Thermoelectricity: From Atoms to Systems

Week 3: Thermoelectric Characterization

Lecture 3.6: Summary of Week 3

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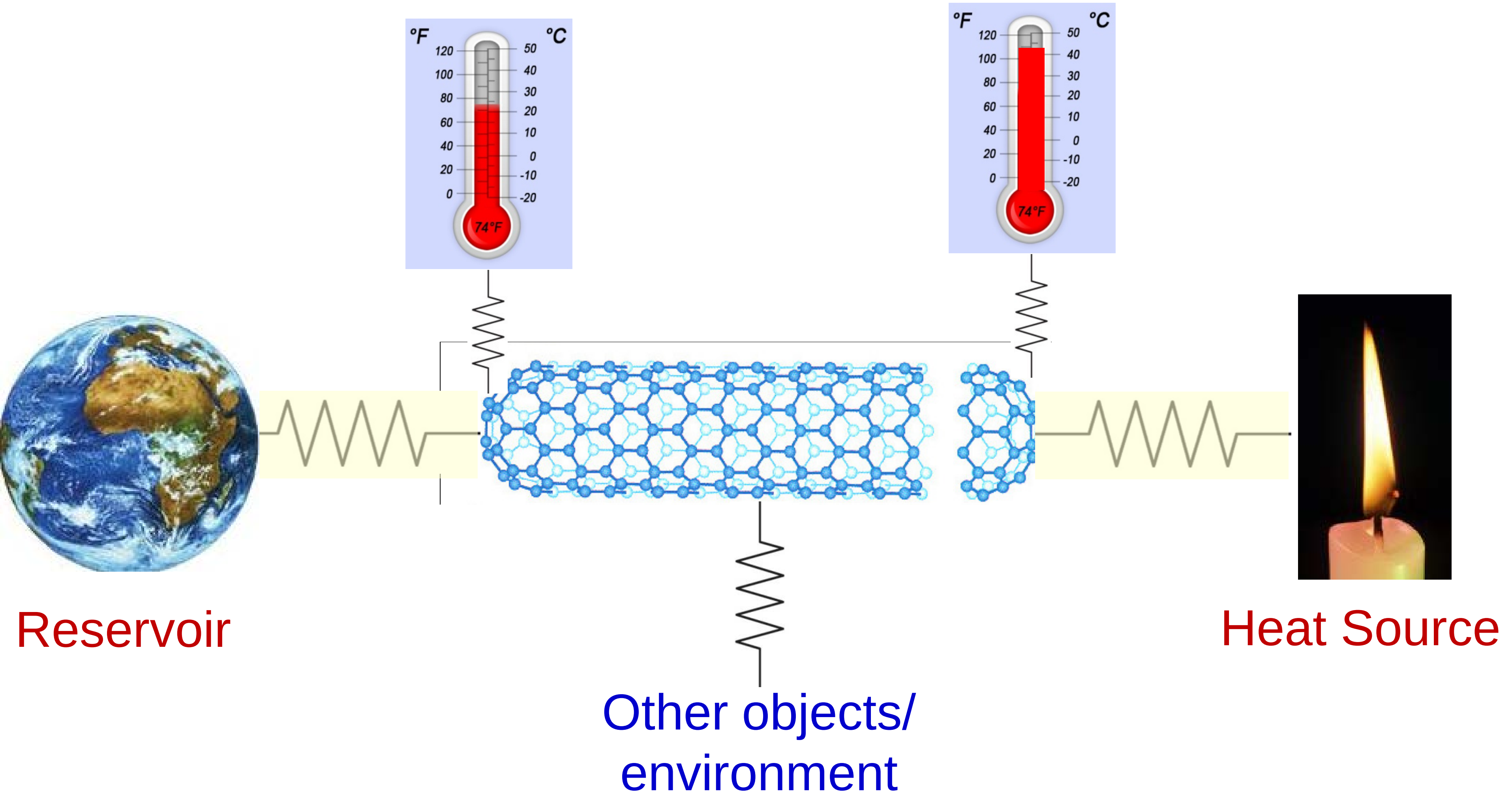
Birck Nanotechnology Center

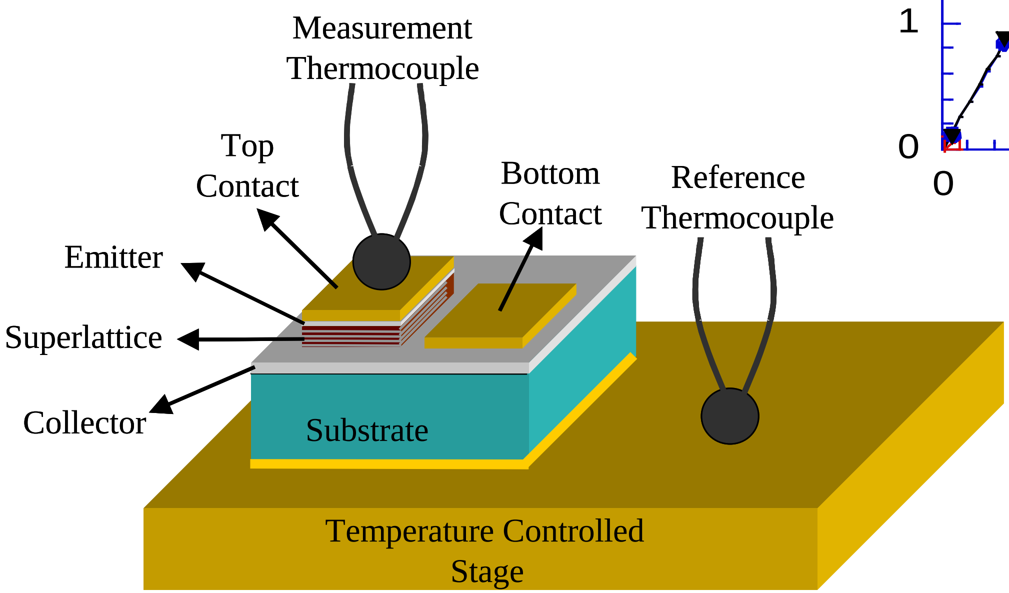
Purdue University

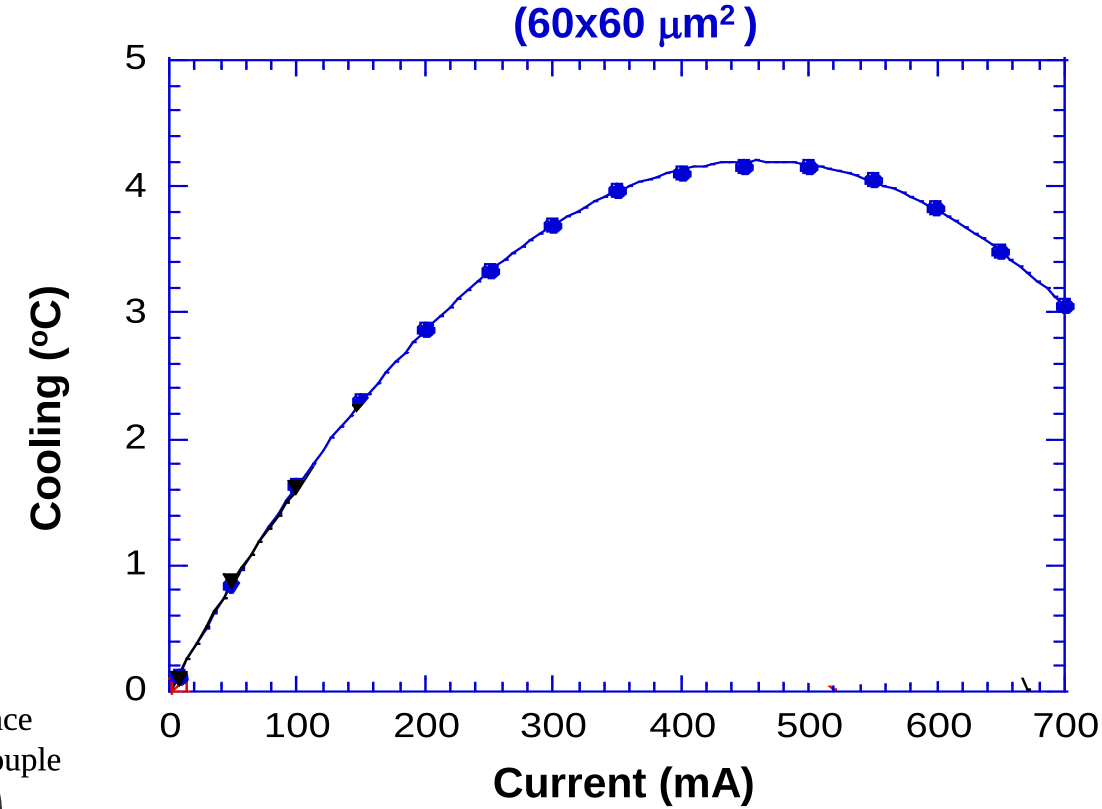
Measuring heat flow at nanometer scale



A. Shakouri, *Advanced Workshop on Energy Transport in Low-Dimensional Systems*, ICTP, Trieste, Italy; Oct. 2012

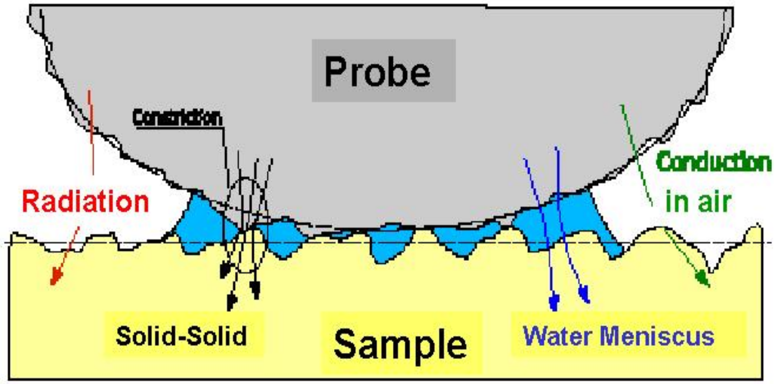
Micro thermocouple measurements

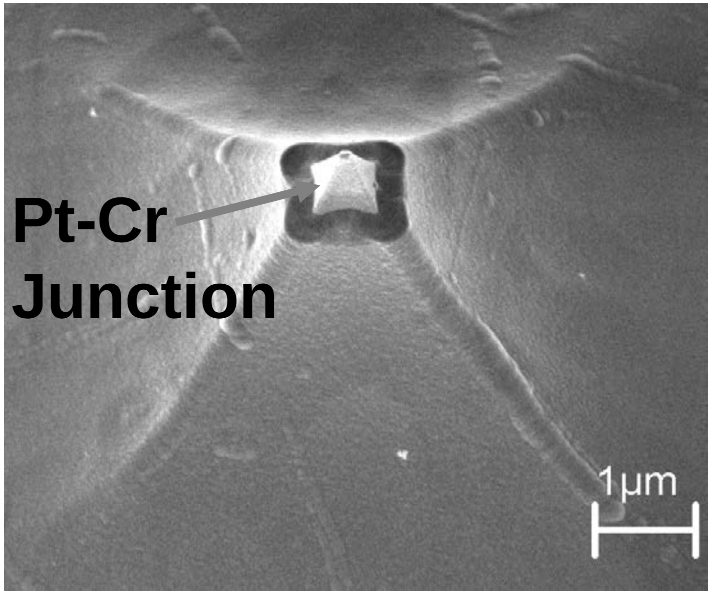


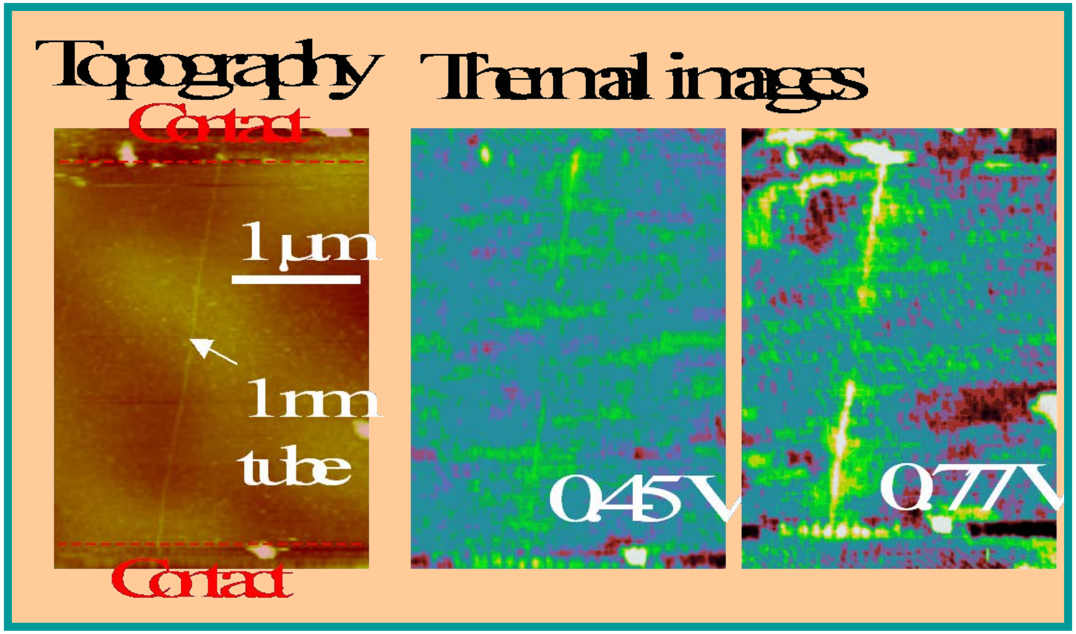


X. Fan, E. Croke, A. Shakouri, J. E. Bowers, … "**SiGe/Si Superlattice Coolers**," Phys. Low-Dim. Struct., 5/6 (2000) pp. 1-10.

Scanning Thermal Microscopy (SThM)



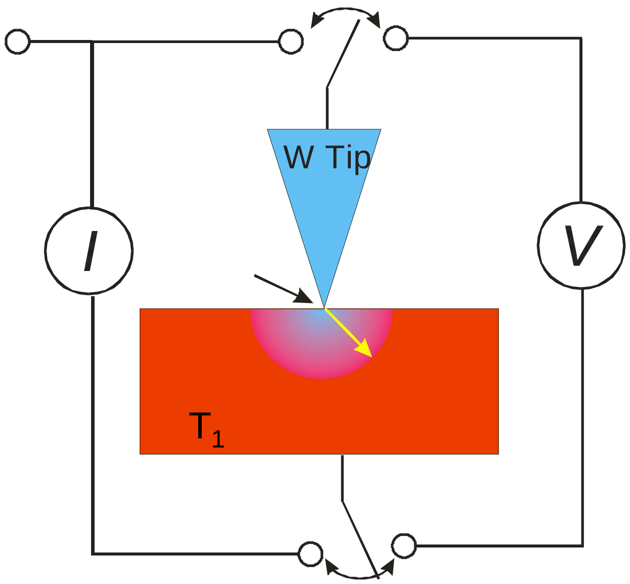


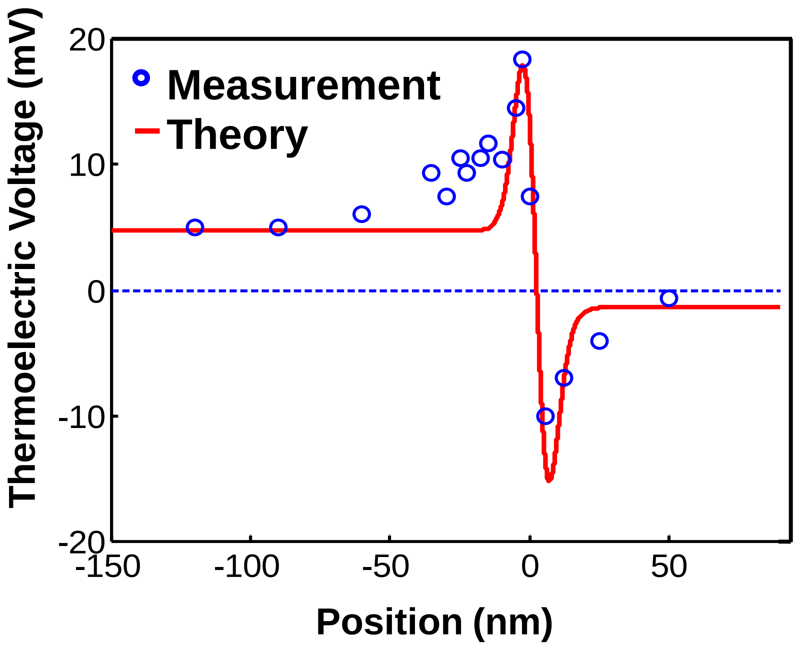


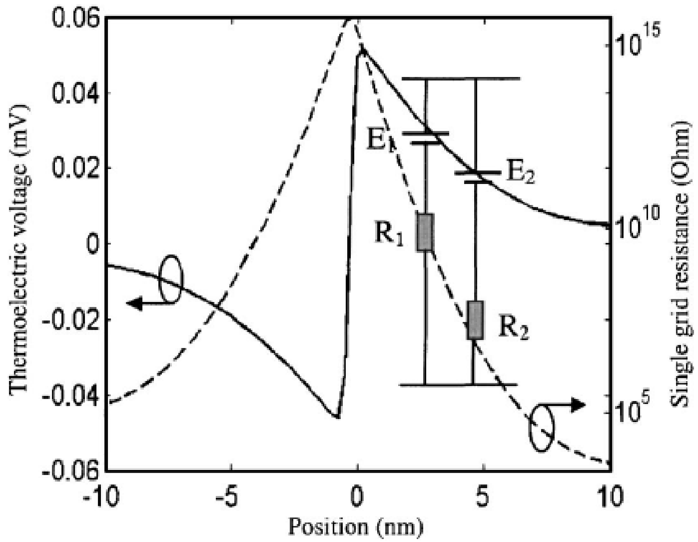
Courtesy: Arun Majumdar, UC Berkeley; Stefan Dilhaire, Univ. Bordeaux

J. Christofferson, et al, *J. Electronic Packaging*, 130 (4) 041101, 2008

UHV Scanning TE Microscopy



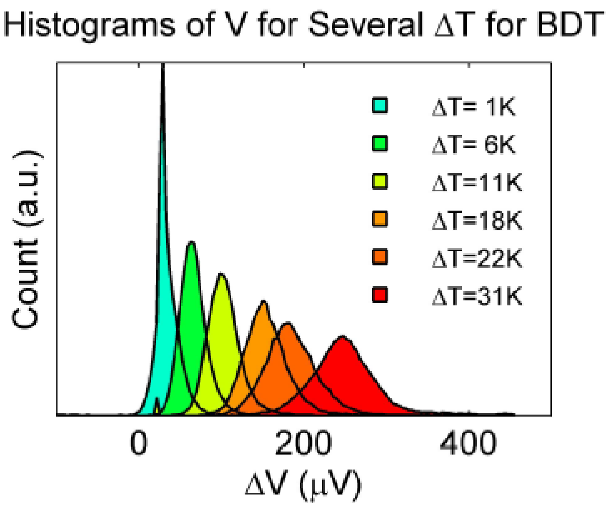


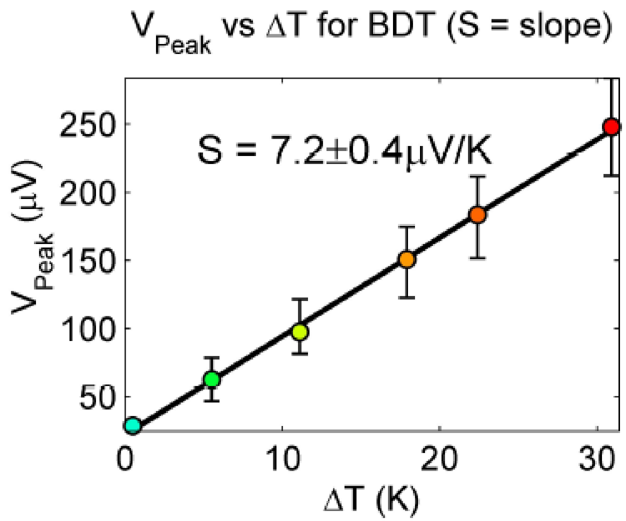


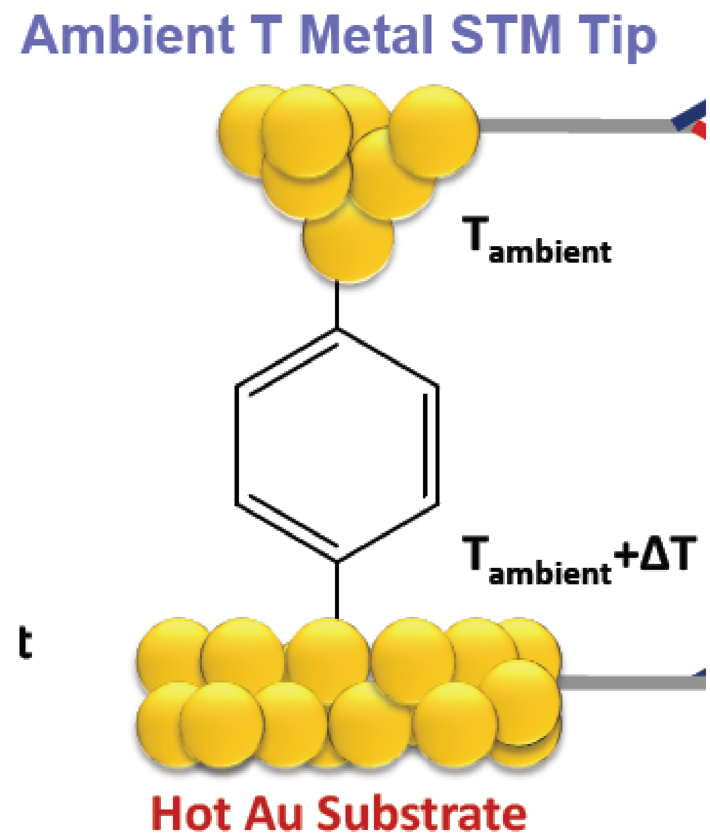
H.-K. Lyeo, A.A. Khajetoorians, L. Shi, K.P. Pipe, R.J. Ram, A. Shakouri, and C.K. Shih. ***Science* 303**, 816 (2004)

Zhixi Bian et al. Appl. Phys. Lett. 87 (5), 53115, 2005

Seebeck of single molecules (BDT)



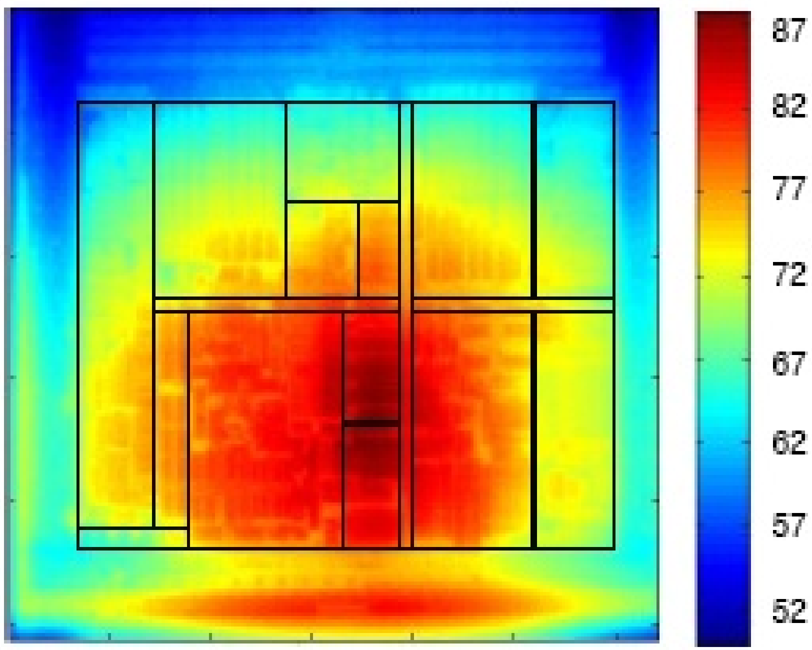




Reddy, Jang, Segalman, Majumdar, *Science* (2007)

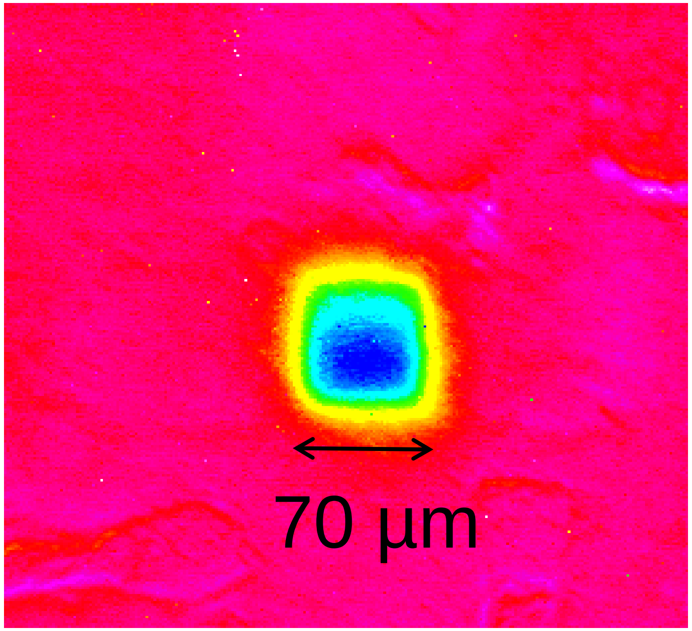
Infrared imaging

Micro processor



Francisco Mesa-Martinez,
Jose Renau, UCSC

Microrefrigerator

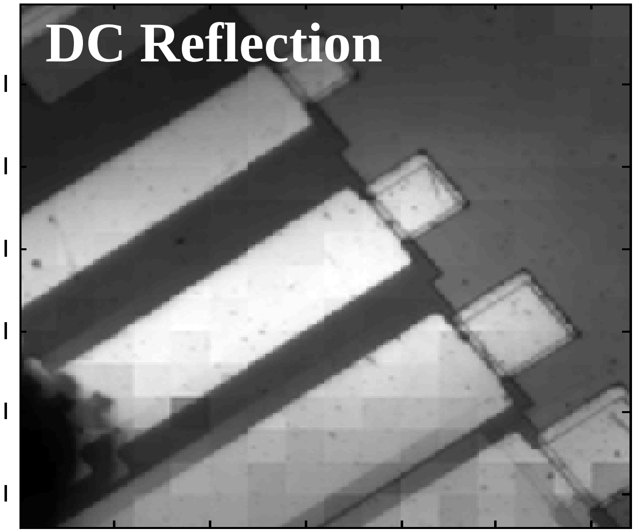


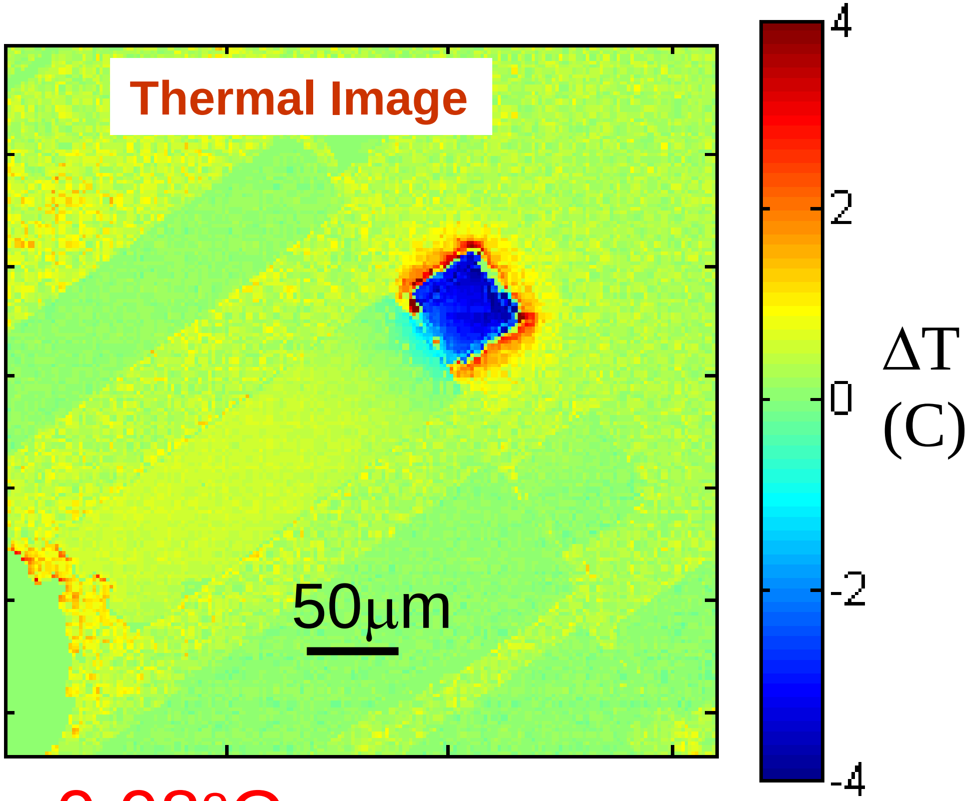
Vivek Sahu, Georgia Tech

Measuring Power and Temperature from Real Processors, Javi Martinez, Jose Renau, et al. *The Next Generation Software (NGS) Workshop* ***(NGS08)***, April 2008

Thermoreflectance image of microcooler

J. Christofferson, A. Shakouri, *Rev. of Scientific Instruments*, 2005

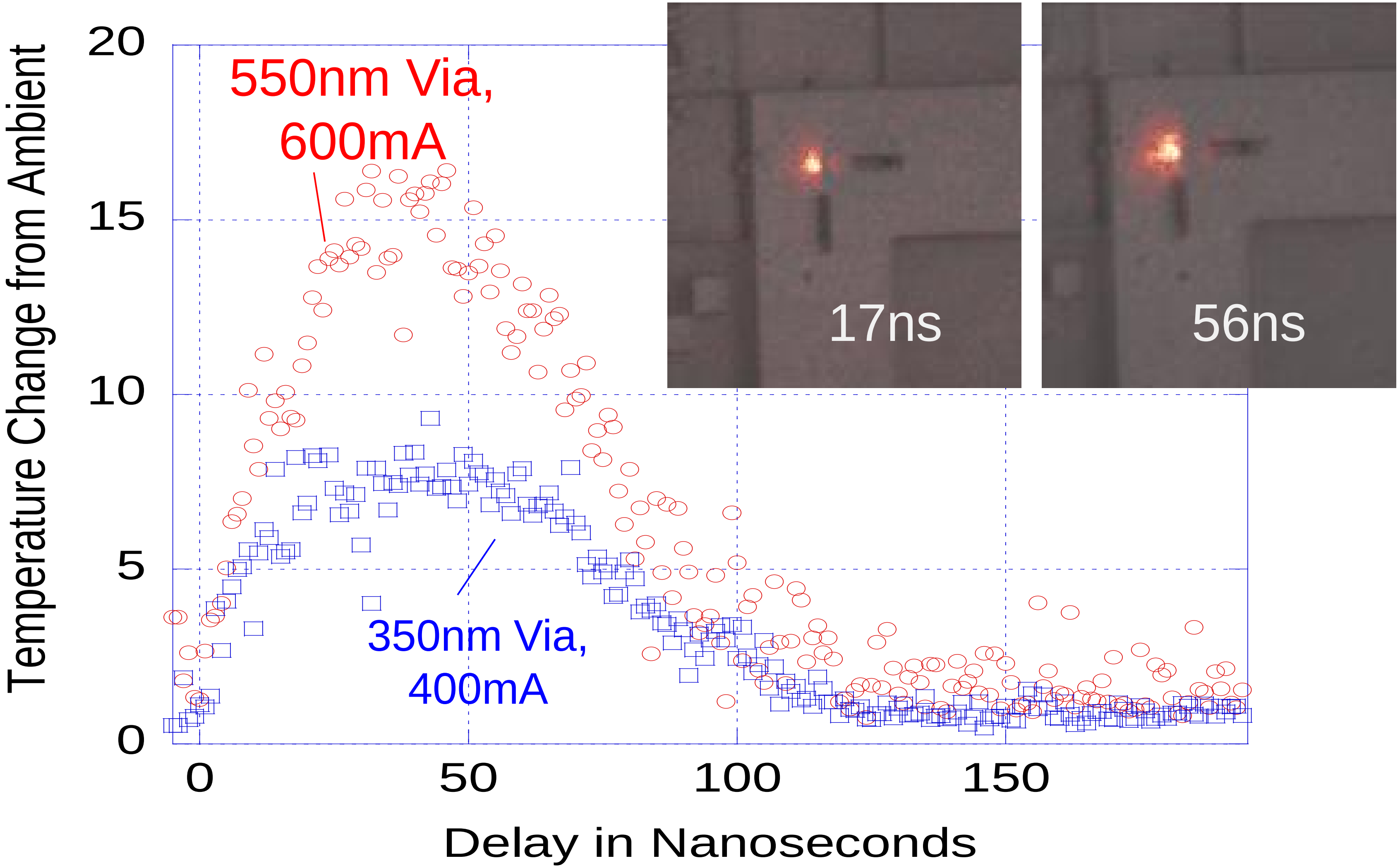




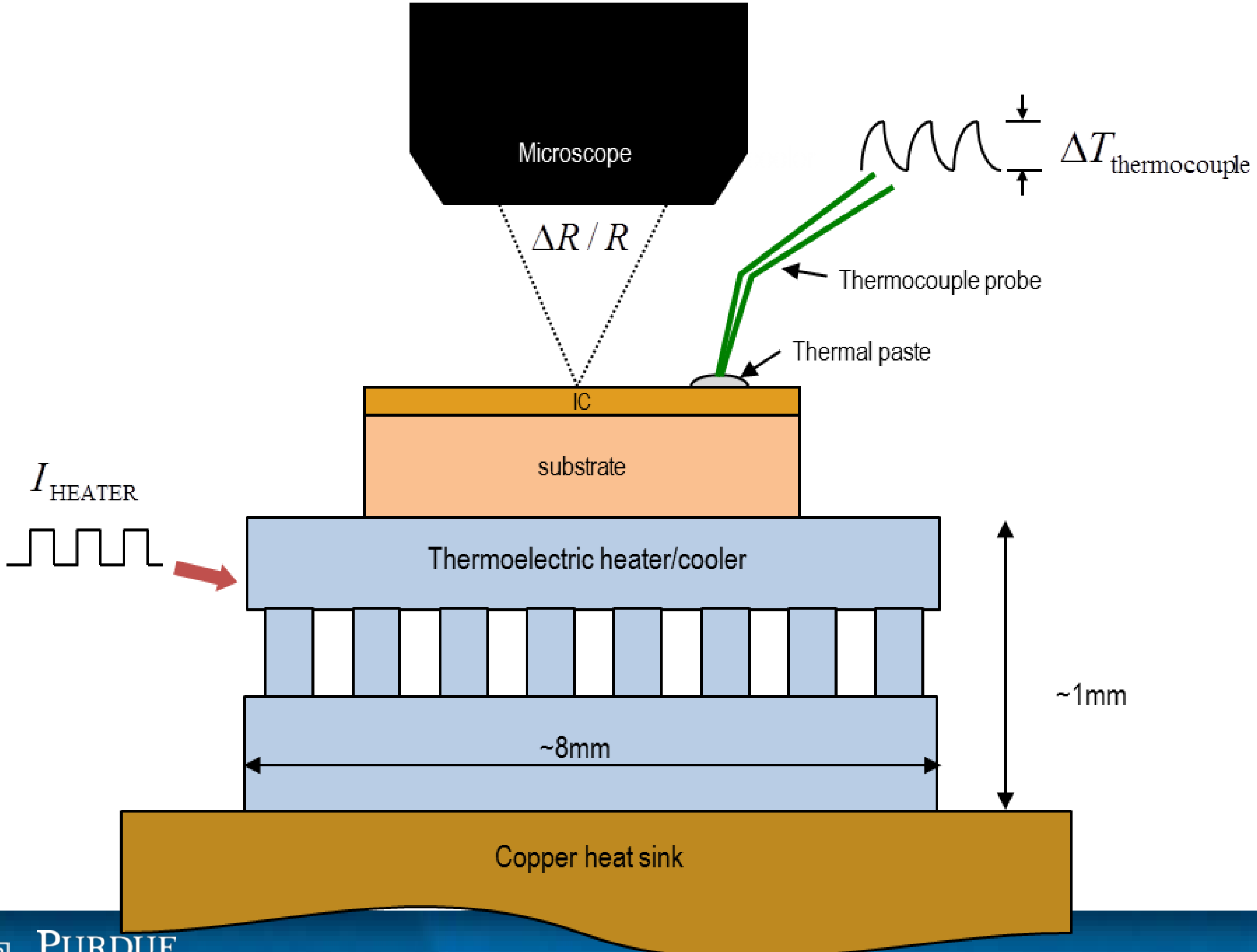
- Temperature resolution: 0.08°C
- Spatial resolution: submicron
- Time resolution: 800ps, 100ns; 1024x1024 pixels

High Speed Thermal Imaging (800ps

J. Christofferson et al., *Heat Transfer Conf., August 2010*

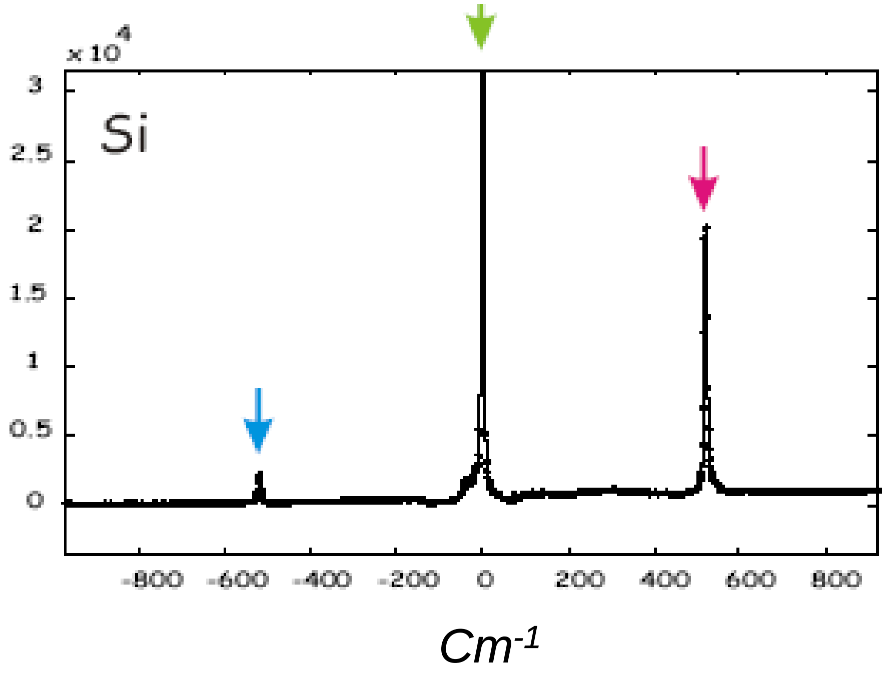


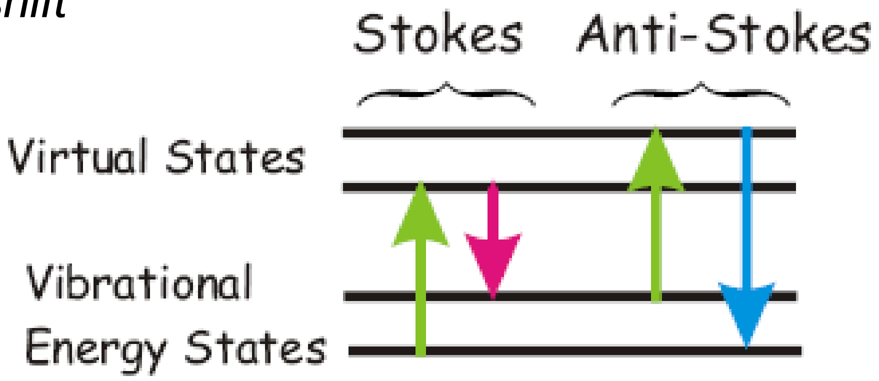
Calibration: experiment determination of thermoreflectance coefficients, C_{TH}

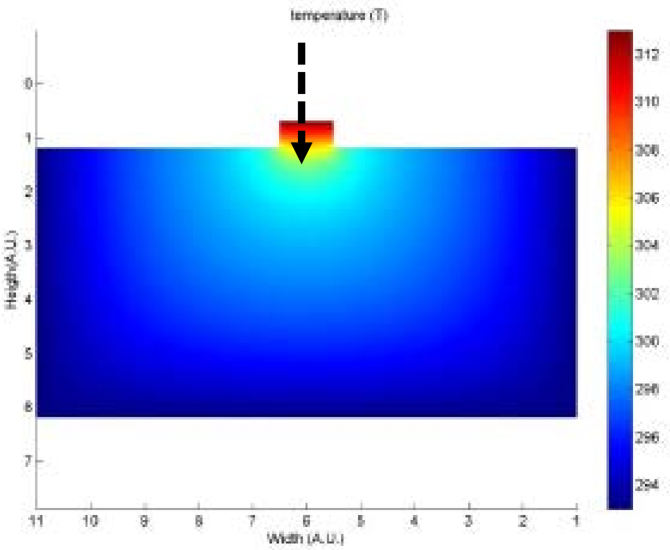


Raman spectroscopy and temperature measurement

Scattered light intensity versus wavelength shift

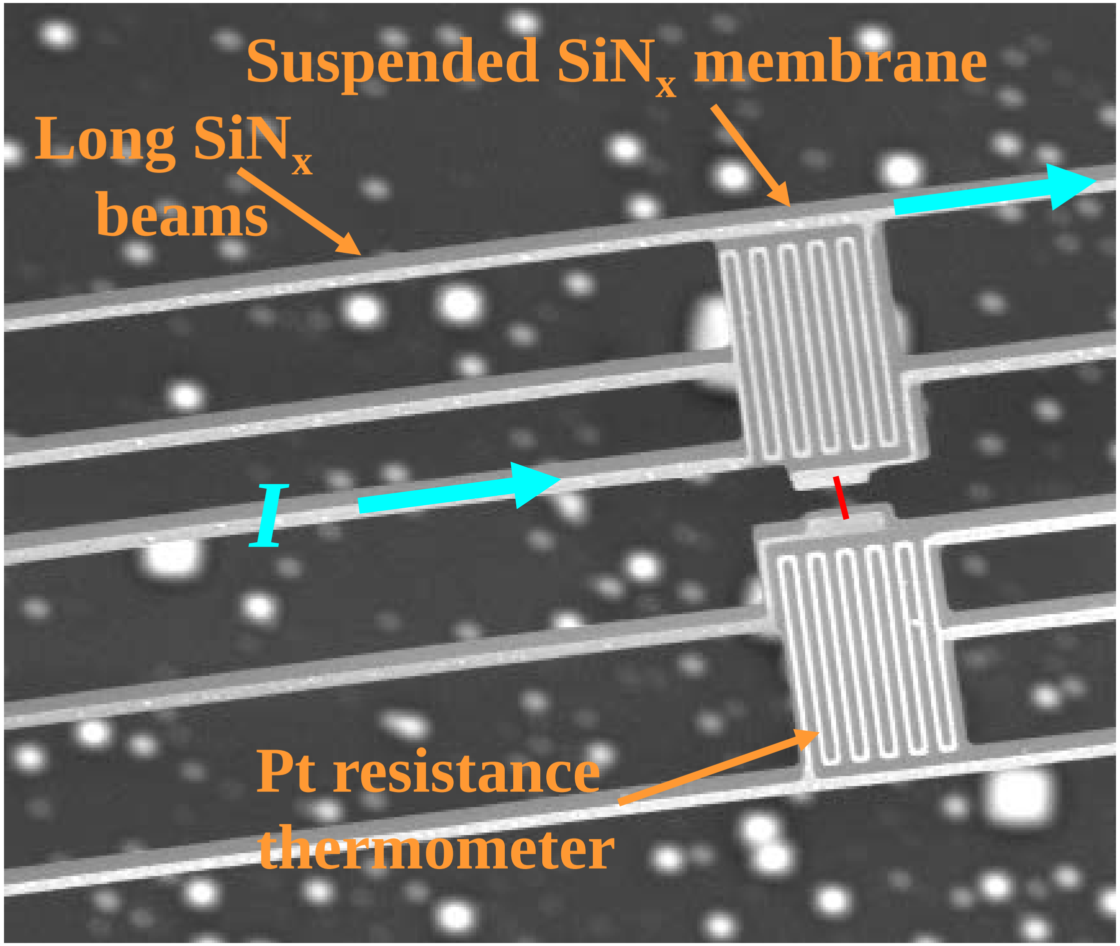






Thermal Measurements of Nanowires

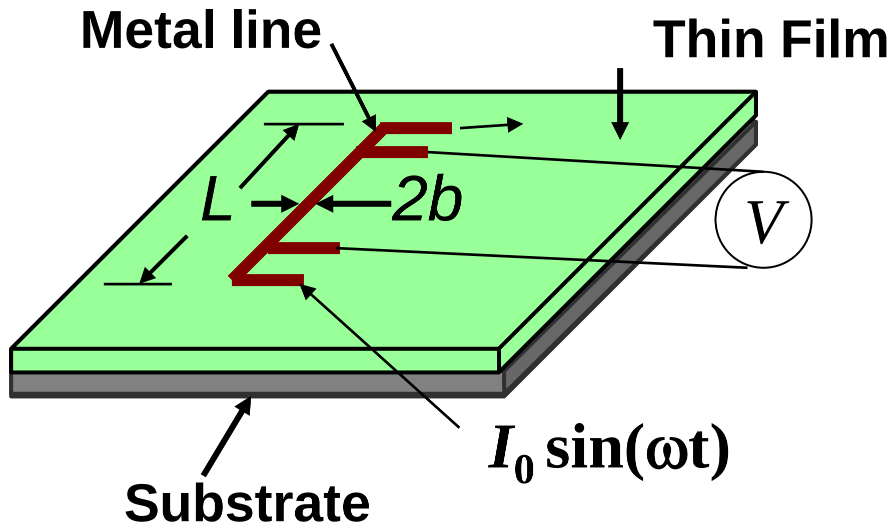
Themal conductance: $G = Q / (T_h - T_s)$



Kim et al, *PRL* **87**, 215502
Shi et al, *JHT*

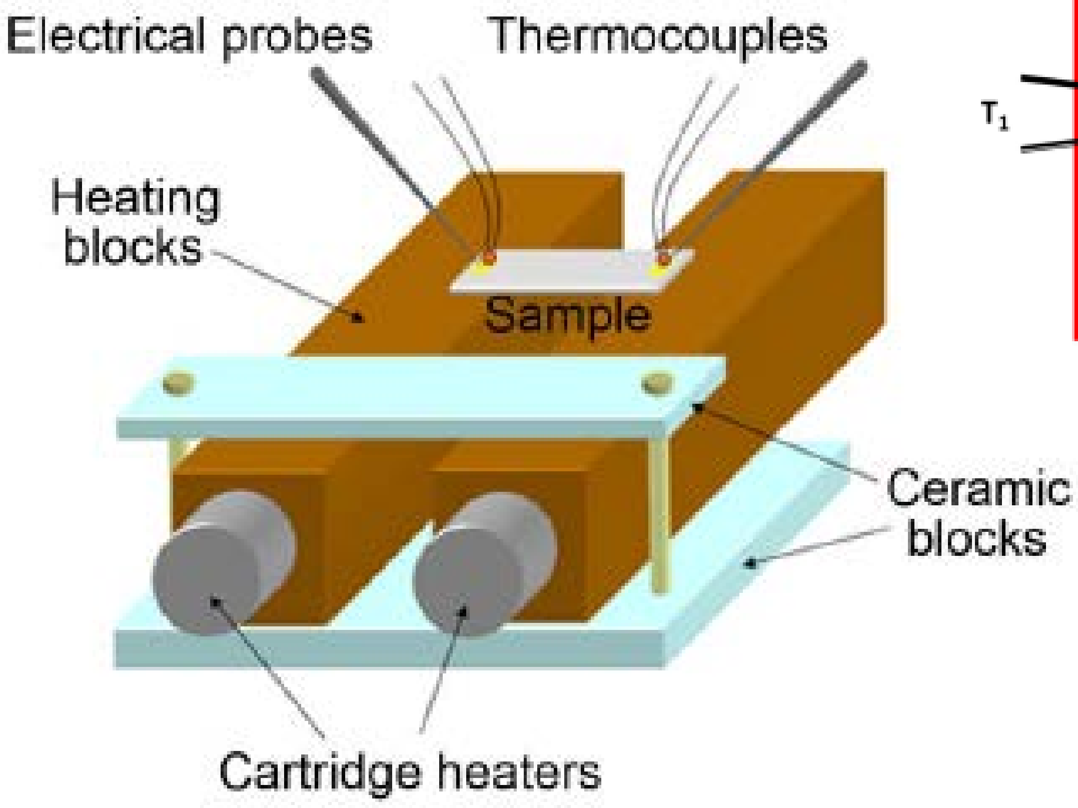
3ω method

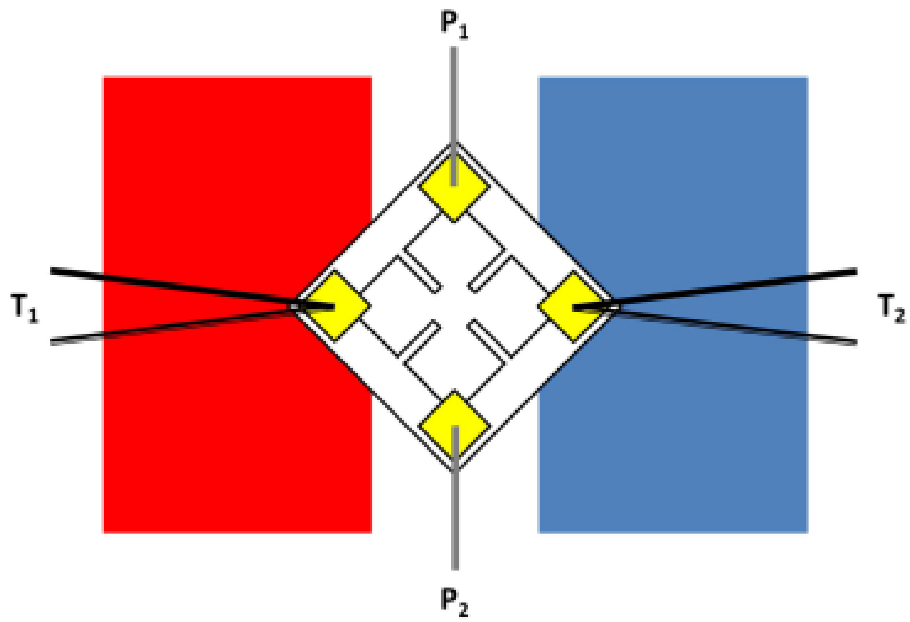
(Cahill, *Rev. Sci. Instrum*. 61, 802)



See: Annual Review of Heat Transfer, Edited by Gang Chen, 2013

In-plane Seebeck/electrical conductivity





J.-H Bahk, T. Favaloro and A. Shakouri, "Thin film thermal characterization techniques," *Annual Review of Heat Transfer, Chapter 3,* 2013

Cross-plane Seebeck/electrical conductivity

J.-H Bahk, T. Favaloro and A. Shakouri,
Annual Review of Heat Transfer, Chapter 3, 2013

(a) Top view

(b) Cross-section view

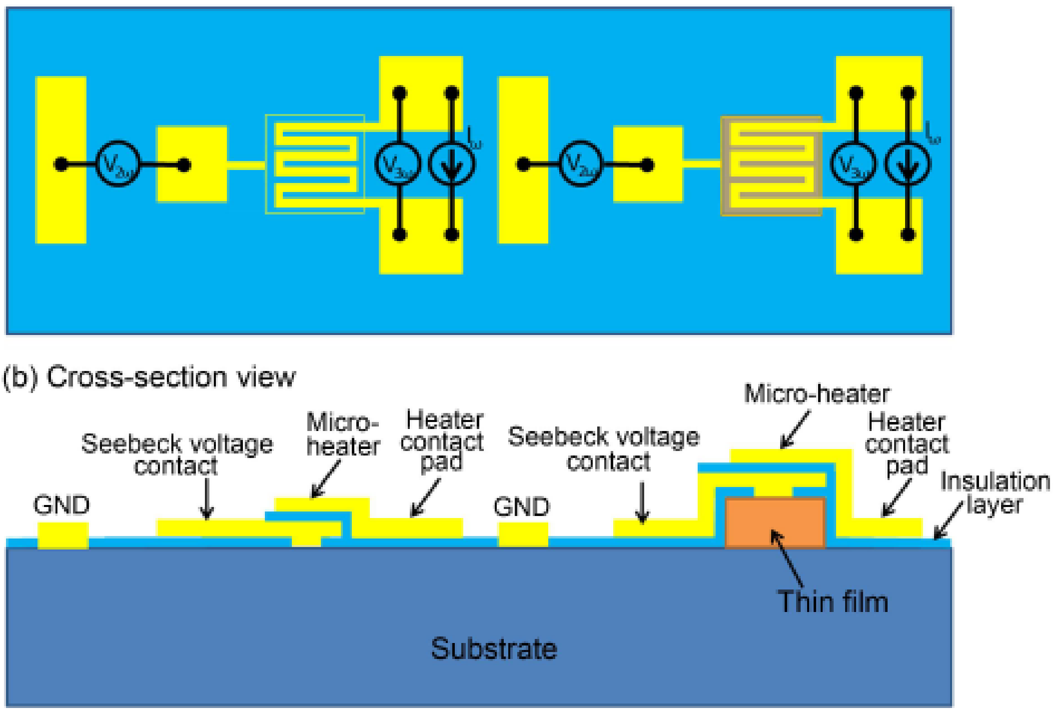
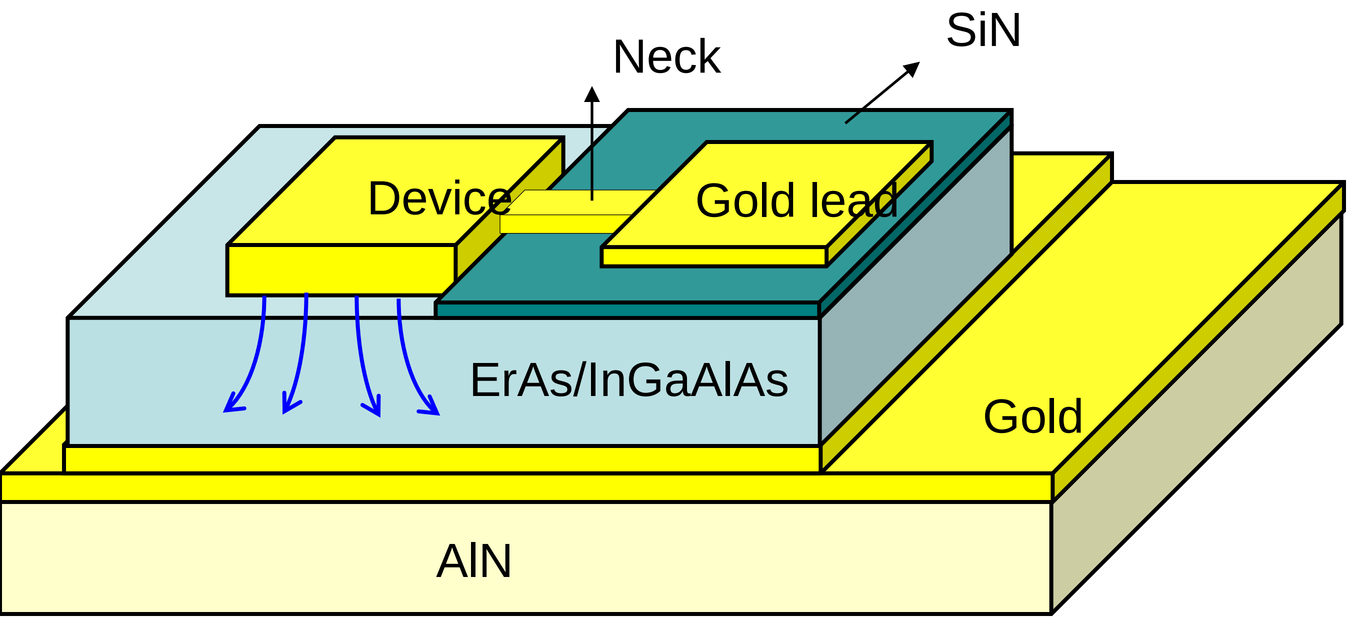
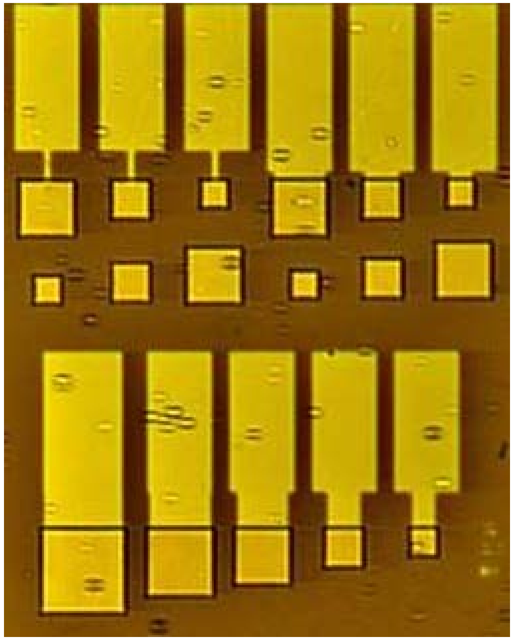


FIG. 8: Schematics, (a) top view and (b) cross-sectional view, of a sample fabricated for cross-plane Seebeck coefficient measurements. Two devices, one with, and one without a thin film mesa, are fabricated (not to scale). Both DC and AC (3ω) measurements are possible. For an AC measurement, a sinusoidal current with 1ω frequency is fed into the microheater, and the 3ω component voltage is measured across the heater line to obtain the temperature difference across the device. Seebeck voltage of 2ω component is measured separately between the voltage pad and the ground contact.





Courtesy:
Gehong Zeng
UCSB

Key issues:

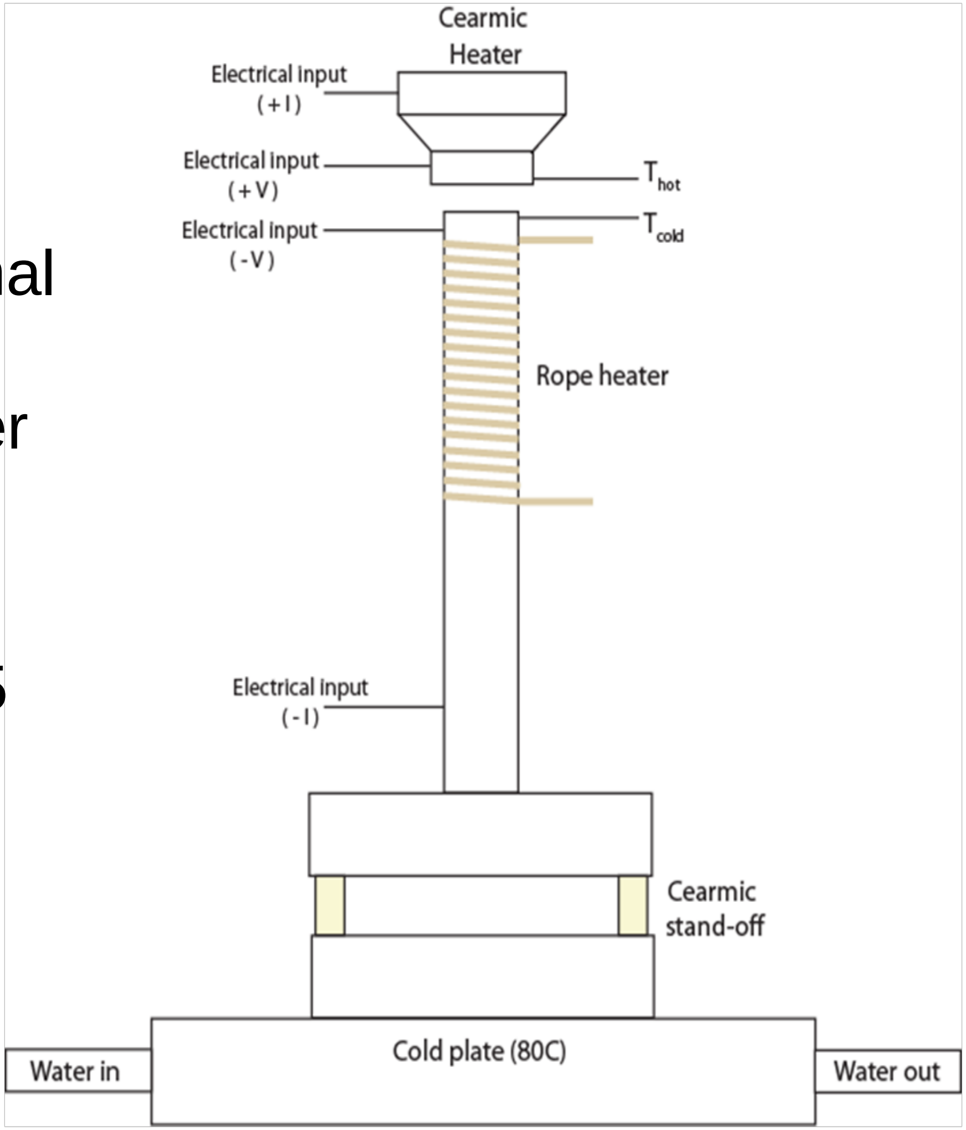
- Current injection uniformity (aspect ratio)
- Heat load from probes or leads
- Transient response in 0.1-10 μsec

R. Singh, Z. Bian et al. Appl. Phys. Lett. 2009 May; 94: 212508

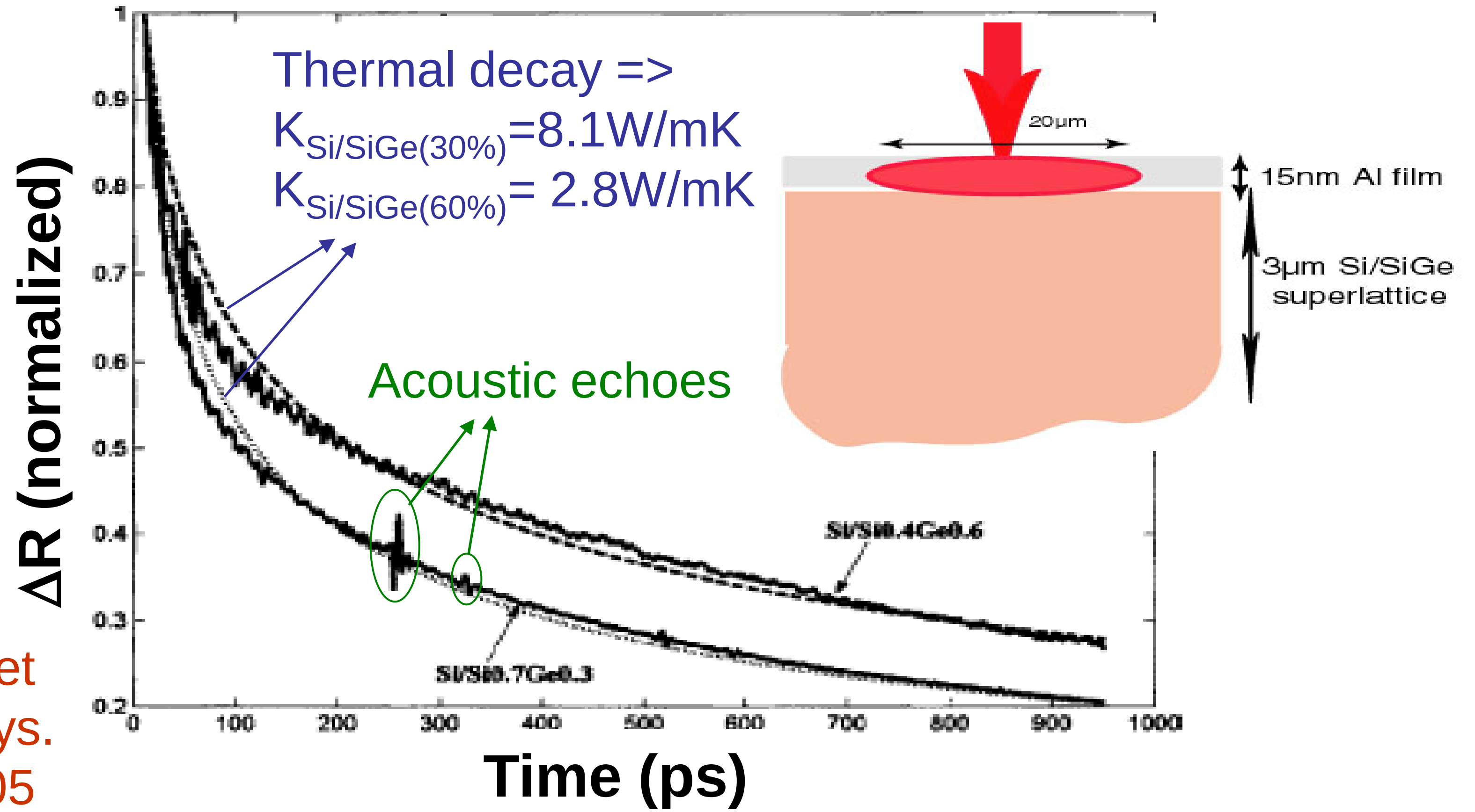
Single leg Z-meter measurement

- Measured parameters: Seebeck coefficient, thermal conductivity and electrical conductivity + output power and efficiency
- 50um thick material (k~3-5 W/mK, σ~500-1000/Ωcm)

Reja Amatya, Katey Lo and Rajeev Ram (MIT)



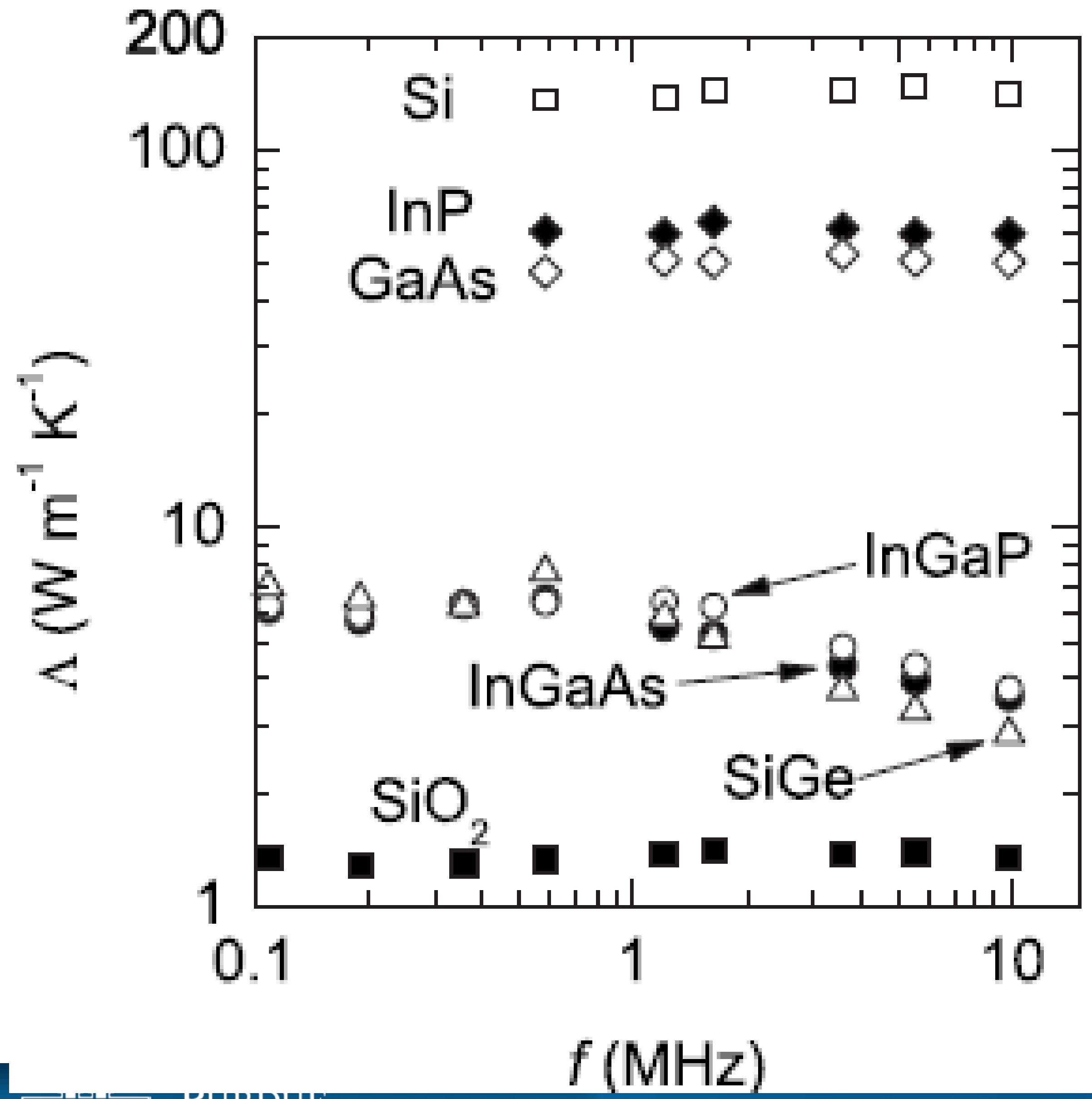
Thin Film Thermal Characterization



Y. Ezzahri et al. Appl. Phys. Letters 2005

Metal film is heated by laser pulse and it acts both as a heat source and a transducer (creates acoustic waves). It can characterize thermal interface resistances as well as interface quality (acoustic mismatch).

Frequency-Dependent Thermal Conductivity



Koh and Cahill, PHYSICAL REVIEW B 76, 075207 (2007)

See also: Minnich, Nelson, Chen, et al. Physical Review Letters, Vol. 107, 095901 (2011)

Week 3: Summary

3.1 • Thermal measurements at nanoscale

- Micro thermocouple, Scanning thermal microscopy

3.2 • Scanning Seebeck Microscopy, Single molecule Seebeck

- Infrared and micro Raman thermal imaging

3.3 • Thermoreflectance imaging

- Suspended heaters for nanowire characterization

3.4 • Thin film electrical/thermal characterization (in-plane, cross-plane)

- Transient Harman/Z-meter

3.5 • Time/Frequency-Domain Thermo Reflectance

- Ballistic vs. Diffusive heat conduction