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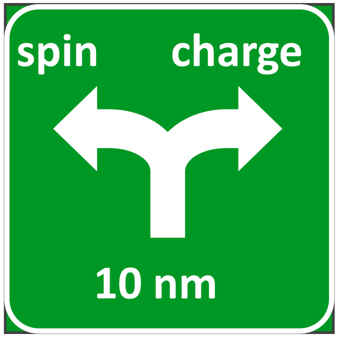
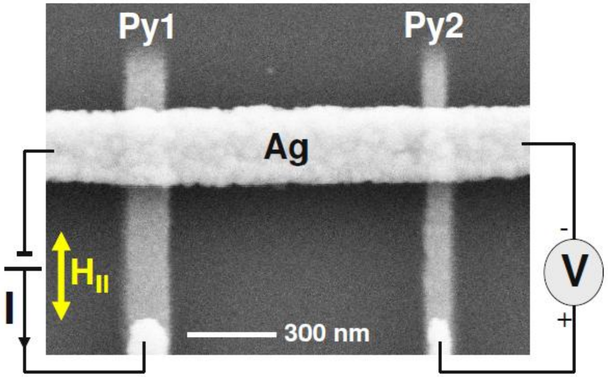
New Insights into Spin Relaxation from Pure Spin Currents





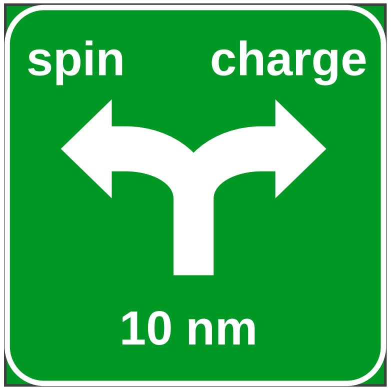
Axel Hoffmann

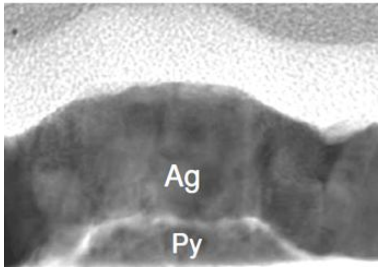
Materials Science Division
Argonne National Laboratory

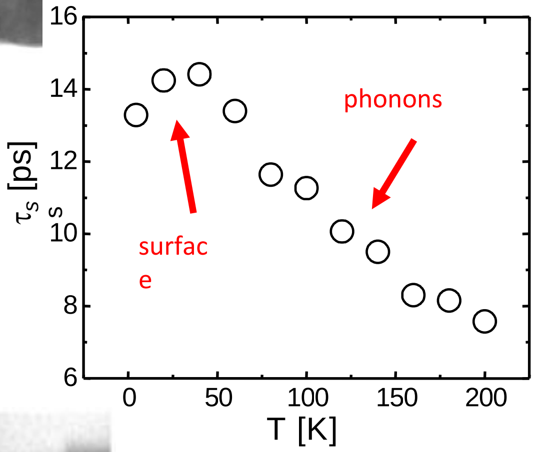
U.S. DEPARTMENT OF ENERGY

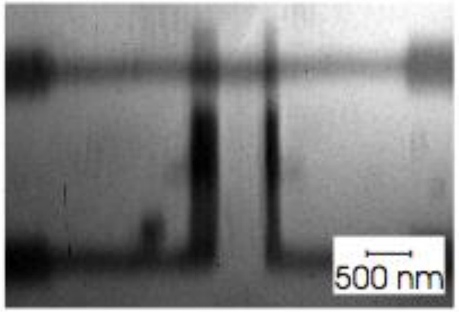
Outline

- Why Pure Spin Currents?
- Interfacial Oxide
- Surface Spin Relaxation
- What about X-rays?
- Conclusions





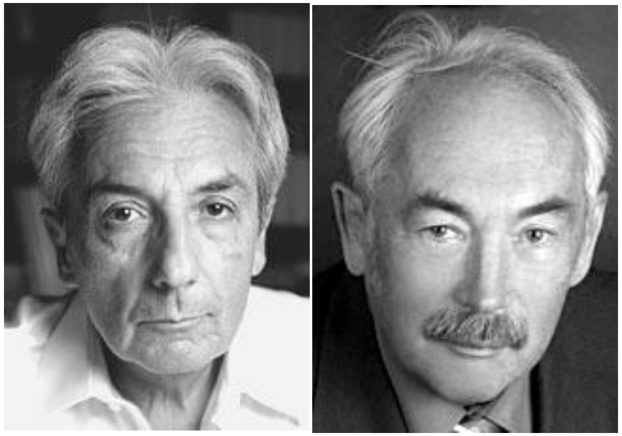




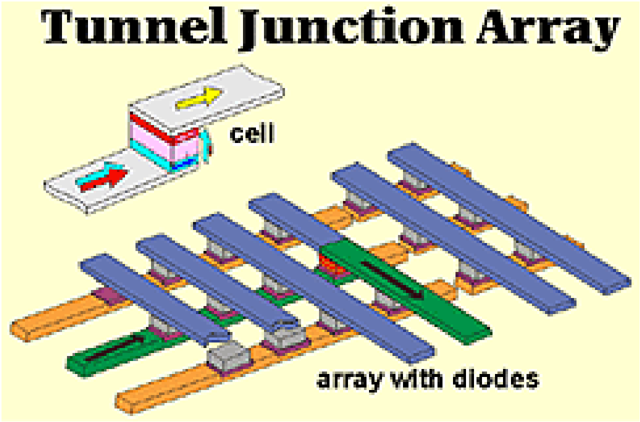
Spintronics

Putting

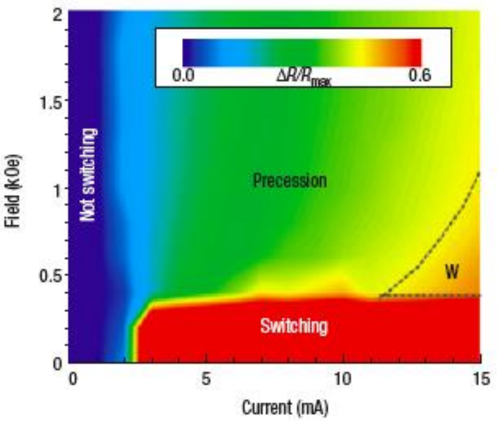
into Electronics



Nobel Prize



Novel Devices



New Physics

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

Charge vs. Spin Currents

Charge

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

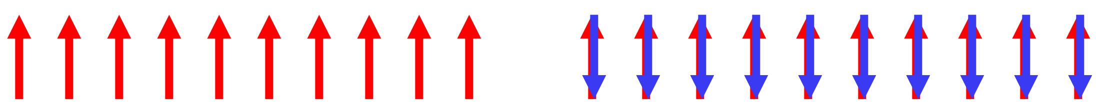
$$\vec{j}_e = q\vec{v}$$

Spin

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

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

Moving Spins | **Spin Dynamics**



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

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

Pure Spin Currents

Spin polarized charge current

$j_c \neq 0$

$j_s \neq 0$

Pure spin current

$j_c = 0$

$j_s \neq 0$

BENEFITS

physics

applications

Direct insights into spin-dependent physics

- role of spin orbit coupling in spin transport
- role of spin in energy transfer
- spin-spin interactions

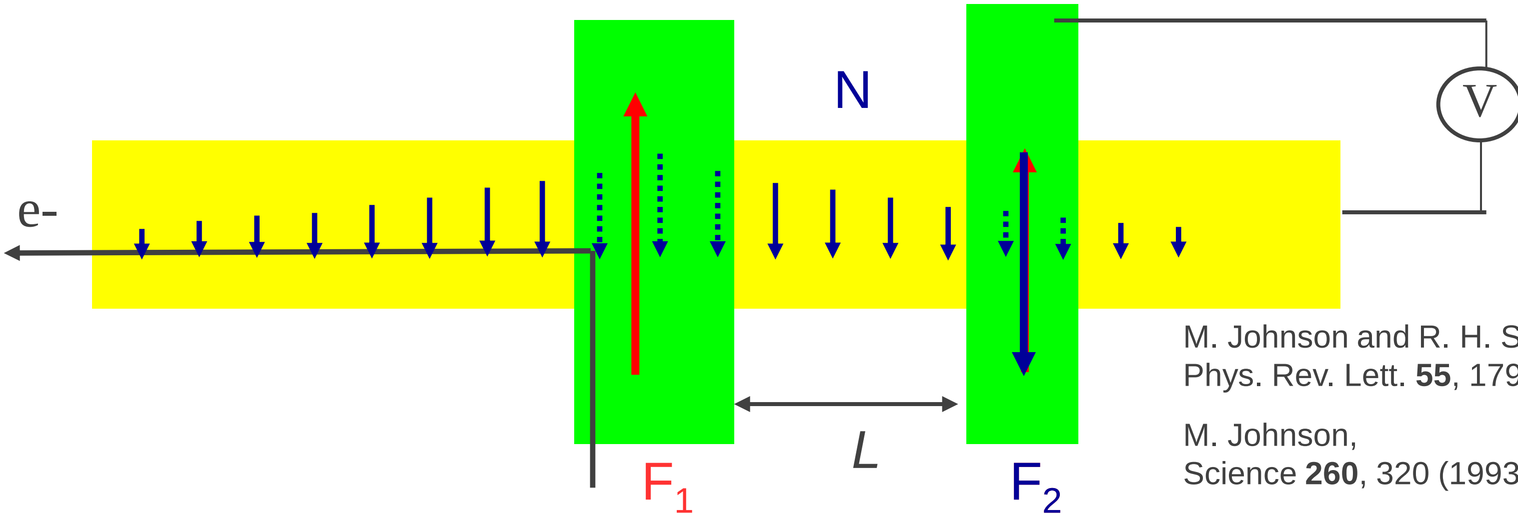
Eliminate undesirable charge transport effects

- heat
- noise
- Oersted fields

New Goal:

Take the Charge out of Spintronics!

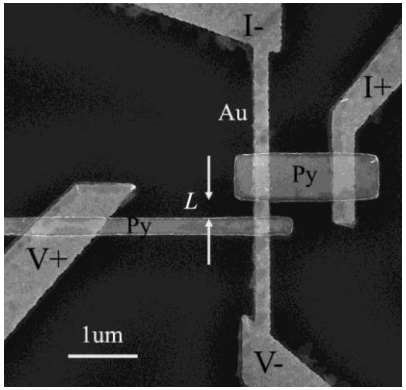
Pure Spin Currents: The Johnson Transistor



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

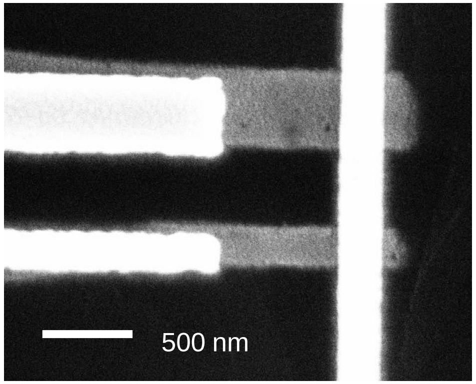
M. Johnson, Science **260**, 320 (1993)

Our Early Work



Au: λ_s = 63±15 nm (10 K)

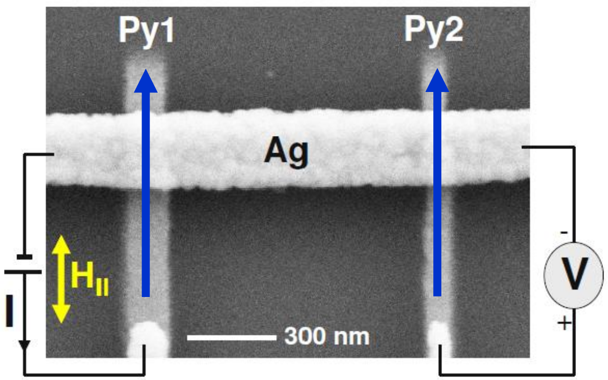
Y. Ji *et al.,* Appl. Phys. Lett. **85**, 6218 (2004)

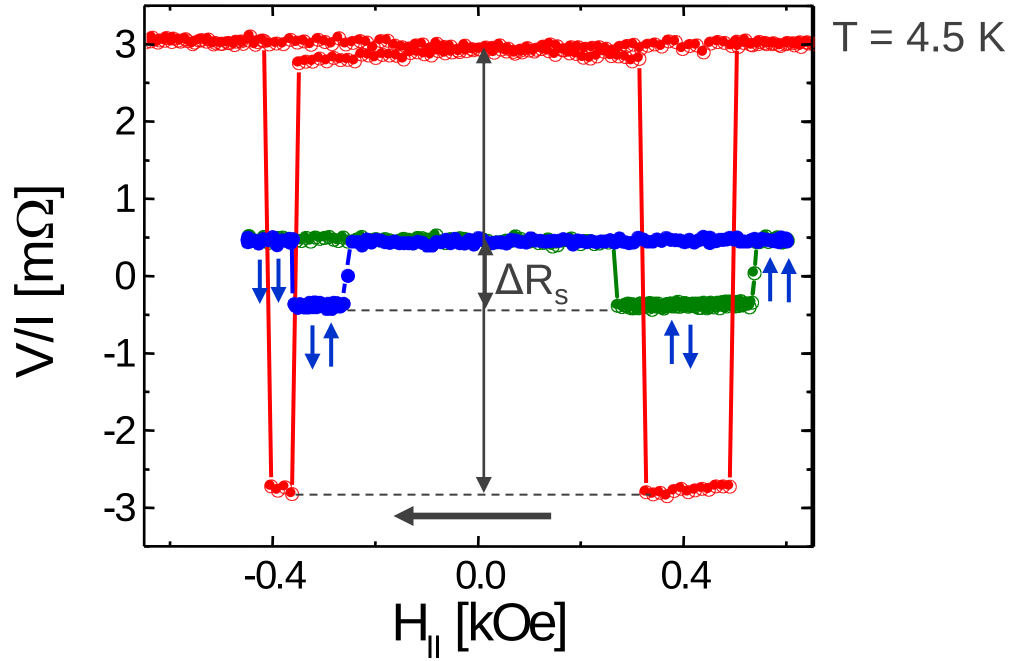


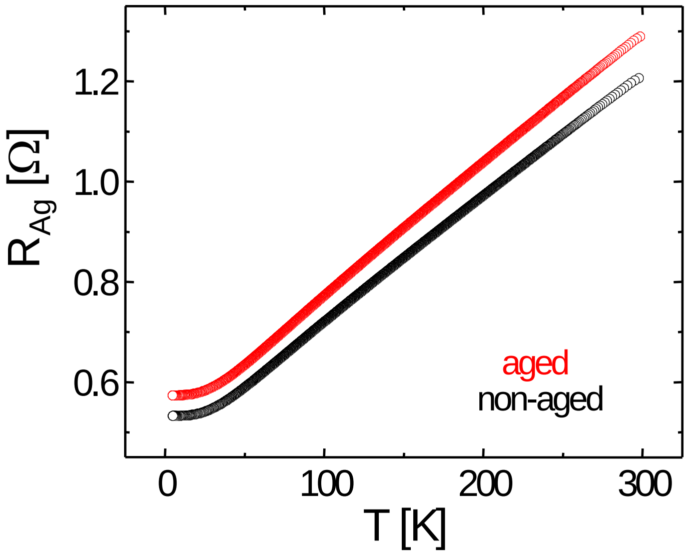
Cu: λ_s = 200 ±20 nm (10 K)

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

Py/Ag Non-Local Spin Valve







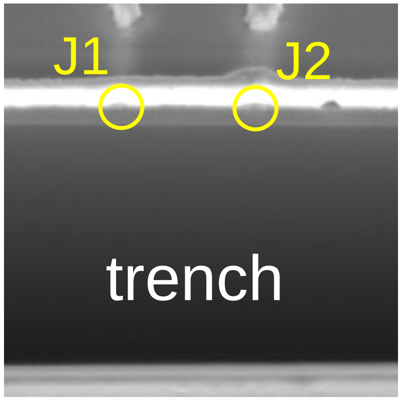
$\Delta R_s = 0.9\ m\Omega$ $\xrightarrow[\text{in air}]{\text{after 2 weeks}}$ $\Delta R_s = 5.9\ m\Omega$

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

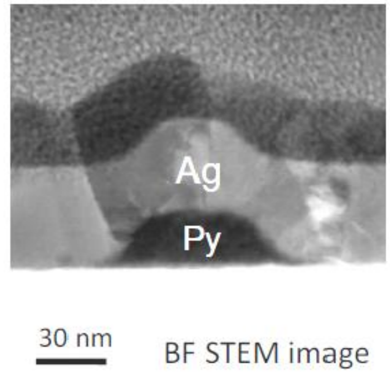
G. Mihajlović *et al.*, Appl. Phys. Lett. **97**, 112502 (2010)

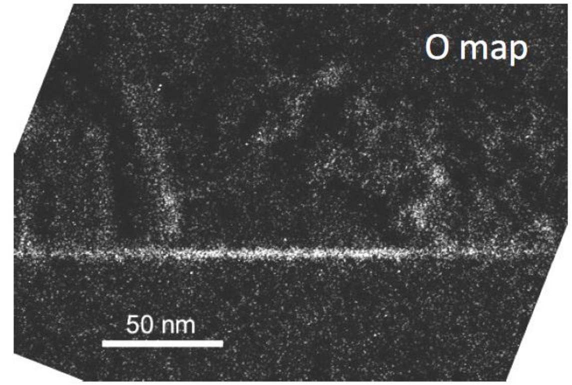
Origin of Enhanced ΔR_s

FIB sliced LSV

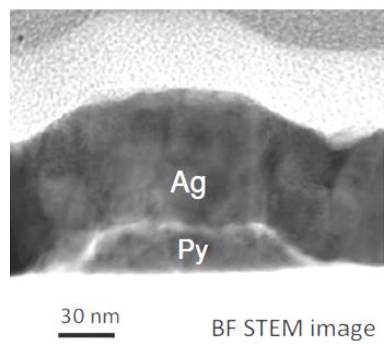


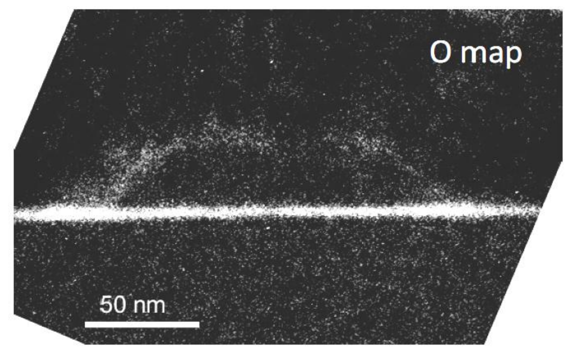
TEM of a non-aged sample





TEM of an aged sample



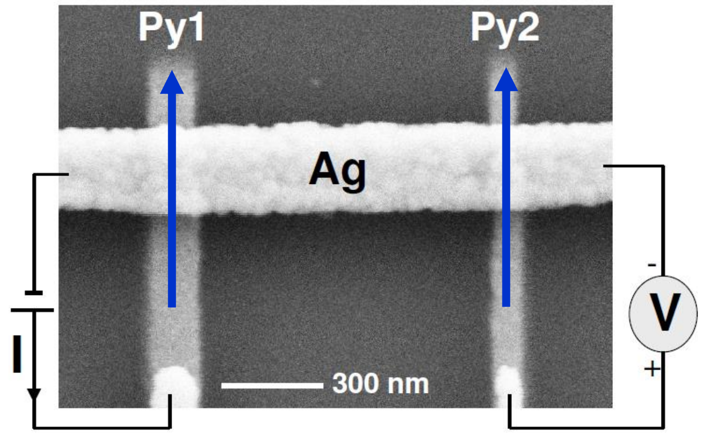


Thin layer of O-rich compound observed at Py-Ag interface in aged samples

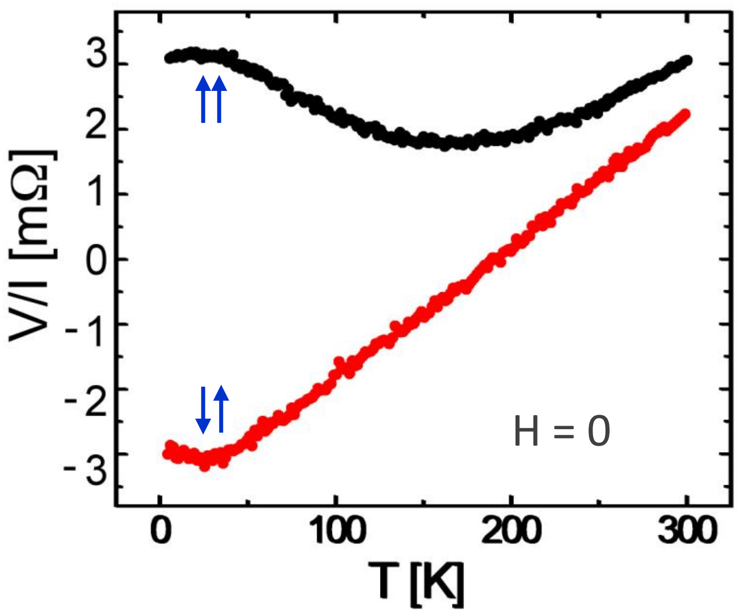
Higher interface resistance ➡ Better spin injection efficiency

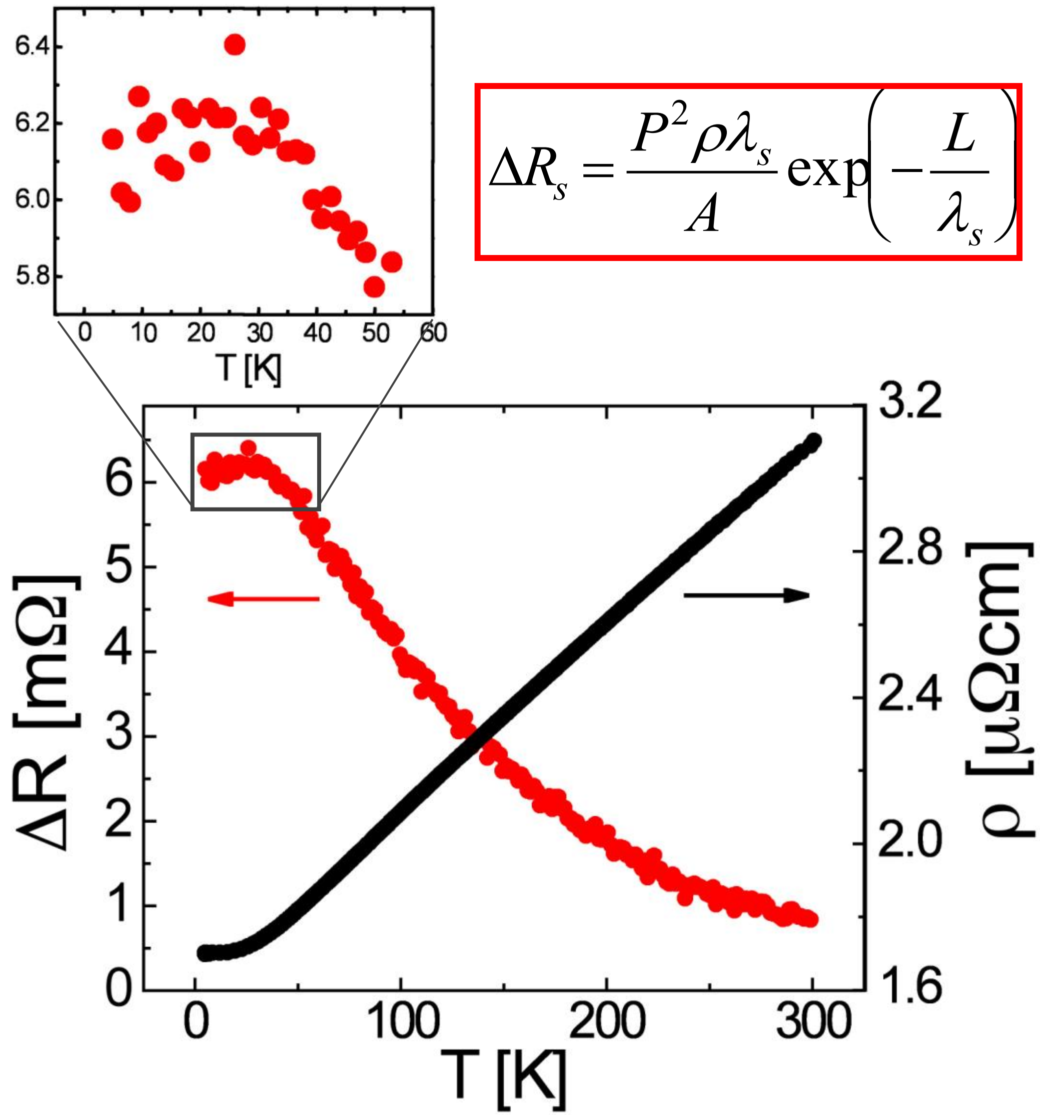
G. Mihajlović *et al.*, Appl. Phys. Lett. **97**, 112502 (2010)

Temperature Dependence of Spin Signal



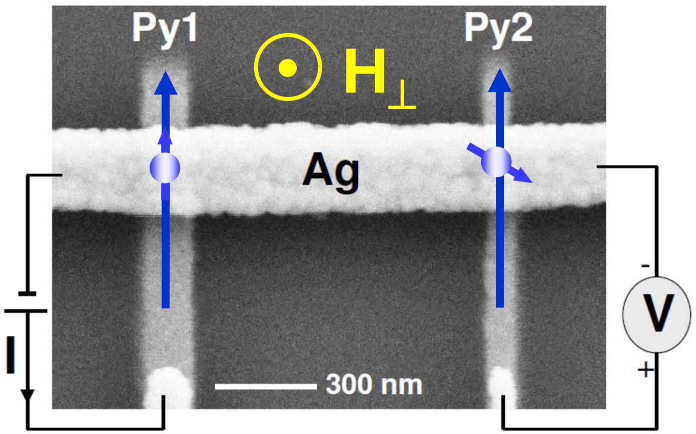
$$\Delta R_s = \frac{P^2 \rho \lambda_s}{A} \exp\left(-\frac{L}{\lambda_s}\right)$$

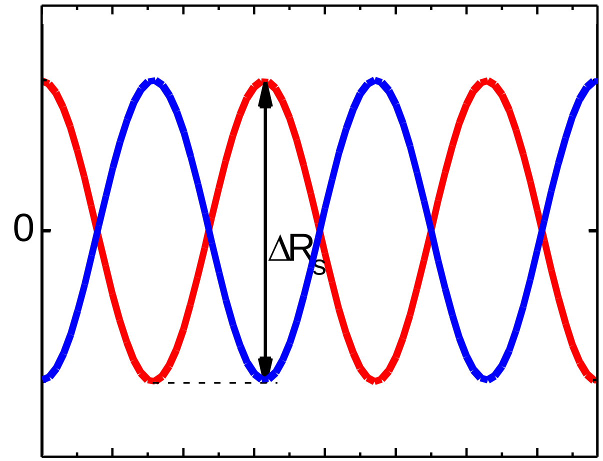




G. Mihajlović *et al.*,
Phys. Rev. Lett. **104**, 237202 (2010)

Hanle Effect in Lateral Spin Valves



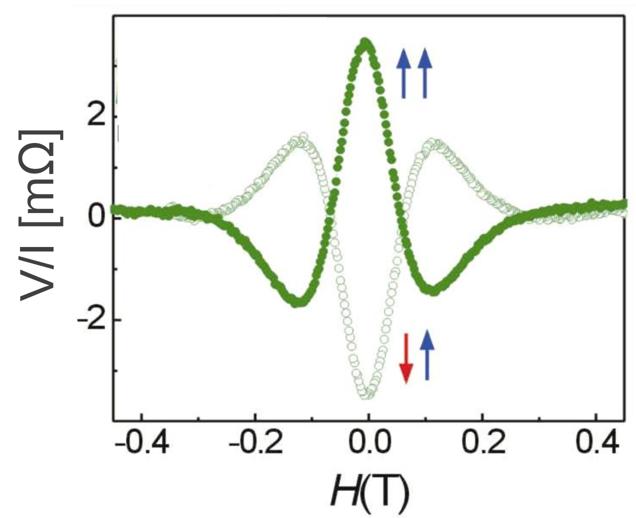


Spin diffusion + Spin relaxation

Spin dephasing

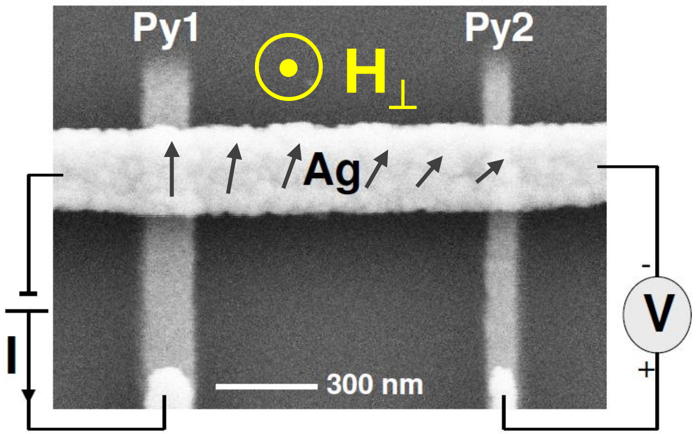
$$R_H^{\uparrow\uparrow}(H_\perp) = \frac{P^2 \rho D}{A} \int_0^\infty \mathcal{P}(t) \cos(\omega_L t) \exp\left(-\frac{t}{\tau_s}\right) dt$$

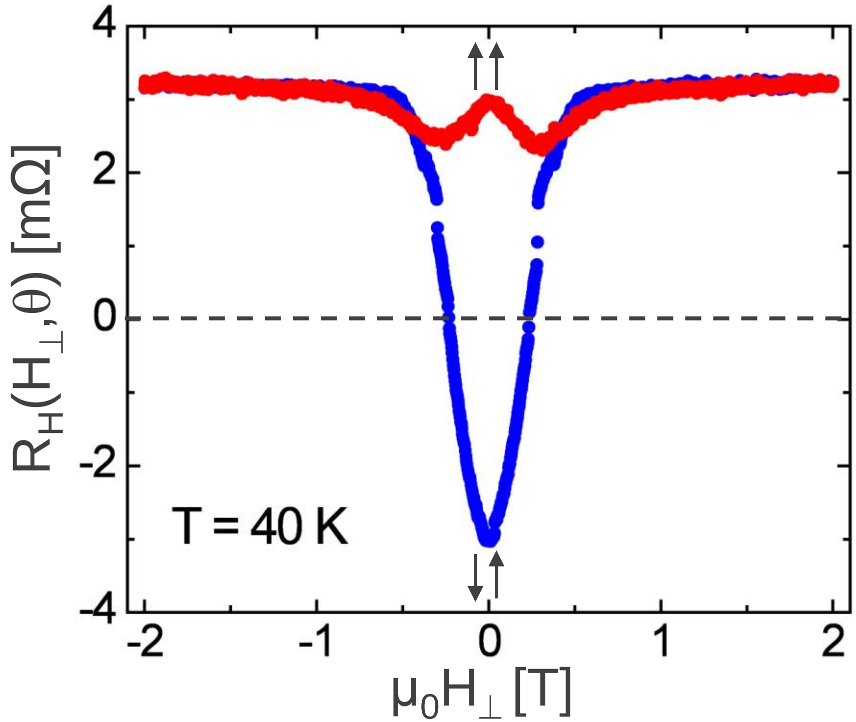
P and τ_s from Hanle curves

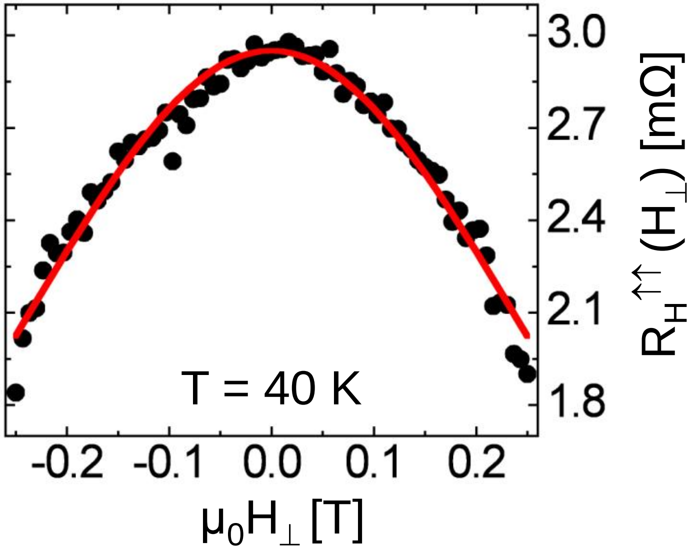


Jedema *et al.*, *Nature* (2002)
Valenzuela & Tinkham, *Nature* (2006)

Hanle Effect in Py/Ag Lateral Spin Valves







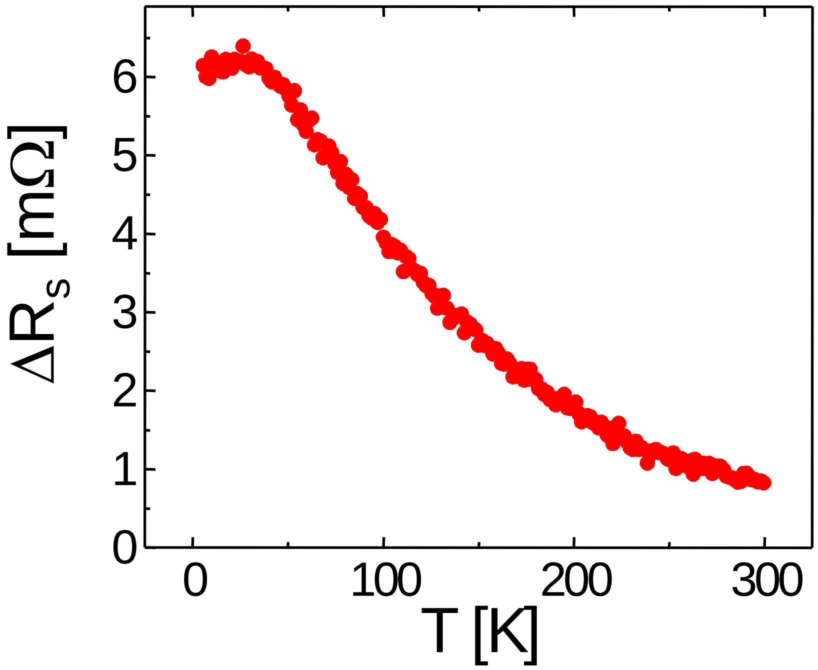
$P = 0.207$

$\tau_s = 14.4$ ps

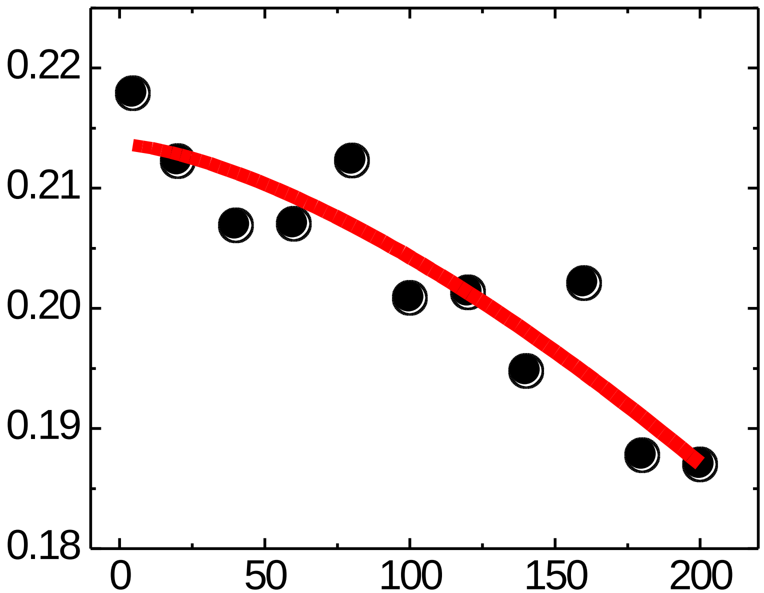
$\lambda_s = 564$ nm

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

T-Dependence of Injection Polarization



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



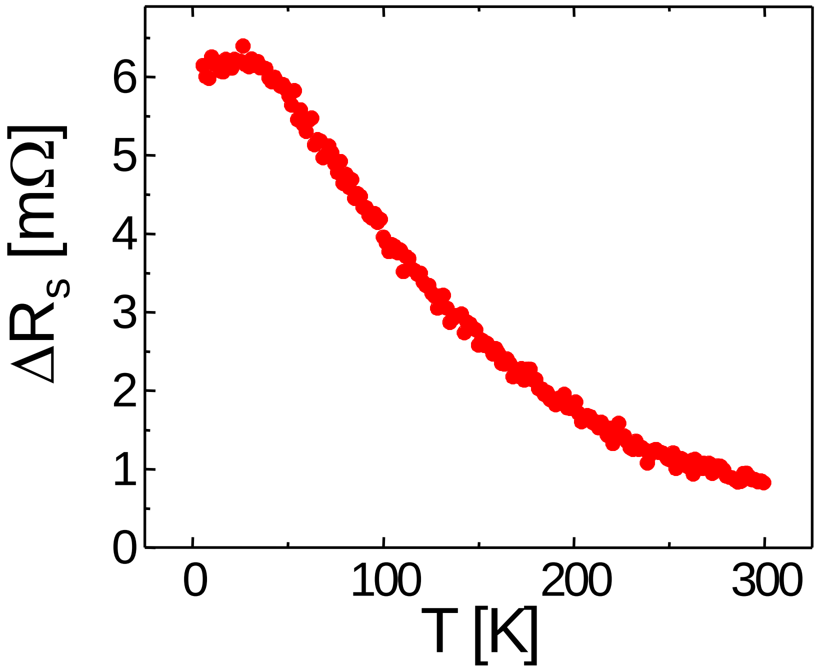
P decreases with T
due to thermally excited spin waves

$$P(T) = P_0(1 - \alpha T^{3/2})$$

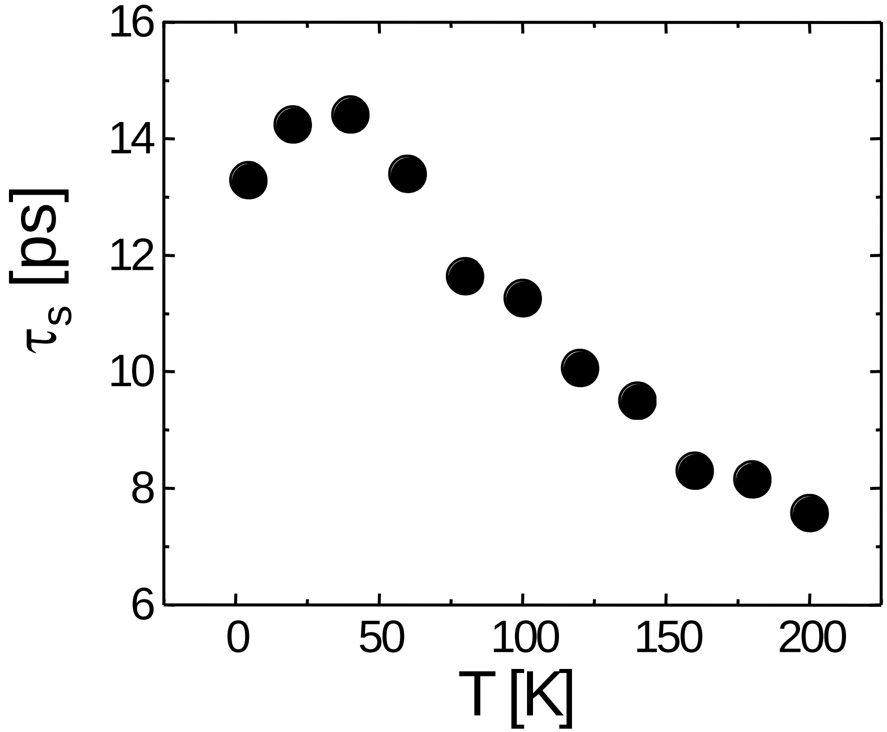
$P_0 = 0.214 \pm 0.003$
$\alpha = (4.0 \pm 0.6) \times 10^{-5}\ K^{-3/2}$

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

T-Dependence of Spin Relaxation Time



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



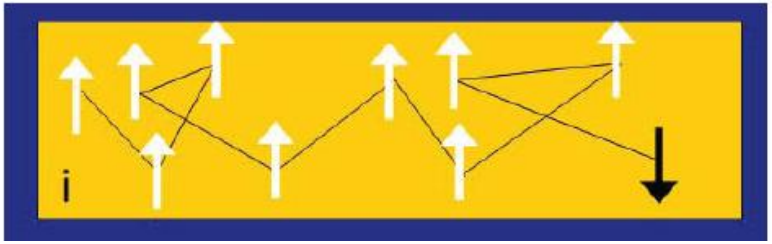
$$\lambda_s = \sqrt{D \tau_s}$$

ΔR_s decreases
due to decreasing τ_s

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

T-Dependence: What about Elliott-Yafet?

momentum relaxation + SOC = spin relaxation



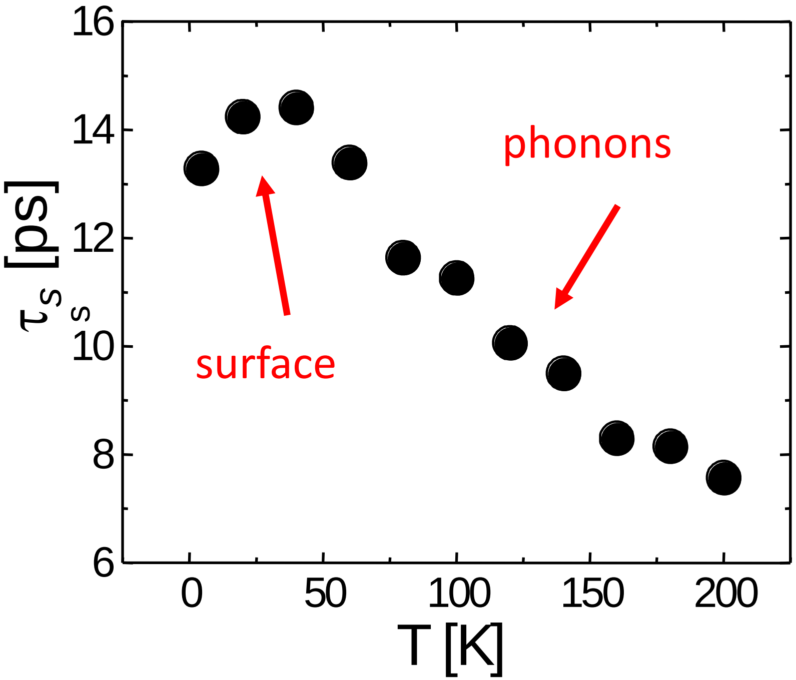
$$\frac{1}{\tau_e} = \frac{1}{\tau_e^{ph}} + \frac{1}{\tau_e^{imp}} + \frac{1}{\tau_e^{S}}$$

$$\frac{1}{\tau_s} = \frac{\varepsilon_{ph}}{\tau_e^{ph}} + \frac{\varepsilon_{imp}}{\tau_e^{imp}} + \frac{\varepsilon_{S}}{\tau_e^{S}}$$

$\propto 1/T$ $\propto T$

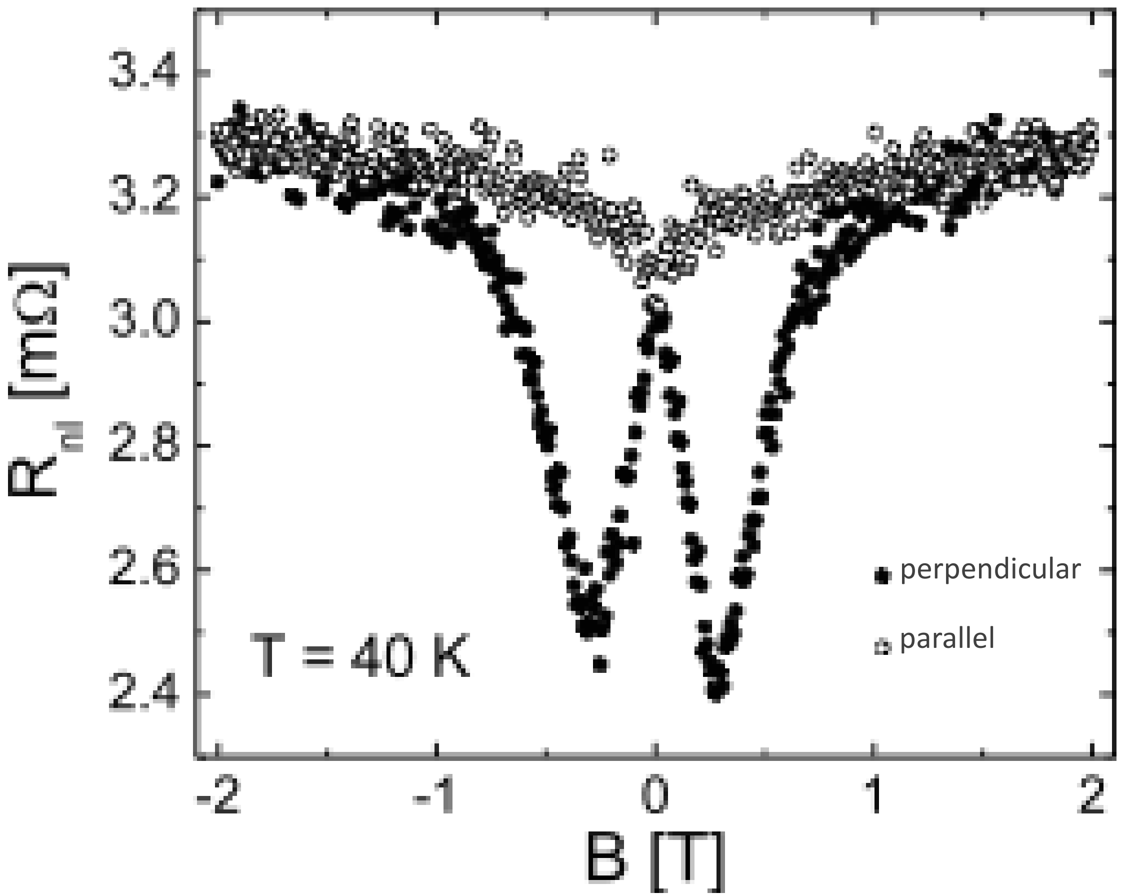
$\tau_s \propto \tau_e$

confirmed many times in bulk metals



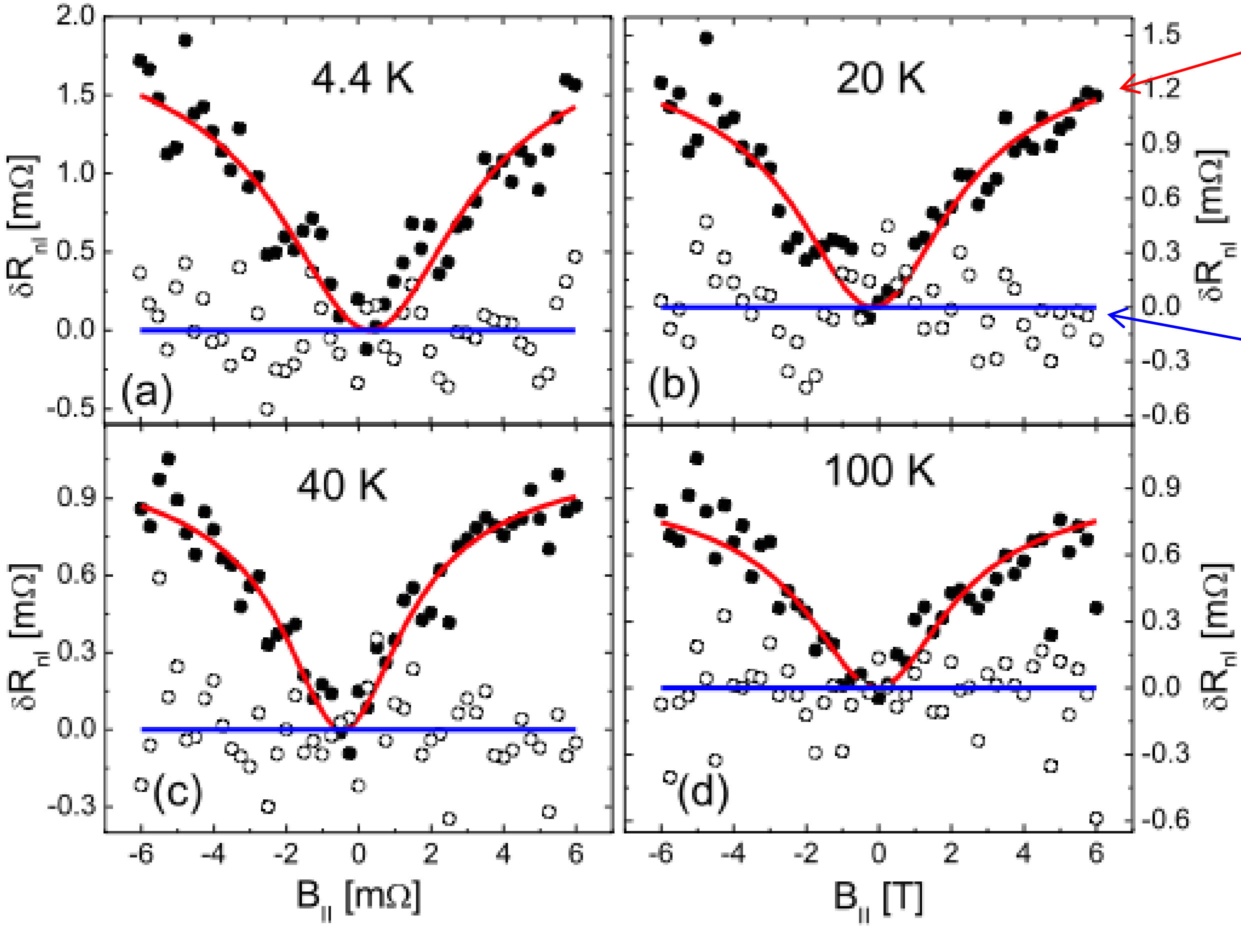
our samples: $\lambda_e < d$ ➡ $\tau_e^S \propto d^2/D_B \propto 1/\tau_e^B \propto T$

Magnetic Field Dependence?



Spin signal increases with field!

Only for Positive Bias!



positive bias
spin extracted from Ag

negative bias
spin injected into Ag

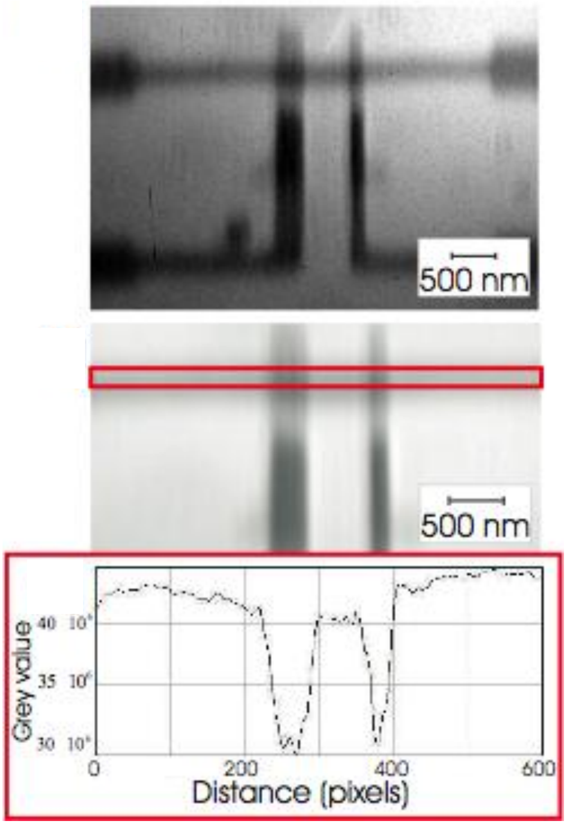
Polarity of spin accumulation matters!

Maybe magnetic impurity scattering is responsible

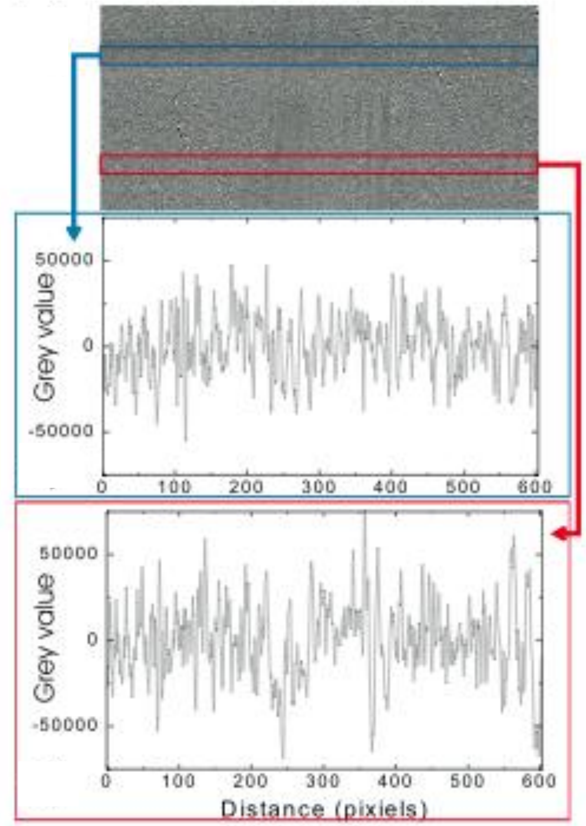
Can we Image Spin Accumulation Directly?

How about X-ray Dichroism?

Image at Cu L-edge



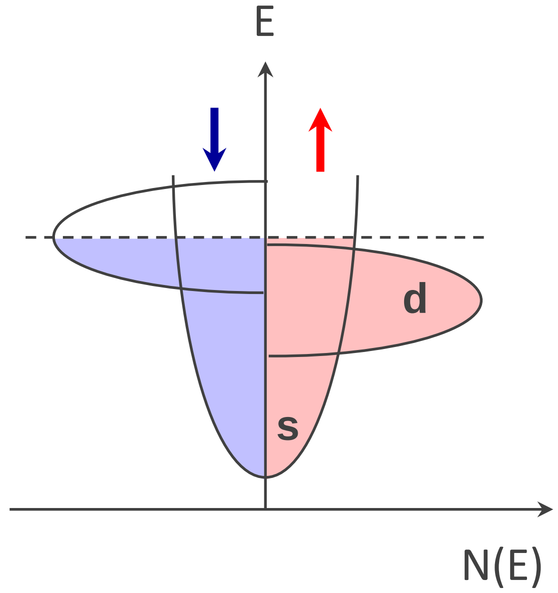
Magnetic Difference Images



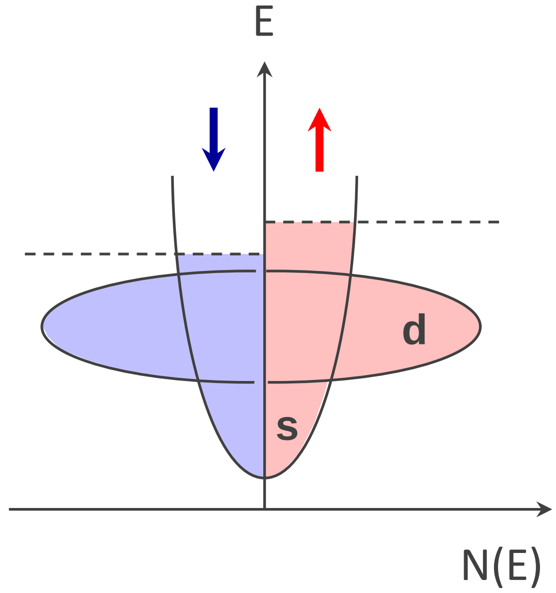
Mosendz *et al.*, Phys. Rev. B **80**, 104439 (2009)

Is There Any Hope for X-rays?

Ferromagnet
(i.e., typical TM)



Spin Accumulation

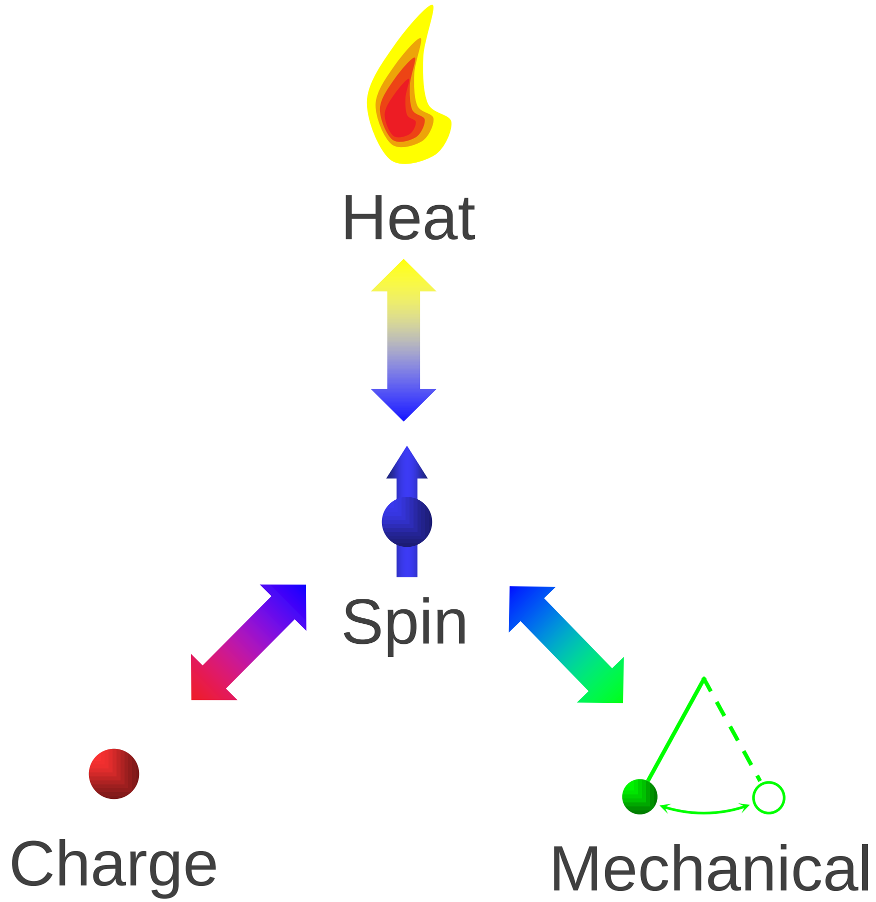


Contrast due to different density of states at Fermi-level

Contrast due to spin-splitting?
Well below 1 meV!

Spin Mediated Energy Conversions

Spin Seebeck ⇔ Spin Peltier

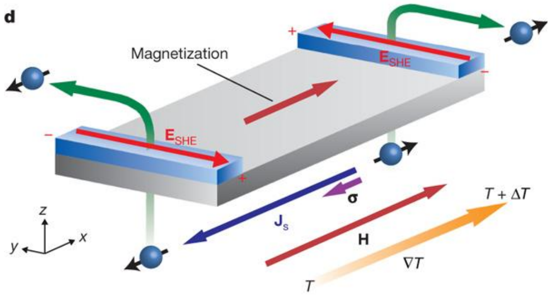


Spin Torque ⇔ EMF from Spin Dynamics

Einstein-de Haas ⇔ Barnett

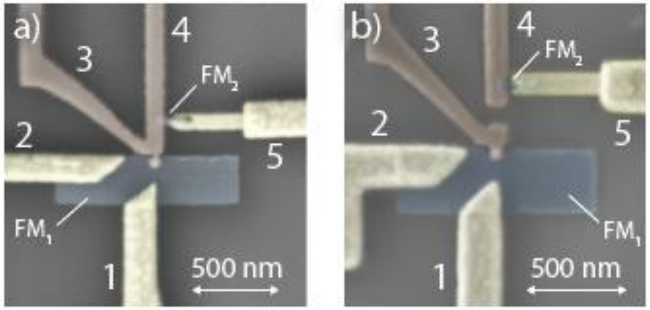
Spin Caloritronics

Spin Seebeck



≈ mm

K. Uchida *et al.*, Nature **455**, 778 (2008)

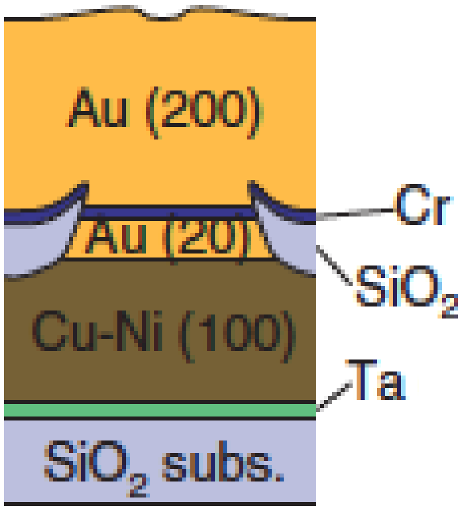


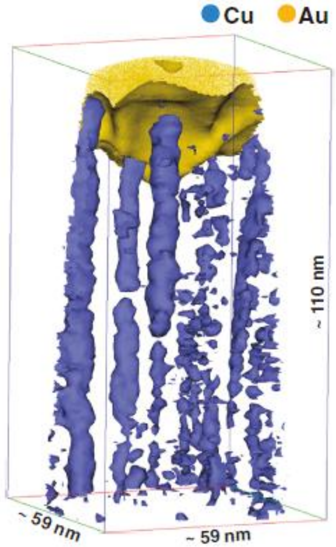
≈ µm

F. L. Bakker *et al.*, Phys. Rev. Lett. **105**, 136601 (2010)

spin waves vs. diffusion?

Spin Peltier





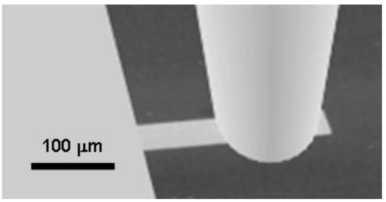
A. Sugihara *et al.*, Appl. Phys. Express **3**, 065204 (2010)

Giant Peltier
more than 160 K cooling!

Magnetomechanical Coupling

Einstein-De Haas in MEMS

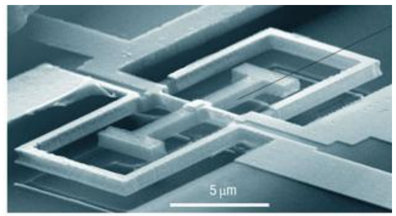
NIST



Moreland et al.,
APL **2006**

Measure
EdH-Effect with μ-cantlever

Boston University



Mohanty et al.,
Nature Nanotechn. **2008**

Measure
electric spin injection with torsional oscillator

NEWS & VIEWS

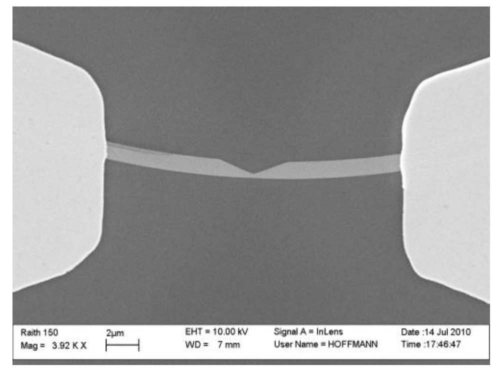
NANOMECHATRONICS

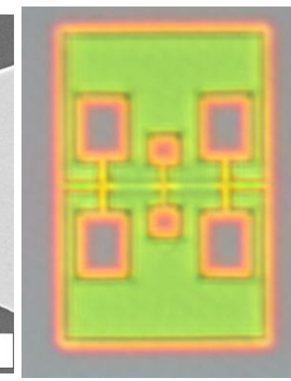
A new twist on a classic experiment

The interplay between angular momentum, electron spin and magnetism at the nanoscale could have applications in spintronics, transducers and actuators, as well as fundamental research.

Kovalev Nature Nanotechn. **2008**

Coupled Magneto-Mechanical Dynamics





Domain Wall

Torsional MEMS

Both about 20 MHz!

Thanks to

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Hitachi Global Storage Technologies

John E. Pearson, Sam D. Bader,
Dan Schreiber, Yuzi Liu, and Amanda Petford-Long
Argonne National Laboratory

Karel Výborný

Academy of Sciences of the Czech Republic

Sigurður I. Erlingsson

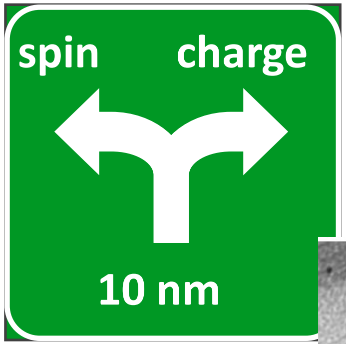
Reykjavik University

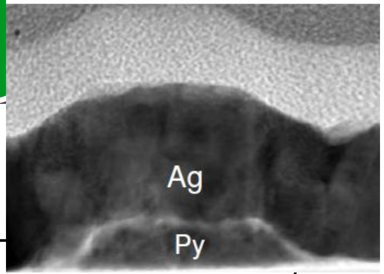
Mi-Young Im and Peter Fischer

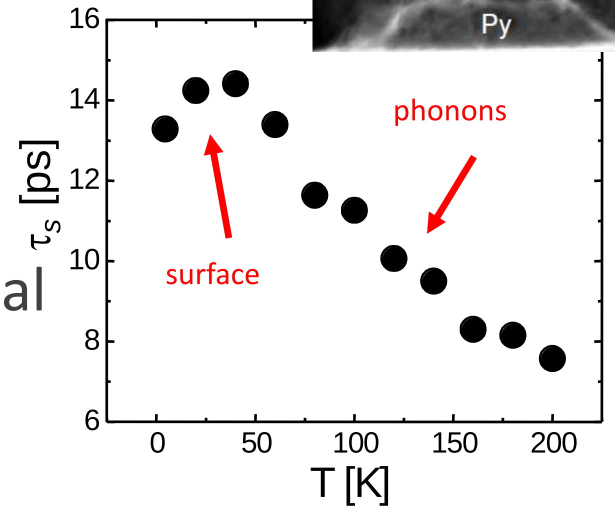
Lawrence Berkeley National Laboratory

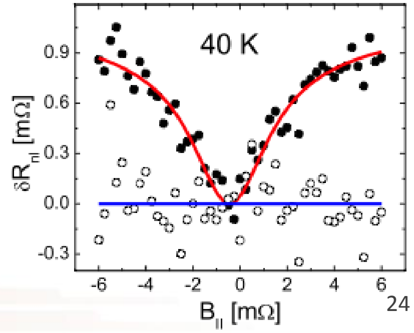
$$$ Financial Support $$$
DOE-BES

Conclusions









- Lateral Spin Valve
  - Enable Pure Spin Currents
- Permalloy/silver lateral spin valves
  - Ambient exposure results in enhanced spin injection
- Temperature dependence of spin signal
  - Surface spin relaxation is significantly larger than bulk
- Magnetic field dependence
  - Possibly due to magnetic impurities