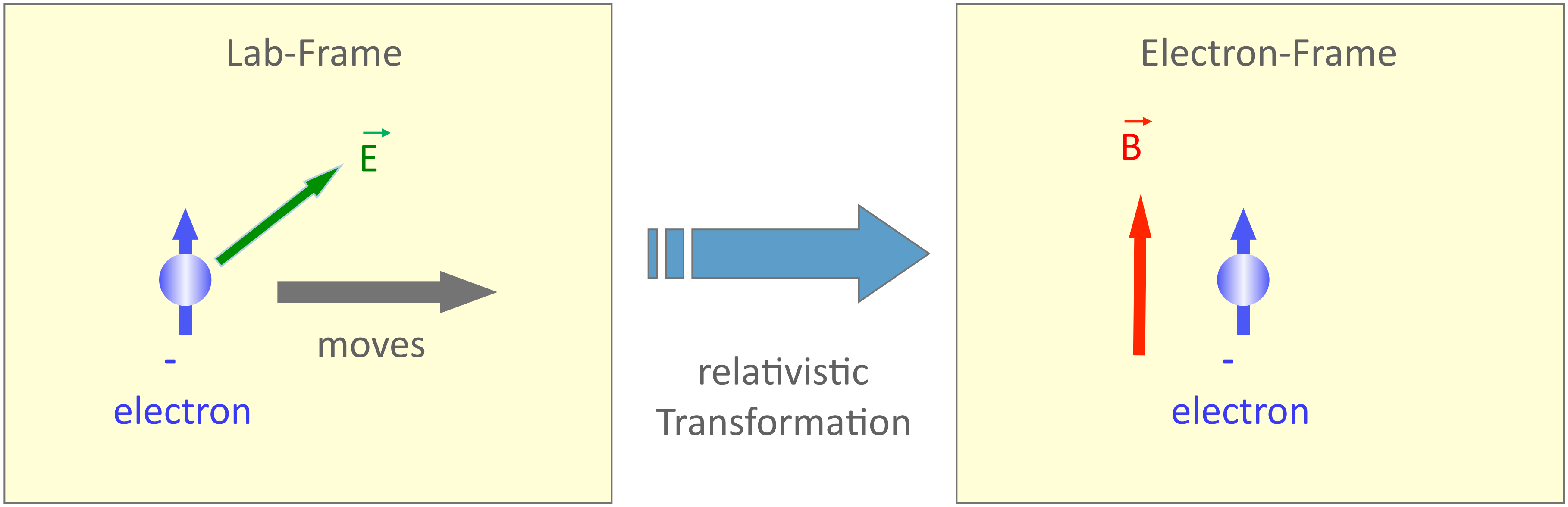
Quantitative analysis of spin flip probability: $\varepsilon_S = 3.6\%$ and $\varepsilon_{ph} = 0.75\%$

due to decreasing τ_s

G. Mihajlović *et al.*, Phys. Rev. Lett. **104**, 237202 (2010)

Spin-Orbit Interaction

$$H_{SO} = \frac{\hbar}{4m^2c^2}\left(\vec{\nabla}V \times \vec{p}\right)\cdot\vec{\sigma}$$



Lab-Frame

electron

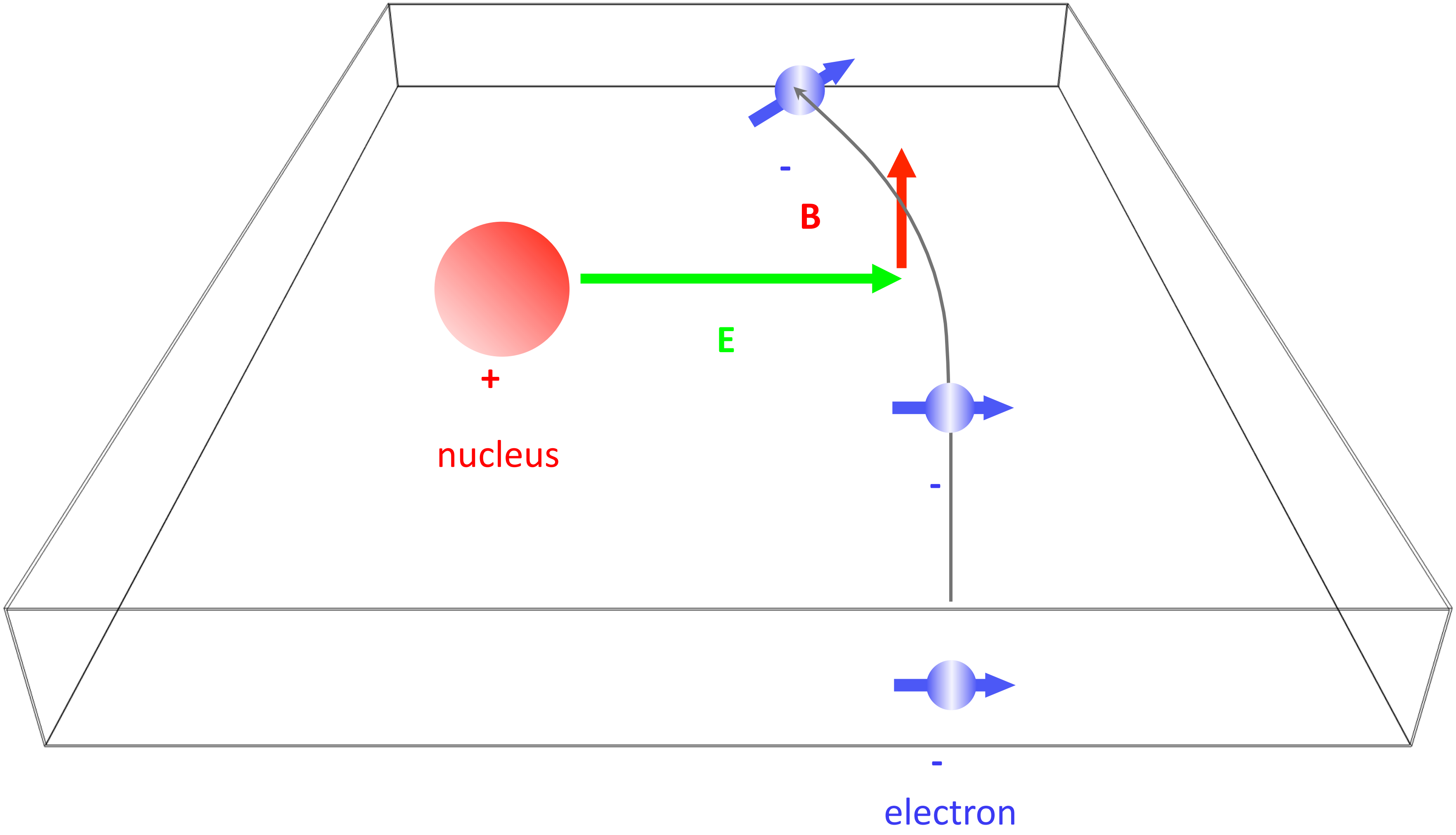
moves

relativistic Transformation

Electron-Frame

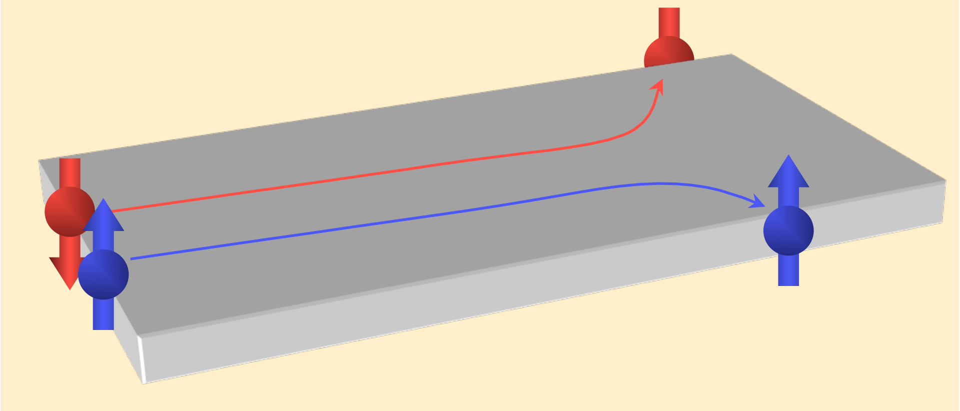
electron

Spin Relaxation (Elliot-Yafet)

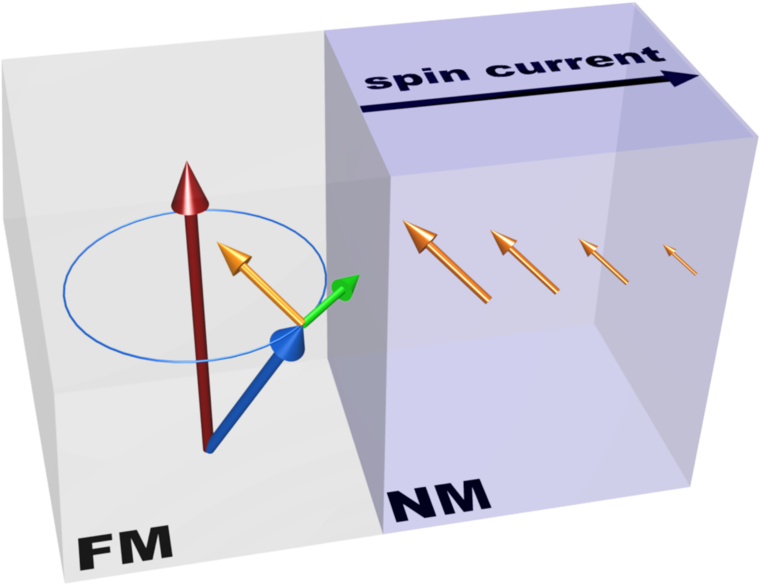


Alternative Approaches to Pure Spin Currents

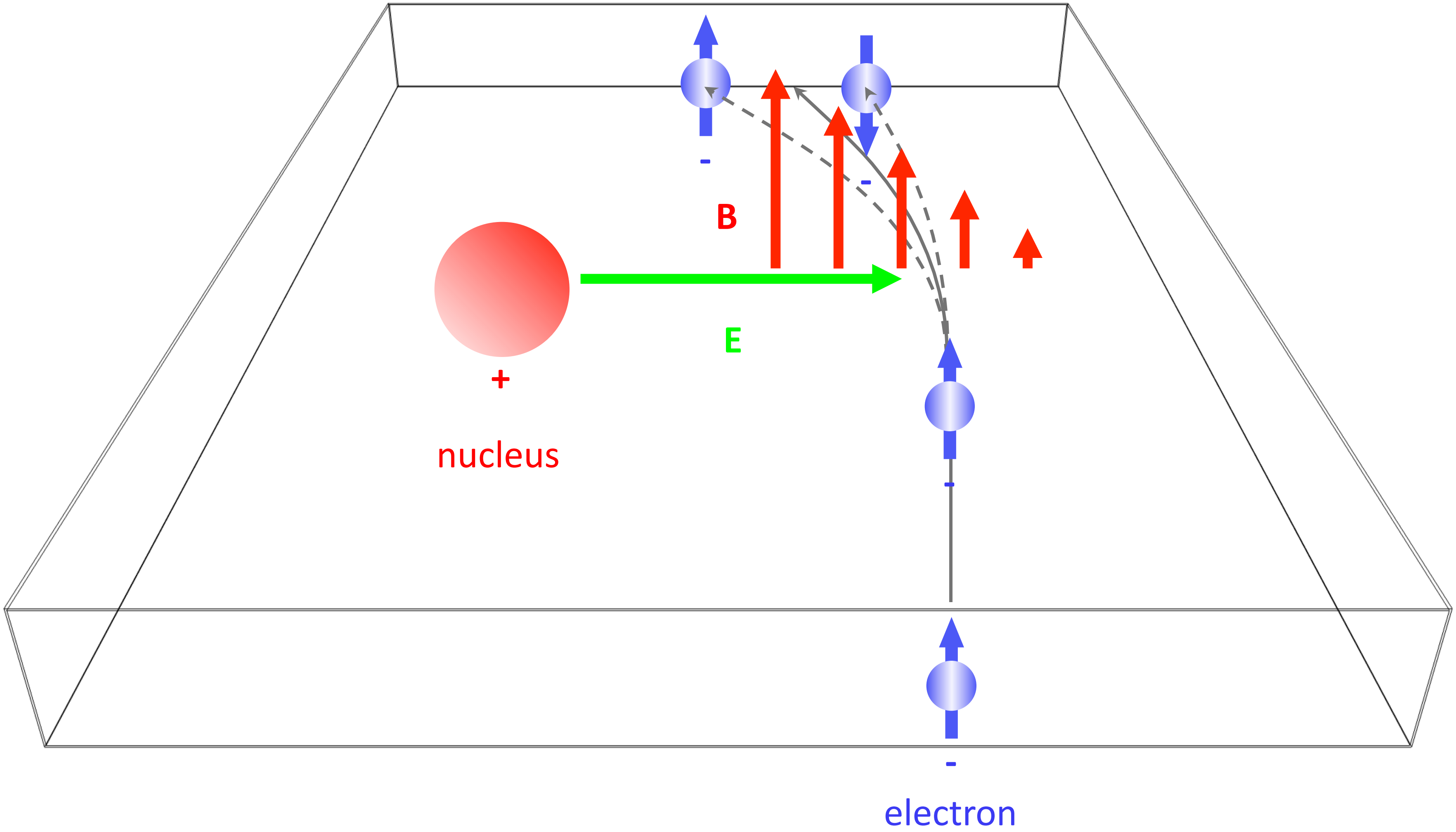
Spin Hall Effect



Spin Pumping



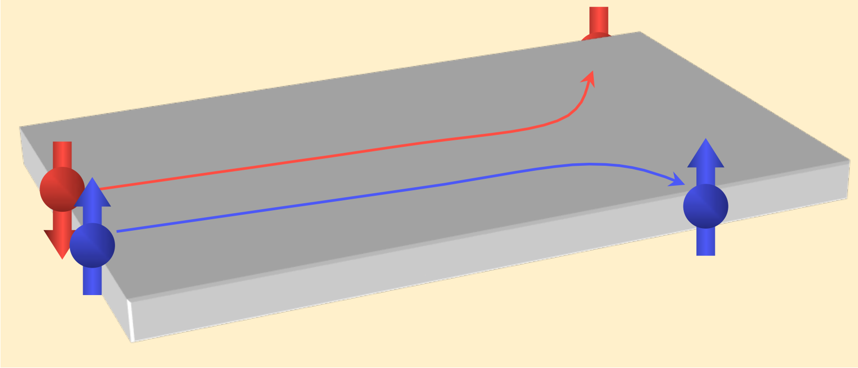
Spin-Skew Scattering

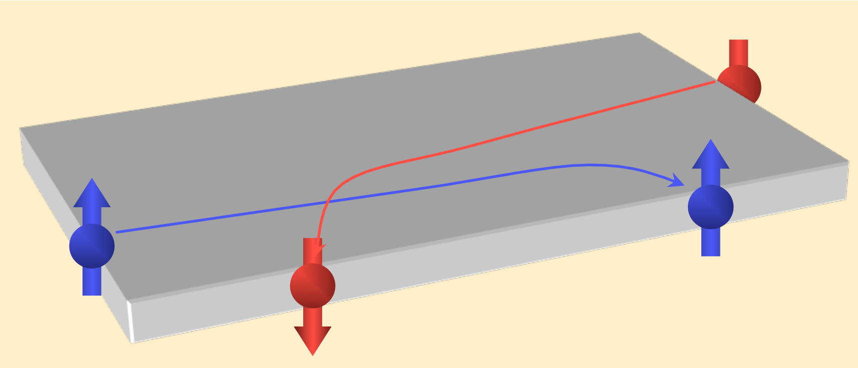


Spin Hall vs. Inverse Spin Hall

M.I. Dyakonov & V. I. Perel, *Sov. Phys. JETP Lett.* **13**, 467 (1971); J.E. Hirsch, *Phys. Rev. Lett.* **83**, 1834 (1999)

Spin Hall		Inverse Spin Hall
Charge Current		**Spin Current**
⇓	**Spin Dependent Scattering**	⇓
Transverse		**Transverse**
Spin Imbalance		**Charge Imbalance**





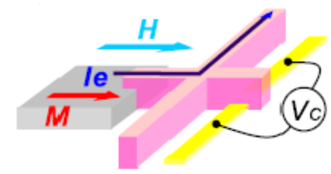
Quantifying Spin Hall Angles in Metals

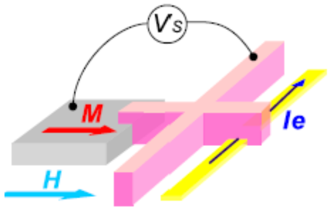
$$\gamma = \frac{\sigma_{SH}}{\sigma_c}$$

← spin Hall conductivity

← charge conductivity

Electrical injection Magnetotransport measurements:





S. O. Valenzuela & M. Tinkham,
Nature **442,** 176 (2006)

Al: γ **= 0.0001- 0.0003**

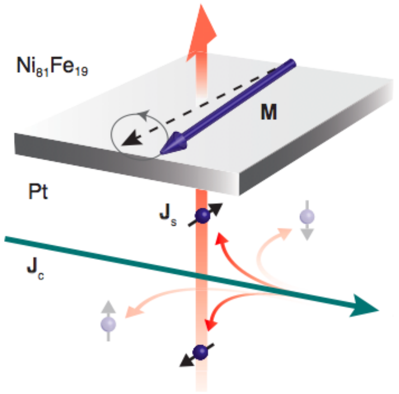
T. Kimura et al.,
PRL **98**, 156601 (2007)

Pt: γ **= 0.0037**

T. Seki et al.,
Nature Mater. **7,** 125 (2008)

Au: γ **= 0.113**

Spin Torque modulated Ferromagnetic resonance:



K. Ando et al.,
PRL **101**, 036601 (2008)

Pt: γ **= 0.08**

L. Liu et al.,
PRL **106**, 036601 (2011)

Pt: γ **= 0.076**

Large discrepancies in γ values !

Need robust technique to quantify spin Hall angle!

Spin-mediated Charge Current Teleportation

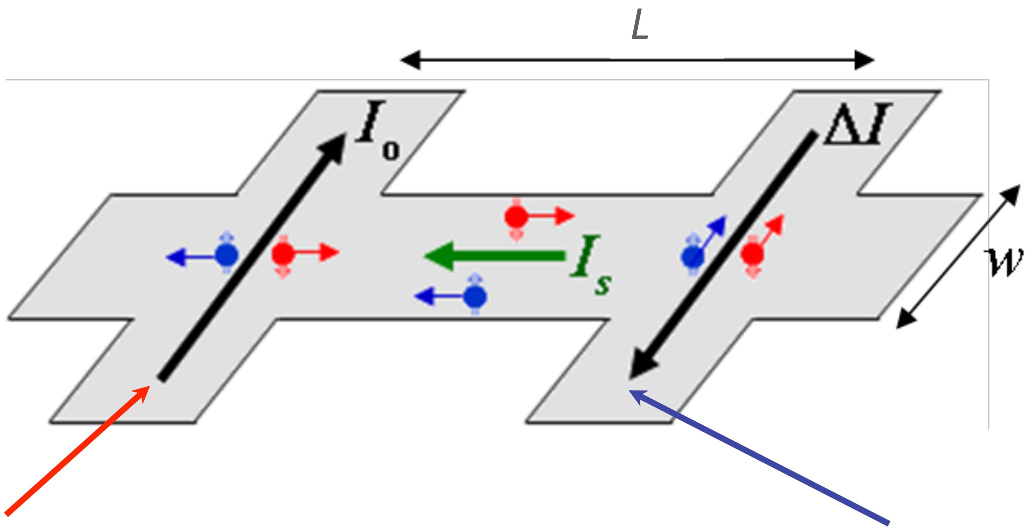
J.E. Hirsch, *Phys. Rev. Lett.* **83**, 1834 (1999)

E. M. Hankiewicz et al., Phys. Rev. B 70, 241301(R) (2004)

M. I. Dyakonov, *Phys. Rev. Lett.* **99**, 126601 (2007)

D. A. Abanin et al., Phys. Rev. B 79, 035304 (2009)

Theoretical Idea: Use Spin Hall Effects Twice!



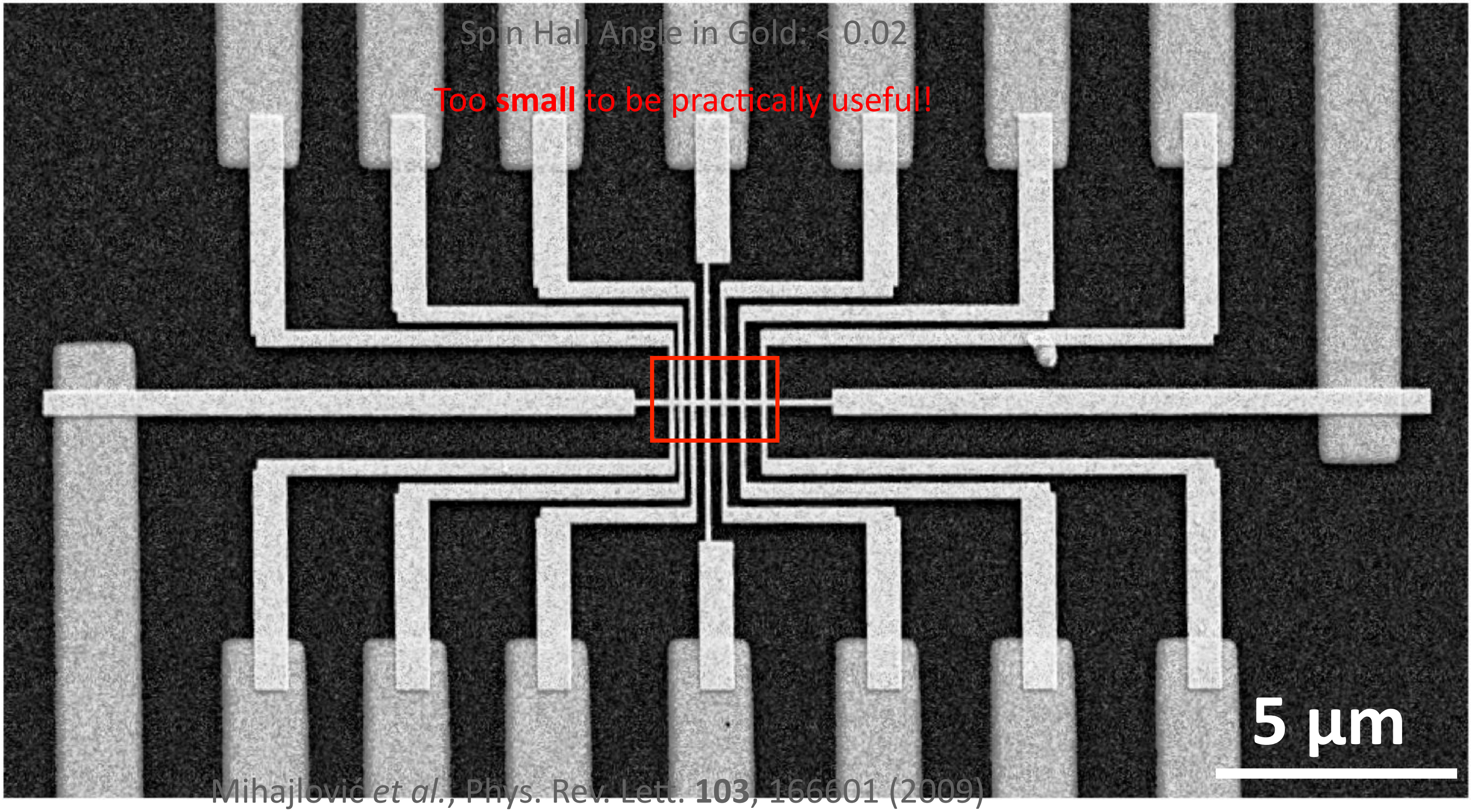
Direct Spin Hall Effect

Generate
Pure Spin Current

Inverse Spin Hall Effect

Detect
Pure Spin Current

Gold Hall Bar Structures



Spin Hall Angle in Gold: < 0.02

Too **small** to be practically useful!

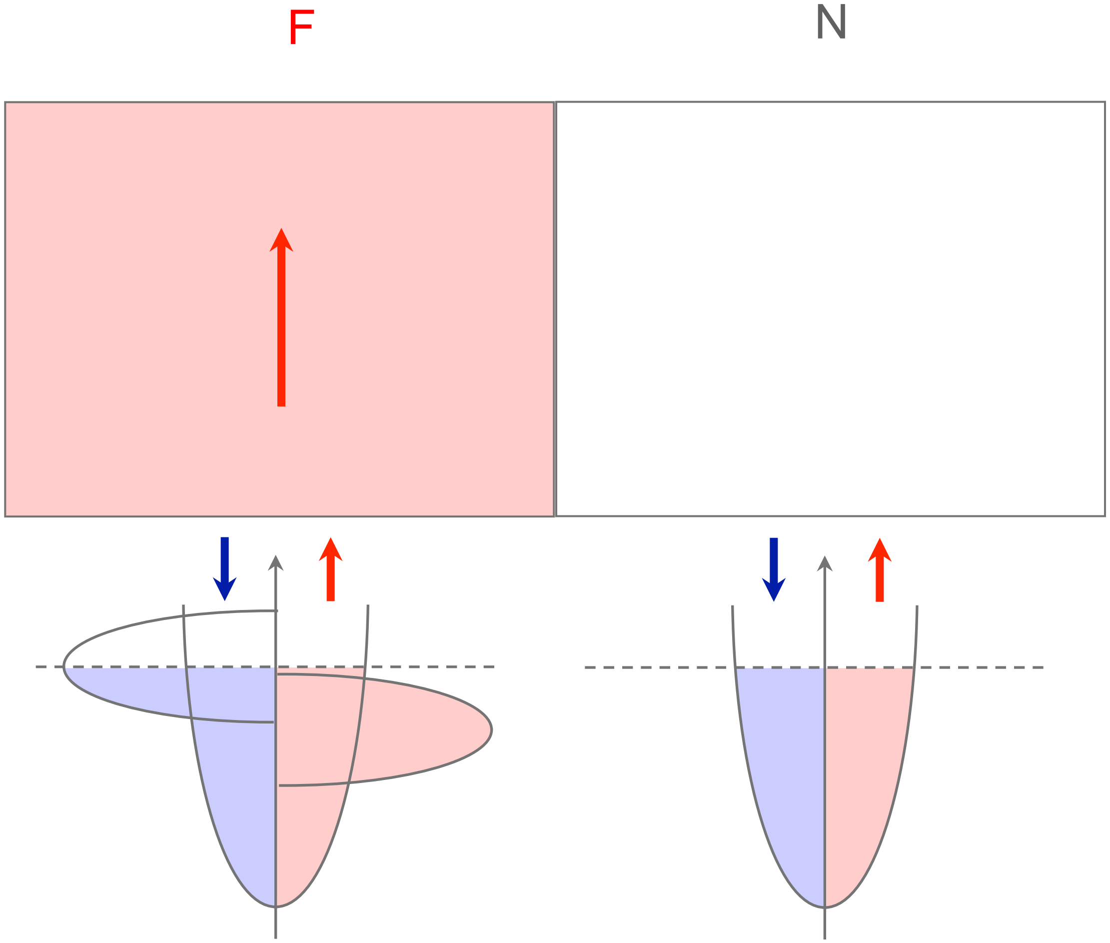
Mihajlović *et al.*, Phys. Rev. Lett. **103**, 166601 (2009)

What do we do now?

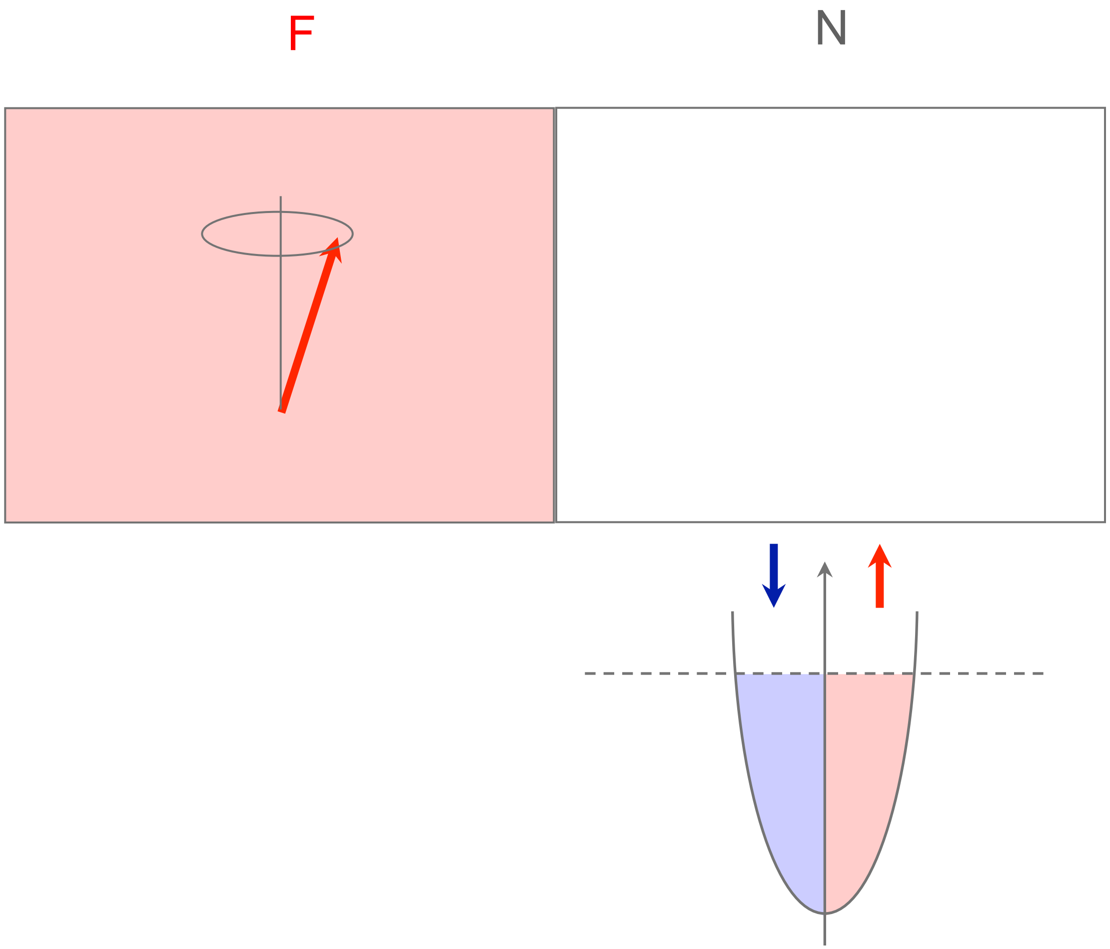
Unusual Application of Spin Dynamics

As found in: Queen Victoria Pub, Durham, U. K.

Spin Pumping

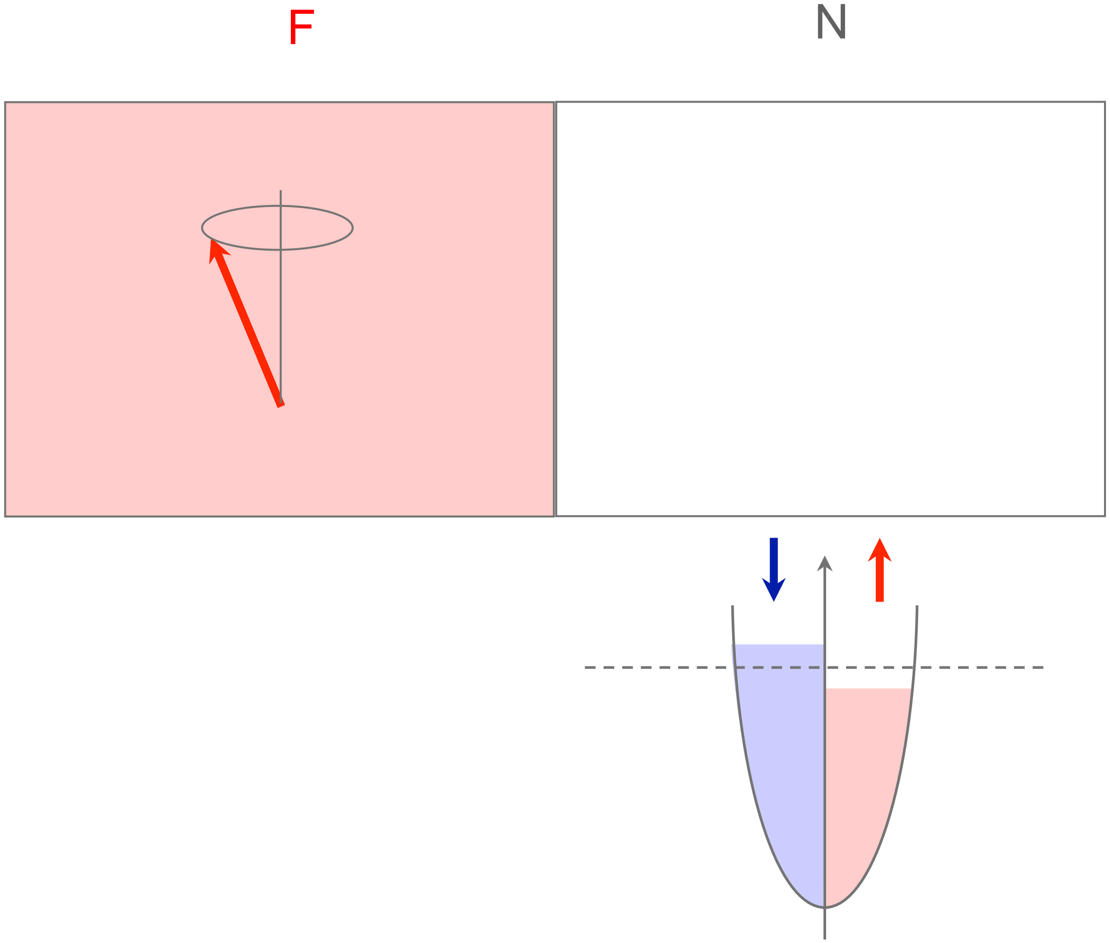


Spin Pumping



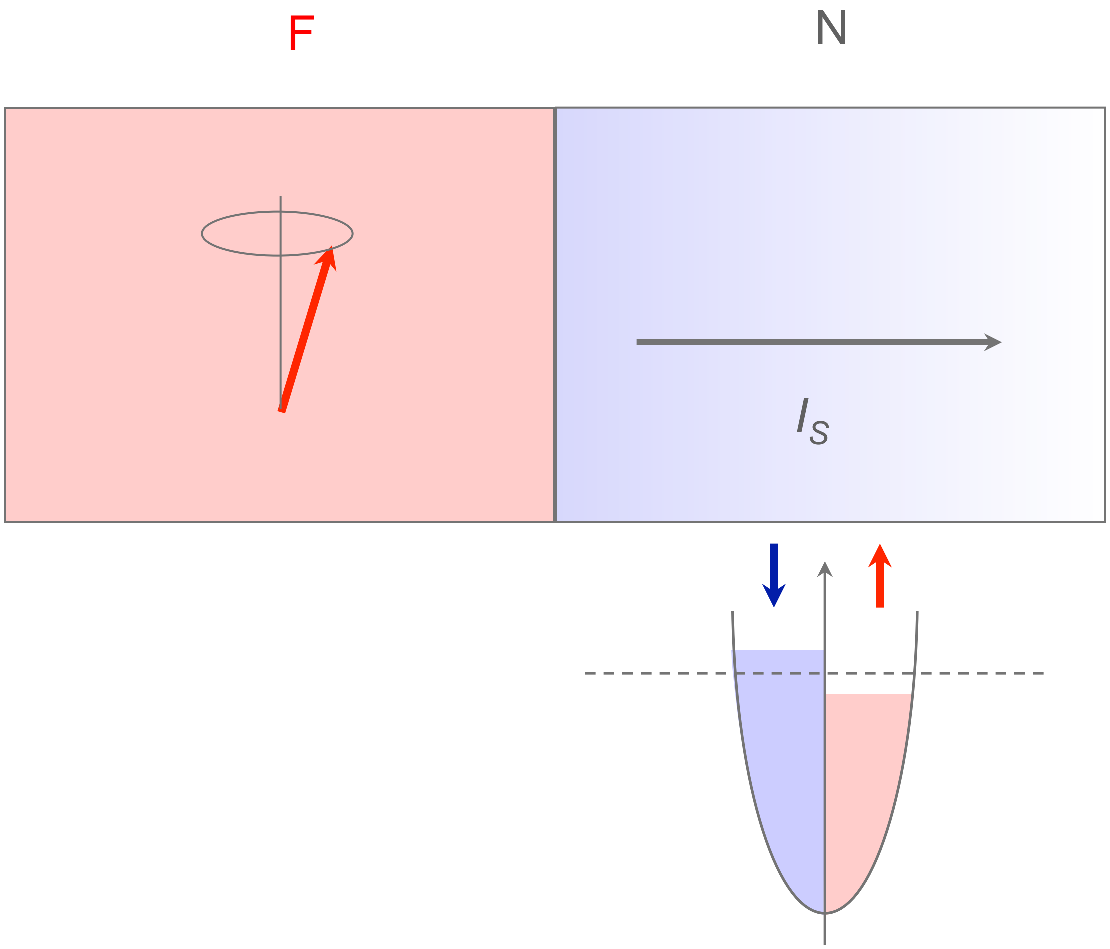
Excite ferromagnetic resonance

Spin Pumping



Time dependent interfacial potential
gives rise to spin accumulation in normal metal

Spin Pumping



Spin accumulation gives rise to spin current in neighboring normal metal

Quantify Spin Current from Spin Pumping

Y. Tserkovnyak, A. Brataas and G.E.W. Bauer, Phys. Rev. Lett. **88**, 117601 (2002)

$$\vec{j}_{spin}^{\,pump} = \frac{\hbar}{8\pi}\mathrm{Re}(2g_{\uparrow\downarrow})\left(\vec{m}\times\frac{d\vec{m}}{dt}\right)$$

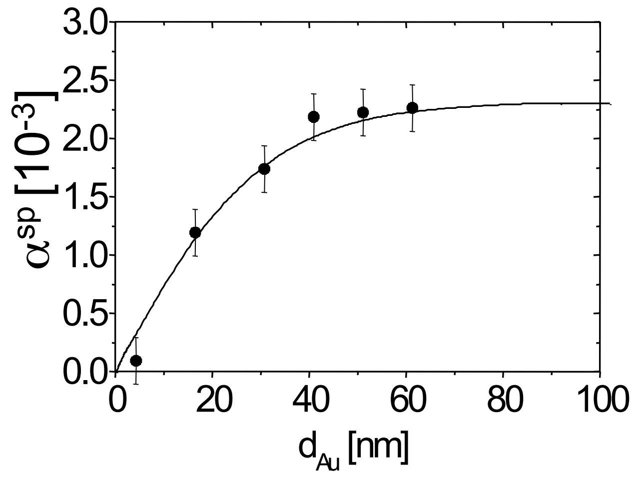
$$\vec{m} = \frac{\vec{M}}{M_s}$$

DC part:

$$j_{s,dc} = \frac{\hbar}{4\pi} g_{\uparrow\downarrow}\,\omega \sin^2\theta$$

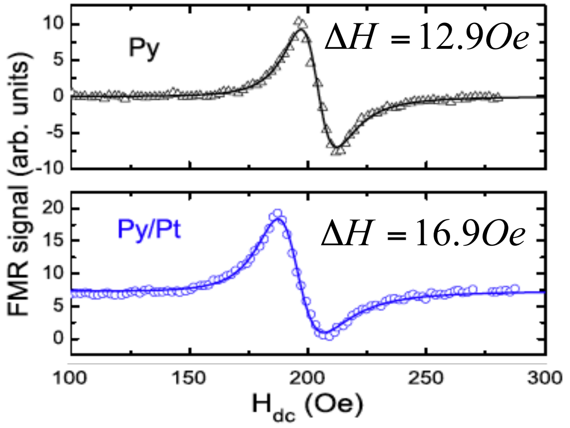
Increased Damping

O. Mosendz *et al.*, Phys. Rev. B **79**, 224412 (2009)

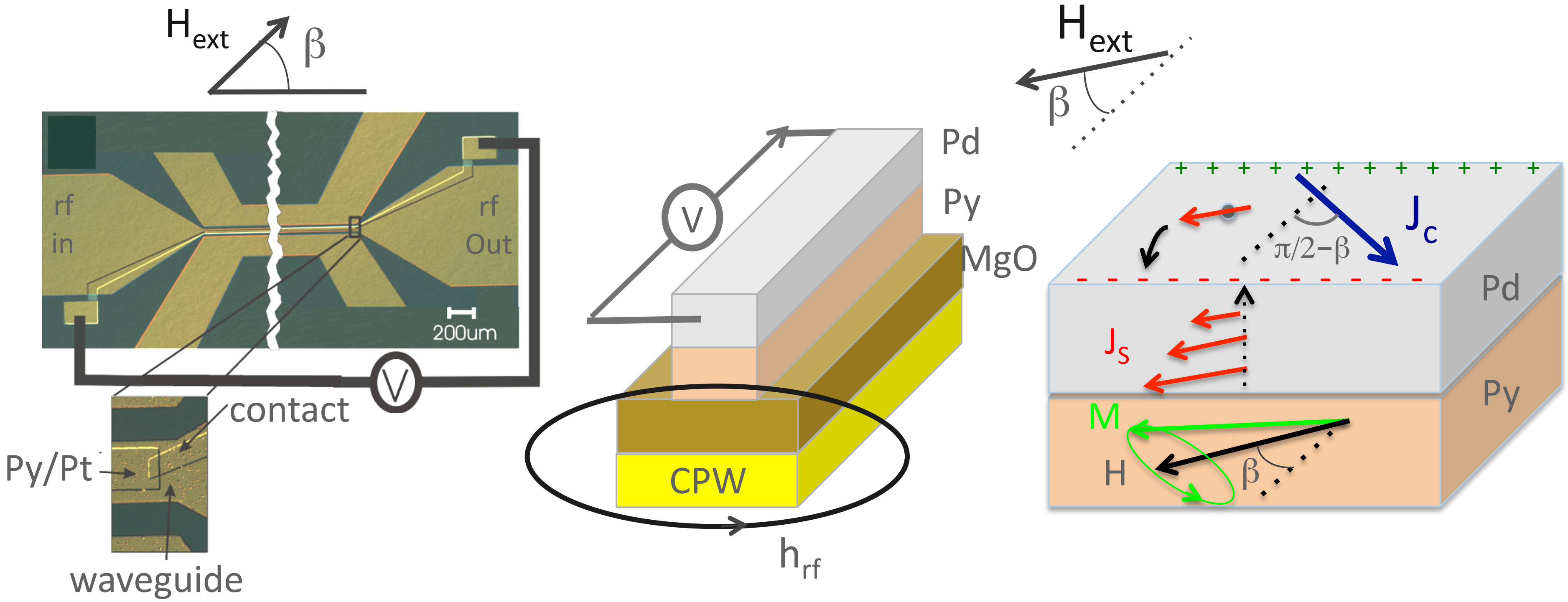


FMR linewidth determines spin mixing conductance

$$g_{\uparrow\downarrow} = \frac{4\pi\gamma_g M_s t_{Py}}{g\mu_B\omega}\left(\Delta H_{NM/Py} - \Delta H_{Py}\right)$$



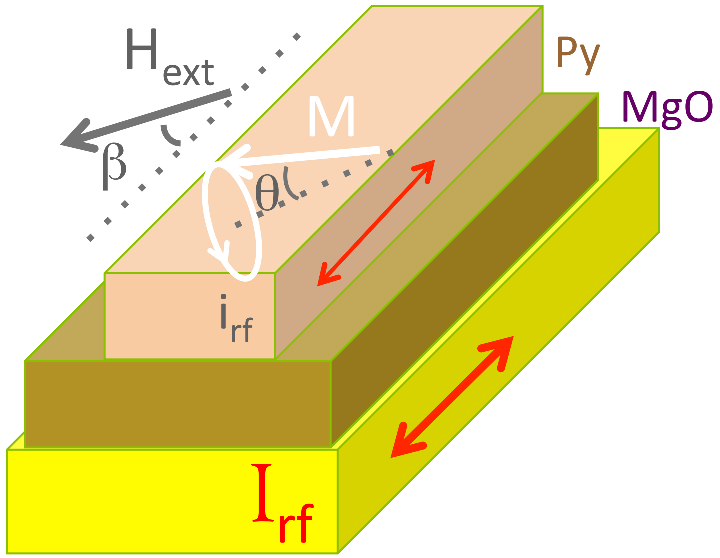
Combine Spin Pumping and Inverse Spin Hall Effect

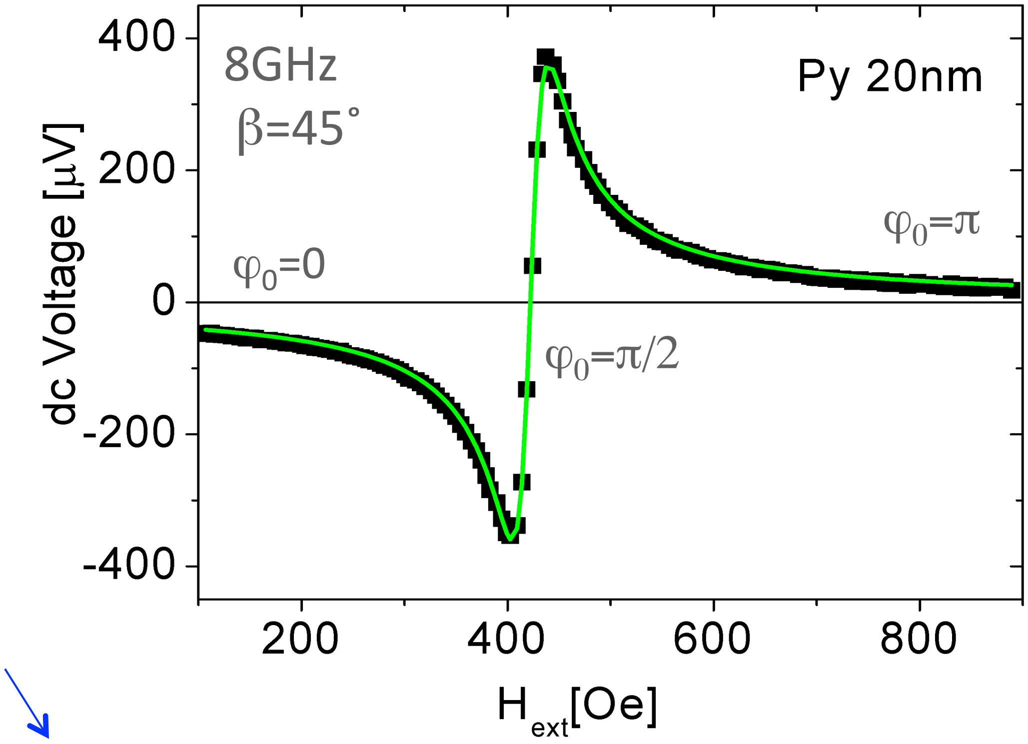


- Use Spin Pumping to Generate Pure Spin Current
  E. Saitoh, *et al.*, Appl. Phys. Lett. **88**, 182509 (2006)
- Quantify Spin Current from FMR
- Measured Voltage Directly Determines Spin Hall Conductivity
  O. Mosendz, *et al.*, Phys. Rev. Lett. **104**, 046601 (2010); Phys. Rev. B **82**, 214403 (2010)

Measured Voltage - only Py

Single layer of Permalloy → Antisymmetric signal





cone angle

$$\langle V_{AMR}\rangle = I_{rf}^{m}\frac{R_{CPL}}{R_S}\Delta R_{AMR}\frac{\sin 2\theta}{2}\frac{\sin 2\beta}{2}\cos\varphi_0$$

phase shift

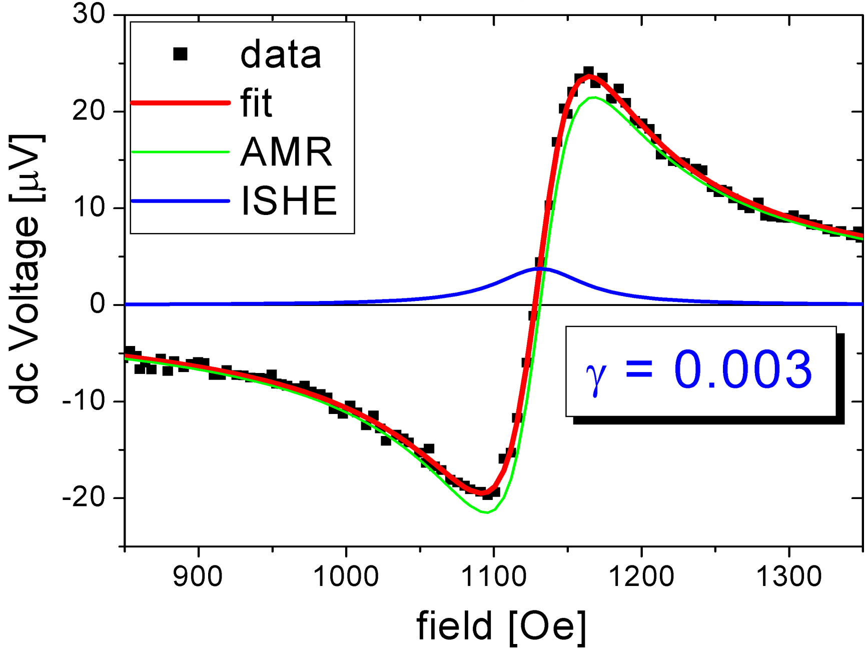
Measured Voltage - Spin Hall Effects

Bi-layers F/N → Symmetric component in the signal

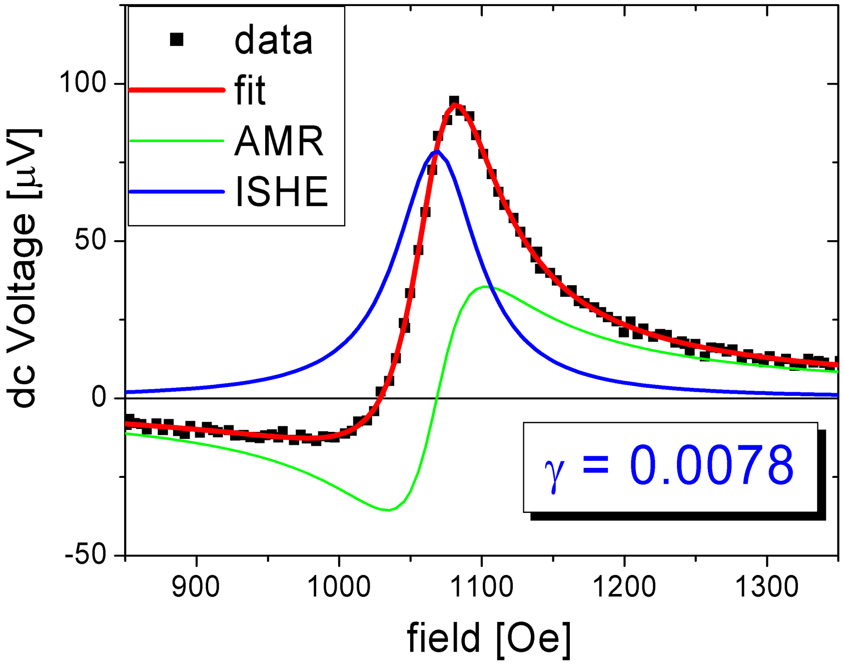
$$V_{SHE} = -\frac{\gamma}{\sigma}\frac{eL}{2\pi} E\, g_{\uparrow\downarrow}\frac{\lambda_s}{t_N}\omega \sin^2\theta \sin\beta \tanh\left(t_N/2\lambda_s\right)$$

High sensitivity to even small γ, as signal scales with dimension *L*

50 Au / 15 Py , 10 GHz



15Pd/15Py, 10GHz, β=40˚



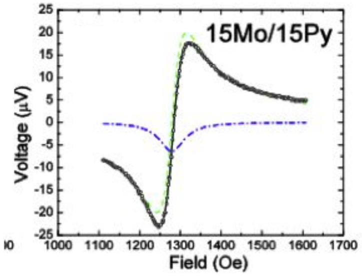
Determine Spin Hall Angle for Many Materials

O. Mosendz, *et al.*, Phys. Rev. Lett. **104**, 046601 (2010); Phys. Rev. B **82**, 214403 (2010)

4d

Mo

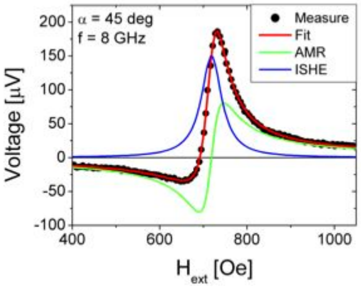
γ = -0.05%±0.01



• • •

Pd

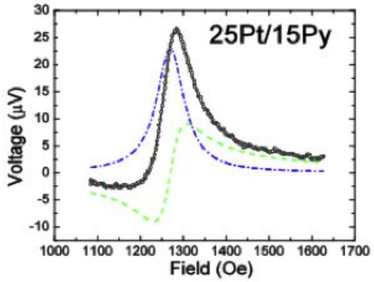
γ = 0.75%±0.1



5d

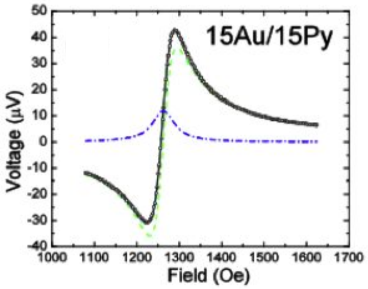
Pt

γ = 1.3%±0.2



Au

γ = 0.35%±0.03



Technique easily adapted
to any material!

preliminary Bi: γ = 0.85%±0.2

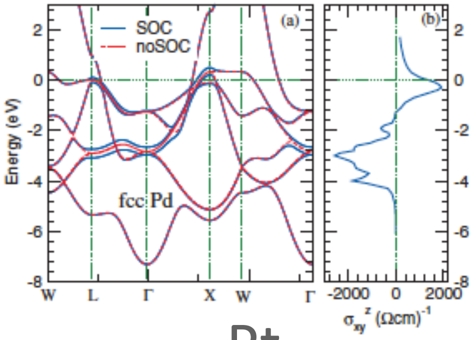
Theory vs. Experiment

G. Y. Guo, *et al.*,
Phys. Rev. Lett. **100**, 096401 (2008);
J. Appl. Phys. **105**, 07C701 (2009)

O. Mosendz, *et al.*,
Phys. Rev. B **82**, 214403 (2010)

Pd

$\sigma_{SH} = 240\ (\Omega\mathrm{cm})^{-1}$

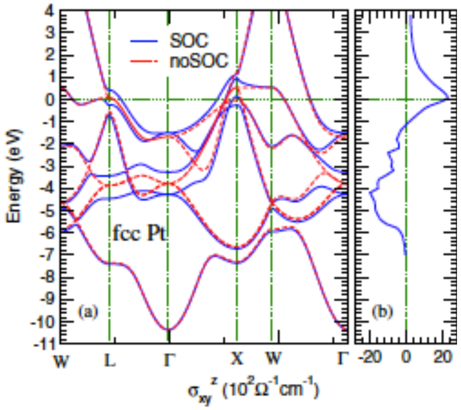


Pd

$\sigma_{SH} = 256\ (\Omega\mathrm{cm})^{-1}$

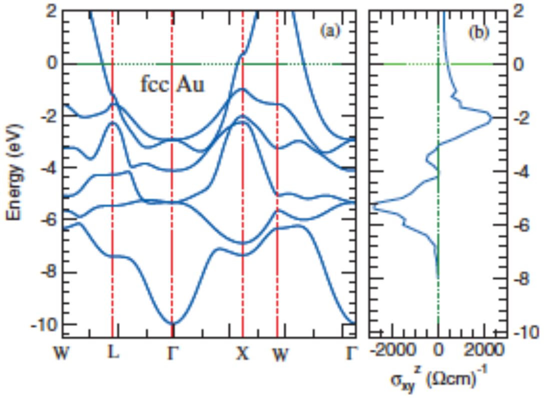
Pt

$\sigma_{SH} = 330\ (\Omega\mathrm{cm})^{-1}$



Au

$\sigma_{SH} = 750\ (\Omega\mathrm{cm})^{-1}$



Pt

$\sigma_{SH} = 312\ (\Omega\mathrm{cm})^{-1}$

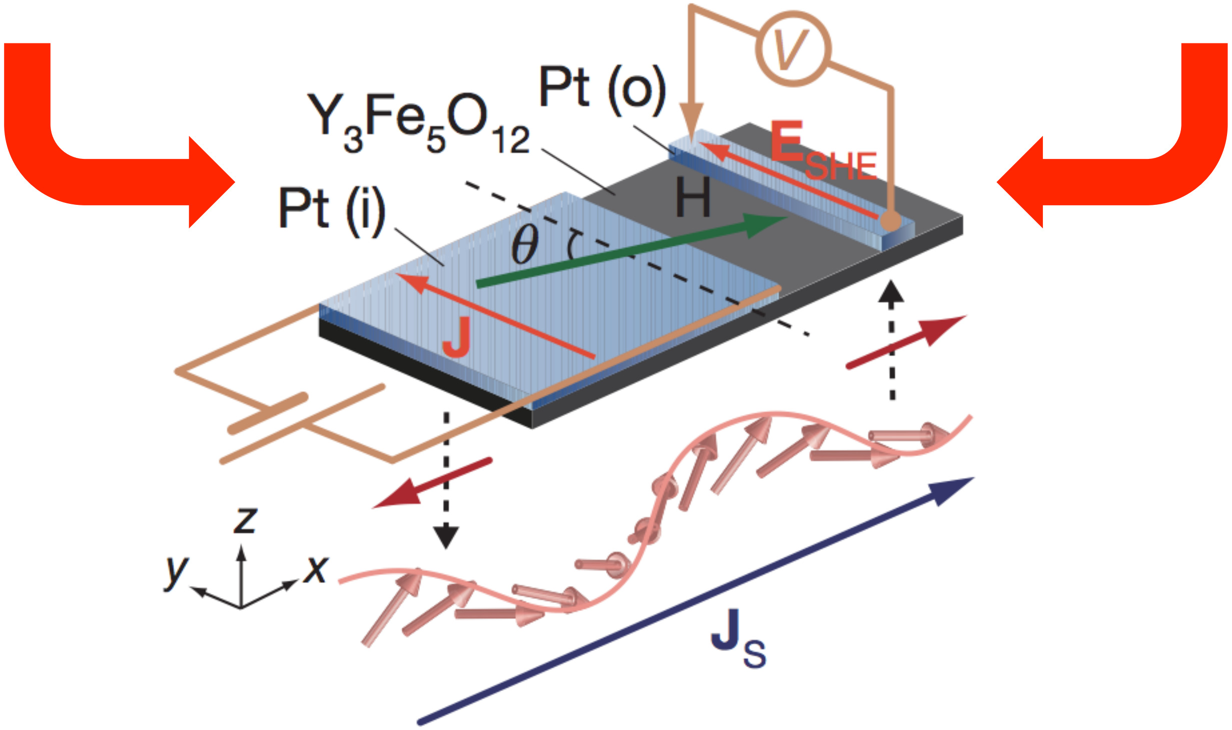
Au

$\sigma_{SH} = 882\ (\Omega\mathrm{cm})^{-1}$

Spin Currents in Insulators

Use Direct Spin Hall Effect to excite magnetization dynamics

Use Inverse Spin Hall Effect and Spin Pumping
for detection

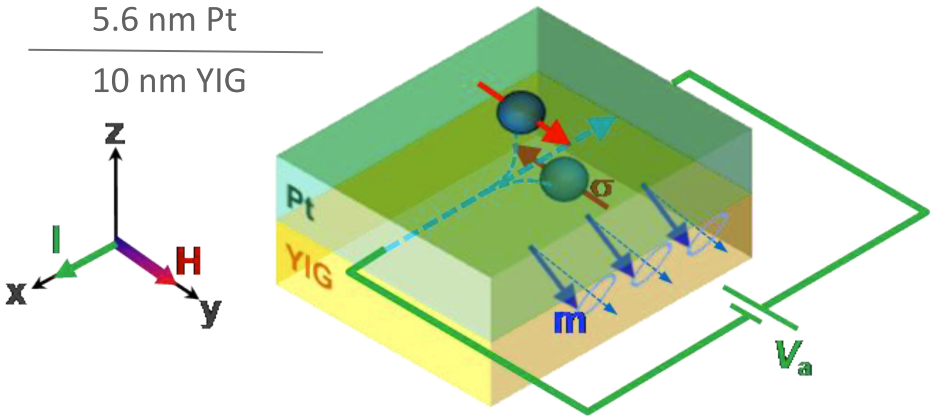


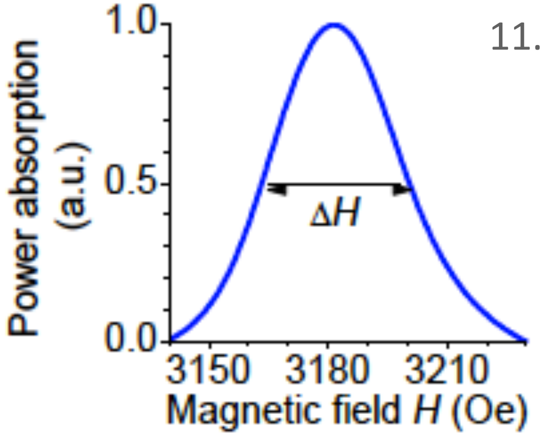
Y. Kajiwara *et al.*, Nature **464**, 262 (2010)
C. W. Sandweg *et al.*, Appl. Phys. Lett. **97**, 252502 (2010)

Spin Torque from Spin Hall

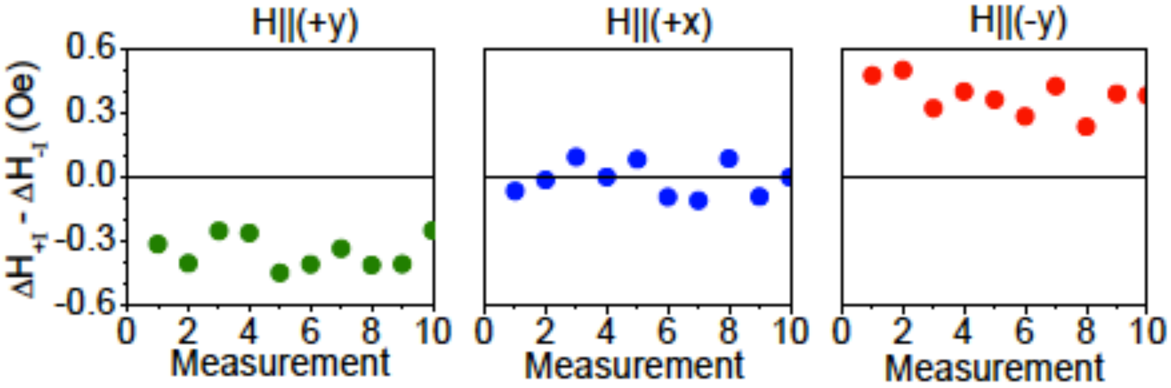
5.6 nm Pt

10 nm YIG





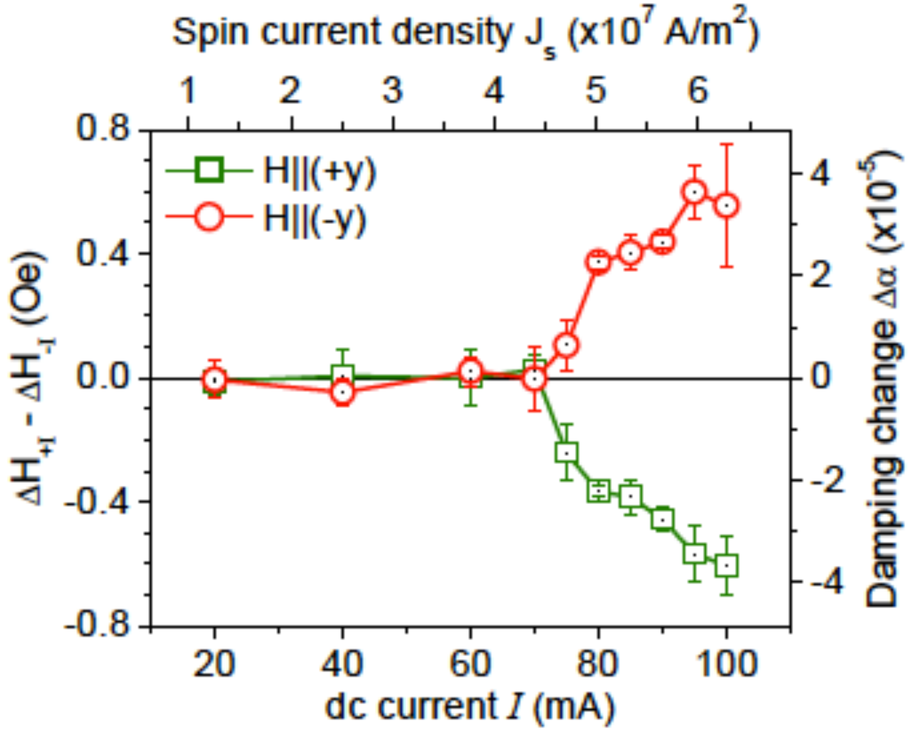
11.5 GHz



Detect current dependent line-width change depending on field orientation

Z. Wang *et al.*, Appl. Phys. Lett. **99**, 162511 (2011)

Threshold for Spin Transfer Torque?

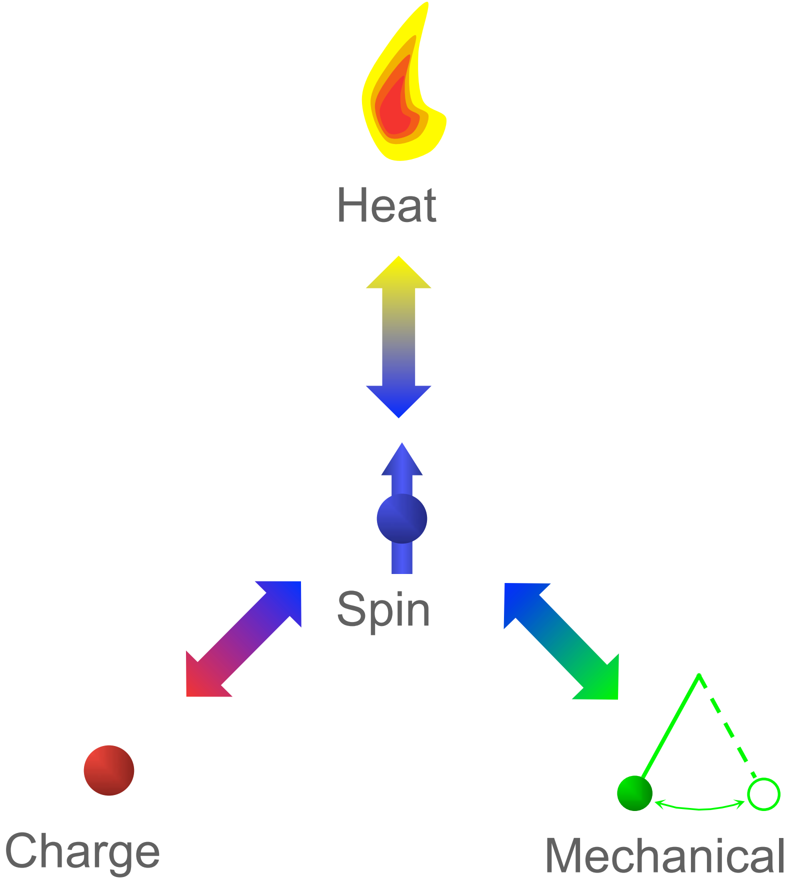


Non-linear dependence on current

Z. Wang *et al.*, Appl. Phys. Lett. **99**, 162511 (2011)

Spin Mediated Energy Conversions

Spin Seebeck ⇔ Spin Peltier



Spin Torque ⇔ EMF from Spin Dynamics

Einstein-de Haas ⇔ Barnett

Thanks to

Goran Mihajlović and Oleksandr Mosendz

Hitachi Global Storage Technologies

Helmut Schultheiß, Vincent Vlaminck, John E. Pearson, Frank Y. Fradin, Sam D. Bader, Dan Schreiber, Yuzi Liu, and Amanda Petford-Long
Argonne National Laboratory

Miguel A. Garcia

Instituto de Cerámica y Vidrio, Consejo Superior de Investigaciones Científicas

Gerrit E. W. Bauer

Delft University of Technology and Tohoku University

Toru Hirahara

University of Tokyo

Zihui Wang, Yiyan Sun, Young-Yeal Song, and Mingzhong Wu

Colorado State University

Financial Support $$$
DOE-BES

Conclusions

- Spin Currents behave different compared to Charge Currents
  - Possibility of Reduced Power Dissipation
- Non-Local Electrical Injection
  - Generate Pure Spin Currents
  - Study Spin Relaxation
- Spin Hall Effects
  - Generate and Detect Spin Currents w/o Ferromagnets
- Spin Pumping
  - Generate Spin Currents w/o Electric Charge Currents
- New Opportunities for Spin Mediated Effects