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Picosecond spin caloritronics

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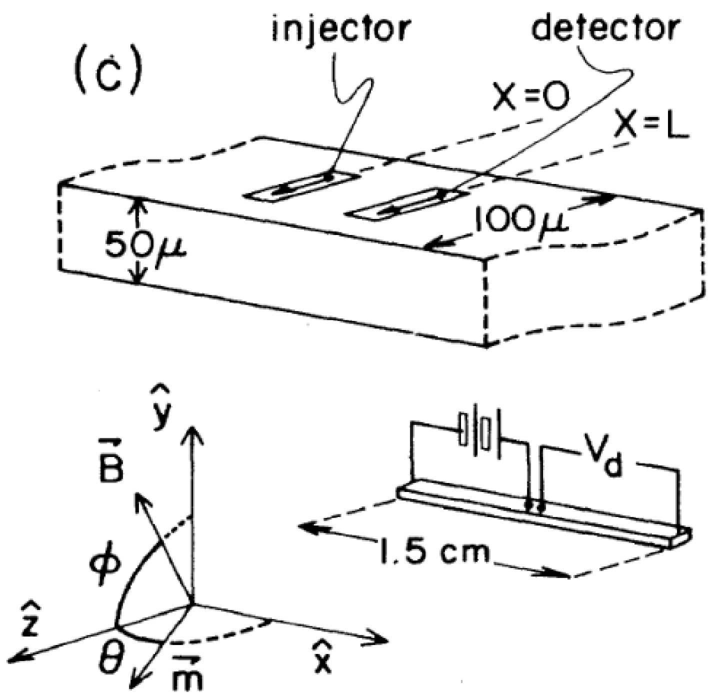
Spintronics in 1985

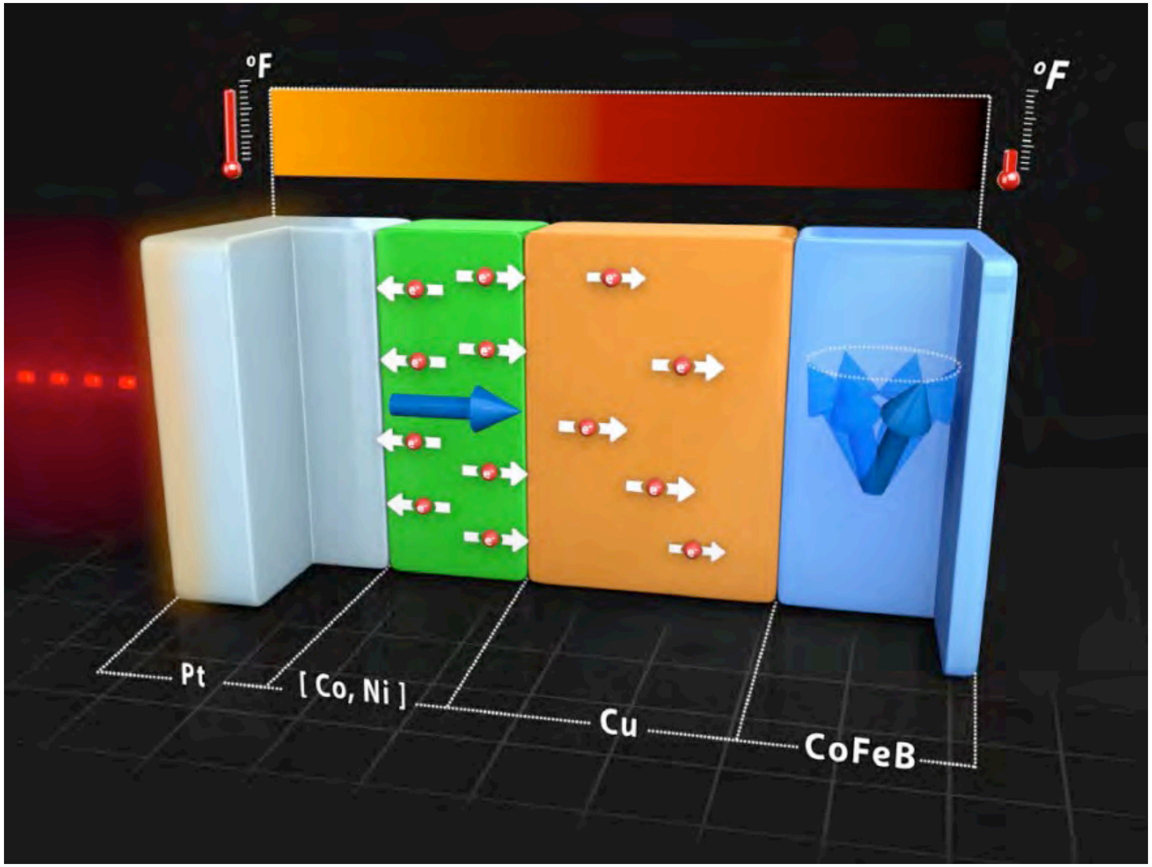
Interfacial Charge-Spin Coupling: Injection and Detection of Spin Magnetization in Metals

Mark Johnson and R. H. Silsbee
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853
(Received 1 July 1985)



Drive spin currents with heat instead of charge

- In "picosecond spin caloritronics", we inject spin current using heat transport and detect spin optically, all on picosecond time scales.



Choi *et al.*, Nature Physics (2015)

Picosecond time-scales enable enormous heat currents (unit of time in the denominator)

- Conventional heat currents, e.g., heat diffusion equation, Fourier's law in steady-state governed by thermal conductivity Λ

$$J_Q = -\Lambda \nabla T \qquad \Lambda \propto \mathrm{W\ m^{-1}\ K^{-1}}$$

- Interface thermal conductance *G,* ΔT=temperature across an interface

$$J_Q = G \Delta T \qquad G \propto \mathrm{W\ m^{-2}\ K^{-1}}$$

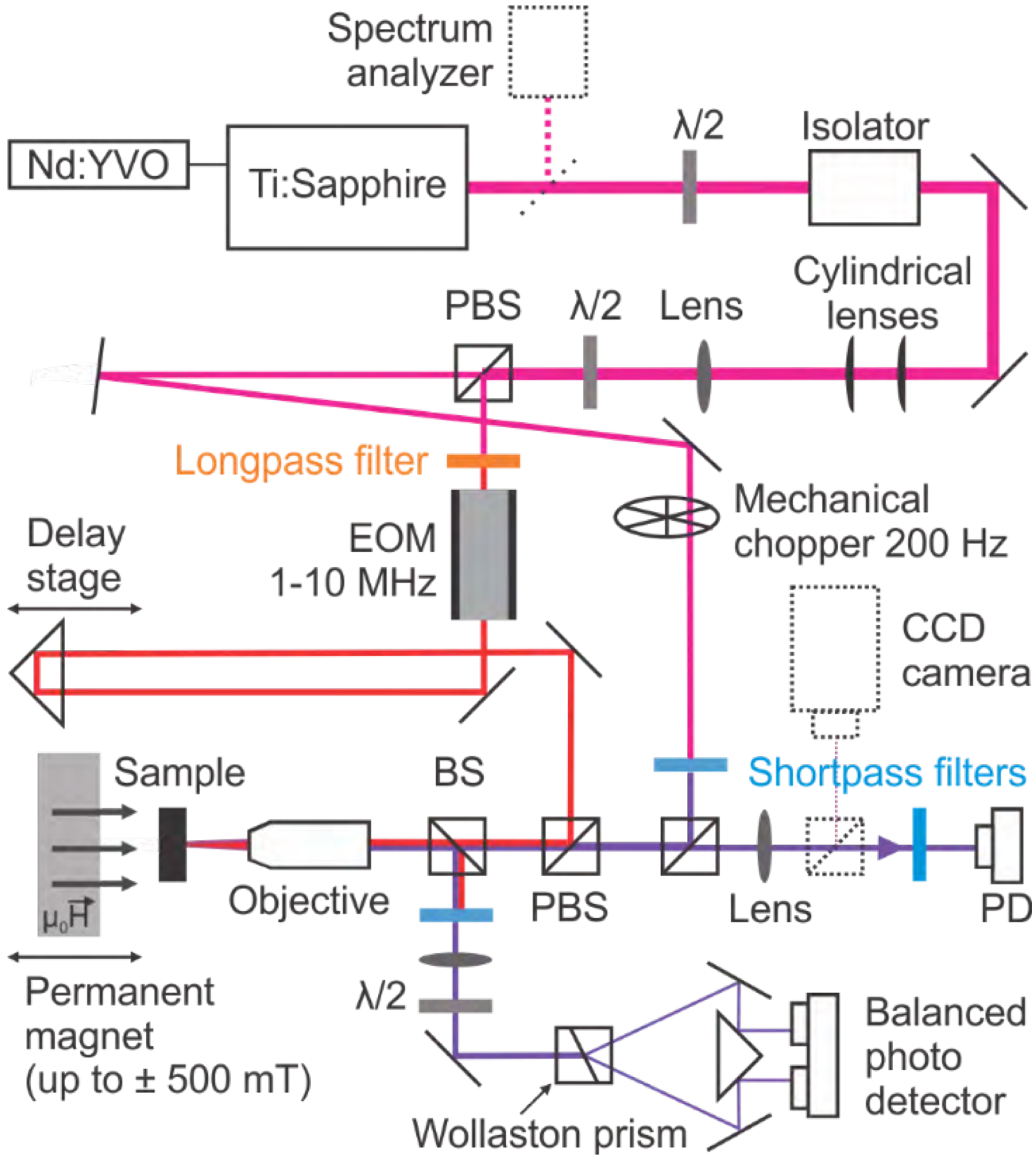
- Volumetric heat currents exchanged between excitation, e.g., two-temperature model of electrons and magnons

$$j_Q = g_{em}(T_e - T_m) \qquad g_{em} \propto \mathrm{W\ m^{-3}\ K^{-1}}$$

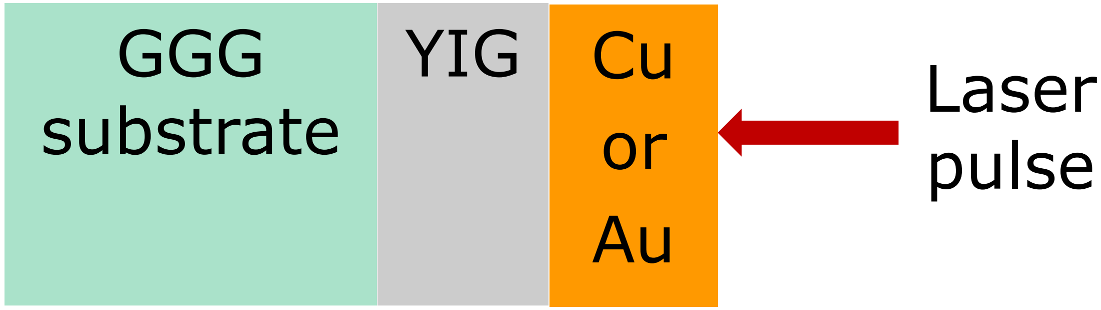
Outline

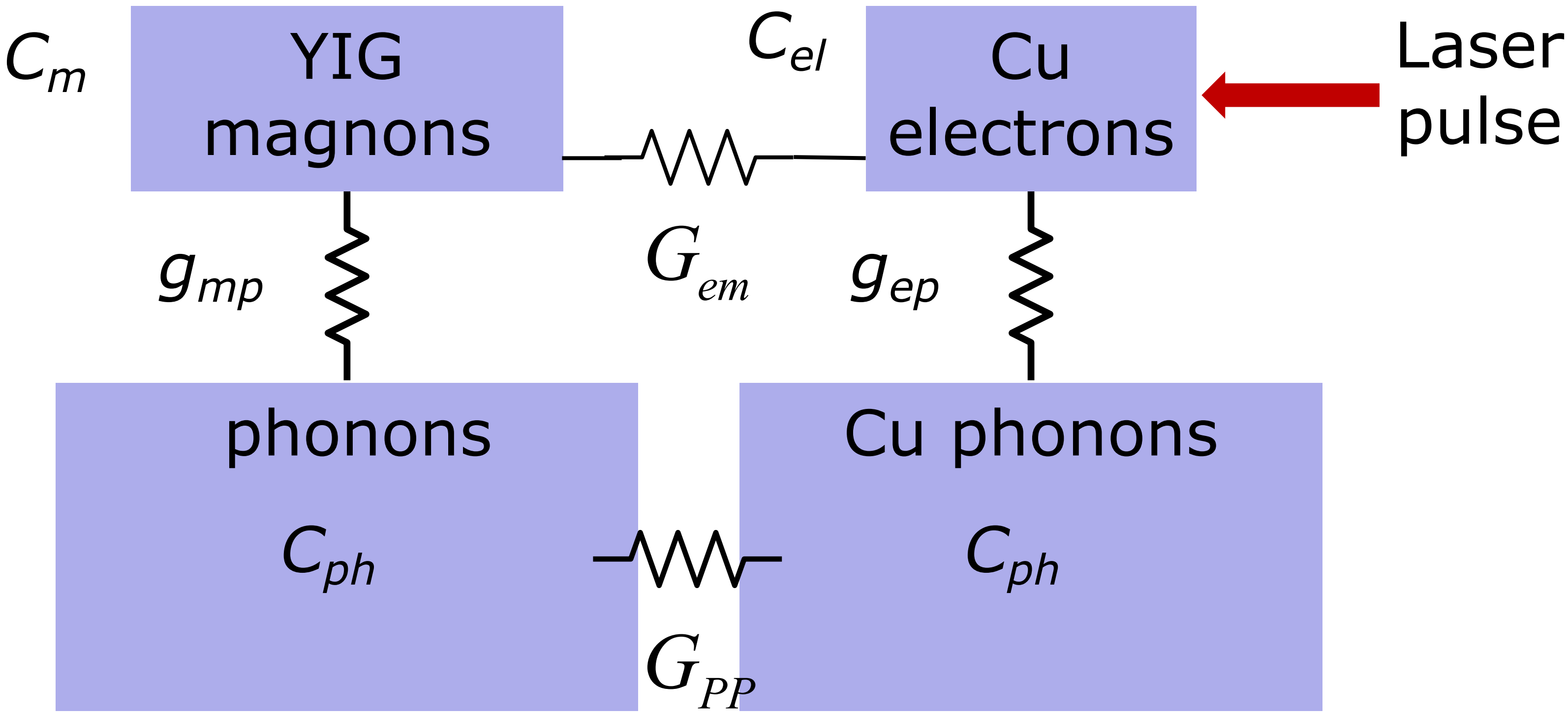
- **2 Layers** Au/YIG
  - Measure time-resolved spin accumulation in a rapidly heated normal metal by magneto-optic Kerr effect (MOKE)
  - Source of spin is the **interfacial spin-Seebeck effect**
- **3 Layers** Pt/[Co,Pt]/Cu
  - Measure time-resolved spin accumulation in a normal metal by MOKE
  - Dominant source of spin accumulation is **thermally-driven demagnetization**
- **4 Layers** Pt/[Co,Pt]/Cu/CoFeB
  - Measure magnetization dynamics by MOKE
  - Additional spin transfer torque coming from the **spin-dependent Seebeck effect**

Detect spin accumulation and magnetization dynamics by time-resolved magneto-optic Kerr effect (TR-MOKE)



Thermal circuit for picosecond spin Seebeck effect





Difficult to directly compare the volume and interface thermal conductances (different units)

- At room temperature
  - electron-phonon coupling in Cu

    $$g_{ep} \approx 8\times10^{16}\ \mathrm{W\ m^{-3}\ K^{-1}}$$

  - magnon-phonon coupling in a cuprate spin ladder

    $$g_{em} \approx 5\times10^{15}\ \mathrm{W\ m^{-3}\ K^{-1}}$$

  - phonon-phonon interface conductance

    $$G_{pp} \approx 200\ \mathrm{MW\ m^{-2}\ K^{-1}}$$

  - tentative estimate from our data

    $$G_{em} \approx \left(10^{8}\ \mathrm{A\ m^{-2}\ K^{-1}}\right)\left(\frac{k_B T}{e}\right) \sim 2\ \mathrm{MW\ m^{-2}\ K^{-1}}$$

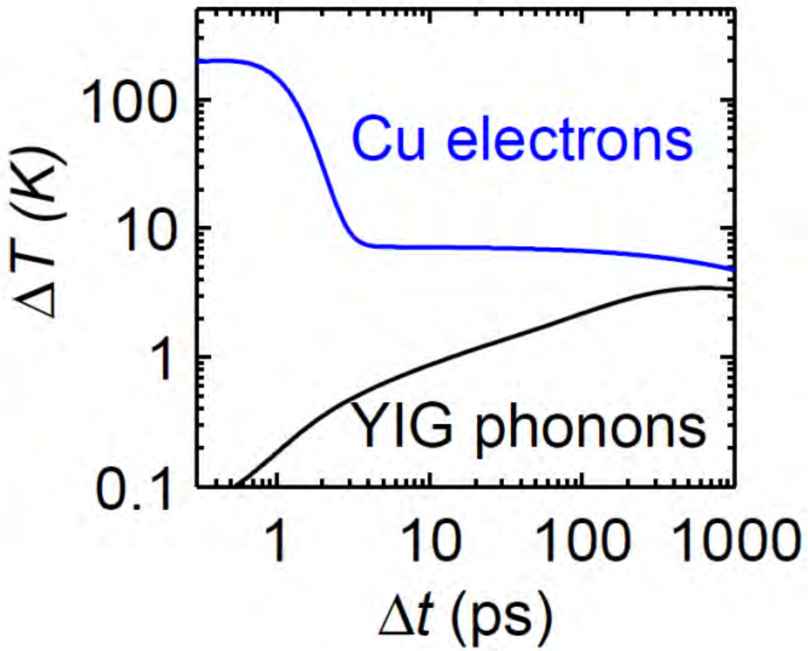
First solve the heat problem

Solve two-temperature model in Cu and couple to phonons in YIG through an interface thermal conductance.

For Cu:

$$C_\mathrm{e}\frac{\partial T_\mathrm{e}}{\partial t} - \Lambda_\mathrm{e}\frac{\partial^2 T_\mathrm{e}}{\partial z^2} = g_\mathrm{ep}(T_\mathrm{p} - T_\mathrm{e})$$

$$C_\mathrm{p}\frac{\partial T_\mathrm{p}}{\partial t} - \Lambda_\mathrm{p}\frac{\partial^2 T_\mathrm{p}}{\partial z^2} = g_\mathrm{ep}(T_\mathrm{e} - T_\mathrm{p})$$

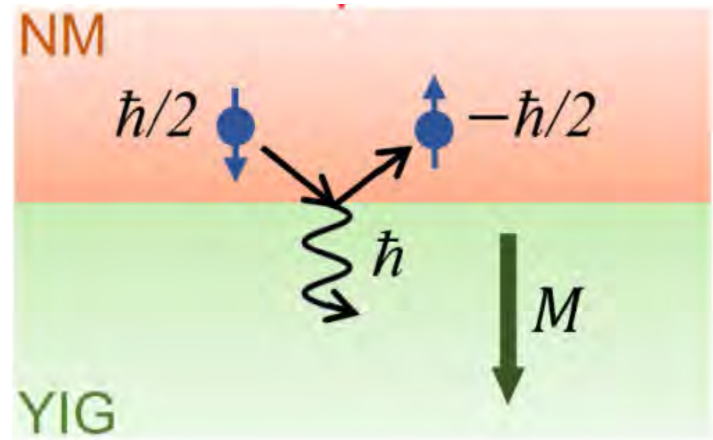


Kimling et al., arXiv:1608.00702

Then solve the spin diffusion problem using the spin-Seebeck effect as a boundary condition at the Cu/YIG interface

$$j_S = g_{\uparrow\downarrow}\frac{e^2}{h}S_S(T_e - T_m) \qquad S_S = \left(\frac{\gamma h}{\pi M_s V_a}\right)\left(\frac{k_B}{e}\right)$$

$$\alpha \equiv g_{\uparrow\downarrow}\frac{e^2}{h}S_S$$



$$j_\uparrow - j_\downarrow = \frac{\sigma}{2e}\frac{\partial(\zeta_\uparrow - \zeta_\downarrow)}{\partial x}$$

$$\frac{\partial(\zeta_\uparrow - \zeta_\downarrow)}{\partial t} - \frac{2}{eN}\frac{\partial(j_\uparrow - j_\downarrow)}{\partial x} = -\frac{\zeta_\uparrow - \zeta_\downarrow}{\tau}$$

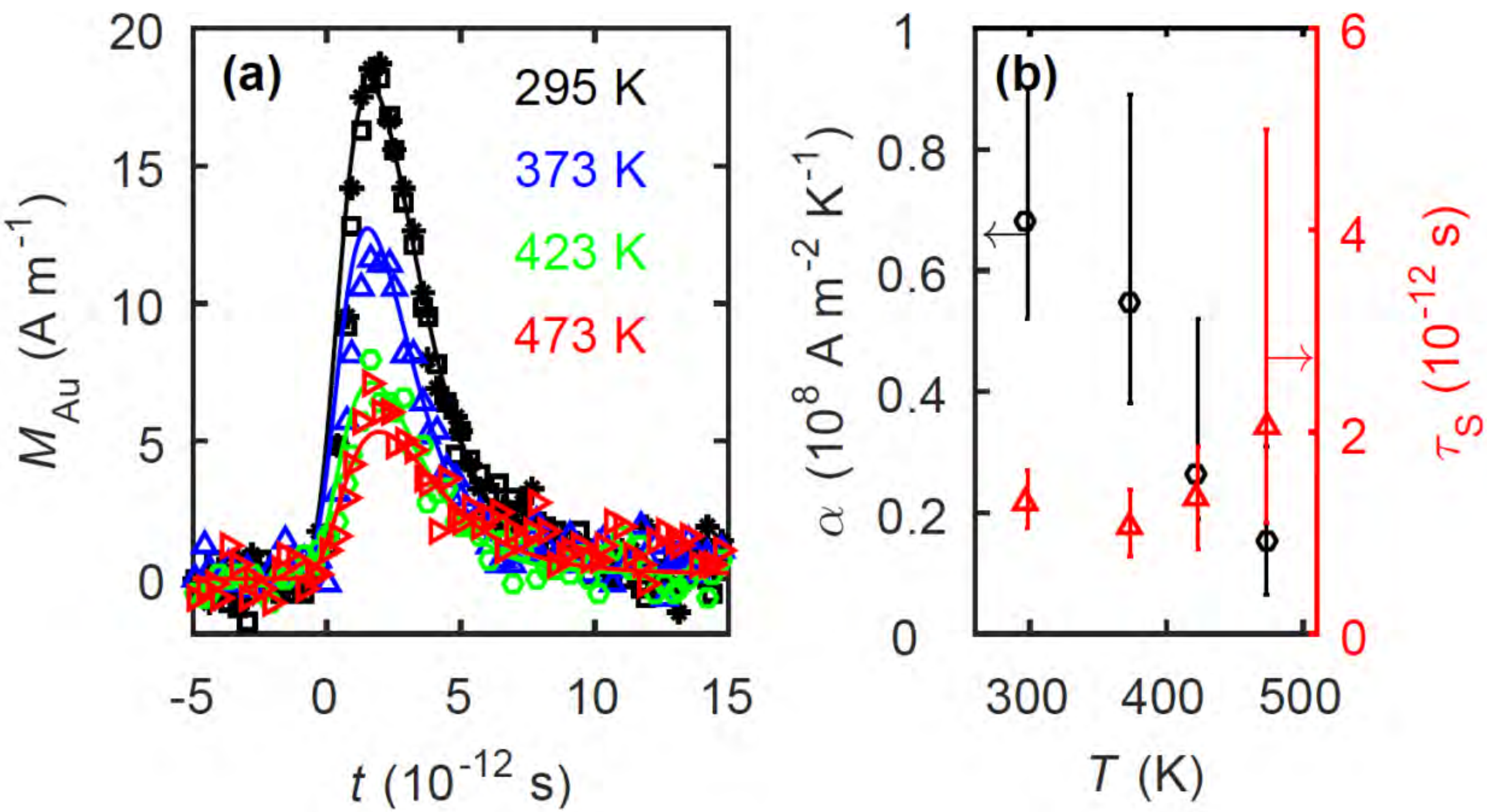
Spin relaxation time
Fit parameter

Measure spin accumulation in Cu or Au by the polar Kerr effect and convert to magnetization using a previously determined calibration

Cu: $\theta_K \approx (10\ \text{nrad m A}^{-1})M$

Au: $\theta_K \approx (50\ \text{nrad m A}^{-1})M$

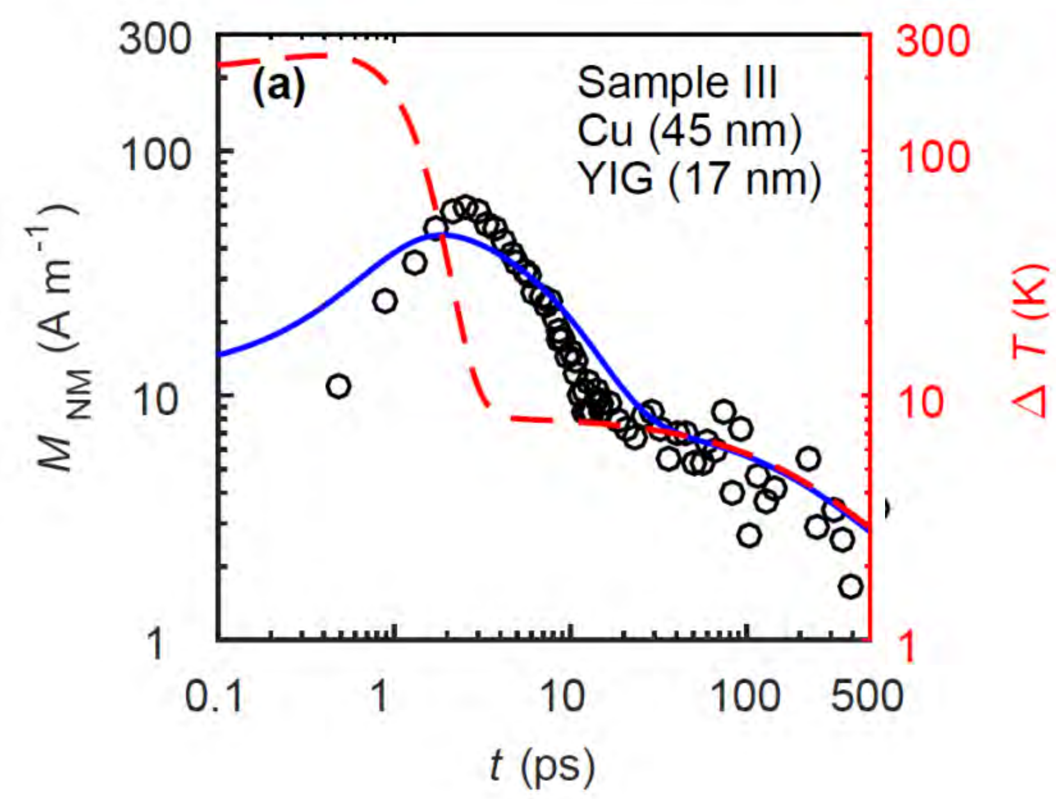
Au(60 nm)/YIG(20 nm)



Kimling et al., arXiv:1608.00702

Long time decay of signal is consistent with signal proportional to interface ΔT

At t>3 ps, $(T_e - T_m) \approx (T_{Cu} - T_{YIG})$



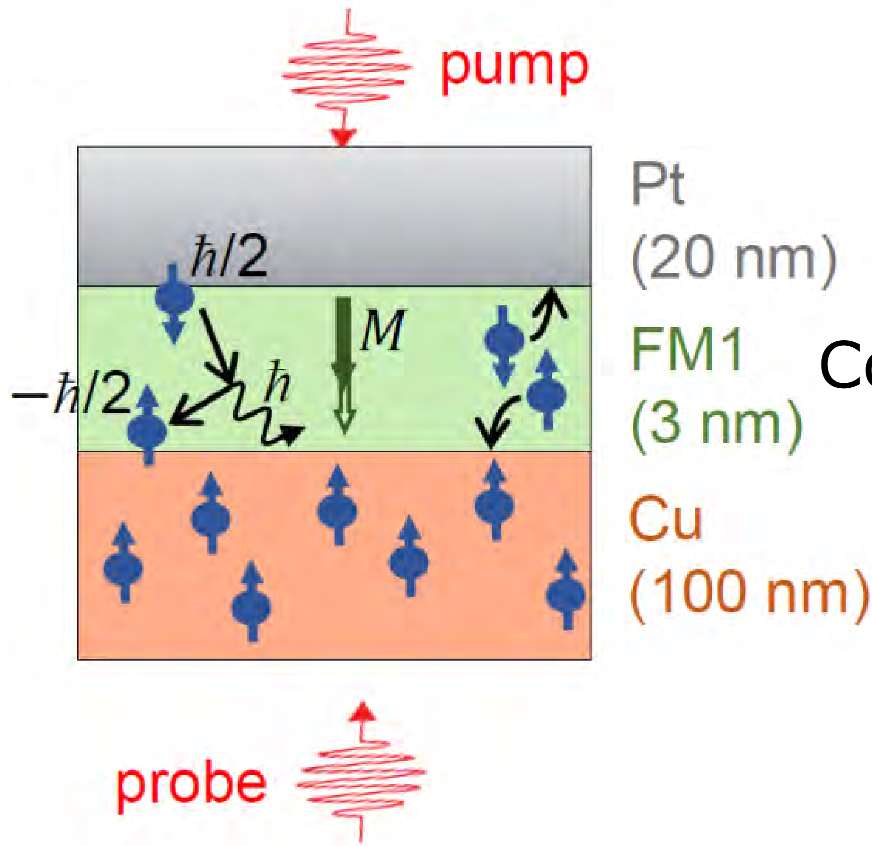
Need better systematic control of the metal/YIG interface. Some tentative conclusions from 6 samples

$$\alpha \sim 10^8 \text{ A m}^{-2} \text{ K}^{-1}$$

- α independent of YIG thickness
- α independent of metal thickness
- α larger for Cu/YIG than for Au/YIG
- in-situ deposited Au has higher α than ex-situ

	Sample I	Sample II	Sample III	Sample IV	Sample V	Sample VI
NM	Au	Au	Cu	Au	Au	Cu
h_{NM} (nm)	60	60	45	103	29	35
h_{YIG} (nm)	20	100	17	50	51	17
α (10^8 A m^{-2} K^{-1})	0.84±0.12	0.66±0.29	3.02±1.05	0.29±0.11	0.30±0.05	2.32±0.24
τ_{S} (ps)	1.14±0.13	0.99±0.26	3.79±0.85	2.67±0.91	1.74±0.29	2.52±0.27

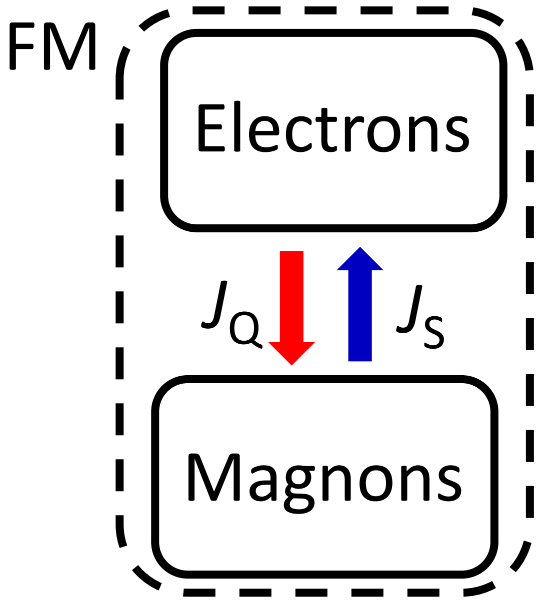
3 layer metal structure: Place a perpendicular metallic ferromagnet layer between a Pt heater and a Cu heat sink



Co/Pt or Co/Ni

Two mechanisms for thermally-driven spin generation

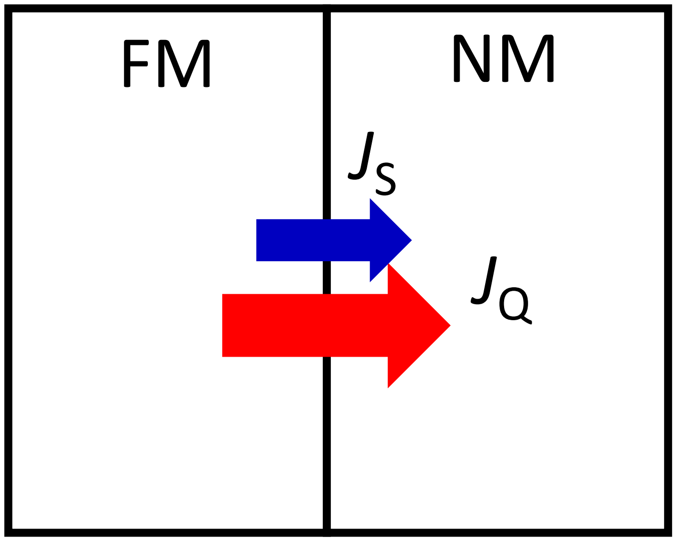
Ultrafast demagnetization



$$g_S = -\frac{dM}{dt}$$

Choi, *et al.* Nature Commun. **5**, 4334 (2014)

Spin-dependent Seebeck effect



First approximation: treat as an interface spin source

$$G_S = -\left(\frac{\mu_B}{eLT}\right) S_s J_Q$$

Slachter, *et al.* Nature Phys. **6**, 879 (2010)

Choi, *et al.* Nature Phys. **11**, 576 (2015)

FM layer thickness is actually comparable to the spin diffusion length (particularly for Co/Ni) drop the boundary condition approximation

spin Seebeck coefficient $$S_{\mathrm{S}} = S_{\uparrow} - S_{\downarrow}$$

spin current $$j_{\uparrow} - j_{\downarrow} = \frac{2\sigma_{\uparrow}\sigma_{\downarrow}}{e(\sigma_{\uparrow} + \sigma_{\downarrow})}\left[\frac{\partial\zeta_{\uparrow} - \zeta_{\downarrow})}{\partial z} - eS_{\mathrm{S}}\frac{\partial T}{\partial z}\right],$$

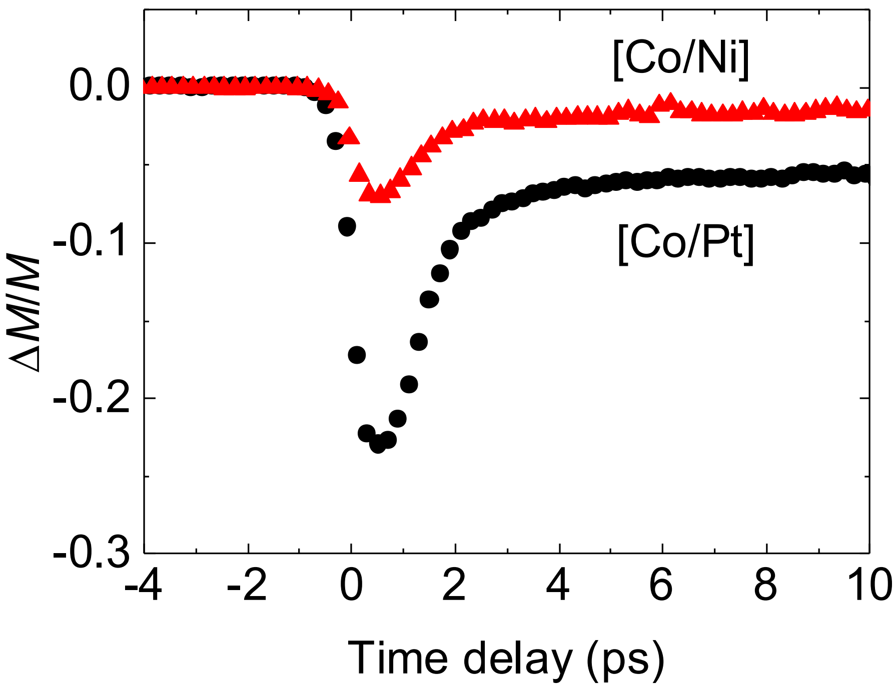
spin chemical potential $$\frac{\partial(\zeta_{\uparrow} - \zeta_{\downarrow})}{\partial t} - D\left[\frac{\partial^2(\zeta_{\uparrow} - \zeta_{\downarrow})}{\partial z^2} - eS_{\mathrm{S}}\frac{\partial^2 T}{\partial z^2}\right] = -\frac{\zeta_{\uparrow} - \zeta_{\downarrow}}{\tau_{\mathrm{S}}}$$

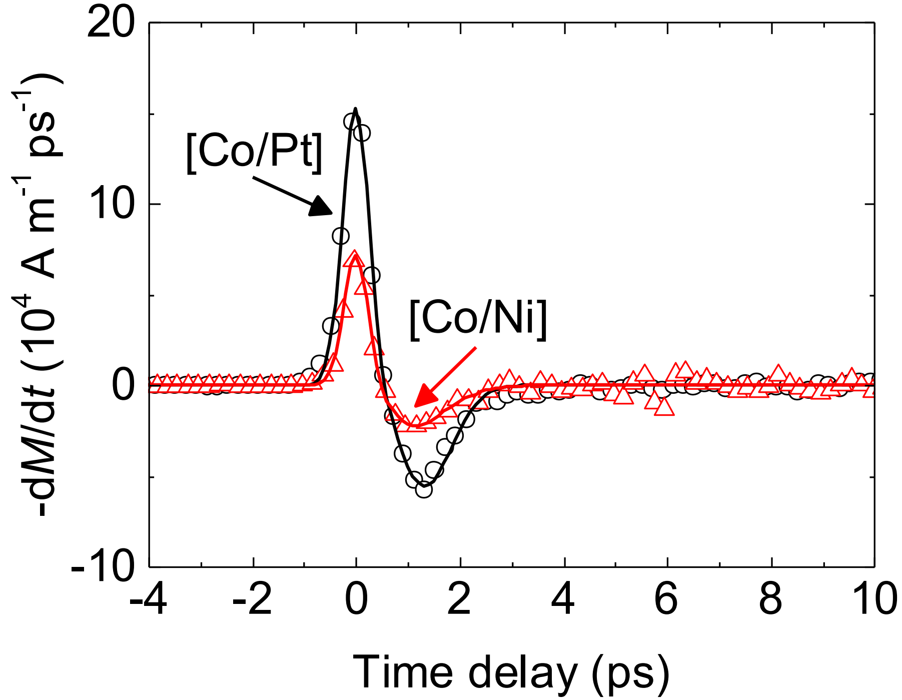
- Notes $j = j_{\uparrow} + j_{\downarrow} = 0$
  - Zero charge current is a good approximation
  - These equations assume the same *T* for both spin populations. Will return to this point later…
  - Choi et al. (2015) used a different definition of S_S

Kimling, et al. (submitted)

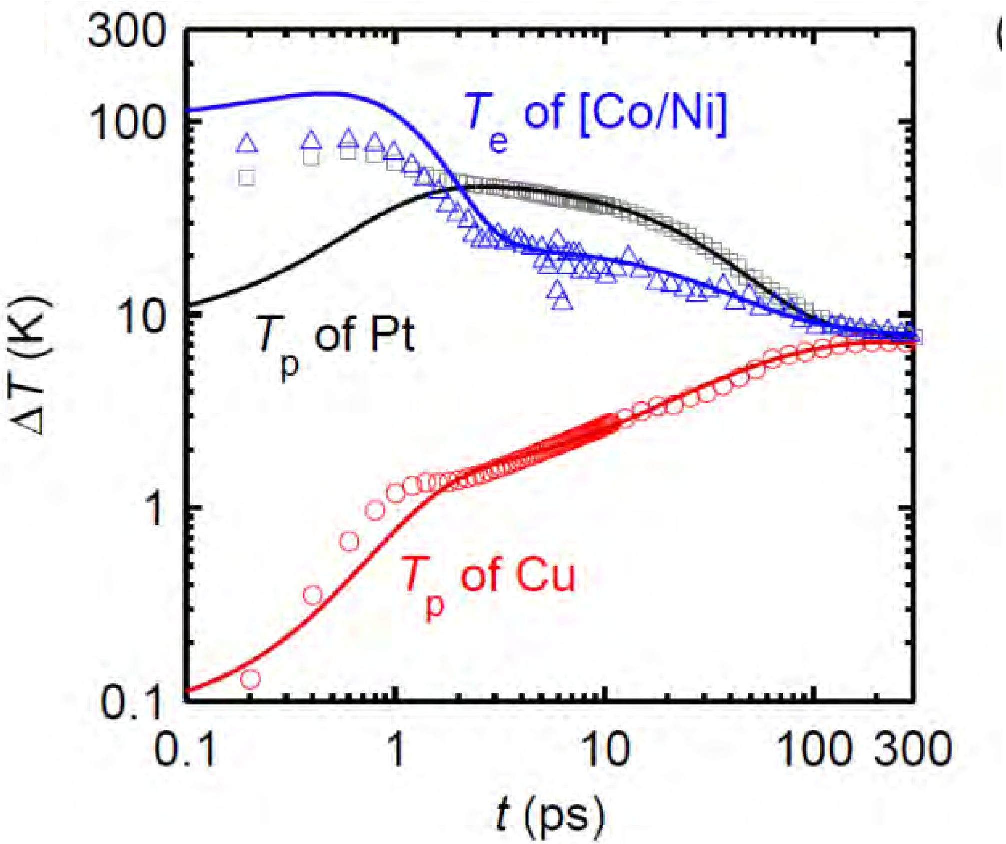
Measure M(t) of FM1 by TR-MOKE

$$g_S = -\frac{dM}{dt}$$

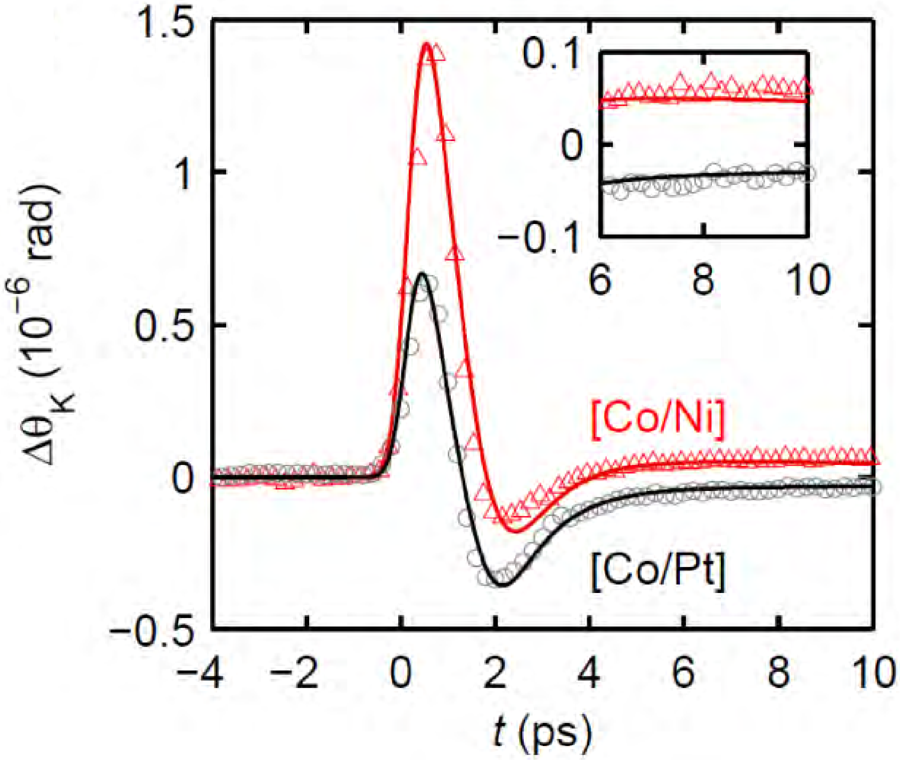




Measure temperatures of Pt and Cu by time domain thermoreflectance (TDTR) and use data to refine thermal model for electron and phonon temperatures



Measure spin accumulation in Cu by TR-MOKE and compare to spin diffusion model

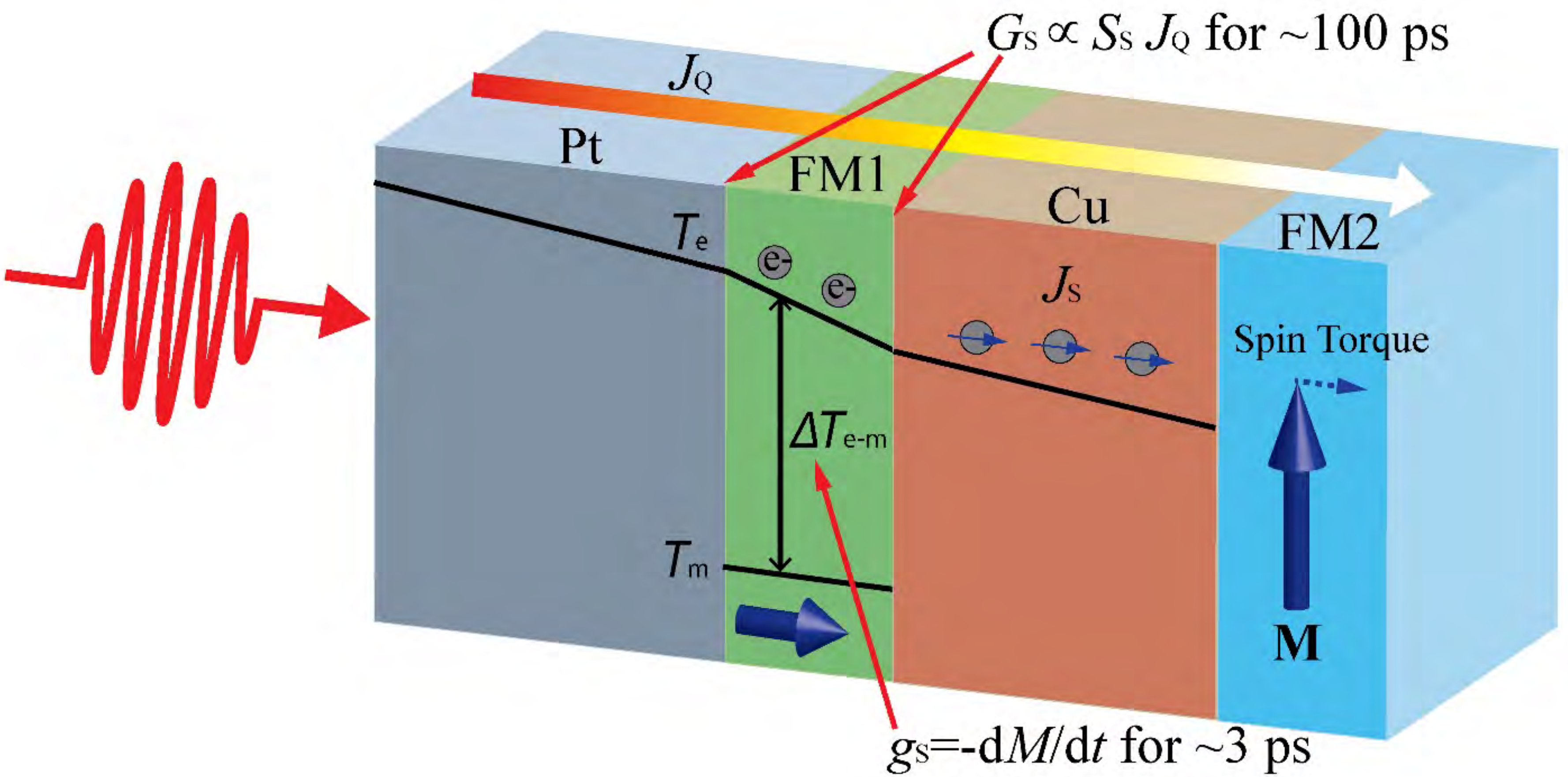


- Three fitting parameters for each sample.
  1. spin relaxation time in FM1
  2. S_S
  3. coefficient relating Kerr rotation and spin accumulation (10 nrad A^{-1} m)

Choi et al. Nature Physics (2015); Kimling et al. (submitted)

4-layer structure: Thermal spin-transfer torque

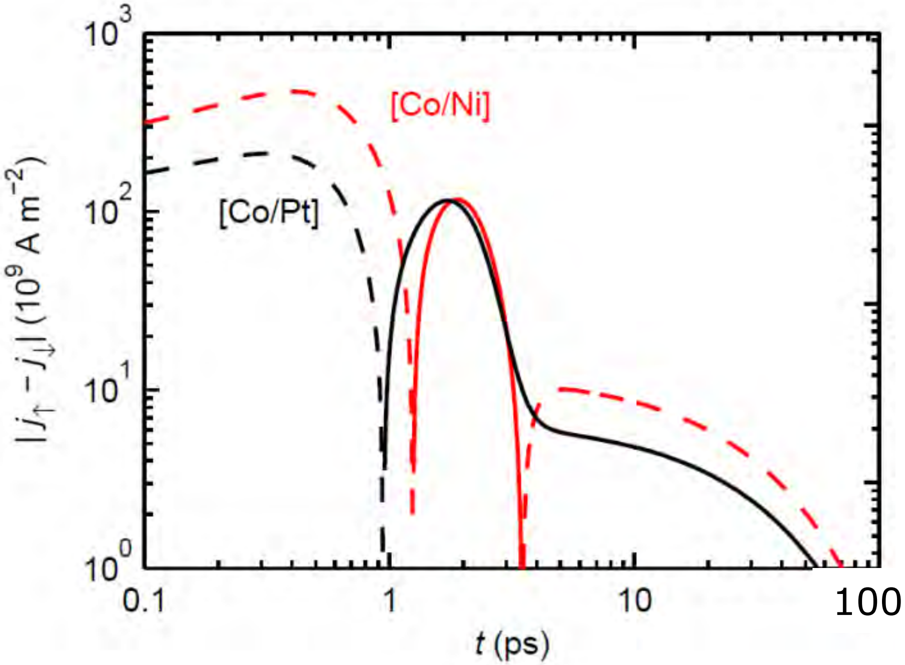
Pt (20)/ [Co/Pt] or [Co/Ni] (3)/ Cu (100)/ CoFeB (2) (nm)

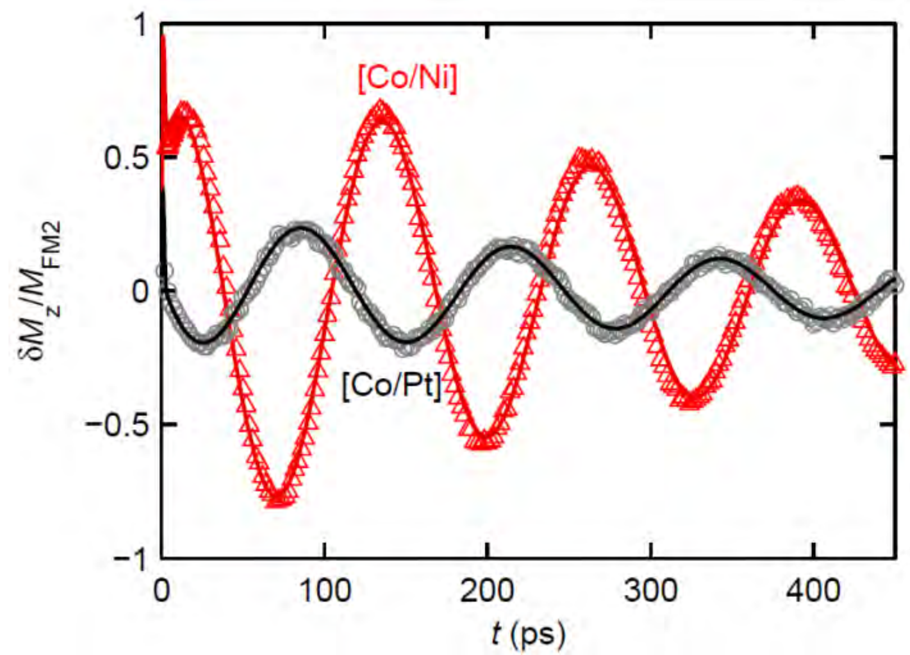


Choi, *et al.* Nature Physics (2015)
Kimling, et al. (submitted)

Model spin current (FM2 is a perfect sink of spin) and magnetization dynamics created by the spin transfer torque. Compare to experiment

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma_e \mu_0 \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha_G \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \frac{\mu_B (j_\uparrow - j_\downarrow)}{e M_S h} \mathbf{m} \times (\mathbf{m} \times \mathbf{e}_z)$$





Choi, *et al.* Nature Physics (2015), Kimling, et al. (submitted)

Two free parameters: spin relaxation time τ_s and spin-dependent Seebeck coefficient S_s

Nat. Phys (2015)

Fitting parameter	[Co/Pt]	[Co/Ni]
τ_S (fs)	20	100
S_S (μV/K)	12	-24

Pt/FM1/Cu

Cu spin accumulation

Fitting parameter	[Co/Pt]	[Co/Ni]
τ_S (fs)	22	108
S_S (μV/K)	22	-25

Pt/FM1/Cu/FM2

FM2 precession

Fitting parameter	[Co/Pt]	[Co/Ni]
τ_S (fs)	19	140
S_S (μV/K)	19	-25

Assumption of equal temperatures for up and down spin channels is probably not a valid approximation

spin current

$$j_\uparrow - j_\downarrow = \frac{2\sigma_\uparrow\sigma_\downarrow}{(\sigma_\uparrow + \sigma_\downarrow)}\left(-S_\uparrow\frac{\partial T_\uparrow}{\partial z} + S_\downarrow\frac{\partial T_\downarrow}{\partial z}\right)$$

assume W-F law holds
for both channel

$$j_\uparrow - j_\downarrow = \frac{2(\Lambda_\uparrow S_\downarrow q_\downarrow - \Lambda_\downarrow S_\uparrow q_\uparrow)}{(\Lambda_\uparrow + \Lambda_\downarrow)L_0 T_\mathrm{e}}$$

Rewrite in terms of asymmetry parameters β for material properties (Seebeck *S* and thermal conductivity Λ)
and instantaneous heat current *q*.

$$\beta_S = (S_\uparrow - S_\downarrow)/(S_\uparrow + S_\downarrow)$$

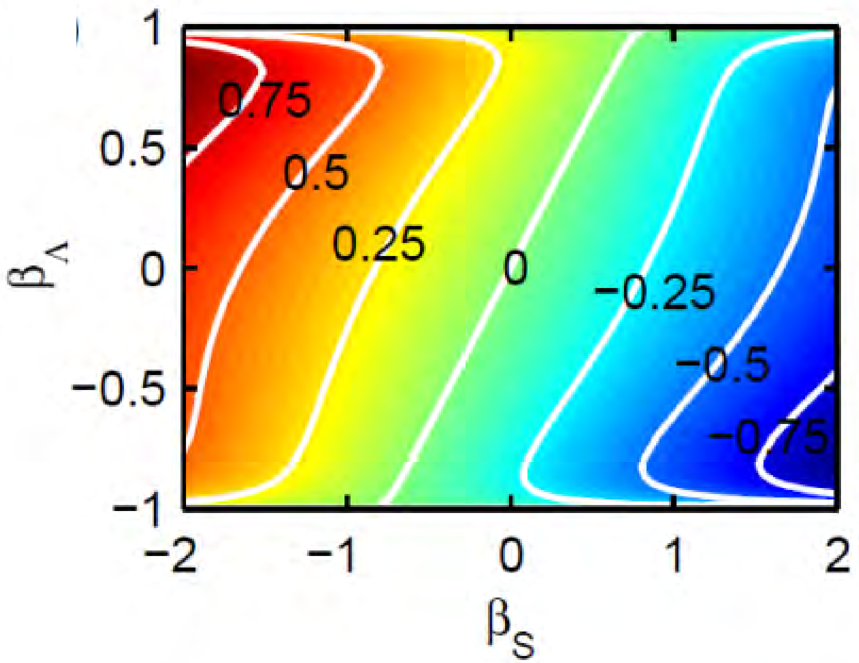
$$j_\uparrow - j_\downarrow = \frac{S q_\mathrm{e}}{2L_0 T_\mathrm{e}}\left[(\beta_\Lambda\beta_S - 1)\beta_q + (\beta_\Lambda - \beta_S)\right]$$

Kimling *et al*. (submitted)

Complicated phase space of material parameters. Take home message is that spin heat accumulation can help generate larger spin currents

Precession amplitude increases with the time integral of spin current

$$I = \int (j_\uparrow - j_\downarrow) dt$$



Contours of constant I in units (A s m^{-2})

Summary

- Picosecond second time-scale isolates the interface contribution to spin Seebeck effect at normal-metal/ferromagnetic-insulator interfaces.
  - Order of magnitude of the coefficient is consistent with theory and prior measurements of spin mixing conductance.
- In metallic structures, ultrafast demagnetization and spin-dependent Seebeck S_S are of similar absolute magnitude.
  - For [Co,Ni] the two mechanisms reinforce each other and produce a 1% tilting of the magnetization in spin-valve structure.
- S_S coefficient can be measured accurately.
  - Difficult, however, to relate to microscope parameters that describe the Seebeck coefficients and thermal conductivities of the spin-up and spin-down channels (if the two channels are indeed not at the same temperature).