Thermoelectricity: From Atoms to Systems

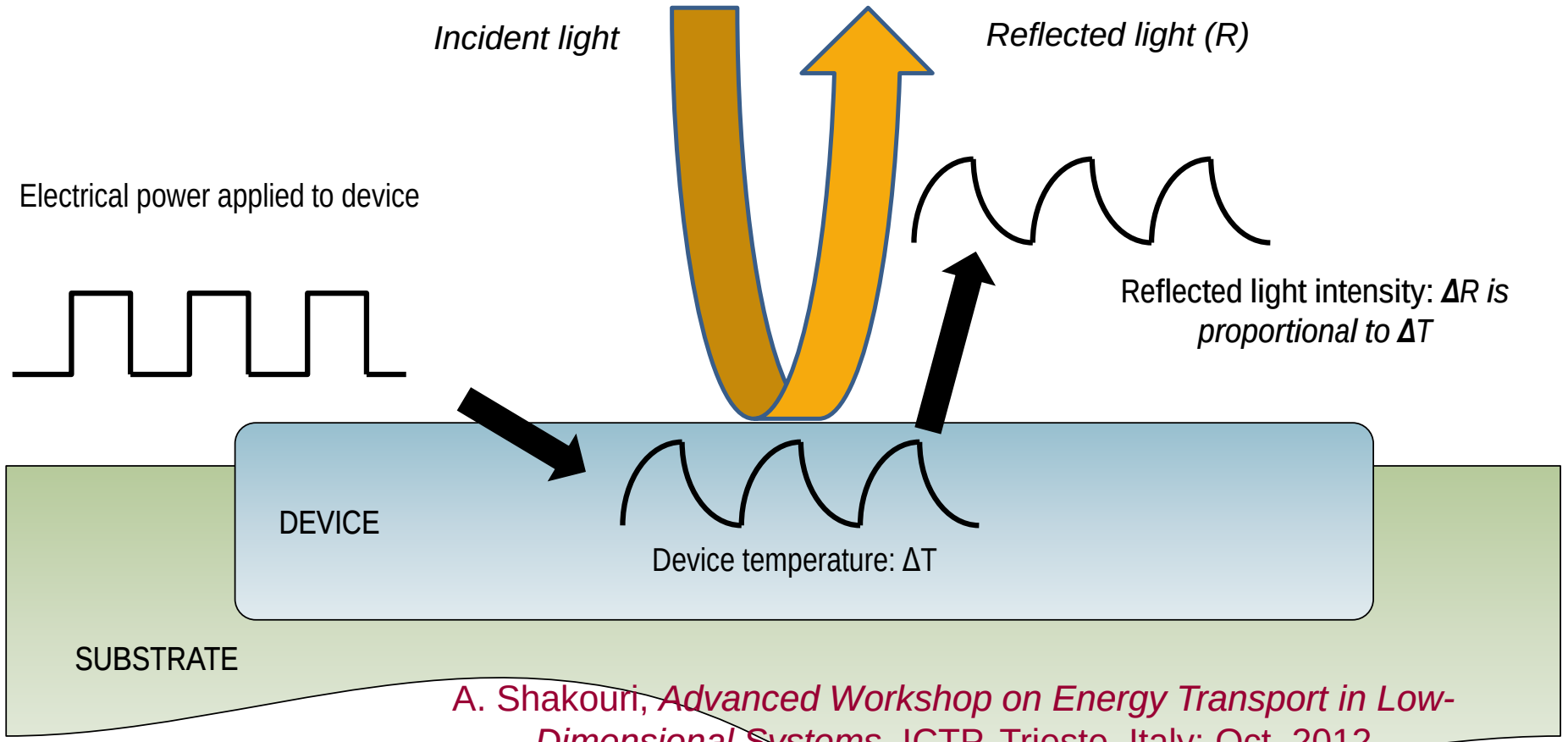
Week 3: Thermoelectric Characterization

Lecture 3.3: Thermoreflectance, Micro Raman, Suspended Heaters

By Ali Shakouri
Professor of Electrical and Computer Engineering
Birck Nanotechnology Center
Purdue University

Thermoreflectance Imaging

Optical reflectance changes with material temperature



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

J. Phys. D: Appl. Phys. 42 (2009) 143001

CCD-based thermoreflectance microscopy: principles and applications

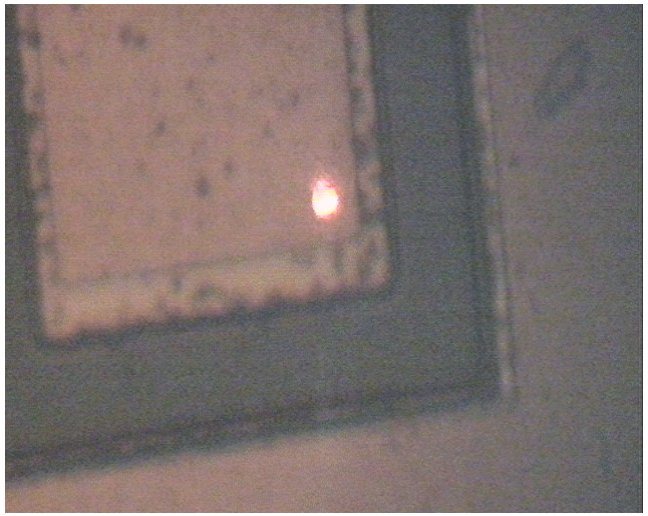
M Farzaneh[1,8], K Maize[2], D Lüerßen[3,4,9], J A Summers[3], P M Mayer[4,10], P E Raad[5,6], K P Pipe[7], A Shakouri[2], R J Ram[4] and Janice A Hudgings[3]

$$\frac{\Delta R}{R} = \left(\frac{1}{R}\frac{\partial R}{\partial T}\right)\Delta T = \kappa \Delta T, \qquad (1)$$

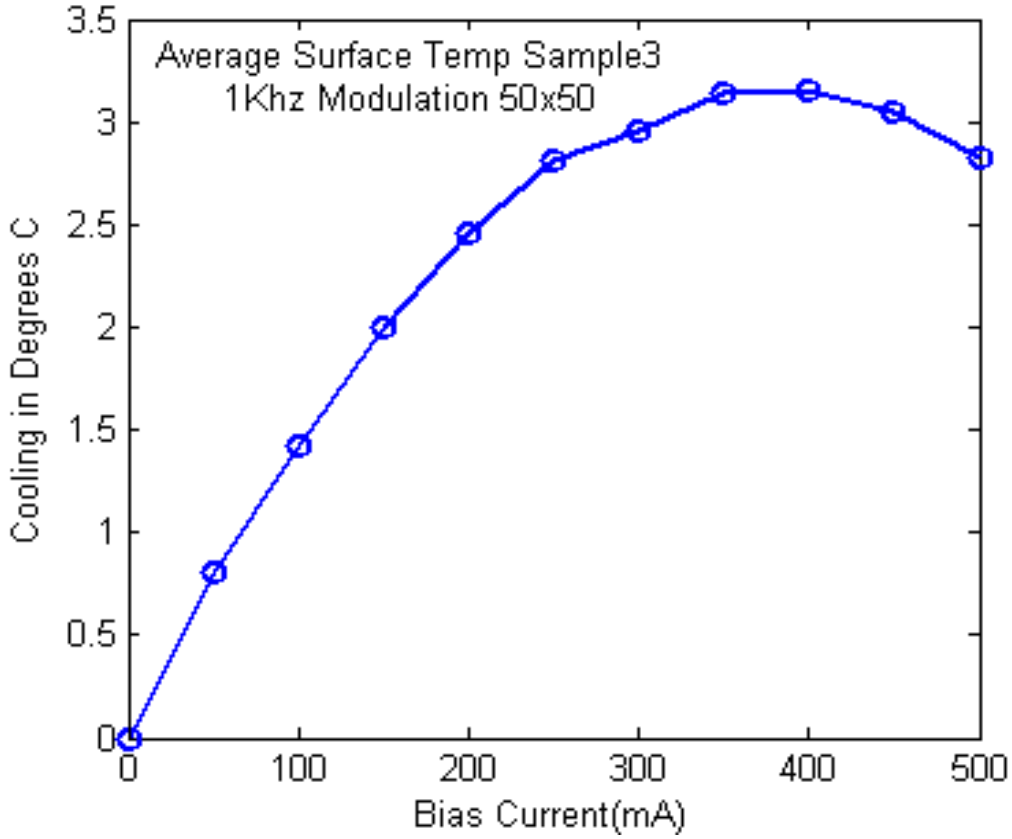
where κ, which is typically of the order of 10^{-2}–$10^{-5}\,\mathrm{K}^{-1}$,

Laser measurement of localized temperature

J. Christofferson et al., SEMITHERM XVII , San Jose, Ca, March 2001.



Laser Probe on a micro cooler lock-in detection at 1KHz



Pioneering works by: Claeys, Fournier, Dilhaire, Tessier, …

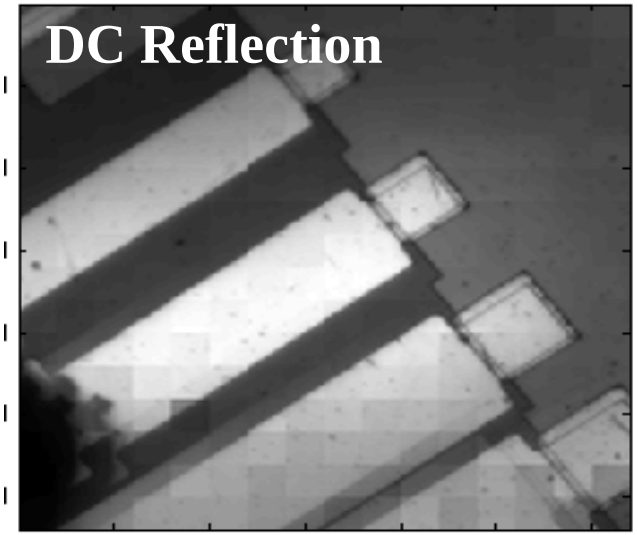
By modulating the device temperature, and by lock-in detection a small change in surface reflectivity due to temperature variation is detected.

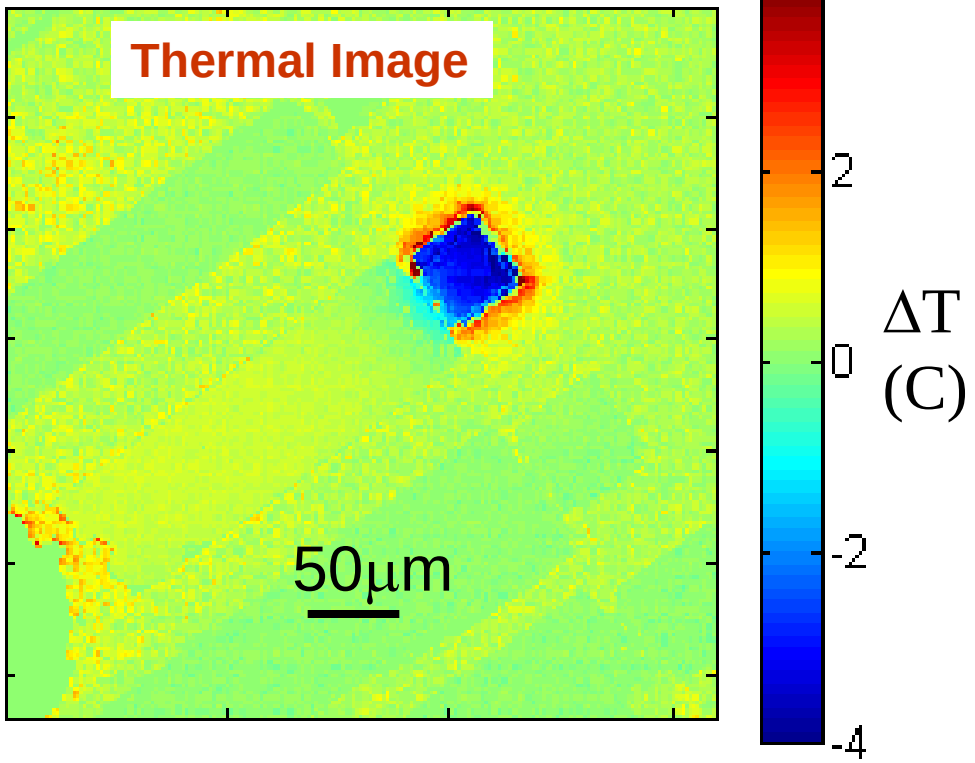
Thermoreflectance image of microcooler

James Christofferson

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

$\Delta T = 0.006K$

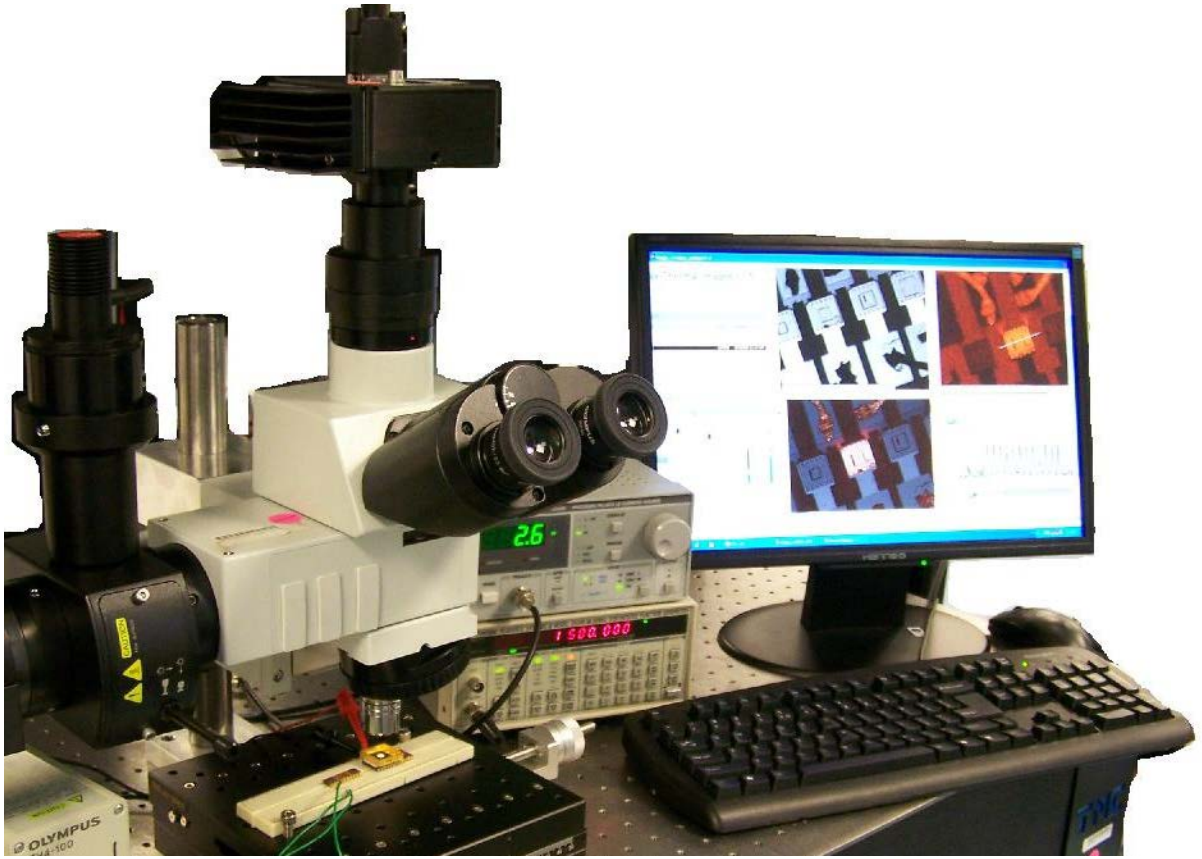




256 channel parallel lock-in amplifiers. Scan the sensor to increase image pixels. Full image in couple of minutes.

CCD-based Thermoreflectance Imaging

- Temperature resolution: 0.08^{o}C
- Spatial resolution: submicron
- Time resolution: 800ps, 100ns; 1024x1024 pixels



K. Yazawa, A. Shakouri, *Electronics Cooling Magazine*, Vol. 3, p.10, March 2011

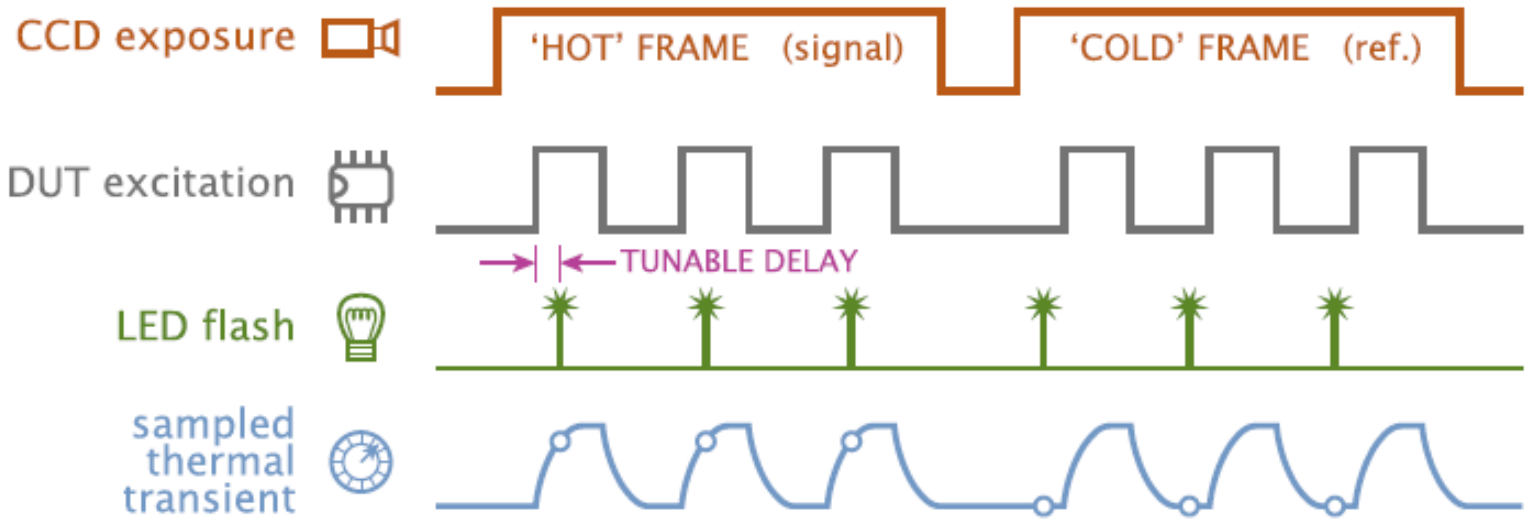
http://Microsanj.com

JOURNAL OF APPLIED PHYSICS **113**, 104502 (2013)

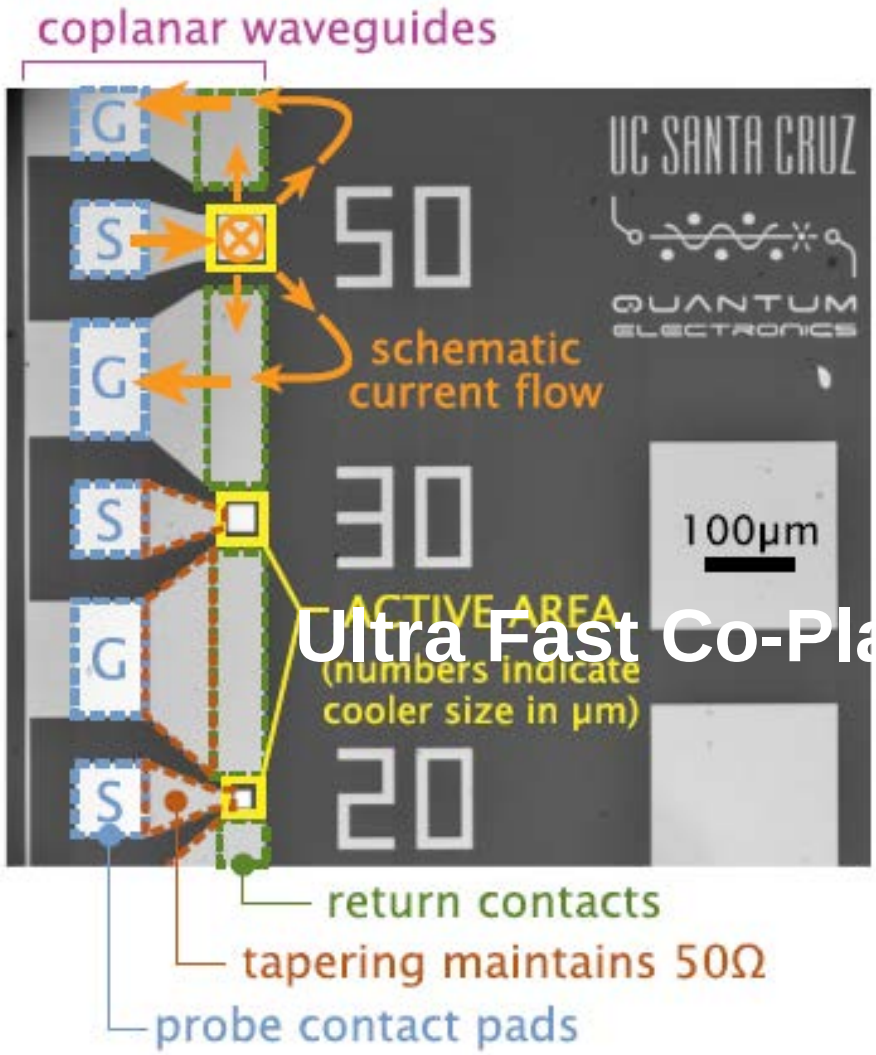
Thermoreflectance imaging of sub 100 ns pulsed cooling in high-speed thermoelectric microcoolers

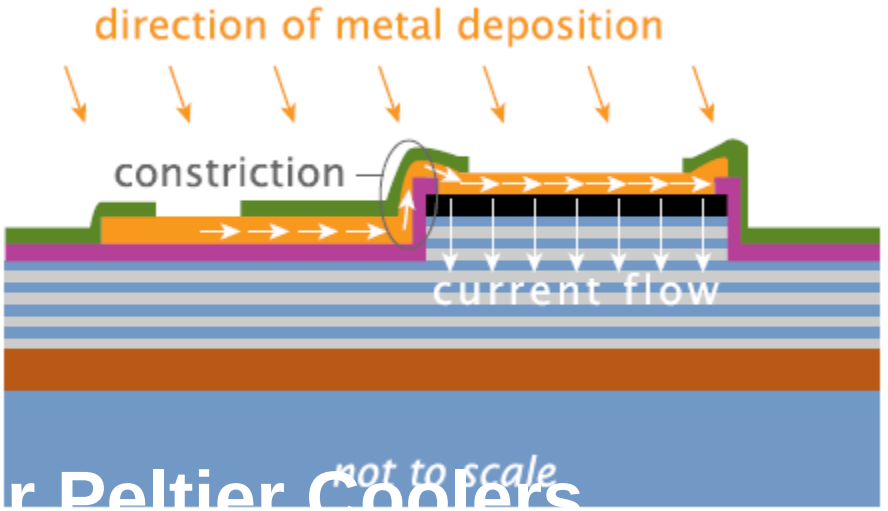
Bjorn Vermeersch,[1,2,a)] Je-Hyeong Bahk,[1,2] James Christofferson,[3] and Ali Shakouri[1,2,b)]

Bjorn Vermeersch



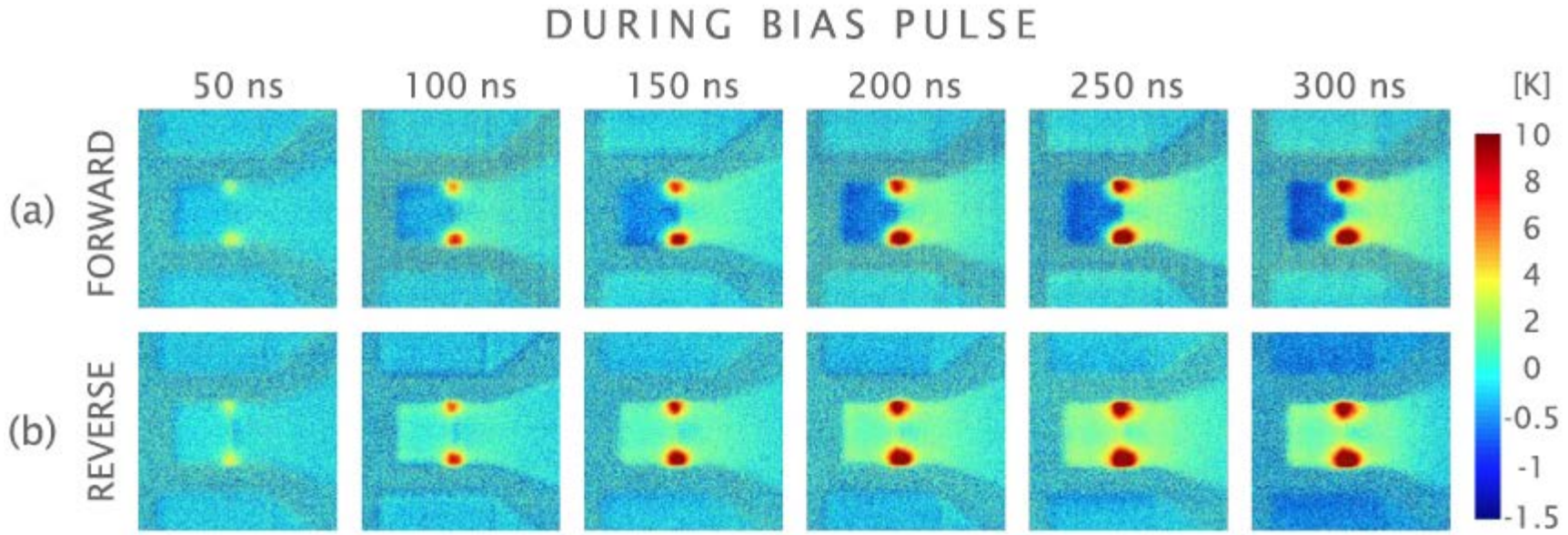
B. Vermeersch, J. Bahk et al. JAP 2013





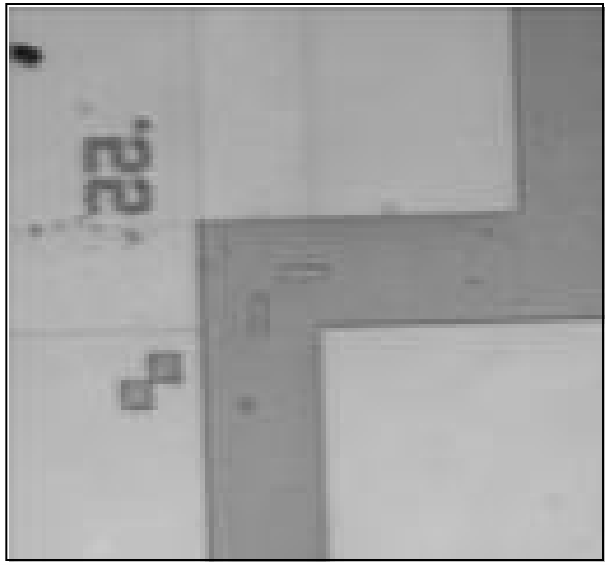
Ultra Fast Co-Pla r Peltier Coolers

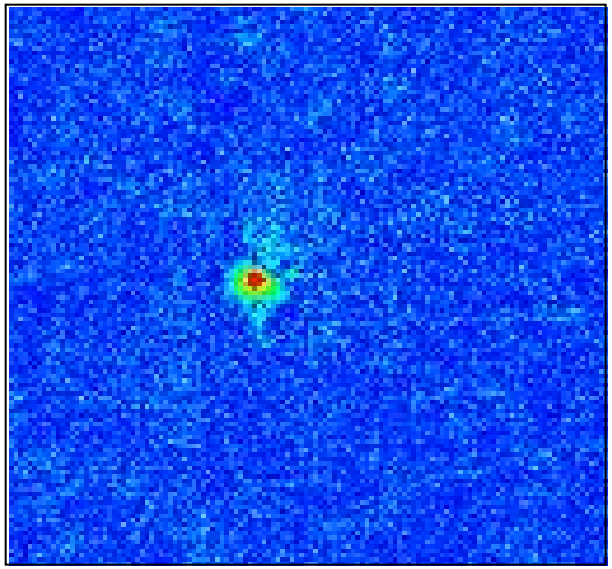
Je-Hyeong Bahk



B. Vermeersch et al. JAP 2013

Picosecond thermal imaging (800ps)

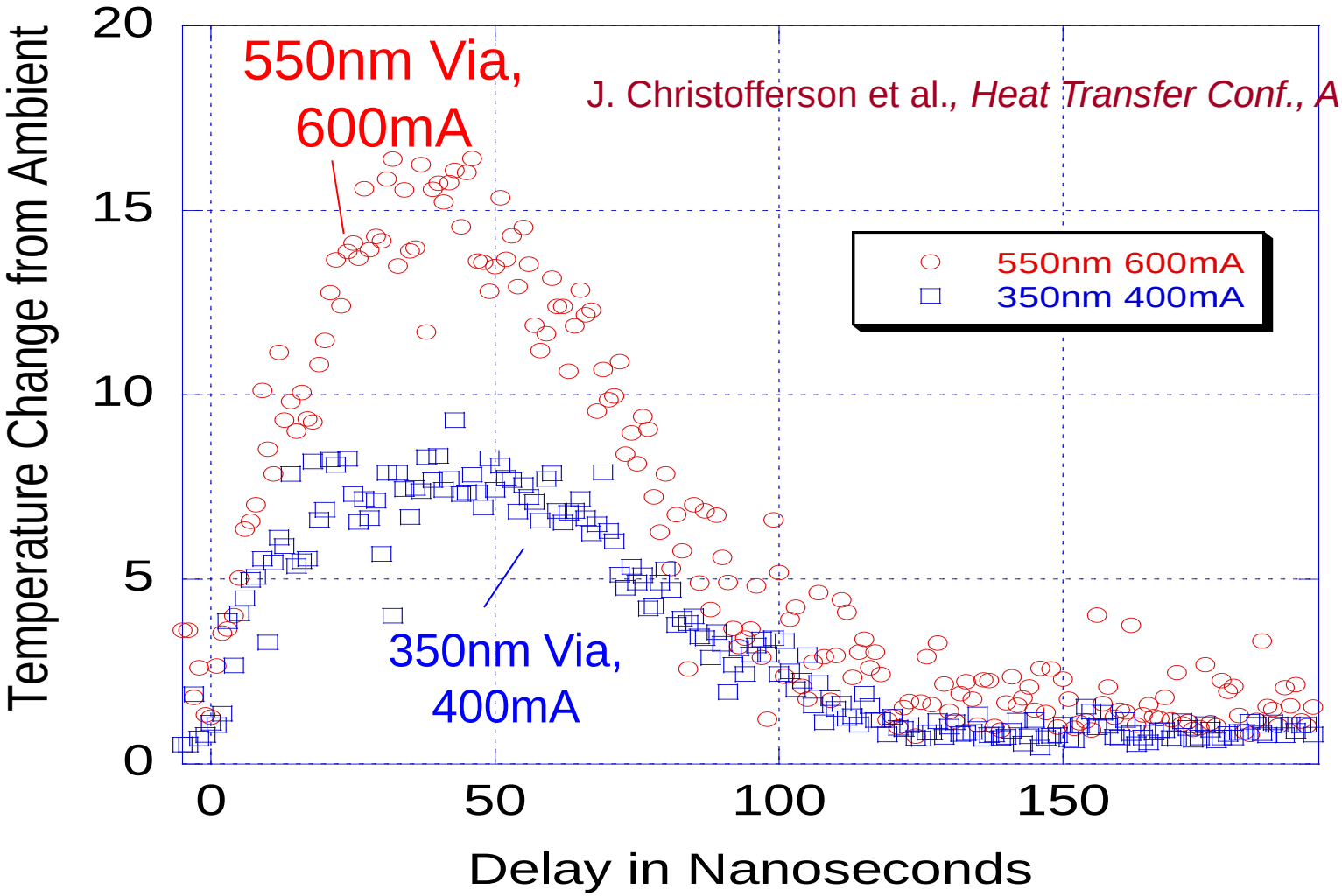




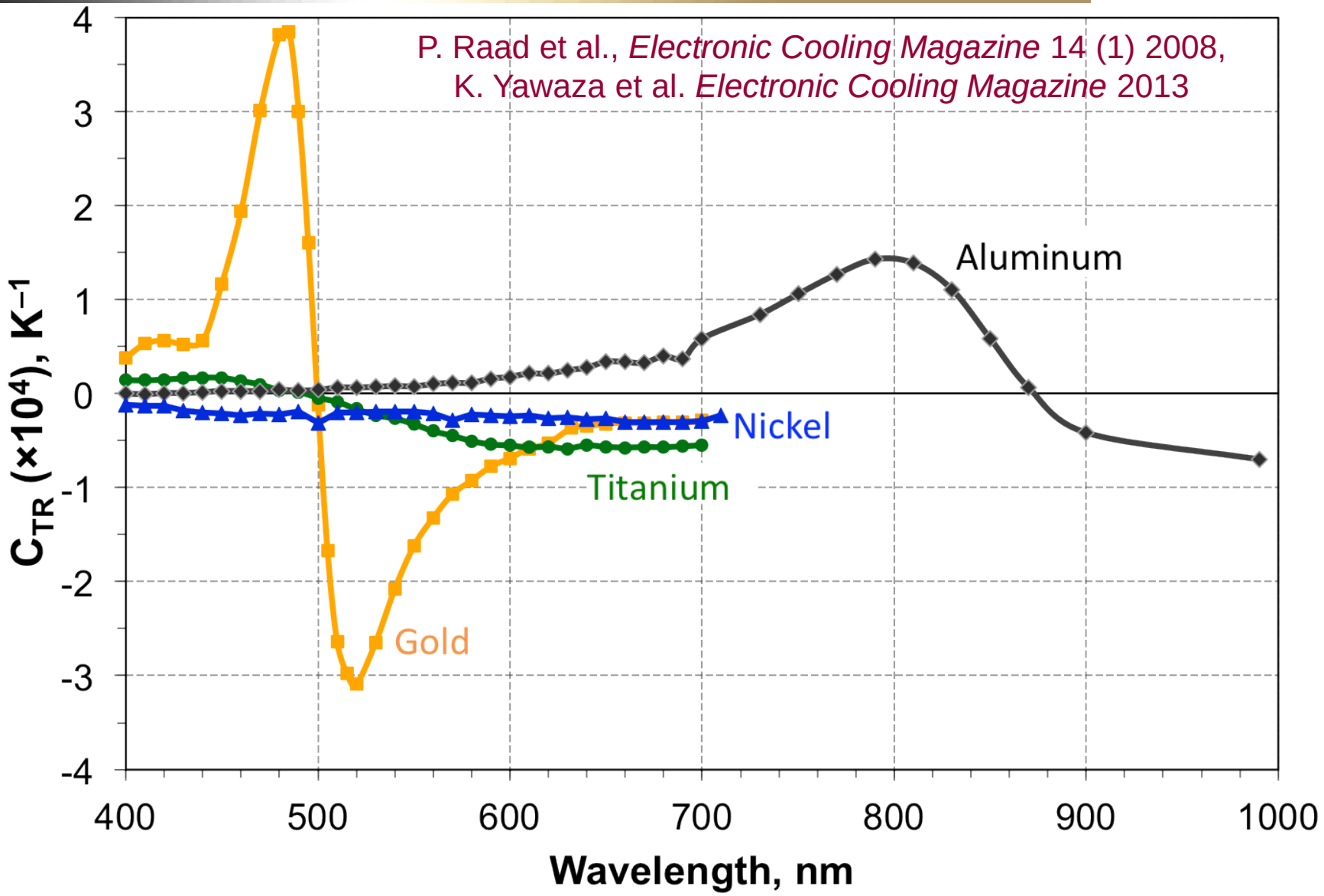
J. Christofferson et al., *Int. Heat Transfer Conf., August 2010*

High Speed Thermal Imaging (800ps

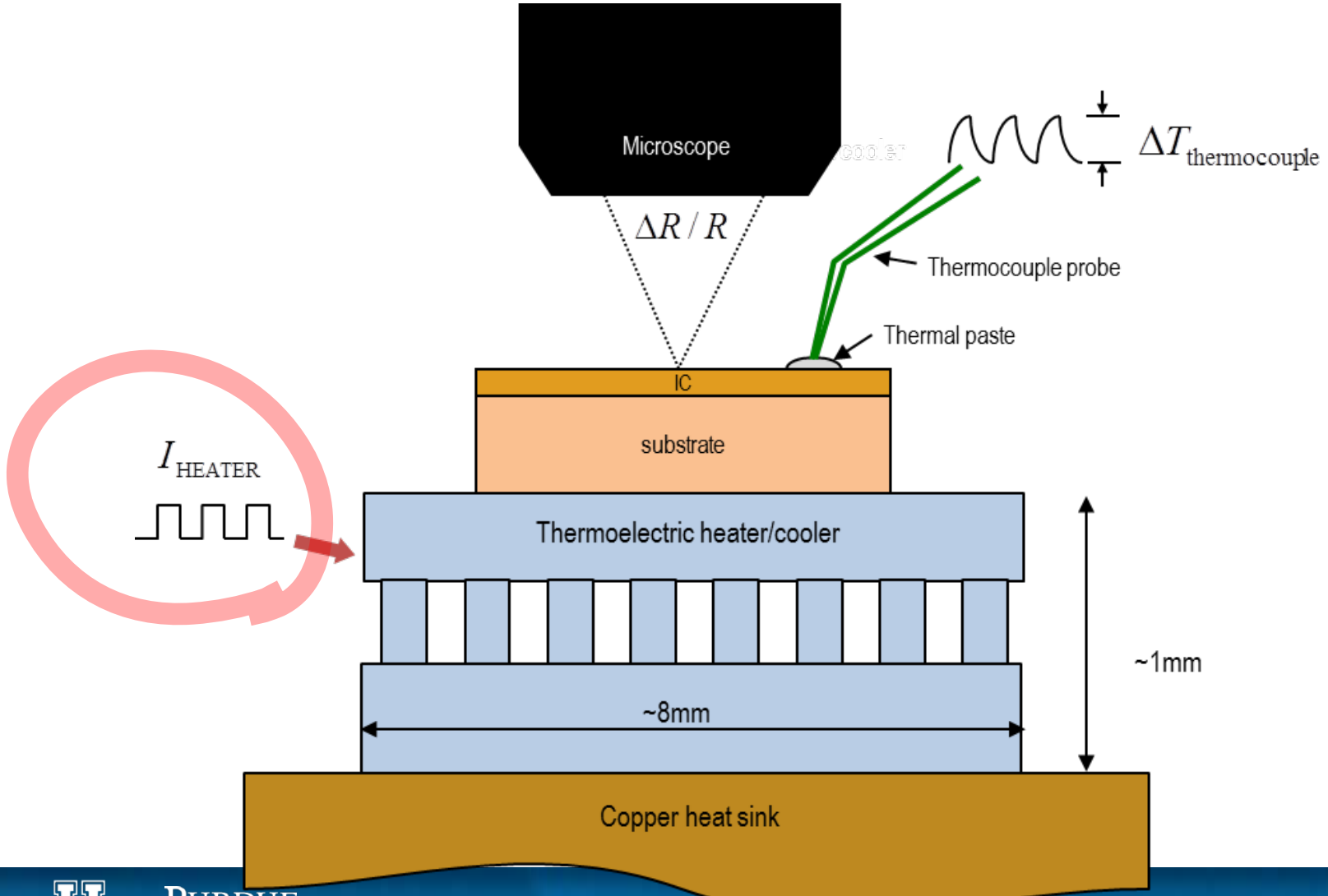
Study of heating in submicron interconnect vias



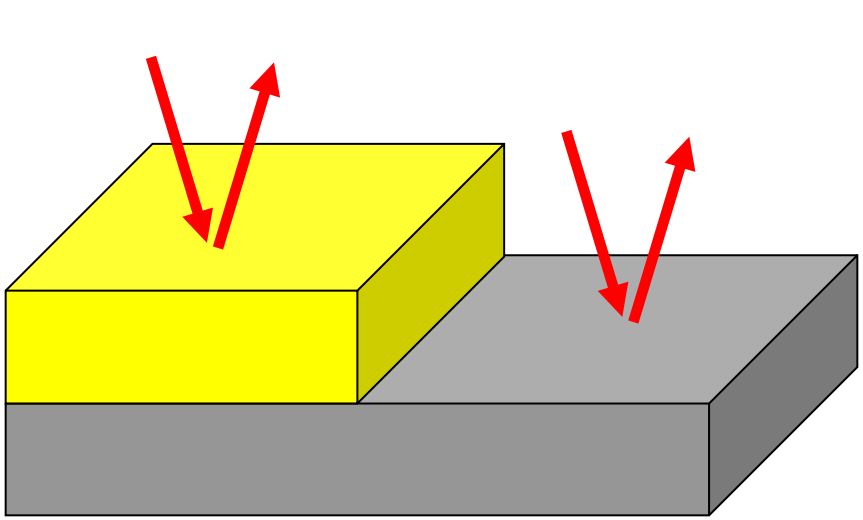
Thermoreflectance coefficient

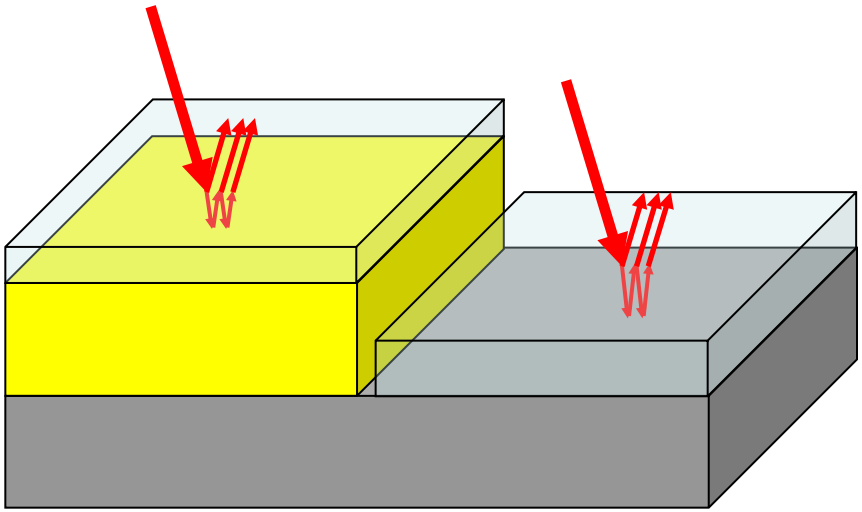


Calibration: experiment determination of thermoreflectance coefficients, C_{TH}



Thermoreflectance coefficient for different surfaces



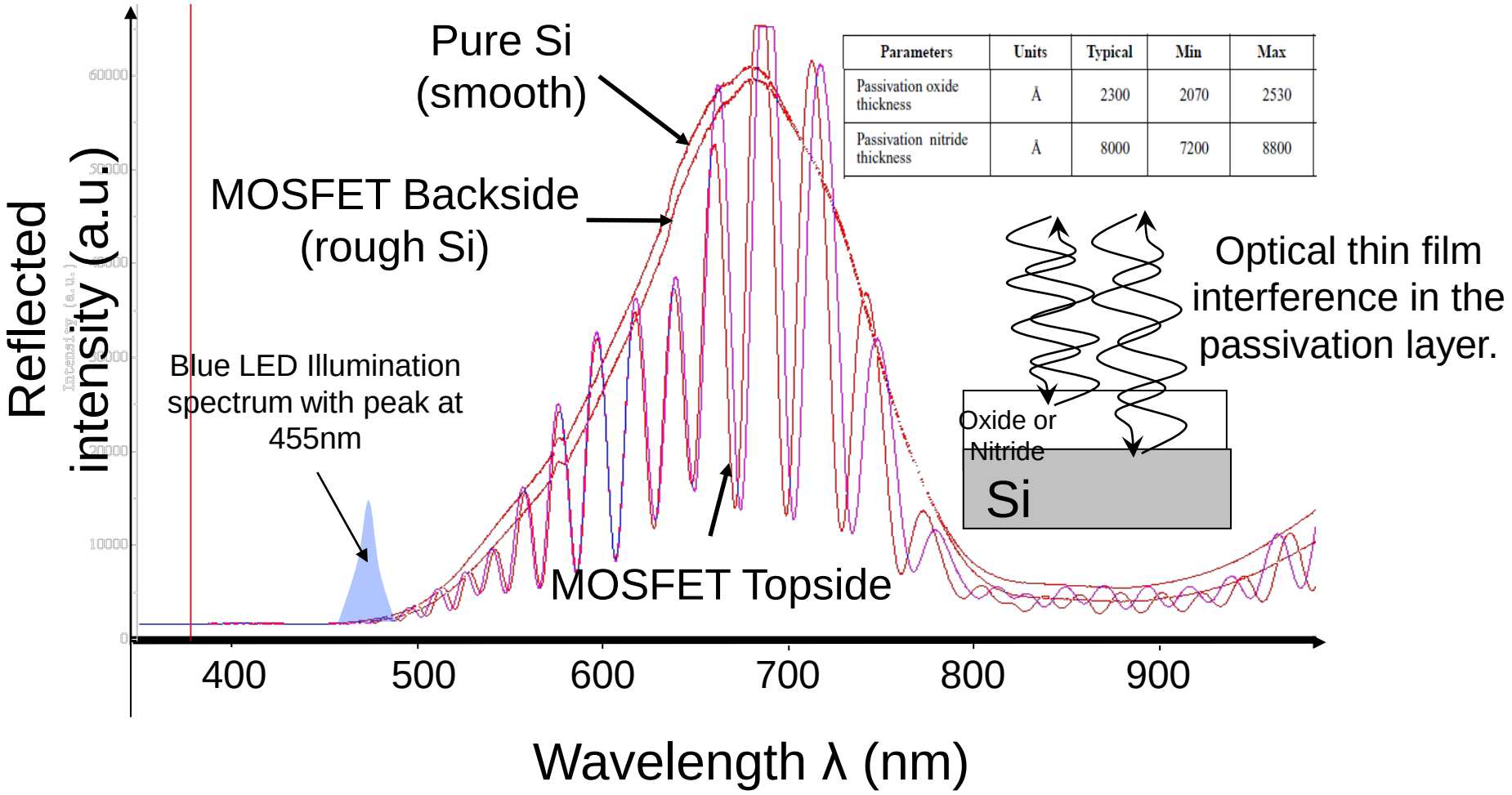


R and $\frac{\partial R}{\partial T}$ vary sharply due to interference

Spatial selectivity: a few μm
Spectral resolution: ~1 nm
Sensitivity: $\Delta R/R \sim 3.10^{-5}$ in 1 min

Tessier et al. (2006)

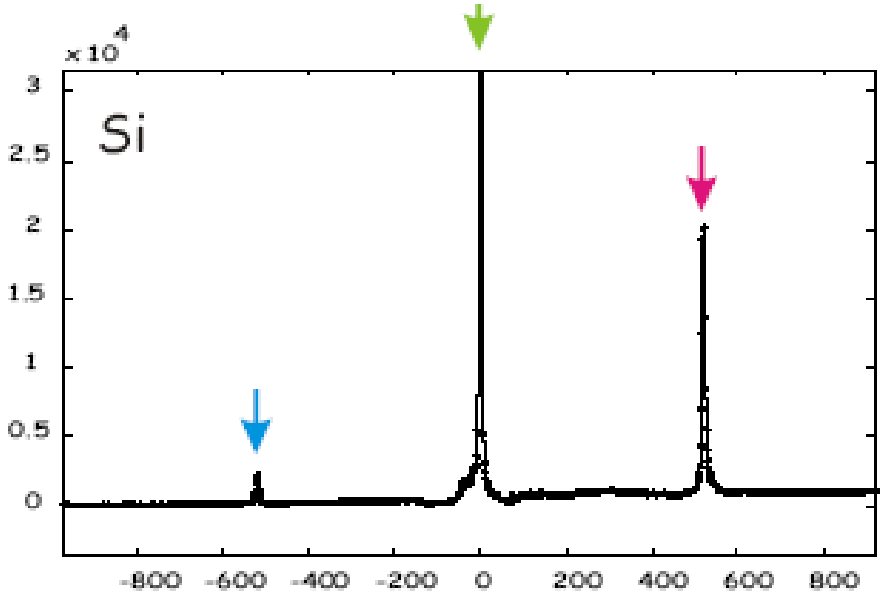
Optical thin film interference in passivation layer



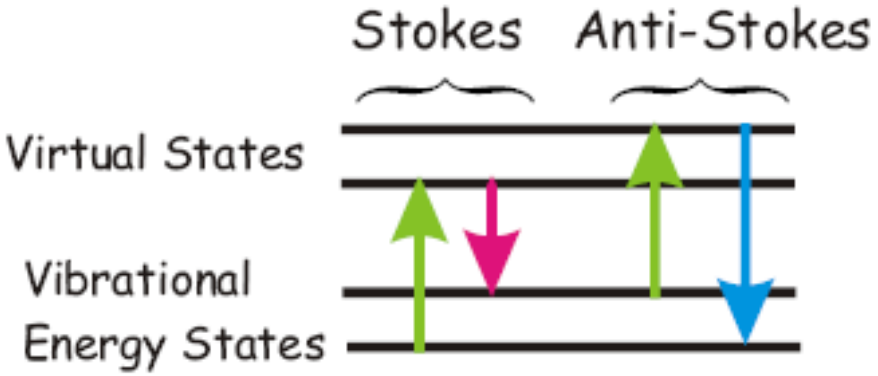
Parameters	Units	Typical	Min	Max
Passivation oxide thickness	Å	2300	2070	2530
Passivation nitride thickness	Å	8000	7200	8800

Raman spectroscopy and temperature measurement

Scattered light intensity versus wavelength shift



Cm^{-1}

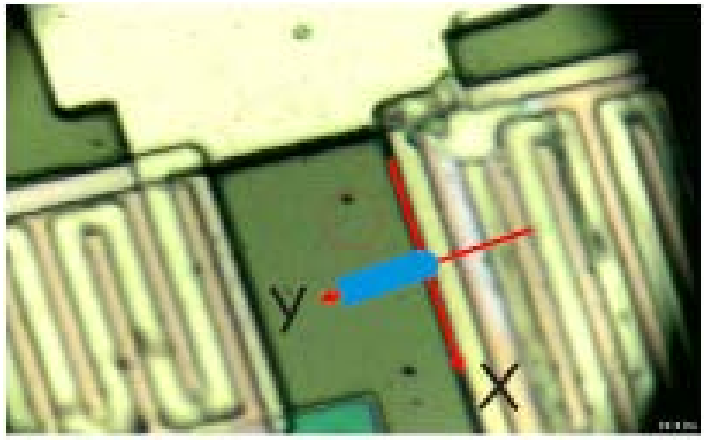


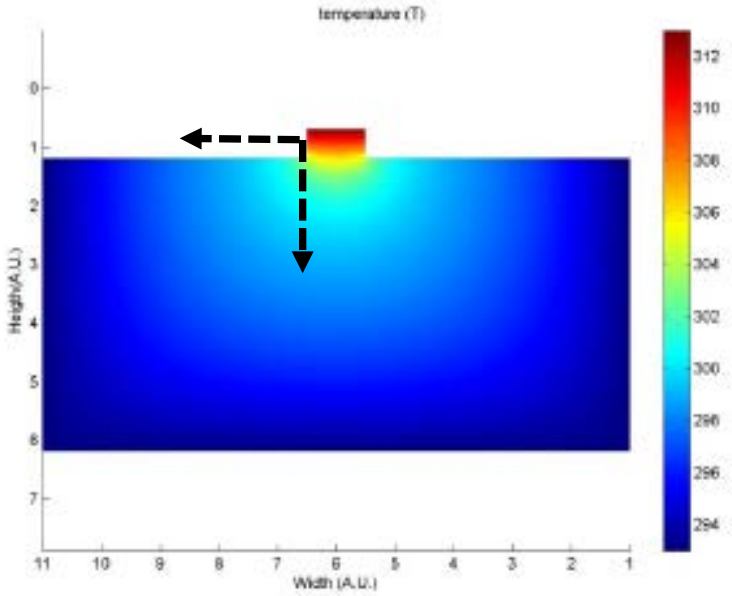
Needs laser illumination, high resolution spectrometer and a notch filter

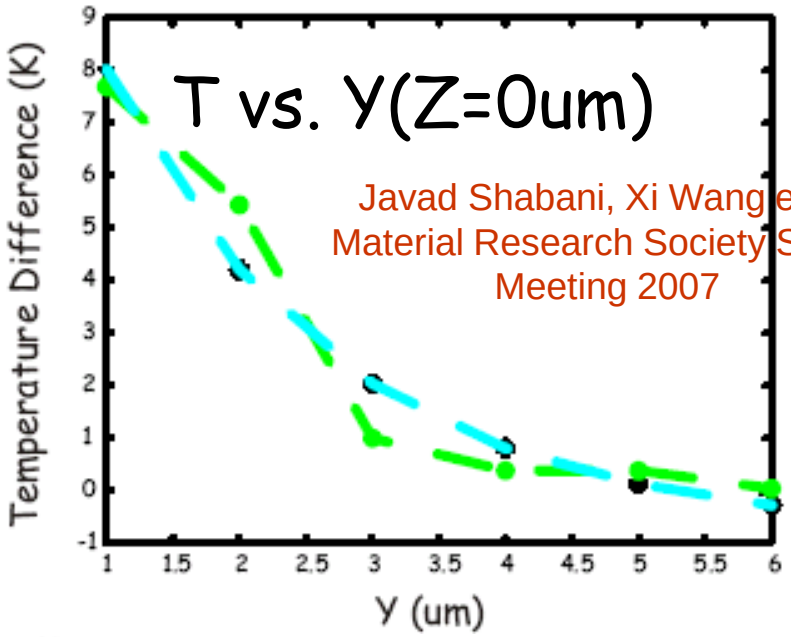
J. Christofferson, et al, *J. Electronic Packaging*, 130 (4) 041101, 2008

3D Raman temperature measurement

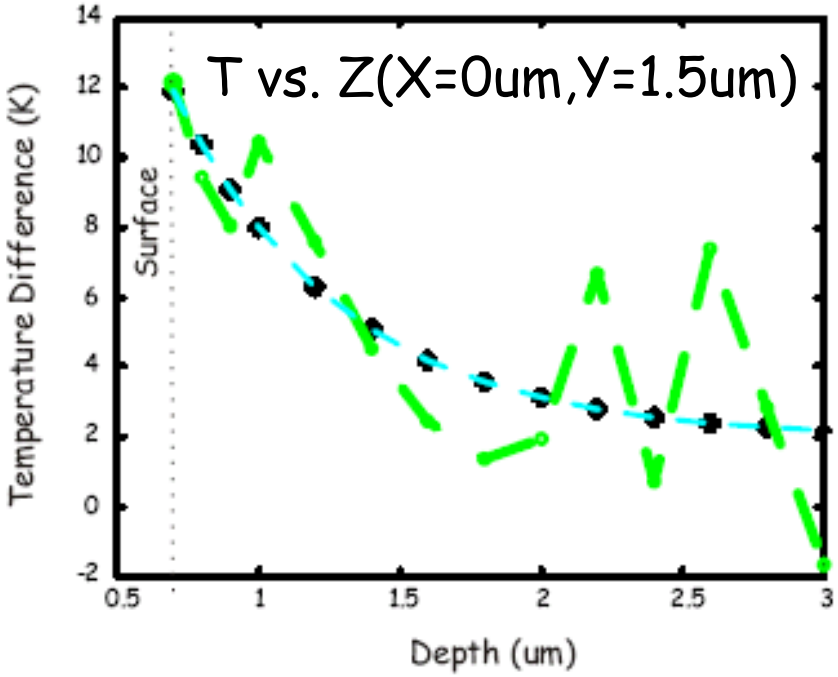
J. Christofferson, et al, *J. Electronic Packaging*, 130 (4) 041101, 2008





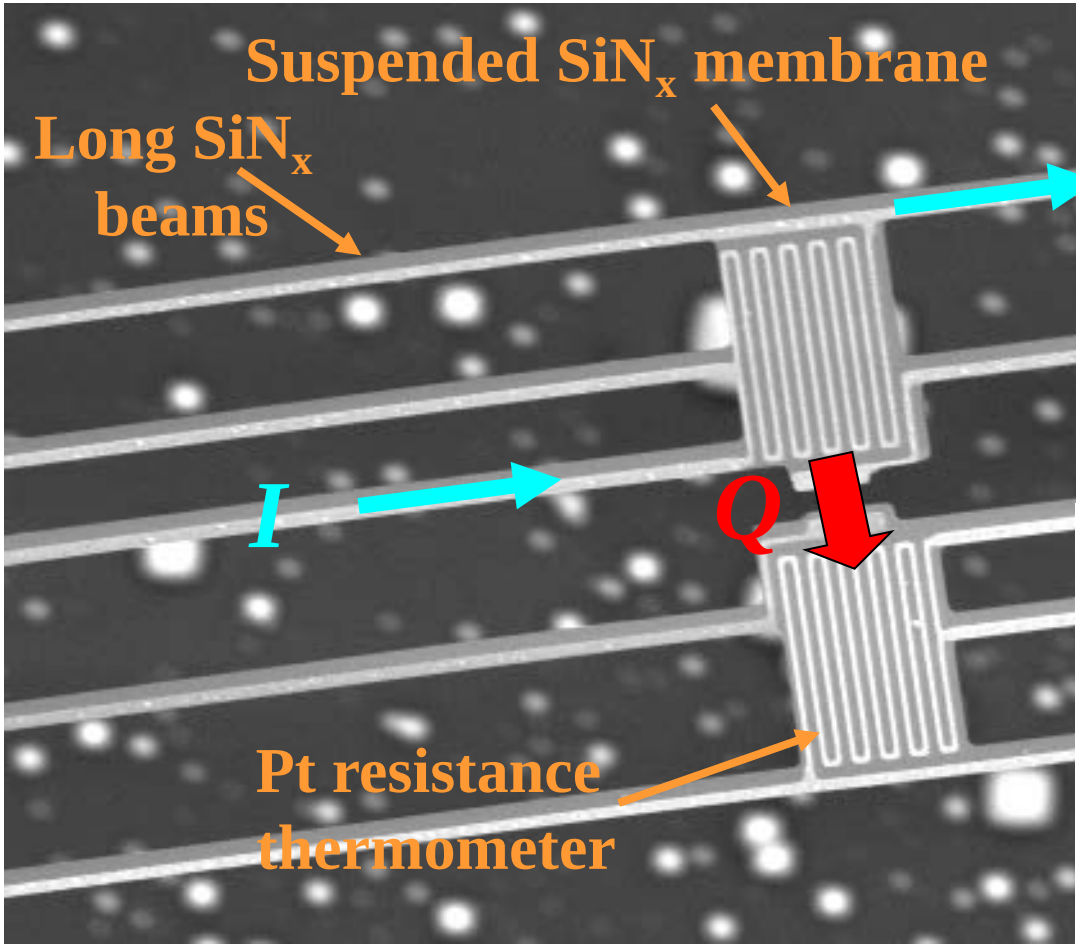


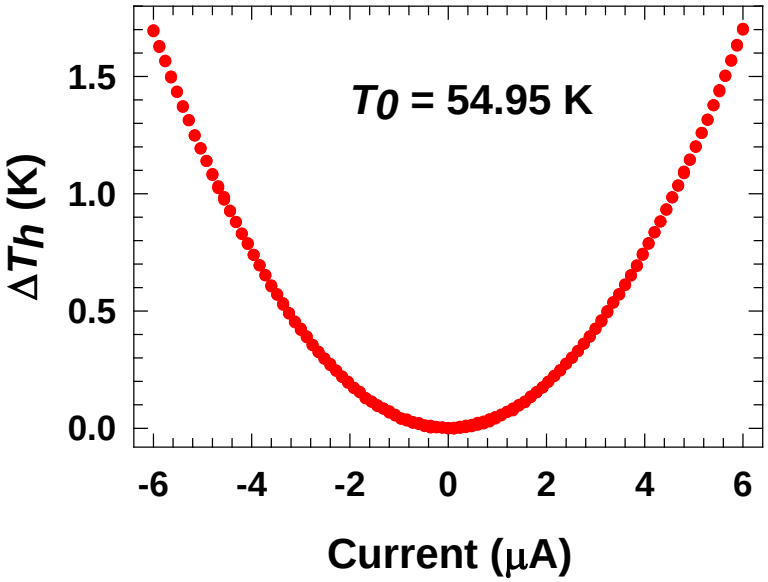
Javad Shabani, Xi Wang et al. Material Research Society Spring Meeting 2007

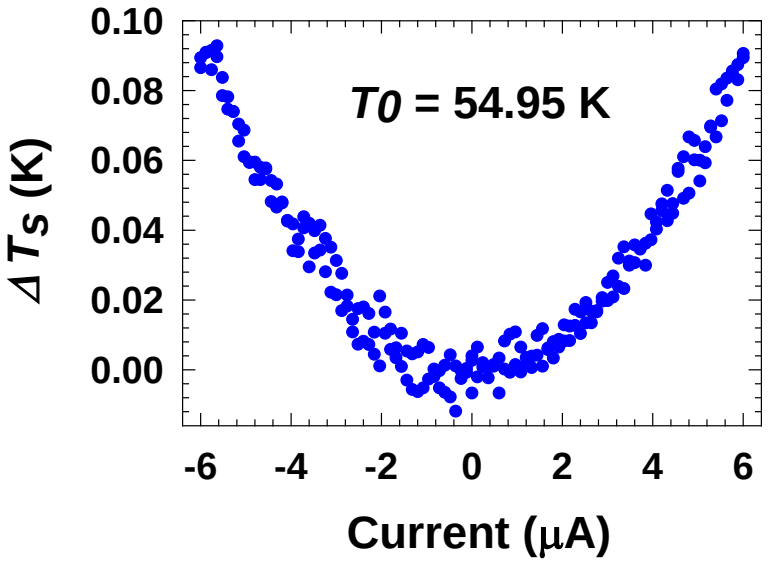


Thermal Measurements of Nanowires

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



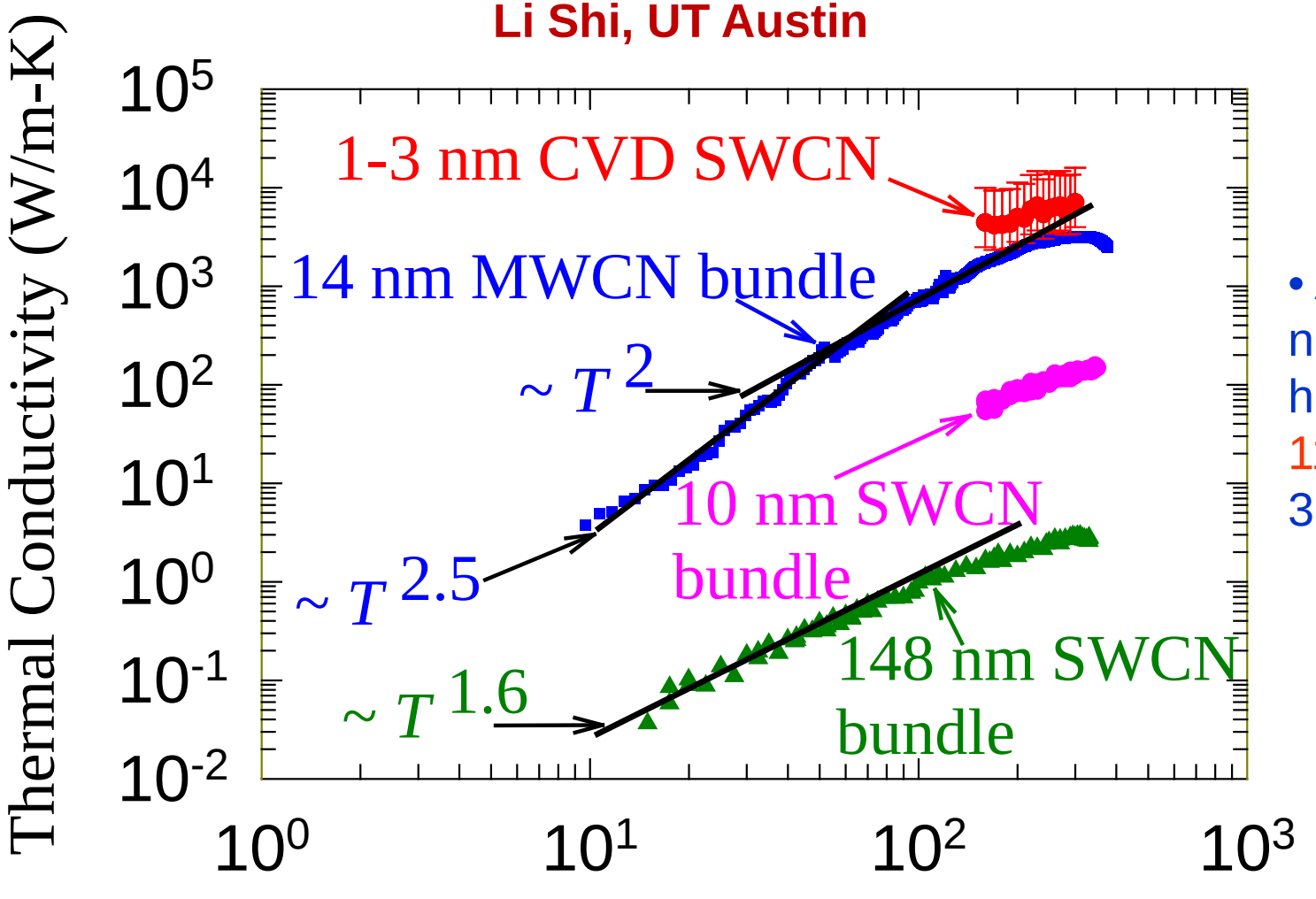




Kim et al, *PRL* **87**, 215502
Shi et al, *JHT*

Thermal Conductivity of Carbon Nanotubes

Li Shi, UT Austin

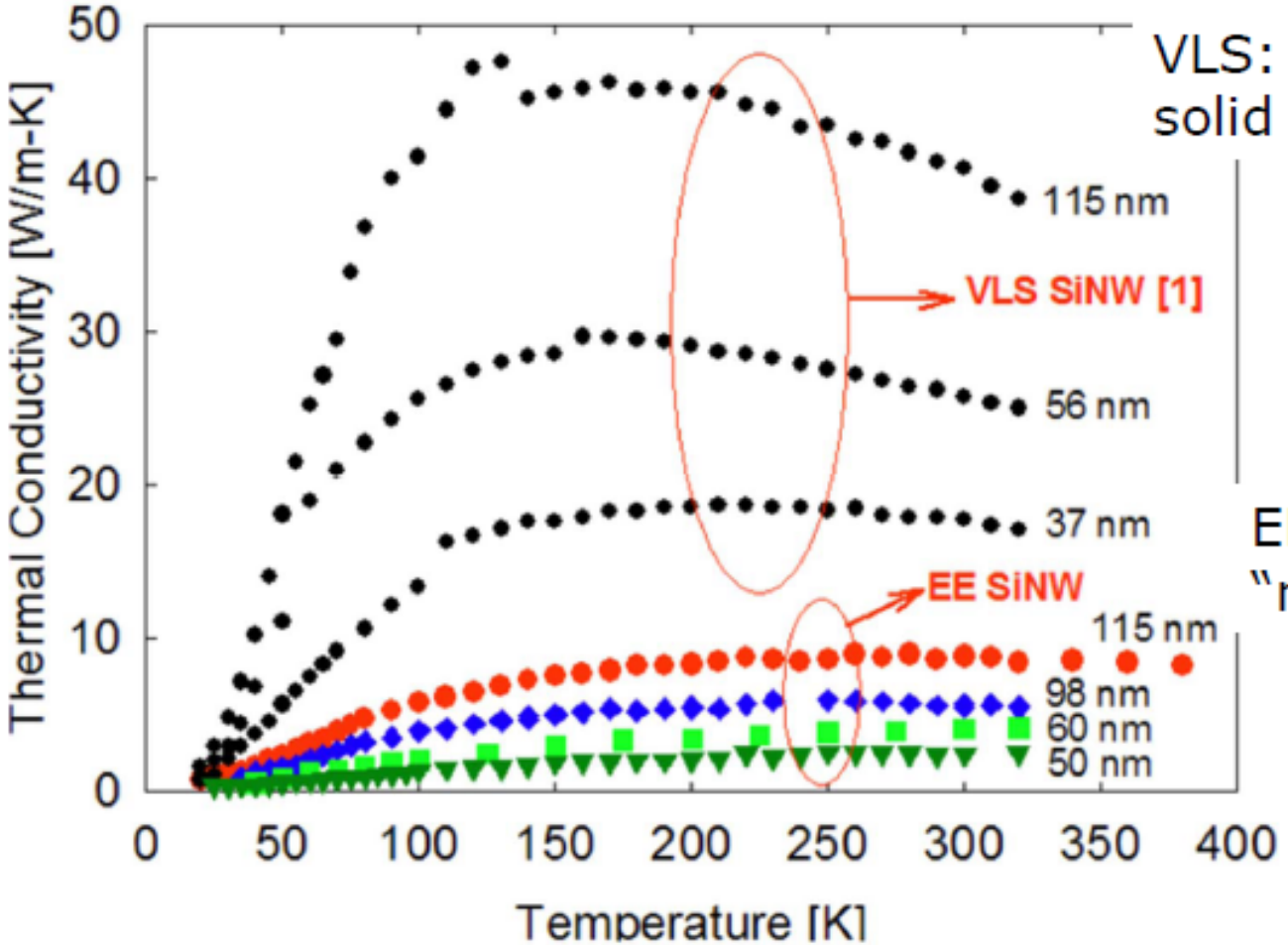


- An individual nanotube has a high *k* ~ 2000-11000 W/m-K at 300 K

A. Shakouri, *Proceedings of IEEE*, July 2006

New phonon physics in roughened nanowires?

Single Si nanowire measurements by Majumdar, Yang, and co-workers (2008)



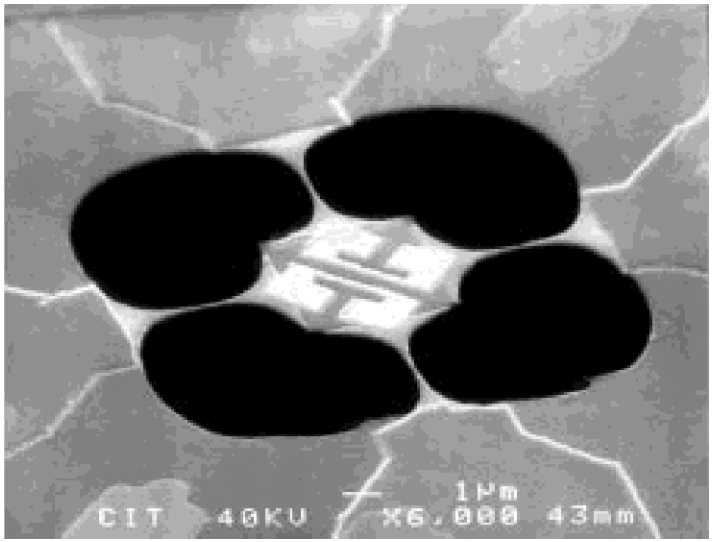
VLS: vapor-liquid-solid "smooth"

EE: electroless-etched "rough"

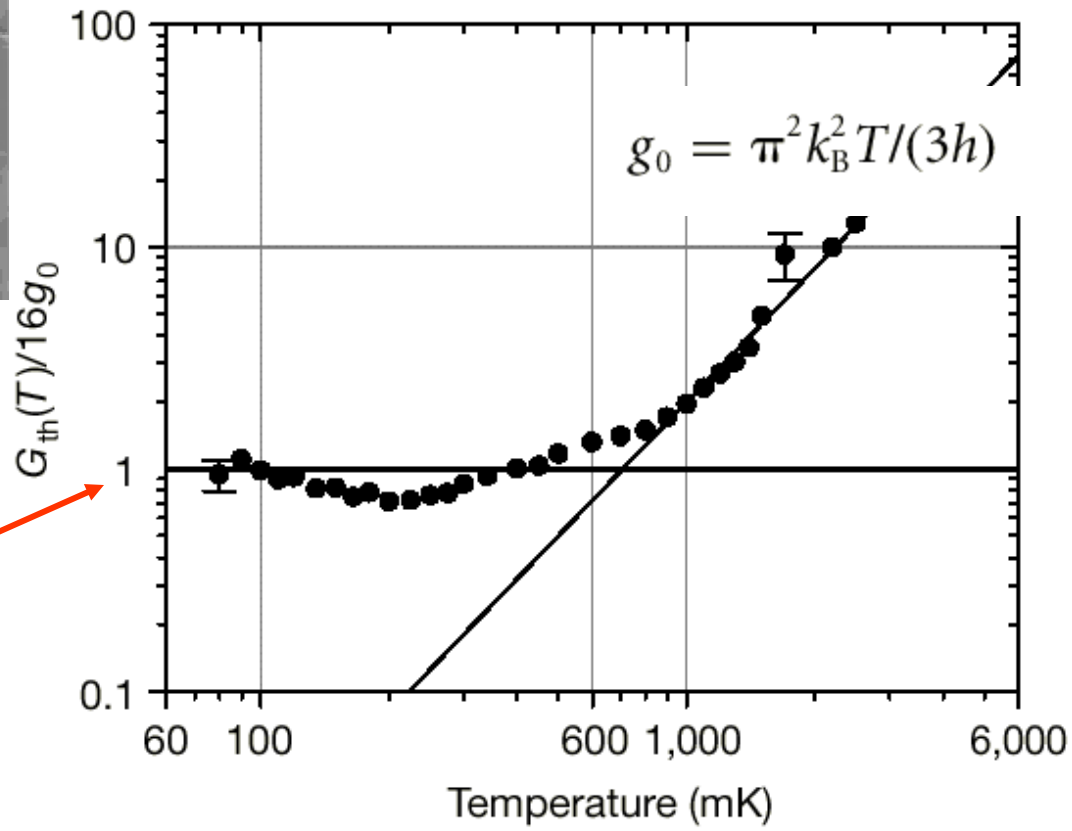
David Cahill (UIUC)

Nano Electromechanical System (NEMS)

Thermal conductance quantization in nanoscale SiN_x beams
(Schwab *et al.*, *Nature* 404, 974)



Quantum of Thermal Conductance



Lecture 3.3: Summary

- Thermoreflectance imaging
  - Steady-state and transient measurements
  - Calibration issues
- Micro Raman
- Suspended heaters