SCHOOL of ENGINEERING & APPLIED SCIENCE
UNIVERSITY of VIRGINIA

Semiconductor thermal conductivity measurements using FDTR/TDTR without a metal transducer

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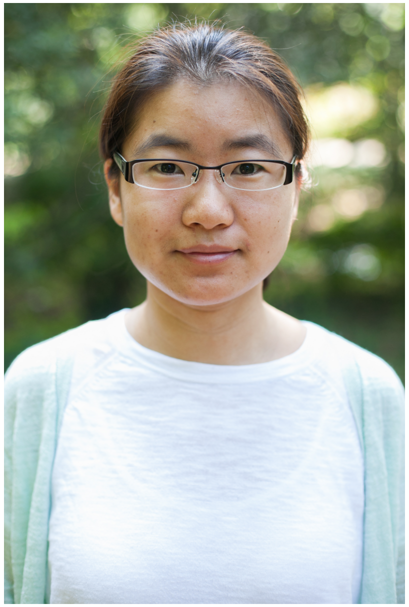
UNITED STATES AIR FORCE



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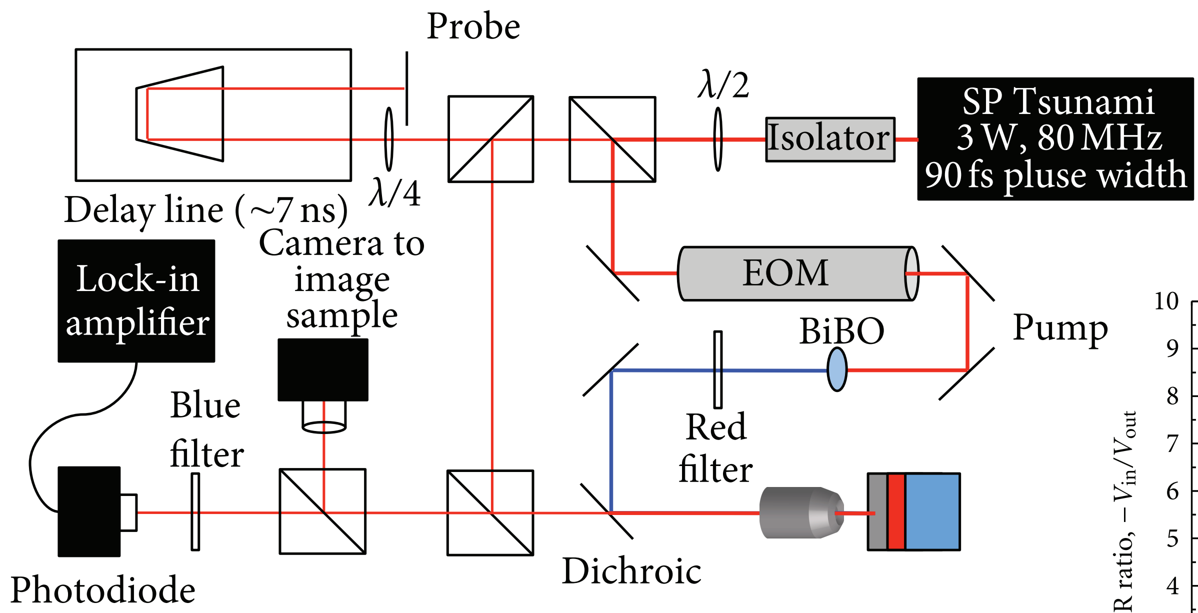
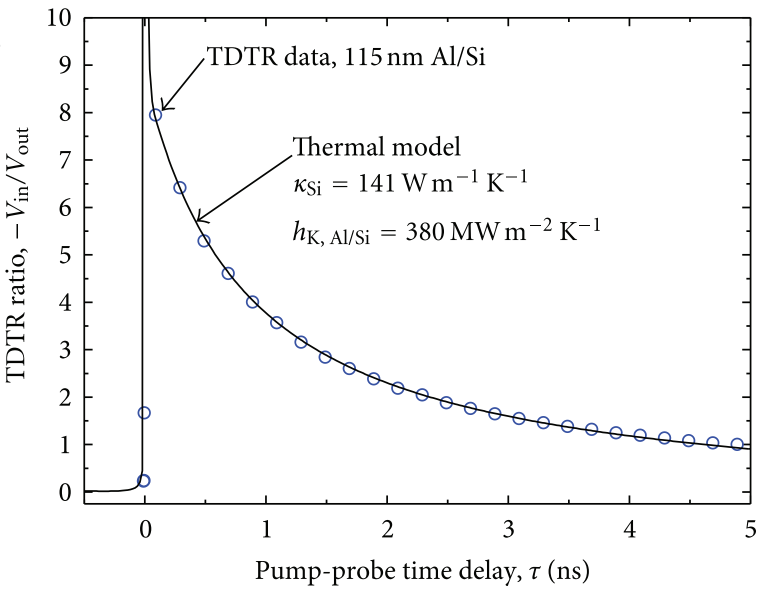
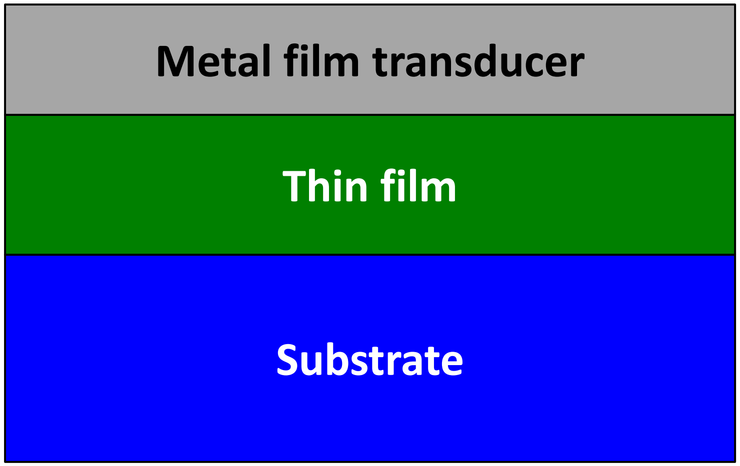
The “standard” TDTR/FDTR detection/configuration







TDTR Reviews and Analyses

Rev. Sci. Instr. **75**, 5119

Rev. Sci. Instr. **79**, 114902

J. Heat Trans. **132**, 081302

Ann. Rev. Heat Trans. **16**, 159

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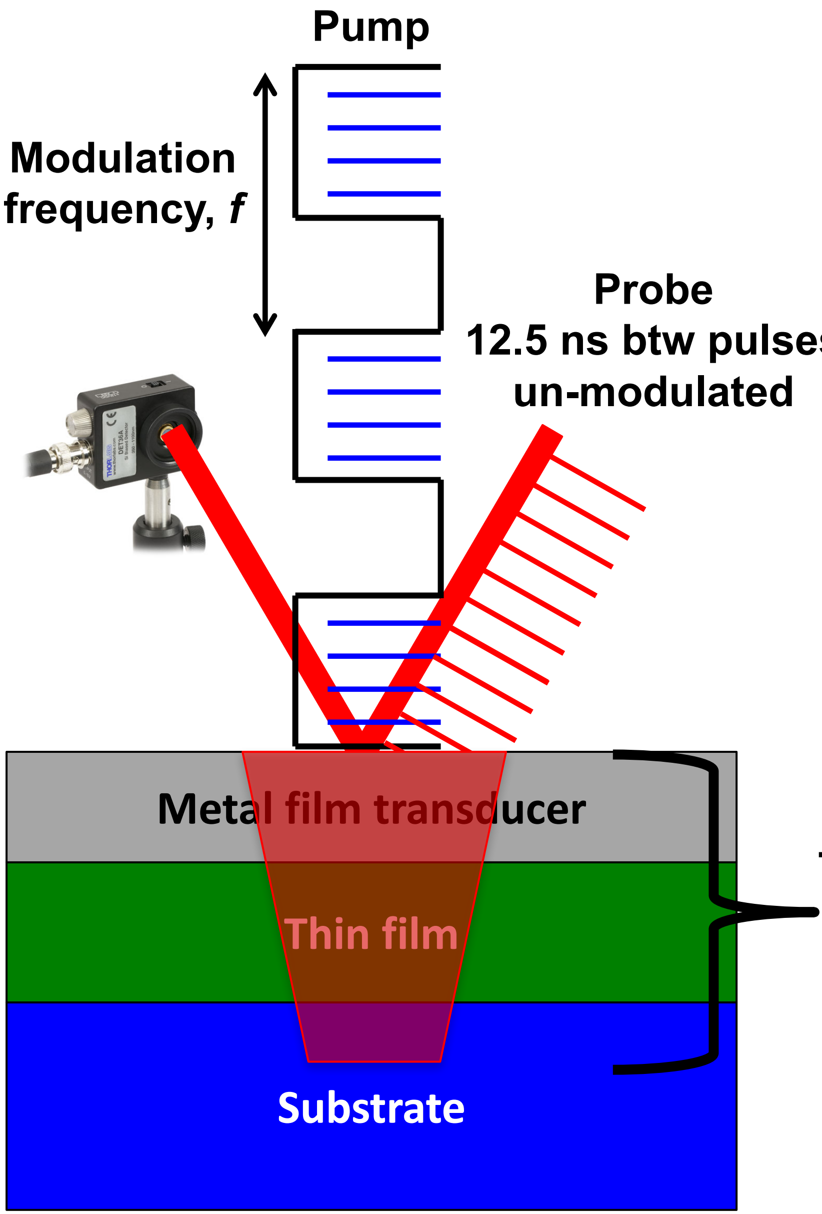

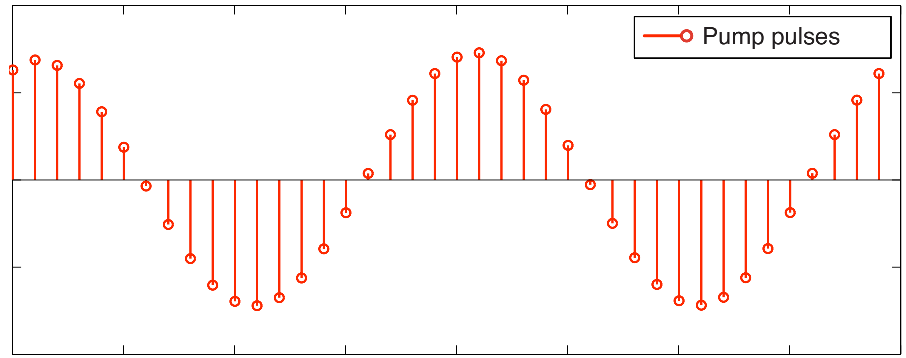

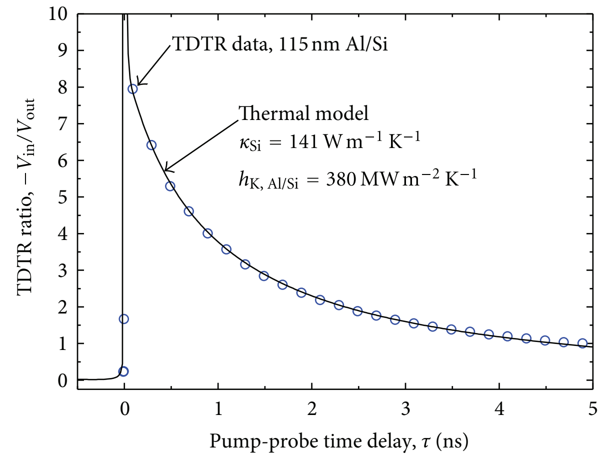

Thermal penetration depth
"Measurement volume"

$$\delta_{\mathrm{thermal}} = \sqrt{\frac{\kappa}{\pi C f}}$$

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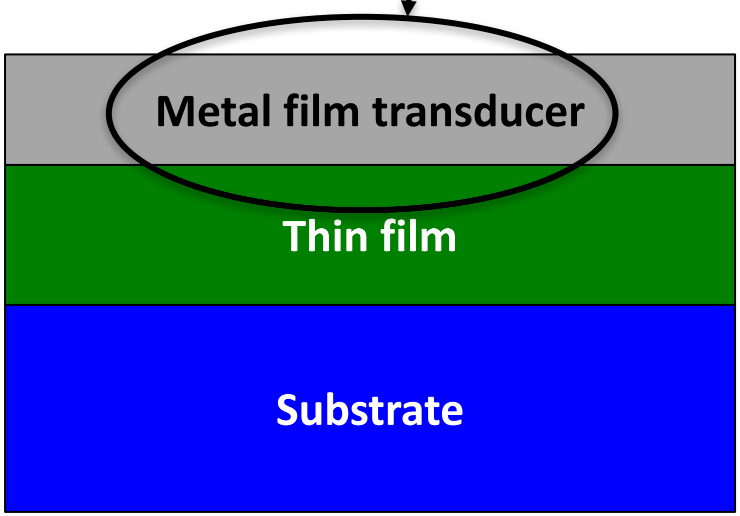
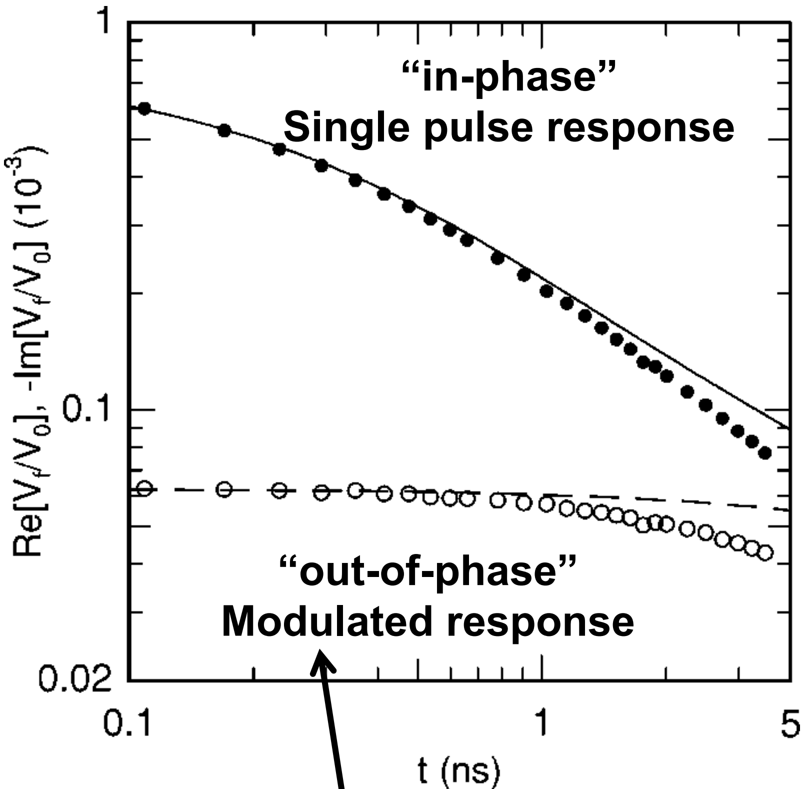
The "standard" TDTR/FDTR detection/configuration

Why?

1) Spatial resolution
~10 nm absorption depth using wavelengths typical in TDTR
2) Reflectivity ~ temperature
- Electronic thermalization in metals is fast (~ps)
- NOT necessarily case for non-metals

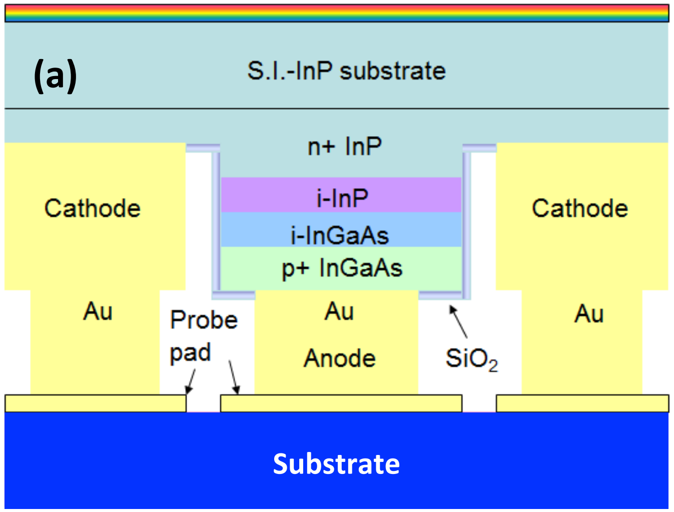


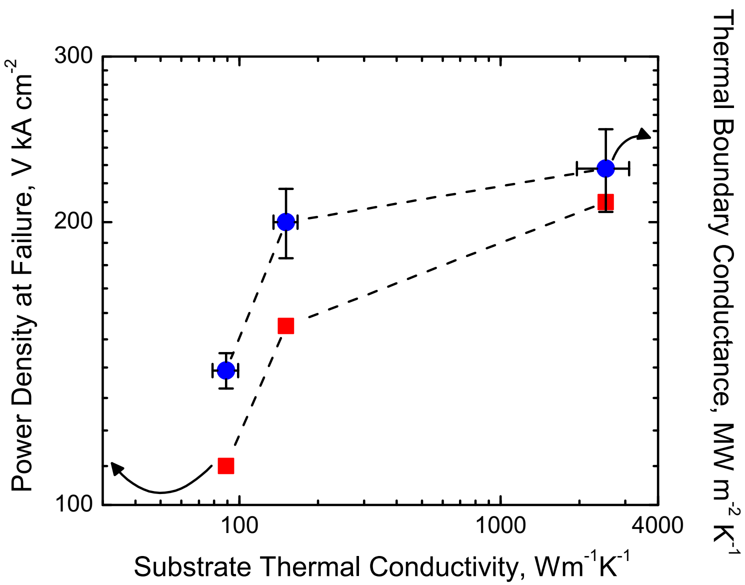


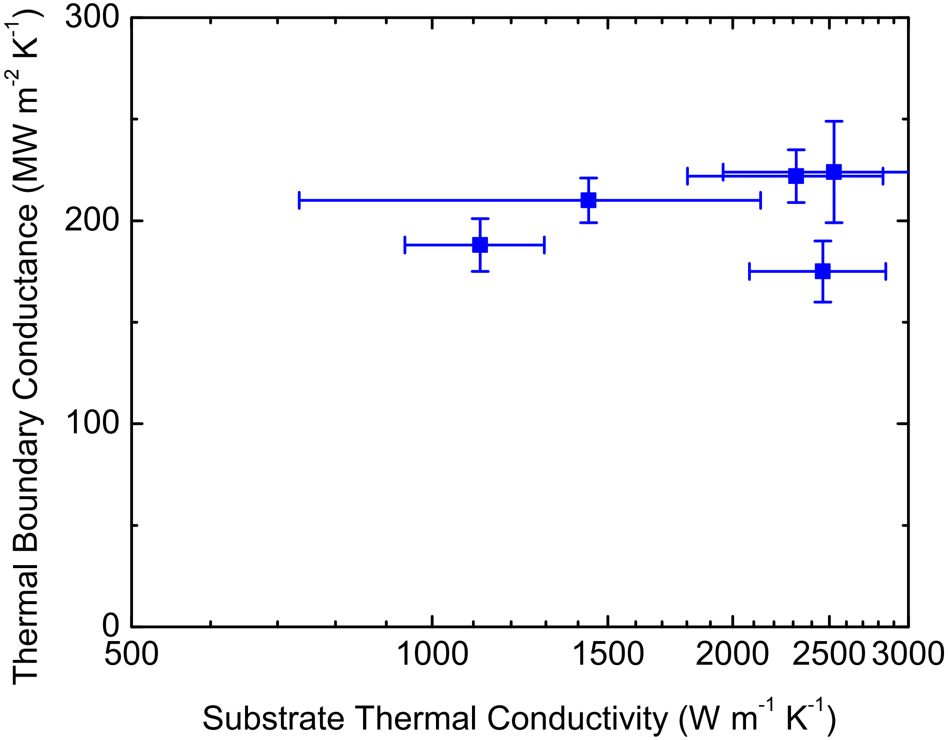
Most of the information/sensitivity to thermal conductivity

Some issues that have arisen with the metal transducer

Sensitivity to thermal conductivity of high κ substrates



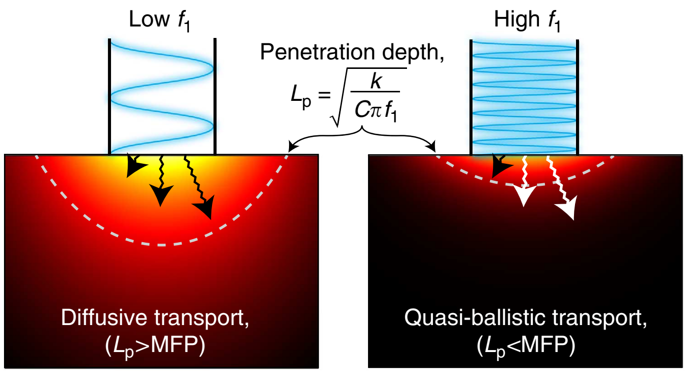


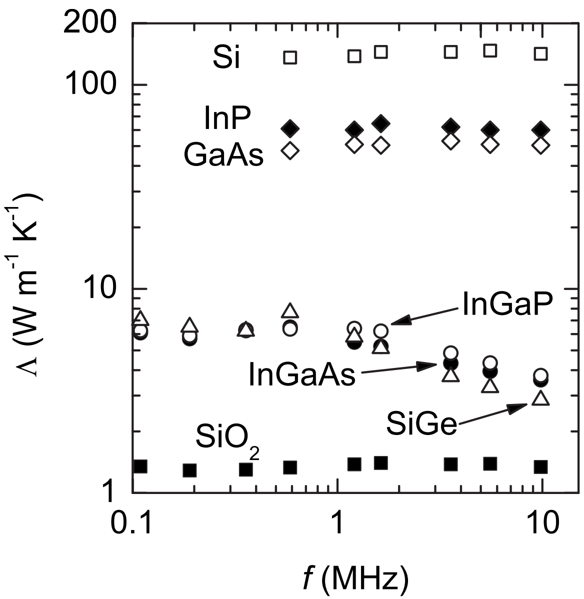


It's hard to measure thermal conductivity of high k substrates with TDTR with TBC is too low!

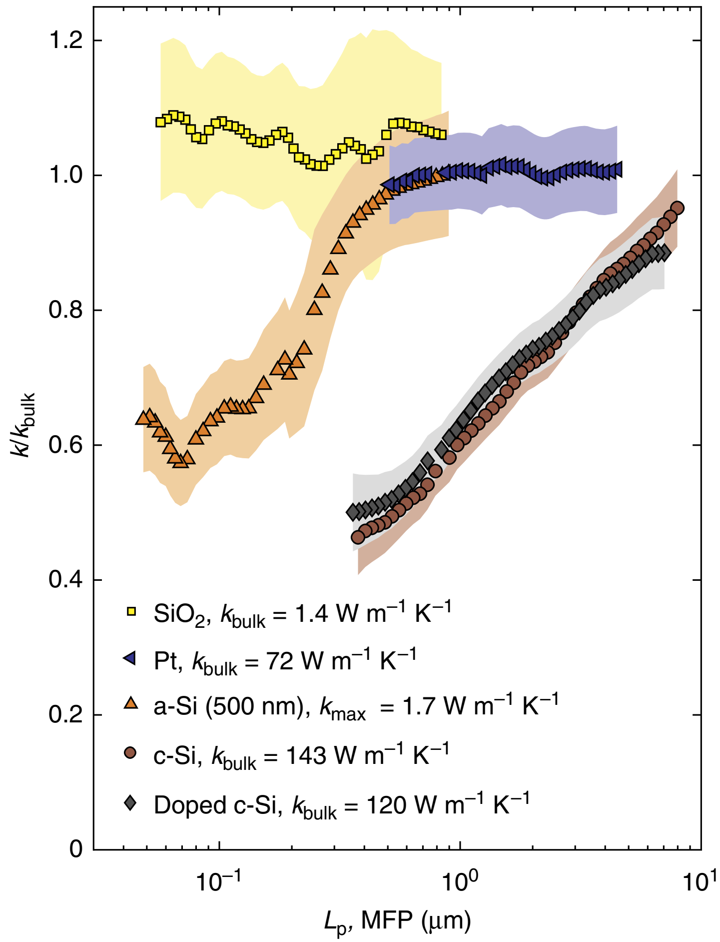
Some issues that have arisen with the metal transducer

"Mean free path spectroscopy" based on modulation frequency





PRB **76**, 075207 (2007)



Nat. Comm. **4**, 1640 (2013)

Some issues that have arisen with the metal transducer

PHYSICAL REVIEW B **90**, 064302 (2014)

Analytical interpretation of nondiffusive phonon transport in thermoreflectance thermal conductivity measurements

K. T. Regner,[1] A. J. H. McGaughey,[1,2] and J. A. Malen[1,2,*]

PHYSICAL REVIEW B **88**, 144305 (2013)

Two-channel model for nonequilibrium thermal transport in pump-probe experiments

R. B. Wilson,[*] Joseph P. Feser, Gregory T. Hohensee, and David G. Cahill

ADVANCES IN STUDYING PHONON MEAN FREE PATH DEPENDENT CONTRIBUTIONS TO THERMAL CONDUCTIVITY

Keith T. Regner[1], Justin P. Freedman[2], and Jonathan A. Malen[1,2]

PHYSICAL REVIEW B **90**, 205412 (2014)

Nonlocal theory for heat transport at high frequencies

Yee Kan Koh,[1,2] David G. Cahill,[2] and Bo Sun[1]

ARTICLE

Received 3 Dec 2013 | Accepted 26 Aug 2014 | Published 1 Oct 2014 DOI: 10.1038/ncomms6075

Anisotropic failure of Fourier theory in time-domain thermoreflectance experiments

R.B. Wilson[1] & David G. Cahill[1]

Discussion items in above works

- Standard thermal conductivity analyses can fail
- Spectrum of phonons "launched" into substrate affects measured κ (*e.g.*, metal film, nonequilibrium)

Can we use TDTR/FDTR w/o a transducer?

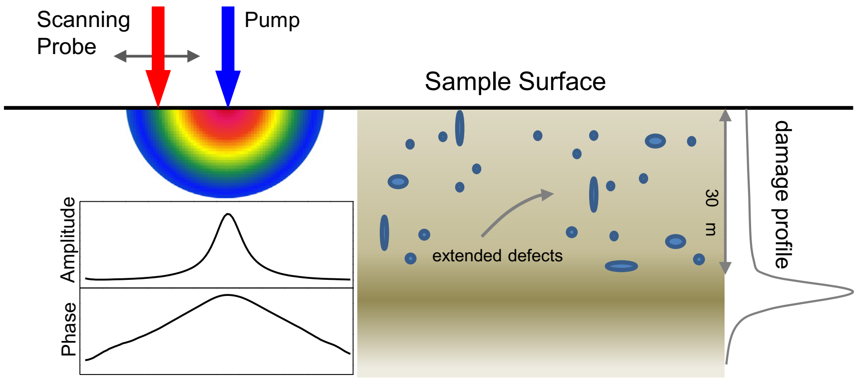
- Previous works
  - Well established in frequency domain (Opsal, Christofides, Mandelis, and Othonos)
  - Recently: Aaron Schmidt and David Hurley
  - Thermal vs. plasma effects – incorporating the "standard" TDTR procedure and analysis
- Combined FDTR/TDTR – using the time domain data
- Bulk system measurements and uncertainty

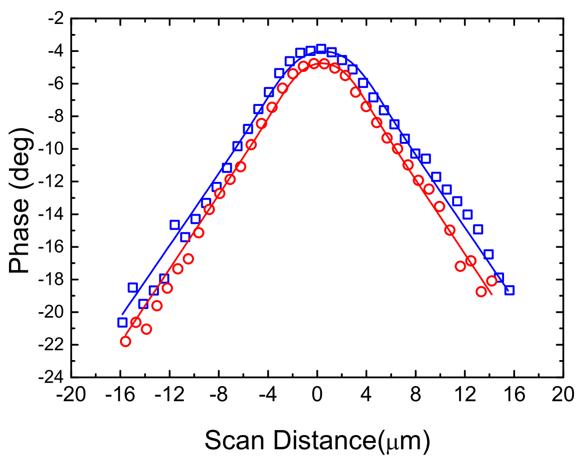
Key Challenge

•Need ***photo***thermoreflectance signal to be dominated by temperature
•Ensure ***photo***thermoreflectance is pure ***thermo***reflectance

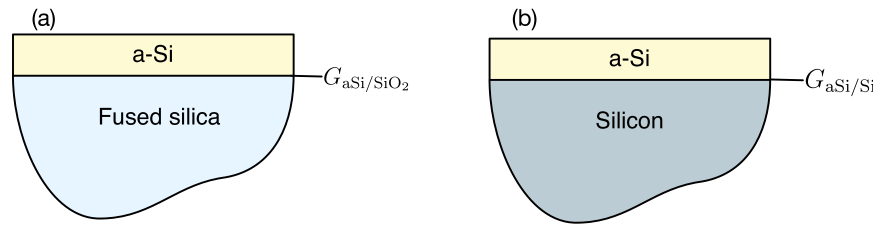
Recent works using thermoreflectance w/o metal films

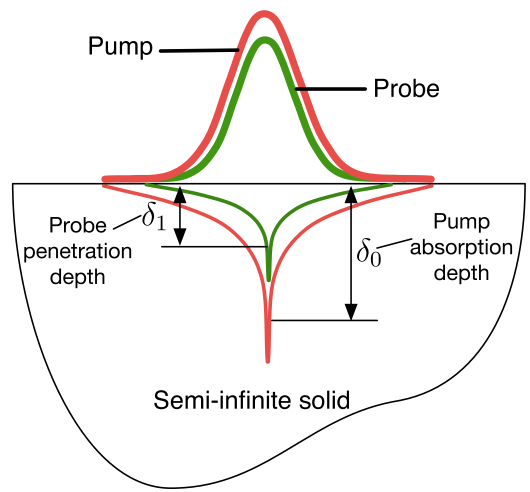
Beam offset
Nuclear Inst. Meth. Phys. Res. B **325**, 11 (2014)

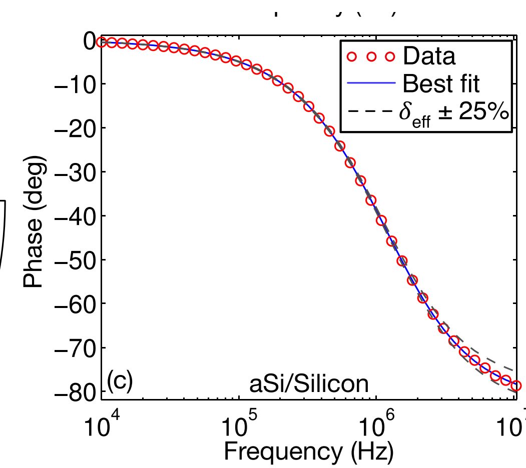




Standard FDTR with non-surface source
JAP **119**, 095107 (2016)





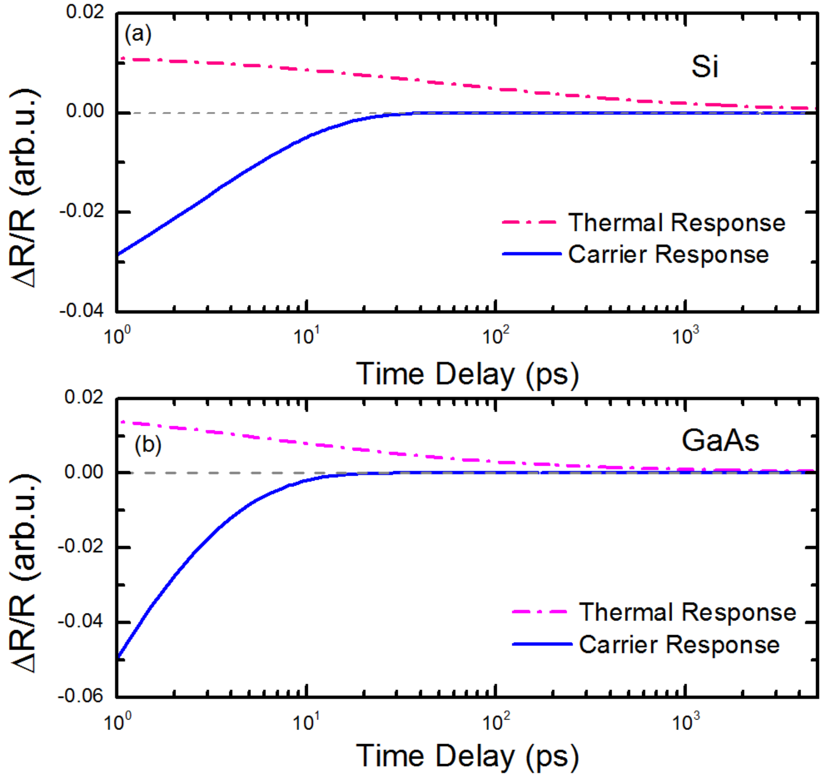


Thermal vs. plasma effects – separate in the time domain

Coupled thermal/plasma model

When is plasma contribution negligible?

(*JAP* **82**, 4033 (1997))



$$\Delta R = \frac{\partial R}{\partial T}\Delta T + \frac{\partial R}{\partial N}\Delta N$$

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 094902 (2016)

Thermal conductivity measurements of non-metals via combined time- and frequency-domain thermoreflectance without a metal film transducer

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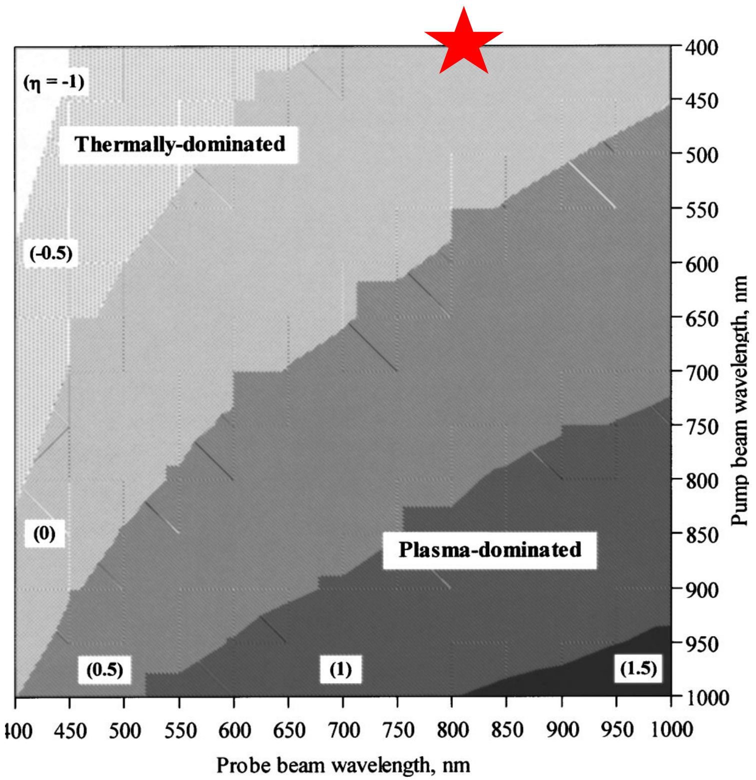
Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, Virginia 22904, USA

Thermal vs. plasma effects – pump/probe wavelengths

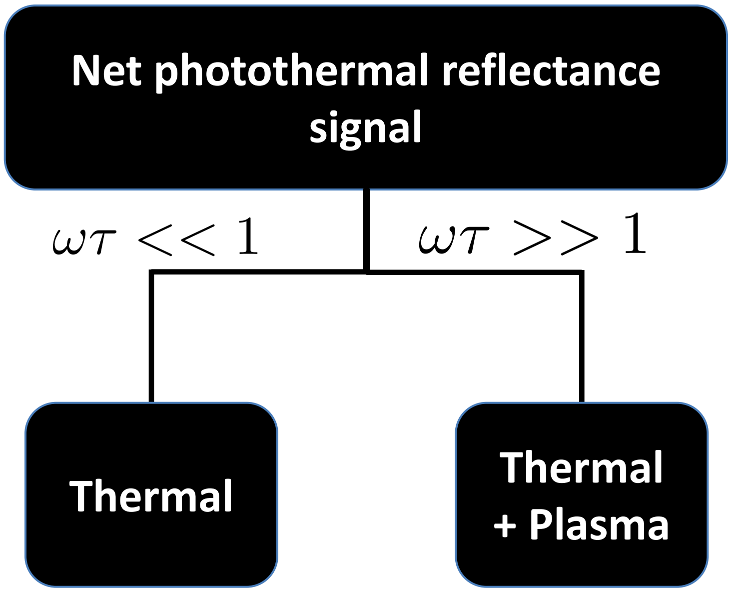
Coupled thermal/plasma model

When is plasma contribution negligible?

(*RSI* **74**, 545 (2003), *JAP* **67**, 15 (1990))



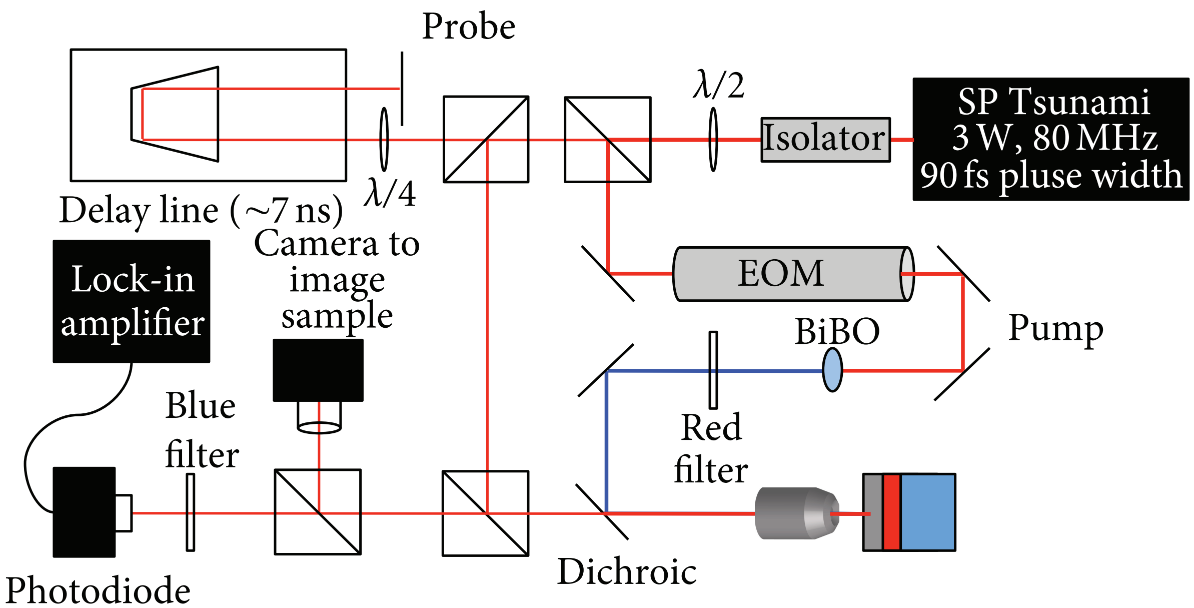
$$\Delta R = \frac{\partial R}{\partial T}\Delta T + \frac{\partial R}{\partial N}\Delta N$$

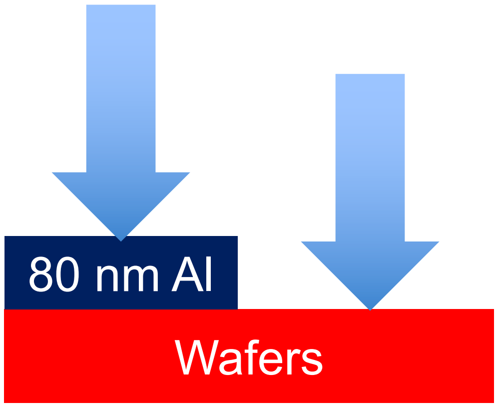


Key Experimental Design

- Low modulation frequency
- Short plasma relaxation time

Standard TDTR/FDTR – with and without metal transducer





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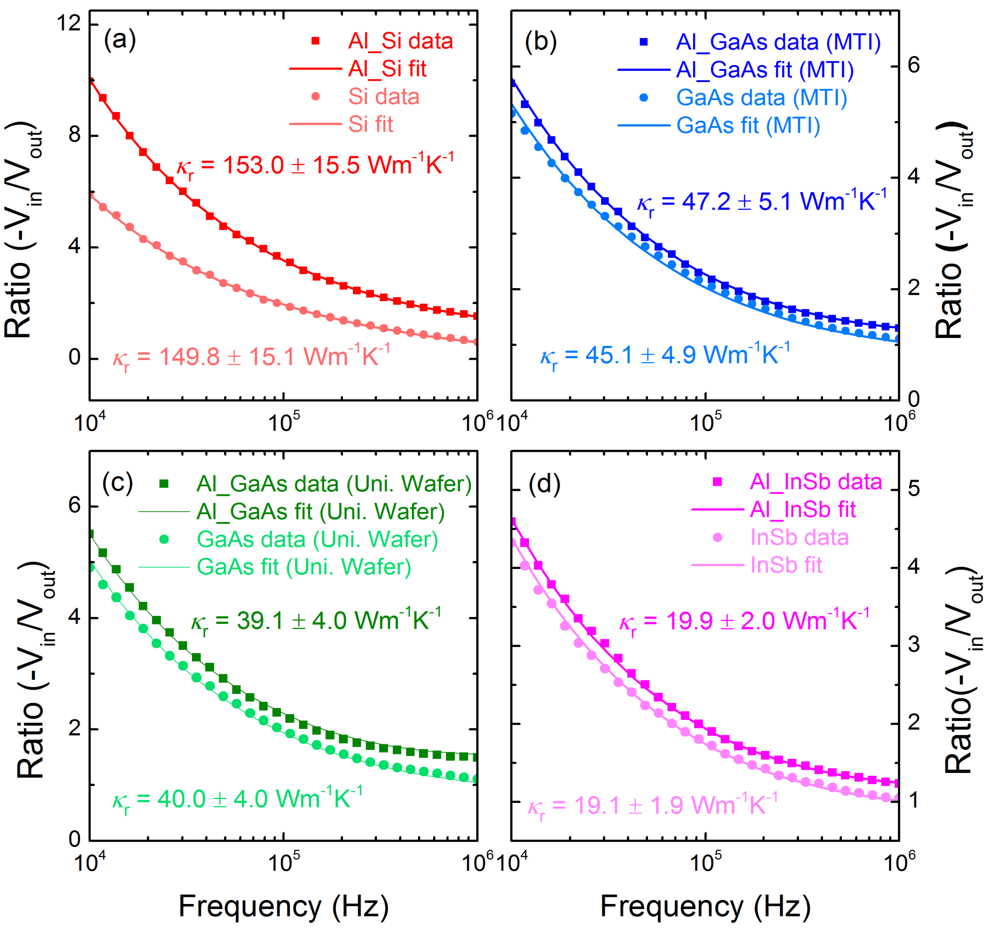
Key Experimental Design

- Low modulation frequency: FDTR below 1 MHz
- Short plasma relaxation time: 400 nm pump, FDTR @ 5 ns delay

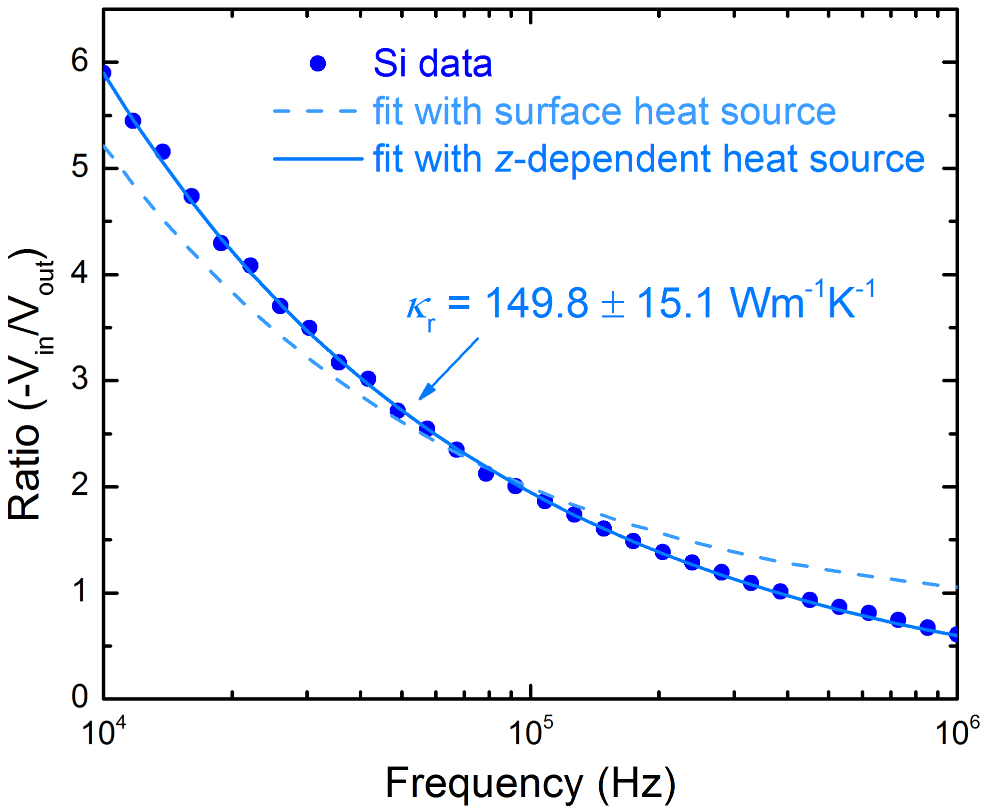
Standard TDTR/FDTR – with and without metal transducer



<u>Key Experimental Design</u>

- **Low modulation frequency: FDTR below 1 MHz**
- **Short plasma relaxation time: 400 nm pump, FDTR @ 5 ns delay**

z-dependent source important in Si at these wavelengths



<u>Probe optical penetration depth</u>

δ_{Si} = 9.73 μm (800 nm)

<u>Pump optical/heat source penetration depth</u>

ζ_{Si} = 97.9 nm (400 nm)

Note, these are ***not*** the "thermal penetration depth"

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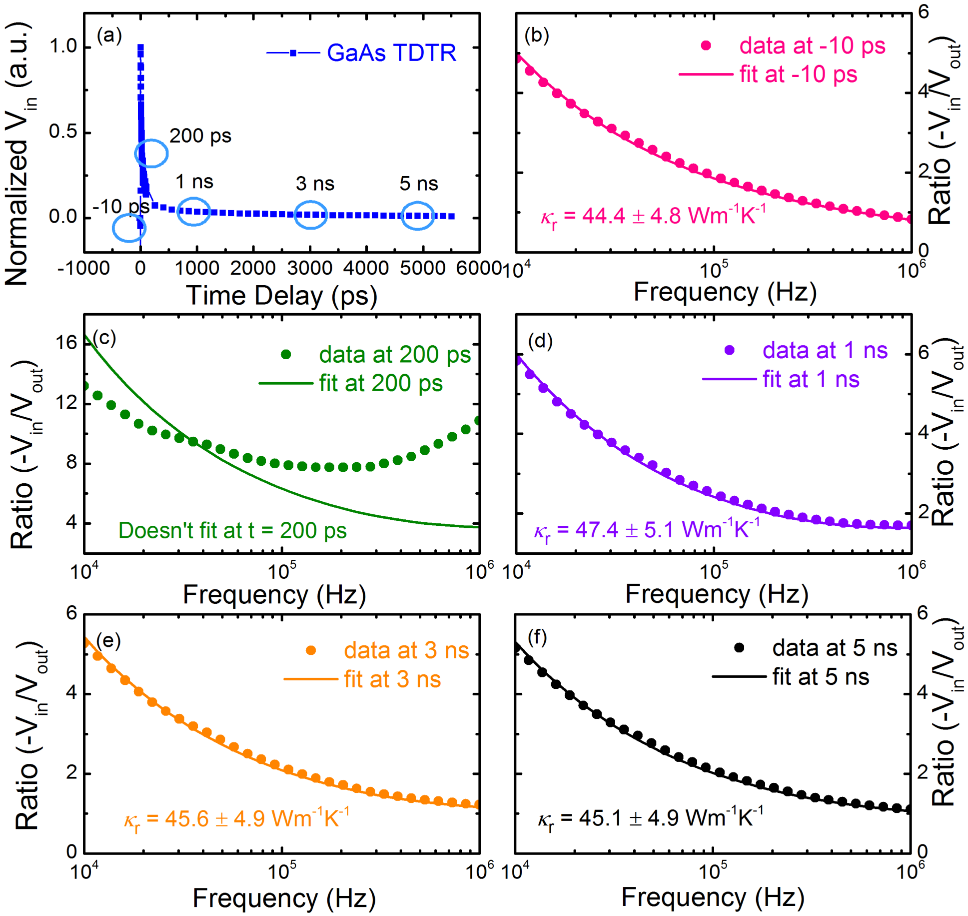
Must choose time to be greater than plasma relaxation time



From analysis of in-phase signal and FDTR signal in tandem

τ_{GaAs} ~ 400 ps

Already studied in Si

50 ps – 2 ns

(*JAP* **82**, 4033 (1997))

(*PRL* **110**, 025901 (2013))

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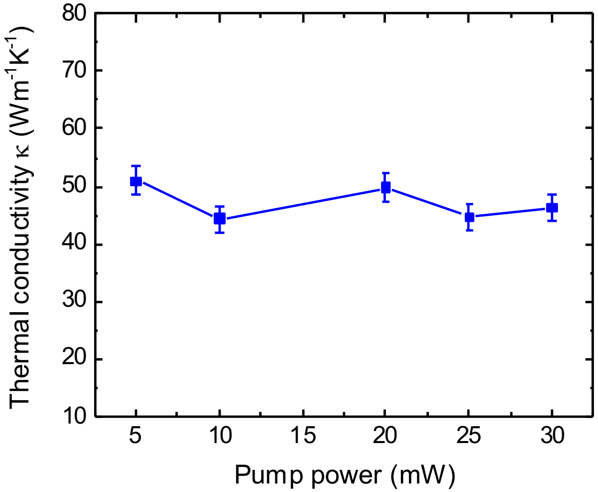
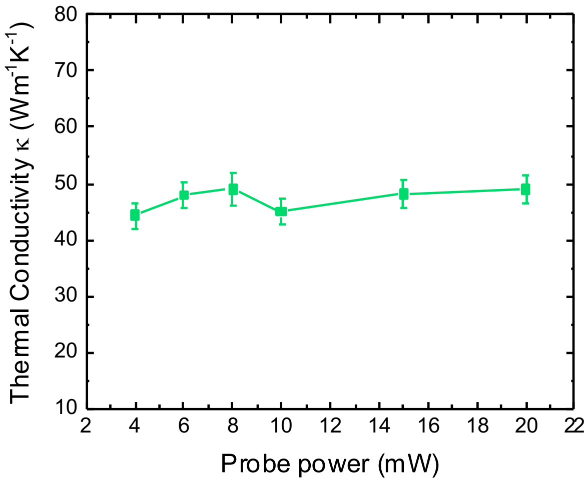
- **Short plasma relaxation time: 400 nm pump, FDTR @ 5 ns delay**

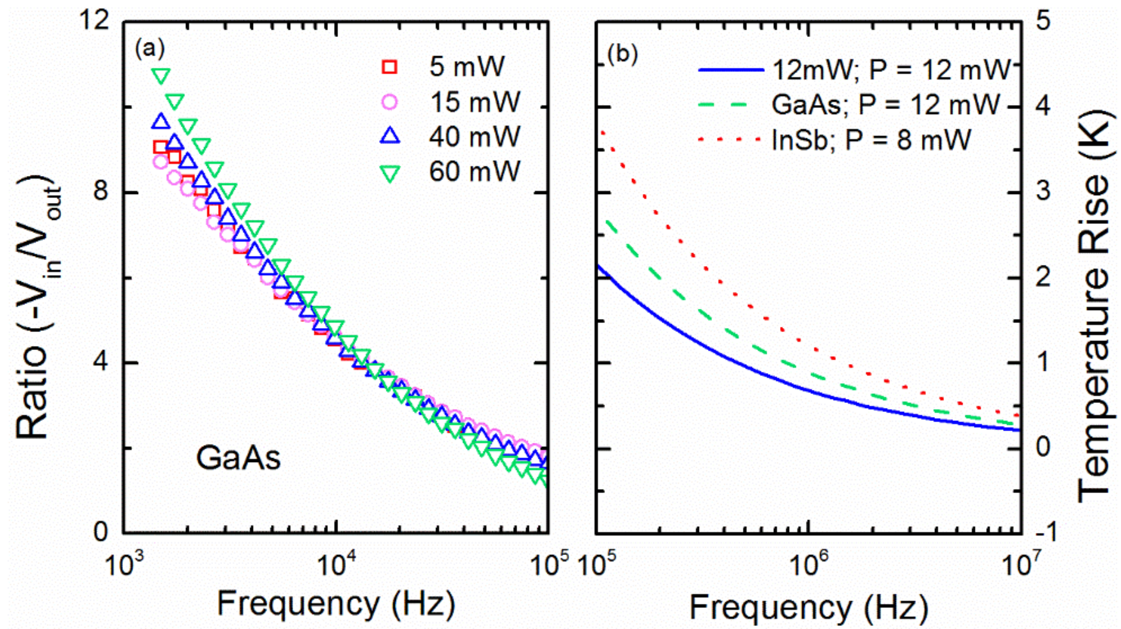
Need to maintain "perturbative" ΔT





Both for assumption of:

1) constant properties
2) No temperature/fluence dependence in plasma decay



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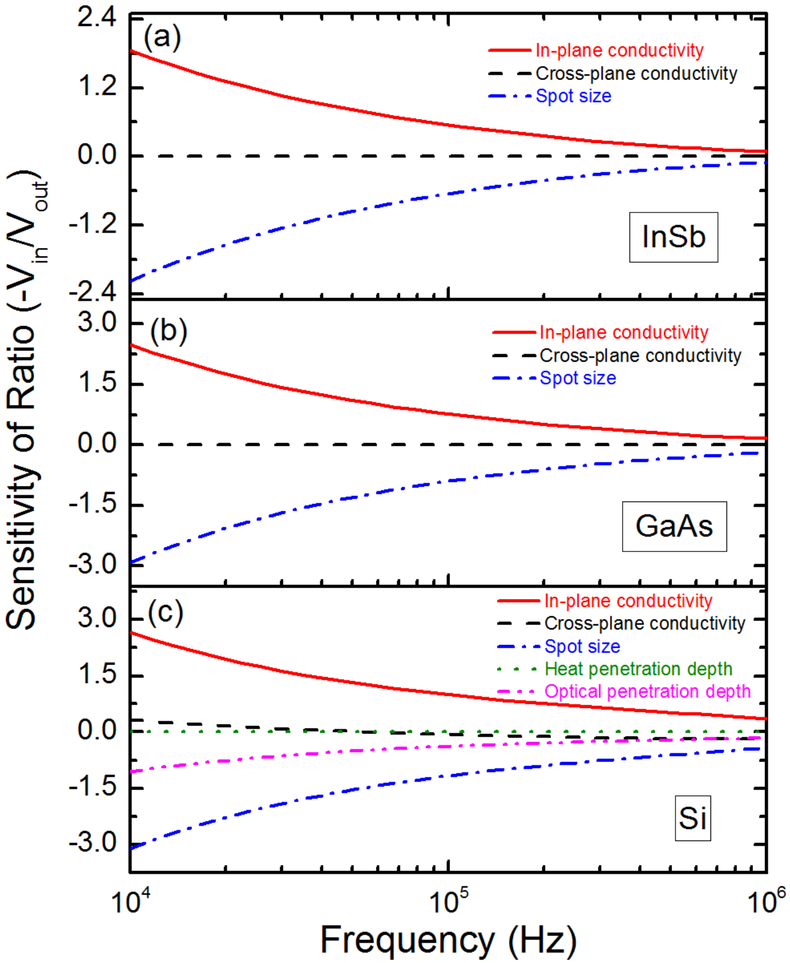
So what are we measuring? What are we sensitive to?



<u>For bulk wafers, sensitive to:</u>

1) *<u>In-plane</u>* thermal conductivity
2) Spot size
3) (to lesser extent) Optical penetration depth

<u>For example</u>

5% variation in both pump and probe spot sizes

=

10% variation in κ

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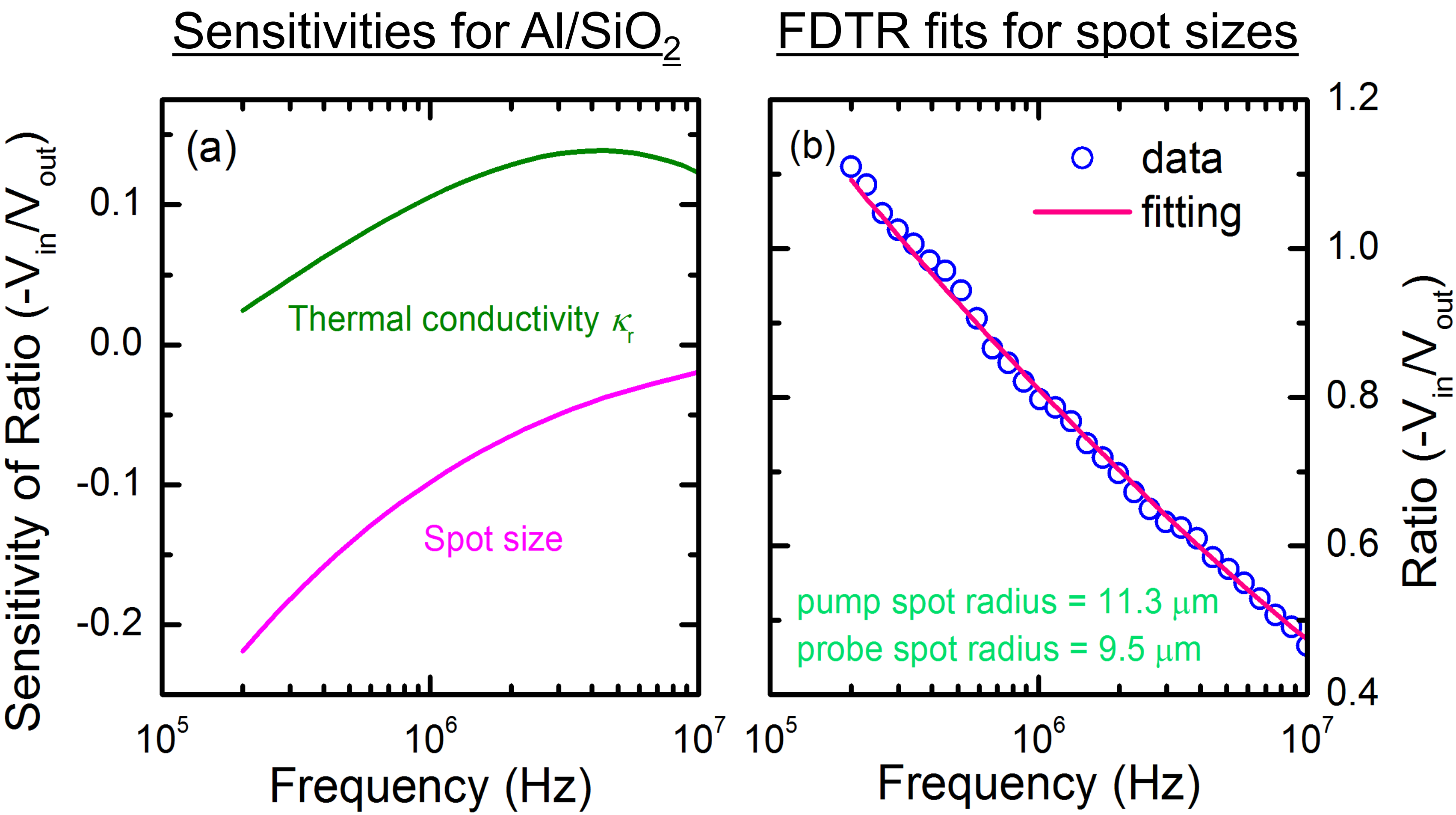
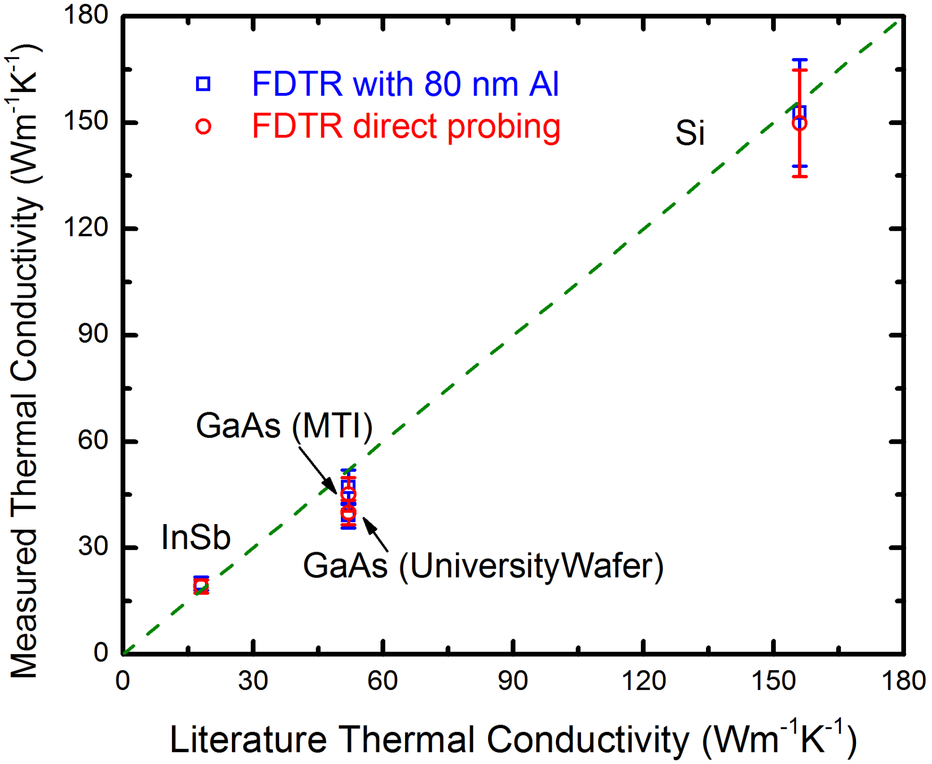
Should rigorously measure spot size *"in situ"*



All measurements and analyses at 5 ns where large sensitivities to spot size in FDTR

Conclusions

- With understanding of plasma contribution, can use FDTR/TDTR w/o a transducer
- Keys: high energy pump (and probe), time delays after plasma relaxation, low frequencies
- Next steps: FDTR/TDTR at higher photon energies for pump and probe



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