Nonlocal Spin Detection and the Spin Hall Effect

Sergio O. Valenzuela

Sergio.Valenzuela.icn@uab.es

ICREA and Centre d'Investigació en Nanociència i Nanotecnologia (ICN-CSIC), Barcelona

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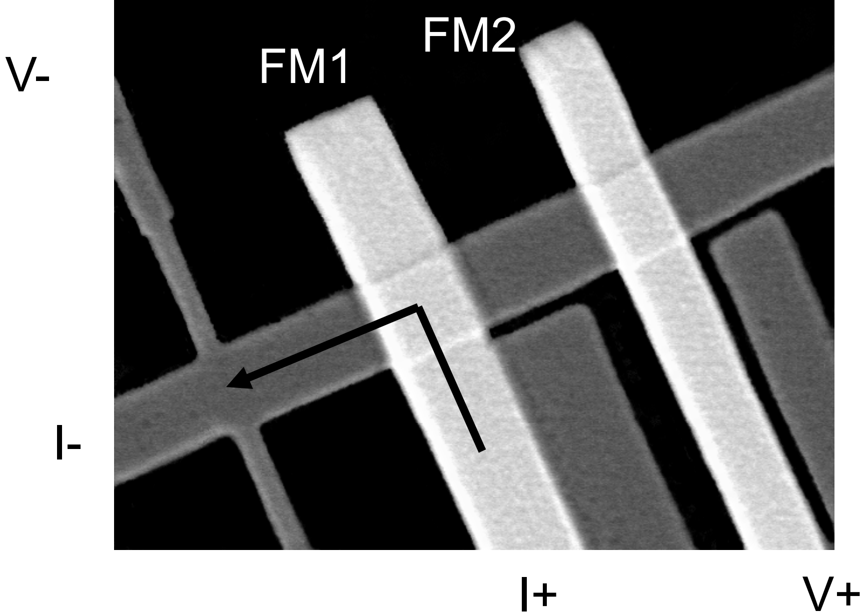
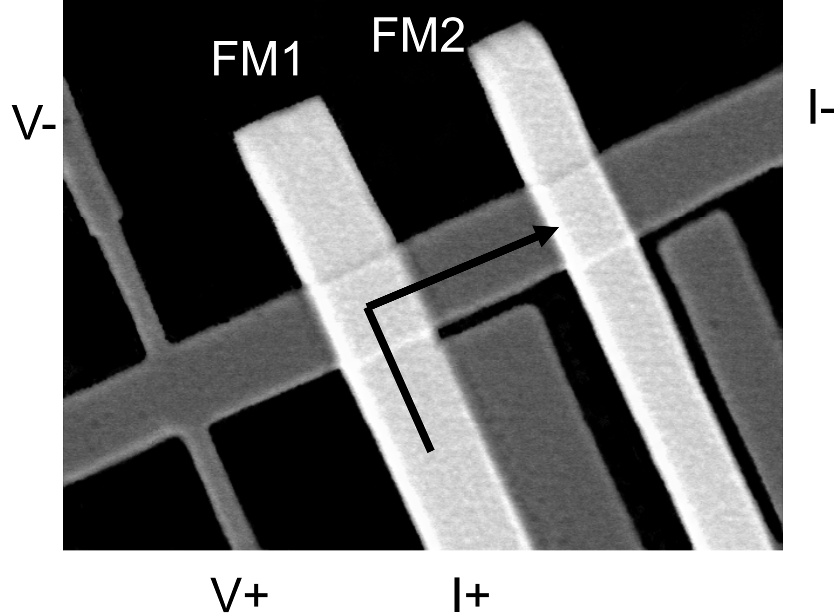
Outline. Measurement technique

Lateral Spin-Valve



Spin Hall Effect



SOV, Int. J. Mod. Phys. B **23**, 2413 (2009)

Nonlocal Spin Detection and the Spin Hall Effect

- Introduction
  - Nonlocal Spin Detection, Lateral Spin-Valve

- Spin Hall Effect
  - Nonlocal Electrical Detection of the Spin-Current Induced Hall Effect. Reverse Spin Hall Effect.
  - Comparison with Lateral Spin-Valve

- Conclusions

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Collaborators

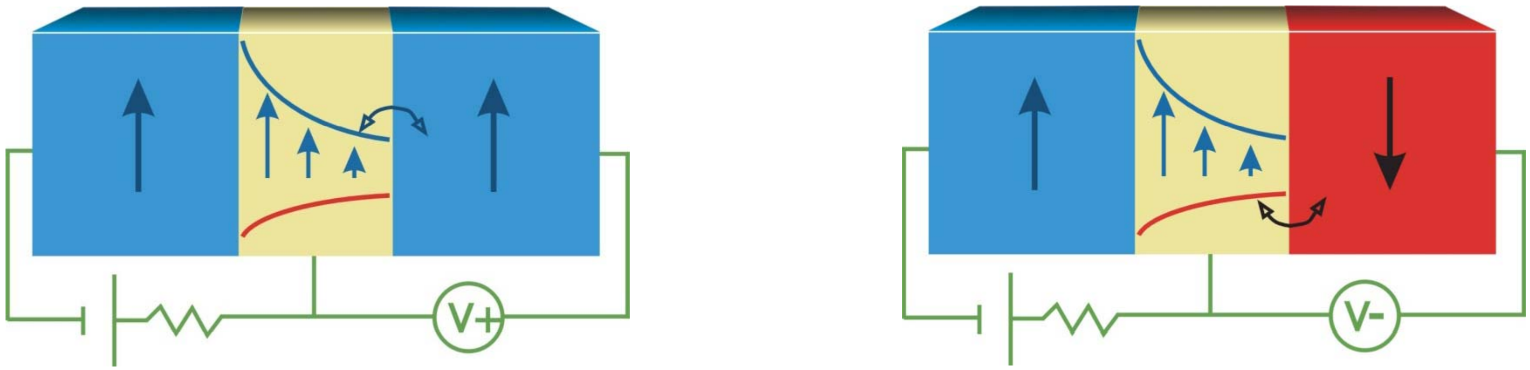
Lateral Spin-Valve

M. Tinkham
D.J. Monsma
C.M. Marcus
V. Narayanamurti
(Harvard)

Spin-Hall effect

M. Tinkham
(Harvard)

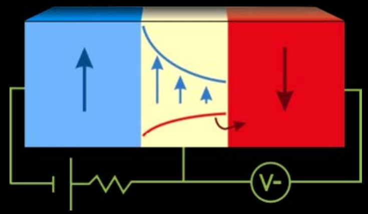
Nonlocal spin electronics



The measured voltage depends on the relative magnetization of the ferromagnets

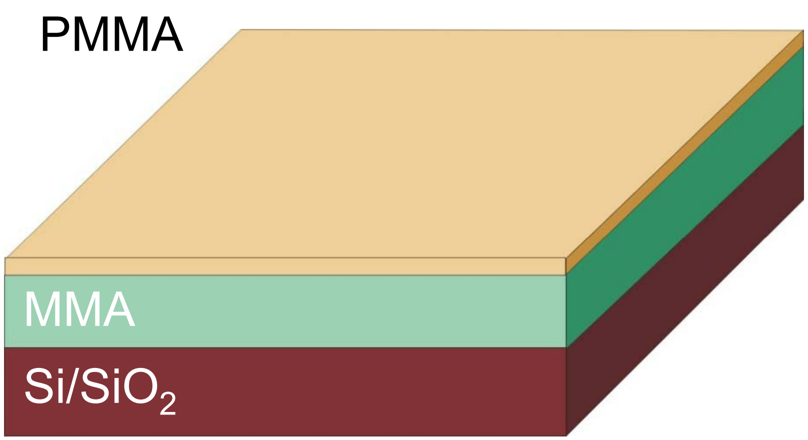
Johnson and Silsbee (1985); Aronov (1976)

Nonlocal spin injection/detection



- Johnson and Silsbee (PRL 55, 1790 (1985))
  - “Bulk” aluminum crystal
  - pV signal (SQUID picovoltmeter)
  - T < 77 K
  - Spin relaxation length ~ 450 μm (4.2K); 180 μm (37K)
- Jedema *et al* (Nature 416, 713 (2002))
  - Aluminum thin films. Much smaller volume. Tunnel barriers
  - Signal 6 order of magnitude larger than Johnson
  - V/I ~ 10 mΩ
- Reduced sample size and improved spin injection
  - V/I ~1Ω
  - Spin relaxation length ~0.2-1 μm (4.2 K); 0.2-0.5 μm (RT)

Device fabrication



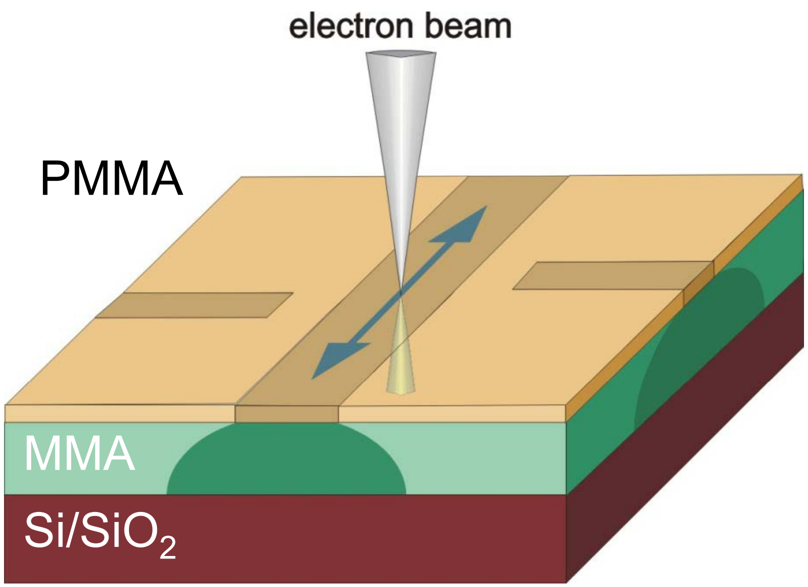
MMA/PMMA bilayer

e-beam lithography. Large undercut by preferentially exposing more sensitive MMA

Free-standing PMMA mask

SOV and M. Tinkham, APL **85**, 5914 (2004)

Device fabrication



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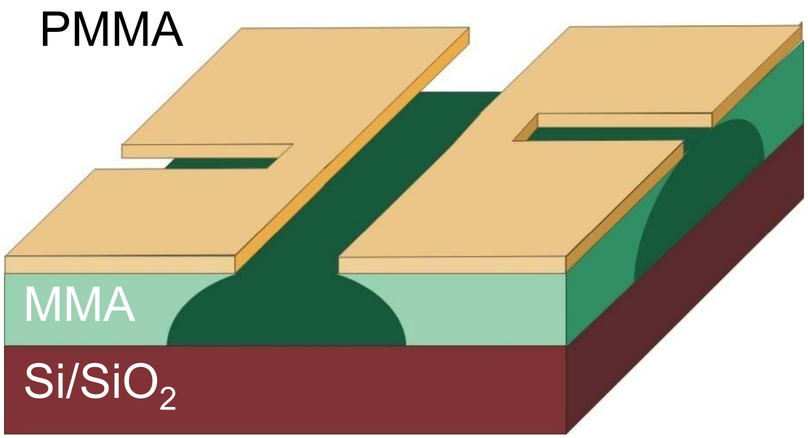

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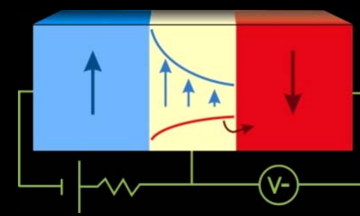
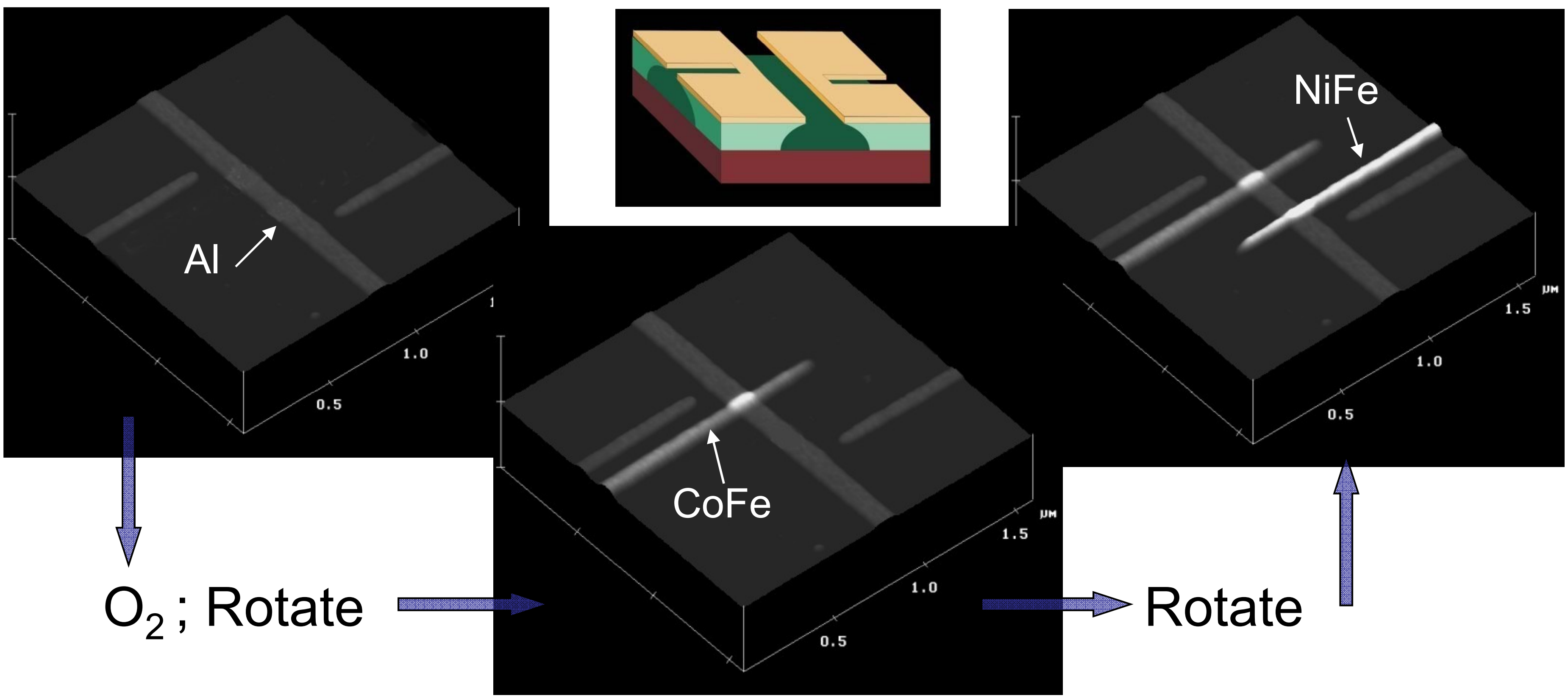
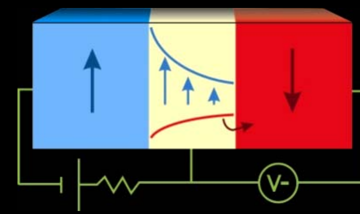
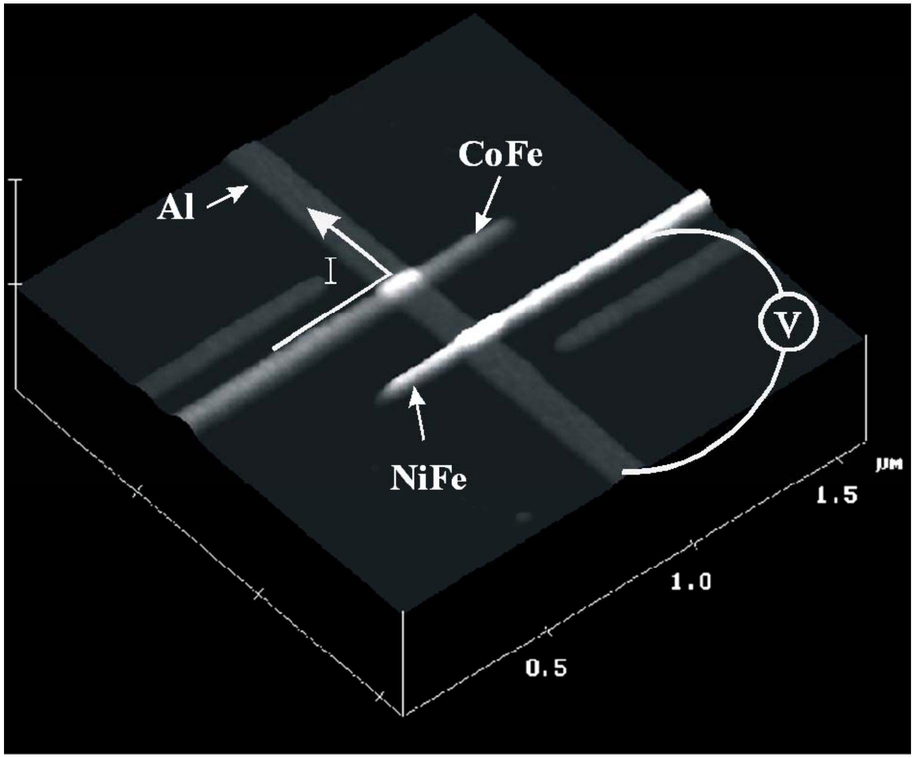


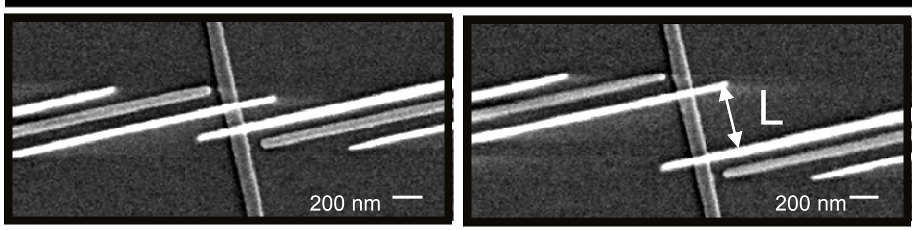
- e-beam evaporation. Tunnel barriers between FM and Aluminum *in situ* (without breaking vacuum)
- Ferromagnet with intrinsically different coercive field (NiFe and CoFe) and different thicknesses.



Measurement scheme







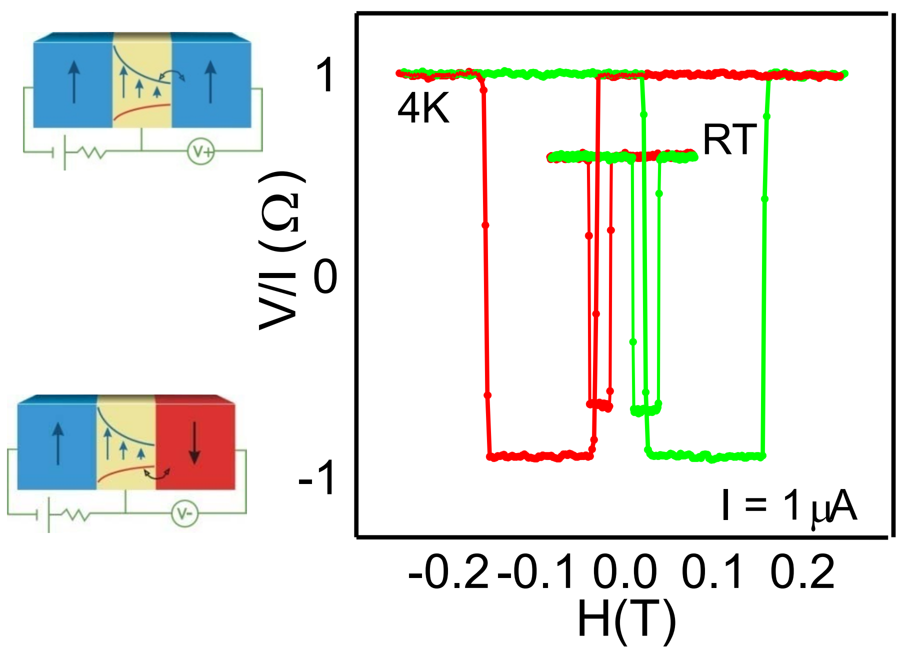
- Current *I* injected into Al strip from one of the ferromagnets (CoFe)

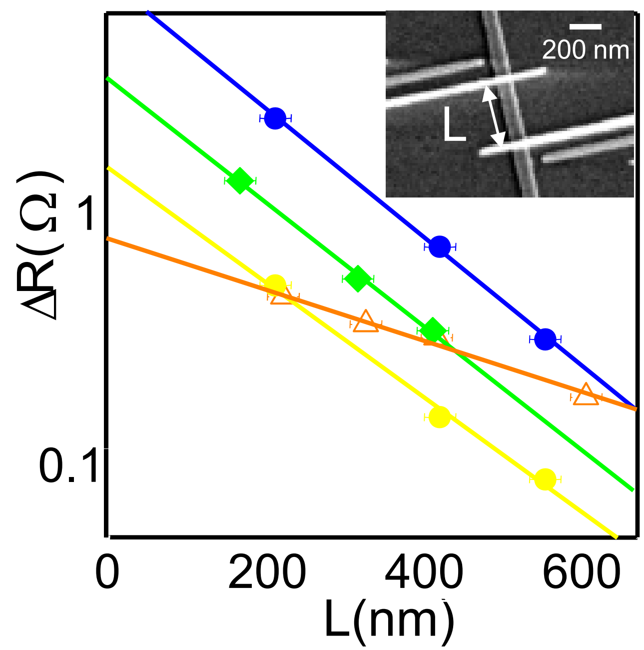
- Non-equilibrium spin density (spin accumulation)

- The detector (NiFe) samples the electrochemical potential of the spin populations

- *L* is varied to obtain the spin relaxation length

Spin relaxation, spin transfer through interfaces





$$\frac{V_{\pm}}{I} = \pm\frac{1}{2} P_{CoFe} P_{NiFe} \frac{\lambda_{sf}}{\sigma_{Al} A} e^{-L/\lambda_{sf}}$$

4K: $P = (P_{NiFe} P_{CoFe})^{1/2}$ ~25%; λ_{sf} ~0.2-1 μm

Room T: P ~ 17%; λ_{sf} ~0.2-0.4 μm

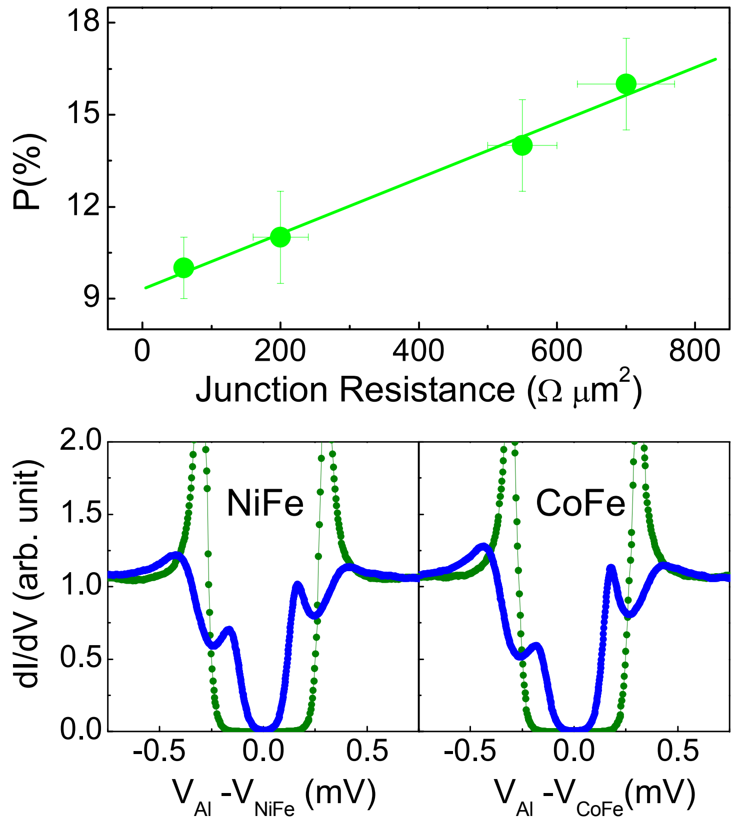
Spin flip time

$$\left.\begin{aligned} \lambda_{sf} &= \sqrt{D\tau_{sf}} \\ \sigma &= e^2 N_{Al} D \end{aligned}\right\} \tau_{sf} \sim 50\text{ps at RT}$$

SOV and M. Tinkham, APL **85**, 5914 (2004)

SOV, Int. J. Mod. Phys. B **23**, 2413 (2009)

Tunneling spin polarization



H= 0; 2T

- *P* depends on the barrier transparency (oxidation time)
- *P* can be directly compared with the polarization obtained with the Meservey-Tedrow (MT) technique in the ***same*** sample

$P_{Spin\ Valve}(4K) = (P_{NiFe}P_{CoFe})^{1/2} \sim 25\%$

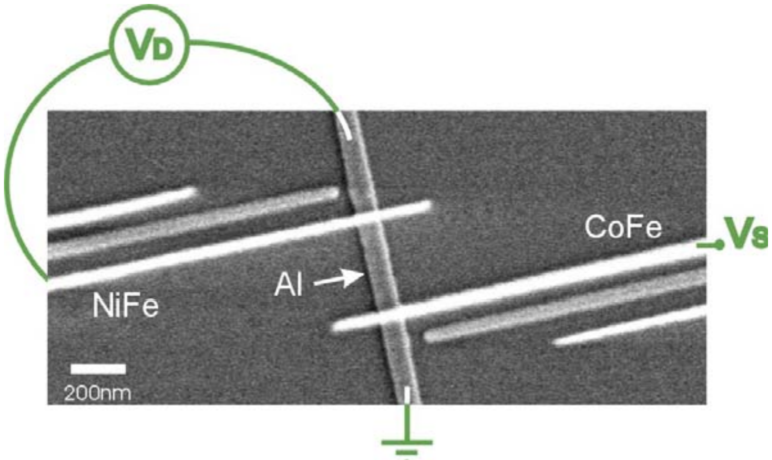
$P_{MT\text{-}NiFe}(250mK) \sim 19\%$

$P_{MT} = 27\%$

$P_{MT\text{-}CoFe}(250mK) \sim 38\%$

SOV and M. Tinkham, APL **85**, 5914 (2004) I.I. Mazin, PRL **83**, 1427-1430 (1999)

Spin polarized tunneling at finite bias

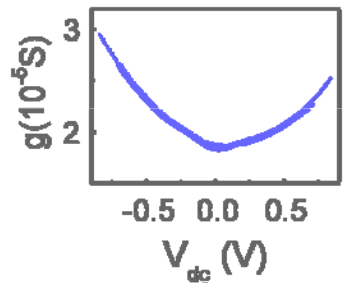


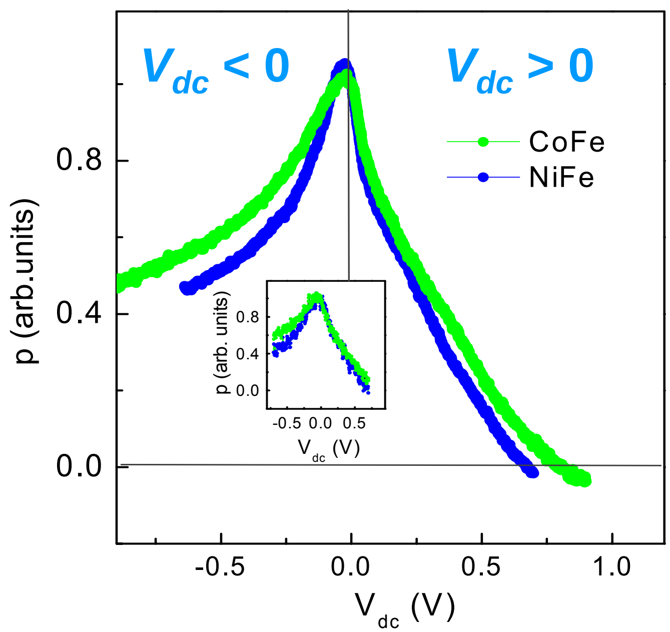
$V_S = V_{dc} + V_{ac}$

$V_{ac} \sim 10 - 30$ mV

$|V_{dc}| < 1.5$ V

$$p_{NiFe,CoFe} = \frac{g_M - g_m}{g_M + g_m}$$





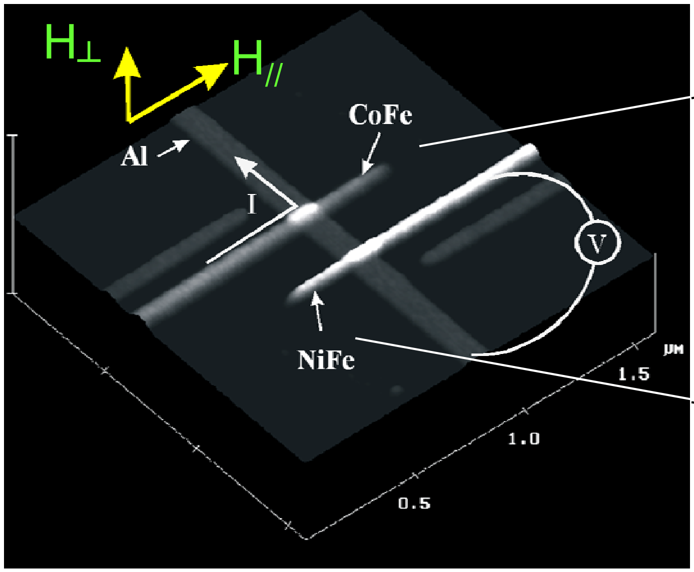
$V_{dc} > 0$ electrons tunnel *into* FM

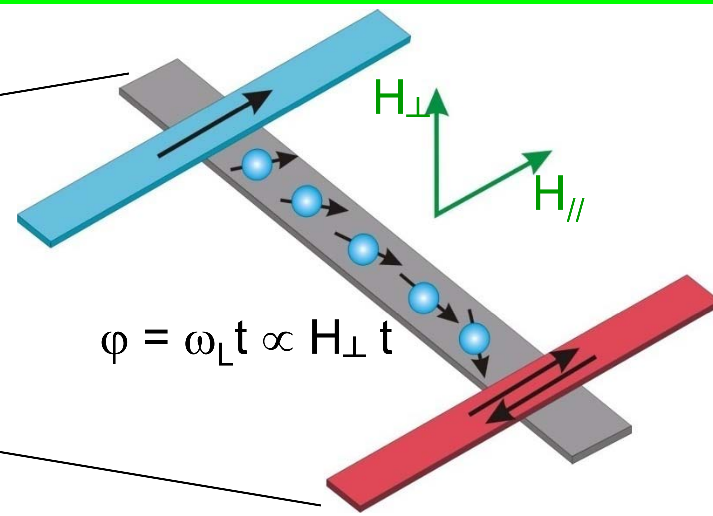
$V_{dc} < 0$ electrons tunnel *out of* FM

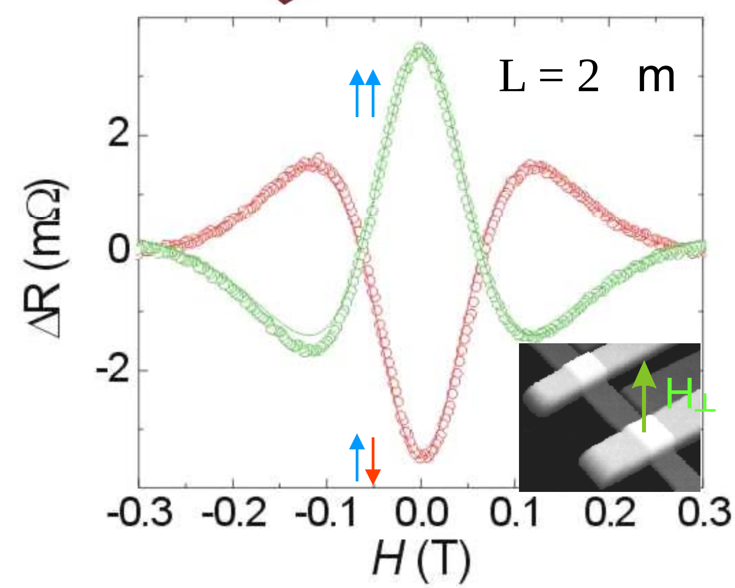
Asymmetry in the tunneling

SOV *et al.*, PRL **94**, 196601 (2005)

Spin precession







Polarization and
diffusion characteristics
from a single measurement

Johnson and Silsbee PRL **55**, 1790 (1985)
Jedema *et al.*, Nature **416**, 713 (2002)

Nonlocal measurements applications

Spin transport in metals and through interfaces

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- Y. Ji, A. Hoffmann, J.S. Jiang, S.D. Bader, Appl. Phys. Lett. **85**, 6218 (2004).
- S. Garzon, I. Zutic, and R.A. Webb, Phys. Rev. Lett. **94**, 176601 (2005).
- Y. Ji, A. Hoffmann, J.E. Pearson, and S.D. Bader, Appl. Phys. Lett. **88**, 052509 (2006).
- R. Godfrey and M. Johnson, Phys. Rev. Lett. **96**, 136601 (2006).
- J.H. Ku, J. Chang, K. Kim, and J. Eom, Appl. Phys. Lett. **88**, 172510 (2006).
- N. Poli, M. Urech, V. Korenivski, and D.B. Haviland, J. Appl. Phys. **99**, 08H701 (2006).

Zero dimensional structures

- M. Zaffalon, and B.J. van Wees, Phys. Rev. Lett. **91**, 186601 (2003).

Superconductors

- D. Beckmann, H.B. Weber, and H.v. Löhneysen, Phys. Rev. Lett. **93**, 197003 (2004).
- M. Urech, J. Johansson, N. Poli, V. Korenivski, and D.B. Haviland, J. Appl. Phys. **99**, 08M513 (2006).

Semiconductors

- X. Lou *et al.* cond-mat/0701021, Nat. Phys. **3**, 197 (2007).

Nanotubes/Graphene

- N. Tombros, S.J. van der Molen, and B.J. van Wees, Phys. Rev. B **73**, 233403 (2006).
- N. Tombros *et al.* Nature **448**, 571 (2007).

Spin torque by pure spin currents

- T. Kimura *et al.*, Nature Phys. **4**, 11 (2008).

Review

- S.O. Valenzuela, Int. J. Mod. Phys. B 23, 2413 (2009).

Spin Dynamics in Metallic Nanostructures

- Introduction
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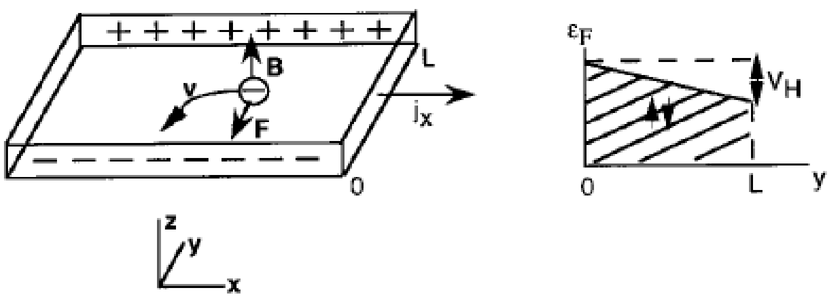
- Spin Hall Effect
  - Nonlocal Electrical Detection of the Reverse Spin Hall Effect
  - Comparison with Lateral Spin-Valve
- Conclusions

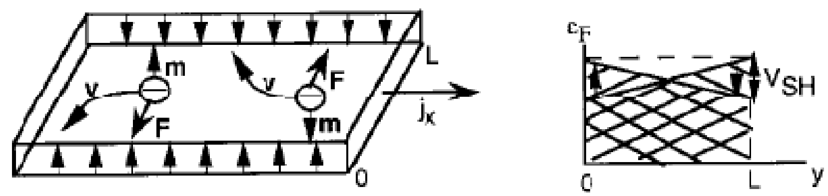
Spin Hall effect

Spin current generation and spin accumulation without magnetic fields or ferromagnets

Hall effect



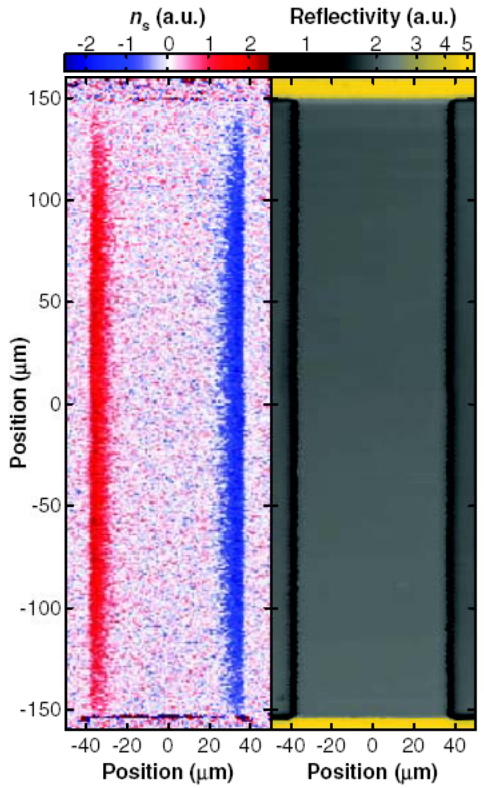
Spin Hall effect

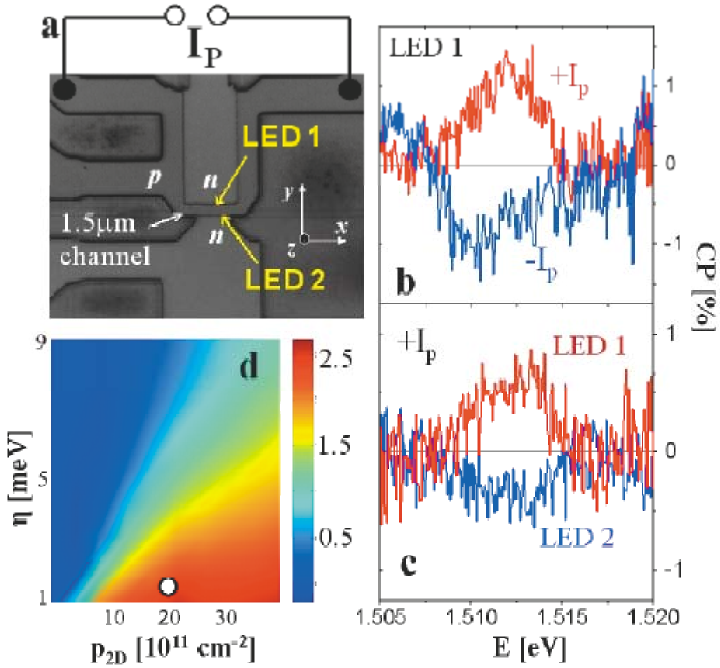


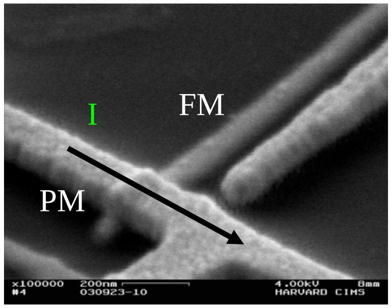
M.I. Dyakonov & V.I. Perel, JETP Lett. **13**, 467 (1971); J.E. Hirsch, PRL **83**, 1834 (1999);

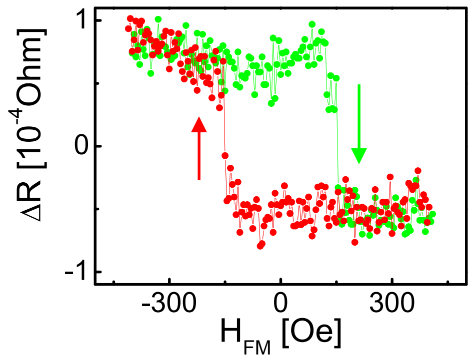
S. Zhang, PRL **85**, 393 (2000); S. Murakami, N. Nagaosa, S.C. & Zhang. Science **301**, 1348 (2003); J. Sinova, *et al.,* PRL **92**, 126603 (2004).

Spin Hall effect









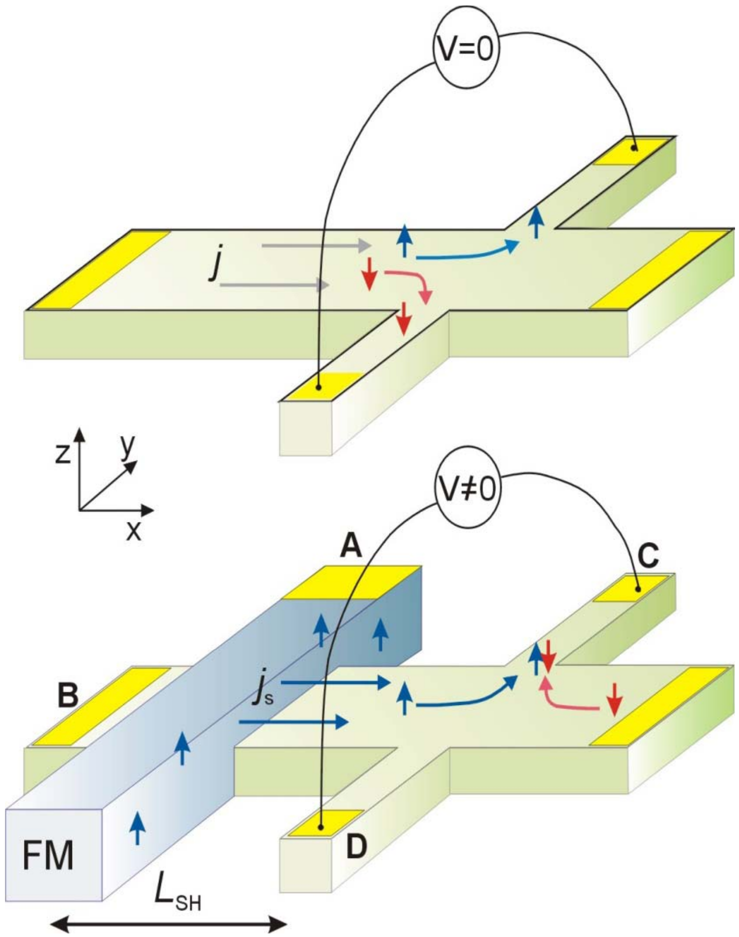
Spin accumulation in PM detected with FM
Experimental artifacts?

Y.K. Kato *et al.* Science **306**, 1910 (2004); J. Wunderlich, *et al.* PRL **94**, 047204 (2005).

V. Sih *et al.* Nature Physics **1**, 31 (2005).

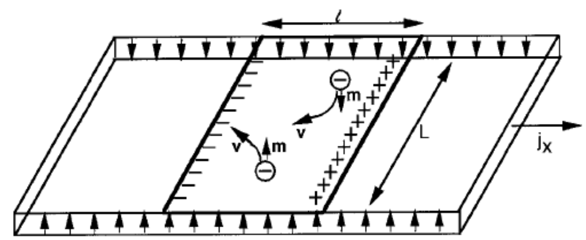
S. Zhang PRL (2000).

Spin Hall effect. Electronic detection



J.E. Hirsch. PRL **83**, 1834 (1999).

A.A. Bakun *et al.*, Sov. Phys. JETP Lett. **40**, 1293 (1984).

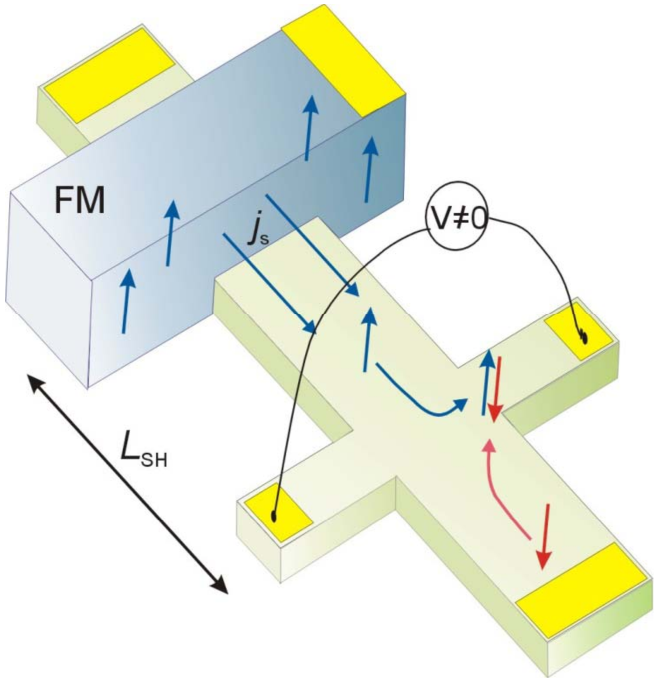


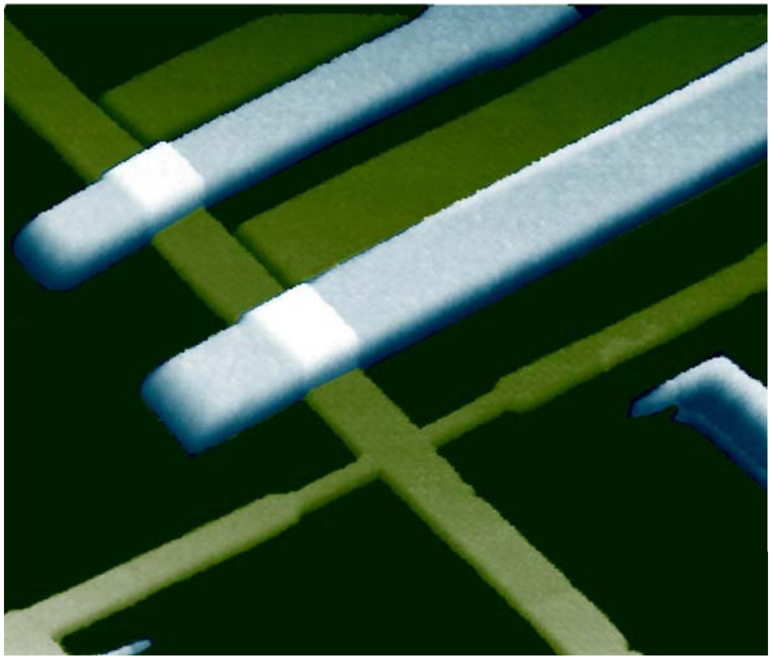
A current generates a spin imbalance trough the spin Hall effect in an Al strip

The spin imbalance drives a spin current which generates a voltage in a second Al strip

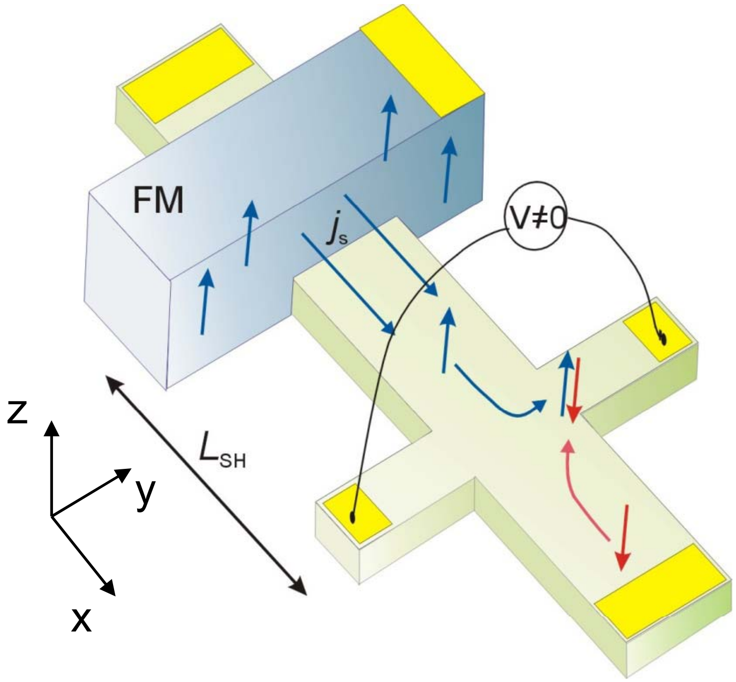
Second order effect

Spin Hall effect. Electronic detection





Spin Hall effect. Electronic detection



Diffusive system

$$\nabla^2 \delta\mu(\mathbf{r}) = \frac{\delta\mu(\mathbf{r})}{\lambda_{sf}^2}; \quad \delta\mu(\mathbf{r}) = \frac{\mu^{\uparrow}(\mathbf{r}) - \mu^{\downarrow}(\mathbf{r})}{2}$$

$$\mathbf{j}_c(\mathbf{r}) = \sigma_c \mathbf{E}(\mathbf{r}) + \frac{\sigma_{SH}}{\sigma_c}[\hat{\mathbf{z}} \times j_s]$$

Charge current in *y* direction is zero

$$V_{SH} \equiv V_{CD} = -E_y(x) w_N = w_N \frac{\sigma_{SH}}{\sigma_c^2} j_s(x)$$

and

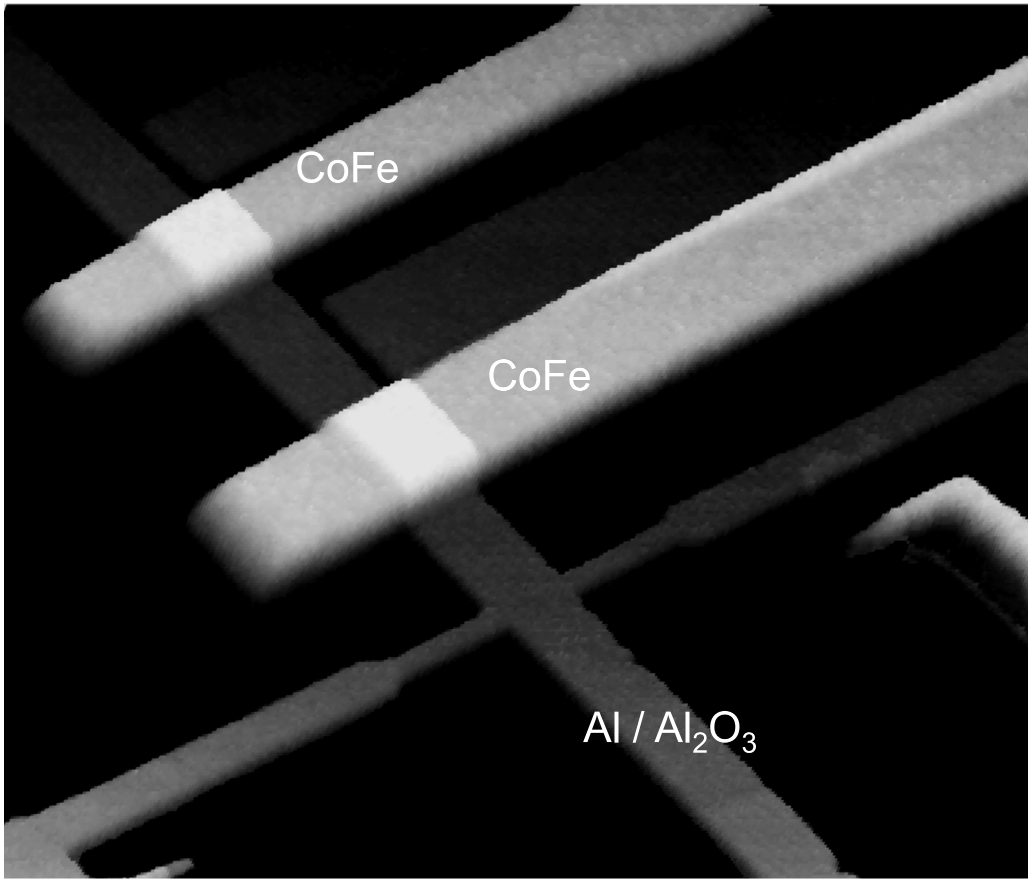
$$j_s(x) = \frac{1}{2} P \frac{I}{A_N} e^{-x/\lambda_{sf}}$$

$$R_{SH} = \frac{1}{2} \frac{P}{t_N} \frac{\sigma_{SH}}{\sigma_c^2} e^{-x/\lambda_{sf}}$$

Zhang, S. PRL **85**, 393 (2000); JAP **89**, 7564 (2001).

S. Takahashi *et al.*, Chapter 8 in *Concepts in spin electronics* (Oxford Univ. Press, 2006).

Sample layout



e-beam lithography

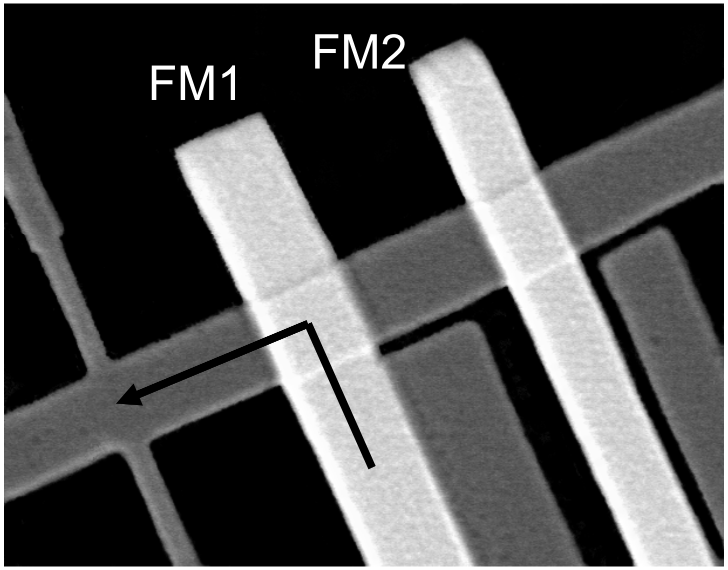
Shadow evaporation

Al Film
Al_2O_3 tunnel barrier
CoFe electrodes

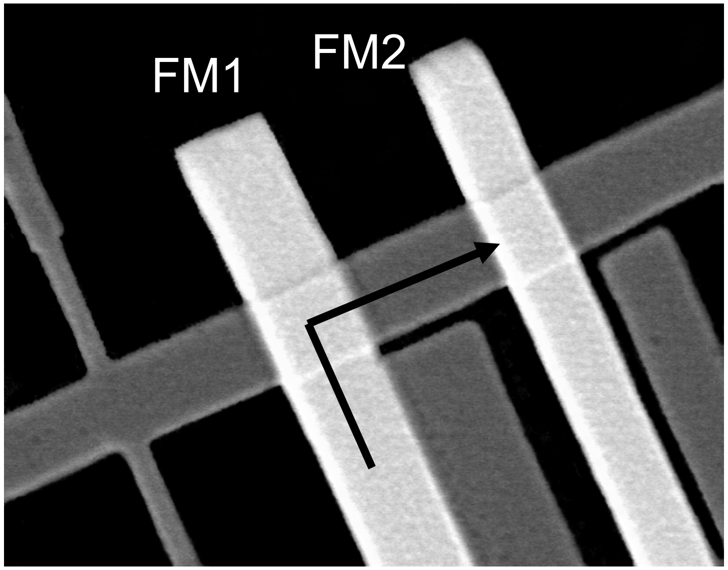
P ~ 30 %

Measurement schemes

Johnson-Silsbee

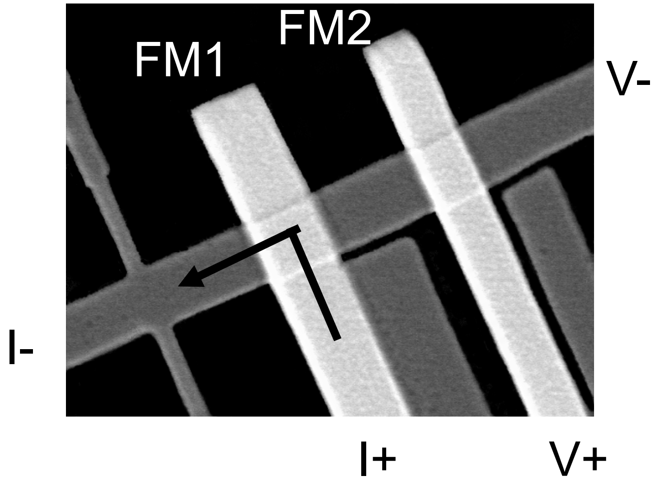


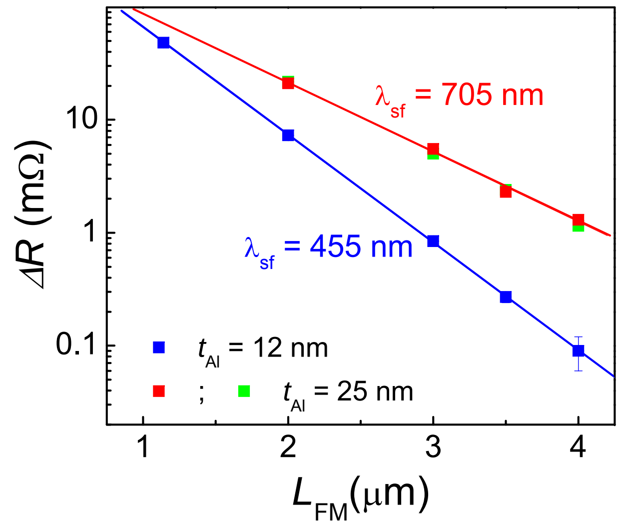
Spin Hall effect

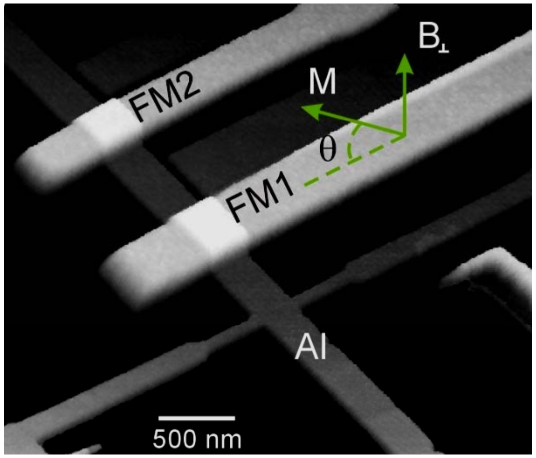


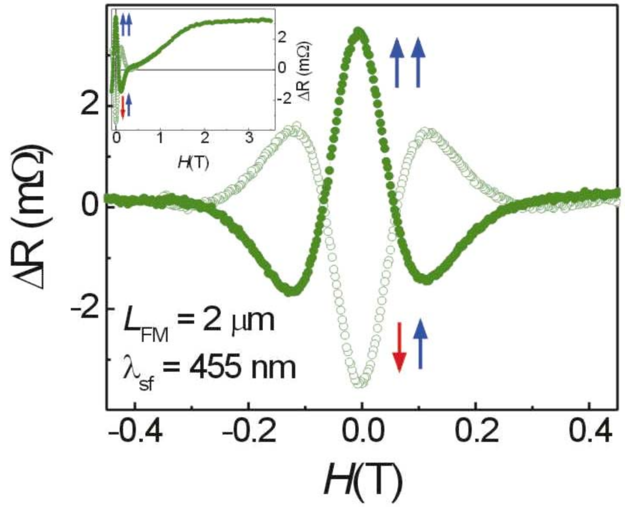
SOV and M. Tinkham, Nature **442**, 176 (2006); Int. J. Mod. Phys. B **23**, 2413 (2009).

Nonlocal spin detection. Spin precession
Jonhson-Silsbee

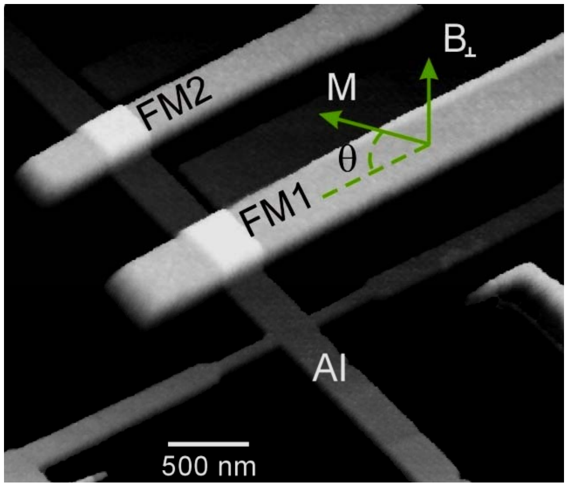


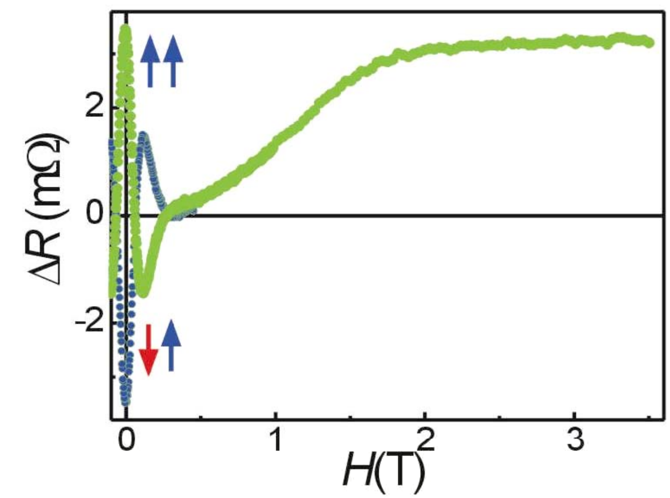






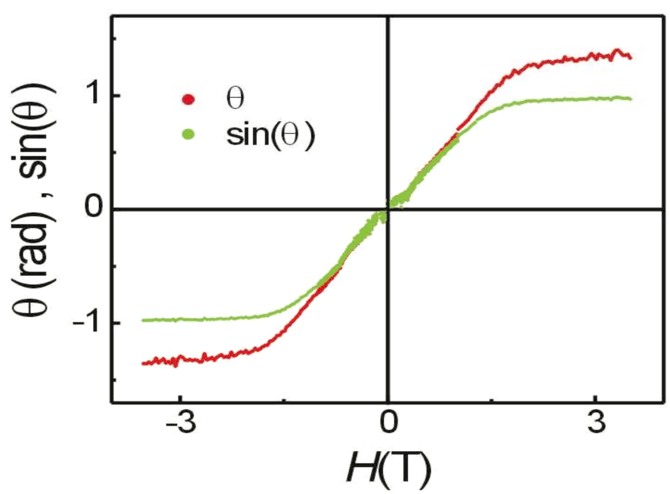
Jonhson-Silsbee





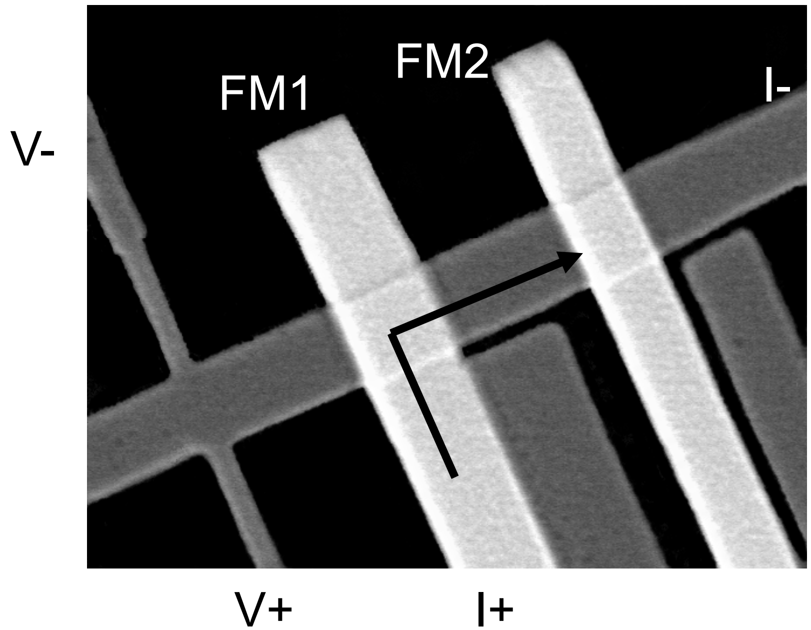
$$\frac{V_{\uparrow\uparrow}}{V_0} = +f(B_\perp)\cos^2\theta + \sin^2\theta$$

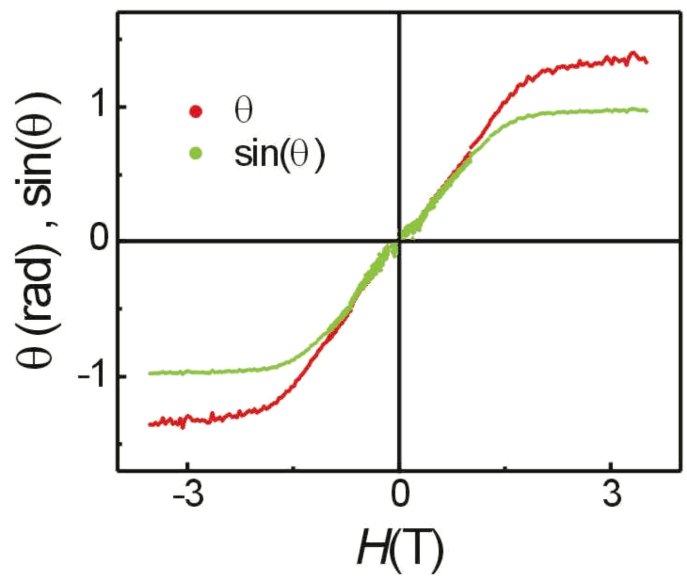
$$\frac{V_{\downarrow\uparrow}}{V_0} = -f(B_\perp)\cos^2\theta + \sin^2\theta$$



Jedema *et al.*, Nature **416**, 713 (2002)

Spin Hall effect





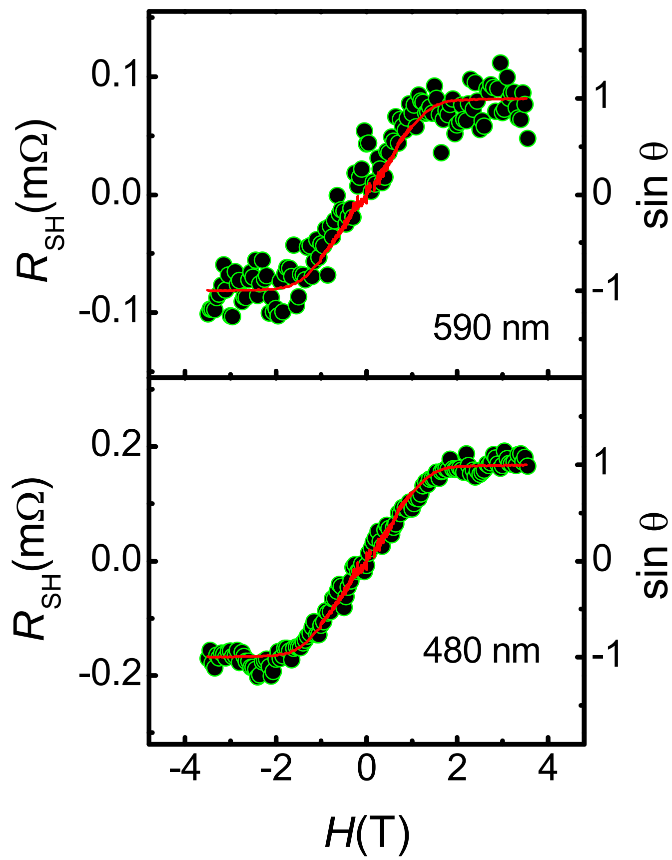
$V/I = R_{SH} = (1/2)\,\Delta R_{SH} \sin\theta$

$\Delta R_{SH} = 2(P\ \sigma_{SH} / t_{Al}\ \sigma^2_c)\ \exp[-L_{SH}/\lambda_{sf}]$

Zhang, S. PRL **85**, 393 (2000)

S. Takahashi *et al.*, Chapter 8 in *Concepts in spin electronics* (Oxford Univ. Press, 2006)

Spin Hall effect



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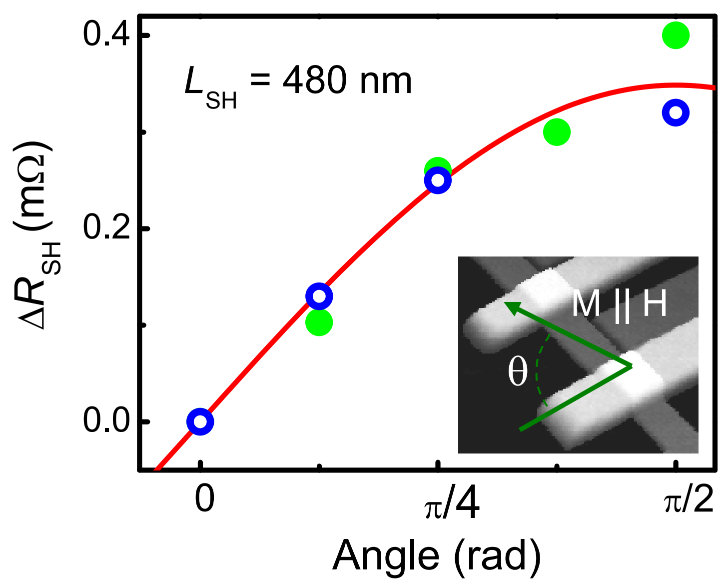
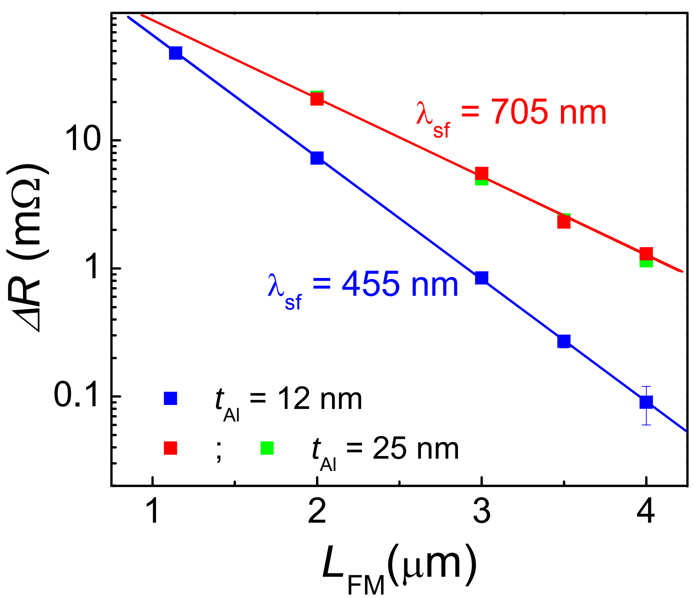
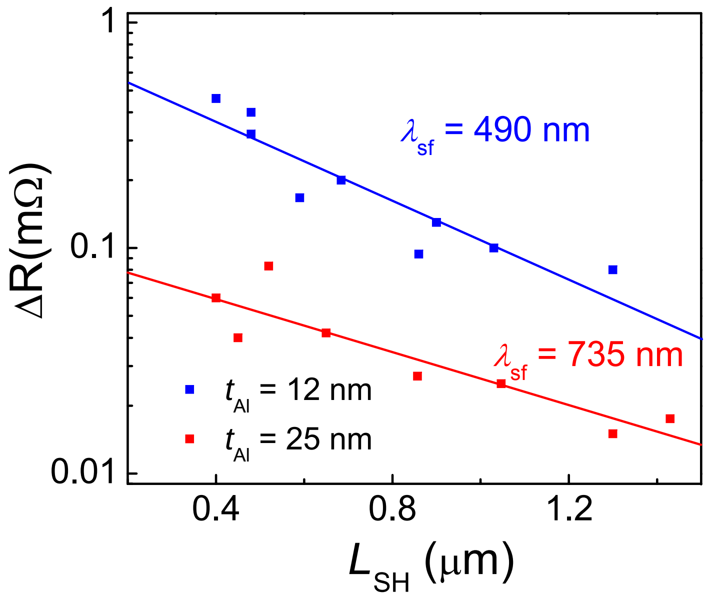


SOV and M. Tinkham, Nature **442**, 176 (2006), J. Appl. Phys. **101**, 09B103 (2007)

Spin Hall effect

Comparison with standard nonlocal detection





$\Delta R_{SH} = 2(P\ \sigma_{SH} / t_{Al}\ \sigma^2_c) \exp[-L_{SH}/\lambda_{sf}]$

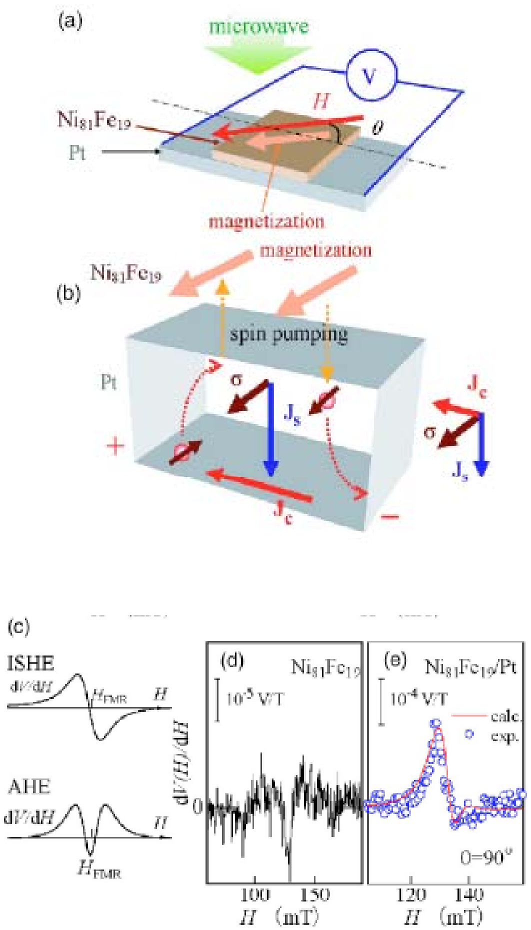
$\sigma_{SH} \sim 30\ (\text{cm})^{-1}$

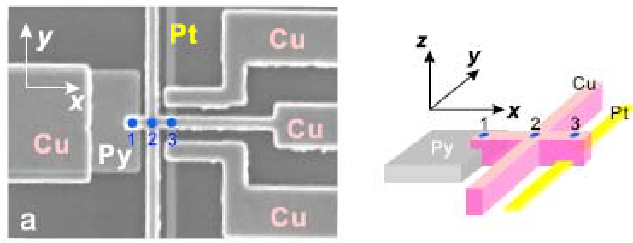
Predicted (extrinsic): $\sigma_{SH} \sim 10\ (\text{cm})^{-1}$

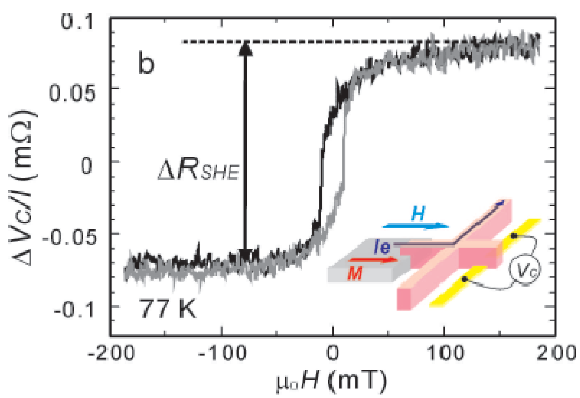
$P \sim 28\ \%$

Zhang, PRL (2001); Shchelushkin & Brataas, PRB (2005)
T. Kimura *et al.*, cond-mat/0609304, PRL 2007

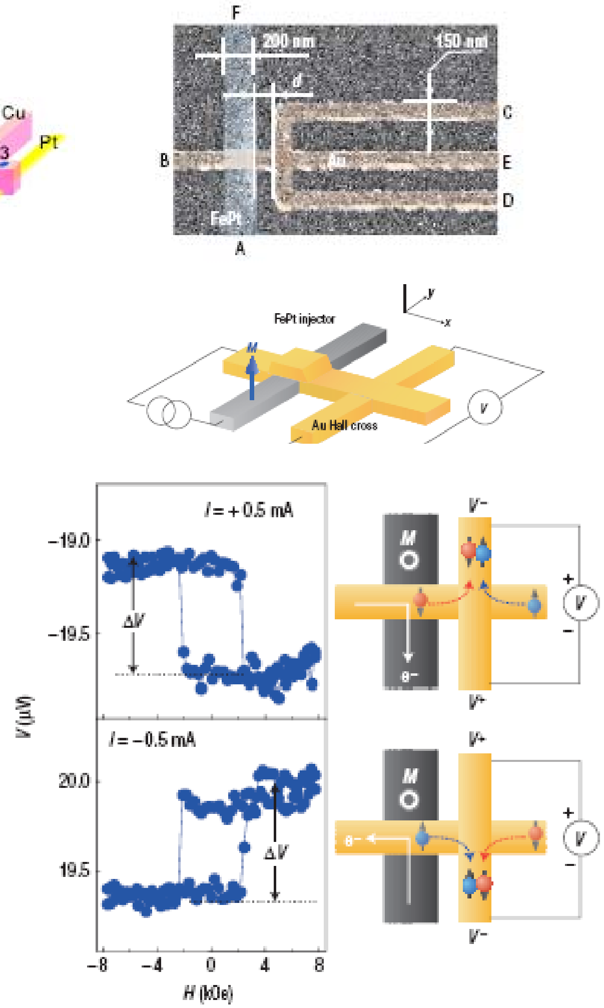
Spin Hall effect







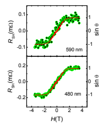
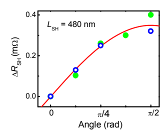
Spin Hall cross adapted for
materials with
short spin relaxation length

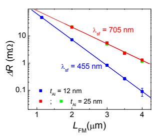
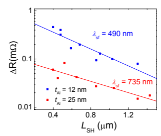


E. Saitoh *et al.*, APL **88**, 182509 (2006)   T. Kimura *et al.*, PRL **98**, 156601 (2007)   T. Seki *et al.*, Nat. Mat. *(*2008)

Conclusions

- Electronic detection of the (reverse) spin Hall effect in a diffusive conductor.
- Results are consistent with those obtained with control Lateral Spin-Valves.

✓ Spin precession experiments and magnetization orientation dependence of the spin Hall effect.  

✓ Spin relaxation length in films with different thickness.  

- Theoretical estimations using   -like scattering centers are in agreement with experimental results, $\sigma_{SH} \sim 30\ (\Omega cm)^{-1}$.