Thermoelectricity: From Atoms to Systems

Week 3: Thermoelectric Characterization
Lecture 3.1: Micro/Nano Scale Temperature Measurement (Part 1)

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Seebeck coefficient

\[ S = \frac{\Delta V}{\Delta T} \]

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

\[ Z = \frac{S^2 \sigma}{k} \]

\[ Z = \frac{(\text{Seebeck})^2 (\text{electrical conductivity})}{(\text{thermal conductivity})} \]
Ohm’s Law/ Electrical Conductivity

Electrical Current Density

\[ J = \sigma E \]

Electrical Field

Electrical Conductivity

\[ I = (1/R) V \]

Georg Ohm, The Galvanic Circuit Investigated Mathematically, 1827
Fourier Law/ Thermal Conductivity

Heat Flow

Temperature Gradient

\[ Q = k \Delta T \]

Thermal conductivity

\[ \frac{\partial T}{\partial t} = \left( \frac{k}{C} \right) \frac{\partial^2 T}{\partial x^2} \]

C: Heat capacity

Jean Baptiste Joseph Fourier, Analytical Theory of Heat, 1822
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

A. Shakouri nanoHUB-U Fall 2013
Thermal Conductivity of Materials

Phillpot, McCaughey, Materials Today, June 2005
Measuring temperature at nanometer scale

Nano Object

Low thermal resistance

Other objects/environment

High thermal resistance

A. Shakouri, Advanced Workshop on Energy Transport in Low-Dimensional Systems, ICTP, Trieste, Italy; Oct. 2012
Measuring heat flow at nanometer scale

A. Shakouri, *Advanced Workshop on Energy Transport in Low-Dimensional Systems*, ICTP, Trieste, Italy; Oct. 2012
<table>
<thead>
<tr>
<th>Method</th>
<th>Resolution</th>
<th>Imaging?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x(μm)</td>
<td>T (K)</td>
<td>t (sec)</td>
</tr>
<tr>
<td>μ thermocouple</td>
<td>50</td>
<td>0.01</td>
<td>0.1-10</td>
</tr>
<tr>
<td>IRTthermography</td>
<td>3-10</td>
<td>0.02-1</td>
<td>1μ</td>
</tr>
<tr>
<td>Lockin IR Thermography</td>
<td>3-10</td>
<td>10μ</td>
<td>NA</td>
</tr>
<tr>
<td>Liquid Crystal Thermography</td>
<td>2-5</td>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>Thermo-reflectance</td>
<td>0.3-0.5</td>
<td>0.08</td>
<td>800p-0.1μ</td>
</tr>
<tr>
<td>Optical Interferometry</td>
<td>0.5</td>
<td>100μ</td>
<td>6n-0.1μ</td>
</tr>
<tr>
<td>Micro Raman</td>
<td>0.5</td>
<td>1</td>
<td>10n</td>
</tr>
<tr>
<td>Near Field (NSOM)</td>
<td>0.05</td>
<td>0.1-1</td>
<td>0.1μ</td>
</tr>
<tr>
<td>Scanning thermal microscopy (SThM)</td>
<td>0.05</td>
<td>0.1</td>
<td>10-100μ</td>
</tr>
</tbody>
</table>

Notes:
- Contact method
- Emissivity dependent
- Need cycling
- Only near phase transition (aging issues)
- Indirect measurement (expansion)
- 3D T-distribution
- S/N dependent Tip/sample interaction
- Contact method surface morphology
Implement selective emission of hot electrons (evaporative cooling) with heterostructure barriers.


Micro thermocouple measurements: Cooling vs. Current

Scanning Thermal Microscopy

Pt-Cr Junction

Pt Line

Tip

Laser Reflector

SiN$_x$ Cantilever

Cr line

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 Dilhaires, Univ. Bordeaux
SThM Metallic Single Wall Nanotube

**Topography**

Contact

1 μm

1 nm
tube

**Thermal images**

Distance (µm) Distance (µm)

0.45 V 0.77 V 1.2 V 1.7 V

ΔT tip

2 K

0

**SThM Thermal Mapping of Microrefrigerators**

Prof. Arun Majumdar, UC Berkeley

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