The Abdus Salam
International Centre
for Theoretical Physics

2371-8

Advanced Workshop on Energy Transport in Low-Dimensional Systems: Achievements and Mysteries

15 - 24 October 2012

Nanoscale Thermal and Thermoelectric Characterization Techniques

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in Low Dimensional Systems
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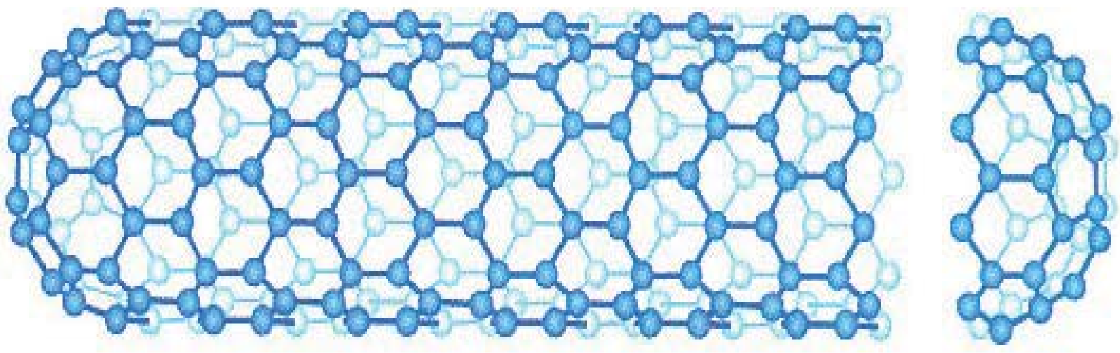
Thermal Transport in Low Dimension

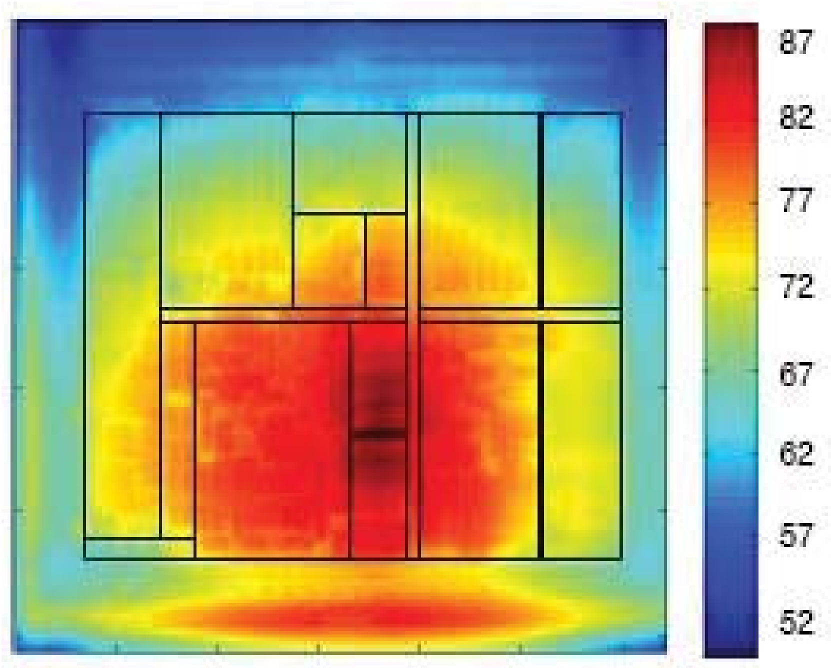


Thermal conductivity value?

Deviations from Fourier?

Non uniform temperature in CPUs (central processing units)

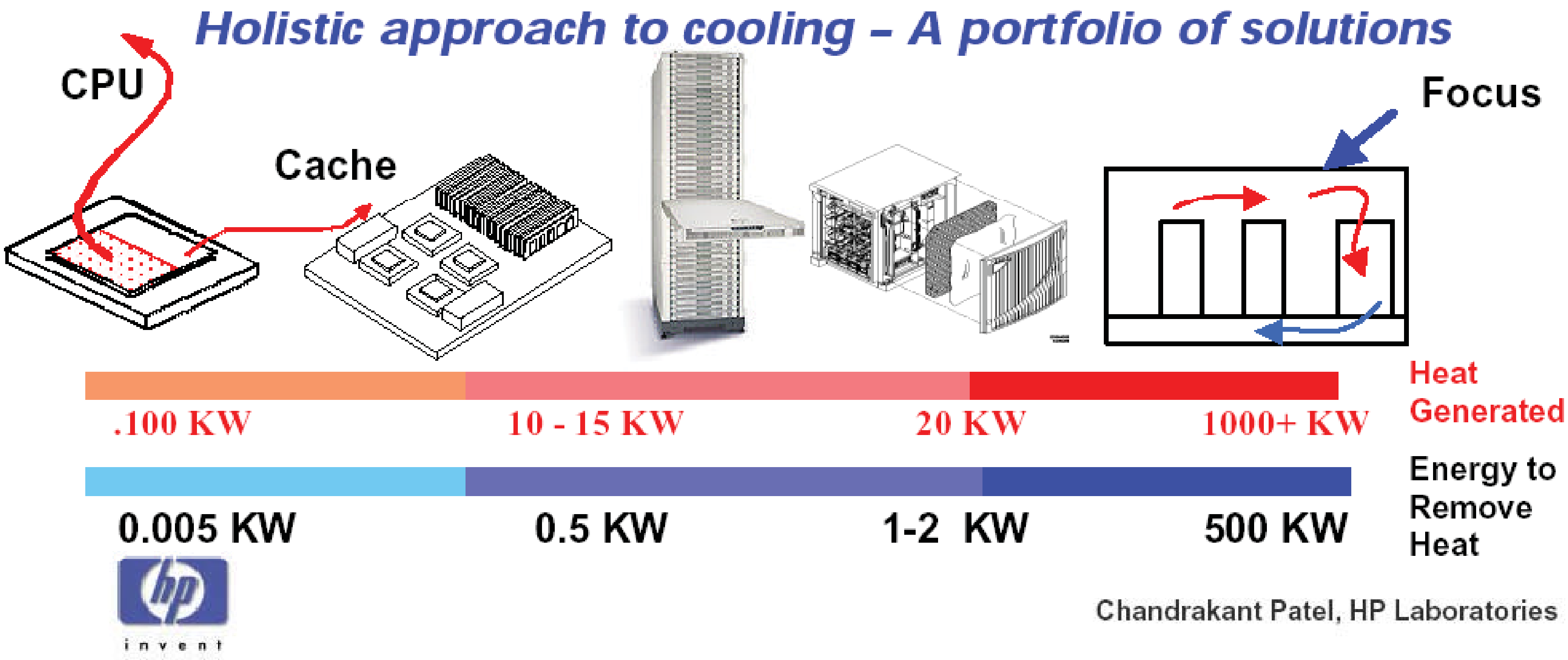
- Leakage power exponential increase with temperature
  - Potential thermal runaway
- Lifetime exponential decrease with temperature
  - (ΔT= 15C → ¼ lifetime)



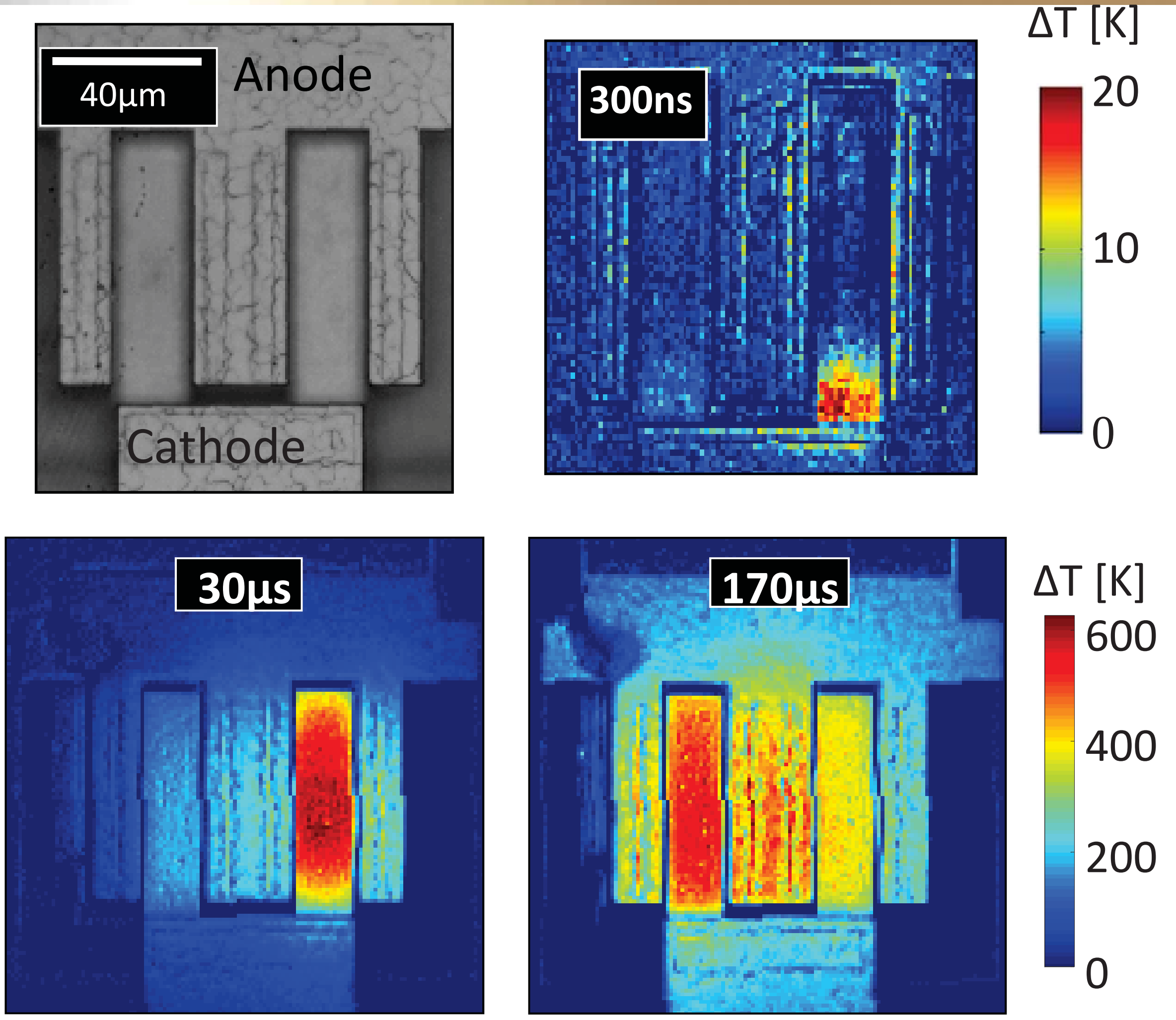
Measuring Power and Temperature from Real Processors, Javi Martinez, Jose Renau, et al. *The Next Generation Software (NGS) Workshop (**NGS08**),* April 2008

http://masc.cse.ucsc.edu

Power dissipation challenges



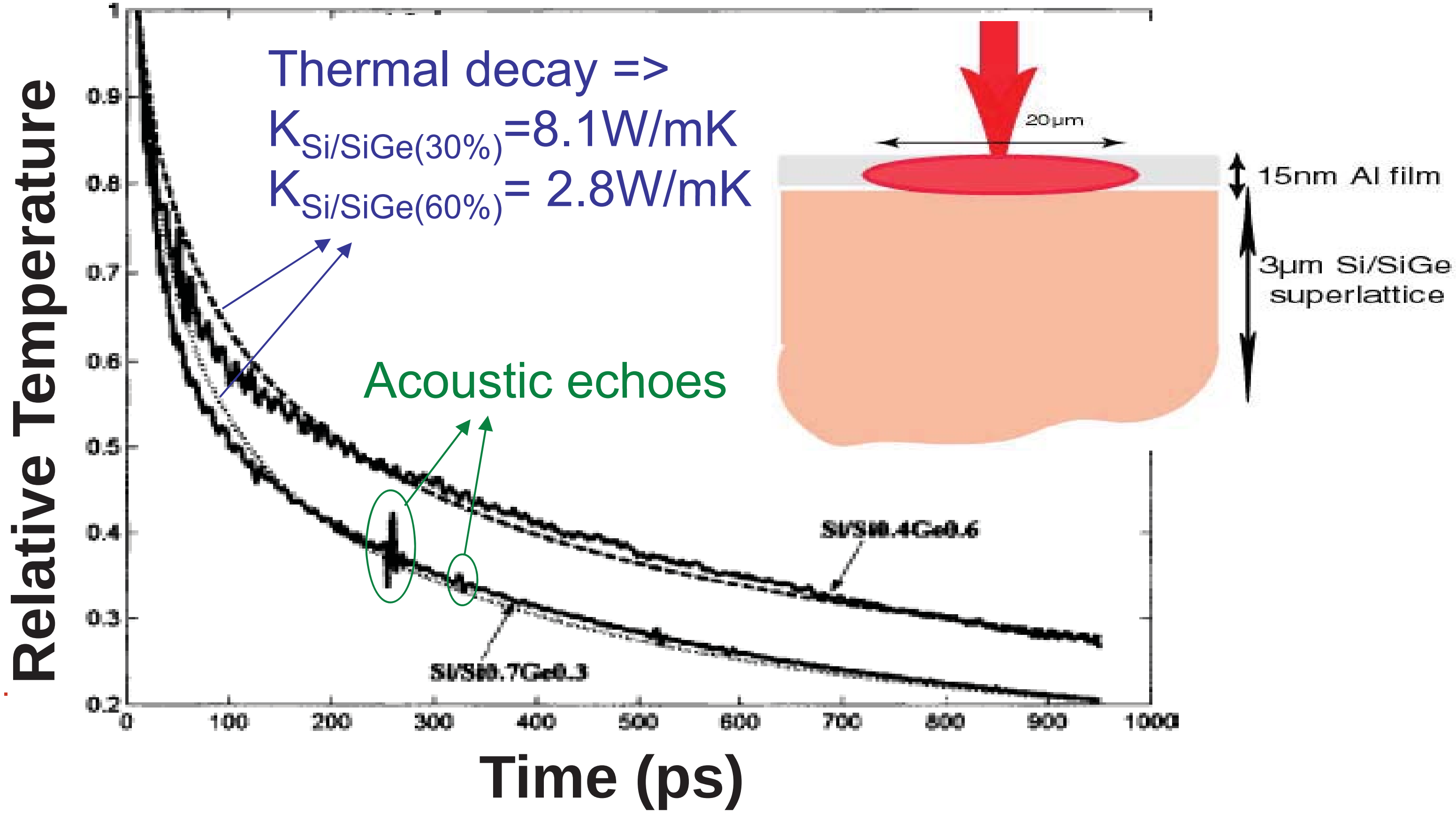
Heating in Electro Static Discharge Devices



Snapback current =1.22A.

K. Maize, V. Vashchenko et al, *IRPS*, 2011.

Thin Film Thermal Characterization



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

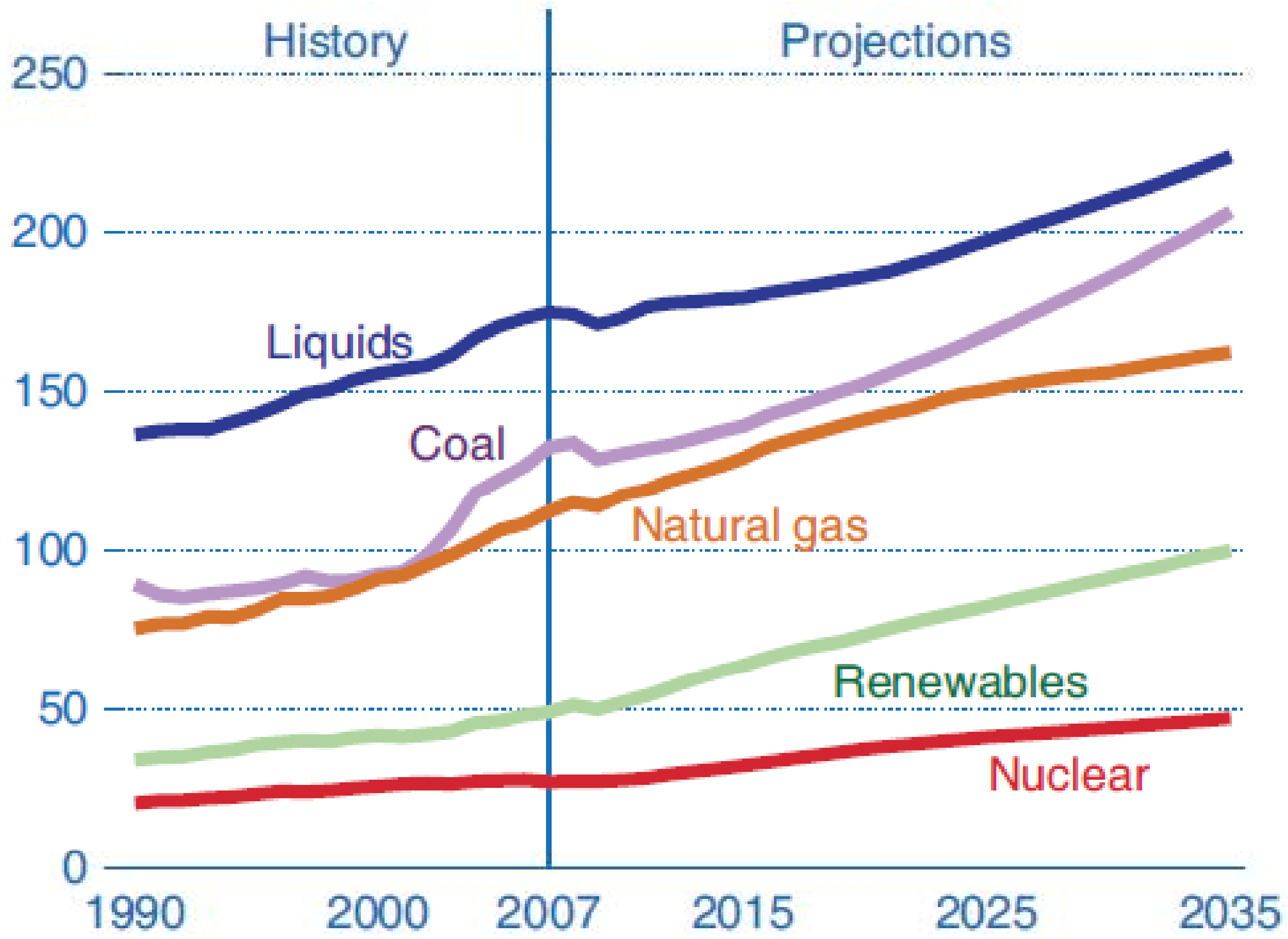
Metal film is heated by laser pulse and it acts as a heat source. It can characterize thermal interface resistances as well as thin film thermal conductivity.

World Marketed Energy Use1990-2035

US Department of Energy; Energy Information Administration (2010)

1 Quad = 1.055 x 10^{18}J

1 EJ = 31.7 GW



CO_2 Emission Goals (2000-2100)

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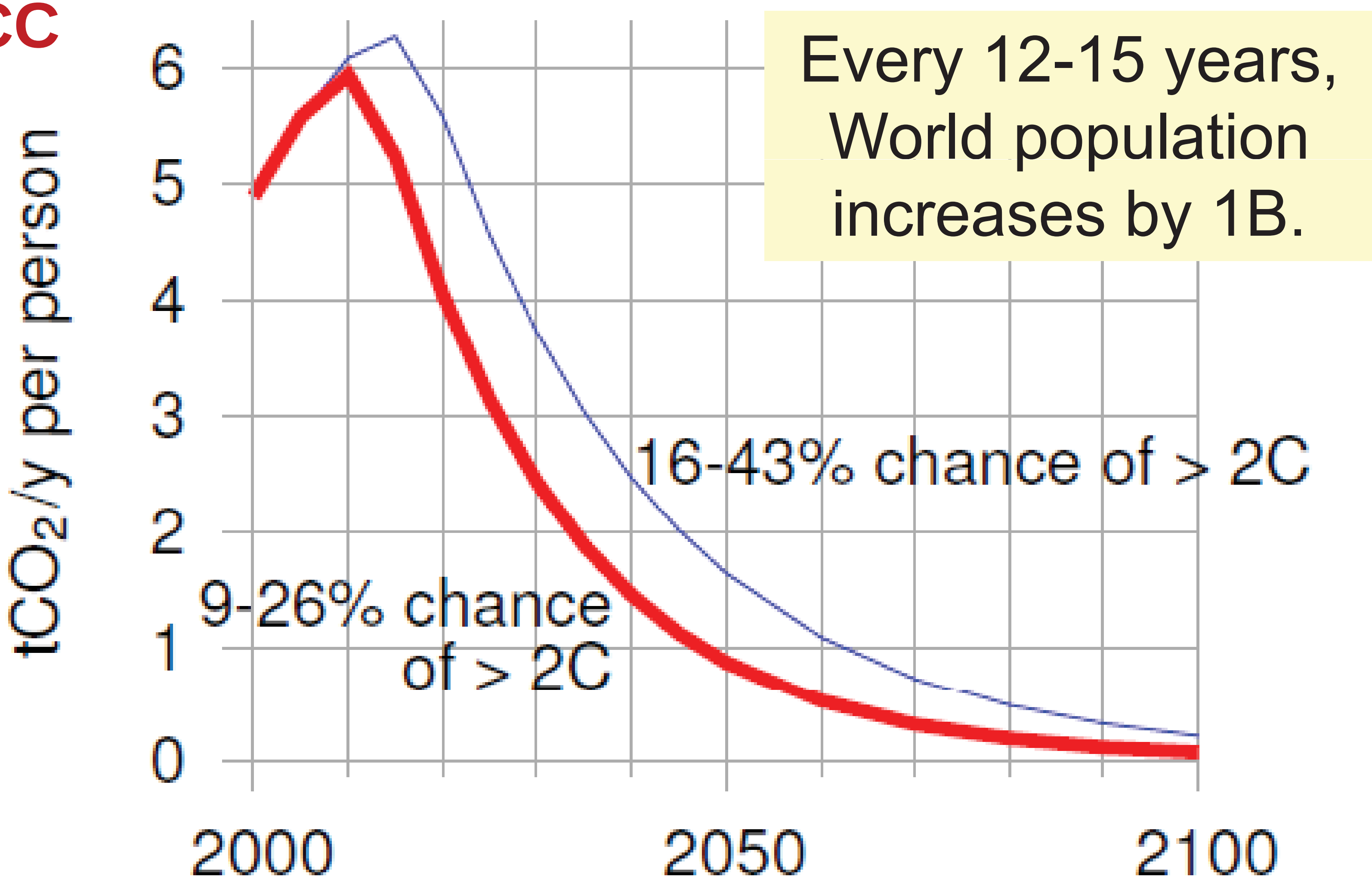
IPCC



David McKay, Sustainable Energy -Without the Hot Air

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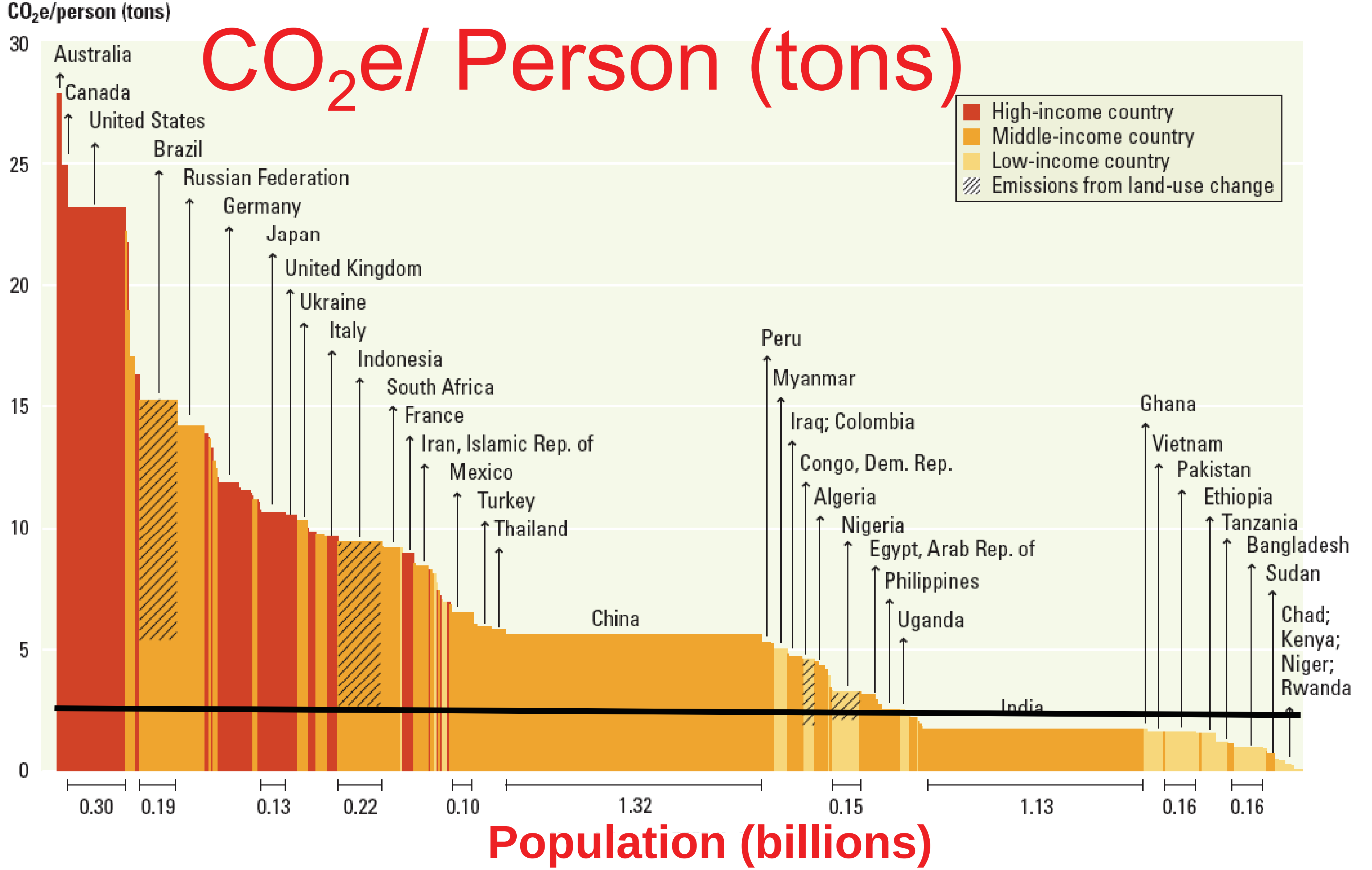
Figure 1.1 Individuals' emissions in high-income countries overwhelm those in developing countries



Sources: Emissions of greenhouse gases in 2005 from WRI 2008, augmented with land-use change emissions from Houghton 2009; population from World Bank 2009c.

Note: The width of each column depicts population and the height depicts per capita emissions, so the area represents total emissions. Per capita emissions of Qatar (55.5 tons of carbon dioxide equivalent per capita), UAE (38.8), and Bahrain (25.4)—greater than the height of the y-axis—are not shown. Among the larger countries, Brazil, Indonesia, the Democratic Republic of Congo, and Nigeria have low energy-related emissions but significant emissions from land-use change; therefore, the share from land-use change is indicated by the hatching.

World Energy Use in 2005 (15TW)

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- More than 90% of primary energy is first converted to heat.
- Overall end-use exergy (12% of sources):
  - Motion 0.95 TW
  - Heat 0.73 TW
  - Cooling/Light/Sound 0.06 TW

Adapted from Cullen and Allwood, *Energy*, 2010

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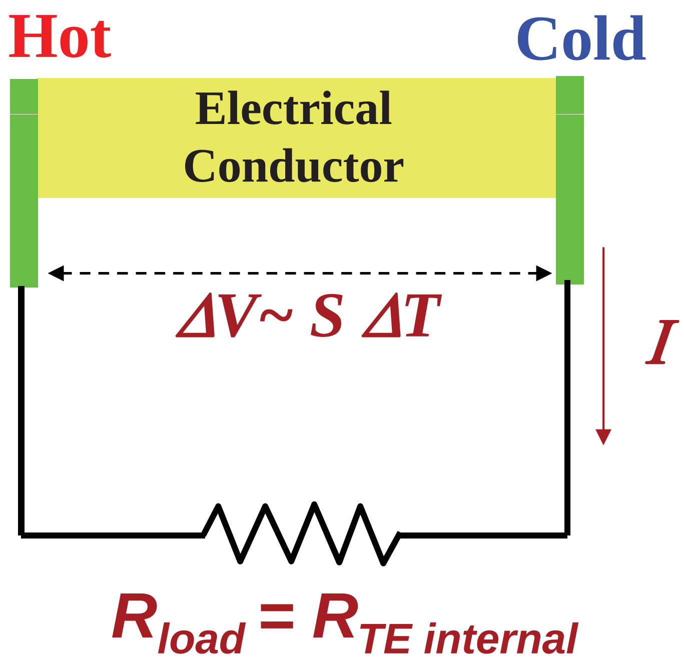
Direct Conversion of Heat into Electricity

Seebeck coefficient (1821) $S = \dfrac{\Delta V}{\Delta T}$

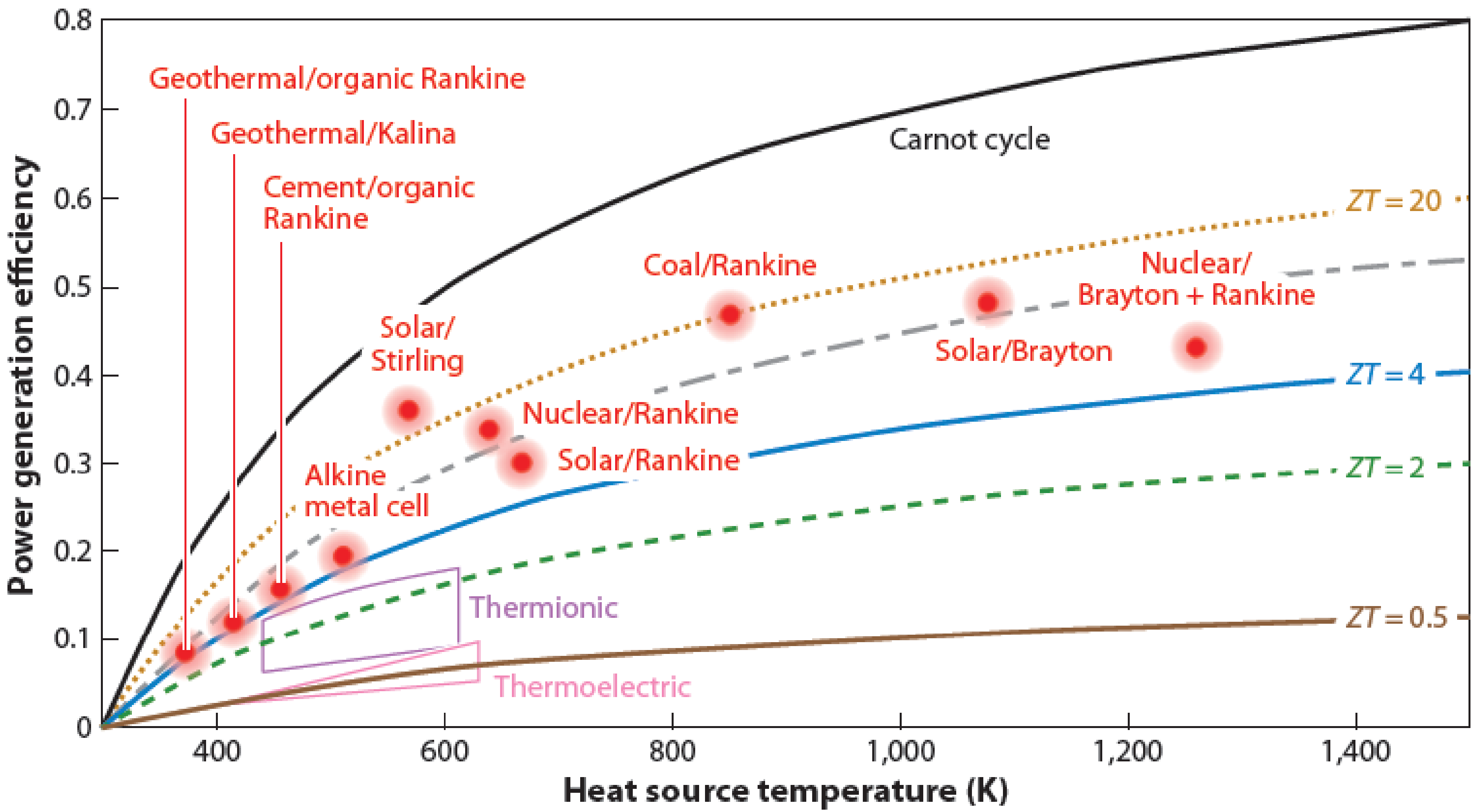


Efficiency function of thermoelectric figure-of-merit (Z)

$$Z = \frac{S^2 \sigma}{k}$$

$$Z = \frac{(Seebeck)^2 (electrical \quad conductivity)}{(thermal \quad conductivity)}$$

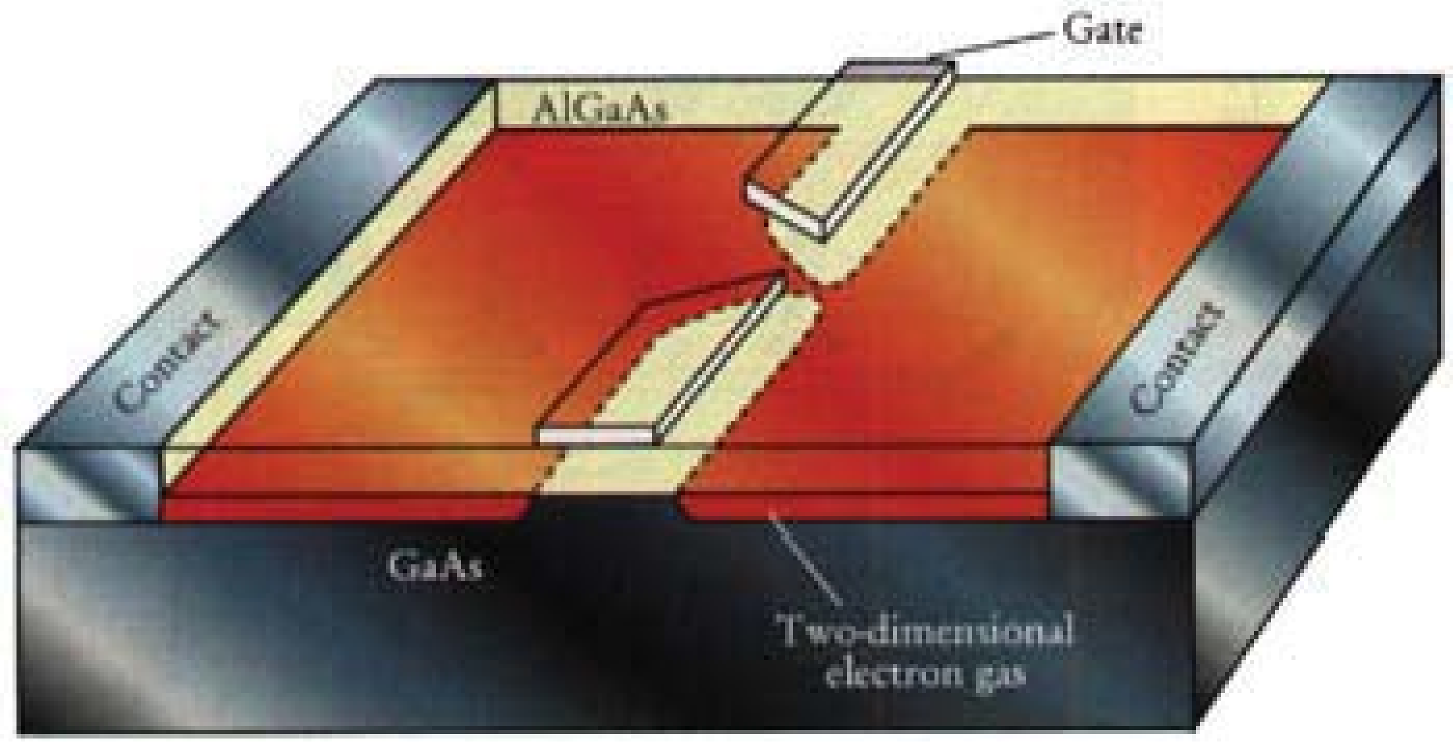
Power Generation Efficiencies



K. Yazawa and A. Shakouri, J. Appl. Phys. 111, 024509 (2012)

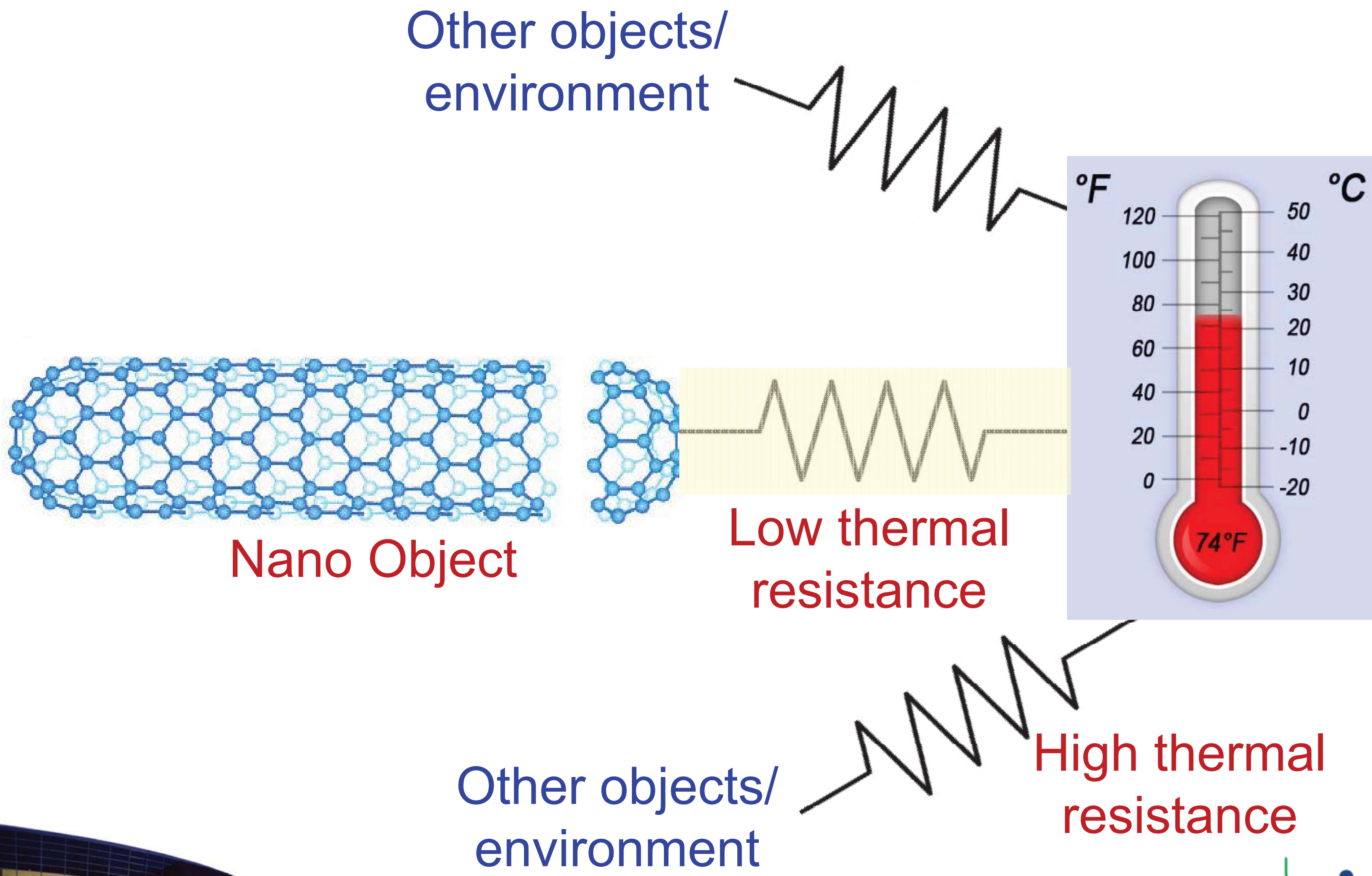
Adapted from Cronin Vining, Nature Materials 2009

Measuring voltage at nanometer scale



Quantum Point Contact

Measuring temperature at nanometer scale



Measuring heat flow at nanometer scale

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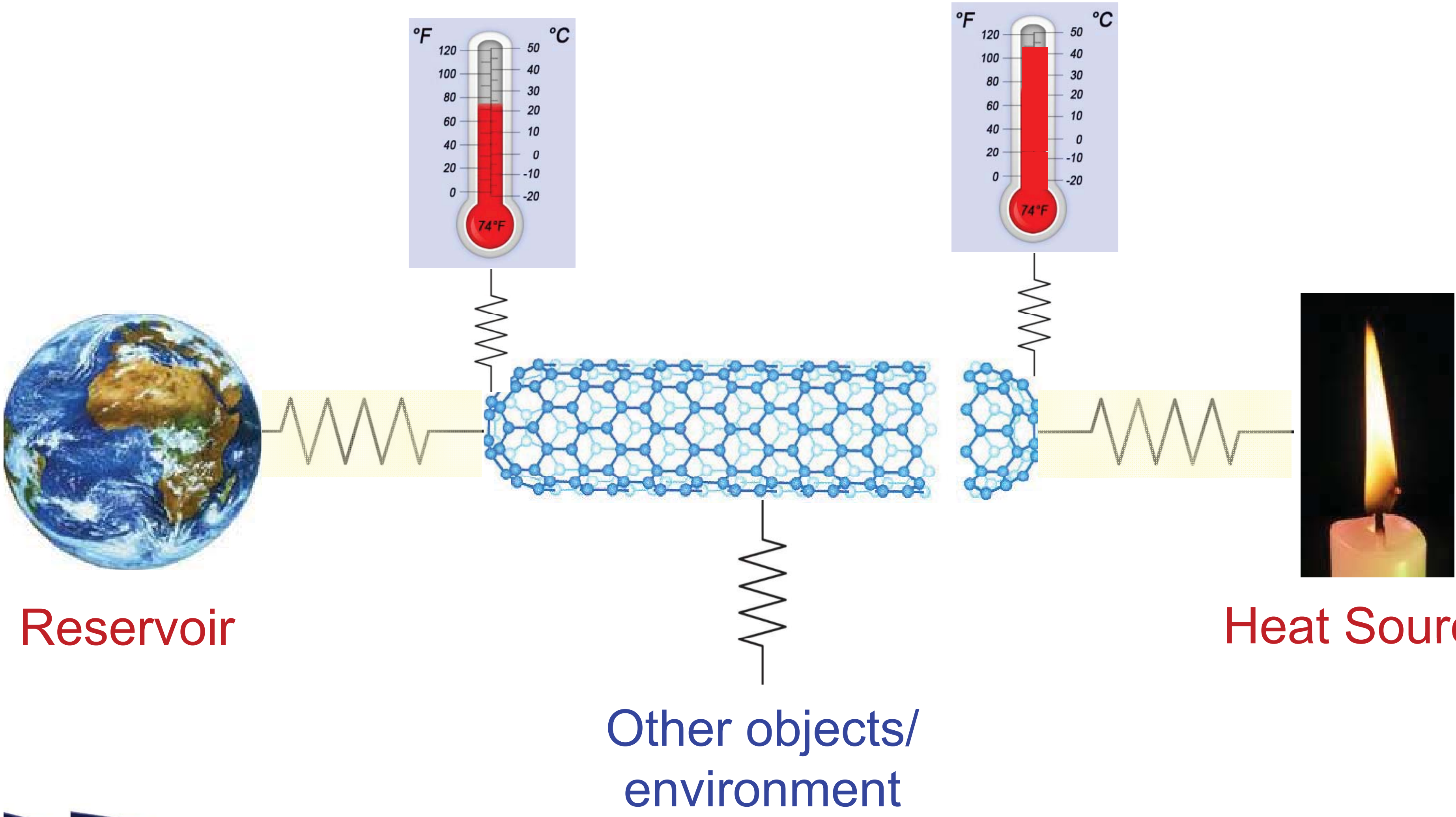
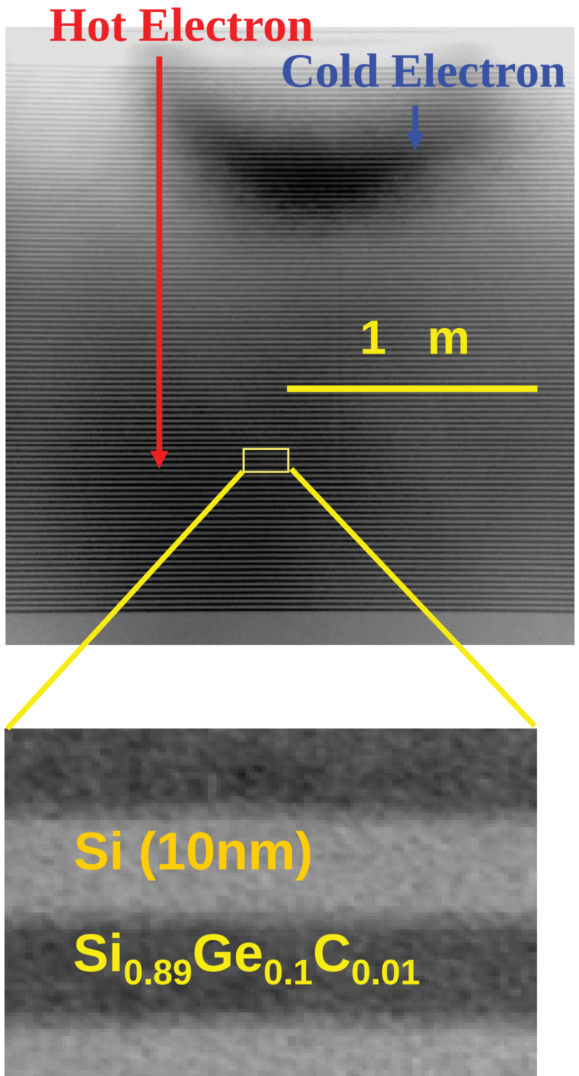


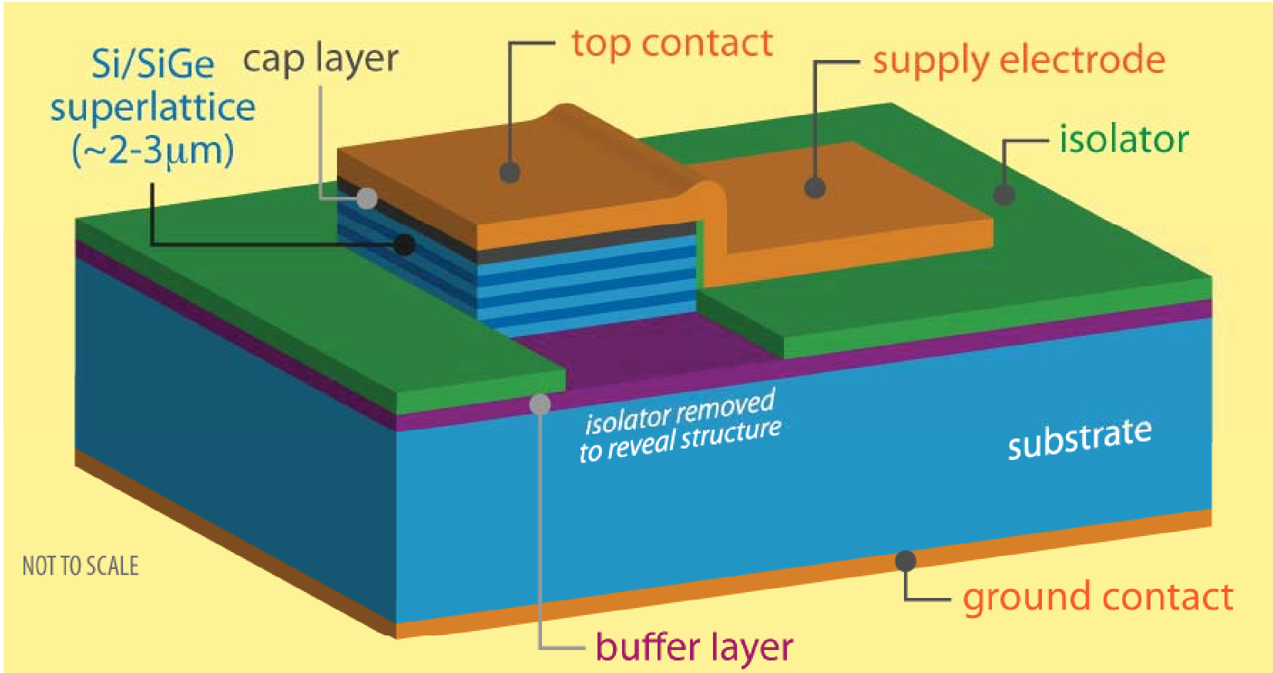
Classical thermal imaging techniques

Method	Principle
Micro-thermocouple	Seebeck effect
Infrared Thermography	Planck blackbody emission
Liquid Crystal Thermography	Crystal phase transitions (change color)

Microrefrigerators on a chip



Implement selective emission of hot electrons (evaporative cooling) with heterostructure barriers.



Heterostructure Integrated Thermionic Coolers; A. Shakouri and John Bowers, **Appl. Phys. Lett.** 1997

Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, **Proceedings of IEEE**, July 2006

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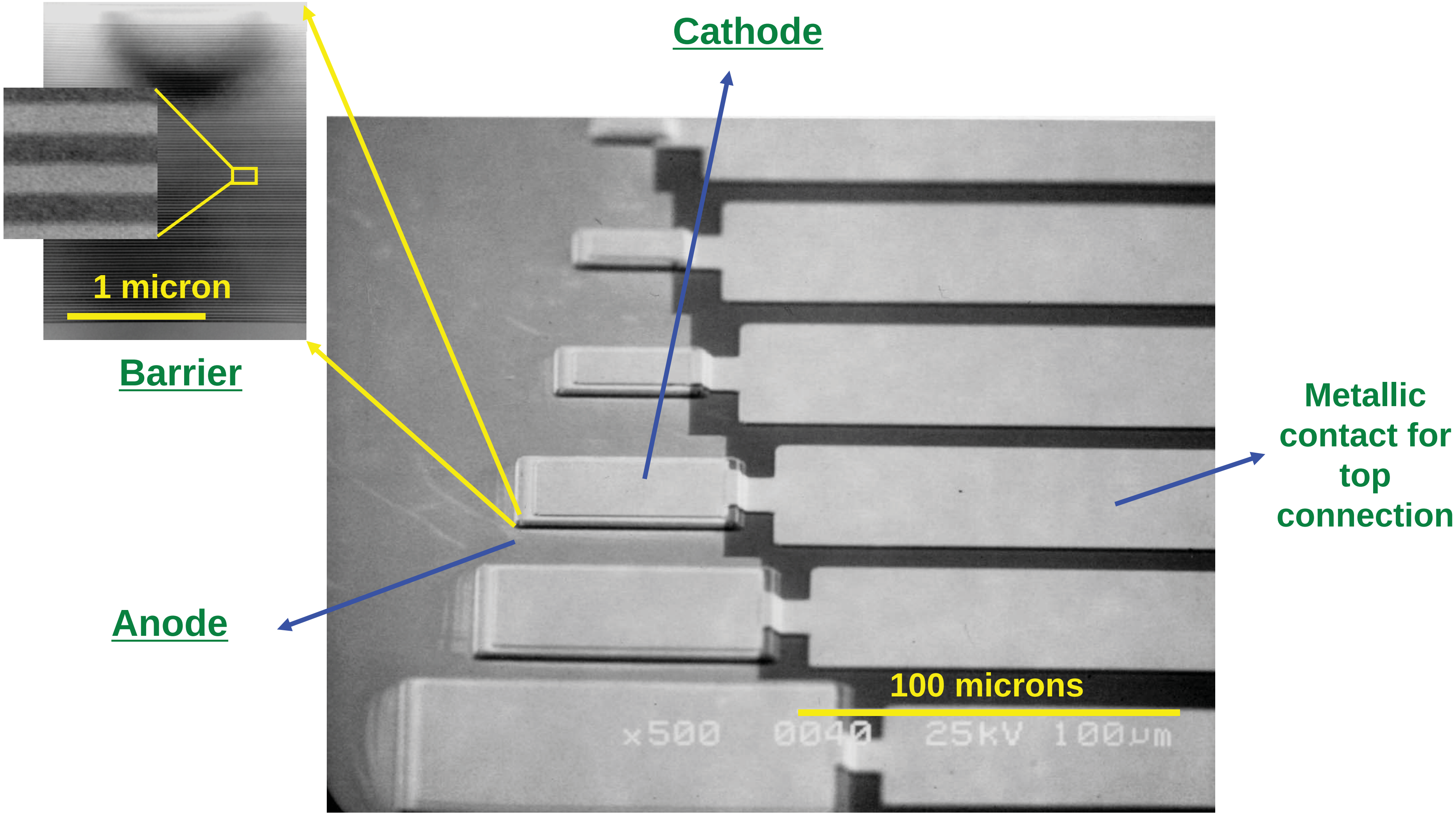
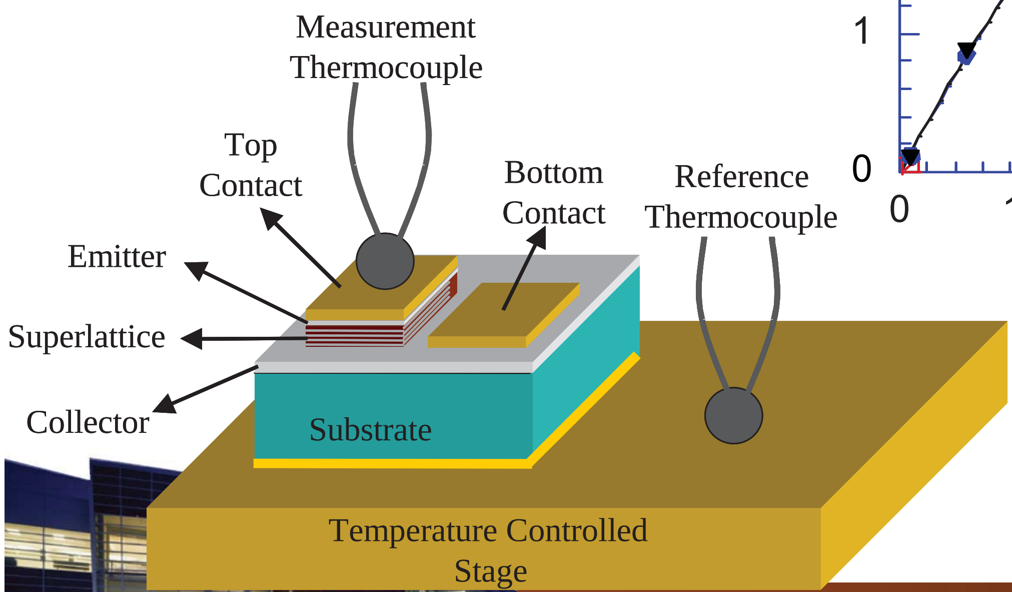
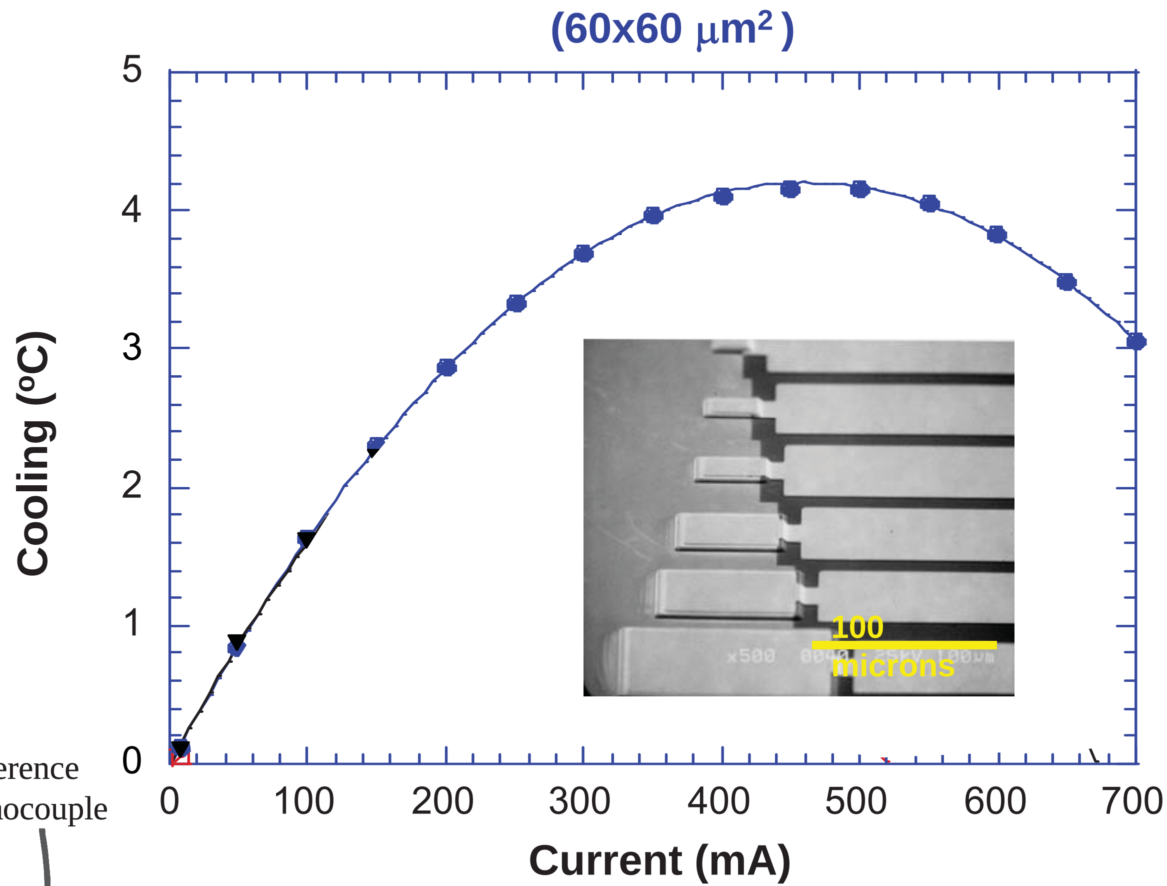
Si/SiGe Micro refrigerator on a chip



X. Fan, E.Croke, J.E. Bowers, A. Shakouri, et al., *Applied Physics Lett.* 78 (11), 2001.

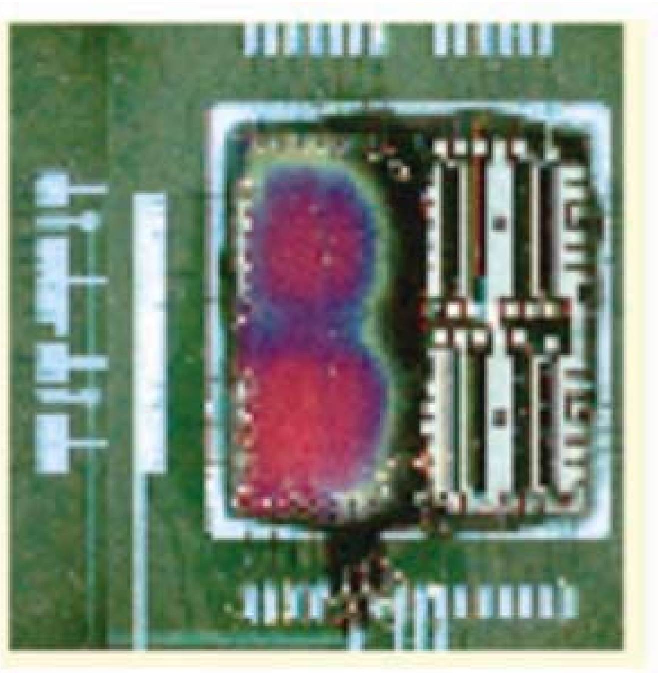
Micro thermocouple measurements: Cooling vs. Current

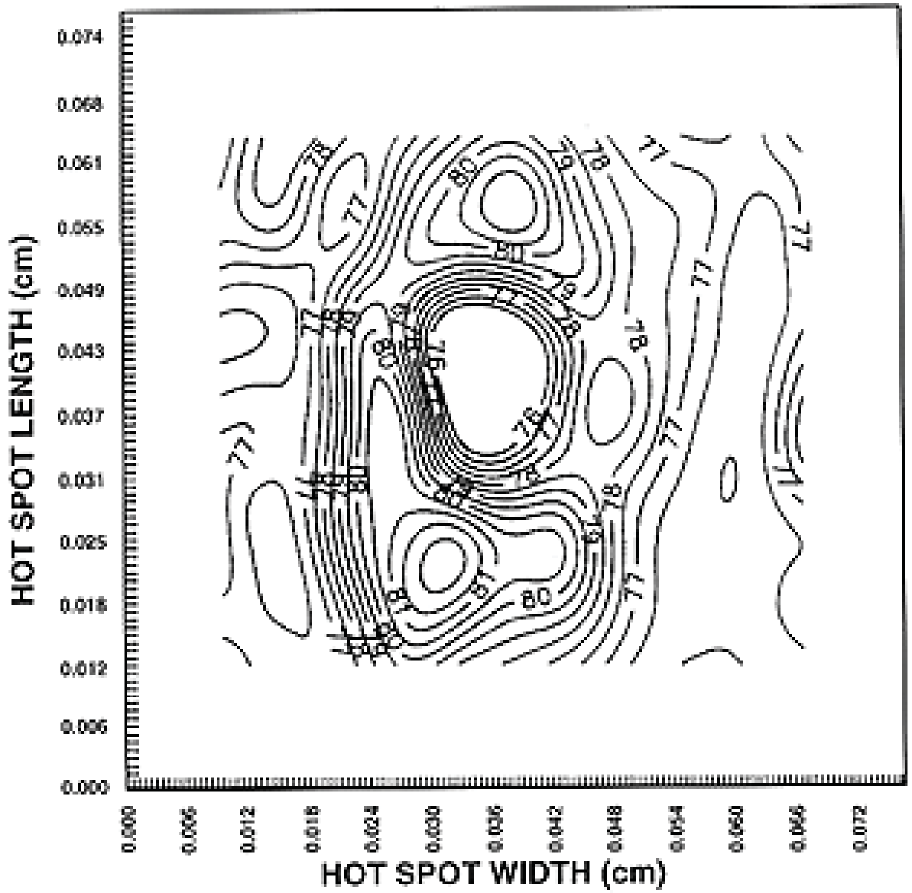




X. Fan, E. Croke, A. Shakouri, J. E. Bowers, …
"**SiGe/Si Superlattice Coolers**," Phys. Low-Dim. Struct., 5/6 (2000) pp. 1-10.

Liquid Crystal Thermography





www.electronics-cooling.com

Calibrated infrared imaging

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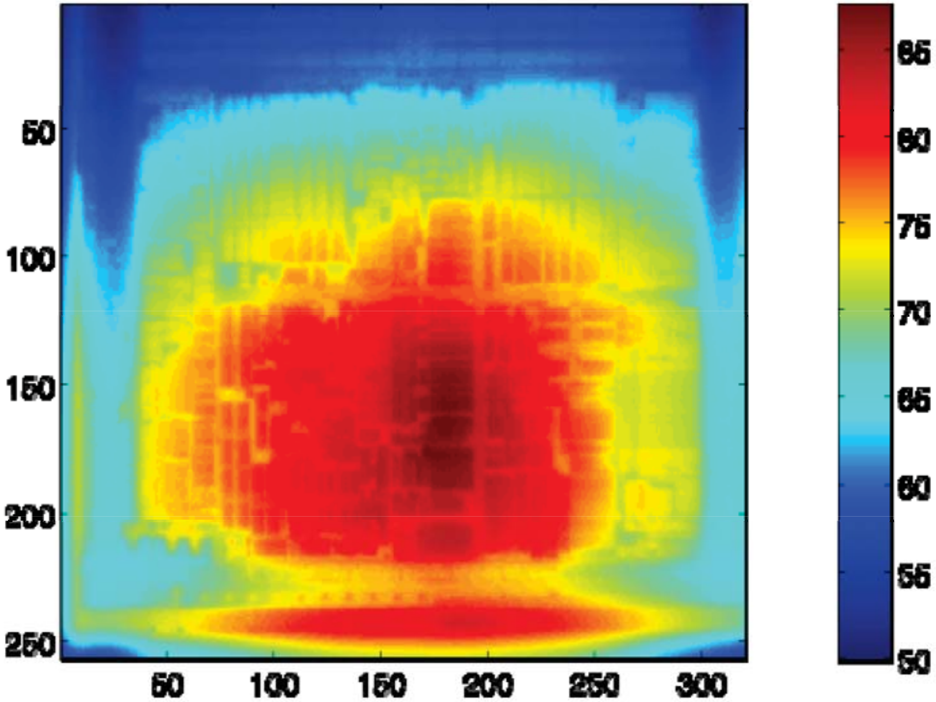
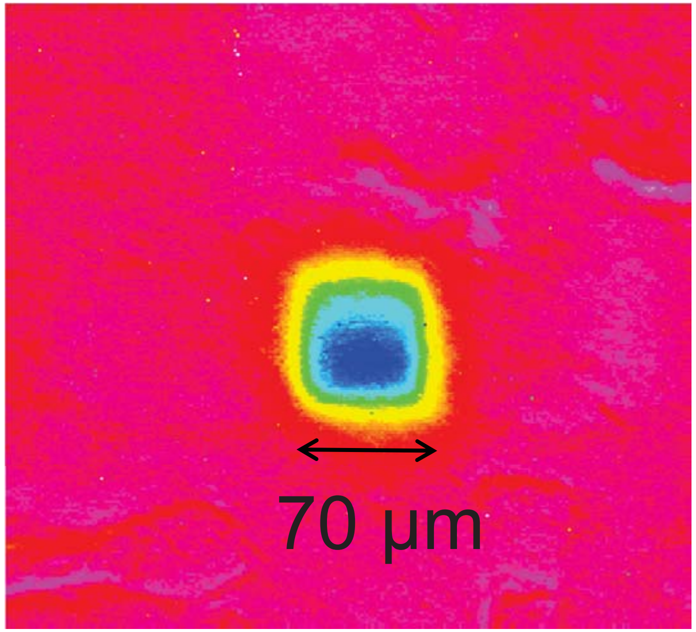
AMD Processor (cm)



Francisco Mesa-Martinez, Jose Renau, UCSC

http://masc.cse.ucsc.edu

Microrefrigerator



Vivek Sahu, Georgia Tech

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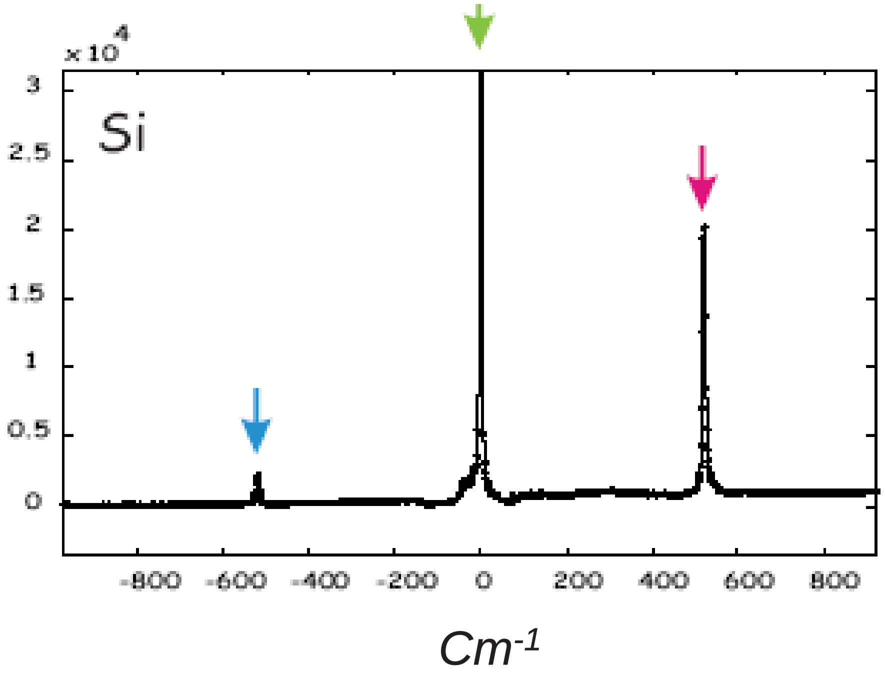
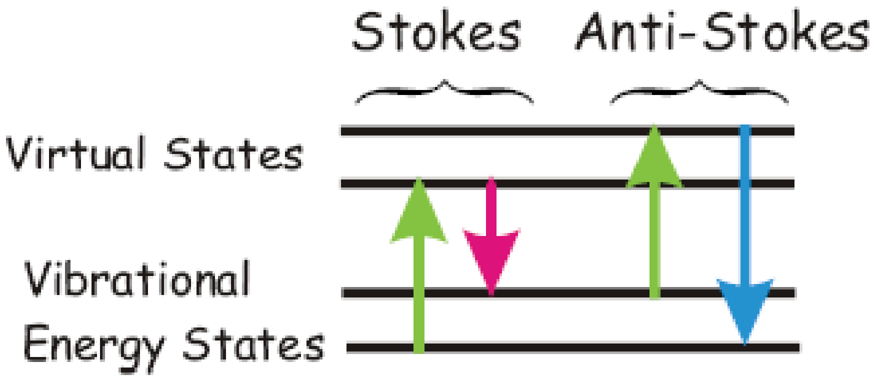
Advanced thermal imaging techniques

Method	Principle
Scanning thermal microscopy (SThM)	AFM with thermocouple or Pt thermistor tip
Optical Interferometry	Thermal Expansion, Michelson type
Micro Raman	Raman peak position and intensity is function of absolute T
Near Field Probe (NSOM)	Use near field to improve optical resolution

Raman spectroscopy and temperature measurement

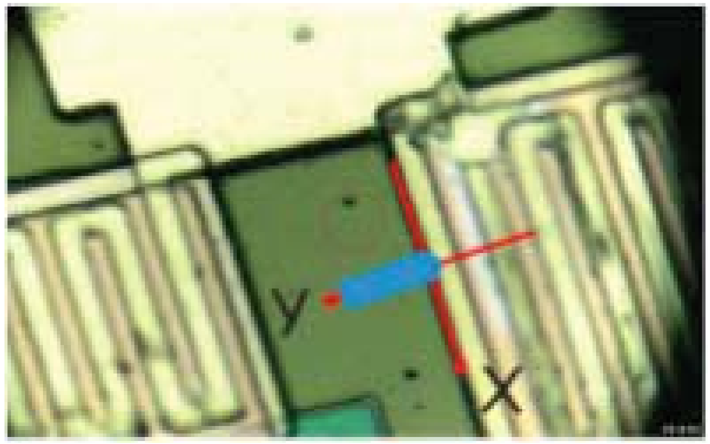
Scattered light intensity versus wavelength shift

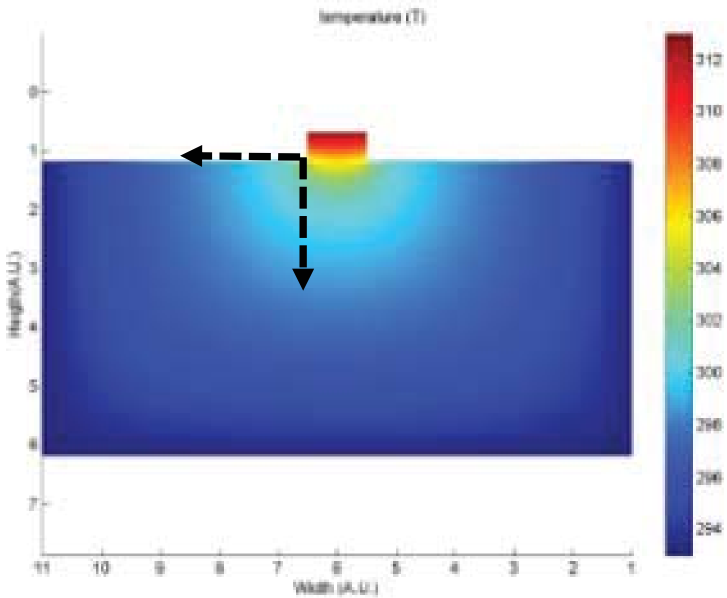


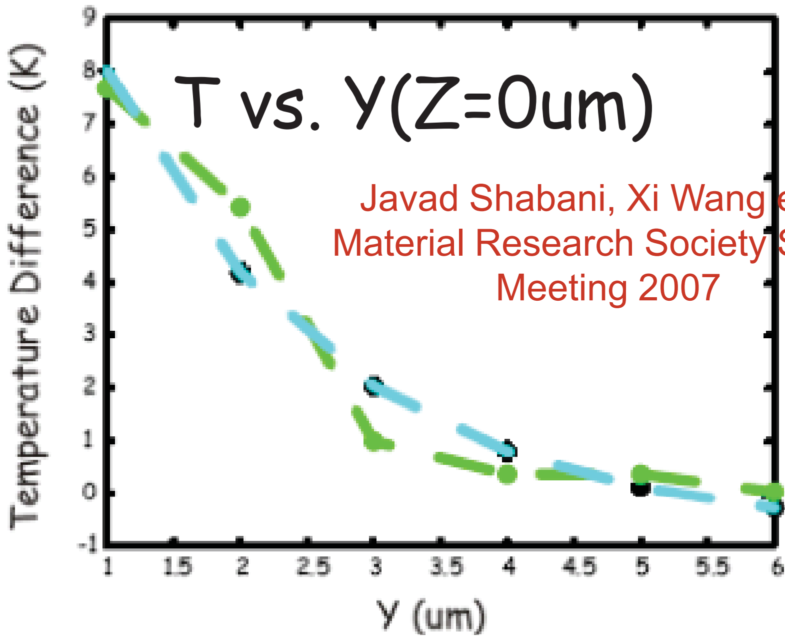


Needs laser illumination, high resolution spectrometer and a notch filter

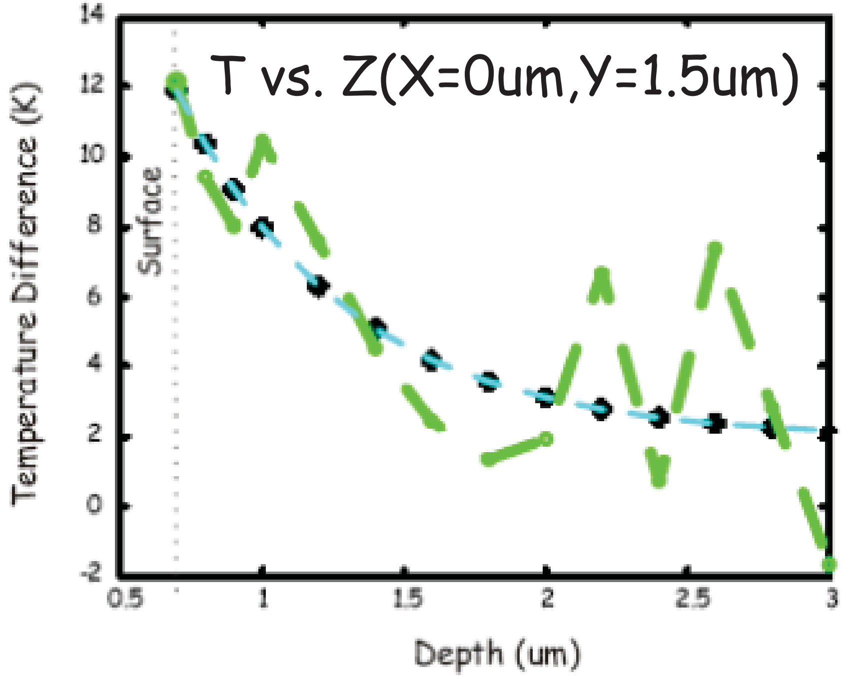
3D Raman temperature measurement



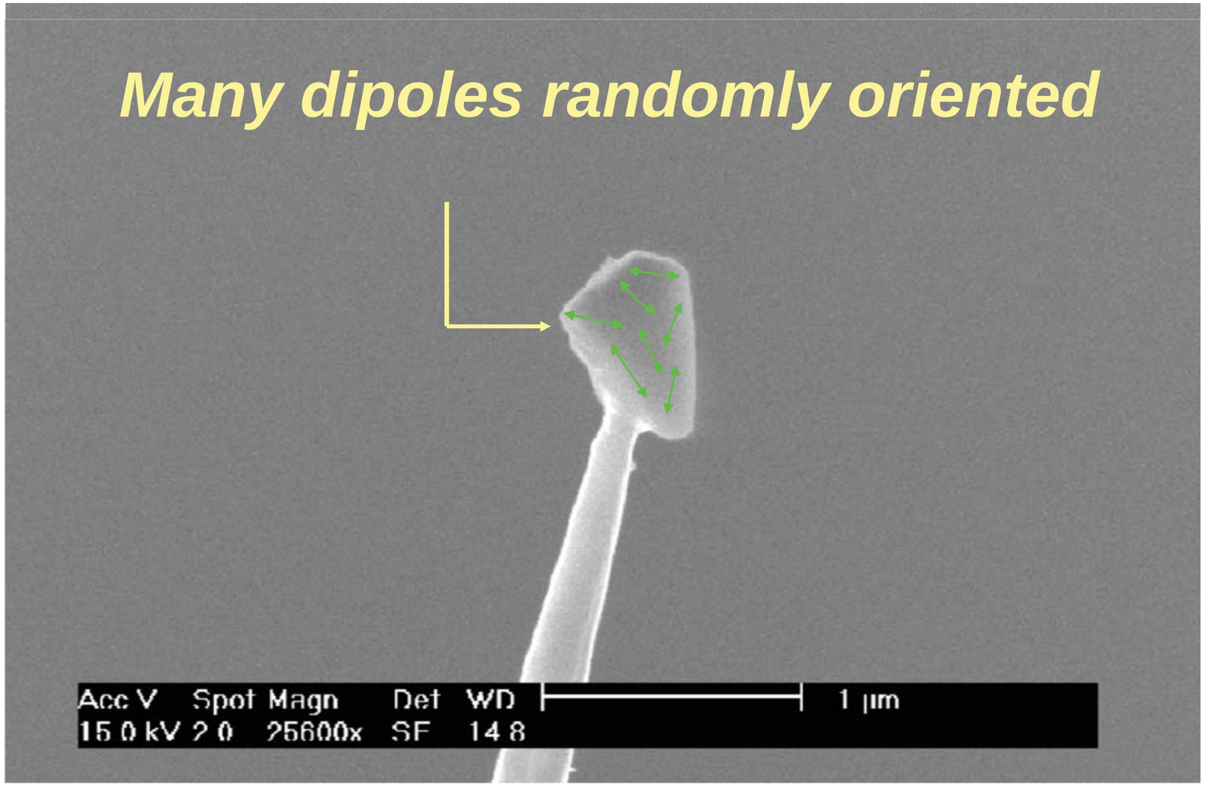




Javad Shabani, Xi Wang et al.
Material Research Society Spring
Meeting 2007



Thermal imaging of nanostructures with a scanning fluorescent particle as a probe



APL, 83, 147 (2003)

Simplicity

Infrared excitation :
emission and absorption lines well separated

Lionel Aigouy, ESPCI, Paris, France

HOW CAN WE DEDUCE THE TEMPERATURE ?

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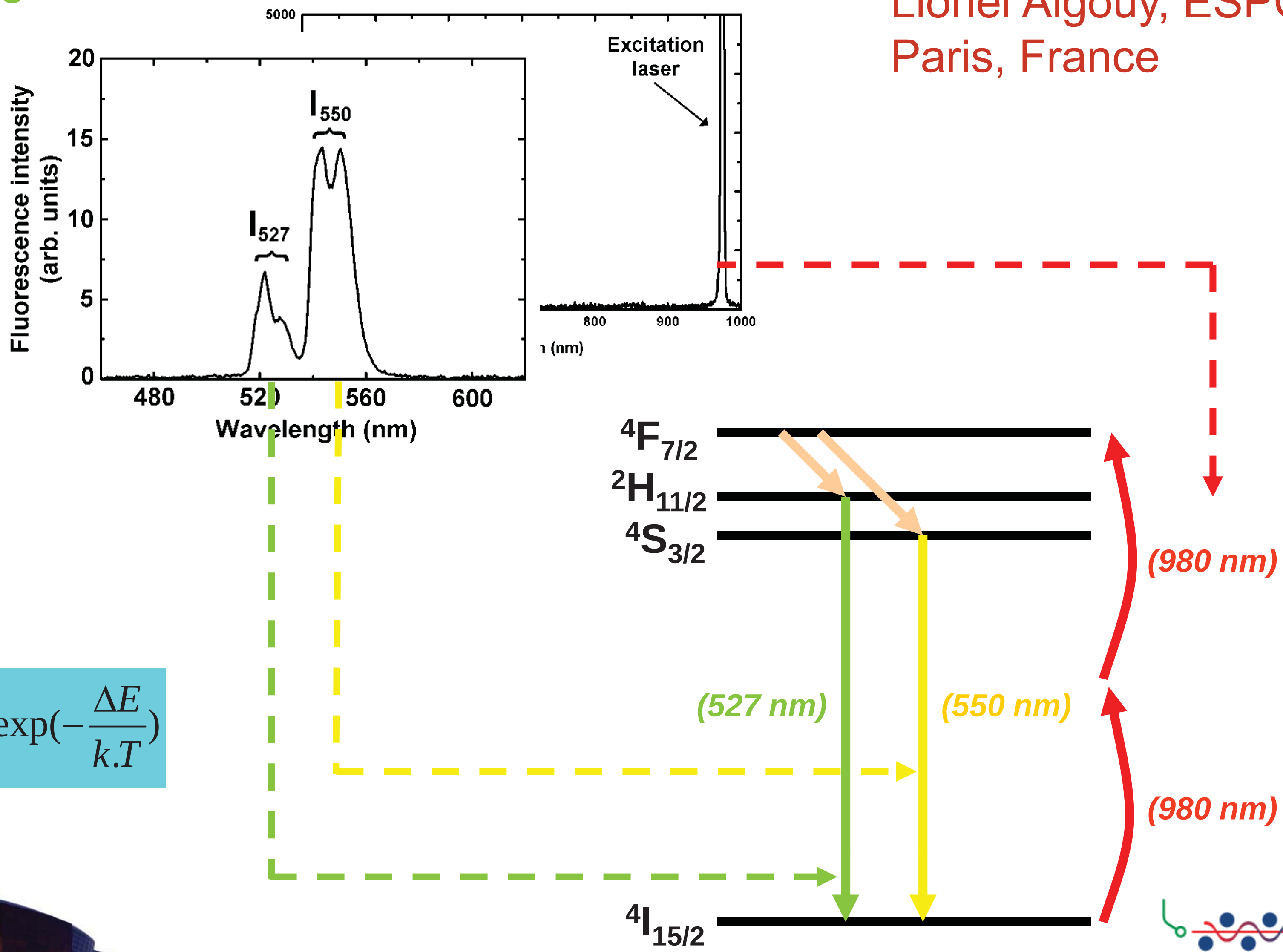
Er / Yb ions

PL spectrum of Er / Yb doped particles

Lionel Aigouy, ESPCI, Paris, France



$$\frac{I_{green}}{I_{yellow}} \propto \exp\left(-\frac{\Delta E}{k.T}\right)$$

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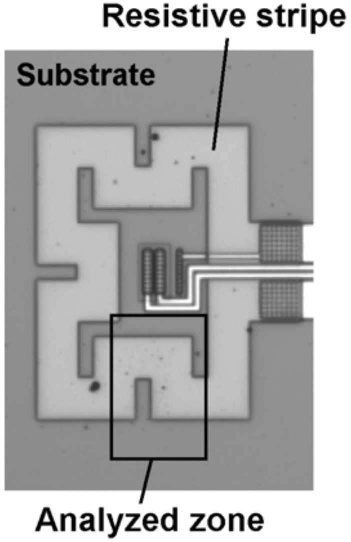
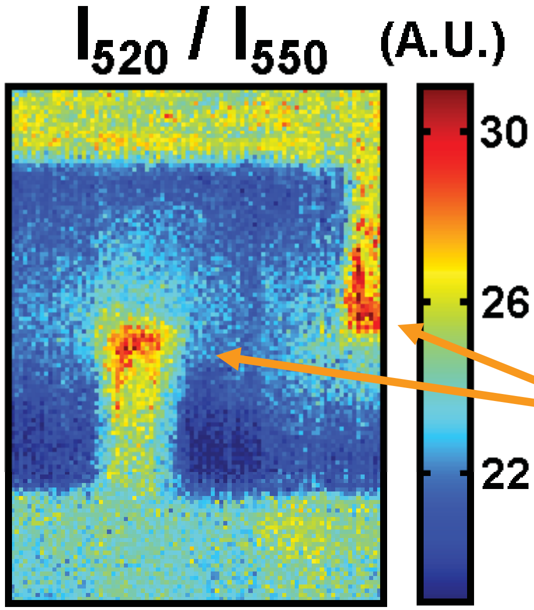
Thermal imaging using Fluorescence Nanoparticles

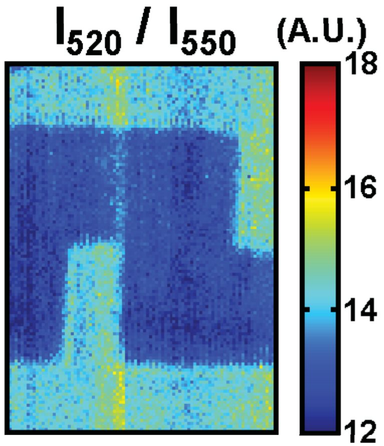
Lionel Aigouy, ESPCI, Paris, France



I = 50 mA



I = 0 mA



Uniform temperature (room temperature)

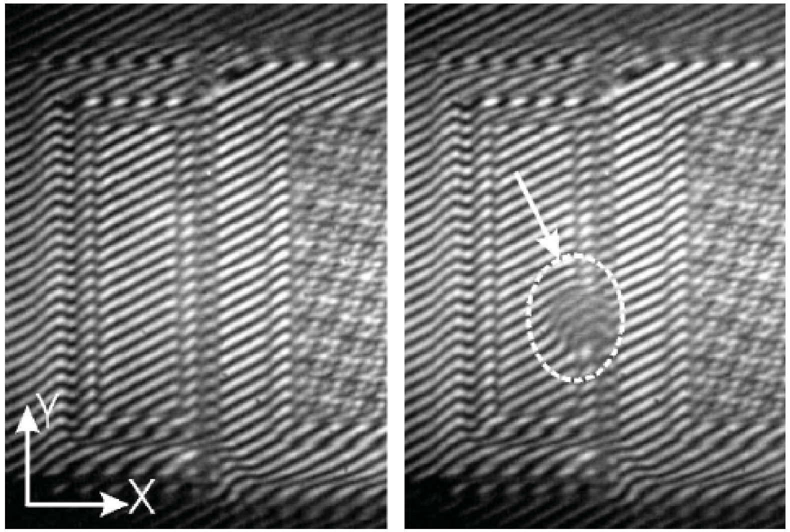
Optical contrast visible between different zones

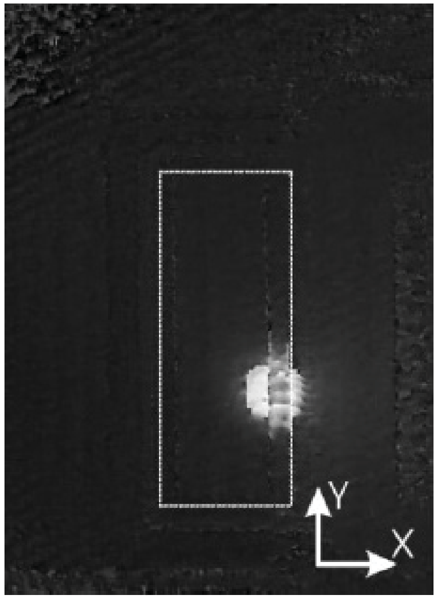
Reference image

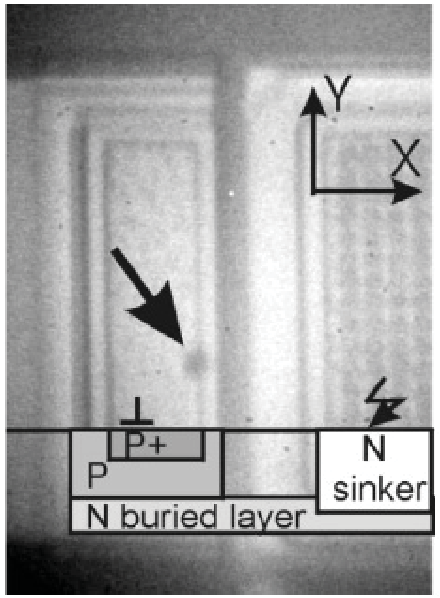
APL, **87**, 184105 (2005).

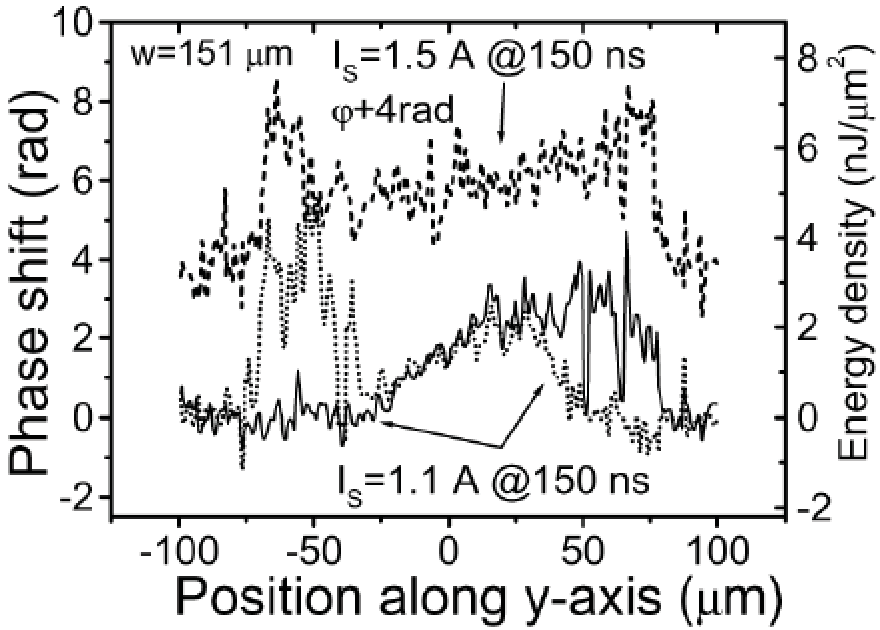
Interferrometric measurements

Pogany, Gornik et al.,
TU Vienna 2003



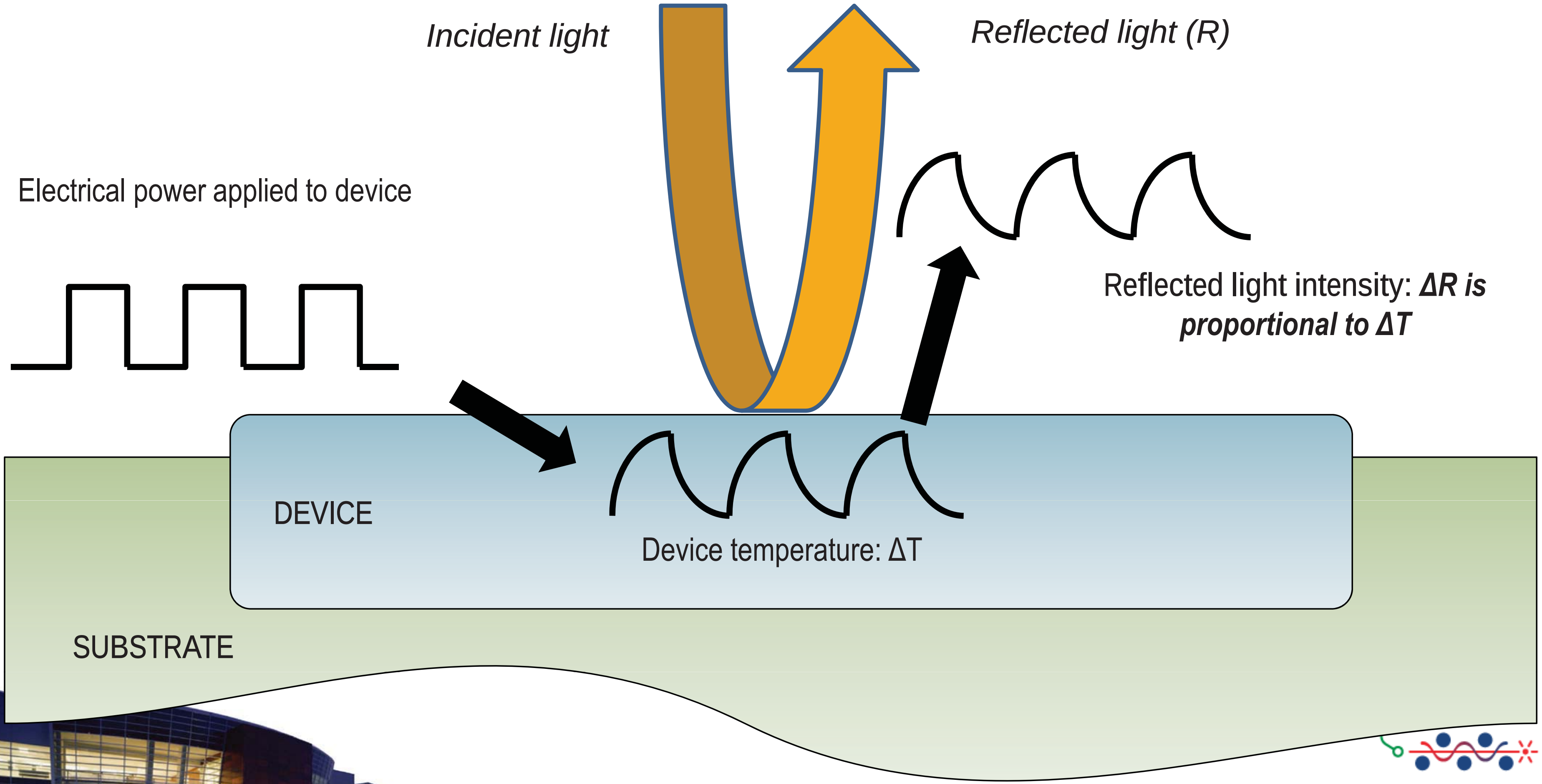






Thermoreflectance Imaging

Optical reflectance changes with material temperature



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}–$10^{-5}\,\mathrm{K}^{-1}$,

The reflectivity R of the material for normal incidence of light has the form

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}, \qquad (3)$$

where n and k are the index of refraction and the extinction coefficient, respectively, and can be written as real and imaginary parts of the complex index of refraction $\hat{n} = n + \mathrm{i}k$. Since Maxwell's equations yield the relation $\hat{\varepsilon} = \hat{n}^2$, it follows that

$$\varepsilon_1 = n^2 - k^2, \qquad (4a)$$

$$\varepsilon_2 = 2nk. \qquad (4b)$$

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

The optical constant ε_2 is related to the band structure through the joint density of states function [29]:

$$\varepsilon_2(E) = \frac{4e^2\hbar^2}{\pi\mu^2E^2}\int \mathrm{d}\boldsymbol{k}|P_{\mathrm{cv}}(\boldsymbol{k})|^2\delta[E_{\mathrm{c}}(\boldsymbol{k}) - E_{\mathrm{v}}(\boldsymbol{k}) - E], \quad (2)$$

where μ is the combined density of states mass, the Dirac δ function represents the joint spectral density of states between the conduction (c) and valence (v) band states which differ by the energy $E_{\mathrm{c}}(\boldsymbol{k}) - E_{\mathrm{v}}(\boldsymbol{k}) = \hbar\omega$ of the incident light, $P_{\mathrm{cv}}(\boldsymbol{k})$ is the momentum matrix element between the conduction and valence band states, and the integration is performed over the first Brillouin zone.

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

the temperature increase causes a shift in the energy gap and broadens the critical point involved. Combining these two effects, one can write

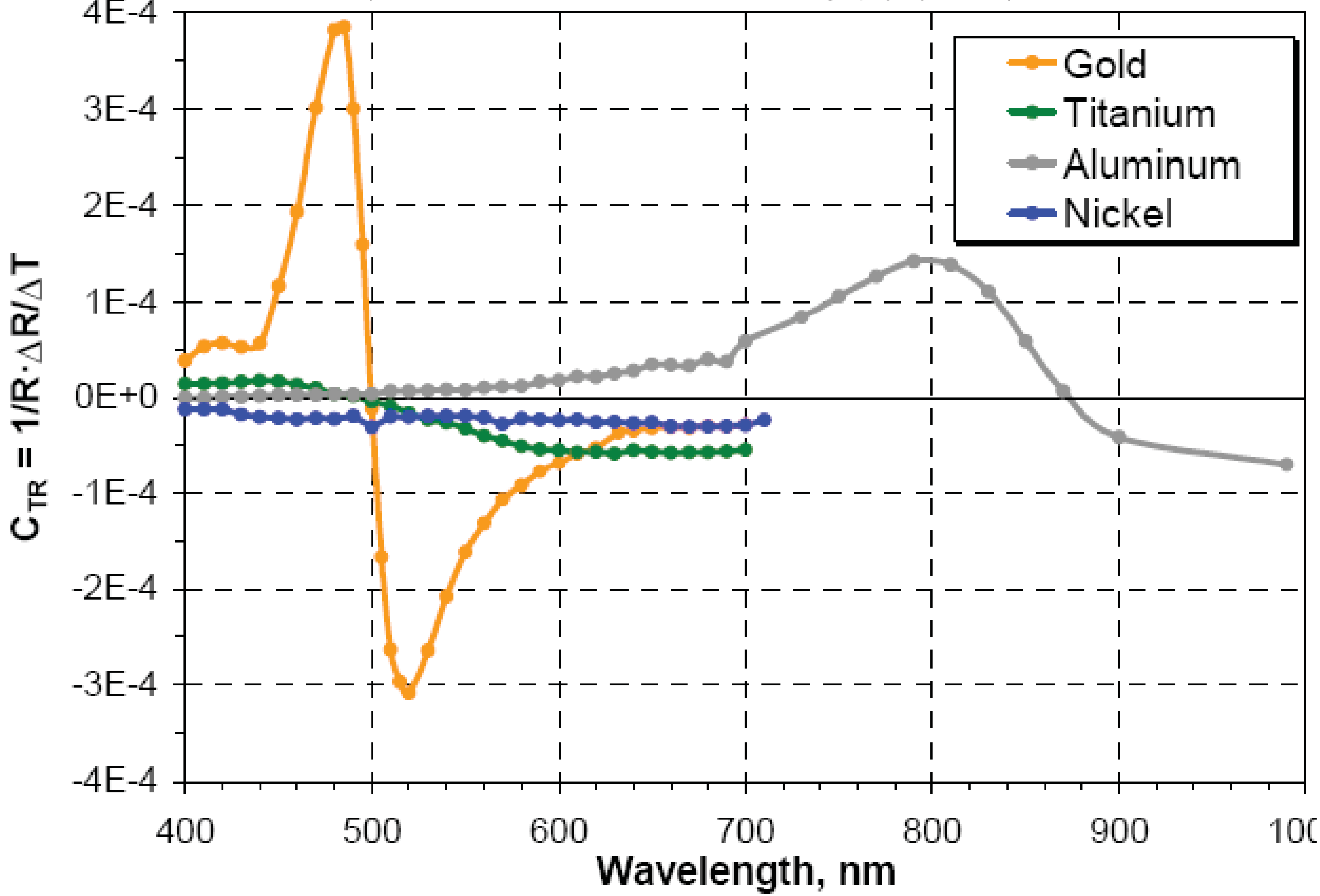
$$\Delta\hat{\varepsilon} = \frac{d\hat{\varepsilon}}{dE_g}\frac{dE_g}{dT}\Delta T + \frac{d\hat{\varepsilon}}{d\Gamma}\frac{d\Gamma}{dT}\Delta T, \qquad (11)$$

where E_g is the energy gap and the broadening is accounted for, phenomenologically, by the broadening parameter Γ.

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

Thermoreflectance coefficient

(Komarov, et al, Thermoreflectance Thermography System…)



Laser measurement of localized temperature

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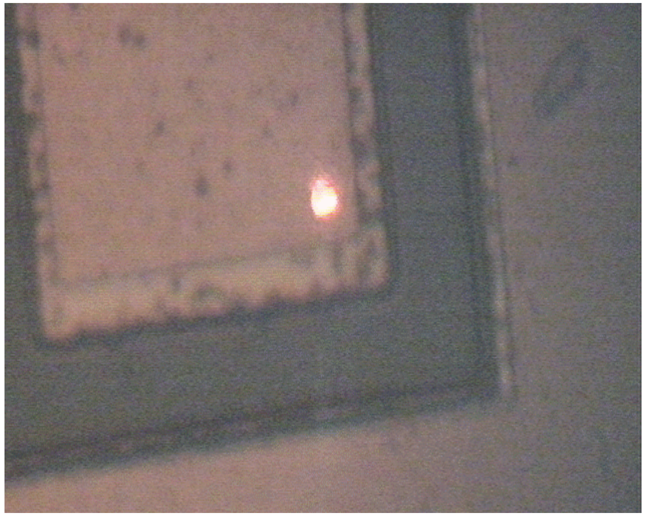
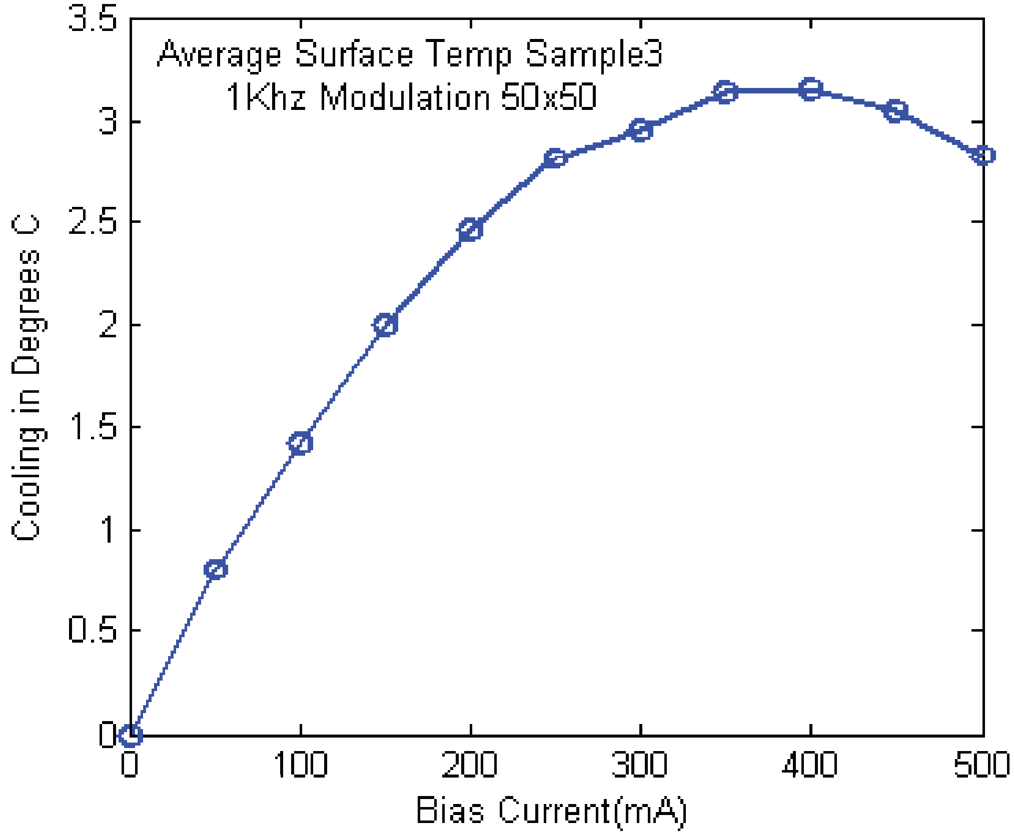
J. Christofferson et al., SEMITHERM XVII , San Jose, Ca, March 2001.



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



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

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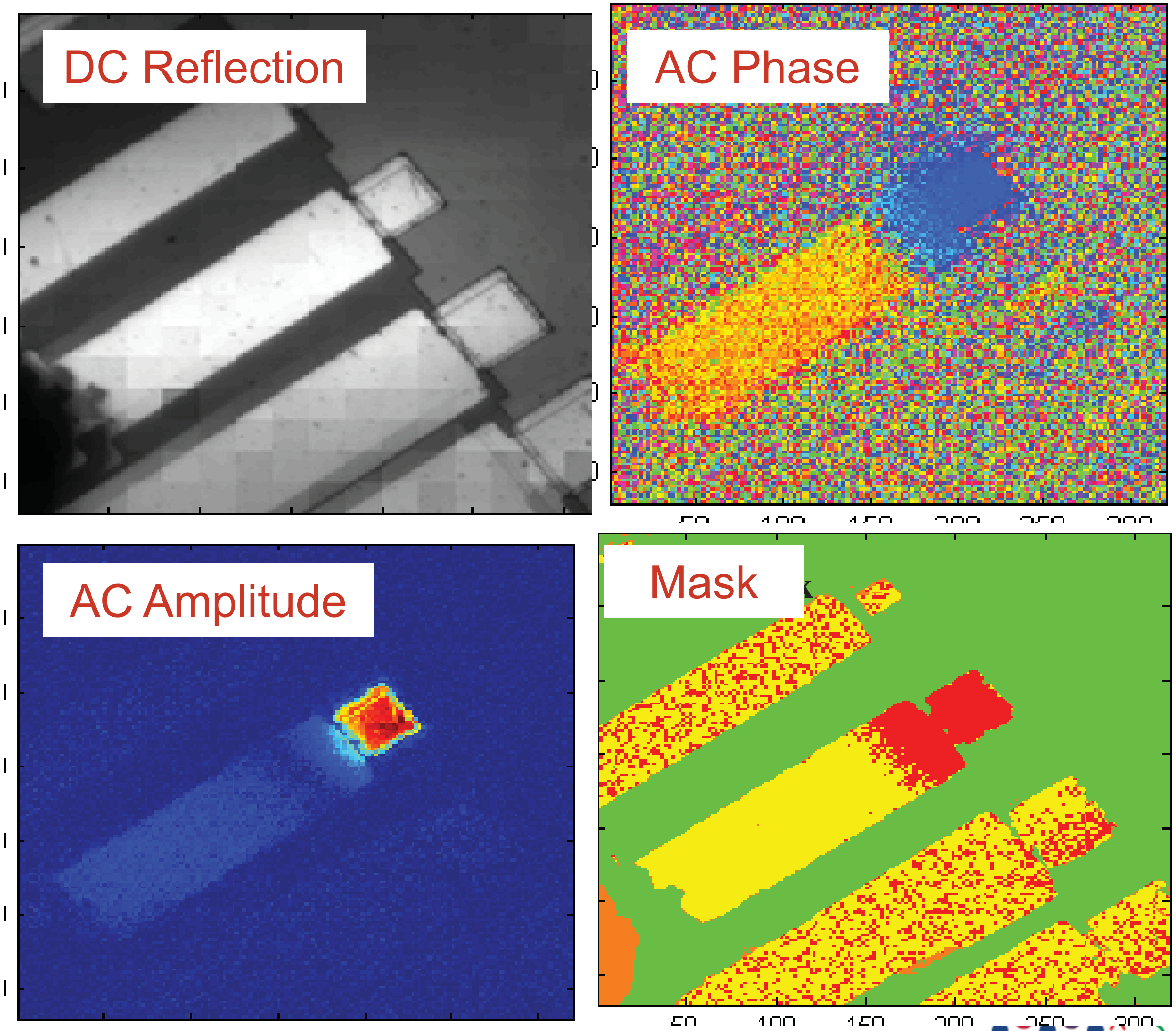
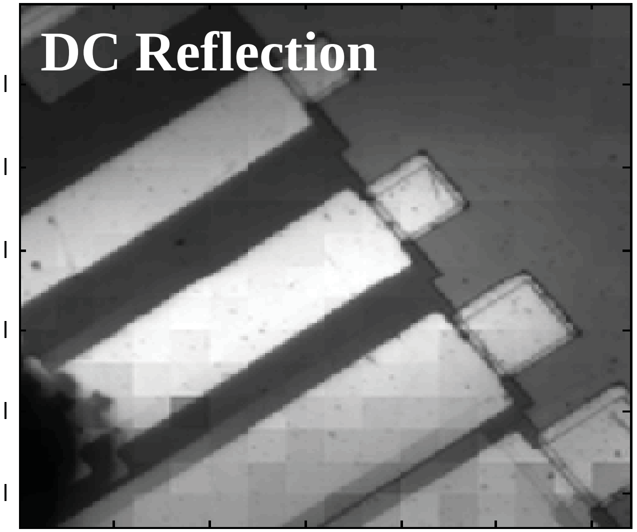
Lock-in imaging result

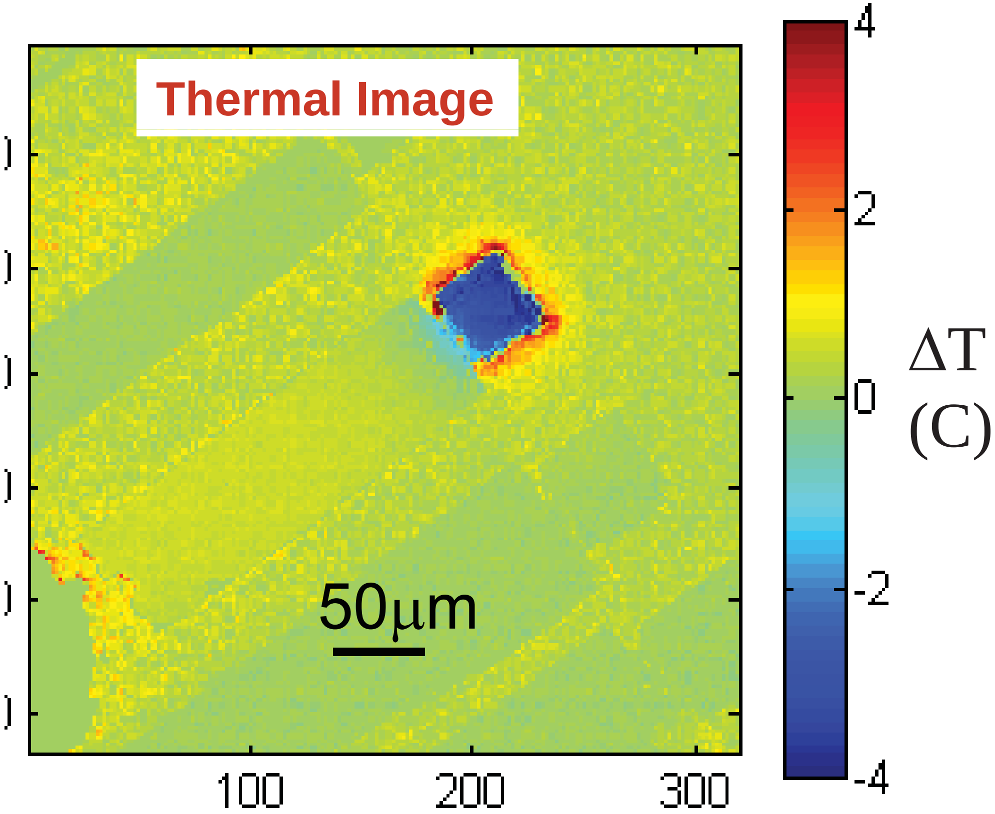
Acquisition time 5 minutes

- DC Reflection
- AC Reflection
  - Phase
  - Amplitude
- Mask
  - Identify different materials, cooling/heating regions



Thermoreflectance image of microcooler



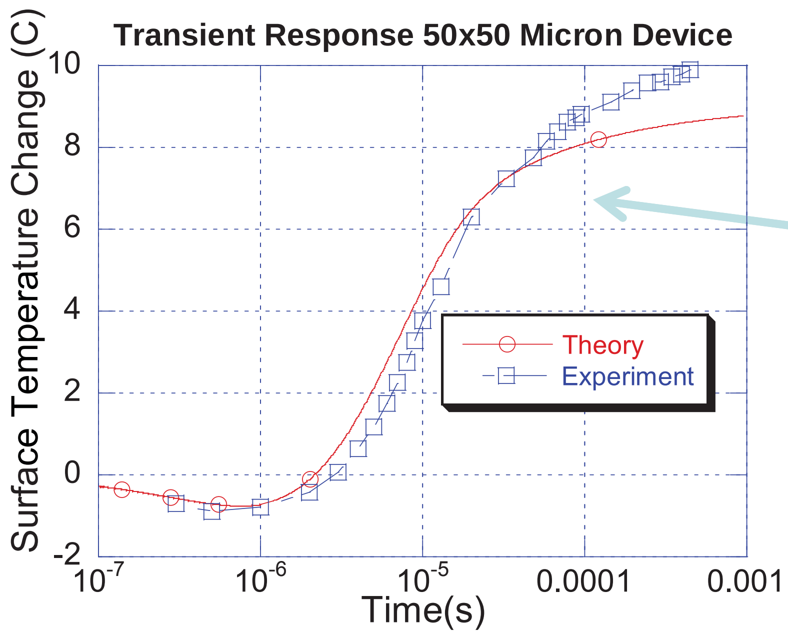


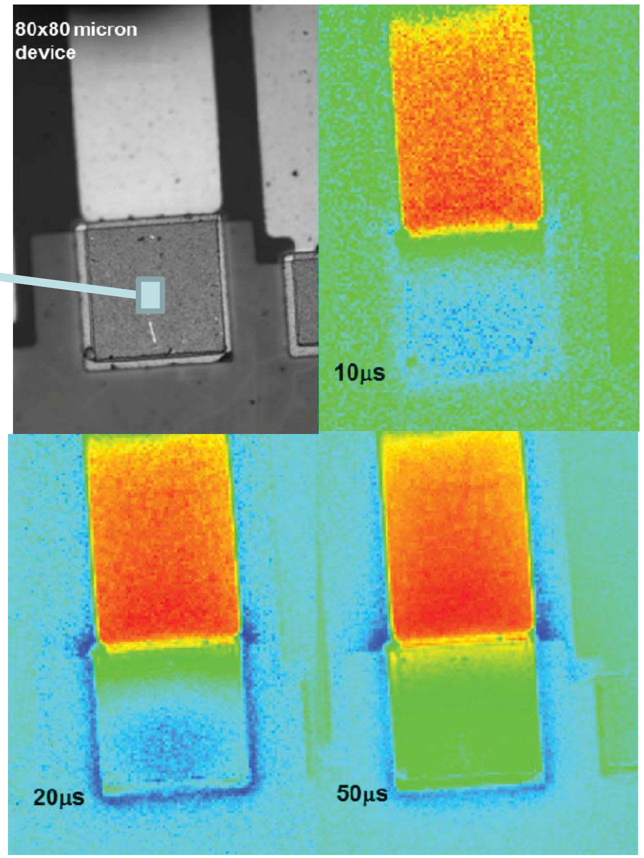
Pioneering works by:
Claeys, Fournier,
Dilhaire, Tessier,…

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

Transient thermal images

Cooling Before Heating measured in Overdriven micro cooler Semitherm 2009

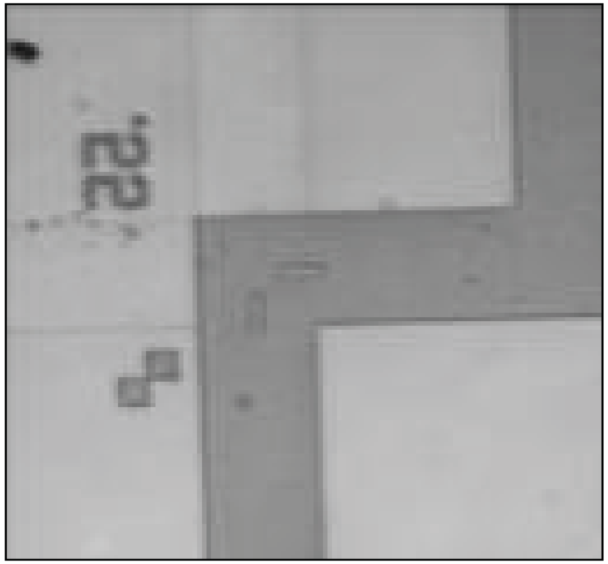


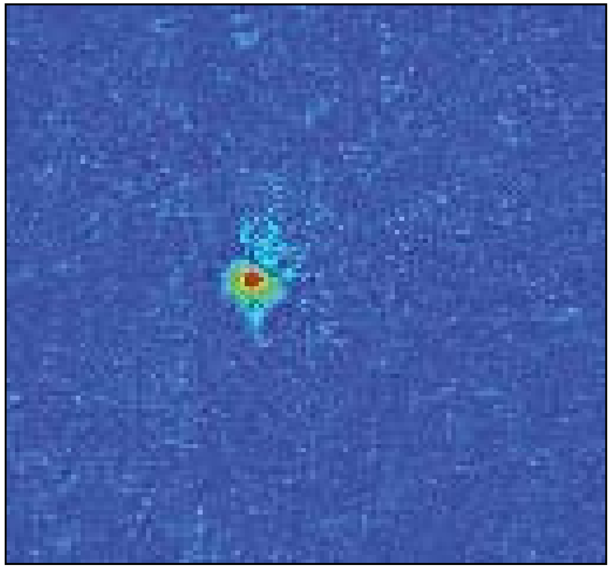


Semitherm Conference 2009

- **CCD based system:** http://www.microsanj.com

Picosecond thermal imaging (800ps)





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

High Speed Thermal Imaging (800ps)

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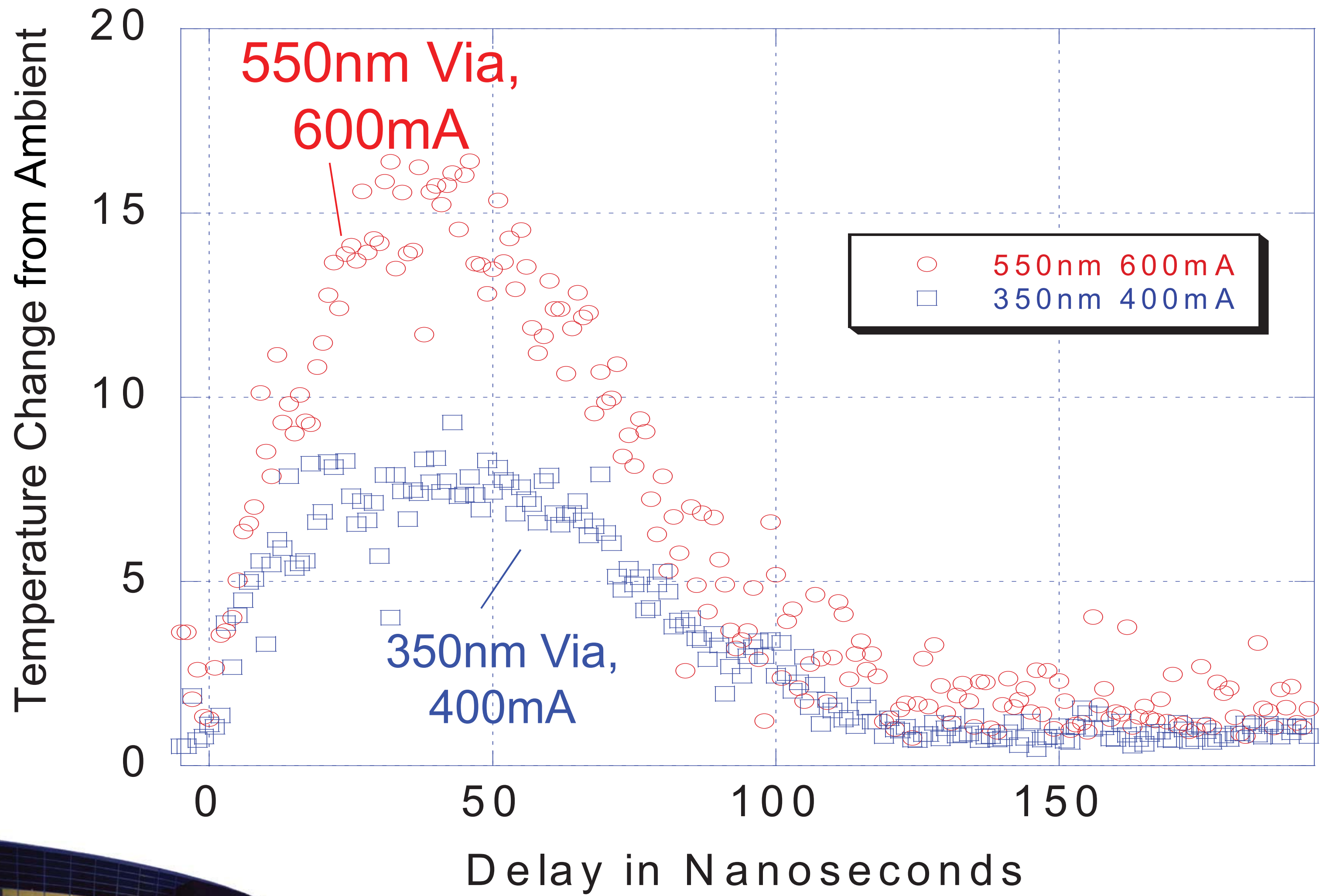
Study of heating in submicron interconnect vias



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

QUANTUM ELECTRONICS

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

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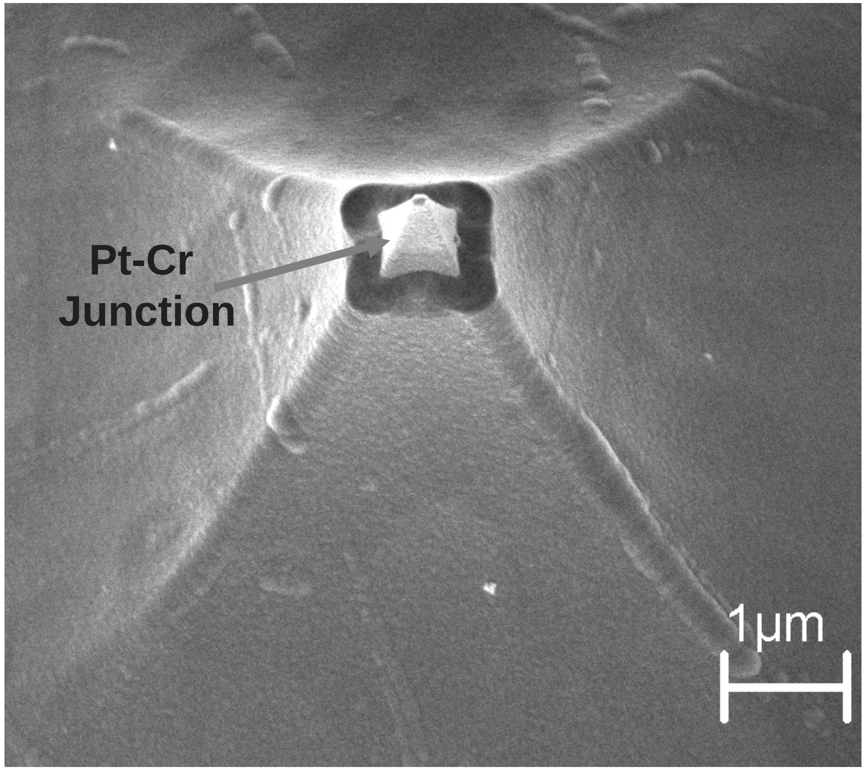
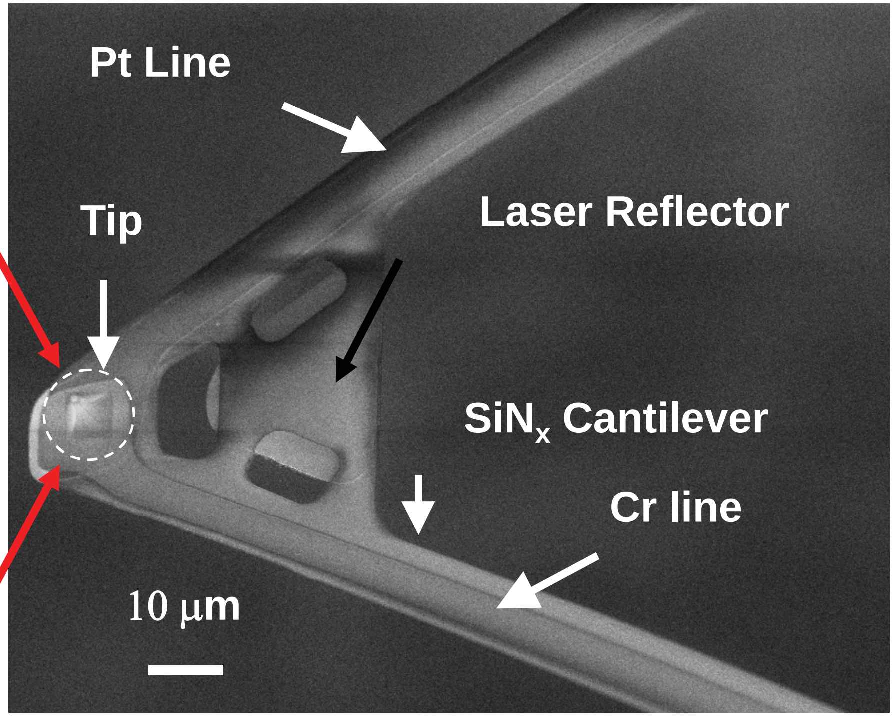
Method	Resolution			Imaging?	Notes
	x(μm)	T (K)	t (sec)		
μ thermocouple	50	0.01	0.1-10	No	Contact method
IRThermography	3-10	0.02-1	1μ	Yes	Emissivity dependent
Lockin IR Thermography	3-10	10μ	NA	Yes	Need cycling
Liquid Crystal Thermography	2-5	0.5	100	Yes	Only near phase transition (aging issues)
Thermo-reflectance	0.3-0.5	0.08	800p-0.1μ	Yes	Need cycling
Optical Interferometry	0.5	100μ	6n-0.1μ	Scan	Indirect measurement (expansion)
Micro Raman	0.5	1	10n	Scan	3D T-distribution
Near Field (NSOM)	0.05	0.1-1	0.1μ	Scan	S/N dependent Tip/sample interaction
Scanning thermal microscopy (SThM)	0.05	0.1	10-100μ	Scan	Contact method surface morphology

Scanning Thermal Microscopy

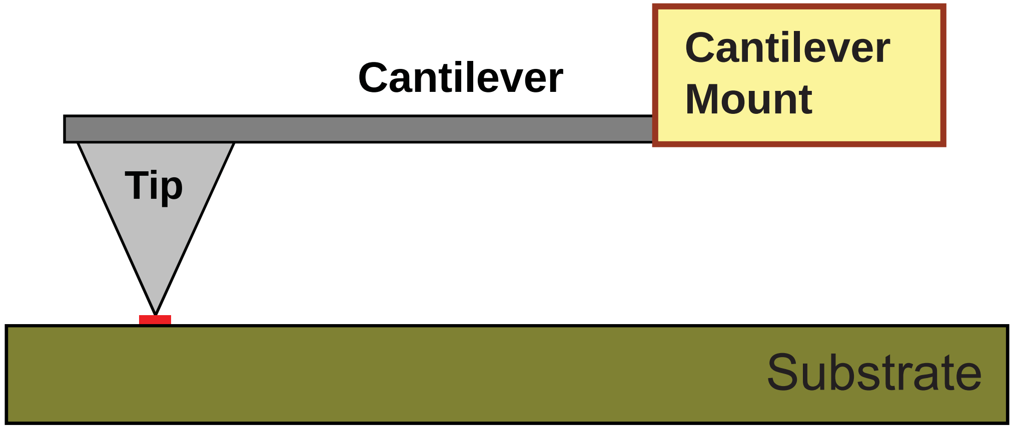


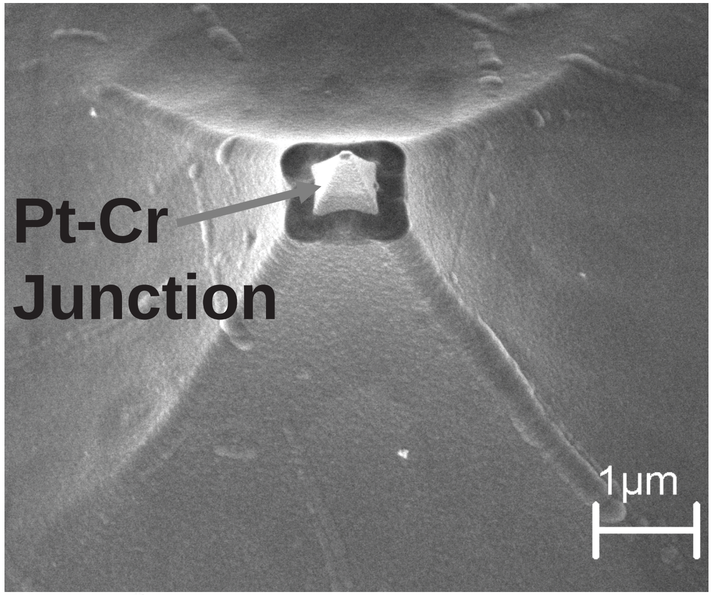


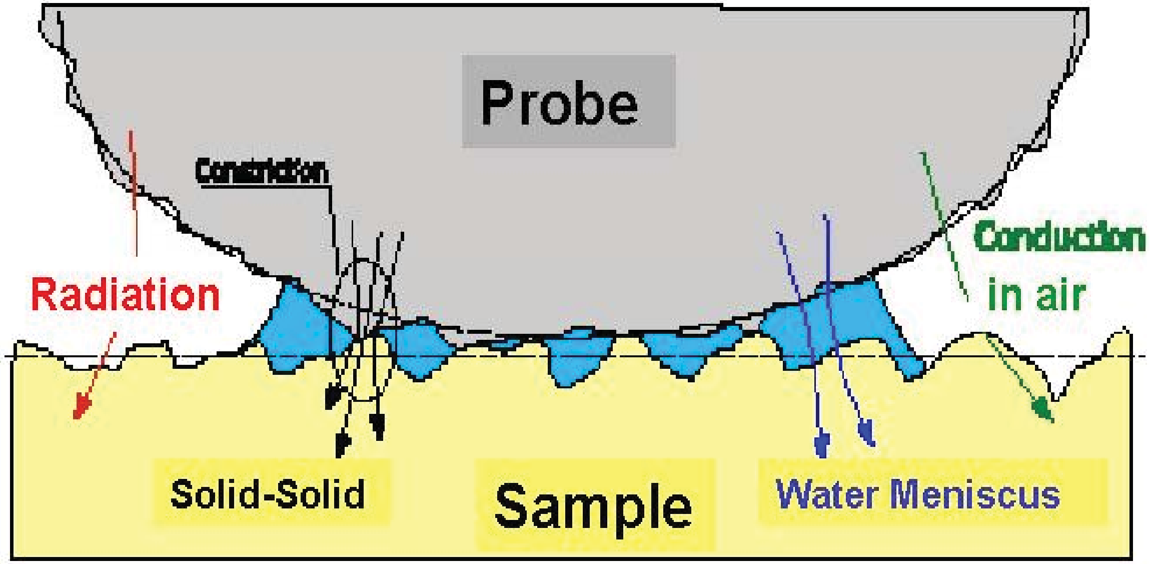
Cantilever Spring Constant: 0.1-1 N/m
Cantilever Deflection
Detection Resolution: 0.01 nm
Force Resolution: 1-10 pN

Shi, Majumdar *et al*., ***J. MEMS***

Scanning Thermal Microscopy (SThM)





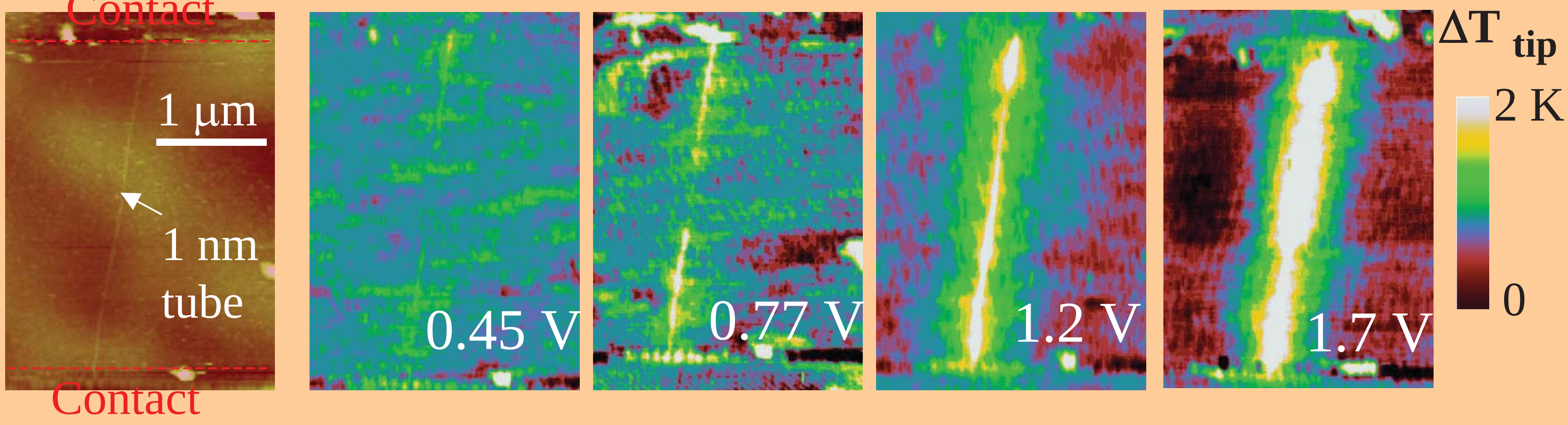


Courtesy: Arun Majumdar, UC Berkeley; Stefan Dilhaire, Univ. Bordeaux

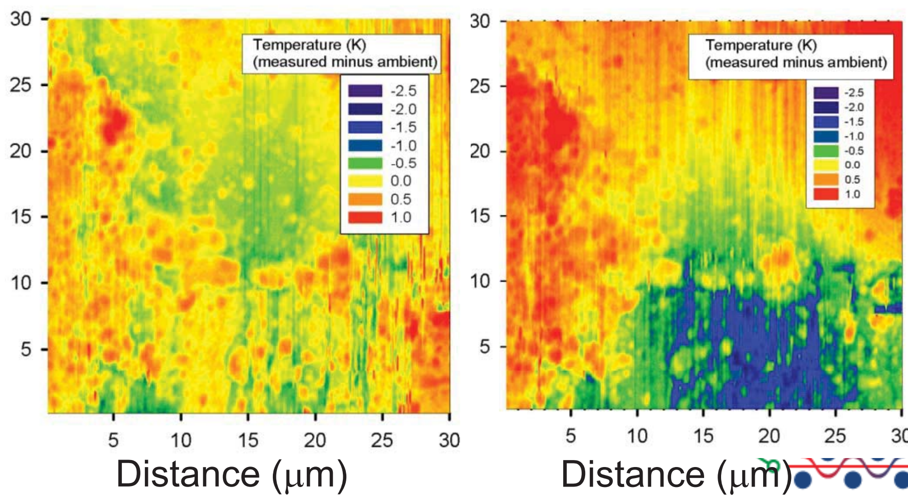
SThM Metallic Single Wall Nanotube

PURDUE UNIVERSITY Discovery Park

Topography Thermal images



Thermal, I=0 Thermal, I=200mA

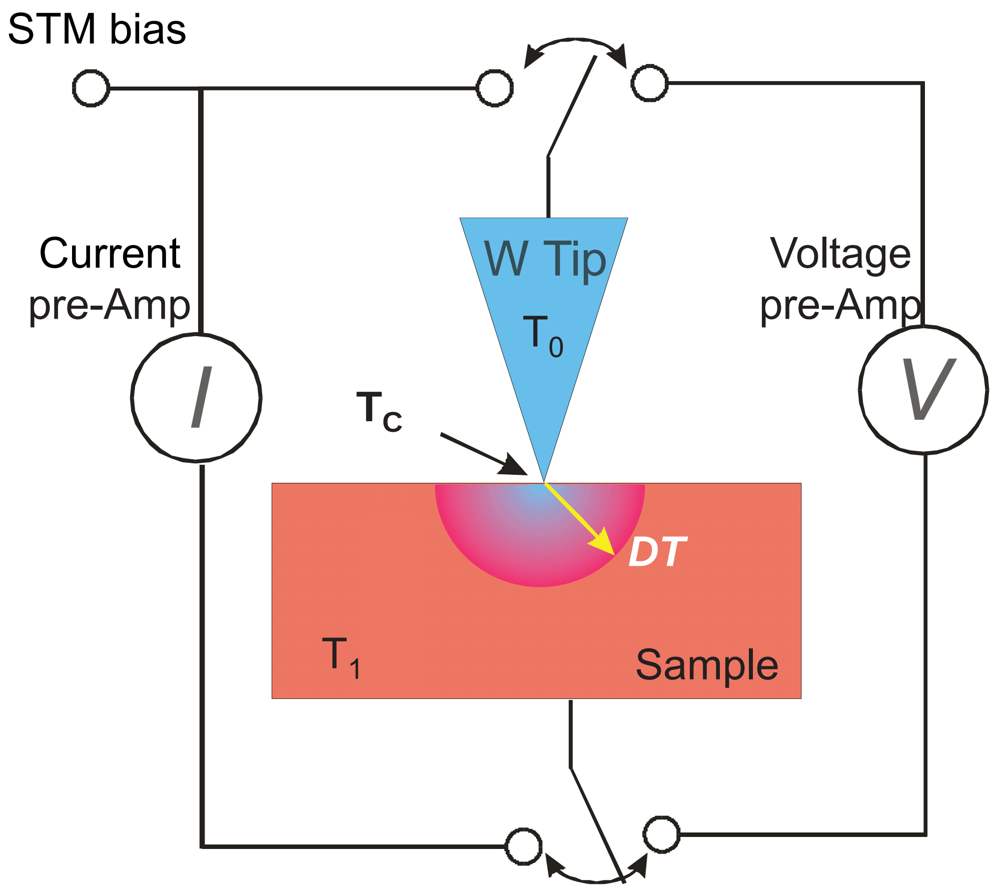


SThM Thermal Mapping of Microrefrigerators

Prof. Arun Majumdar, UC Berkeley

QUANTUM ELECTRONICS

UHV Scanning TE Microscopy



- Elastic Nano-contact between metal tip and heated sample :

$$T_1 > T_c > T_0$$

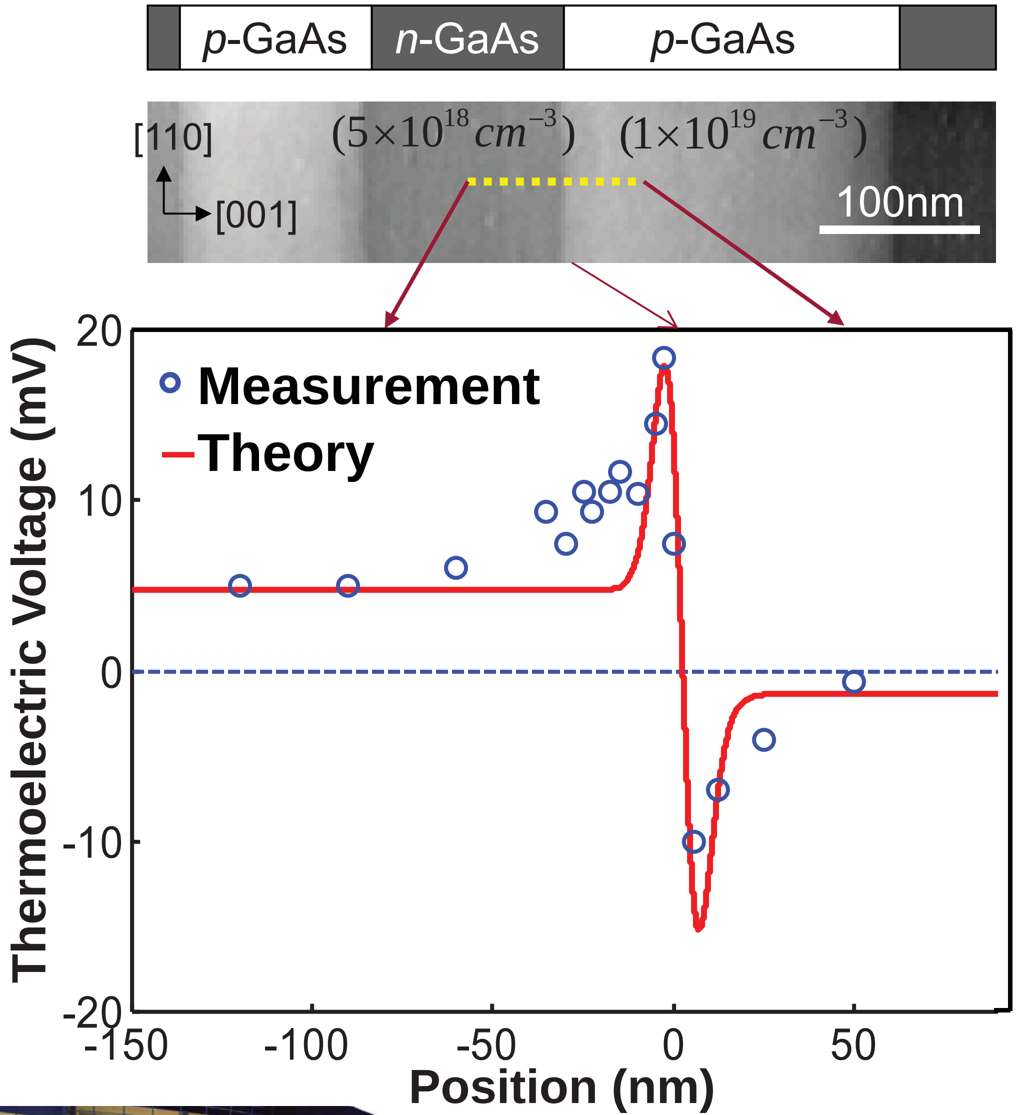
- Local Temperature Gradient $\Delta T \equiv T_1 - T_C$
- Local Thermoelectric Voltage

$$V = S(x,y)(T_1 - T_C)$$

- $V \rightarrow S$ profile

H.-K. Lyeo, L. Shi, and C.K. Shih.
(UT Austin)

Mapping *S* of GaAs *p-n* Junction

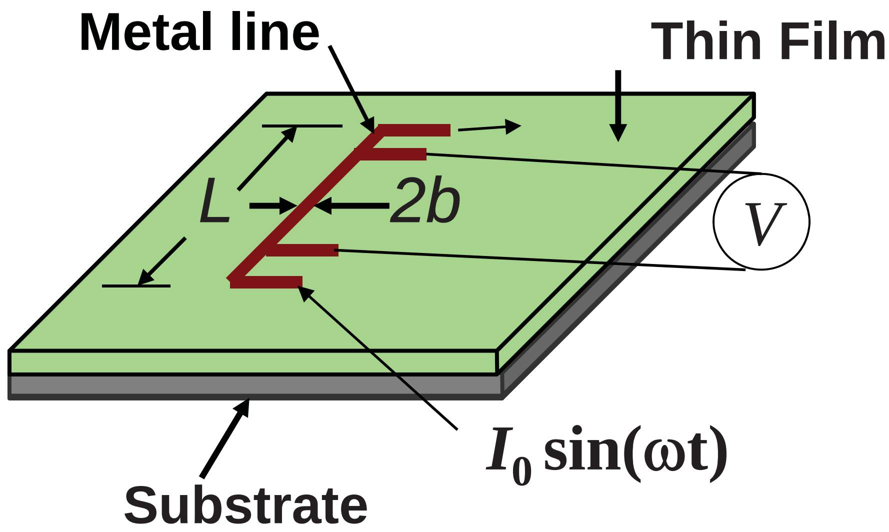


- Sharp transition across the junction
- Resolution of 6 nm
- Measure both carrier concentration and types

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

Thin Film Thermal Conductivity Measurement

3ω method
(Cahill, *Rev. Sci. Instrum*. 61, 802)

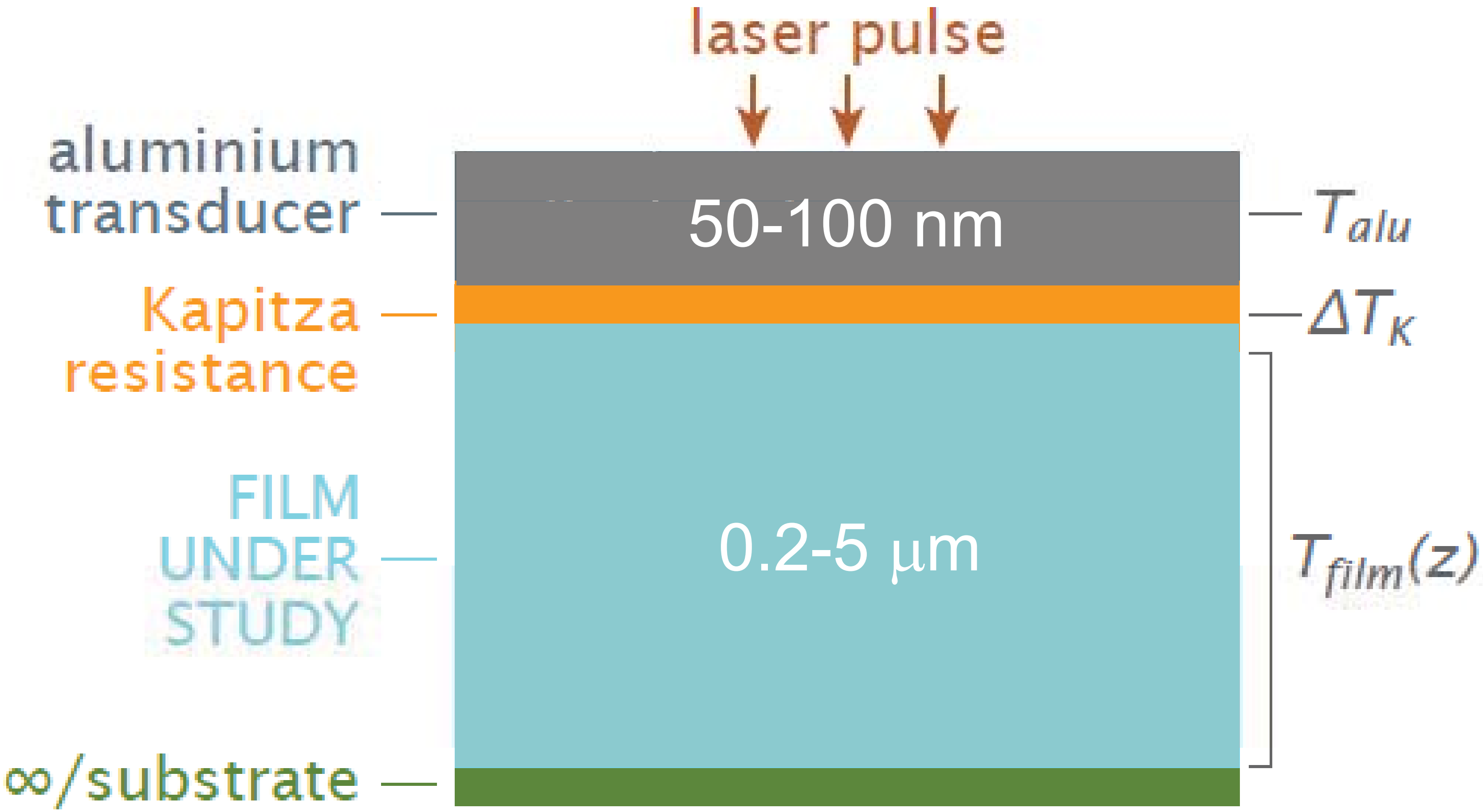


- I ~ 1ω
- T ~ I^2 ~ 2ω
- R ~ T ~ 2ω
- V ~ IR ~3ω

$$\Delta T(2\omega) = \frac{P}{L\pi k_s}\left[\frac{1}{2}\ln\left(\frac{D_s}{b^2}\right) + \eta - \frac{1}{2}\ln(2\omega) - \frac{i\pi}{4}\right] + \frac{Pd}{2Lbk_f}$$

Time Domain Thermoreflectance (TDTR)

PURDUE UNIVERSITY Discovery Park

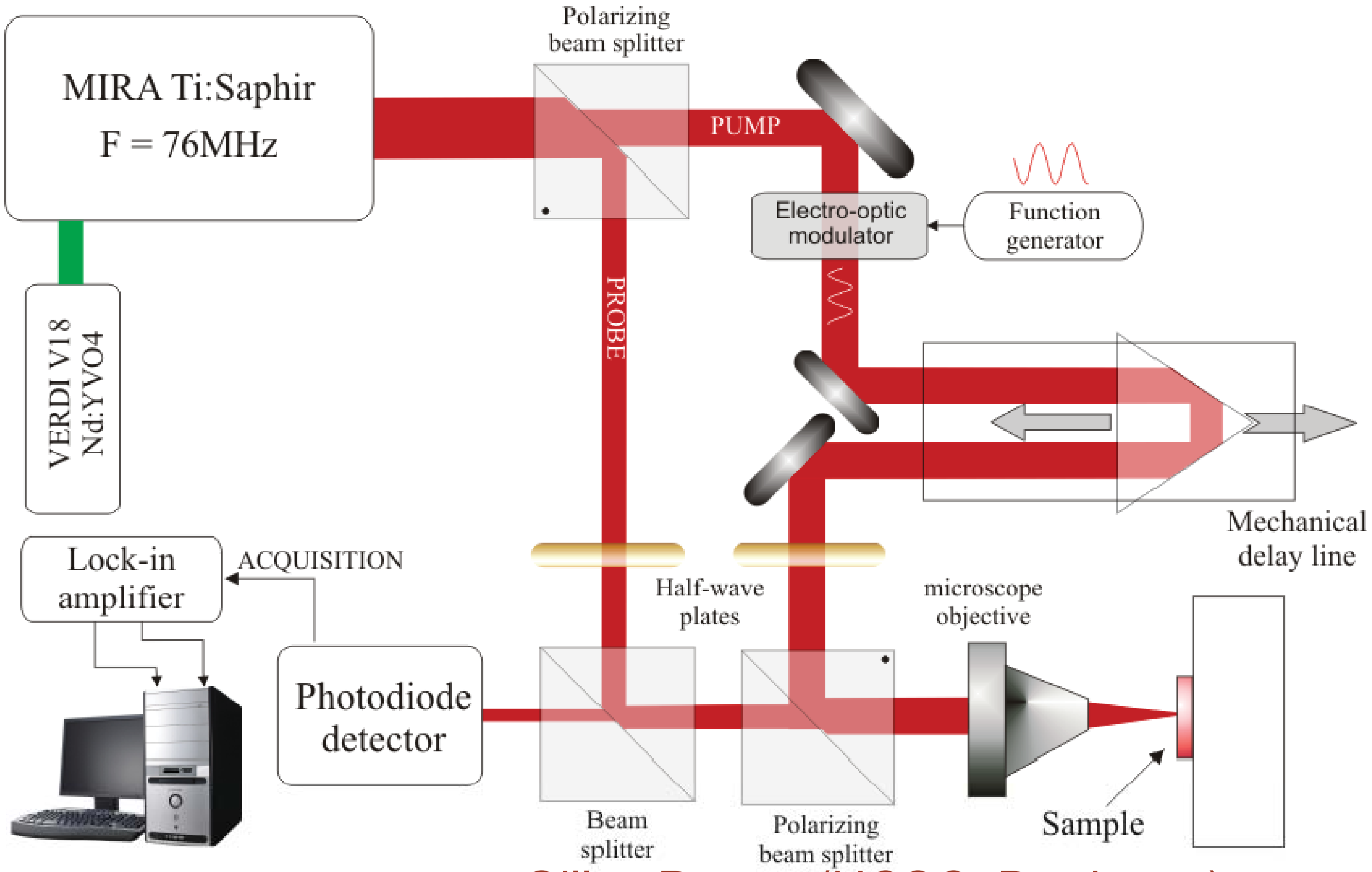


David Cahill, UIUC, 2003

QUANTUM ELECTRONICS

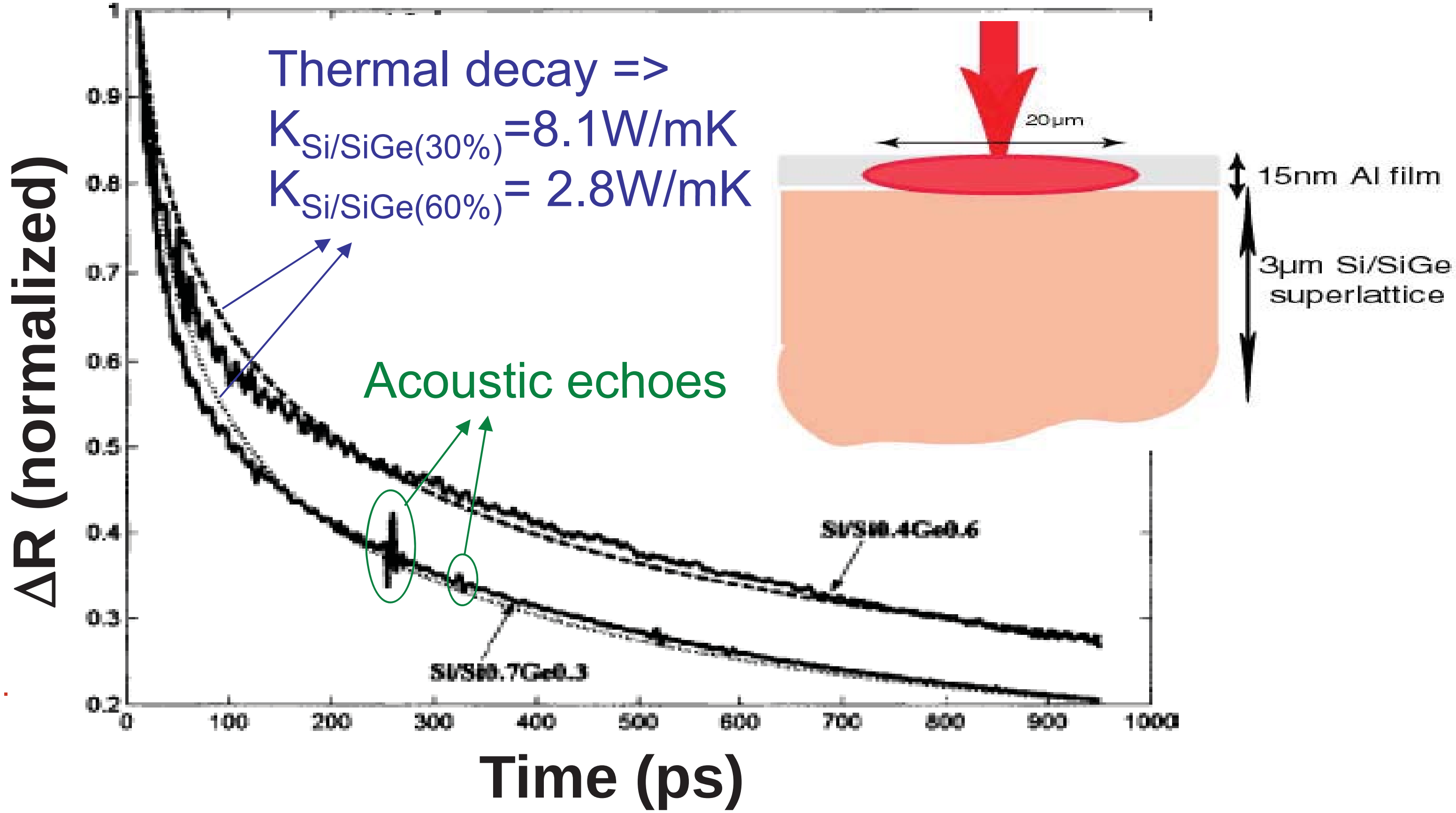
Time Domain ThermoReflectance

- **Modulated** & **delayed** femtosecond laser pulse used as a **Pump.**
- A **Probe** beam measures **reflectivity variation on the surface**
- The lock-in amplifier gives the **In-phase (V_{in})** and **Out-of-phase (V_{out})** signals.



Gilles Pernot (UCSC, Bordeaux)

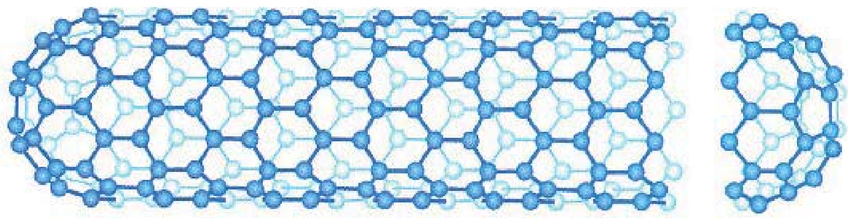
Thin Film Thermal Characterization



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).

Thermal Transport in Carbon Nanotubes



- Few scattering: long mean free path ***l***

Strong SP^2 bonding: high sound velocity ***v***

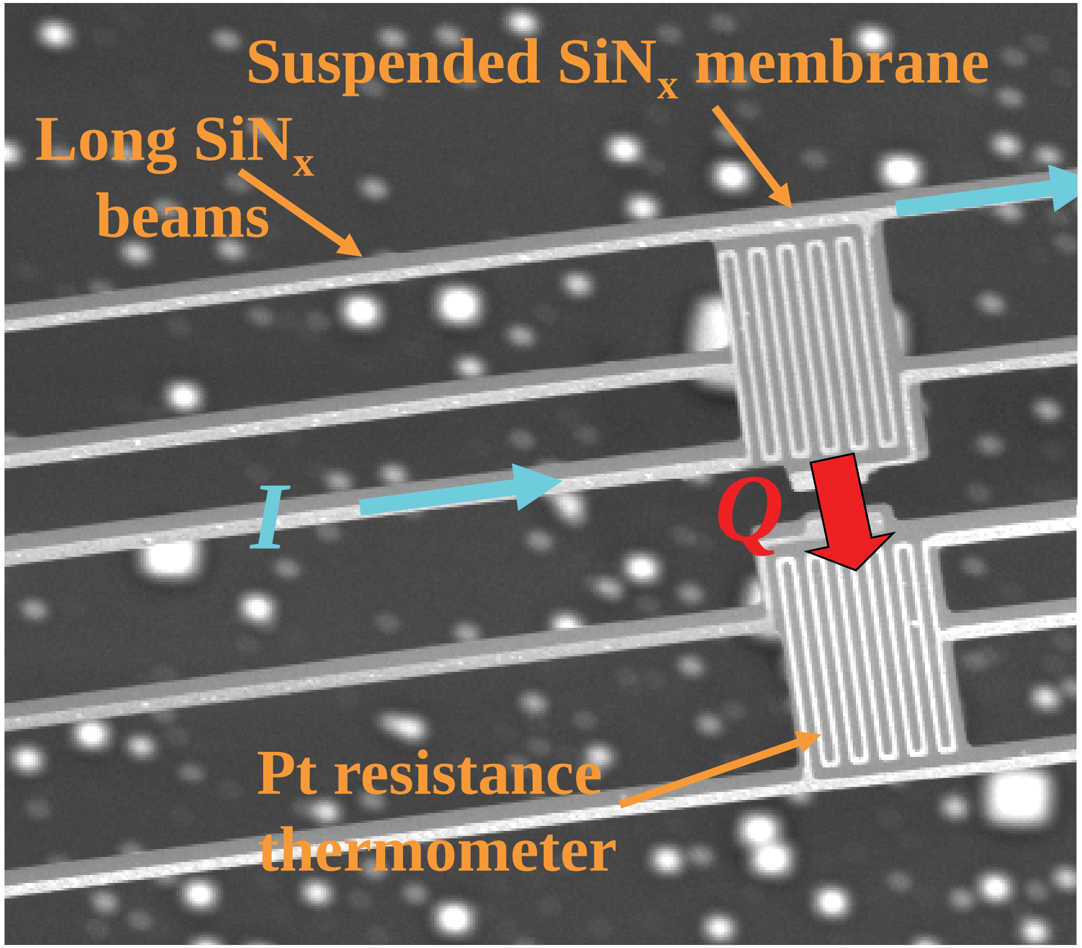
→ high thermal conductivity: $k = Cvl/3$ ~ 6000 W/m-K

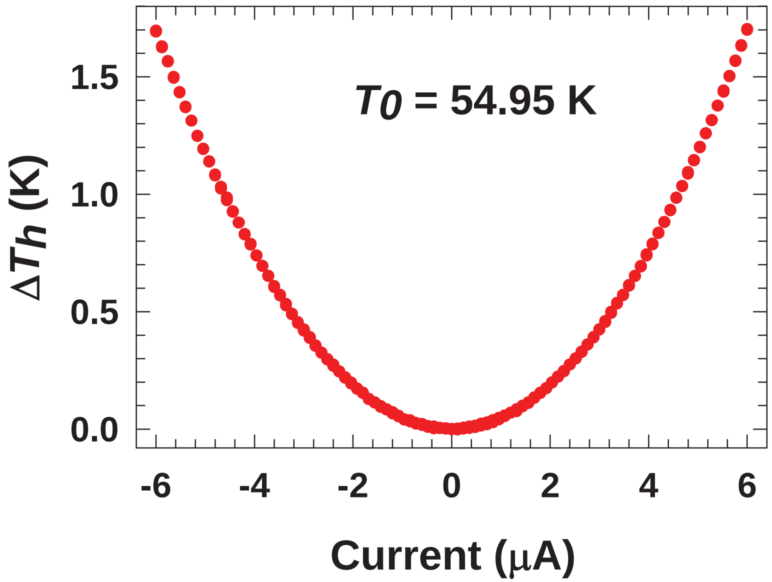
- Below 30 K, thermal conductance → $4G_0 = (4 \times 10^{-12} T)$ W/m-K,

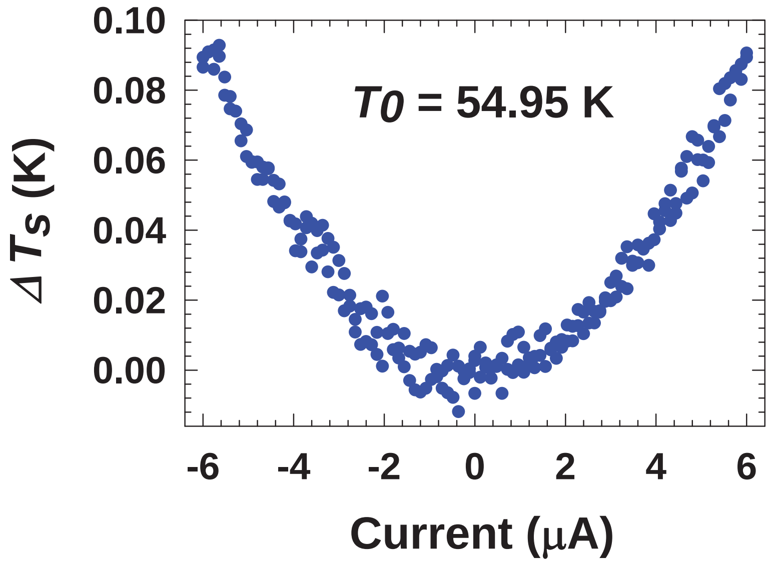
linear T dependence (G_0 :Quantum of thermal conductance)

Thermal Measurements of Nanowires

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

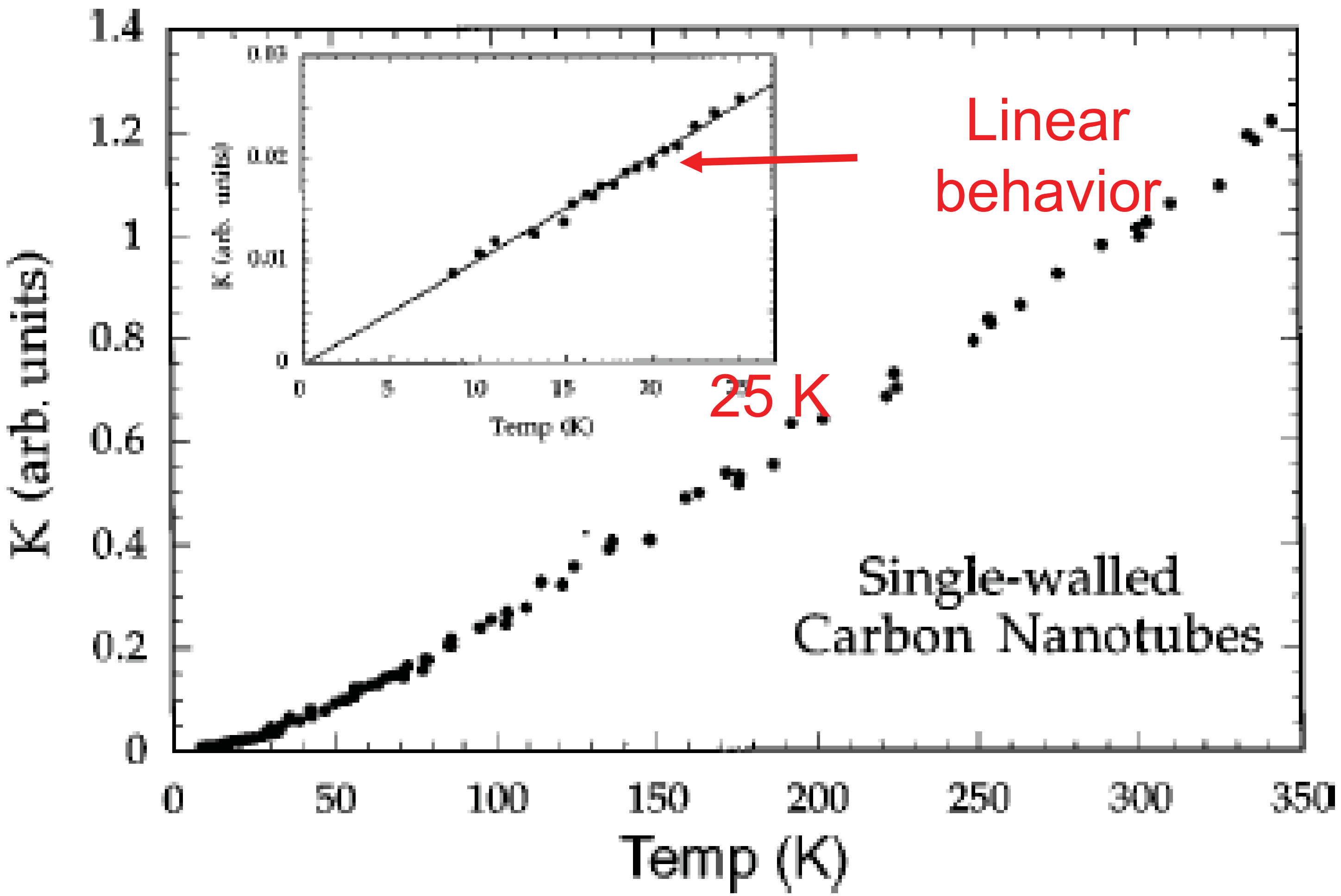






Kim et al, *PRL* **87**, 215502
Shi et al, *JHT*

Thermal Conductance of a Nanotube



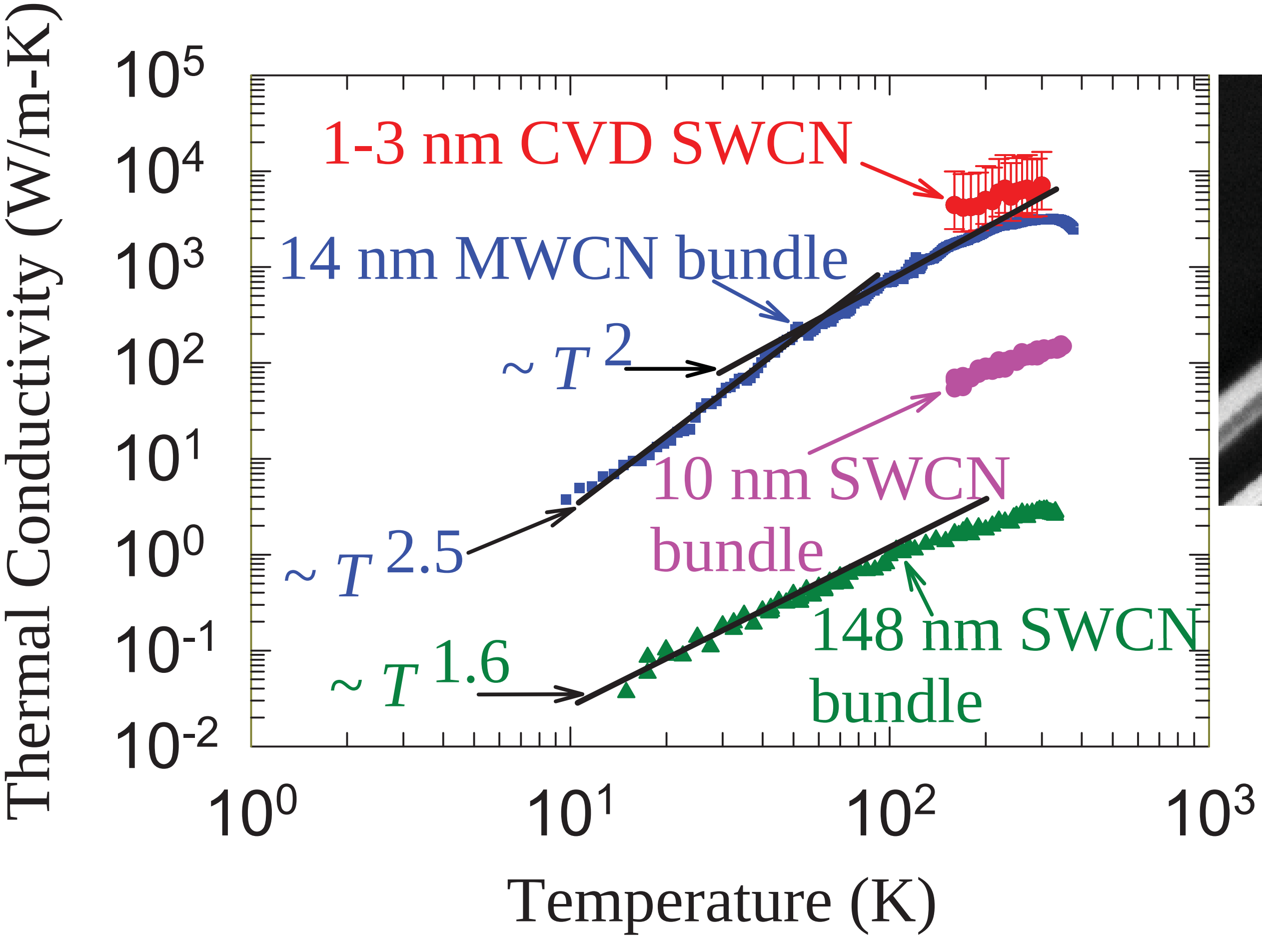
Ref: Hone et al. *APL* **77**, 666

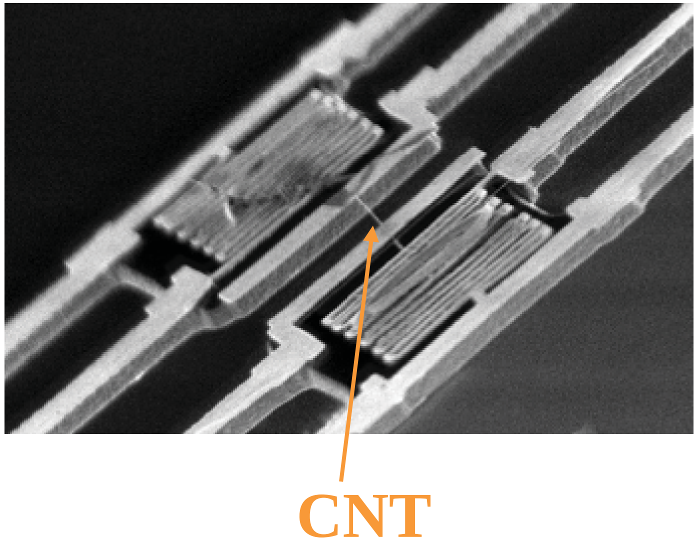
- Estimated thermal conductivity at 300K: ~ 250 << 6000 W/m-K

→ Junction resistance is dominant

- Intrinsic property remains unknown

Thermal Conductivity of Carbon Nanotubes



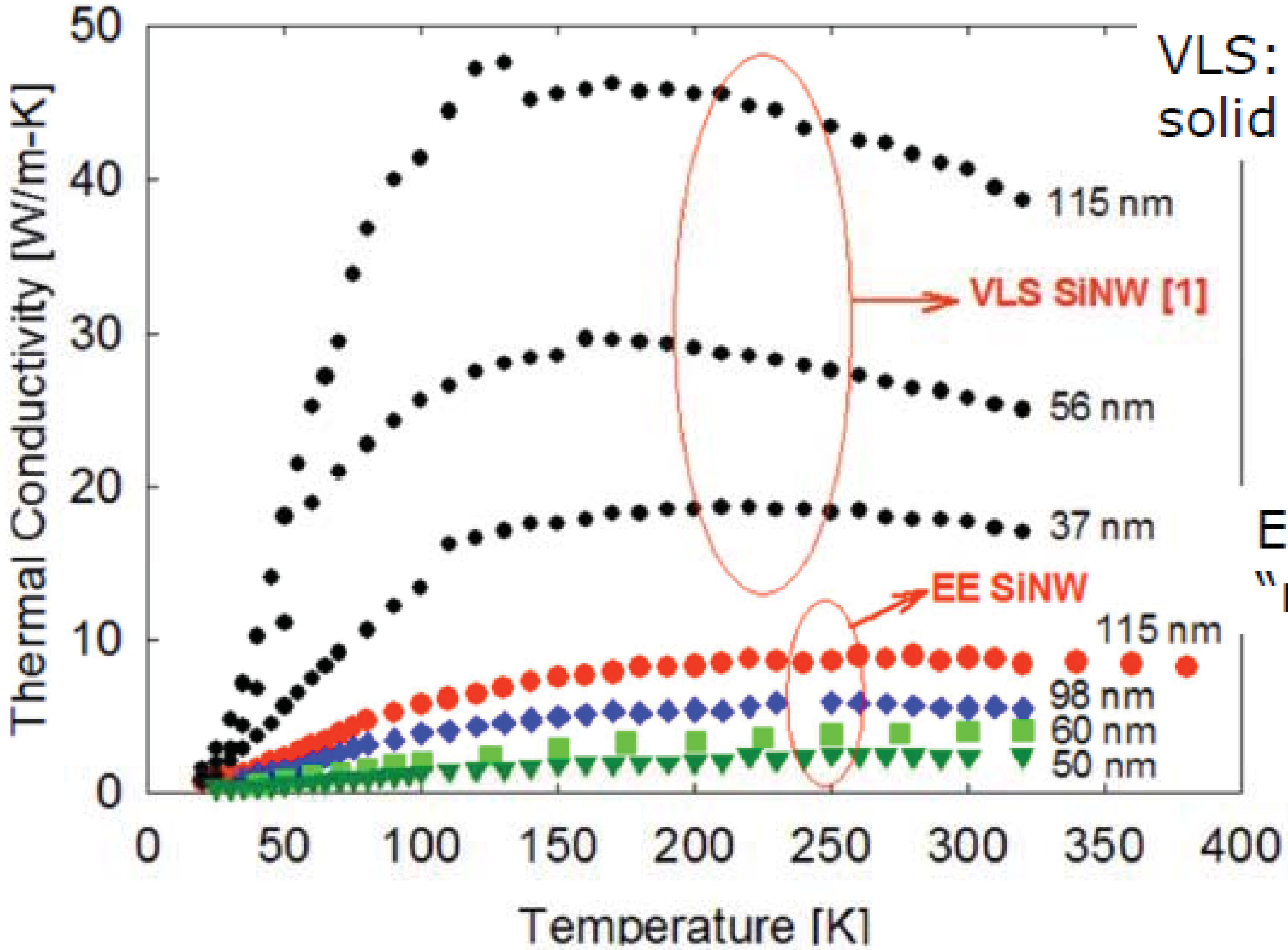


- An individual nanotube has a high $k \sim$ 2000-11000 W/m-K at 300 K

Li Shi, UT Austin

New phonon physics in roughened nanowires?

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



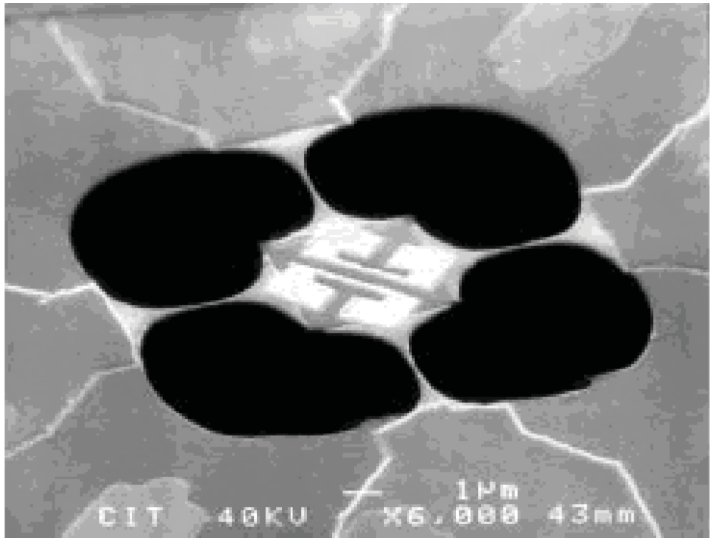
VLS: vapor-liquid-solid "smooth"

EE: electroless-etched "rough"

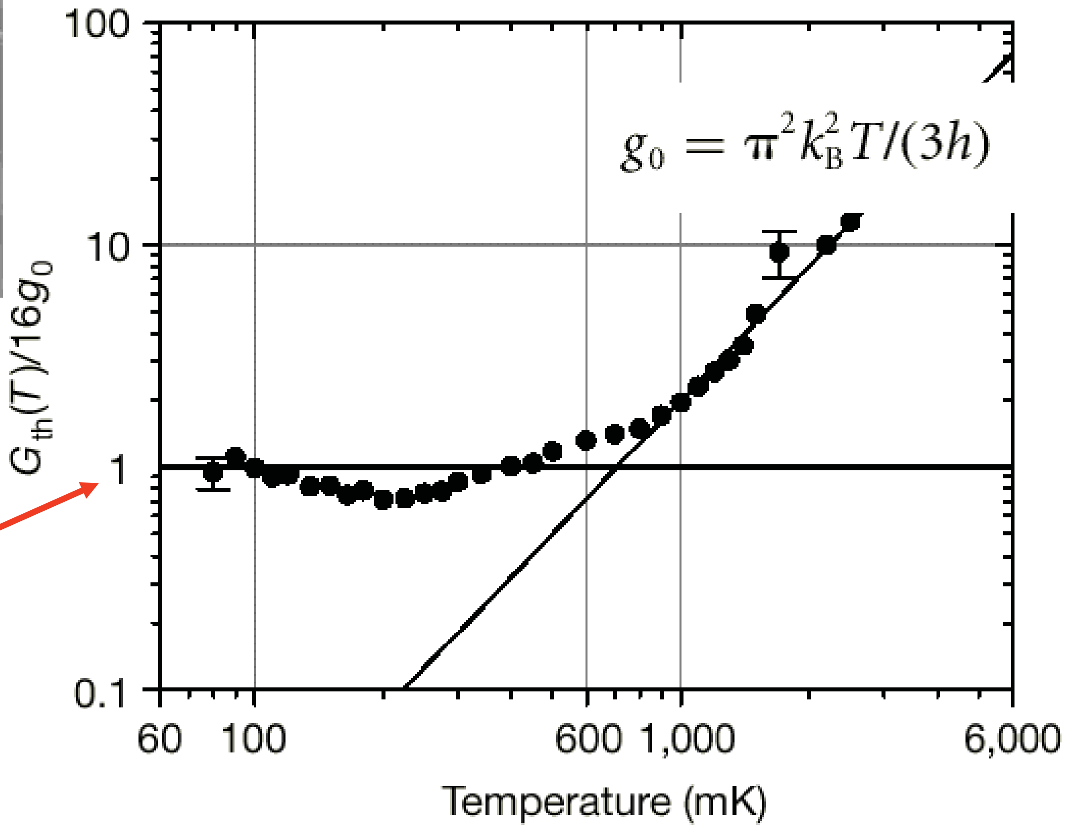
David Cahill (UIUC)

Nano Electromechanical System (NEMS)

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



Quantum of Thermal Conductance



Summary (Part I)

- Thermal characterization techniques
  - Suspended MEMS heaters
  - 3ω
  - Scanning thermal and thermoelectric microscopy
  - Time Domain Thermo Reflectance (TDTR)
  - Raman spectroscopy
- Ultra high thermal conductivity (CNT, graphene)
- Thermoreflectance imaging

Nanoscale heat transport and microrefrigerators on a chip;
A. Shakouri, Proceedings of IEEE, July 2006

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

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