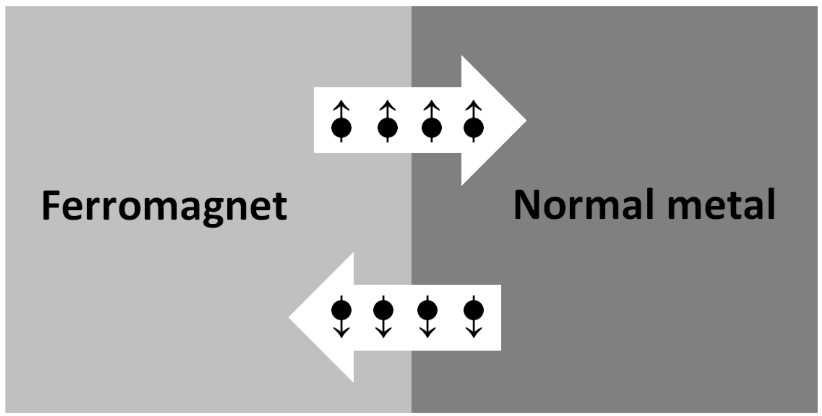
Spin pumping by ferromagnetic resonance



Bachelor project

Hiske Overweg

Supervised by Tim Verhagen and Jan Aarts

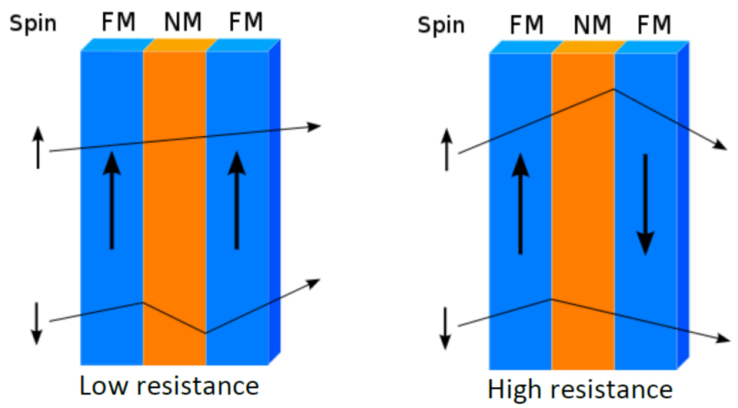
29-6-2011

Outline

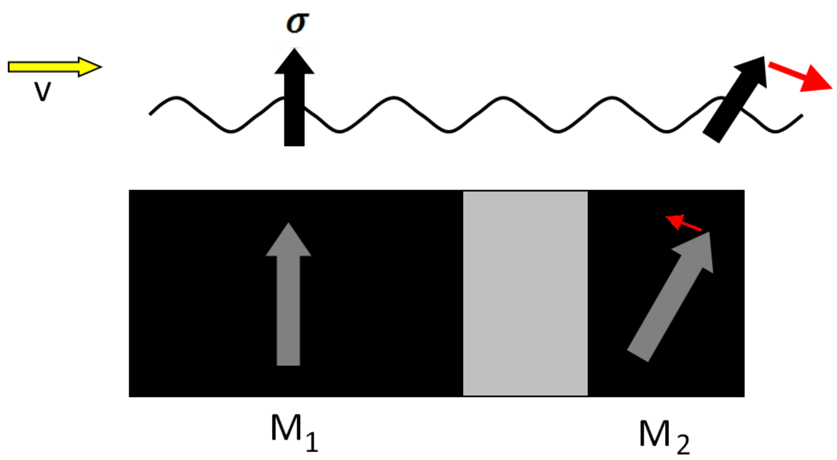
- Background
- Thickness dependence of spin pumping
  - Theory
  - Results
- Inverse spin Hall effect
  - Theory
  - Results
- Conclusion

Giant magnetoresistance and spin transfer torque

Giant magnetoresistance:
Resistance dependent on
spin orientation

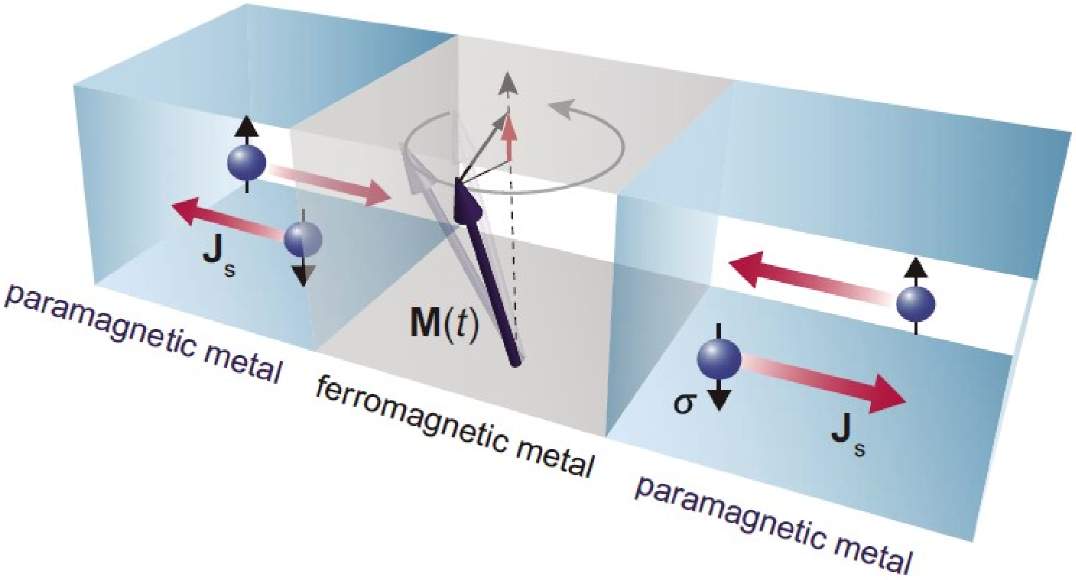


Spin transfer torque: conduction electrons exert torque on magnetisation M_2
→ precession of M_2



Spin pumping

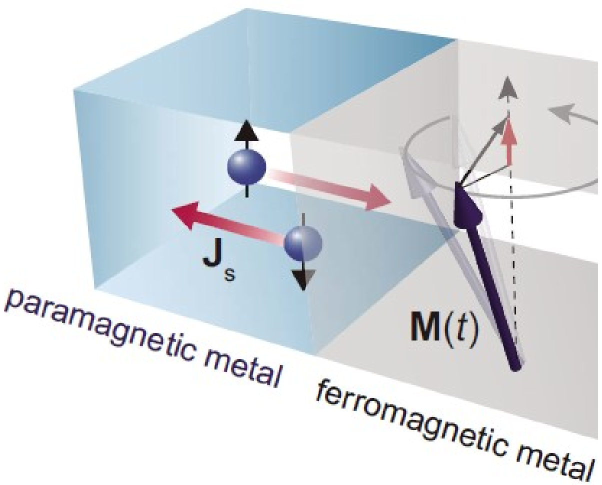
Precession of magnetisation → spin current



K. Ando, T. Yoshino and E. Saitoh, Appl. Phys. Lett. **94**, 152509 (2002)

Spin pumping

Precession of magnetisation → spin current



Science, 5 september 2003:

Dissipationless Quantum Spin Current at Room Temperature

Shuichi Murakami,[1*] Naoto Nagaosa,[1,2,3] Shou-Cheng Zhang[4]

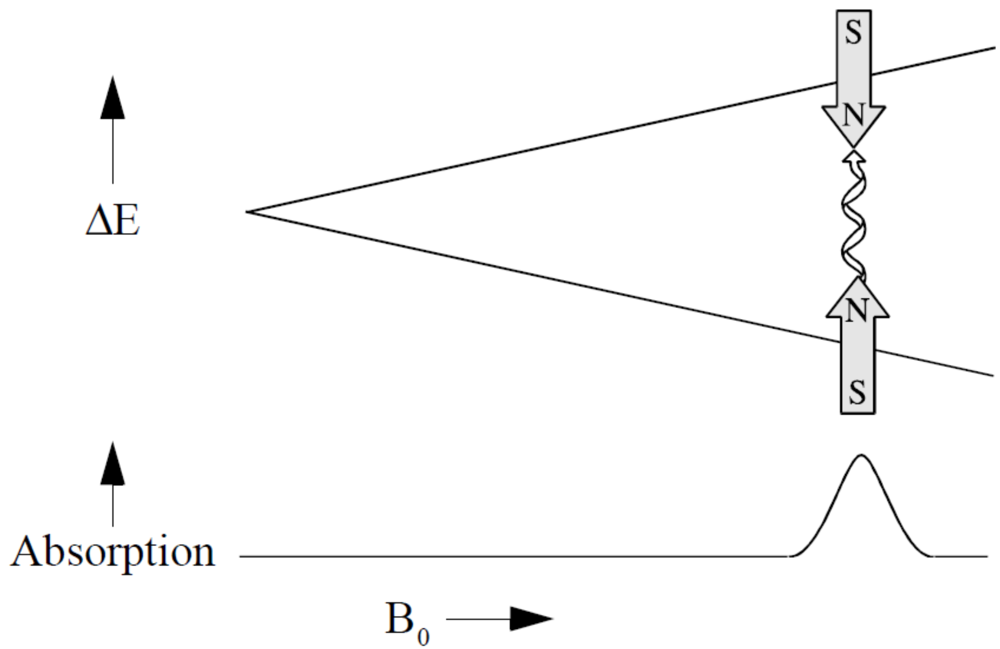
Although microscopic laws of physics are invariant under the reversal of the arrow of time, the transport of energy and information in most devices is an irreversible process. It is this irreversibility that leads to intrinsic dissipations in electronic devices and limits the possibility of quantum computation. We theoretically predict that the electric field can induce a substantial amount of dissipationless quantum spin current at room temperature, in hole-doped semiconductors such as Si, Ge, and GaAs. On the basis of a generalization of the quantum Hall effect, the predicted effect leads to efficient spin injection without the need for metallic ferromagnets. Principles found here could enable quantum spintronic devices with integrated information processing and storage units, operating with low power consumption and performing reversible quantum computation.

K. Ando, T. Yoshino and E. Saitoh, Appl. Phys. Lett. **94**, 152509 (2002)

Ferromagnetic Resonance (FMR)

- Ferromagnet in B-field: Zeeman splitting
- Spin flipping by absorption of microwave radiation

$$\omega = \gamma \boldsymbol{B}_{eff}$$



Peak width depends on damping

- Much damping → broad peak
- Landau-Lifshitz-Gilbert equation

$$\frac{d\boldsymbol{m}}{dt} = -\gamma \boldsymbol{m} \times \boldsymbol{B}_{eff} + \alpha \boldsymbol{m} \times \frac{d\boldsymbol{m}}{dt}$$

- Extra damping caused by spin current

$$\boldsymbol{J}_s \sim \boldsymbol{m} \times \frac{d\boldsymbol{m}}{dt}$$

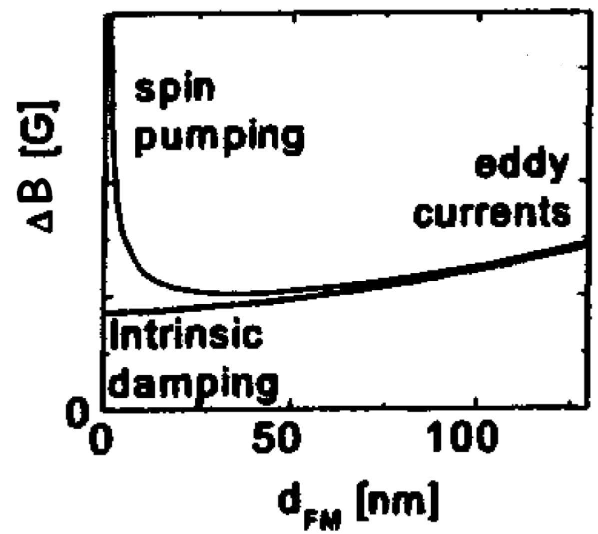
- Important length scale: $\min\{\lambda_J, \lambda_{sd}\}$

$$\lambda_{J,Co} \sim 2 \text{ nm} \qquad \lambda_{sf,Co} \sim 38 \text{ nm}$$

Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, Phys. Rev. Lett. **88**, 117601 (2002)
T. Taniguchi, S. Yakata, H. Imamura and Y. Ando, IEEE Trans. Magn. Mater. **44**, 2636 (2008)

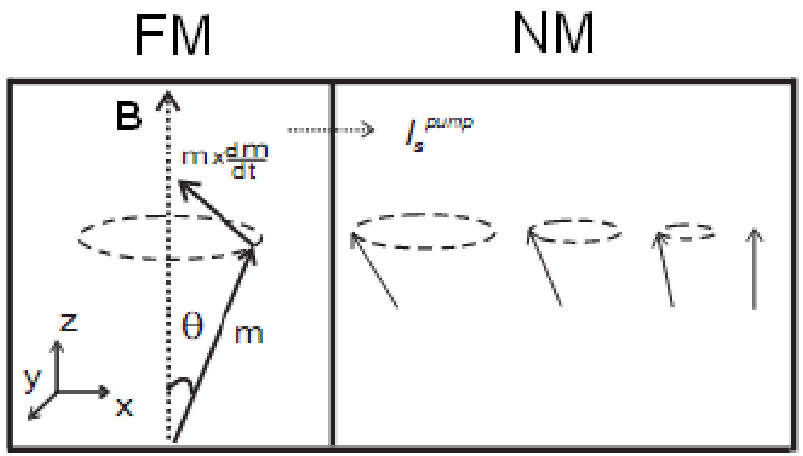
Causes of damping

- Intrinsic damping
- Spin pumping $\alpha \sim d^{-1}$
- Eddy currents $\alpha \sim d^{2}$
- Spin transfer torque (negligible)



Spin sinks

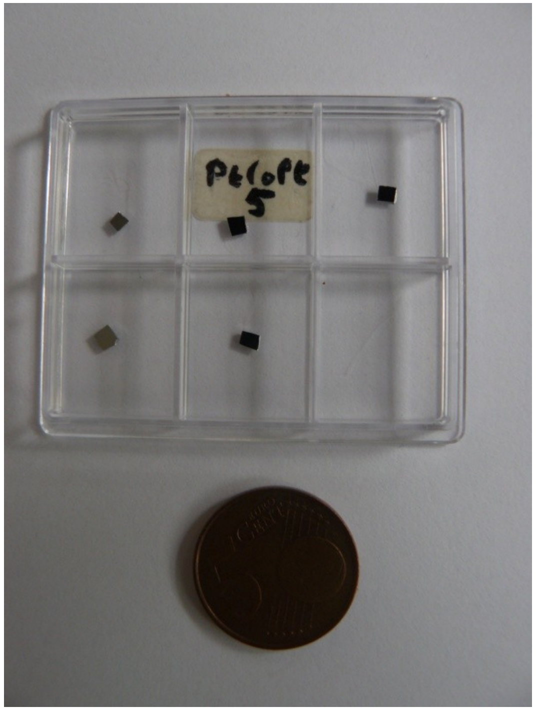
- Good spin sinks absorb spin currents easily because of large spin-orbit coupling $(\sim Z^4)$



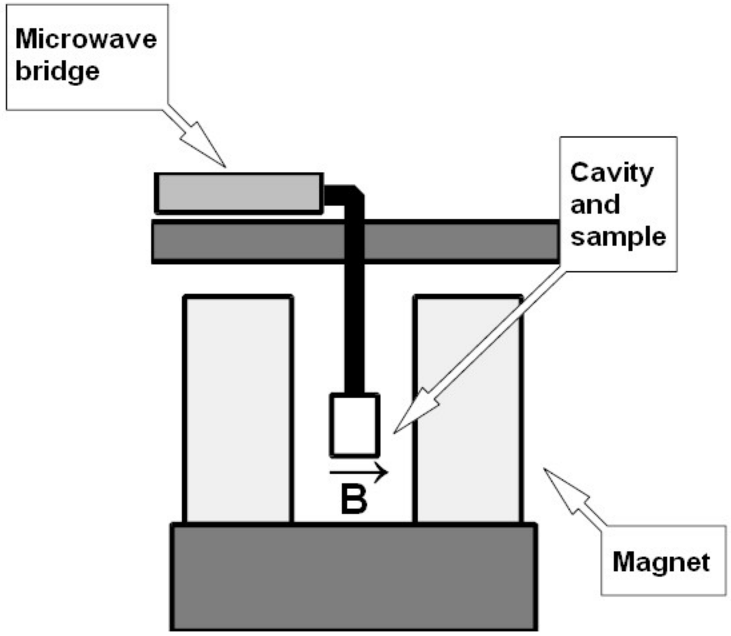
Samples

- $Pt_{(10\ nm)}Co_{(t_{Co}\ nm)}Pt_{(10\ nm)}$ sputtered on silicon substrates (2 mm x 2 mm) in Z-400

- $Cu_{(10\ nm)}Co_{(5\ nm)}Cu_{(10nm)}$
- $Pt_{(10\ nm)}Co_{(5\ nm)}Cu_{(10\ nm)}$
- $Cu_{(10\ nm)}Co_{(5\ nm)}Pt_{(10\ nm)}$

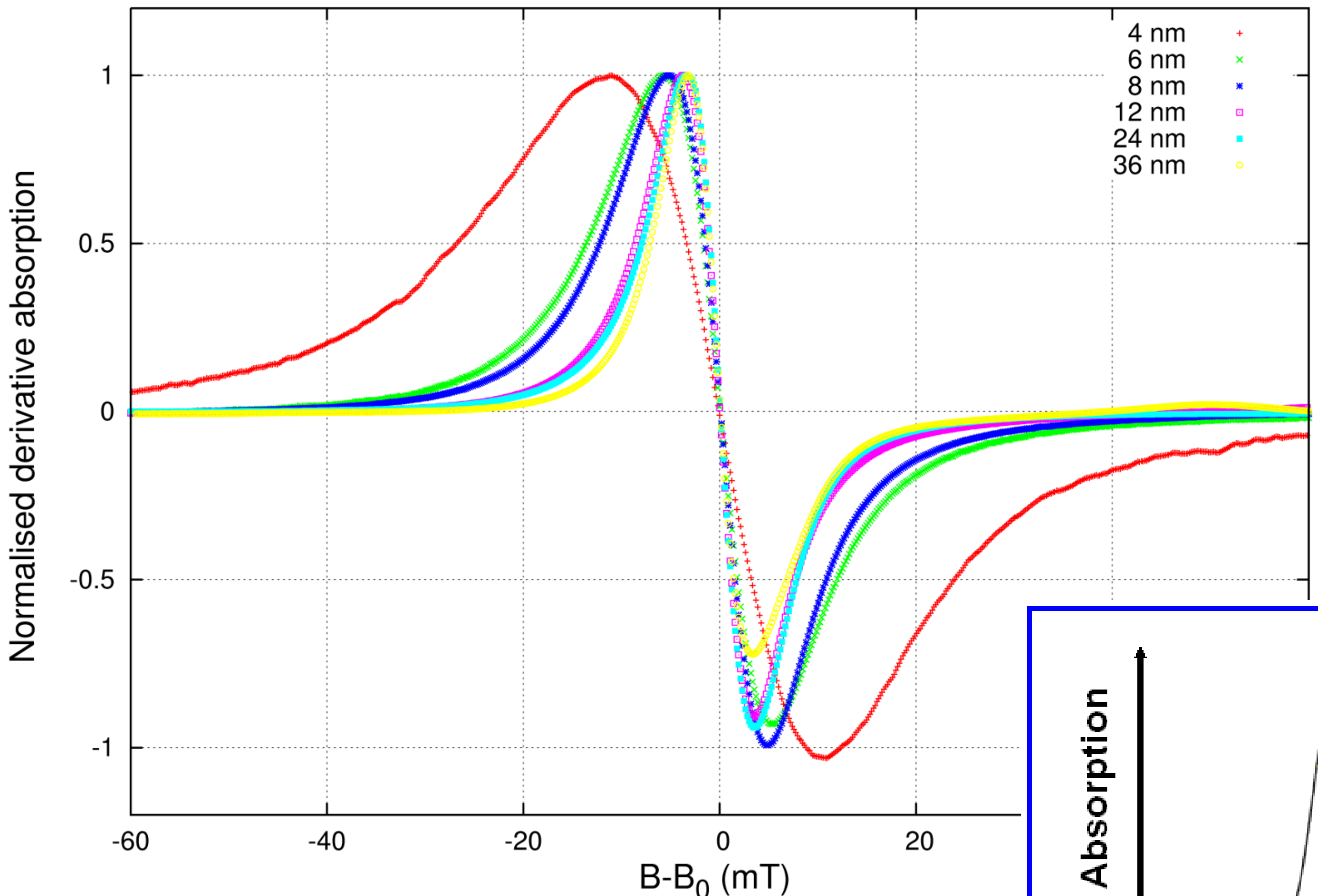


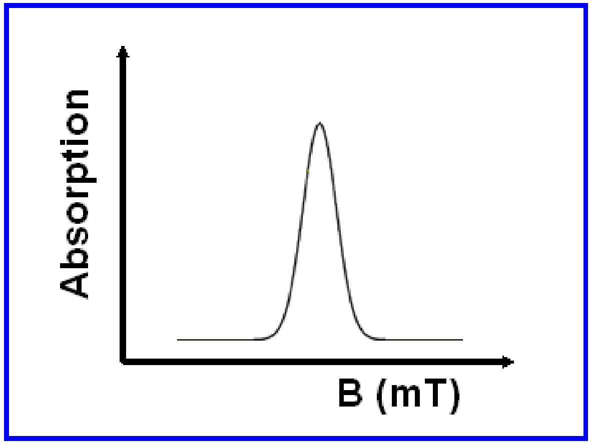
FMR spectrometer



X-band frequency range
Water-cooled magnet (600mT)

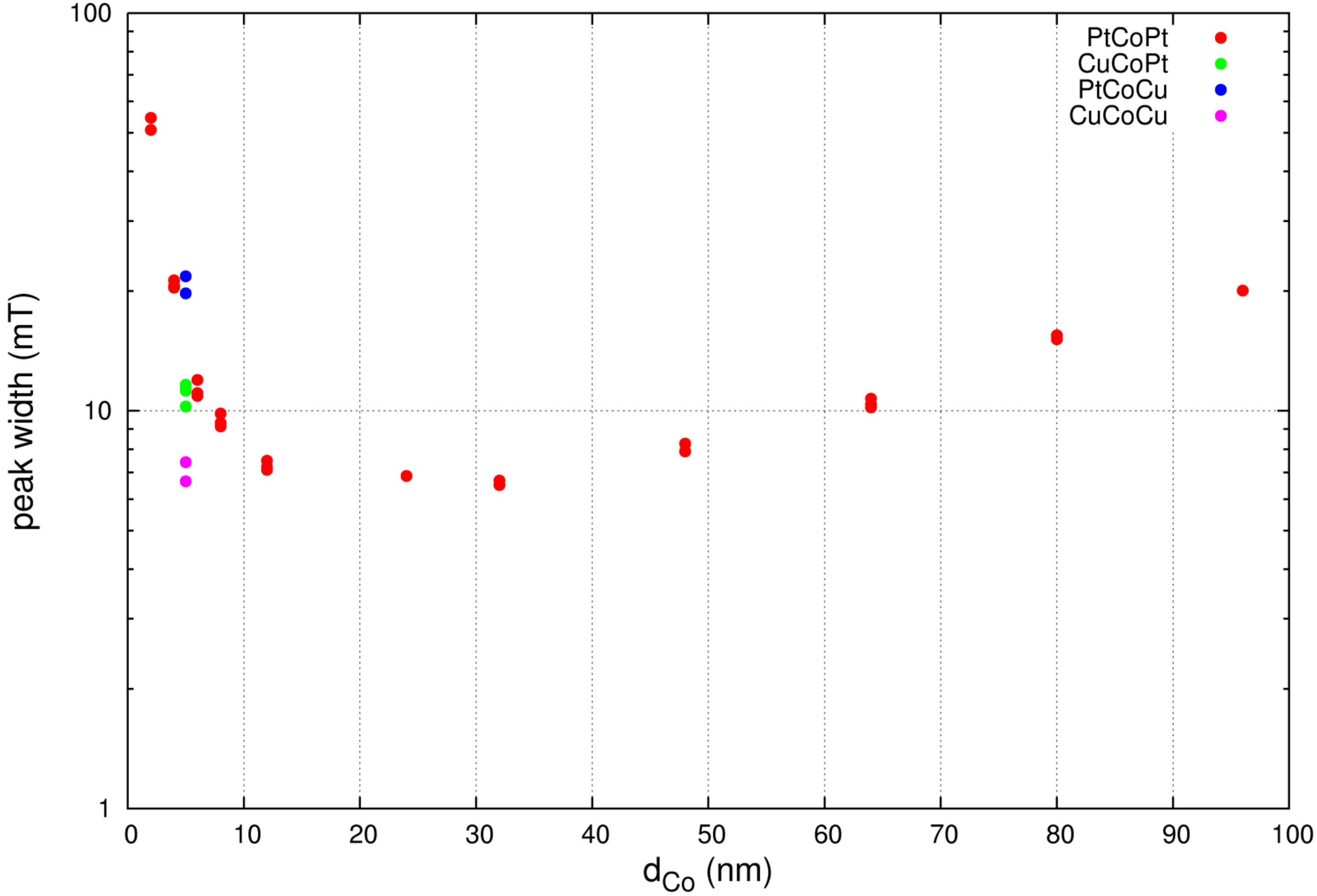
Absorption spectra





$B_0 \approx 60 \text{ mT}$

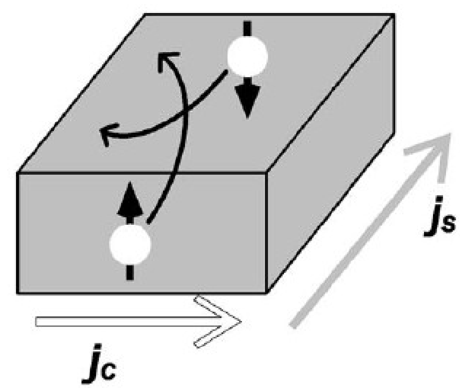
Thickness dependence of peak width



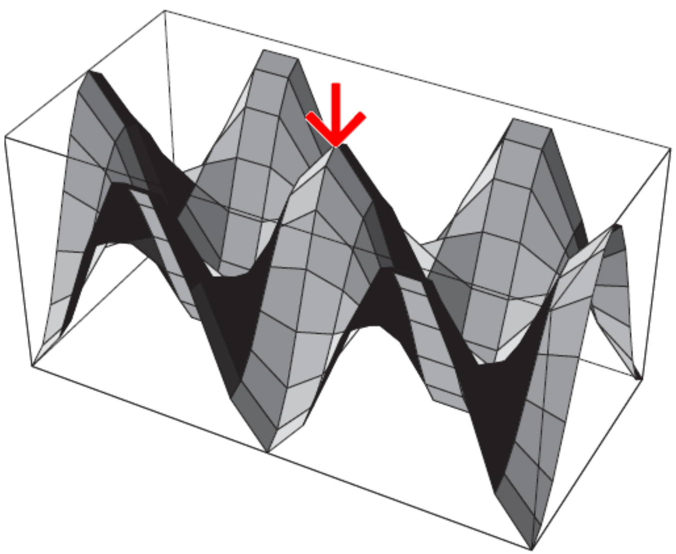
Inverse spin Hall effect

- Spin current $\boldsymbol{J}_S$ induces charge current $\boldsymbol{J}_C$ due to spin-orbit coupling

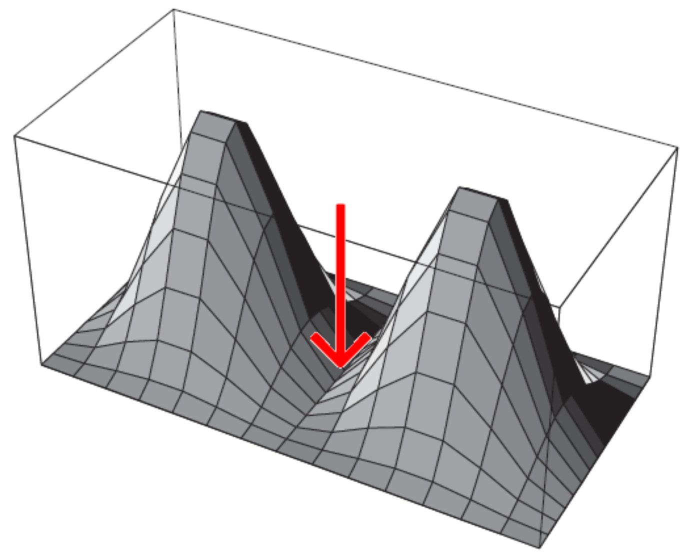
$$\boldsymbol{J}_C \sim \boldsymbol{J}_S \times \boldsymbol{\sigma}$$



B- and E-field distribution in cavity



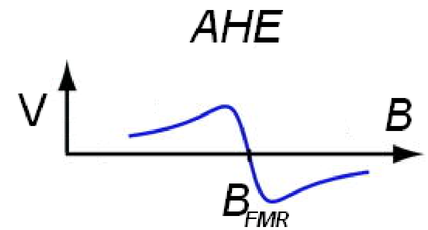
B_1^2



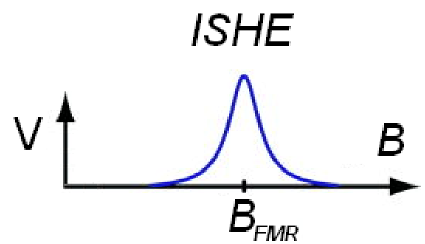
E_1^2

Anomalous Hall effect

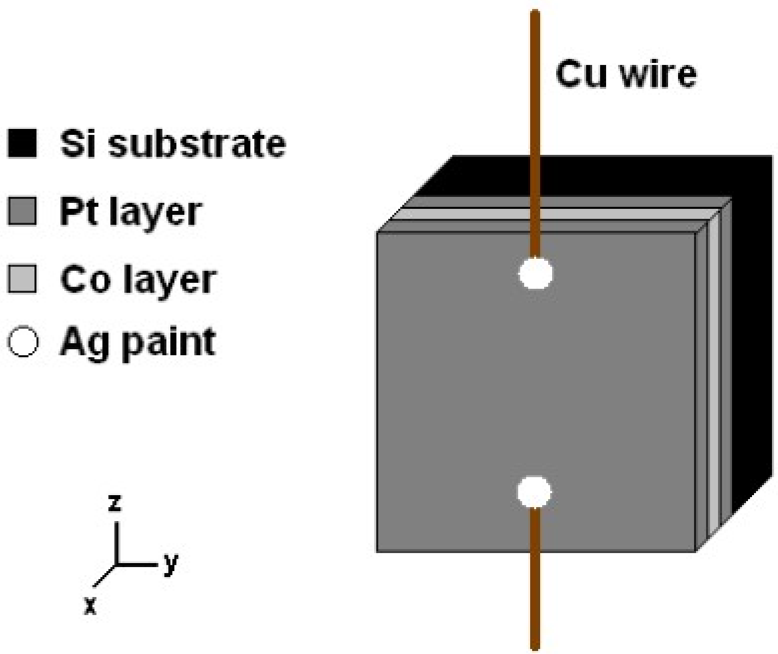
- Scattering at impurities in ferromagnet of J_c induced by E-field microwave radiation
- Induced voltage changes sign at resonance
- AHE: antisymmetric voltage



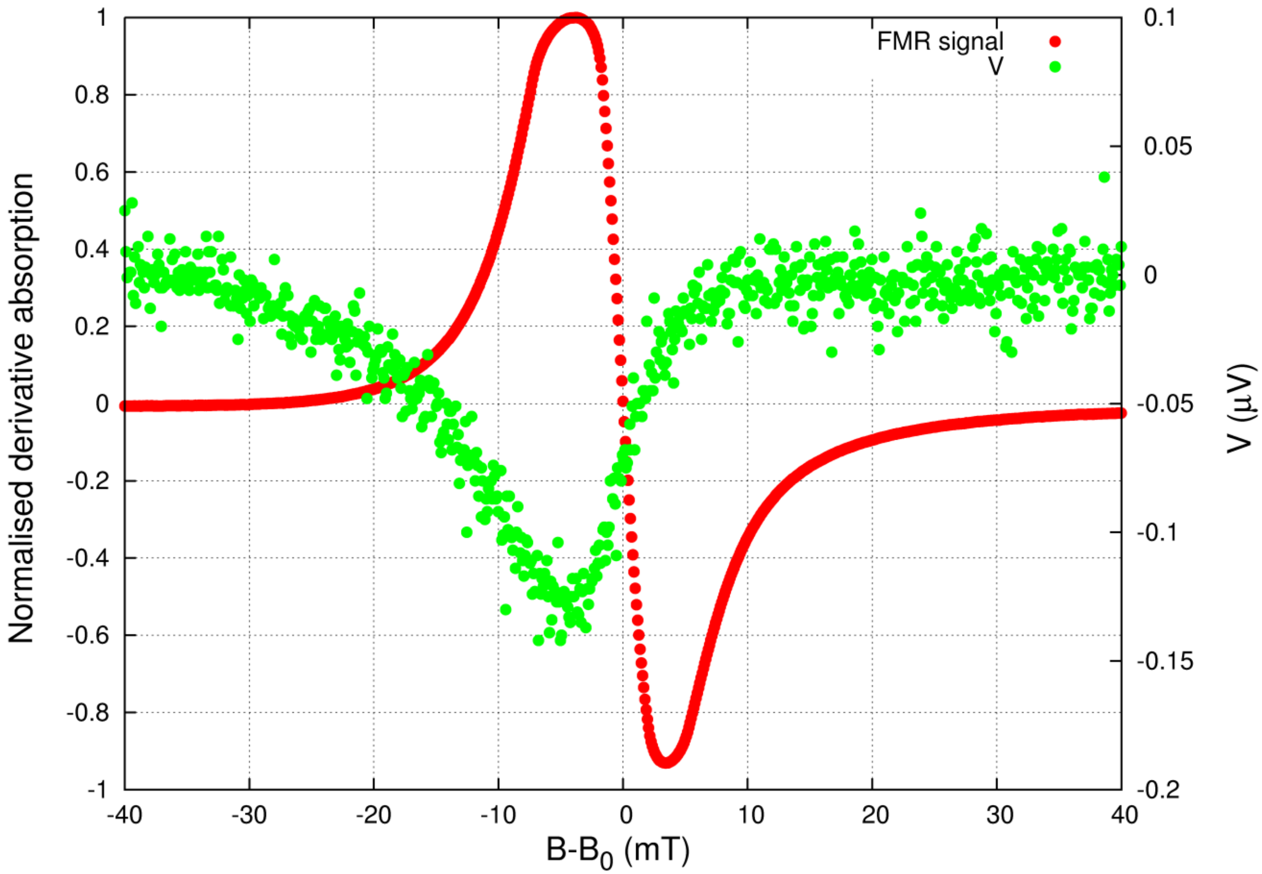
- ISHE: symmetric voltage



Voltage measurement



Absorption spectrum and voltage



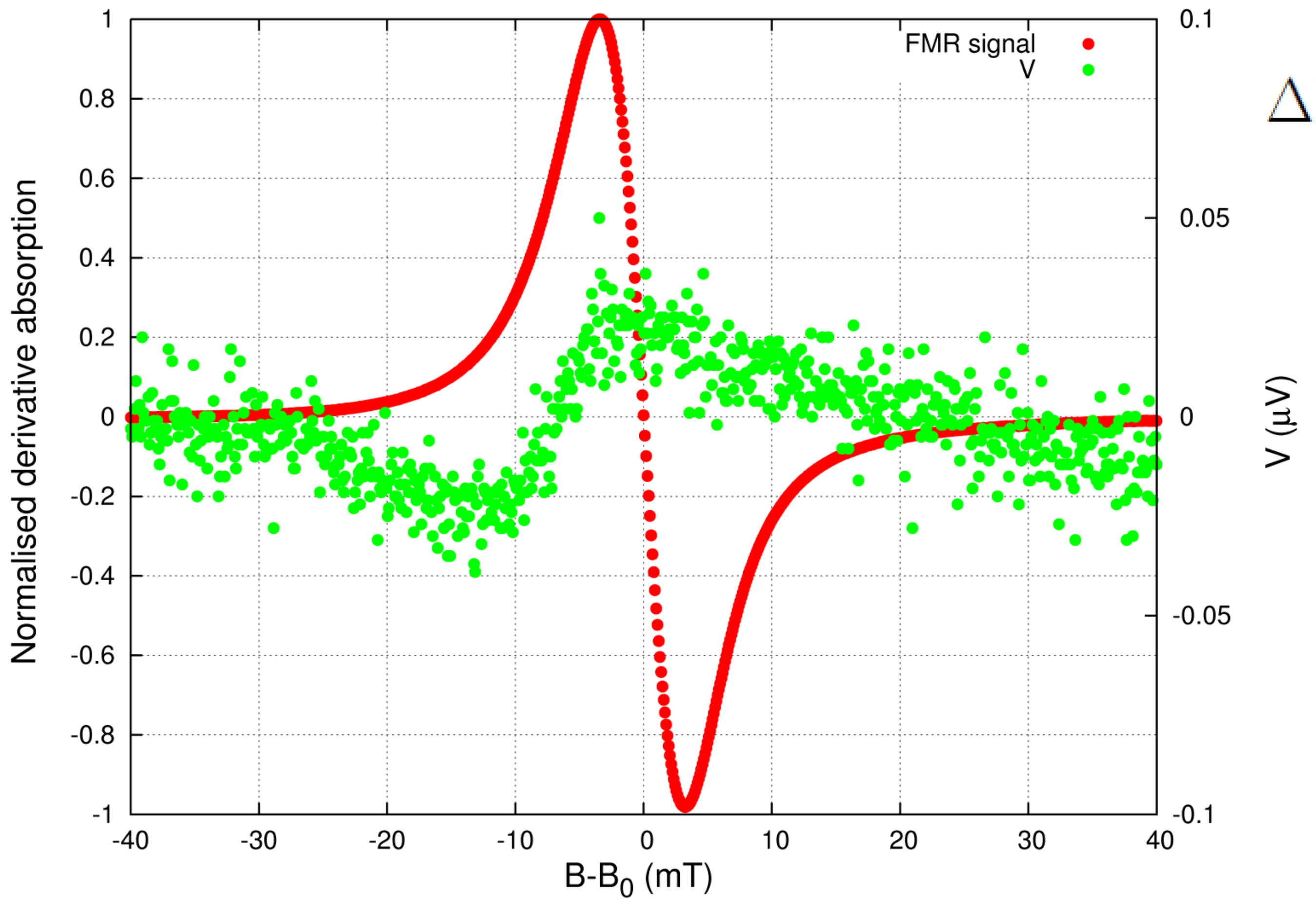
$\Delta V = 0.14\ \mu\text{V}$

Czeschka et. al. :

$\Delta V = 40\ \mu\text{V}$

F. Czeschka, L. Dreher, M. Brandt, M. Weiler, M. Althammer, I. Imort,G. Reiss, A. Thomas, W. Schoch, W. Limmer, H. Huebl, R. Grossand S. Goennenwein, arXiv:1012.3017v1 (2010)

Absorption spectrum and voltage II



$$\Delta V = 0.05 \ \mu\mathrm{V}$$

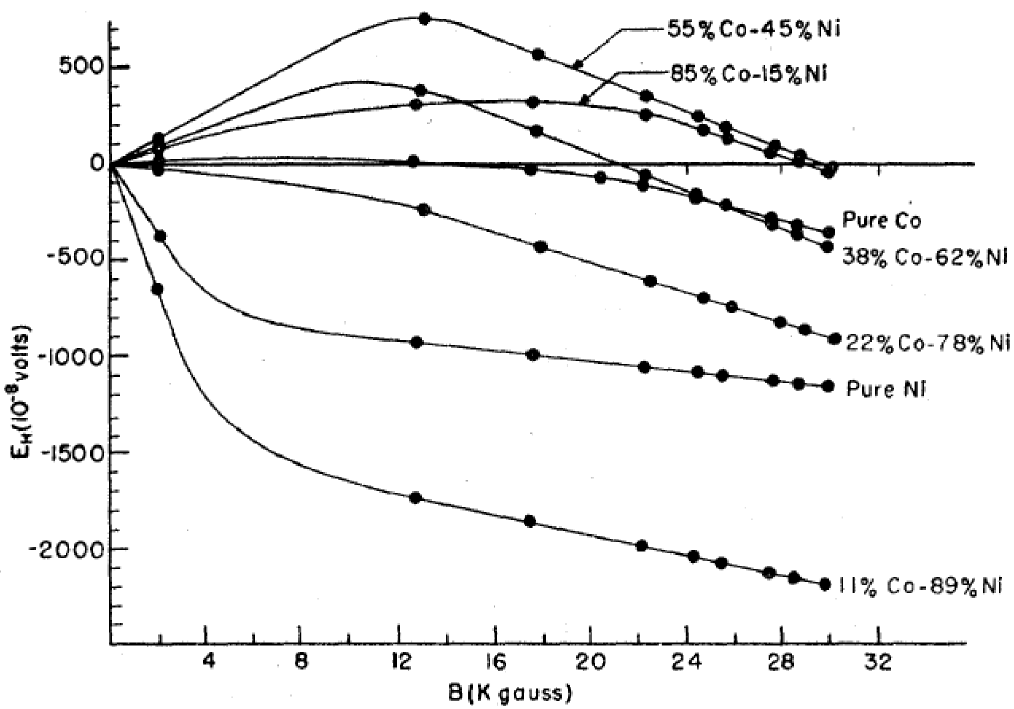
Conclusion

- The peak width of the FMR signal decreases an order of magnitude as a consequence of spin pumping in the regime where $d = \min\{\lambda_J, \lambda_{sd}\}$

- We measured a voltage $\Delta V = 0.14\ \mu\mathrm{V}$ induced by ISHE
  - Better interface quality might increase the signal
  - Minimum of E-field does not seem to be centered in the cavity

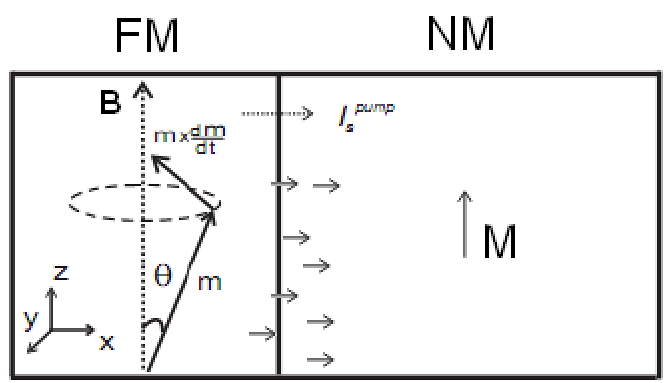
Hall effect in Co

$$e_y = R_0 B + R_1 M$$



E. Pugh and N. Rostoker, Rev. Mod. Phys. **25**, 151 (1953)

Length scales



$$\frac{\partial^2 \boldsymbol{m}_\perp}{\partial t^2} - \frac{\boldsymbol{m}_\perp}{\lambda_{sf}^2} - \frac{\boldsymbol{m}_\perp \times \boldsymbol{M}_d}{\lambda_J^2} = 0$$

S. Zhang, P.M. Levy and A. Fert, Phys. Rev. Lett. **88**, 236601 (2002)