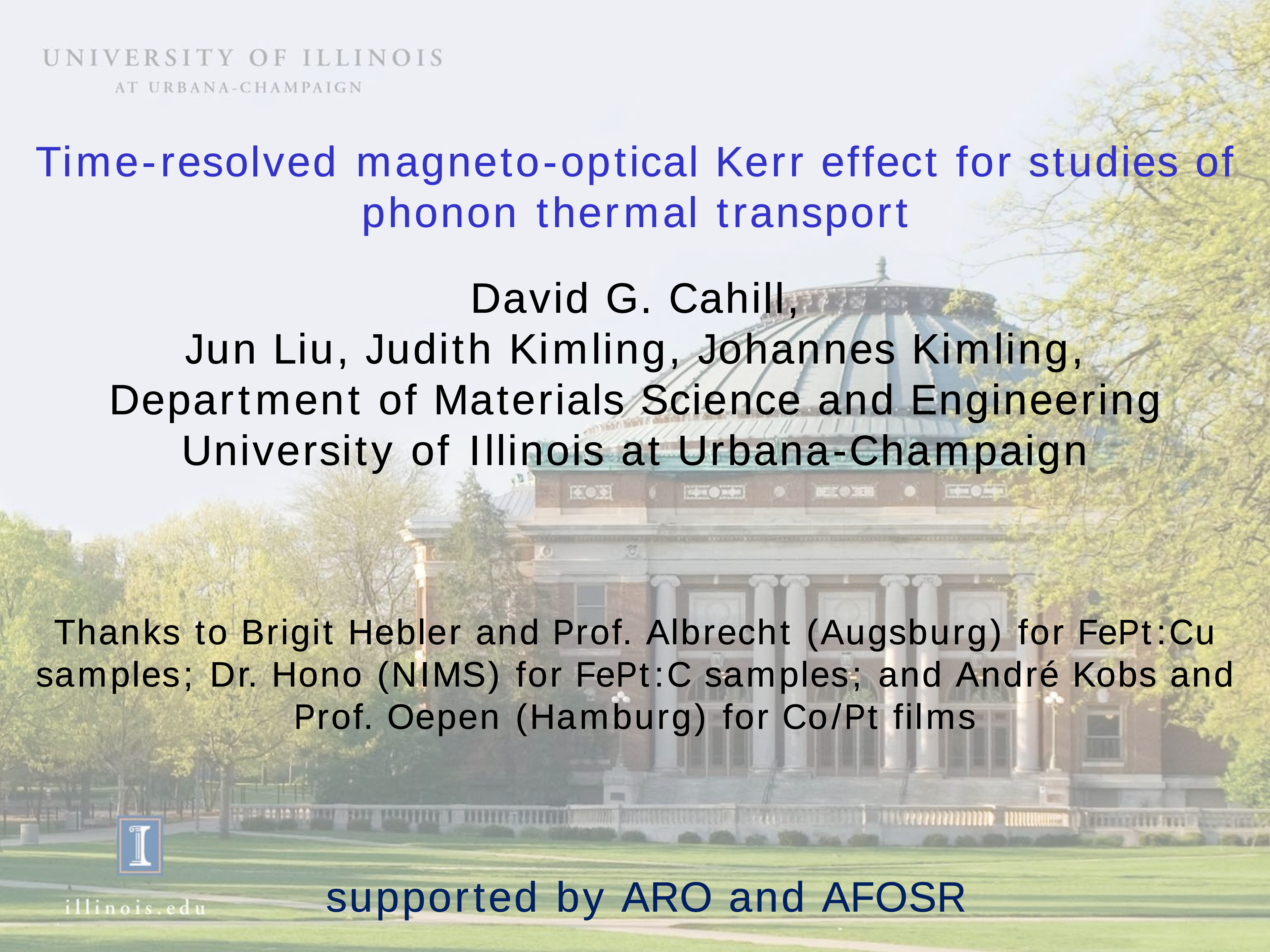


UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

Time-resolved magneto-optical Kerr effect for studies of phonon thermal transport

David G. Cahill,
Jun Liu, Judith Kimling, Johannes Kimling,
Department of Materials Science and Engineering
University of Illinois at Urbana-Champaign

Thanks to Brigit Hebler and Prof. Albrecht (Augsburg) for FePt:Cu samples; Dr. Hono (NIMS) for FePt:C samples; and André Kobs and Prof. Oepen (Hamburg) for Co/Pt films

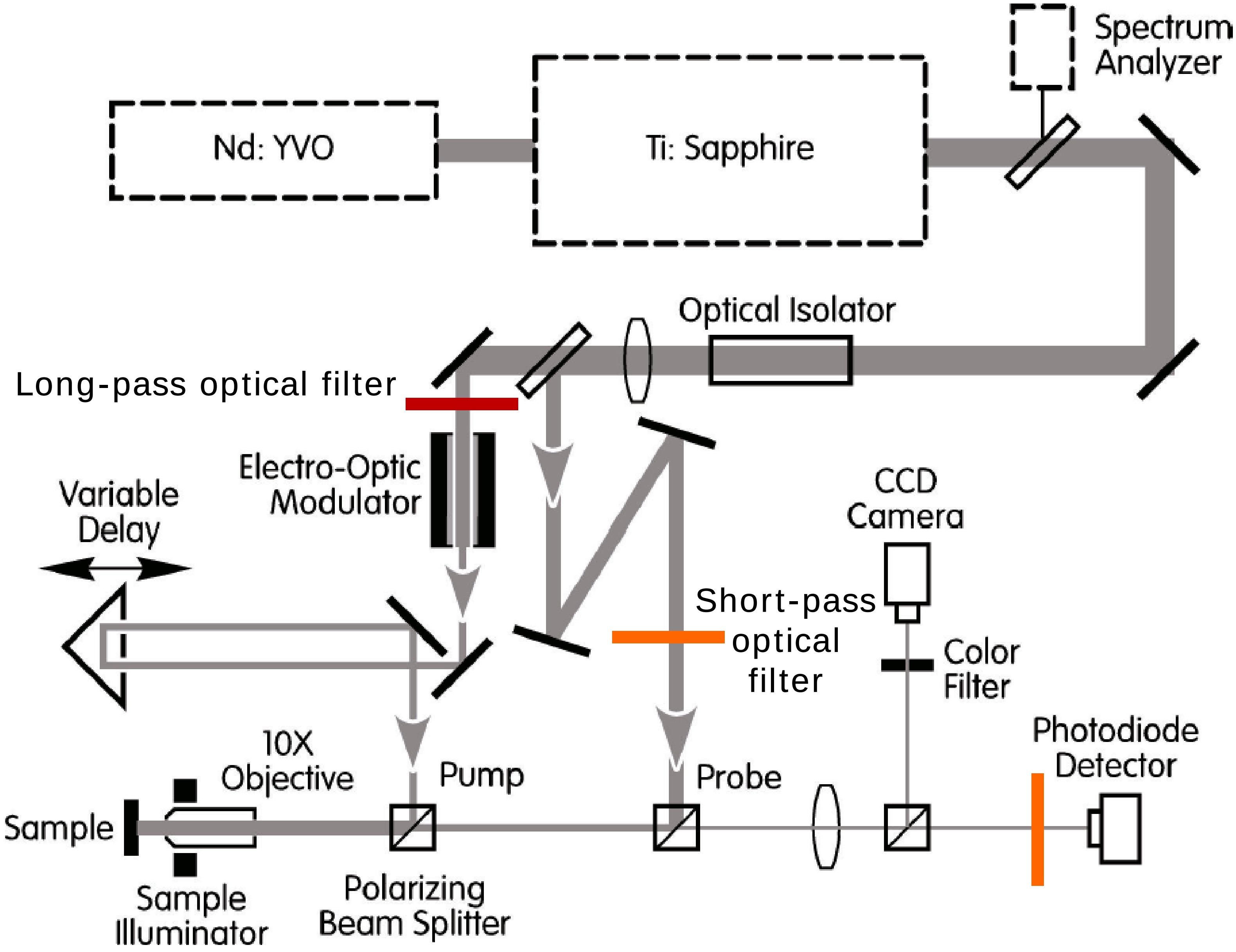
illinois.edu

supported by ARO and AFOSR

Outline

- Introduction to…
  - pump-probe measurements by conventional time-domain thermoreflectance (TDTR);
  - and time-resolved magneto-optic Kerr effect (TR-MOKE)
- Polarization signal generated by a magnetic layer enables use of thinner transducers
  - Less thermal mass → faster time resolution
  - Reduced in-plane thermal conductance
  - Greater sensitivity to interfacial phenomena when the Kapitza length is small
- Some practical issues of TR-MOKE versus TDTR
  - Ultrafast time response
  - Linearity and temperature range
  - Sensitivity and noise

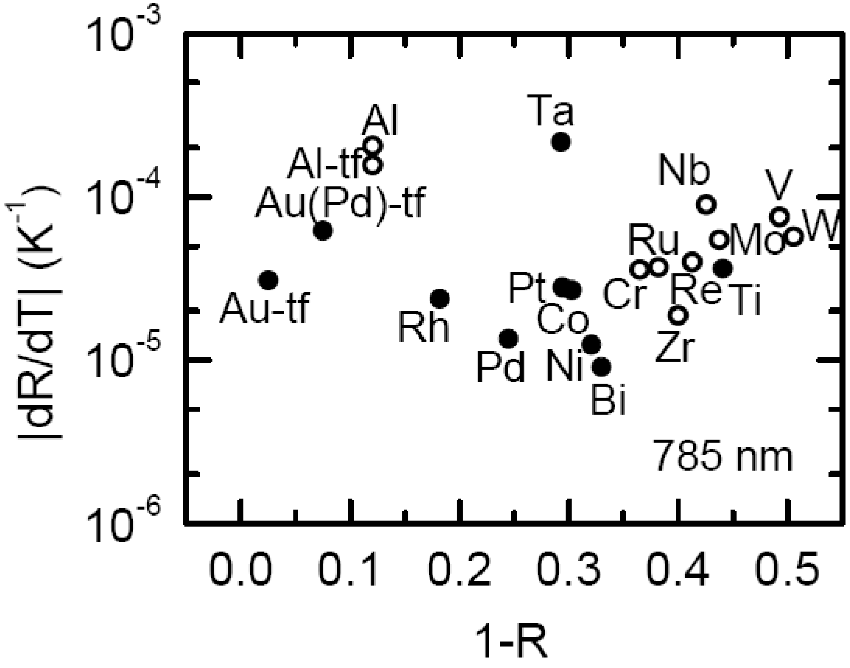
Time-domain thermoreflectance

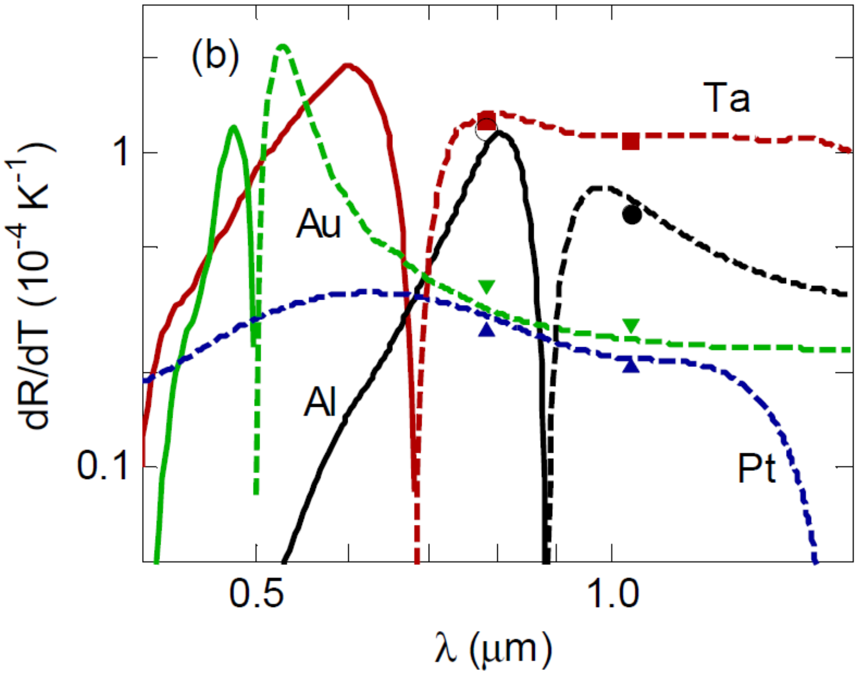


Large dR/dT is desired for higher signal-to-noise

R=optical reflectivity; T=temperature

Ti:sapphire laser





Wang *et al*., JAP (2010)

Wilson *et al*., Optics Express (2012)

Thickness of the transducer sets limits on time-resolution

- Limited by interface conductance.
  - Equivalent to discharging of a capacitor through a resistor

$$\tau_G = \left(\frac{1}{AG}\right)(VC) = \frac{hC}{G}$$

h= 60 nm; C=2.5 MJ m^{-3} K^{-1}; G=200 MW m^{-2} K^{-1}

τ_G = 0.75 ns

Thickness of the transducer sets limits on time-resolution

- Limited by effusivity of the sample
  - When does the heat capacity of a layer of the thermal diffusion distance in the sample equal the heat capacity of the metal film?

$$\left(\sqrt{D\tau_E}\right)C_s = hC_f$$

$$C_f \approx C_s = C; \qquad \tau_E = \frac{h^2}{D}$$

h = 60 nm; D > 10^{-7} $\mathrm{m^2\ s^{-1}}$ (glassy polymer)

$\tau_E < 36$ ns

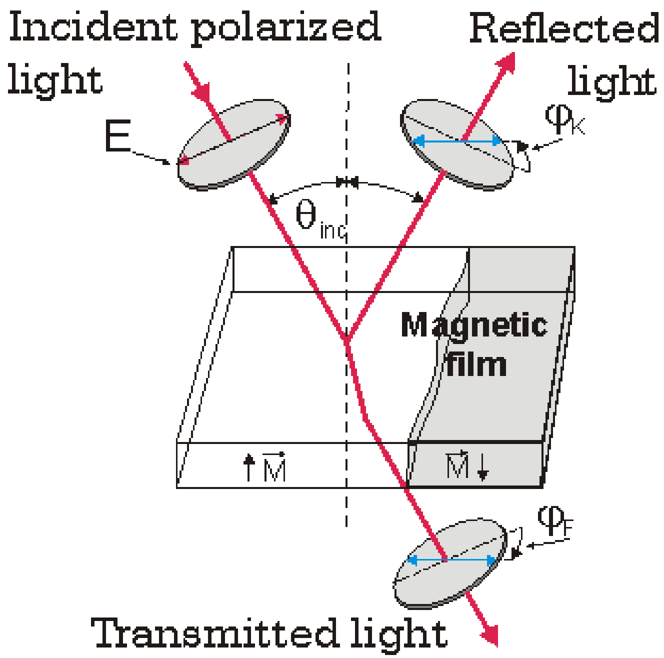
What could we do if the transducer was 6 nm thick instead of 60 nm thick?

- Access time scales in high thermal conductivity crystals down at ~100 ps.
- Increase sensitivity to low thermal conductivity materials by reducing the product of modulation frequency (f = 10 MHz) and the cooling time of the transducer.
  - Even for a glassy polymer $2\pi f \tau_E \ll 1$
- Reduce parasitic in-plane thermal conductance of the metal film transducer, ultimately $h\Lambda_f$ ~0.1 μW K^{-1}
  - In our initial work using TR-MOKE,

    $h\Lambda_f$=0.4 μW K^{-1} (vs. 10 μW K^{-1} for Al in TDTR)

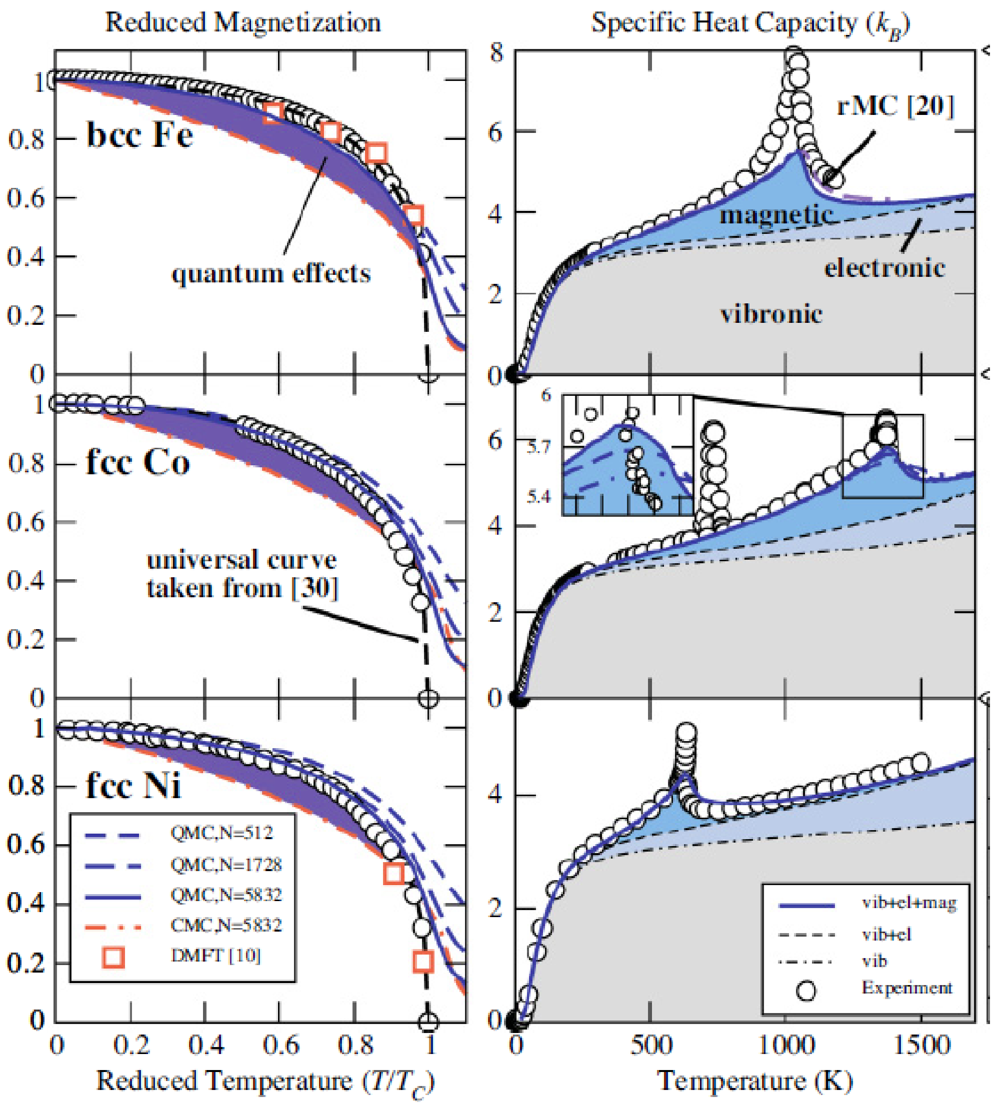
In TR-MOKE, dθ/dT replaces dR/dT of a conventional thermoreflectance measurement

Kerr rotation



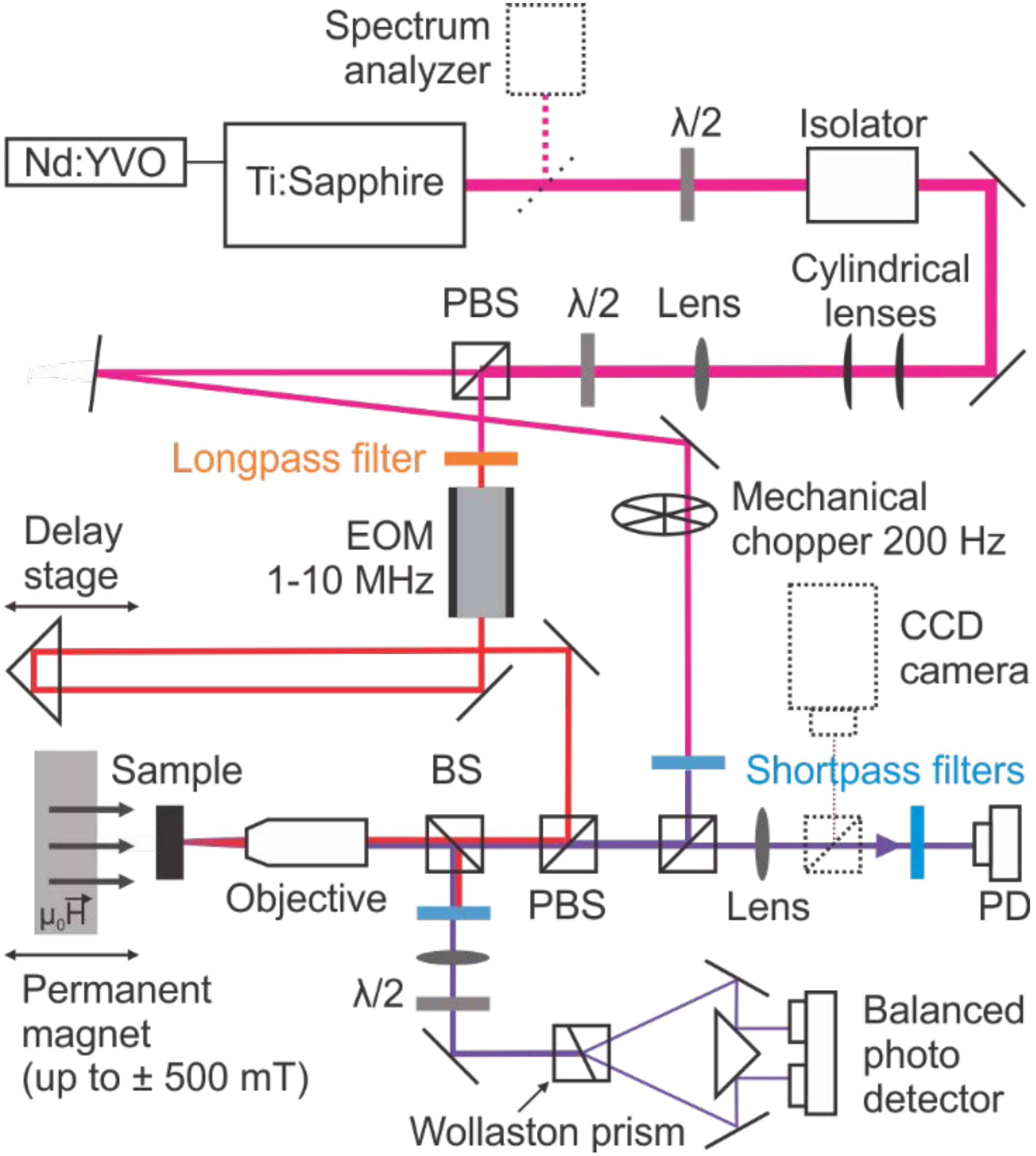
Faraday rotation

http://labfiz.uwb.edu.pl



Körmann *et al*., PRB (2011)

Time-resolved magneto-optic Kerr effect (TR-MOKE)



Perpendicular magnetic materials are the most convenient (polar Kerr effect)

- [Co,Pt] multilayers, 5-20 nm, sputter deposit at room temperature.

$$\frac{d\theta}{dT} \approx 10^{-5}\ \mathrm{K}^{-1}$$

- $L1_0$ phase FePt:Cu, 5 nm, sputter deposit at room temperature followed by rapid thermal annealing to 600 ºC.

$$\frac{d\theta}{dT} \approx 8\times 10^{-5}\ \mathrm{K}^{-1}$$

- Amorphous TbFe (Xiaojia Wang at UMN), 25 nm, sputter deposit, cap with Ta.

$$\frac{d\theta}{dT} \approx 3\times 10^{-5}\ \mathrm{K}^{-1}$$

Kerr signal from a semitransparent magnetic layer is only weakly dependent on dn_s/dT of the sample

- For an optically thin magnetic transducer of thickness *d*, index *n*, and magneto-optic coefficient *Q*, on a sample of index n_s.

$$\theta = \frac{Qn^2}{\frac{\lambda}{4\pi d}\left(n_s^2 - 1\right) + i\left(n_s^2 - n^2\right)}$$

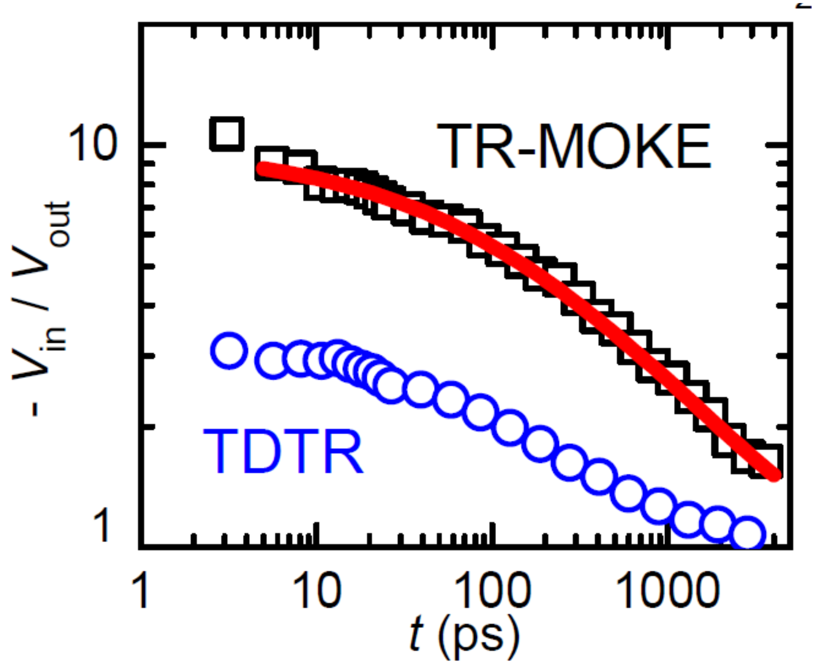
- The critical parameter entering into $\frac{d\theta}{dT}$ is

$$\left|\frac{1}{Q}\frac{dQ}{dT}\right| \sim 10^{-2}\ \mathrm{K}^{-1} \quad \text{for [Co,Pt]}$$

Kerr signal from a semitransparent magnetic layer is only weakly dependent on dn_s/dT of the sample

- Worst case scenario where laser excitation of the Si substrate creates a strong contribution to the TDTR signal. TR-MOKE is immune.

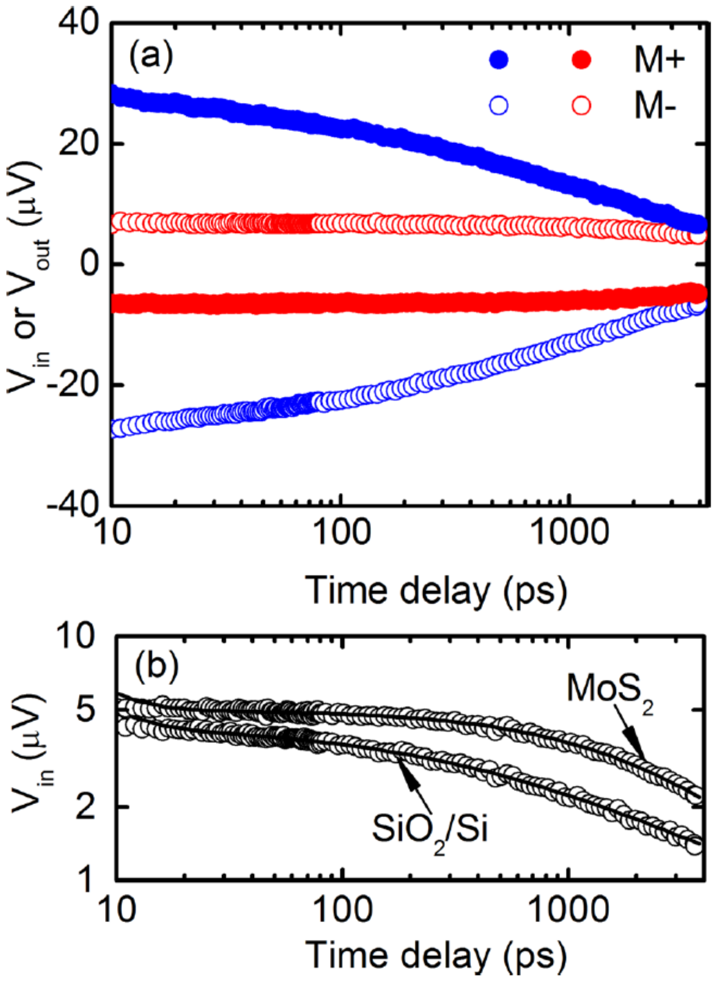
[Co,Pt](8 nm)/SiO_2(240 nm)/Si



Our first application has been in measurements of in-plane thermal conductivity

- Pt/Co multilayers. Structure from top to bottom Pt(1 nm)/[Co(0.5 nm)Pt(1 nm)]×6/Pt(10 nm)

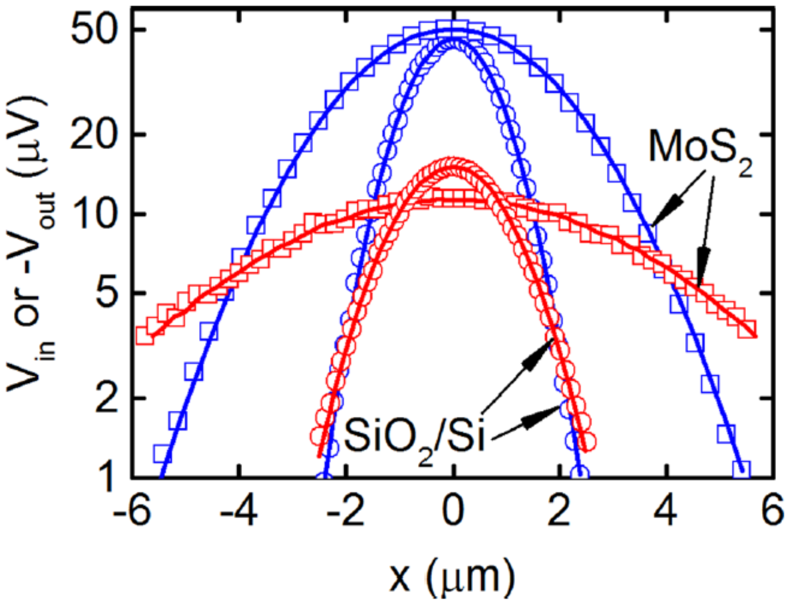
- Measurements are typically done for both orientations of the magnetization. Take difference to remove any residual thermoreflectance signal.

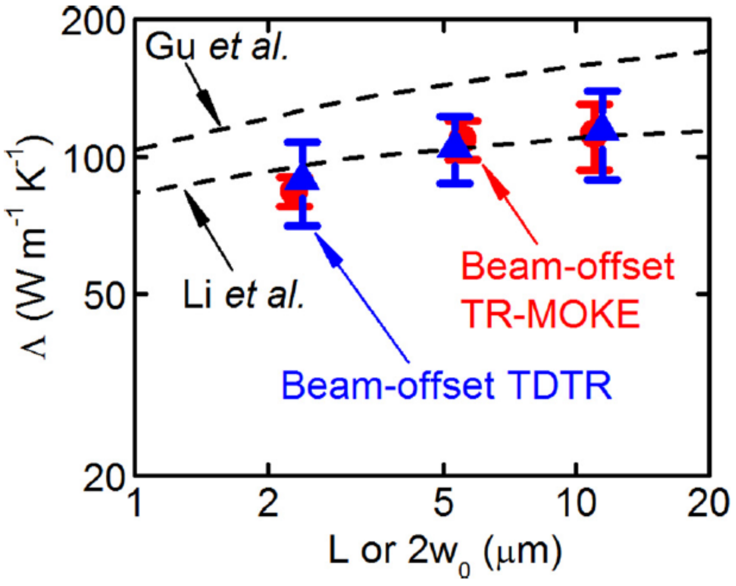


Liu et al., JAP (2014)

Our first application has been in measurements of in-plane thermal conductivity: MoS_2

- Beam offset time-resolved MOKE measurements of [Co,Pt]/MoS_2 to determine in-plane thermal conductivity as a function of laser spot size.



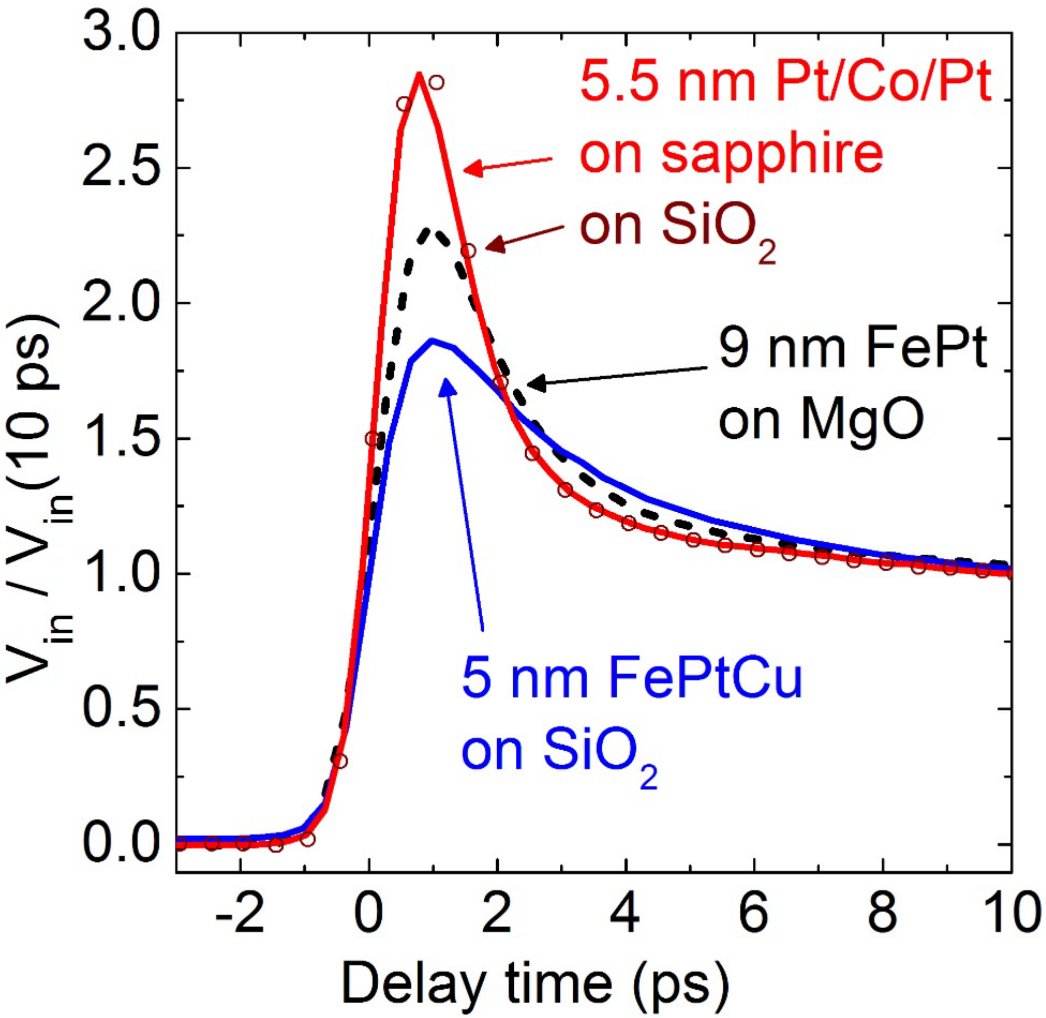


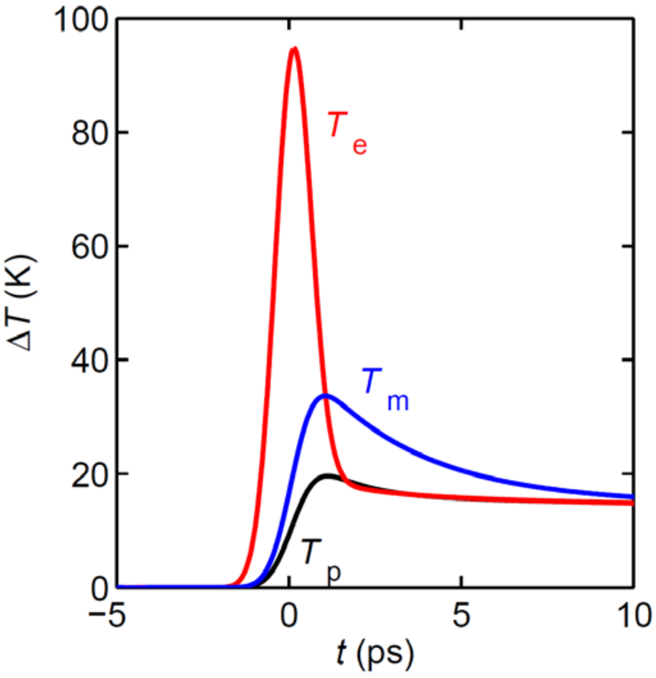
Liu et al., JAP (2014)

Dig into a few more technical details...

- Ultrafast time response
- Linearity and temperature range
- Sensitivity and noise

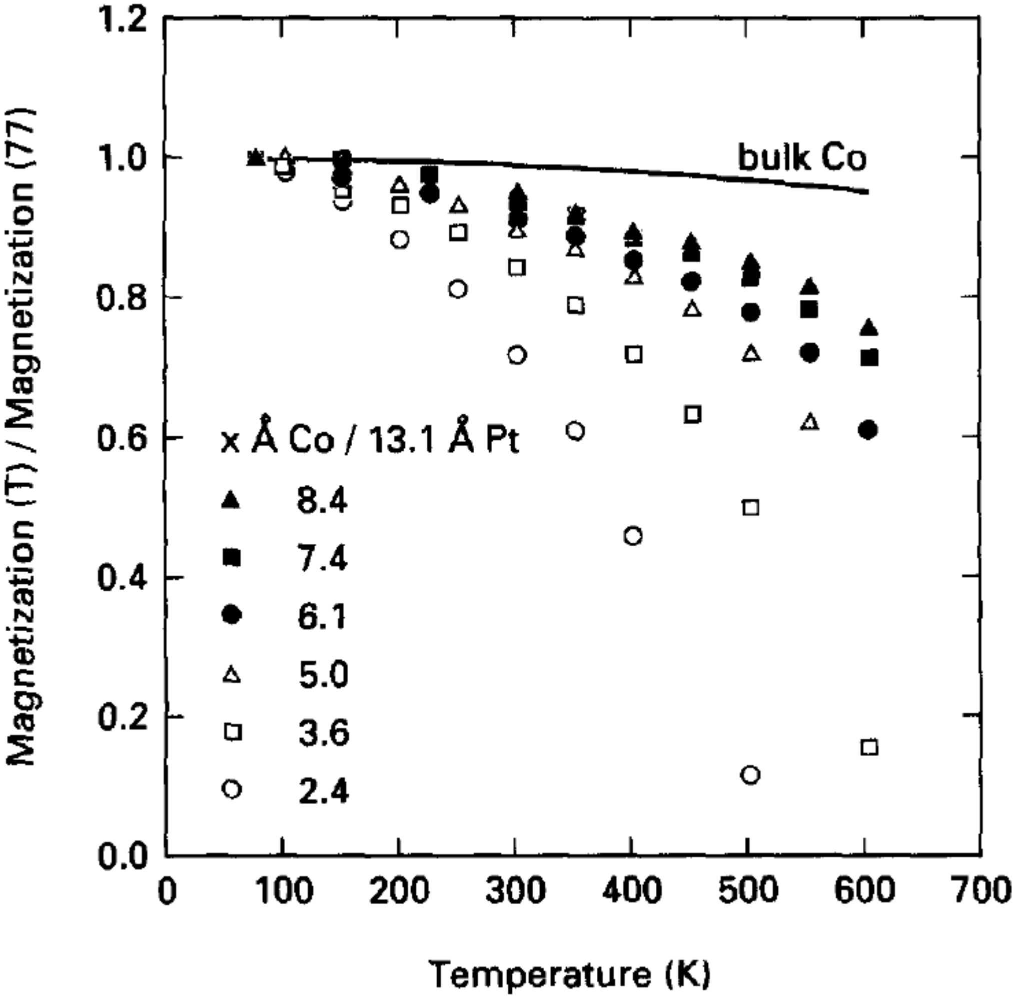
Magnetic transducers (far from T_c) have a time-response of a few ps governed by magnons→electron→phonon coupling





Kimling, PRB (2014)

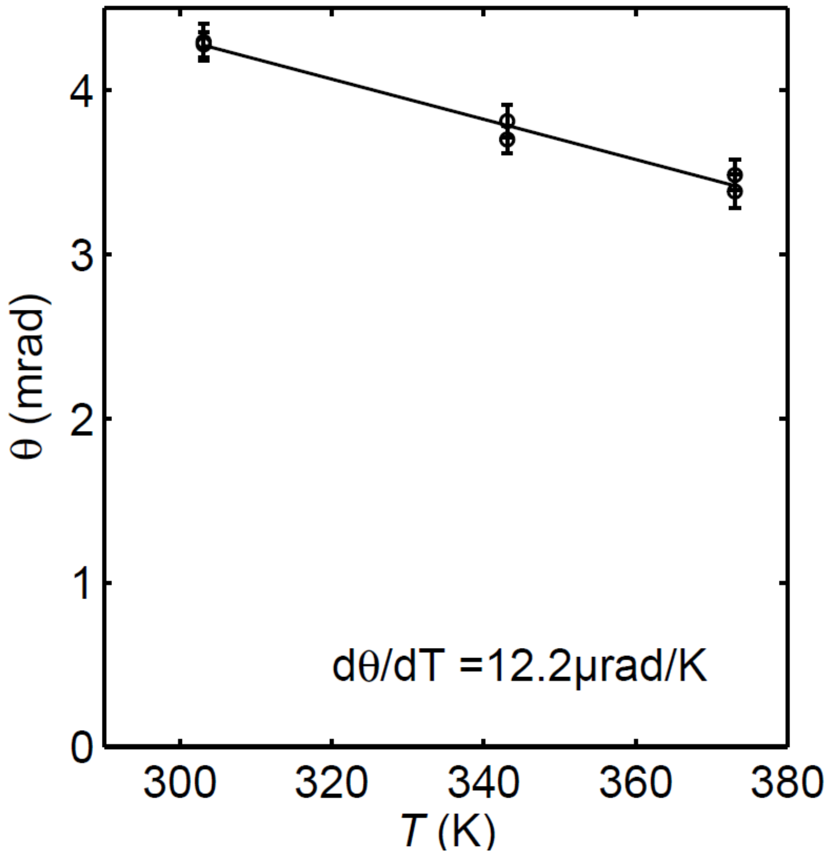
Tradeoffs between sensitivity, linearity, and temperature range. Example of [Co,Pt] multilayers



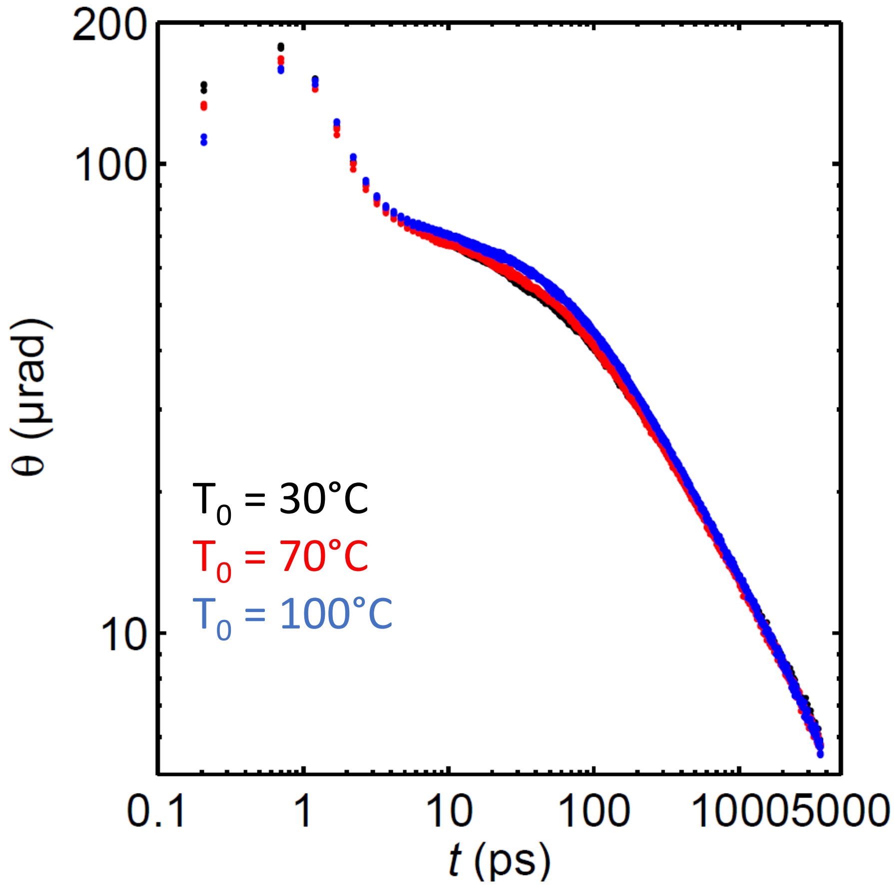
Kesteren and Zeper, JMMM (1993)

Single Co layer (0.8 nm thick) in the middle of 4 nm of Pt on 440 nm SiO_2/Si

Static MOKE

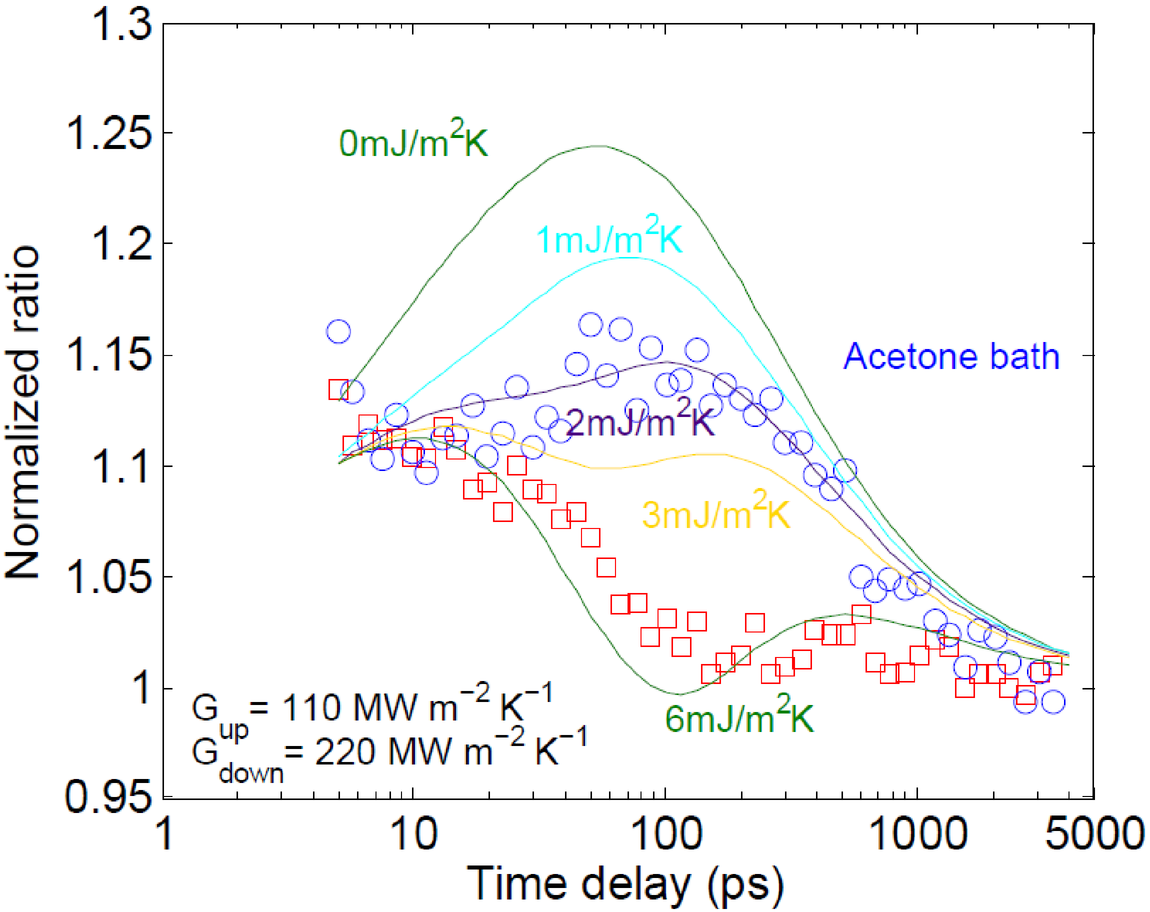


TR-MOKE

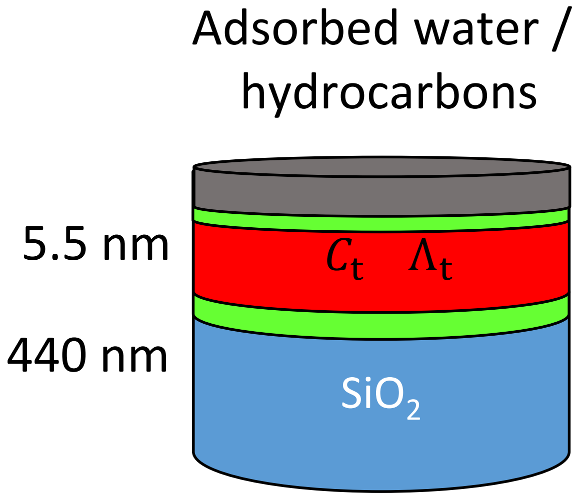


Single Co layer (0.8 nm thick) in the middle of 4 nm of Pt on 440 nm SiO_2/Si

TR-MOKE data normalized to model with G = inf.



Bi-directional thermal model



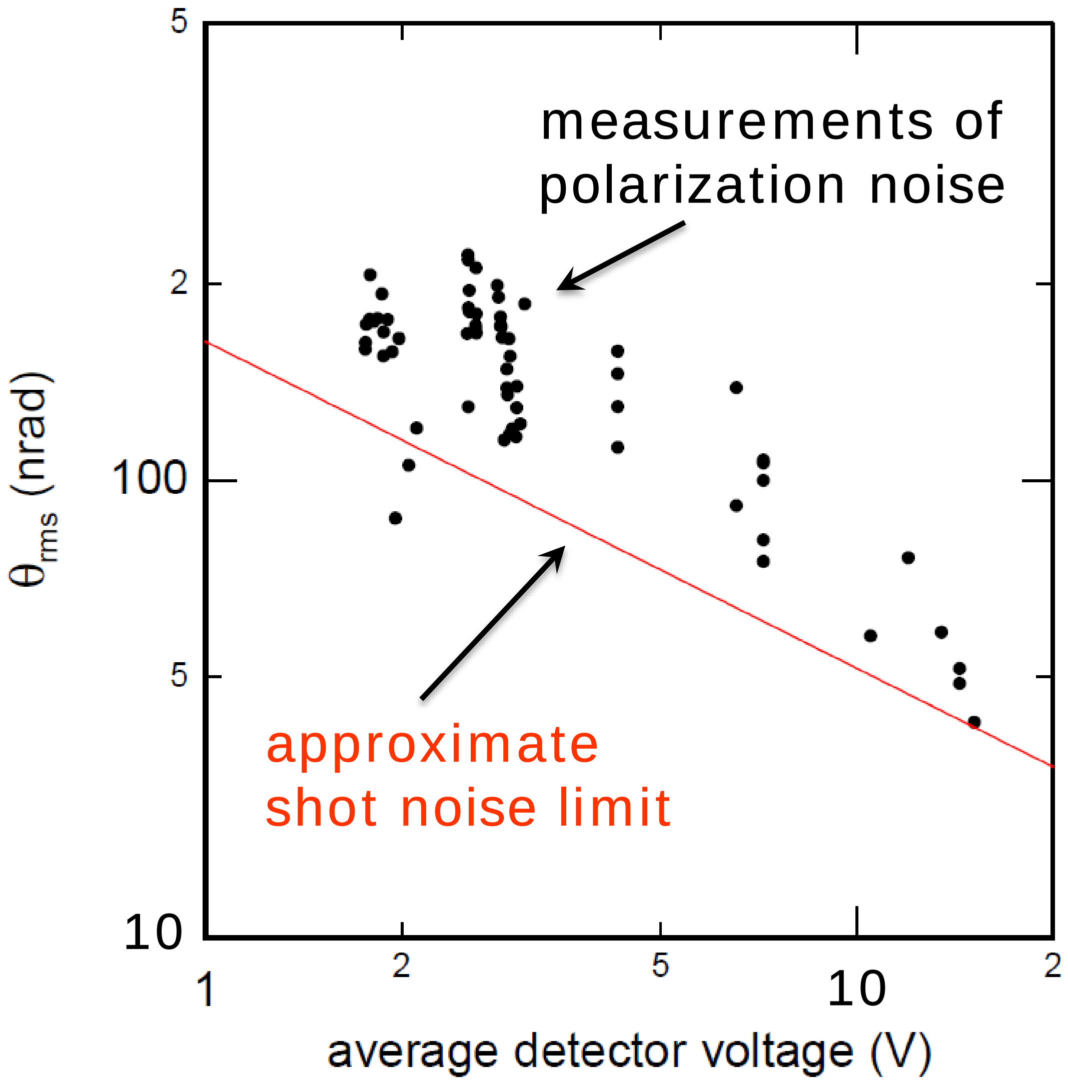
G ≈ 220 MW m^{-2} K^{-1}

Kapitza length ≈ 6 nm

For comparison:

Areal heat capacity of 5.5 nm Co/Pt transducer: 16 mJ/m^2K

Laser intensity noise is almost completely suppressed in a measurement of polarization using a balanced detector



measurements of polarization noise

approximate shot noise limit

Summary

- Thermoreflectance (thermometry by using intensity of light) versus magneto-optic Kerr effect (thermometry using polarization of light)
- Kerr effect transducers are relatively immune to what is happening in other parts of the sample. Polarization rotation is specific to the magnetic layer.
- Thin transducers enable higher time resolution and better sensitivity for in-plane transport.
- A single 0.8 nm layer of Co sandwiched in a 4 nm Pt layer provides high signal-to-noise and extremely small thermal mass. Need to find a simple way to control contamination by hydrocarbons and adsorbed water.
- Great opportunities for materials engineering of improved Kerr effect transducers to improve sensitivity and stability.