New Method to Measure Spin Orbit Torques in Un-patterned Films

to assist development of 3-terminal magnetic memory

Andrew J. Berger[1], Eric R. J. Edwards[1], Hans T. Nembach[1], Justin M. Shaw[1], Alexy D. Karenowska[2], Mathias Weiler[3], Tom J. Silva[1]

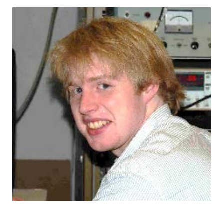
1. NIST, Boulder, CO
2. Physics, University of Oxford, UK
3. Walther-Meissner-Institut, Germany

FCMN 2017, Monterey
March 22, 2017

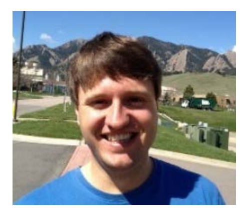
Acknowledgements

- Thank you to all who contributed
  - Andy Berger (postdoc)

  - Eric Edwards (postdoc)



  - Mathias Weiler (Walther-Meissner-Intitute, Munich)



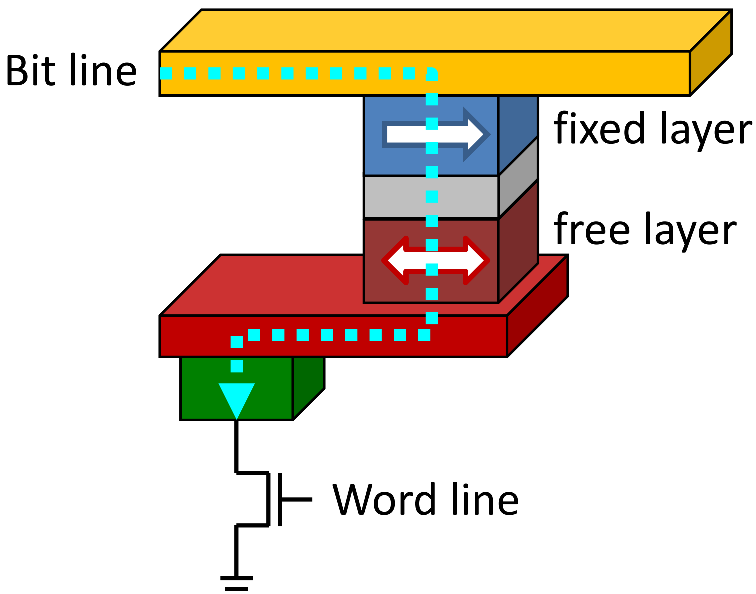
  - Hans Nembach, Justin Shaw (NIST)
  - Alexy Karenowska (Oxford U.)



NIST

Magnetic Memory

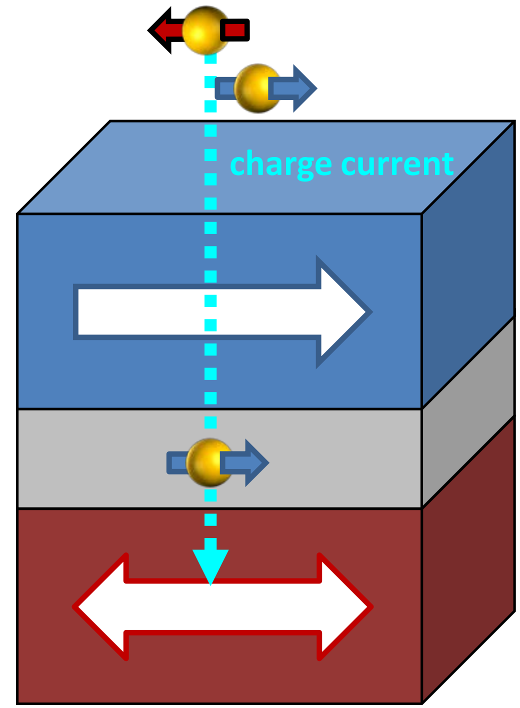
2-terminal Spin-Transfer Torque (STT)



Magnetic Tunnel Junction (MTJ)

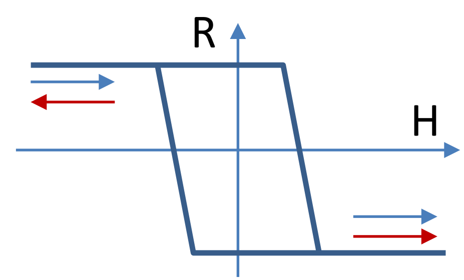
- Same technology used in hard disk drive read heads (large MR)
- Free layer magnetization switched with large applied currents (~10^7 A/m^2)
- Non-volatile

1. spin-filtering effect

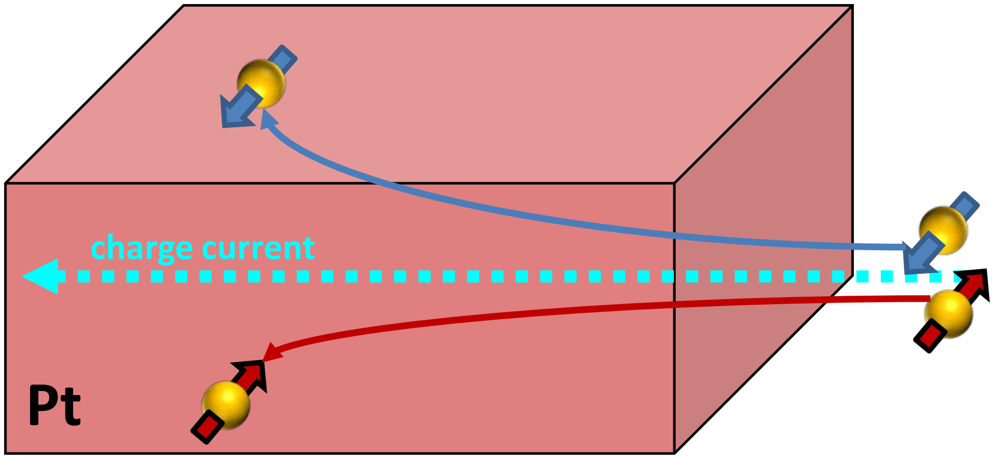


2. spin-transfer torque

3. resistive read-out



Spin Hall Effect

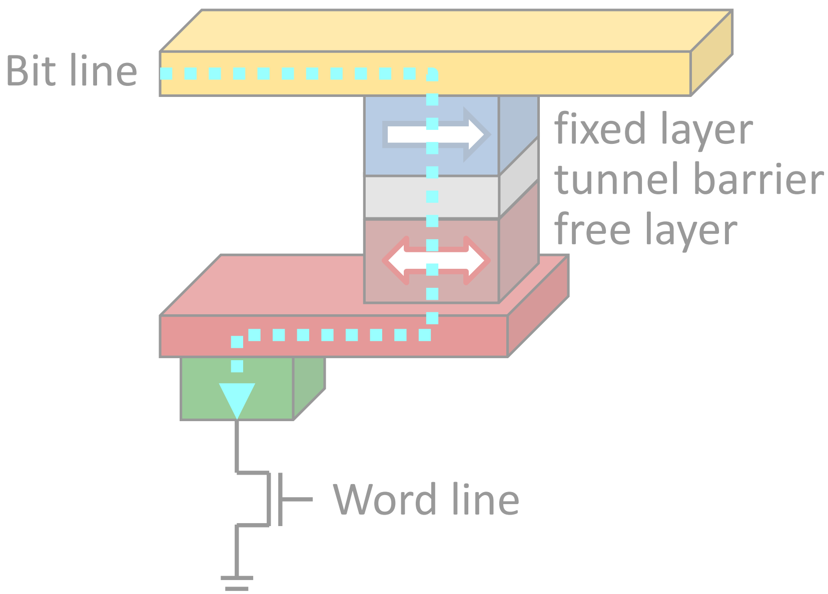


Charge-to-spin conversion without magnetic materials

- Occurs in materials with strong spin-orbit coupling
- Alternative method of creating spin current

Magnetic Memory, revisited

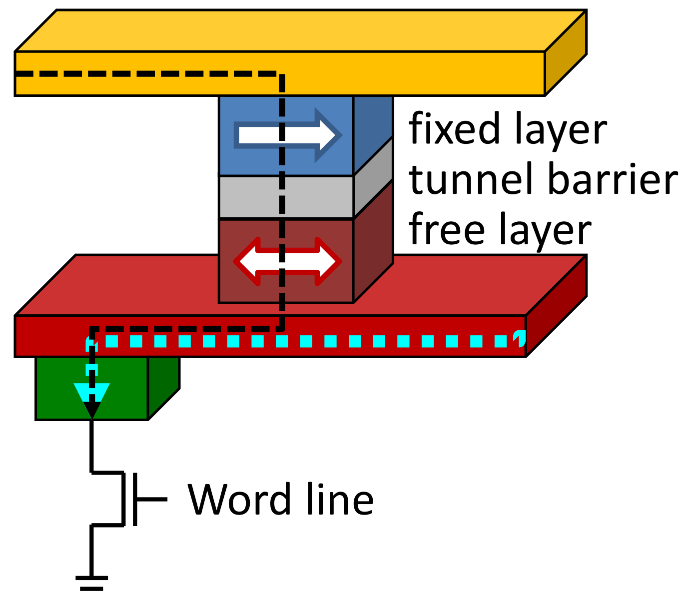
2-terminal Spin-Transfer Torque (STT)



Shared read/write path:

- ✗ Large current density for write operations can damage tunnel barrier
- ✗ Read operations have finite probability of flipping the bit

3-terminal Spin-Orbit Torque (SOT)

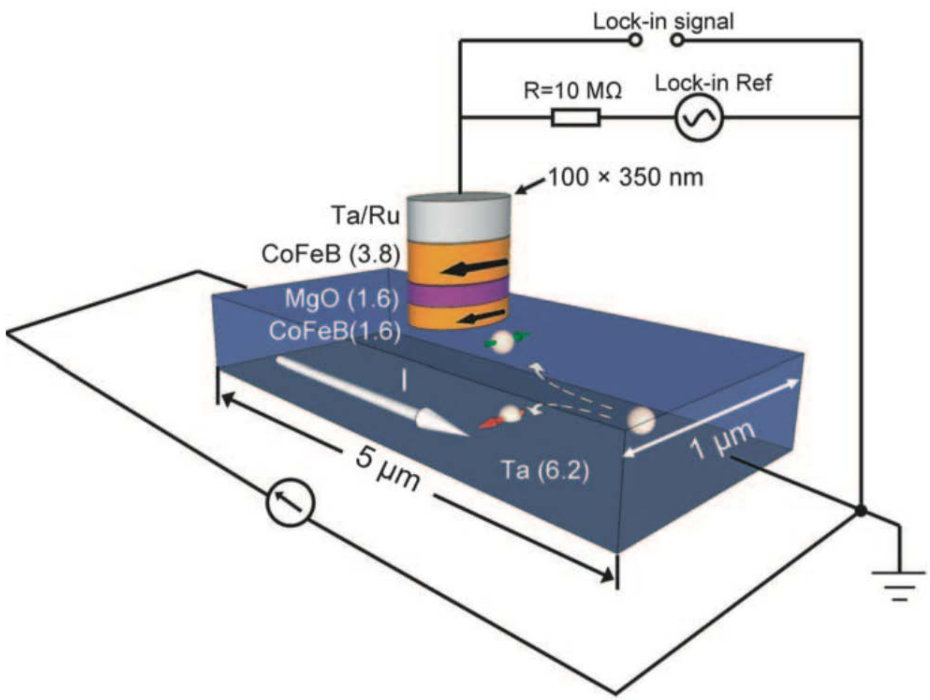


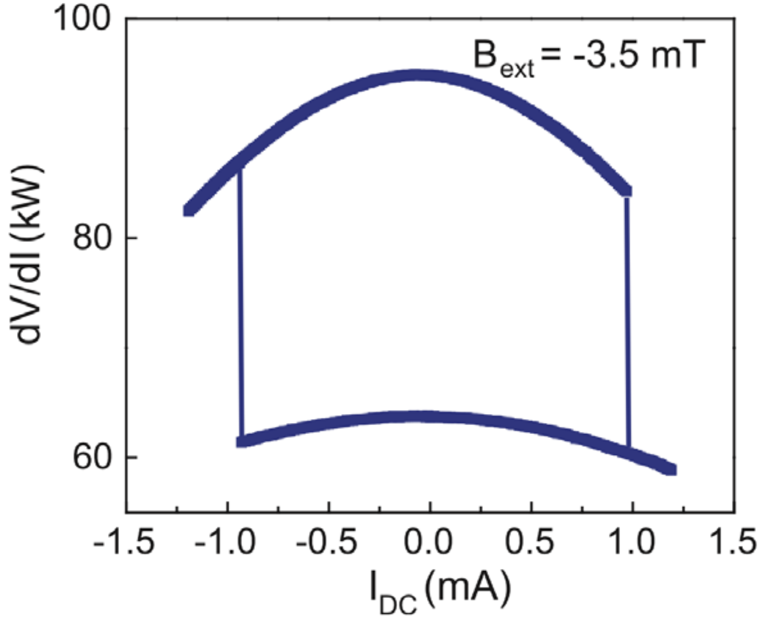
Separate read and write paths

- ✓ Can apply large current density through write line without damaging MTJ

3-terminal spin Hall MRAM

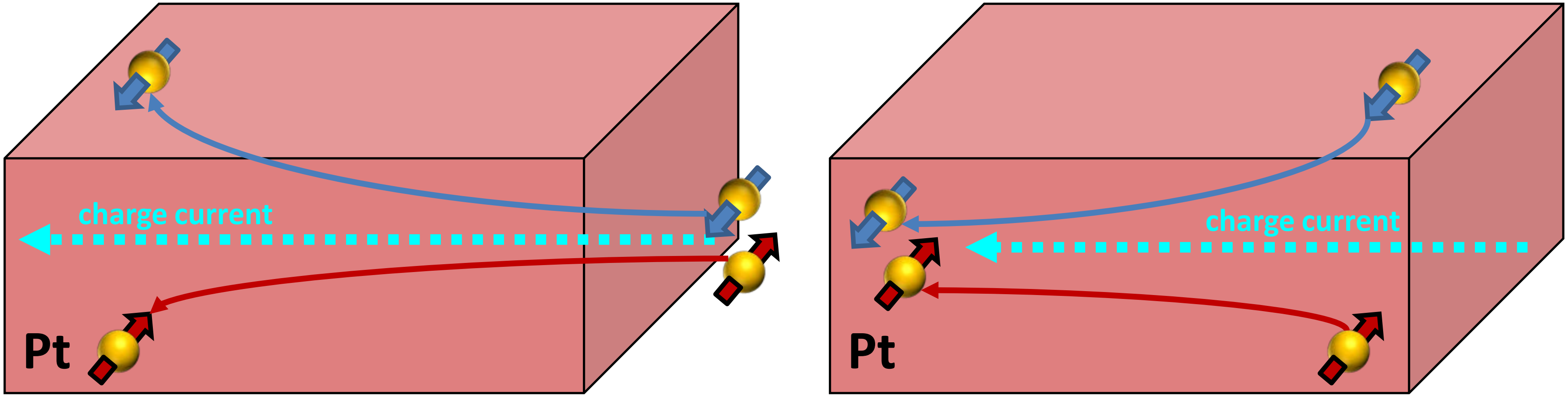
- A way to avoid scaling limitations with 2-terminal non-volatile magnetic memory
  - No need to push large current density through magnetic tunnel junction





Liu, Pai, Li, Tseng, Ralph, Buhrman, Science 336, 555 (2012)

Inverse Spin Hall Effect

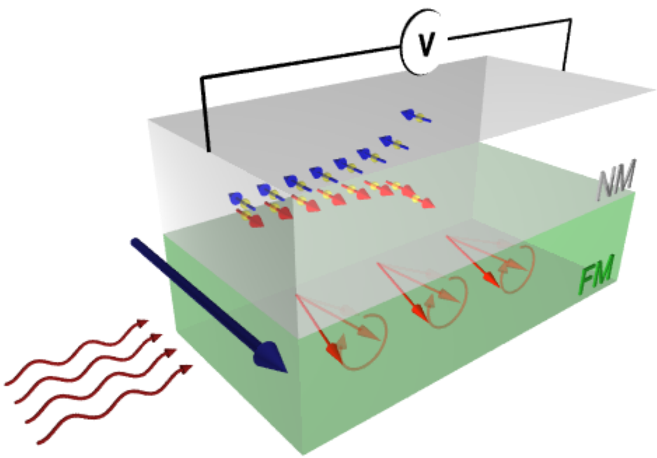


Spin Hall Effect
- Charge current → Spin Current

Inverse Spin Hall Effect
- Spin current → Charge current

NIST

Ferromagnetic Resonance Spin Pumping



E. Saitoh, et al., APL 88, 182509 (2006)

Detecting flow of pure spin current into NM:

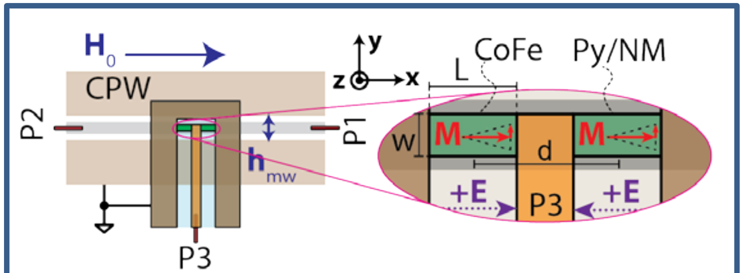
- Easily measured with NM = Pt, some phases of Ta and W. Maybe Au…
- Typically, DC charge current is measured due to challenges in properly separating the sources of AC charge currents

Detecting AC spin-charge transduction due to spin pumping

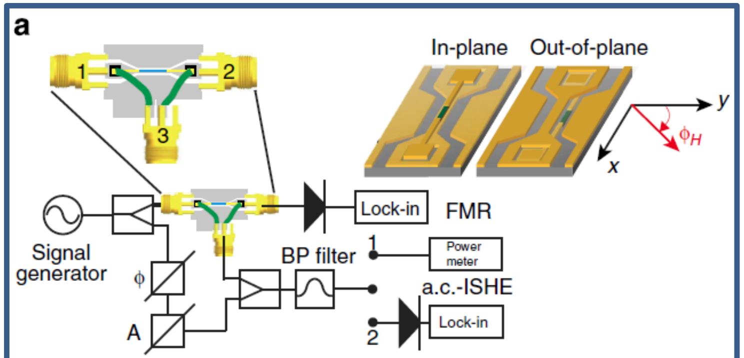
Why AC detection?

- Larger signal for smaller microwave pump. (DC ~ pump power, AC ~ pump amplitude.)
- Geometry: *Not a dc rectification effect*. Free of spurious artifacts, e.g. AMR.
- Phase sensitive: *SNR advantage*.
- Phase sensitive: *Field-like vs. damping-like differentiation*.

Downside
- Device fab required.
- Microwave engineering of complex microwave circuit required.

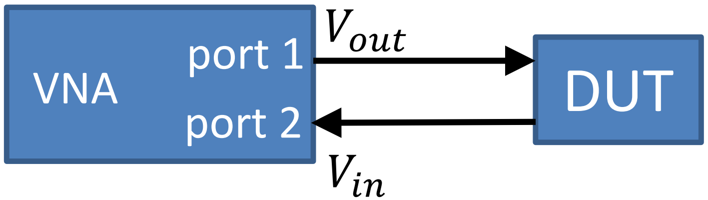


Weiler, Shaw, Nembach, **TJS**, *PRL* **113**, 157204 (2014)



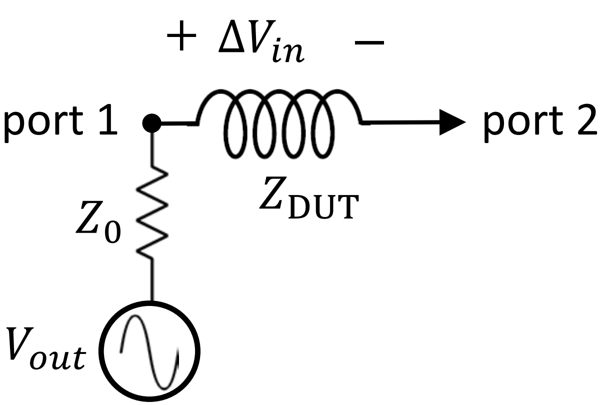
Wei, et al., *Nature Comm*, 5:3768 (2014)

Inductive Measurement of inverse SOT



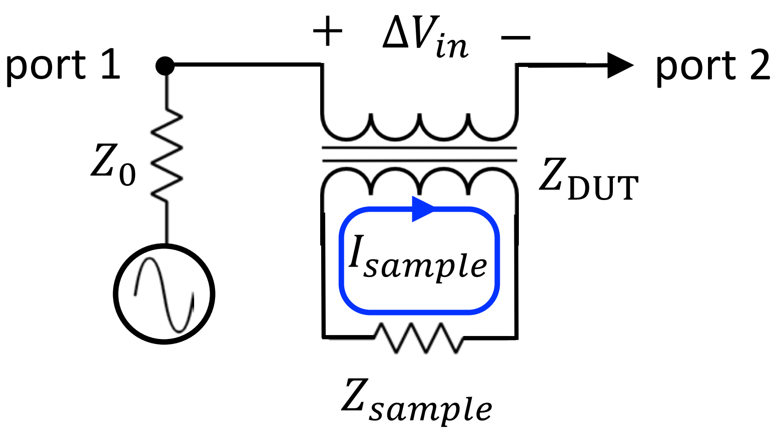
$$\frac{\Delta V_{in}}{V_{out}} = \frac{1}{2}\left(\frac{Z_{\mathrm{DUT}}}{Z_0 + Z_{\mathrm{DUT}}}\right) \cong \frac{1}{2}\frac{Z_{\mathrm{DUT}}}{Z_0}; Z_{\mathrm{DUT}} \ll Z_0$$

Conventional FMR*



$$Z_{\mathrm{DUT}} = i\omega L_{11}(\chi)$$

Conventional FMR + iSOT effects

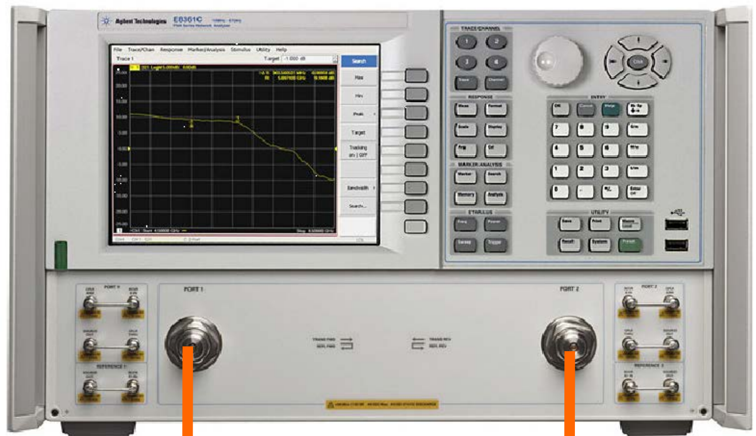


$$Z_{\mathrm{DUT}} \cong i\omega L_{11}(\chi) + \frac{(i\omega L_{12})^2}{Z_{sample}}$$

*TJS, Nembach, Shaw, Doyle, Oguz, O'brien, Doczy, in Characterization and Metrology for Nanostructures, eds. Seiler and Ma (Pan Stanford, 2016)

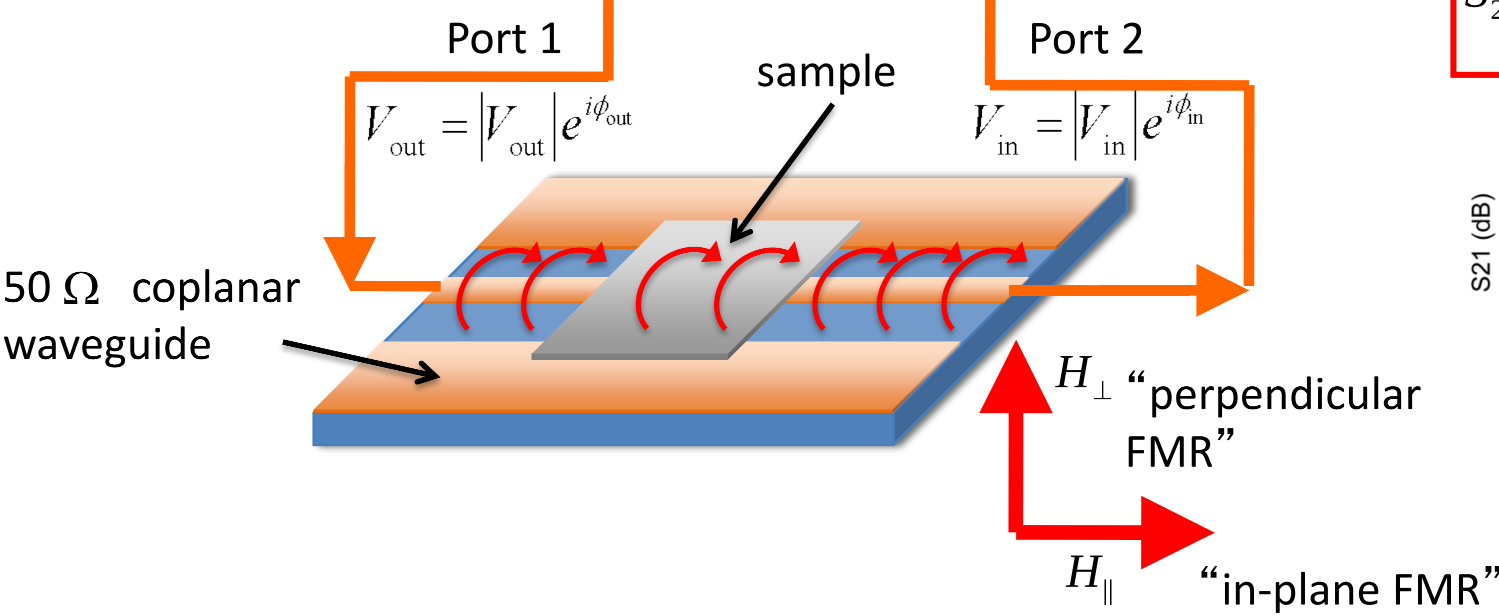
Instrumentation: VNA-FMR

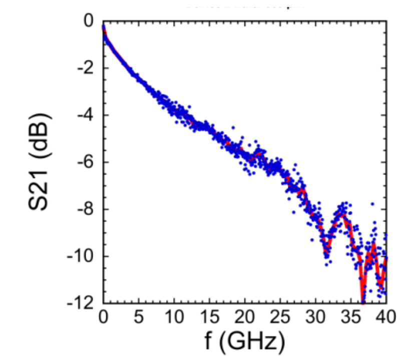
Vector network analyzer



- 10 MHz < f < 67 GHz
- Maximum field: 3 T
- Coplanar waveguides with 50 µm wide center conductor
- 1 Watt max microwave power

$$S_{21} = \frac{|V_{in}| e^{i\phi_{in}}}{|V_{out}| e^{i\phi_{out}}} \propto \chi$$



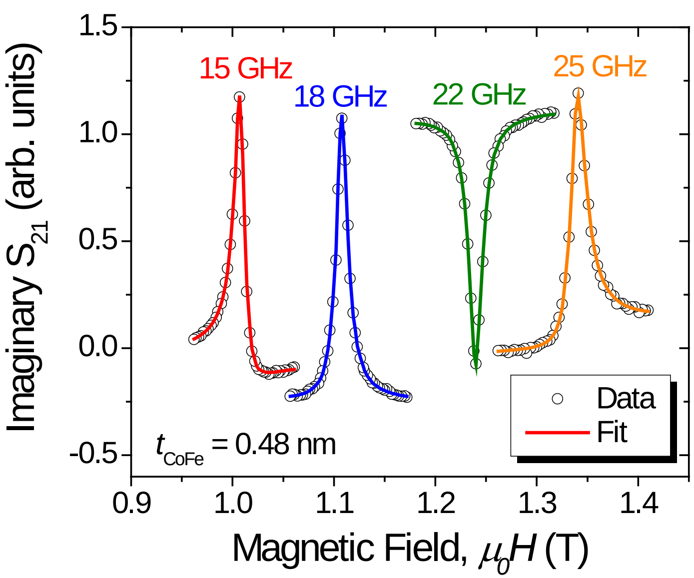


Ferromagnetic Resonance (FMR)

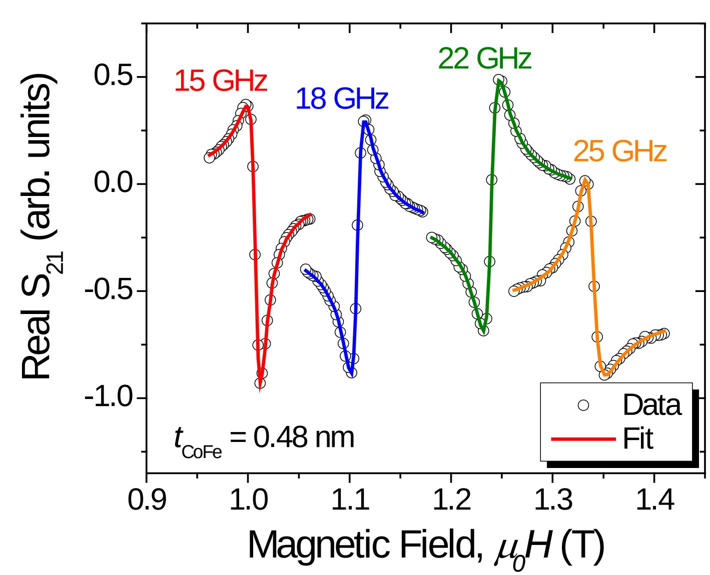
Perpendicular geometry Vector Network Analyzer FMR (VNA-FMR)

- 67 GHz bandwidth, 3 T perpendicular fields
- Eliminate 2-magnon scattering
- Field-swept spectra

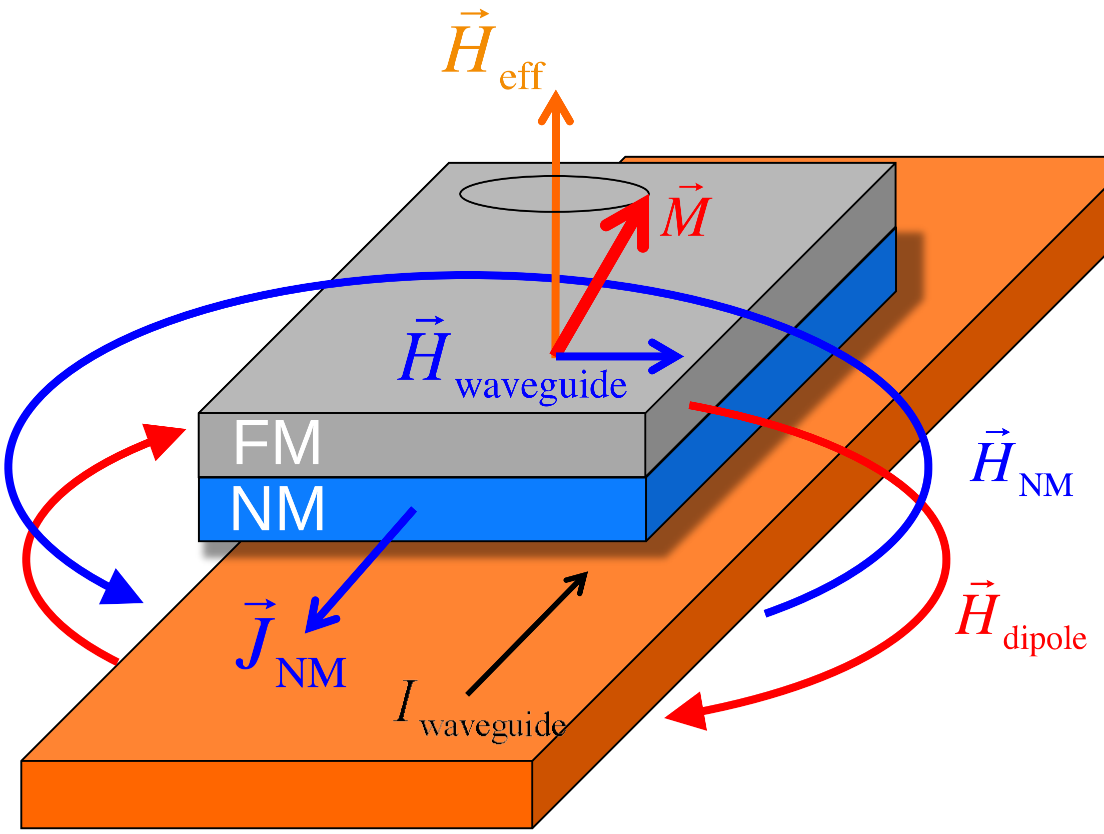
$$\partial_t \vec{M} = -|\gamma|\mu_0\left(\vec{M}\times\vec{H}\right) + \frac{\alpha}{M_s}\left(\vec{M}\times\partial_t\vec{M}\right)$$



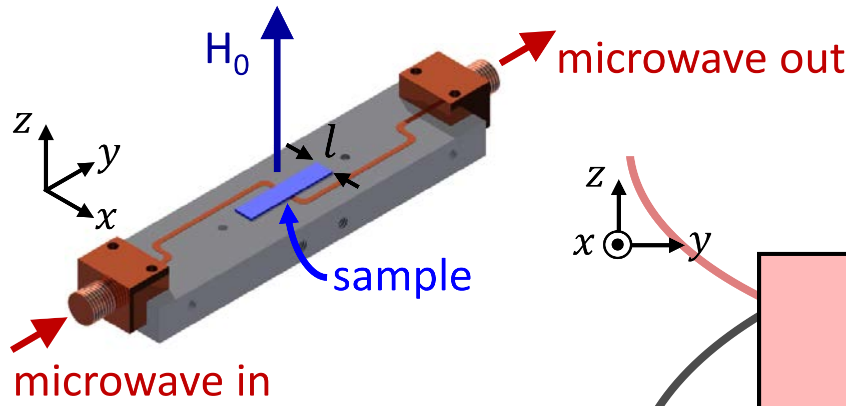
Ex: NIST-grown CoFe/Ni multilayers

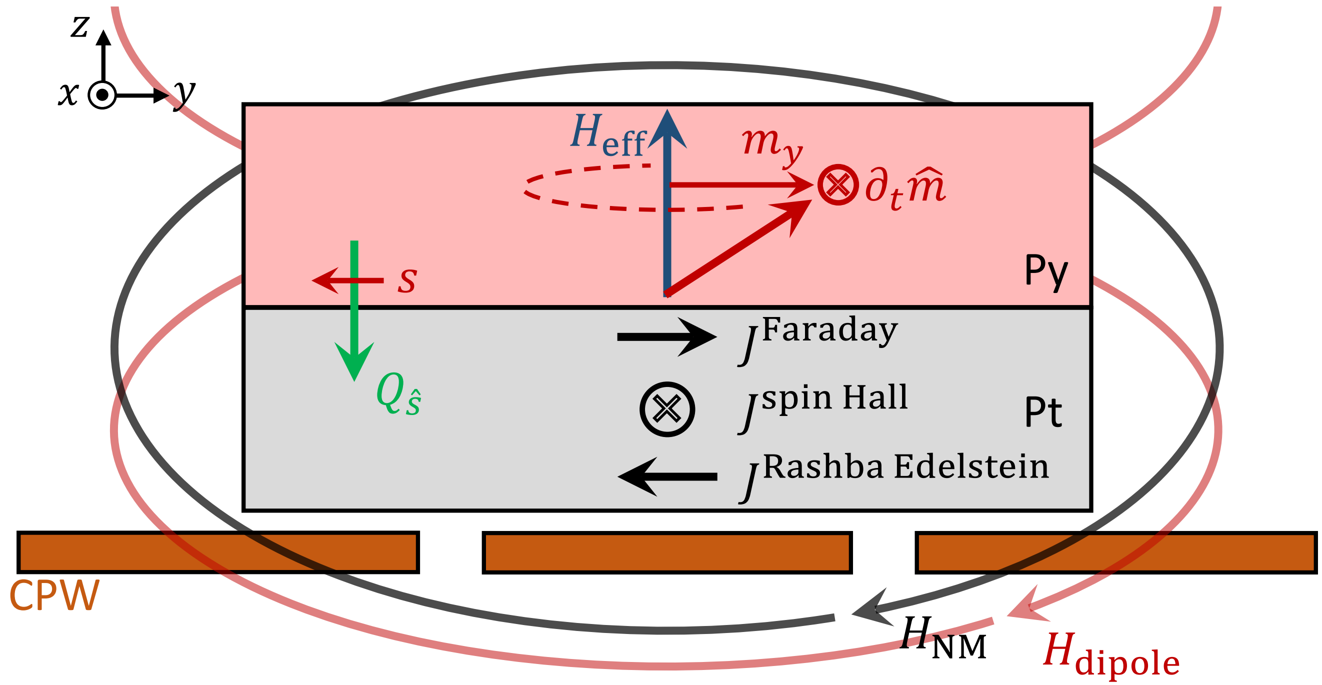


Inductive measurement of ac currents



Total Inductance





The inductance of the sample arises from anything that produces a flux around the CPW

$$L = \frac{\Phi}{I_{\text{CPW}}}$$

1. First-order inductive coupling ~ frequency-independent
2. Second-order inductive coupling ~ $i\omega$ (Faraday-induced currents in the NM)
3. Damping-like ~ ω (e.g. spin Hall effect)
4. Field-like ~ $i\omega$ (e.g. Rashba-Edelstein effect)

} Spin-charge transduction, a.k.a Spin-Orbit Torque (SOT)

Reciprocity and effective conductivity

SOT (& Ampere's Law):

"field-like"
(torque: **e**ven time reversal)

e.g. spin Hall

$$\left[\int_0^{+d_{\mathrm{FM}}} \vec{T}(z)dz\right] = \left(\frac{\hbar}{2e}\right)\frac{1}{\sigma}\left[\left(\sigma_{\mathrm{e}}^{\mathrm{SOT}} - \sigma_{\mathrm{e}}^{\mathrm{Ampere}}\right)\left(\hat{m}\times\left(\hat{z}\times\vec{J}\right)\right) + \sigma_{\mathrm{o}}^{\mathrm{SOT}}\left(\hat{m}\times\left(\hat{m}\times\left(\hat{z}\times\vec{J}\right)\right)\right)\right]$$

e.g. Rashba-Edelstein

"damping-like"
(torque: **o**dd time reversal)

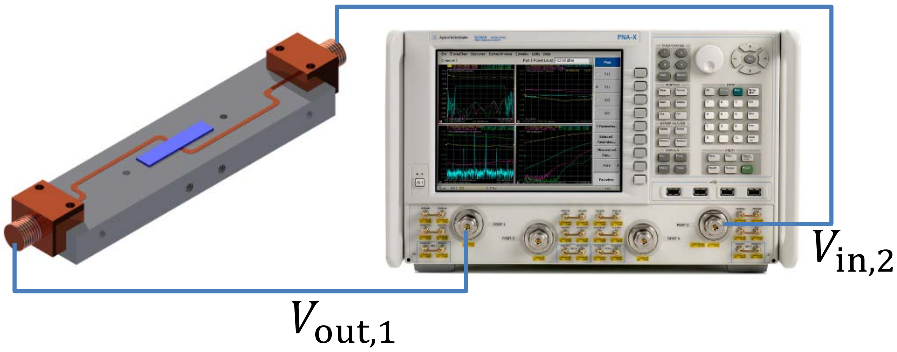
Reciprocity

iSOT (& Faraday's Law):

$$\left[\int_{-d_{\mathrm{NM}}}^{+d_{\mathrm{FM}}} \vec{J}(z)dz\right] = \left(\frac{\hbar}{2e}\right)\left[\left(\sigma_{\mathrm{e}}^{\mathrm{SOT}} - \sigma_{\mathrm{e}}^{\mathrm{Faraday}}\right)\left(\hat{z}\times\partial_t\hat{m}\right) - \sigma_{\mathrm{o}}^{\mathrm{SOT}}\left(\hat{z}\times\left(\hat{m}\times\partial_t\hat{m}\right)\right)\right]$$

Inductively-Coupled Measurement

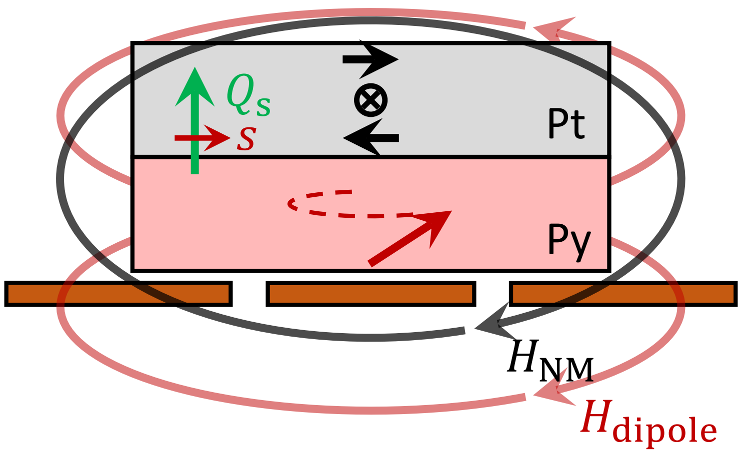
$$L = L_{\text{dipole}} + L_{\text{NM}}$$



$$L_{\text{dipole}} = \mu_0 l \frac{d_{\text{FM}}}{4W_{\text{wg}}} \chi_{yy}$$ “Conventional” VNA-FMR*

$$L_{\text{NM}} = \left(L_{12} \frac{\hbar\omega}{4e} \tilde{\sigma}_{\text{NM}} \right) \left(\frac{\chi_{yy}}{M_s} \right)$$ *New!*

$$\tilde{\sigma}_{\text{NM}} = \left(\sigma_{\text{o}}^{\text{SOT}} + i\left(\sigma_{\text{e}}^{\text{SOT}} - \sigma_{\text{e}}^{\text{F}}\right)\right) \propto \frac{L_{\text{NM}}}{L_{\text{dipole}}}$$



“effective” conductivity describing currents produced in the NM by magnetization dynamics in the FM, *including SOT effects!*

*__TJS__, Nembach, Shaw, Doyle, Oguz, O’brien, Doczy, in Characterization and Metrology for Nanostructures, eds. Seiler and Ma (Pan Stanford, 2016)

Samples

"Py" = $Ni_{81}Fe_{19}$

Sputter deposited. Polycrystalline. (111) texture

1) Si/SiO/Ta(1.5 nm)/Py(3.5 nm)/Pt(6 nm)/Ta(3 nm)/SPR220-7(8 μm)

To minimized capacitive coupling

Stack inversion

2) Si/SiO/Ta(1.5 nm)/Pt(6 nm)/Py(3.5 nm)/Ta(3 nm)/SPR220-7(8 μm)

Control samples:

3) Si/SiO/Ta(1.5 nm)/Py(3.5 nm)/Cu(3.3 nm)/Ta(3 nm)/SPR220-7(8 μm)

Stack inversion

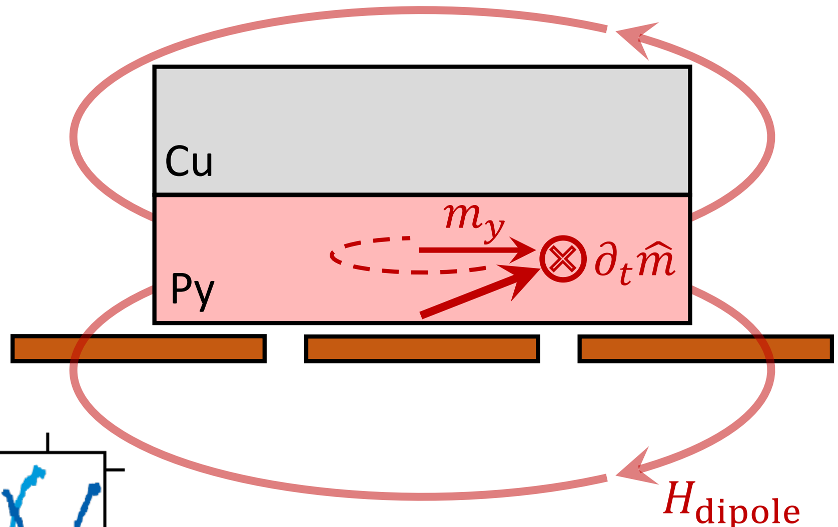
4) Si/SiO/Ta(1.5 nm)/Cu(3.3 nm)/Py(3.5 nm)/Ta(3 nm)/SPR220-7(8 μm)

(All samples have a Ta seed and cap)

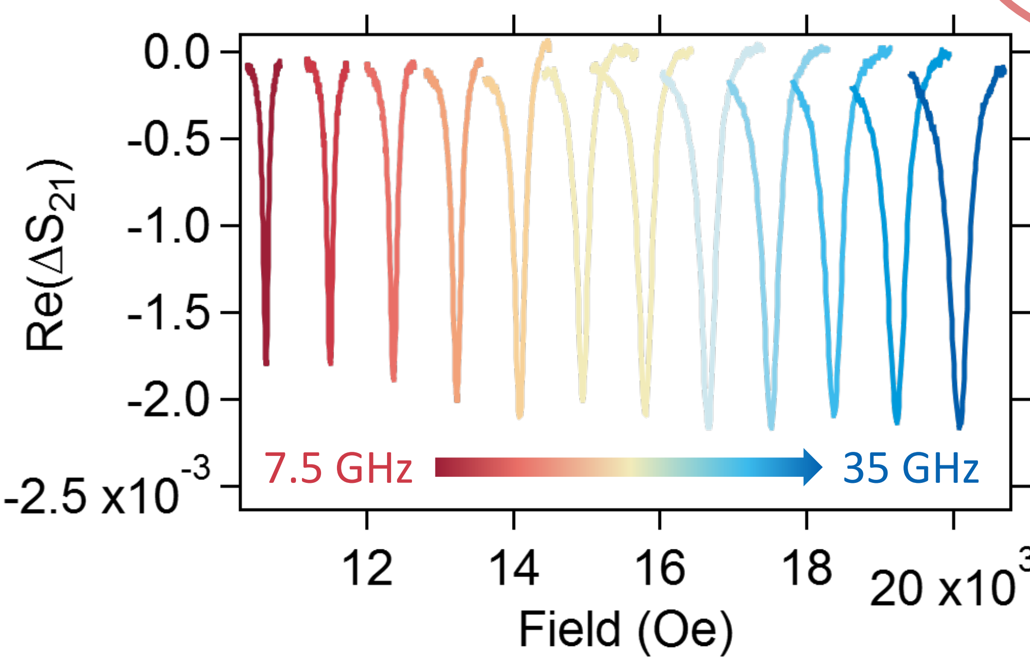
Cu control sample

$$\Delta S_{21} \approx -\frac{i\omega L}{Z_0}$$

$$L = L_{\text{dipole}}$$



$$\Delta S_{21} \propto -\mu_0 l M_s d_{\text{FM}}$$



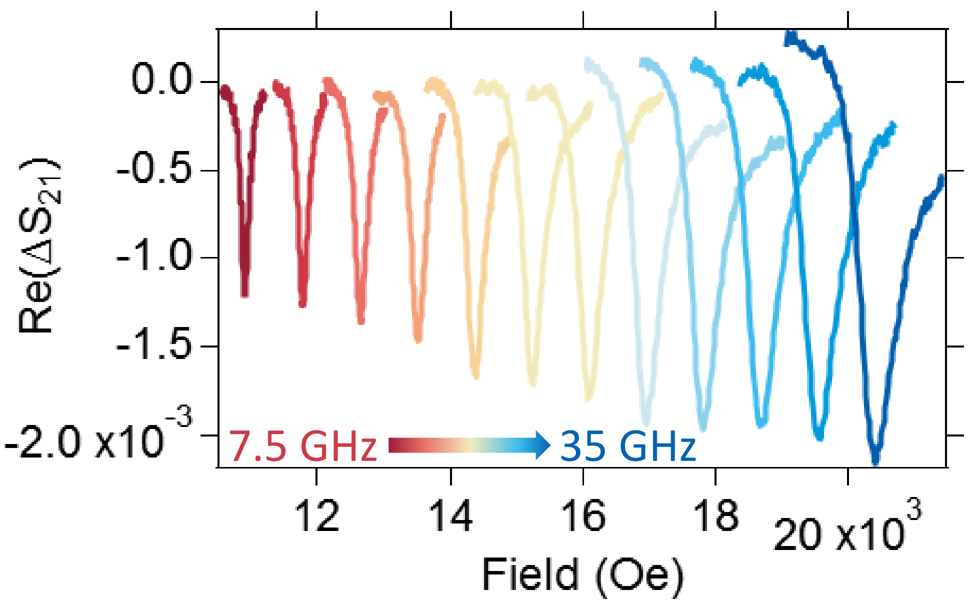
~ Constant signal as a function of frequency

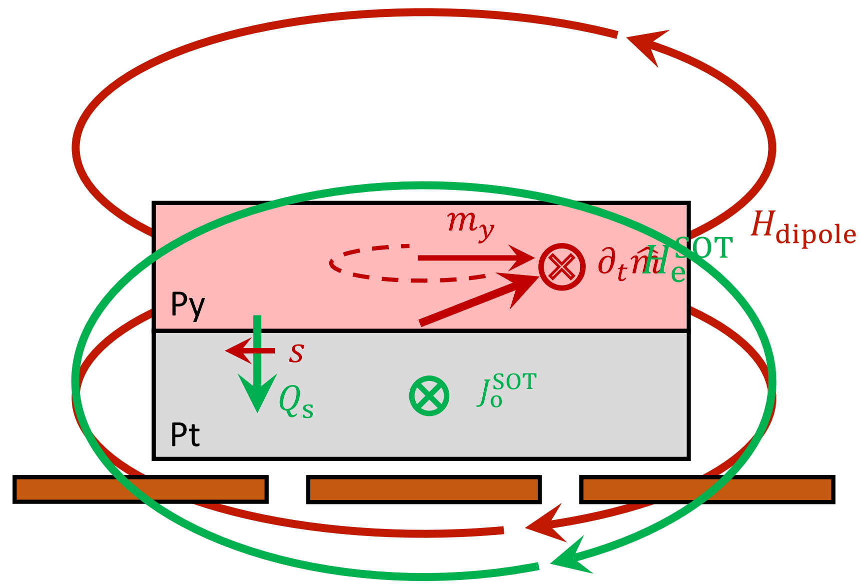
Py/Pt sample

$$\Delta S_{21} \approx -\frac{i\omega L}{Z_0}$$

$$L = L_{\text{dipole}} + L_{\text{NM}}$$

$$\text{Re}\{\Delta S_{21}\} \propto \text{constant} \cdot \text{Re}(\chi_{yy}) - [\sigma_{\text{o}}^{\text{SOT}}\text{Re}(\chi_{yy}) - (\sigma_{\text{e}}^{\text{SOT}} - \sigma_{\text{e}}^{\text{F}})\text{Im}(\chi_{yy})]\ \boldsymbol{\omega}$$





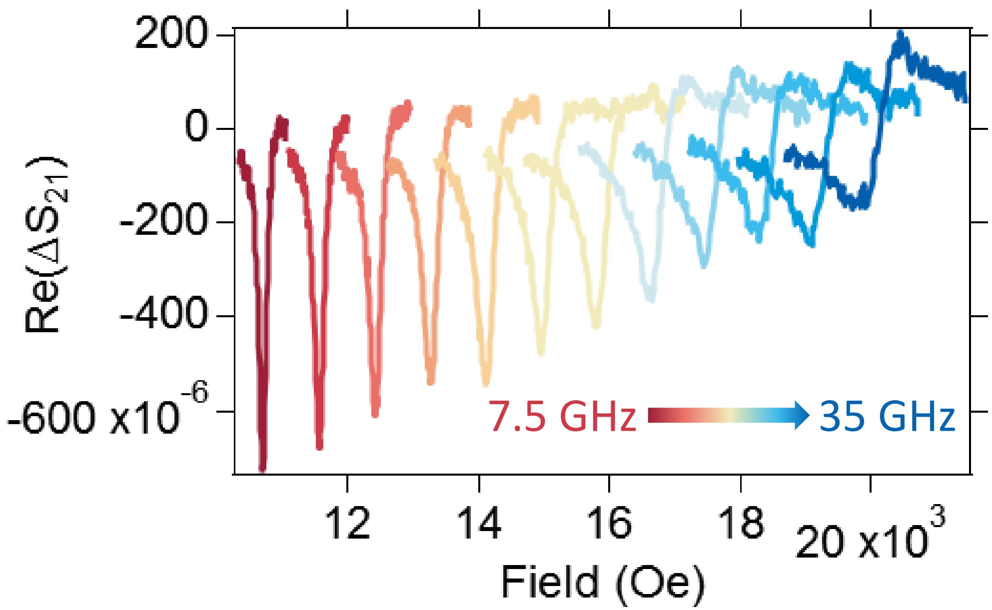
Signal is changing in both magnitude and phase

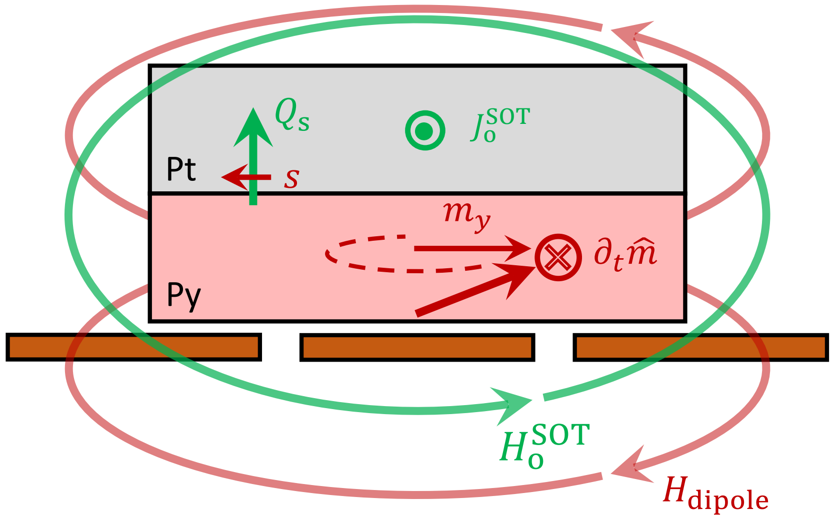
Reversed Stacking Order

$$\Delta S_{21} \approx -\frac{i\omega L}{Z_0}$$

$$L = L_{\text{dipole}} + L_{\text{NM}}$$

$$\text{Re}\{\Delta S_{21}\} \propto \text{constant} \cdot \text{Re}(\chi_{yy}) - [\sigma_{\text{o}}^{\text{SOT}}\text{Re}(\chi_{yy}) - (\sigma_{\text{e}}^{\text{SOT}} - \sigma_{\text{e}}^{\text{F}})\text{Im}(\chi_{yy})]\ \boldsymbol{\omega}$$

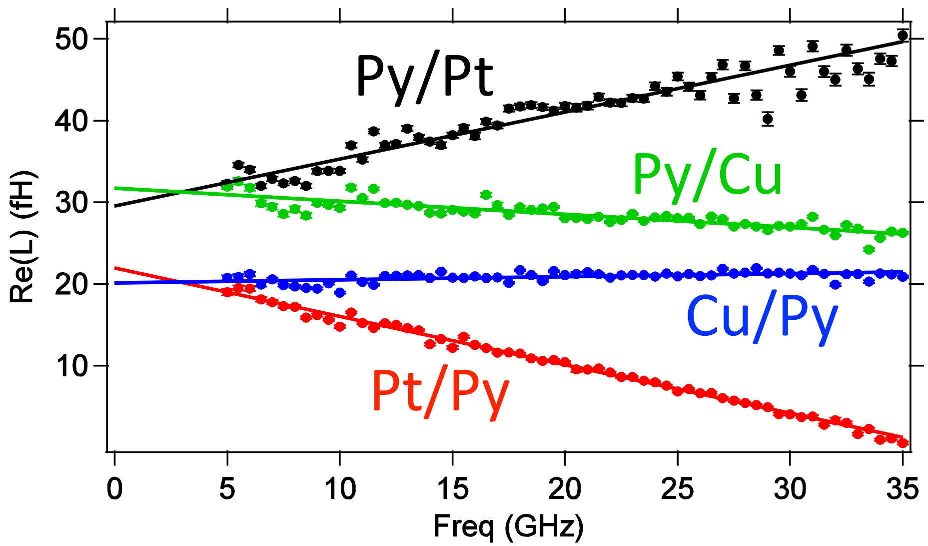




Signal is changing in both magnitude and phase.

Magnitude is trending in opposite direction as original stacking order

Re(L)

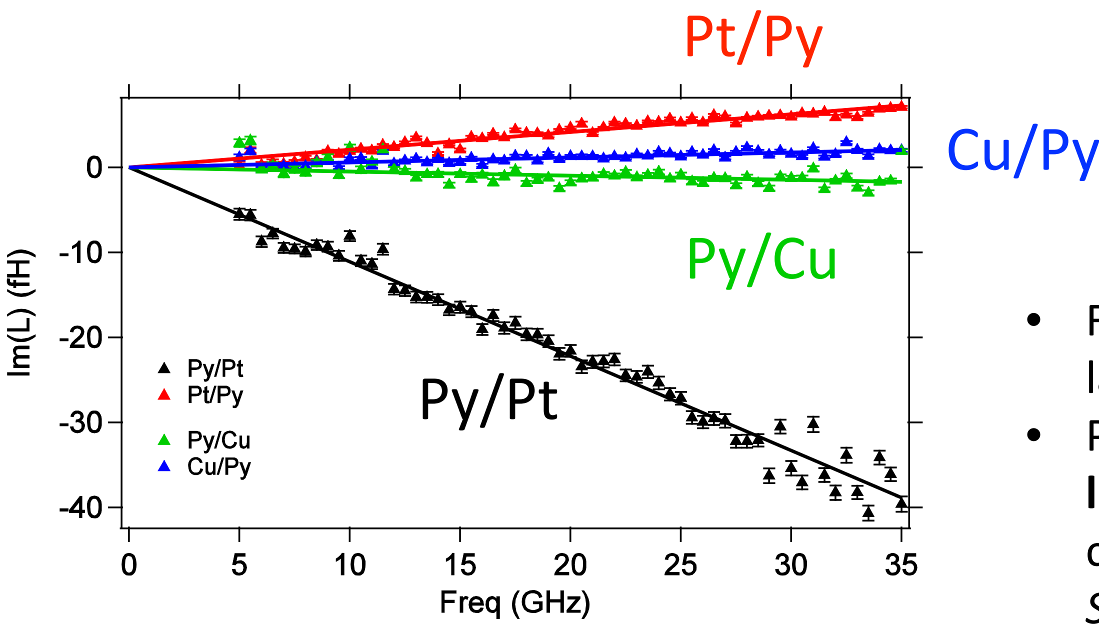


$$\mathrm{Re}(L) \propto \left[\mu_0 l \frac{M_s\, d_{FM}}{W_{wg}} + L_{12} \frac{\hbar \omega}{e} \sigma_o^{SOT} \right]$$

Precessing M — Spin Hall currents

- Spin Hall contribution reverses sign for inverted stack
- Almost no spin Hall contribution for Py/Cu or Cu/Py
- Some variation in zeroth-order inductive signals across all samples
  - Variation in M_s
  - Variation in sample-CPW spacing

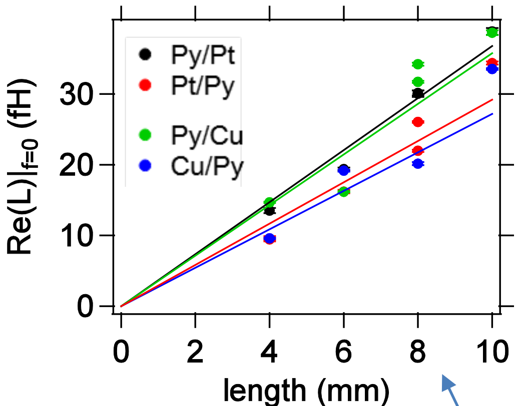
Im(L)

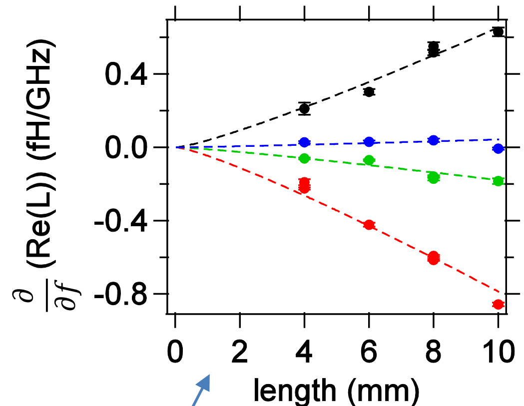


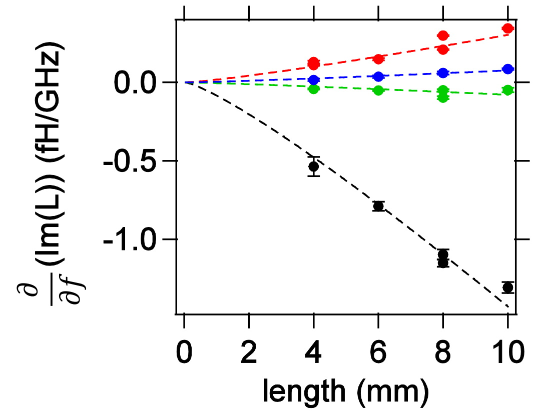
- Faraday-induced currents in NM layer are minimal
- Pt-deposited-on-Py exhibits **large** Rashba-Edelstein-like currents. *2x larger than the Spin-Hall-like signal!!*

$$\mathrm{Im}(L) \propto \left[L_{12} \frac{\hbar\omega}{e} \left(\underbrace{\sigma_e^{\mathrm{SOT}}}_{\text{Rashba-Edelstein currents}} - \underbrace{\sigma_e^{\mathrm{F}}}_{\text{Faraday-induced currents in NM}} \right) \right]$$

Inductance vs. sample length







$$\mathrm{Re}\{L(\omega)\} \propto \left[\mu_0 l \frac{M_s\, d_{\mathrm{FM}}}{W_{\mathrm{wg}}} + L_{12}(\mathrm{length}) \frac{\hbar\omega}{e} \sigma_{\mathrm{o}}^{\mathrm{SOT}}\right]$$

$$\mathrm{Im}\{L(\omega)\} \propto \left[L_{12}(\mathrm{length}) \frac{\hbar\omega}{e} (\sigma_{\mathrm{e}}^{\mathrm{SOT}} - \sigma_{\mathrm{e}}^{\mathrm{F}})\right]$$

Sample	$\sigma_{\mathrm{o}}^{\mathrm{SOT}}$ $(10^5\ \Omega^{-1}\mathrm{m}^{-1})$	$(\sigma_{\mathrm{e}}^{\mathrm{SOT}} - \sigma_{\mathrm{e}}^{\mathrm{F}})(10^5\ \Omega^{-1}\mathrm{m}^{-1})$
Ta/Py/Pt/Ta	0.90 (0.03)	-1.9 (0.1)
Ta/Pt/Py/Ta	1.38 (0.04)	-0.54 (0.02)
Ta/Py/Cu/Ta	-0.28 (0.01)	-0.1 (0.1)
Ta/Cu/Py/Ta	-0.08 (0.03)	-0.1 (0.1)

Possible relations to microscopic parameters

- The effective conductivities $\sigma_{\mathrm{o}}^{\mathrm{SOT}}$ and $\sigma_{\mathrm{e}}^{\mathrm{SOT}}$ can be related to the spin Hall angle θ_{SH} and Rashba parameter α_{R}

$$\sigma_{\mathrm{o}}^{\mathrm{SOT}} = \theta_{\mathrm{SH}}\sigma_{\mathrm{Pt}}\mathrm{Re}\left[\frac{G_{\uparrow\downarrow}}{\left(\frac{\sigma_{\mathrm{Pt}}}{2\lambda_{\mathrm{s}}}\right)\tanh\left(\frac{d_{\mathrm{Pt}}}{\lambda_{\mathrm{s}}}\right) + G_{\uparrow\downarrow}}\right](1-\delta)$$

Boone, et al., *JAP* **117**, 223910 (2015)

$$\sigma_{\mathrm{e}}^{\mathrm{SOT}} = \alpha_{\mathrm{R}}\frac{2m_{\mathrm{e}}}{\hbar^2}\sigma_{\mathrm{int}}Pd_{\mathrm{int}}$$

Kim, et al., *PRL* **111**, 216601 (2013)

	Sample	θ_{SH}	α_{R} (meV nm)	
	Py(3.5)/Pt(6)	0.12 (0.01)	-31 (4)	This study
	Pt(6)/Py(3.5)	0.15 (0.03)	-6.9 (2.4)	This study
(NIST)	Py(5)/Pt(10)	0.10 (0.01)		*IEEE Mag. Lett.* **5,** 3700104 (2014).
(Cornell)	CoFe(1-9)/Pt(4)	0.33 (0.1)		*PRB* **92,** 064426 (2015).
	InAlAs/InGaAs		6.7	*PRL* **78,** 1335–1338 (1997).
	$SrTiO_3$		5	*PRL* **108,** 206601 (2012)
	Bi_2Se_3 (T.I.)		400	*PRL* **107,** 096802 (2011).

NIST

Redux: Take-home message

- Spin-charge transduction in multilayers can be easily measured via conventional FMR!
- Essential ingredients:
  - Phase-sensitive FMR detection
  - Inductive geometry (minimize capacitive coupling)
  - Post-acquisition data processing
  - NO SAMPLE PATTERNING REQUIRED!
- Will enable rapid surveys of material systems, as well as accurate testing of theory/models.
  - Example: We found field-like torque in Permalloy/Pt is well-predicted by recent theory of Kim, Lee, Lee, and Stiles.

arXiv:1611.05798