Thermoelectricity: From Atoms to Systems

Week 3: Thermoelectric Characterization

Lecture 3.1: Micro/Nano Scale Temperature Measurement (Part 1)

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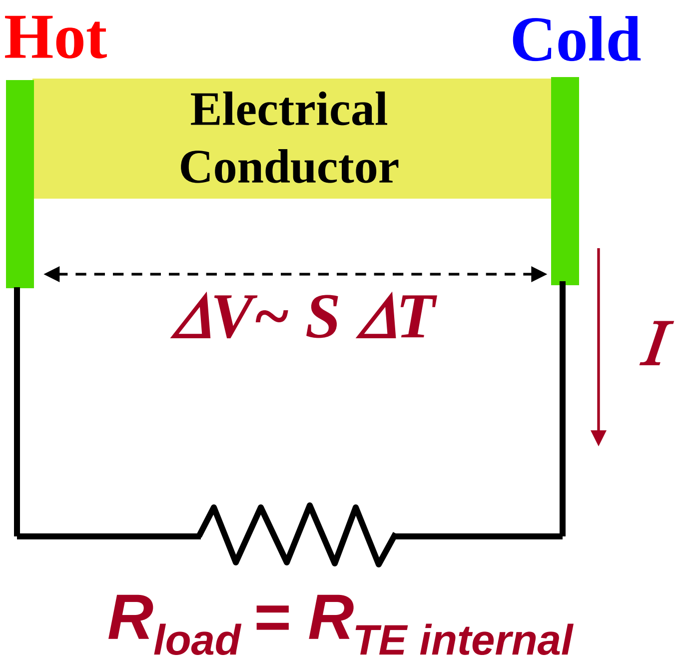
Direct Conversion of Heat into Electricity

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



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

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

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

Ohm's Law/ Electrical Conductivity

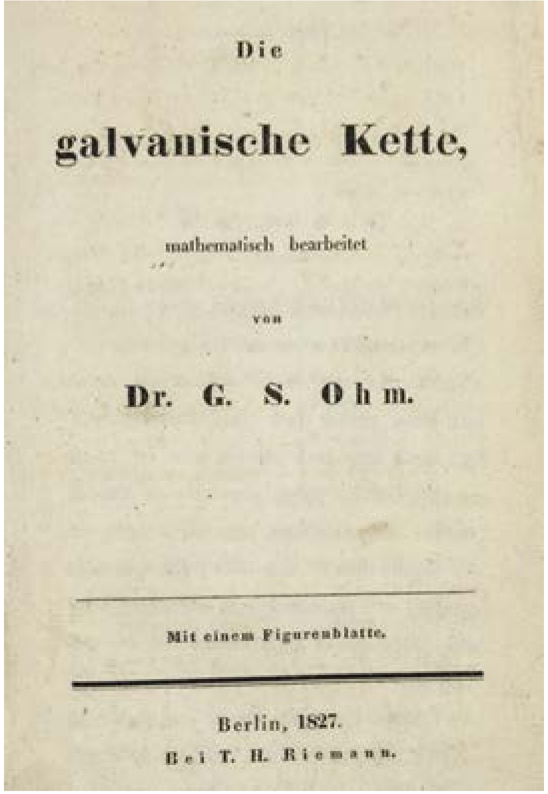
Electrical Current Density

Electrical Field

$$J = \sigma E$$

Electrical Conductivity

$$I = (1/R)\, V$$



Die

galvanische Kette,

mathematisch bearbeitet

von

Dr. G. S. Ohm.

Mit einem Figurenblatte.

Berlin, 1827.

Bei T. H. Riemann.

Georg Ohm, The Galvanic Circuit Investigated Mathematically,1827

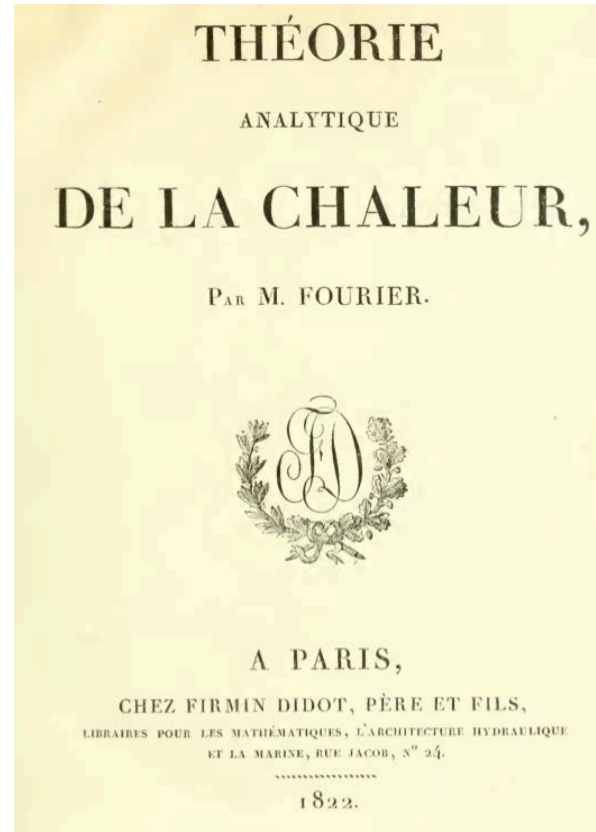
Fourier Law/ Thermal Conductivity

Heat Flow

Temperature Gradient

$$Q = k\,\Delta T$$

Thermal conductivity



THÉORIE

ANALYTIQUE

DE LA CHALEUR,

PAR M. FOURIER.

A PARIS,

CHEZ FIRMIN DIDOT, PÈRE ET FILS,

LIBRAIRES POUR LES MATHÉMATIQUES, L'ARCHITECTURE HYDRAULIQUE ET LA MARINE, RUE JACOB, N° 24.

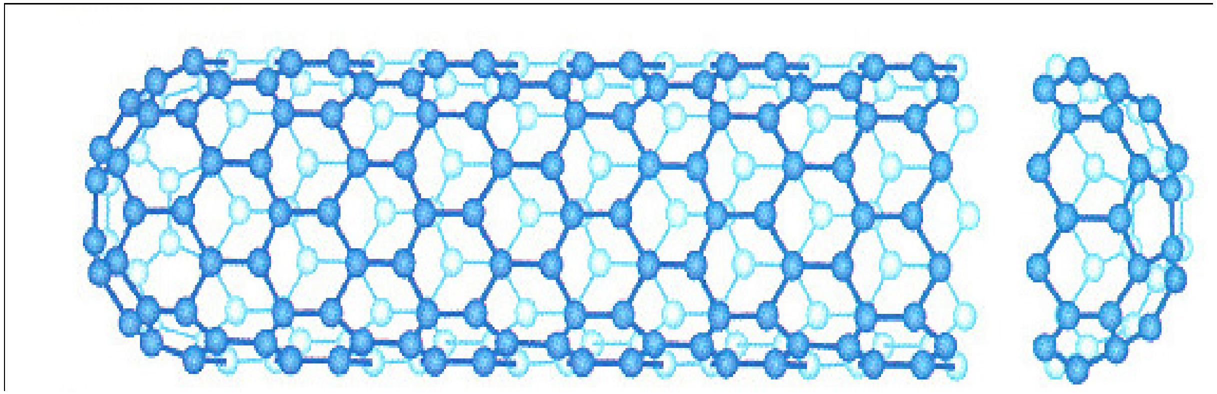
1822.

$$\partial T/\partial t = (k/C)\,\partial^2 T/\partial x^2$$

C: Heat capacity

Jean Baptiste Joseph Fourier, Analytical Theory of Heat,1822

Thermal Transport in Low Dimension



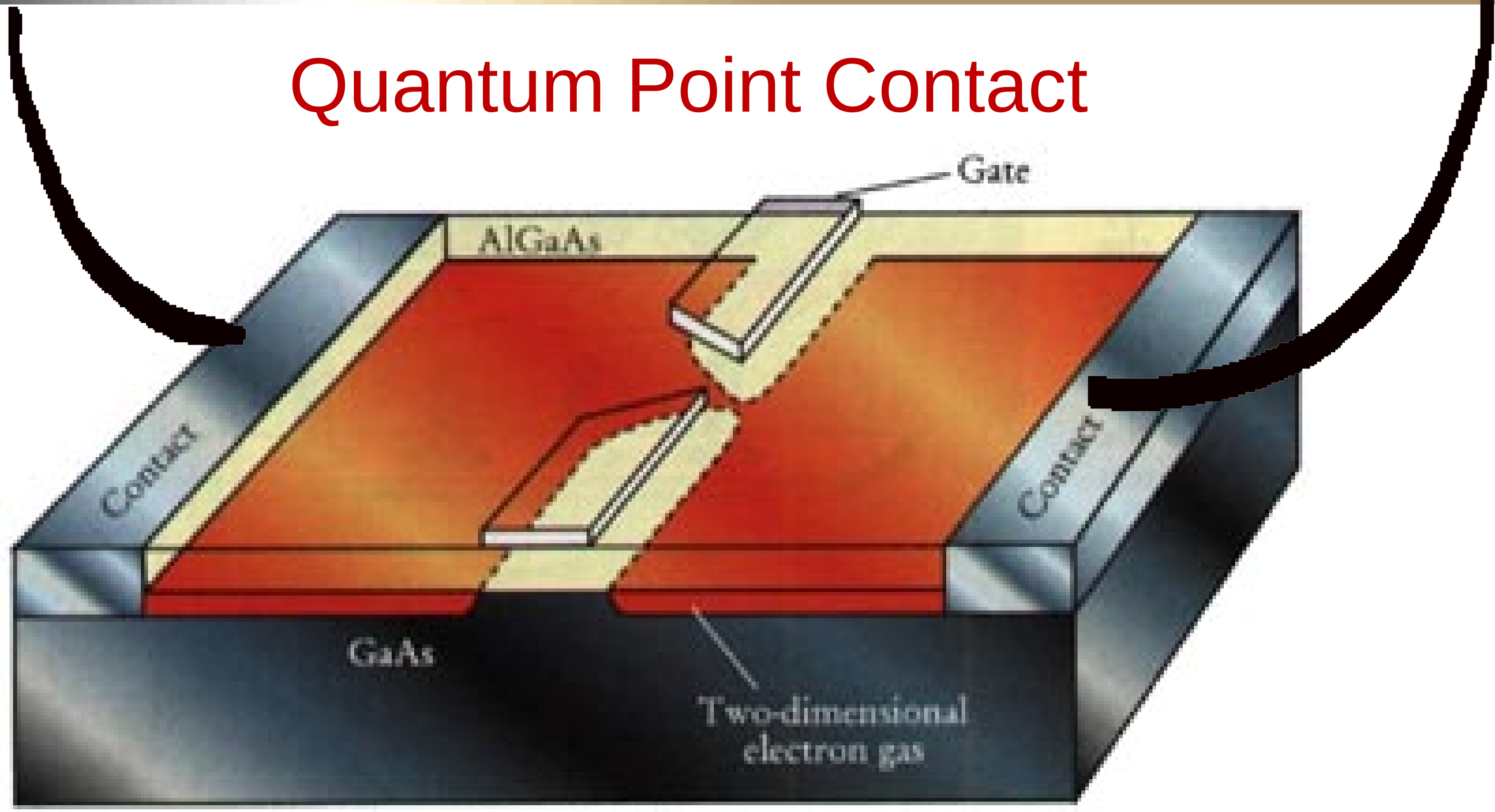
Thermal conductivity value? Seebeck value?

Deviations from diffusive transport?

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

Measuring voltage at nanometer scale

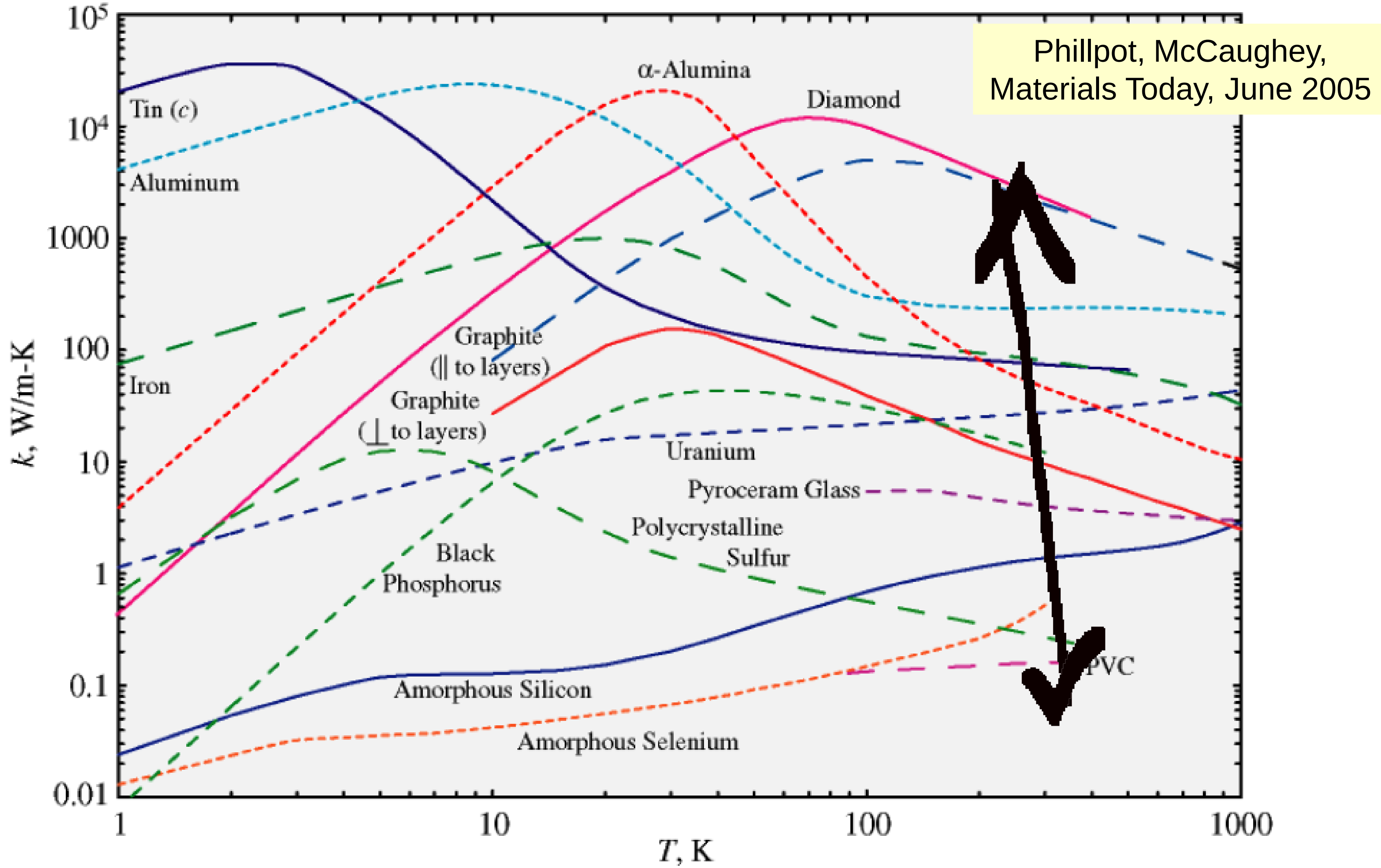
Quantum Point Contact



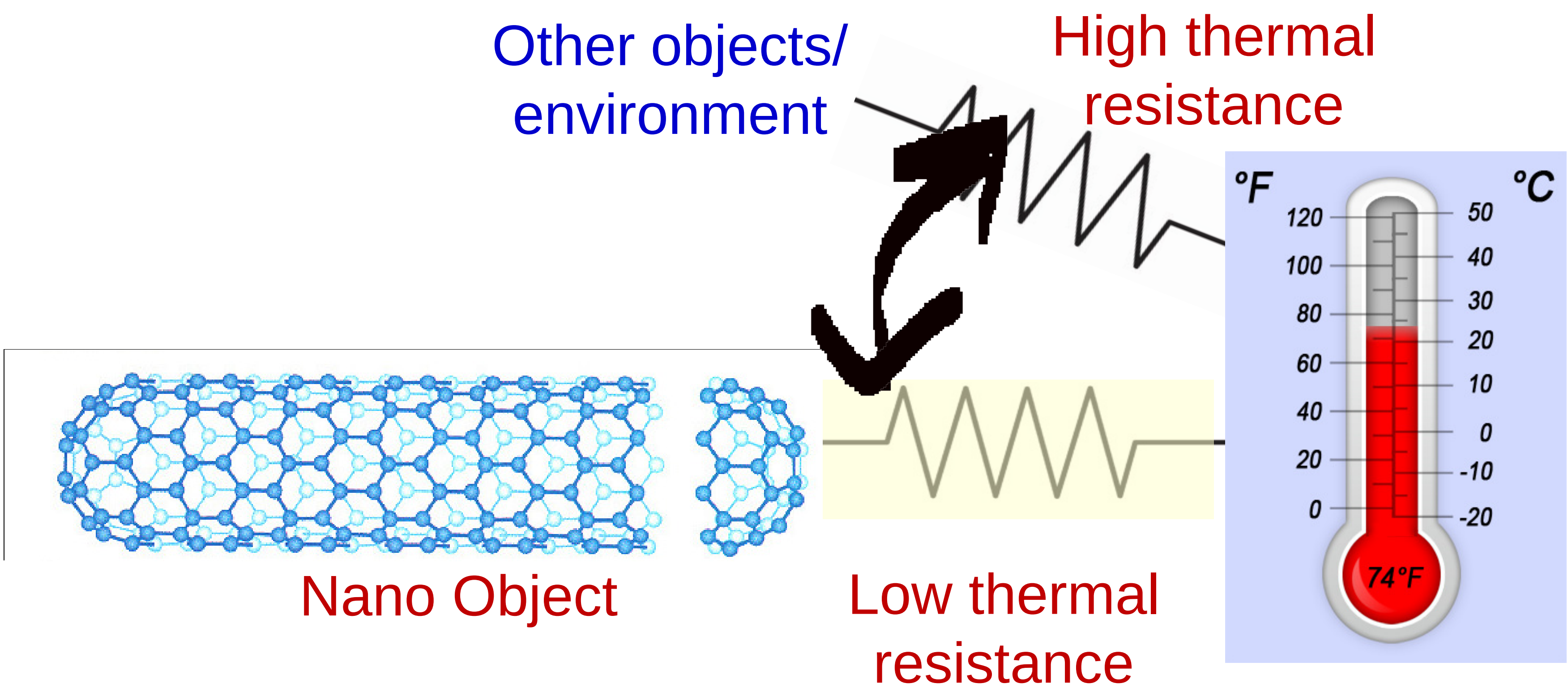
www.lorentz.leidenuniv.nl

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

Thermal Conductivity of Materials

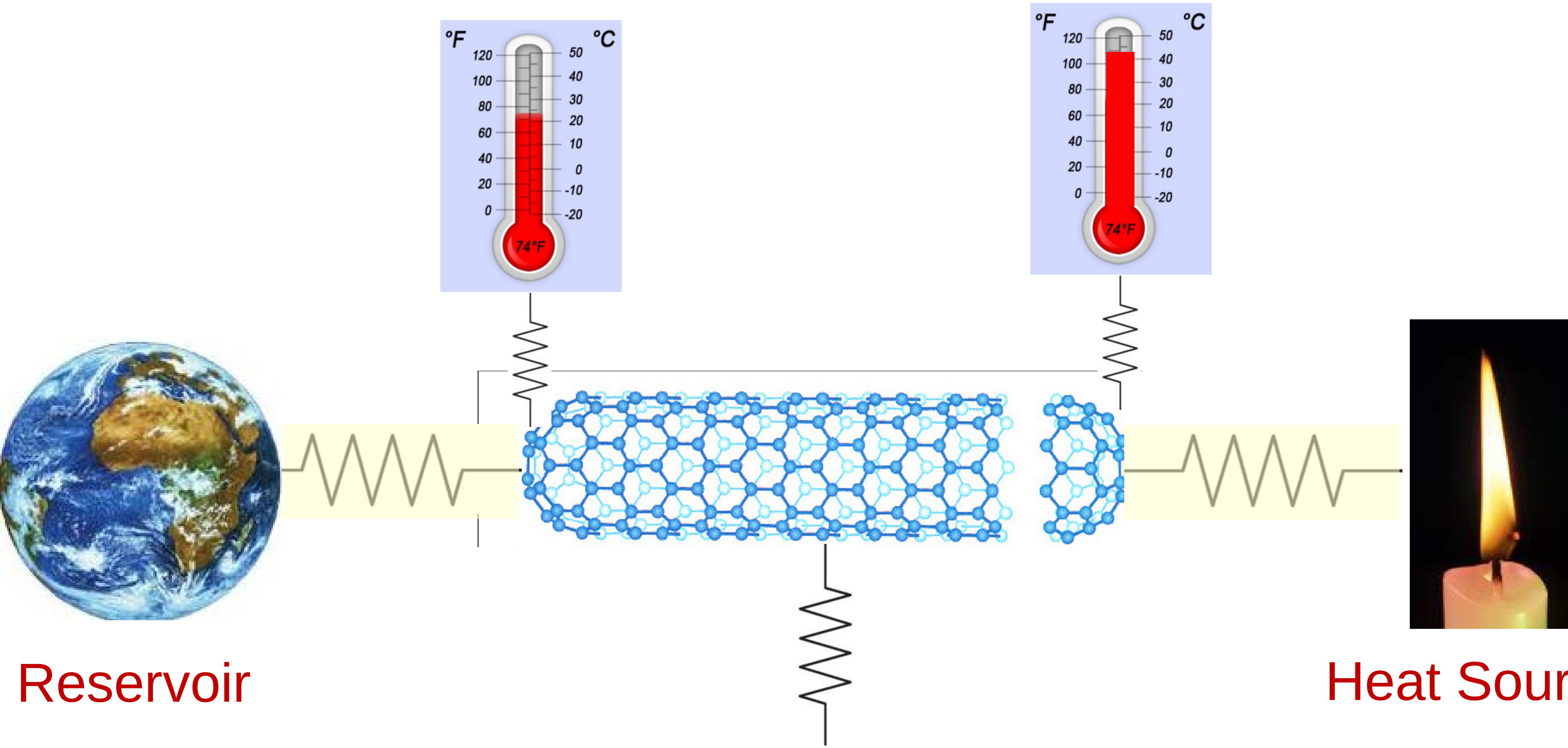


Measuring temperature at nanometer scale



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

Measuring heat flow at nanometer scale



Reservoir

Heat Source

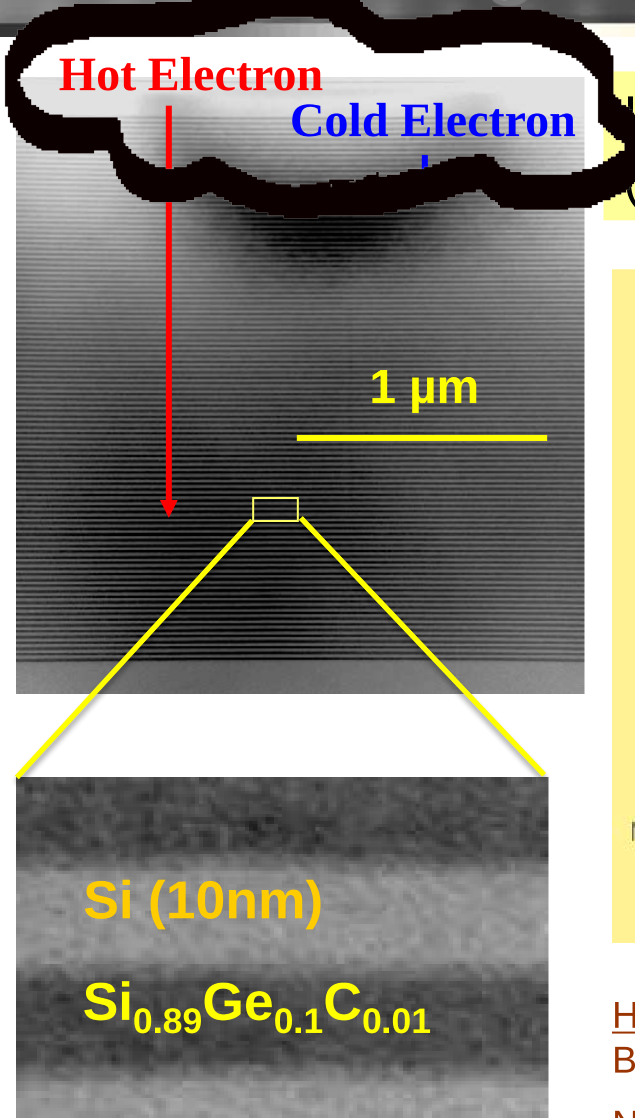
Other objects/
environment

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

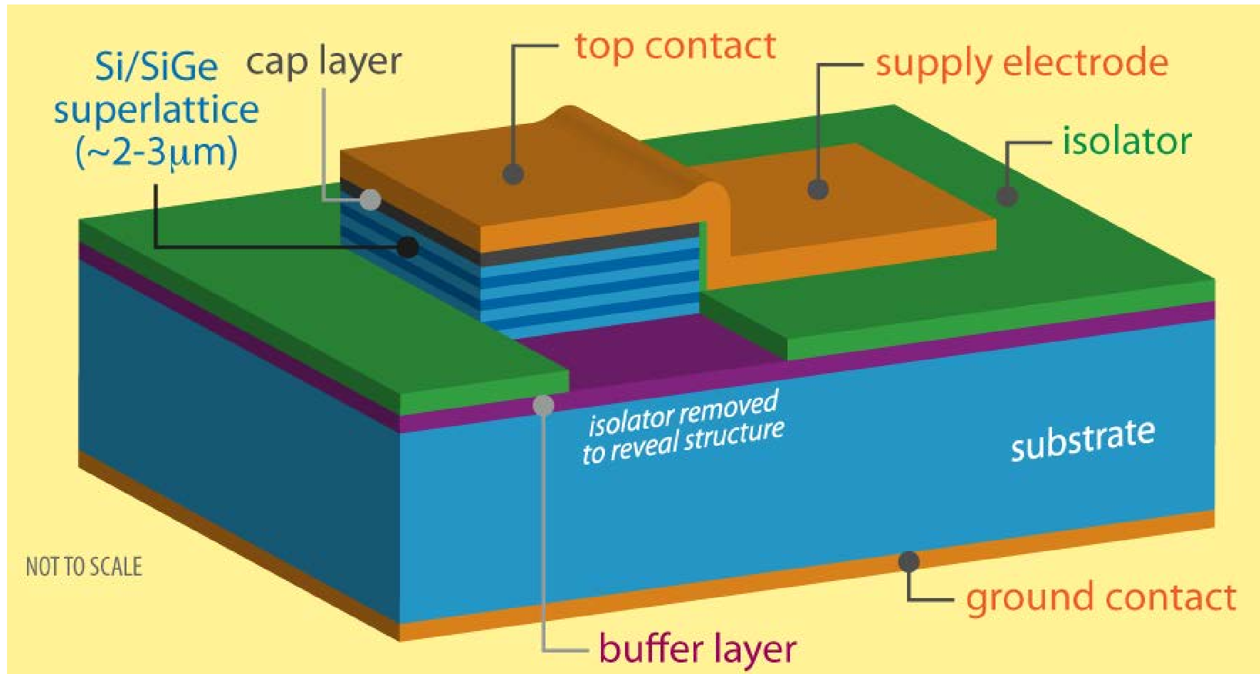
J. Christofferson, et al, *J. Electronic Packaging*,130 (4) 041101, 2008

Method	Resolution			Imag-ing?	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

Microrefrigerators on a chip



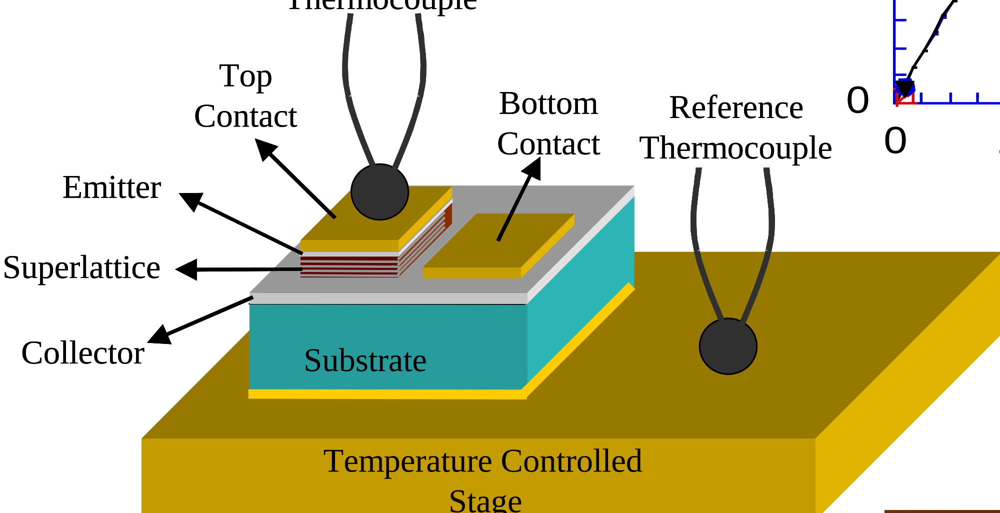
Implement selective emission of hot electrons (evaporative cooling) with heterostructure barriers.

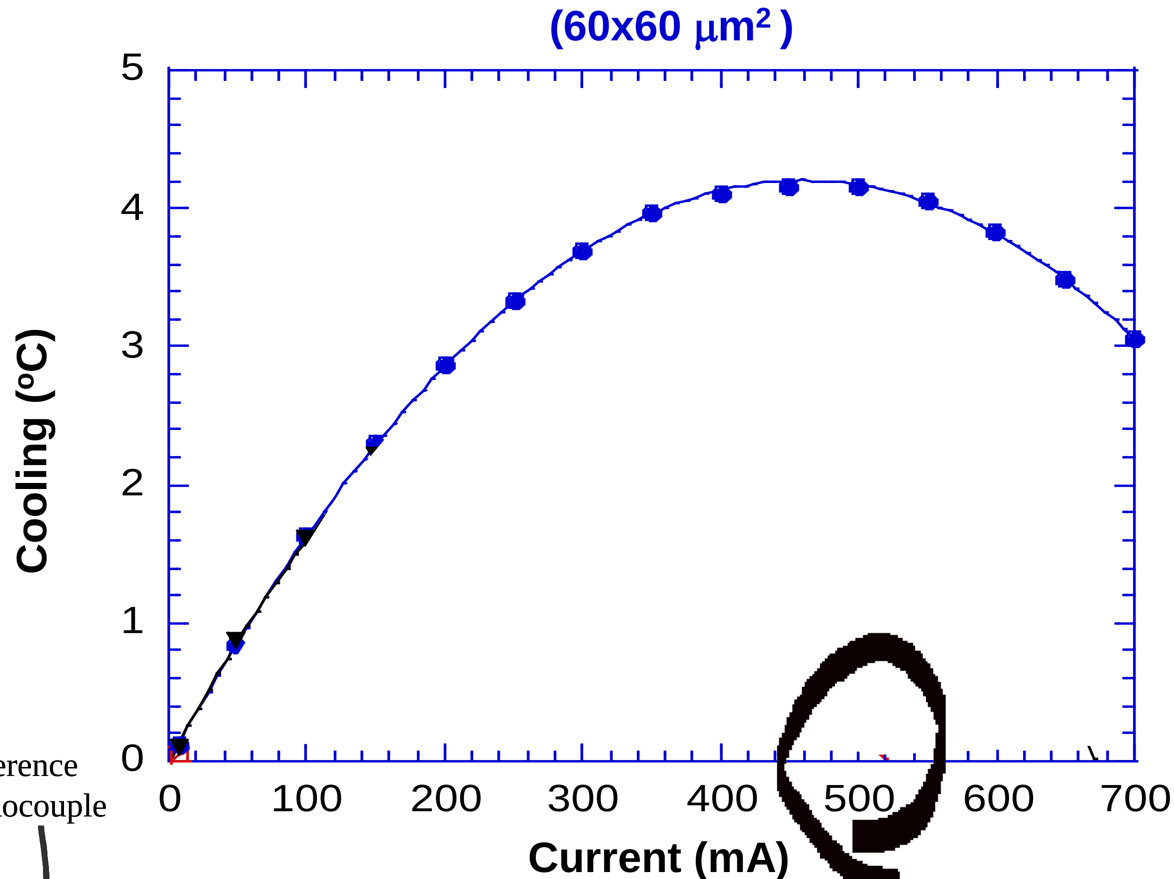


<u>Heterostructure Integrated Thermionic Coolers;</u> A. Shakouri and John Bowers, **Appl. Phys. Lett.** 1997

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

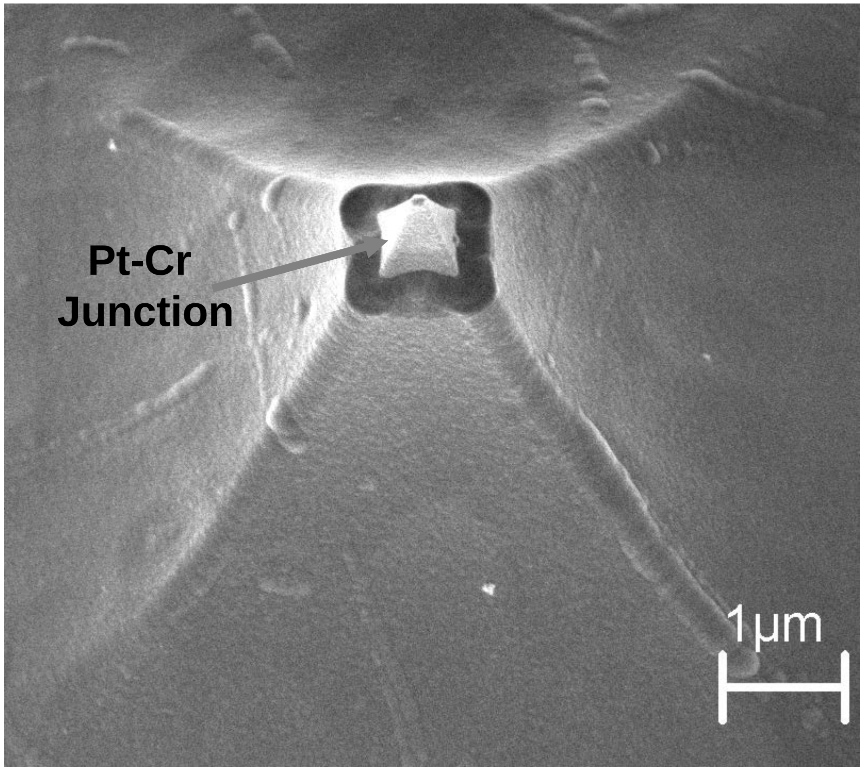
Micro thermocouple measurements: Cooling vs. Current

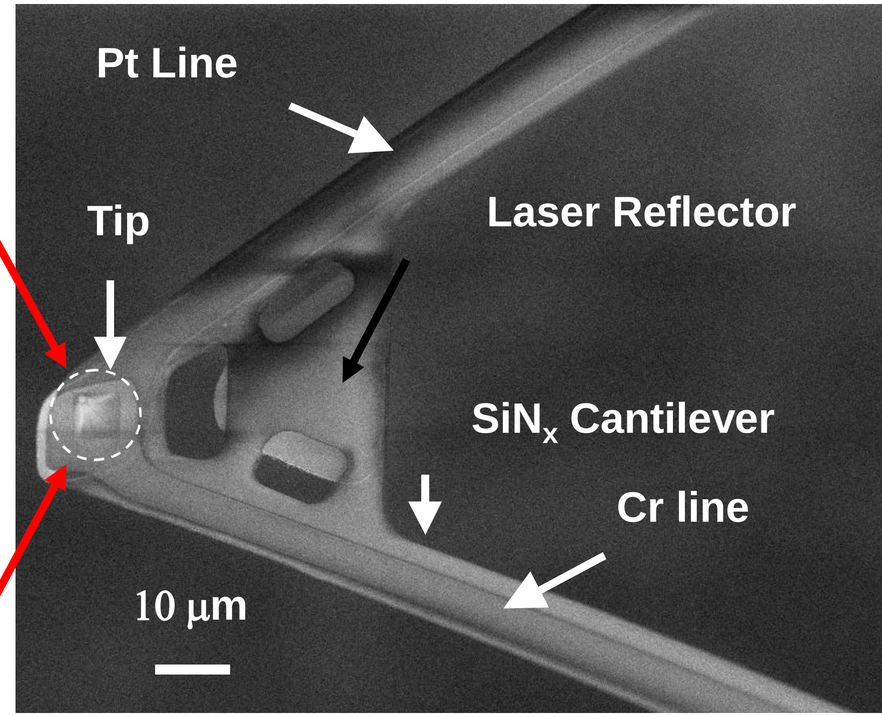




X. Fan, E. Croke, A. Shakouri, J. E. Bowers, … "**SiGe/Si Superlattice Coolers**," Phys. Low-Dim. Struct., 5/6 (2000) pp. 1-10.

Scanning Thermal Microscopy

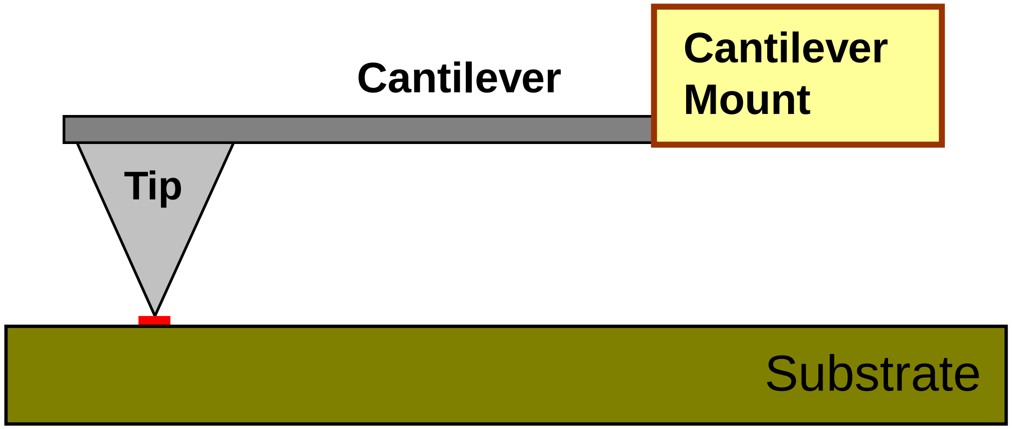


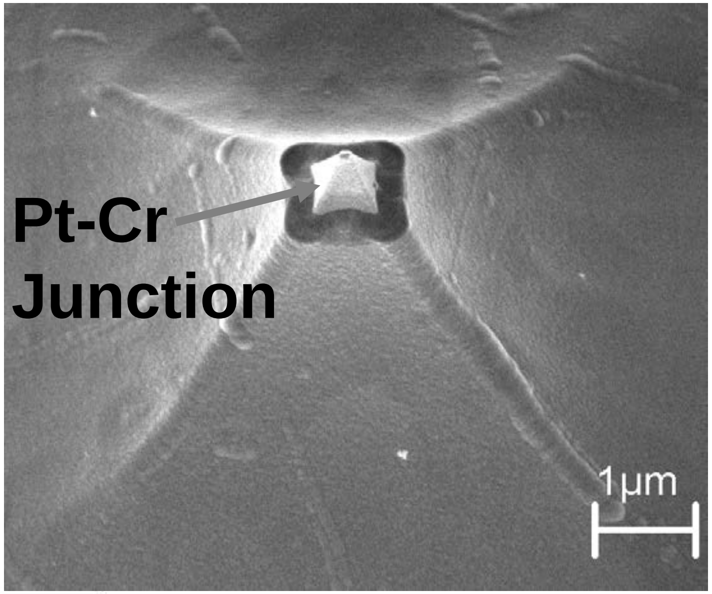


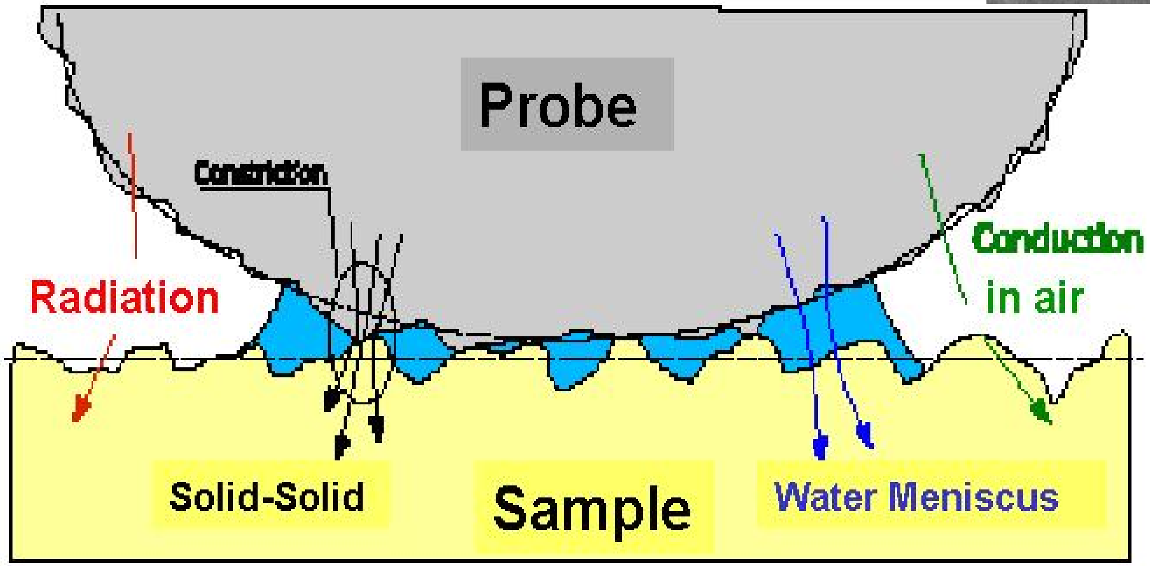
Cantilever Spring Constant:	0.1-1 N/m
Cantilever Deflection Detection Resolution:	0.01 nm
Force Resolution:	1-10 pN

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

Scanning Thermal Microscopy (SThM)



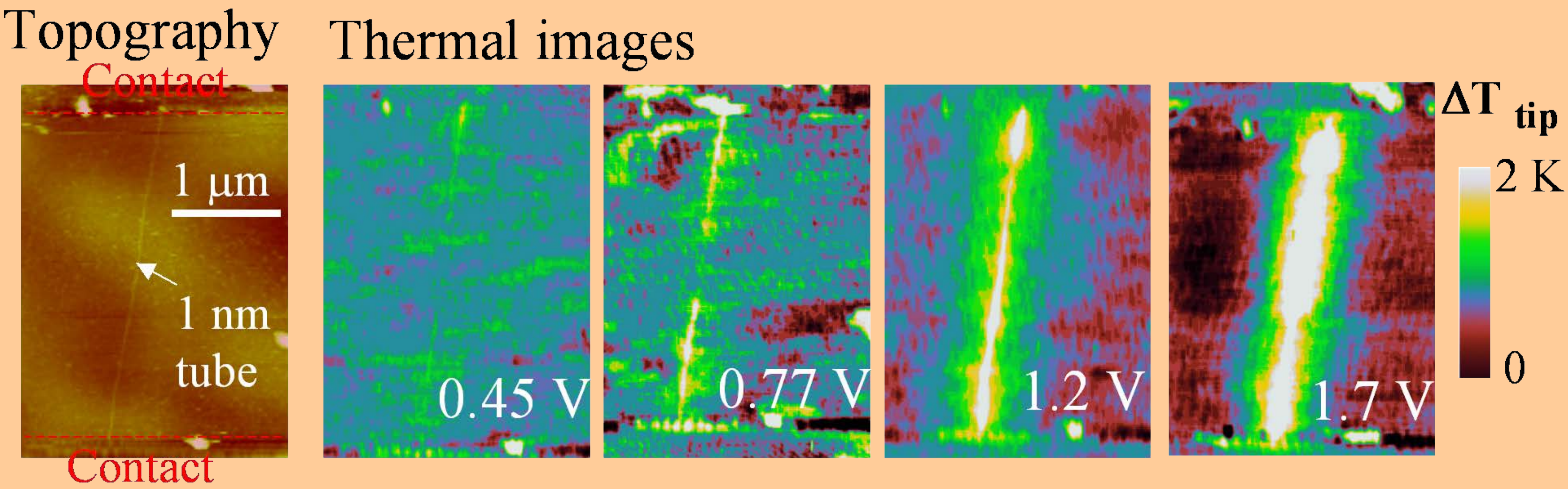




Courtesy: Arun Majumdar, UC Berkeley; Stefan Dilhaire, Univ. Bordeaux

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

SThM Metallic Single Wall Nanotube



SThM Thermal Mapping of Microrefrigerators

Prof. Arun Majumdar, UC Berkeley

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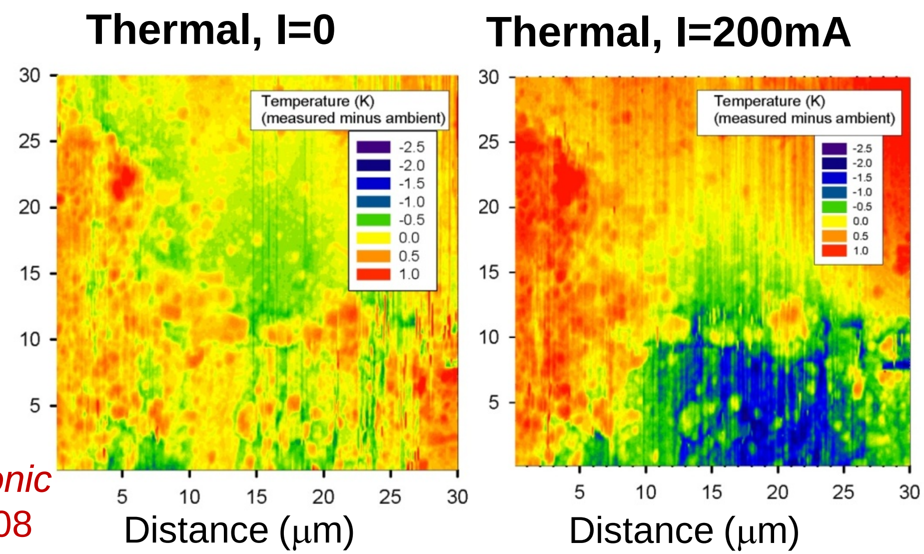

Lecture 3.1: Summary

- Fourier's and Ohm's Laws
- Challenges for temperature and thermal conductivity measurements at nanoscale
- Thermal characterization techniques
  - Micro thermocouple
  - Scanning thermal microscopy

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