Nanoscale Thermal and Thermoelectric Mapping of Devices and Interconnects

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Outline

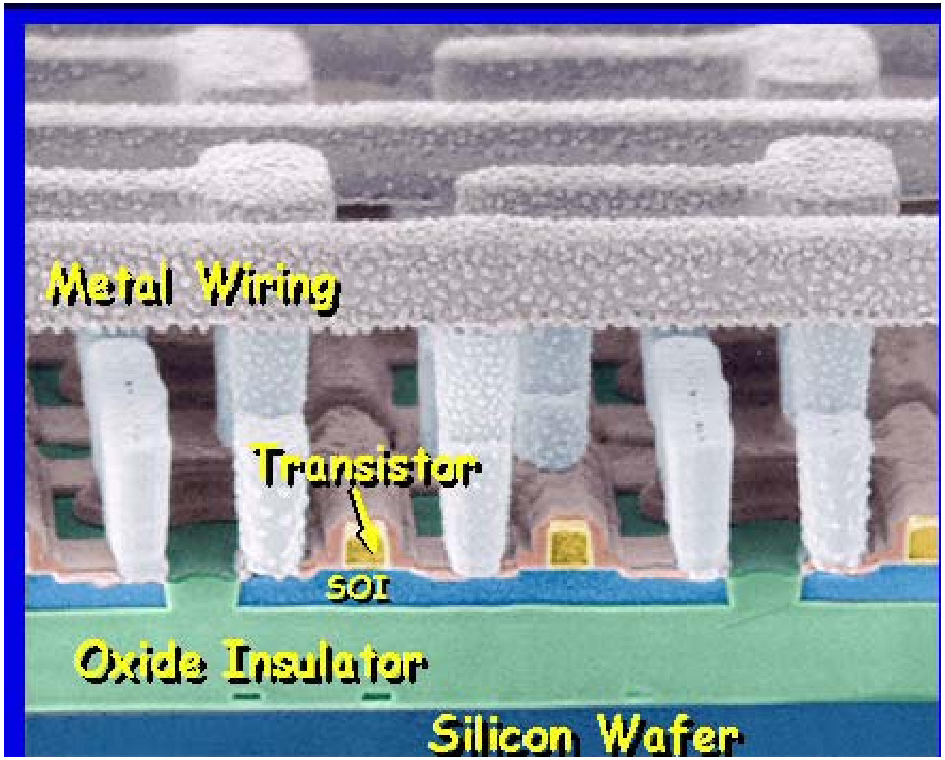
- Scanning Thermal Microscopy (SThM)

- Electrostatic Force Microscopy (EFM)

- Scanning Thermoelectric Microscopy (SThEM)

Silicon Devices

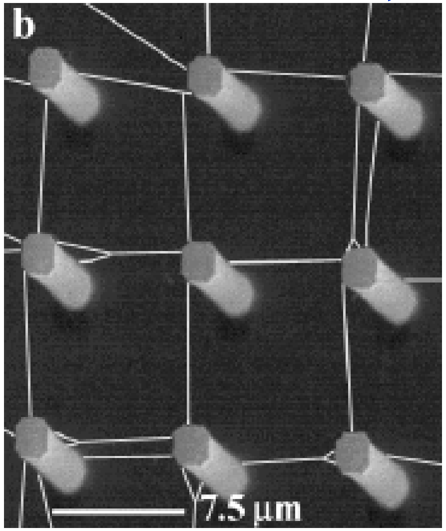
- Device scaling is limited by power consumption
- Heat dissipation influences speed and reliability
- Need to understand dissipation in transistors and interconnects



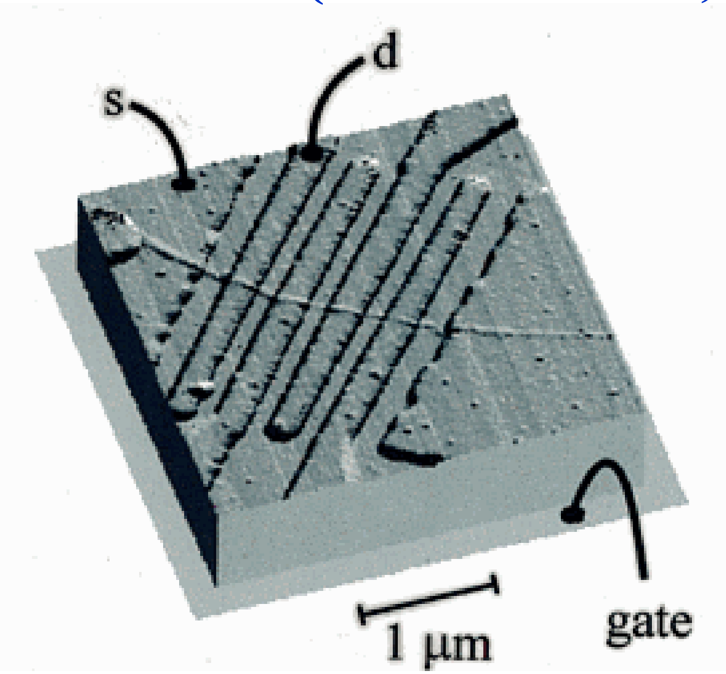
IBM SOI Technology

Nanotube Electronics

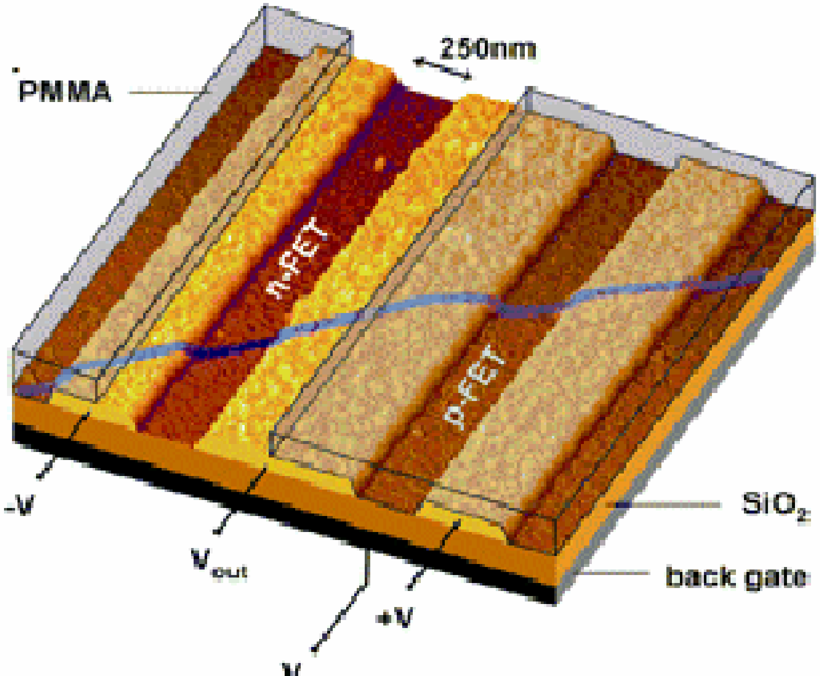
Nanotube Interconnect (Dai *et al.*, Stanford)



TubeFET (McEuen *et al.*, Berkeley)



Nanotube Logic (Avouris *et al.*, IBM)

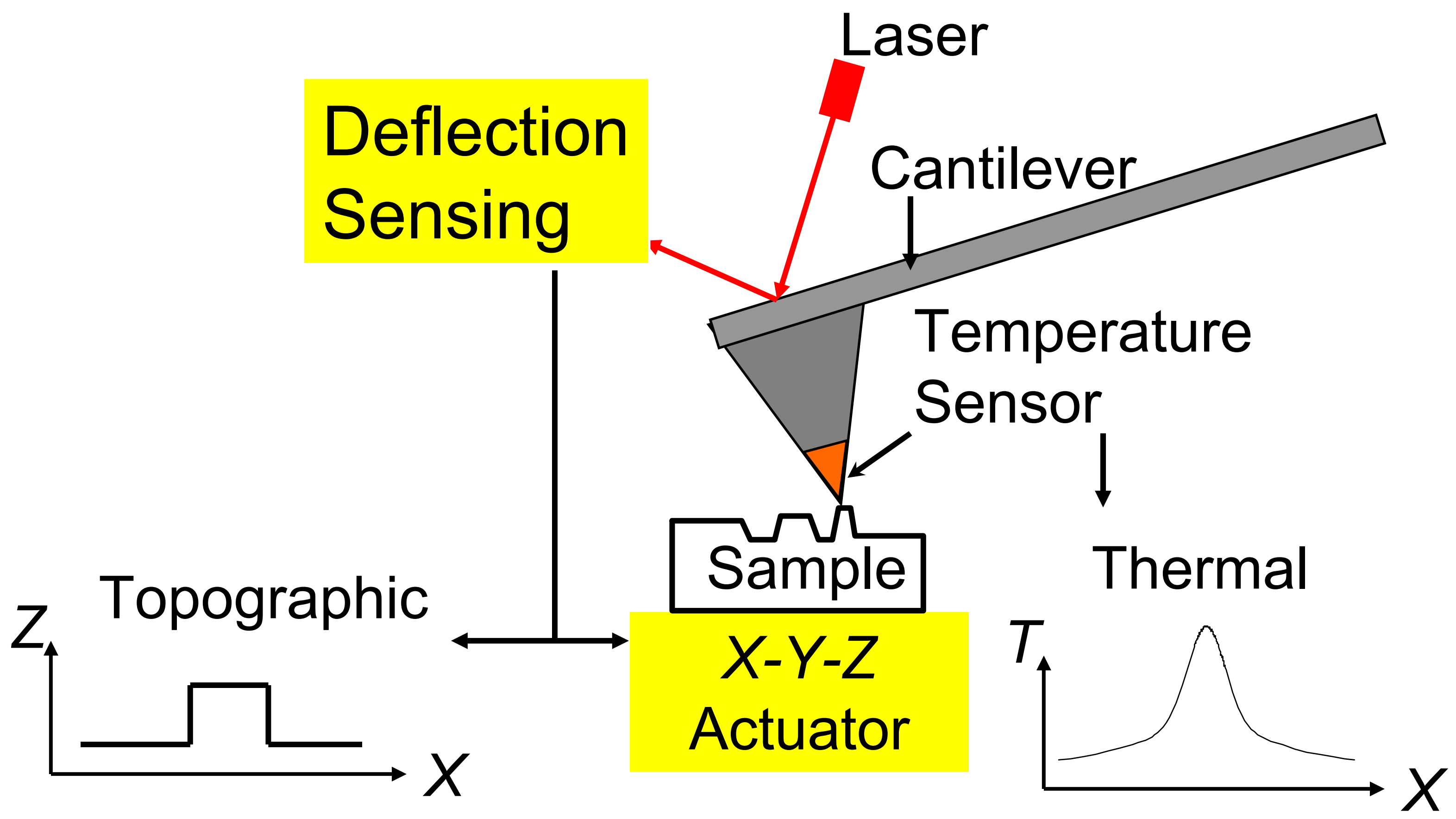


Intriguing heat dissipation physics!

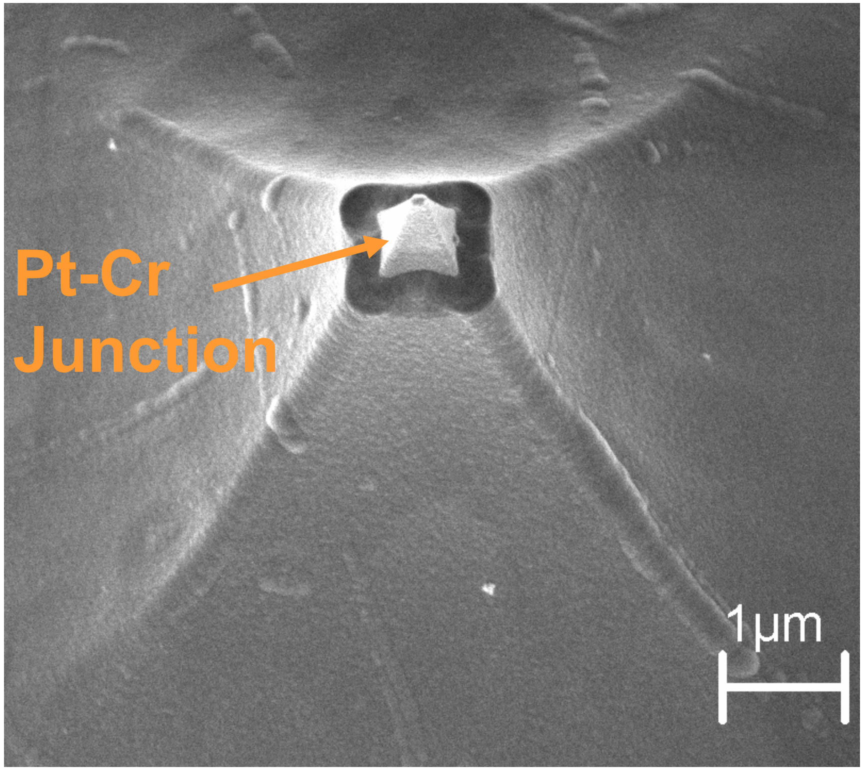
Thermometry of Nanoelectronics

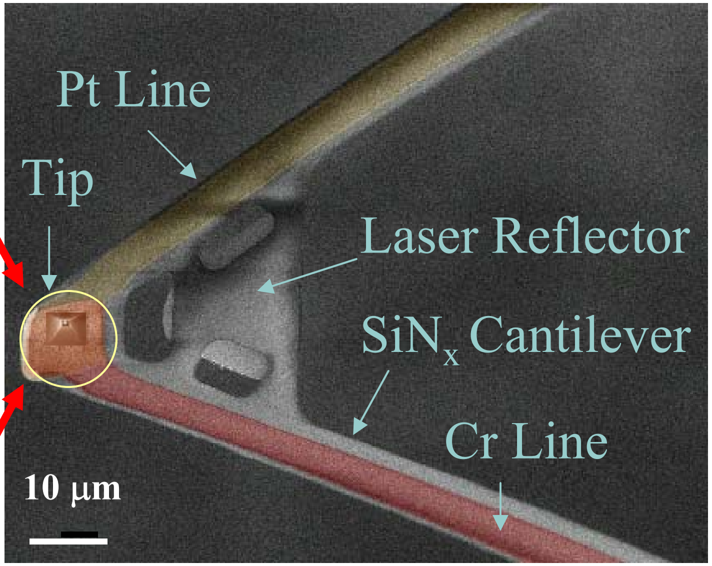
Scanning Thermal Microscope:

Atomic Force Microscope (AFM) + Thermal Probe



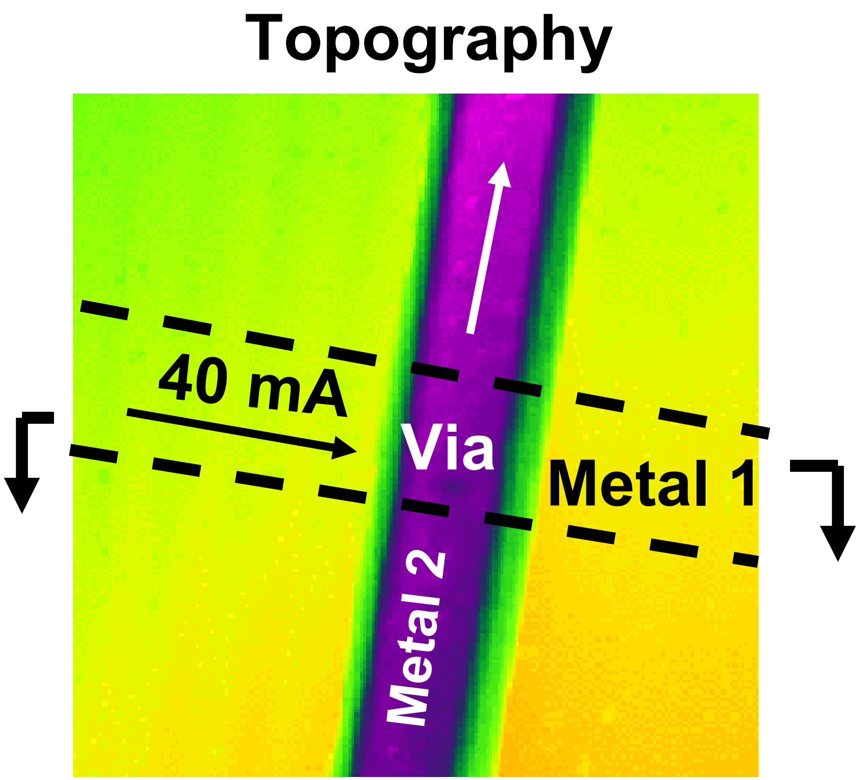
Microfabricated Probes

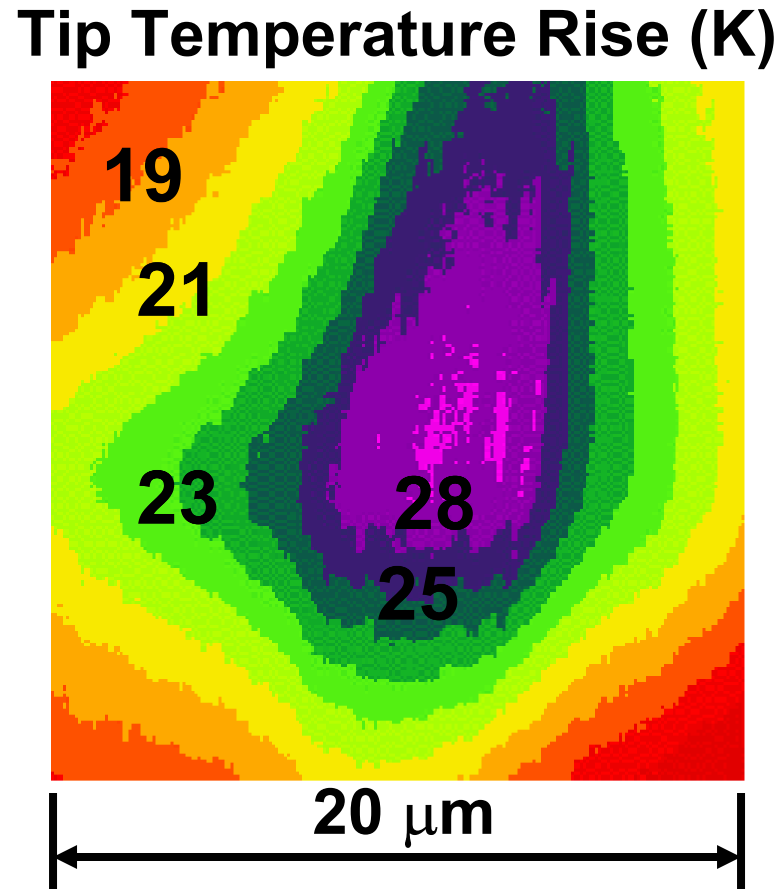


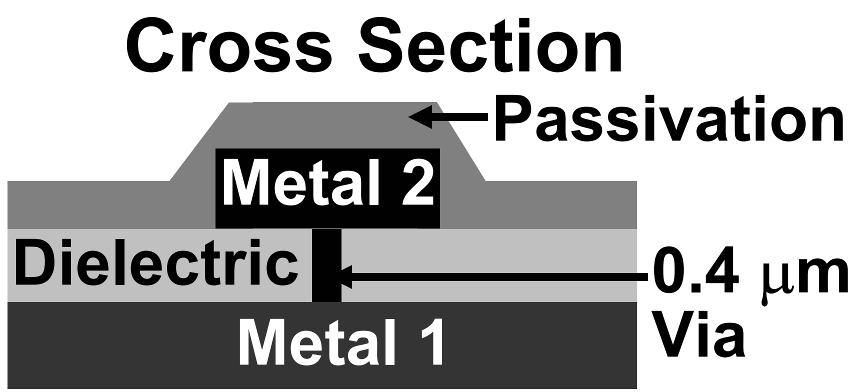


Shi, Kwon, Miner, Majumdar, *J. MicroElectroMechanical Sys.*, **10**, p. 370 (2001)

Locating Defective VLSI Via



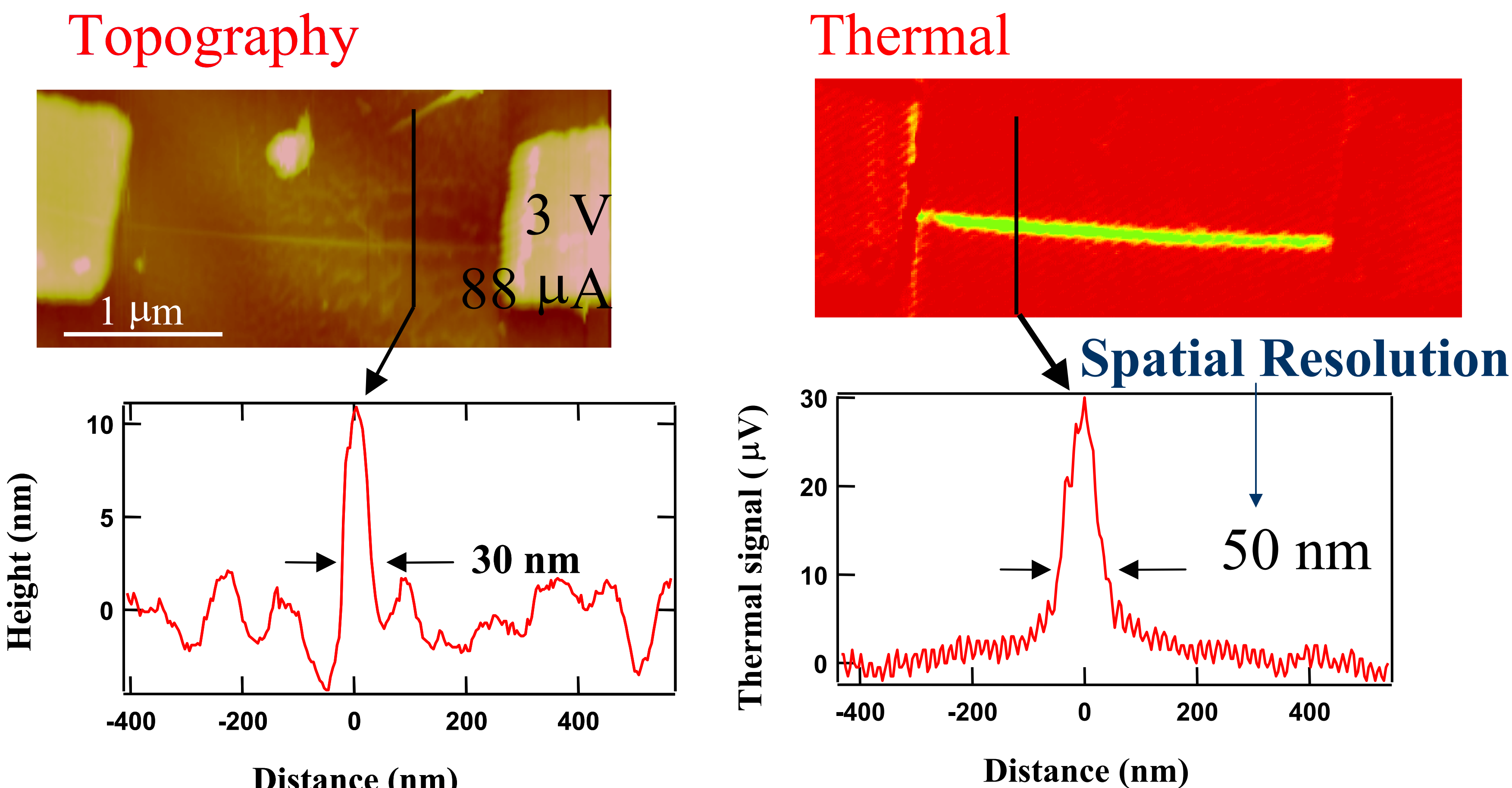




- Collaboration: TI
- Shi *et al.*, *Int. Reli. Phys. Sym.*, p. 394 (2000)

Thermal Imaging of Nanotubes

Multiwall Carbon Nanotube

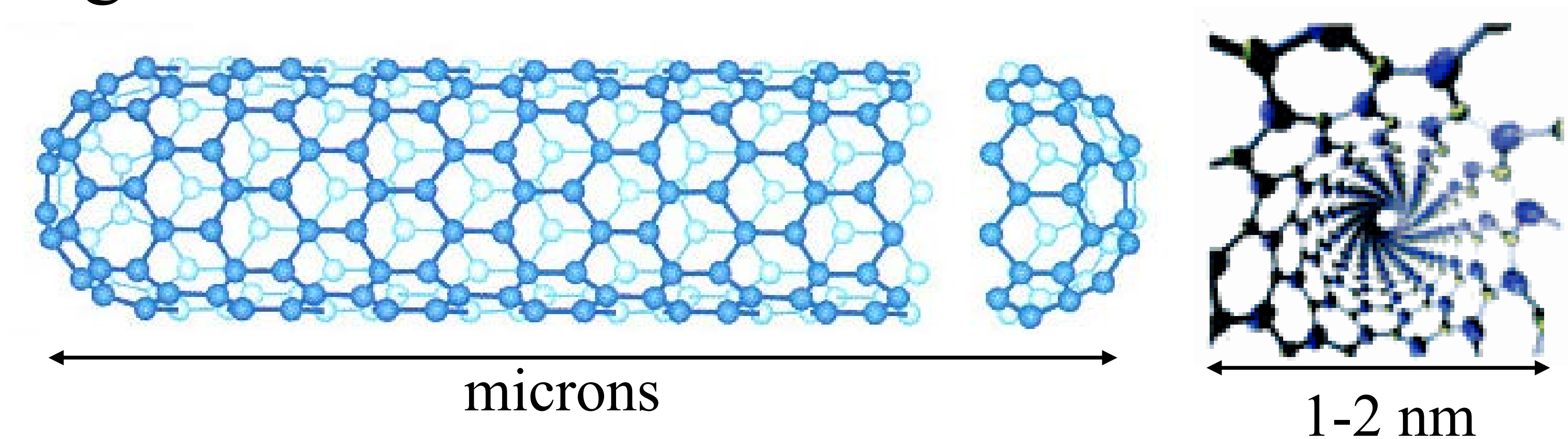


Shi, Plyosunov, Bachtold, McEuen, Majumdar,
Appl. Phys. Lett., **77**, p. 4295 (2000)

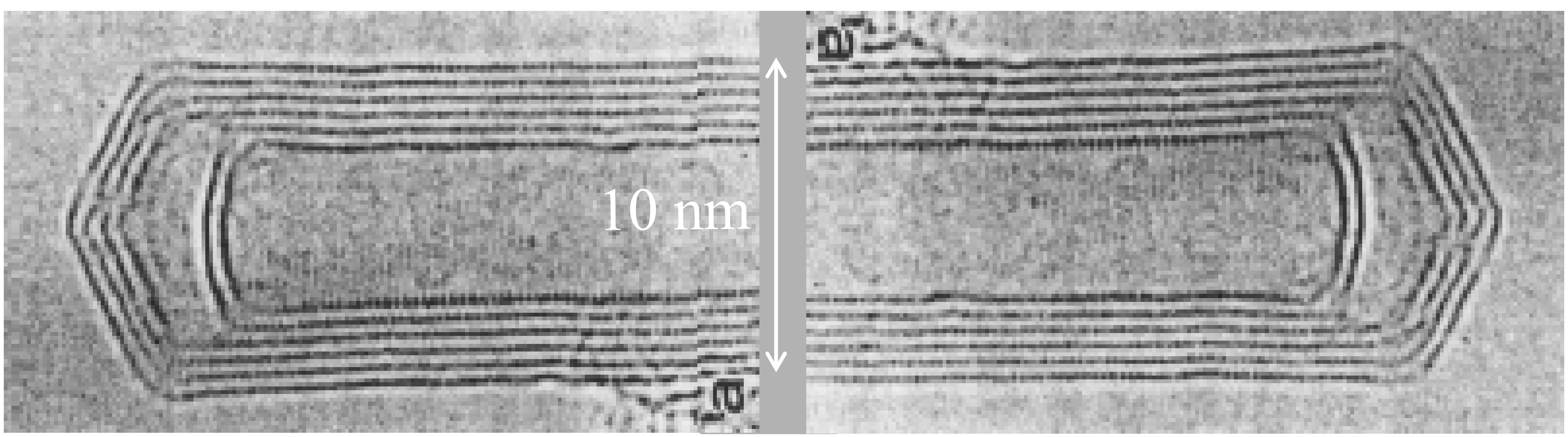
Carbon Nanotubes

Super high current density:
10^9 A/cm^2 !

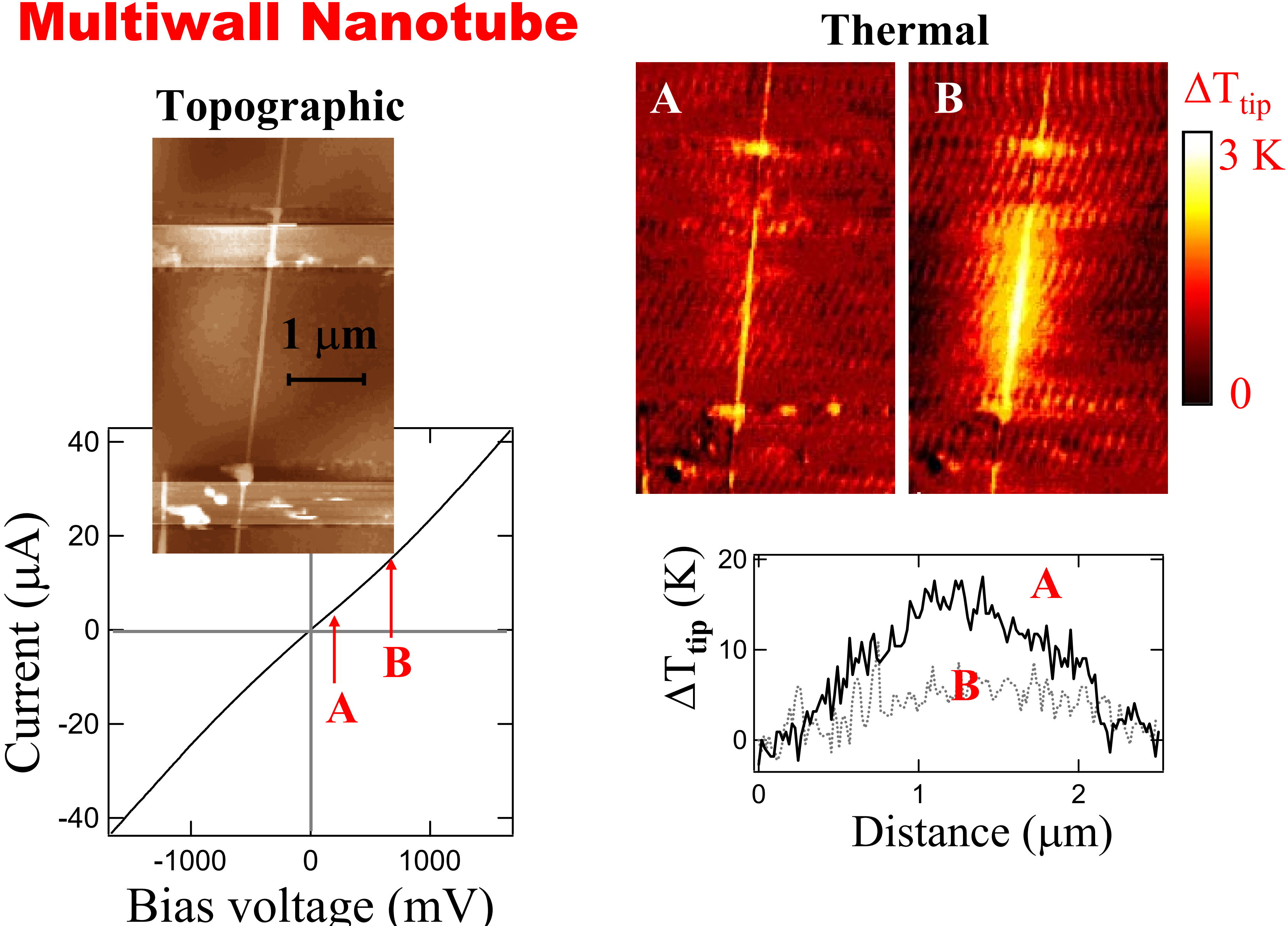
Single Wall -- **Semiconducting or Metallic**



Multiwall -- **Metallic**

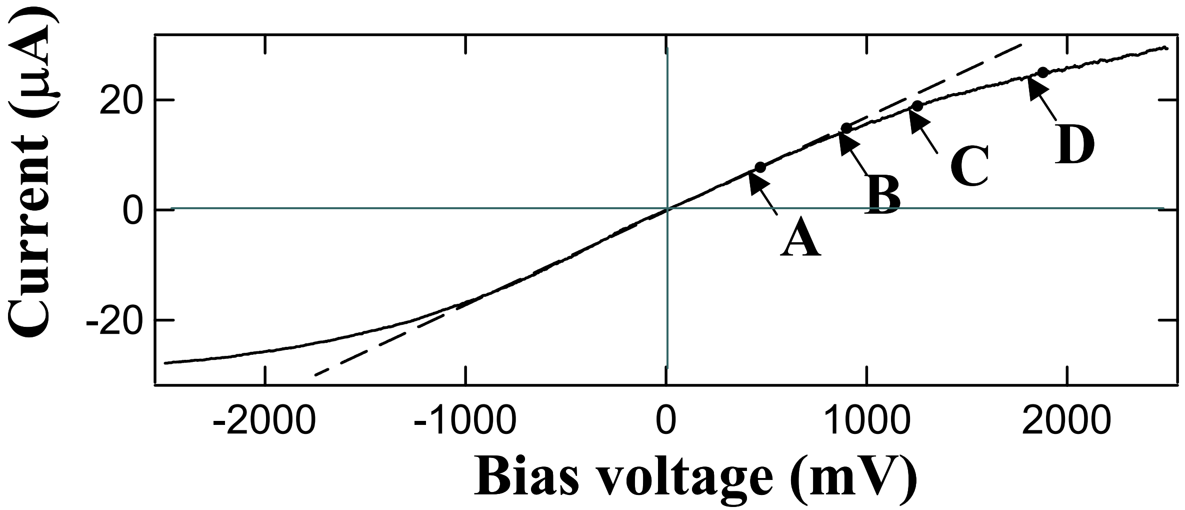


Multiwall Nanotube



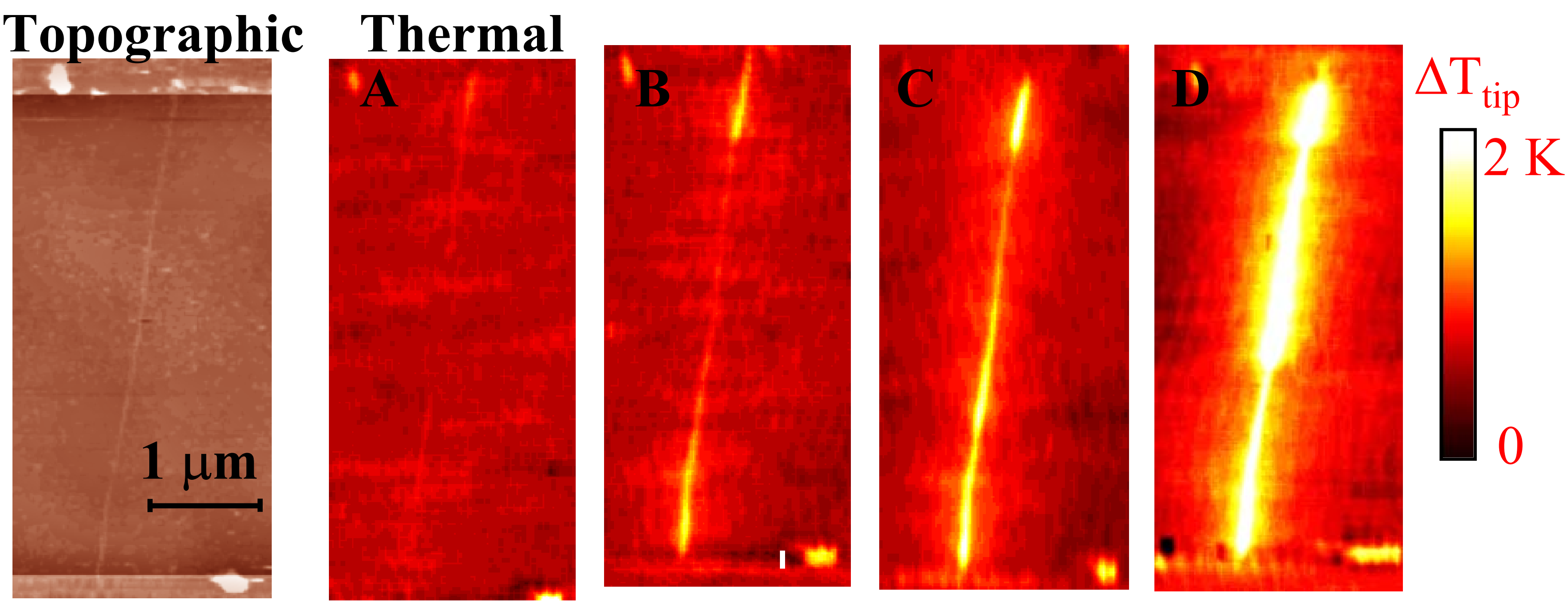
• **Bulk dissipation at low and high voltages**

Metallic Single Wall Nanotube



Low bias:
contact dissipation

High bias:
bulk dissipation



Electron Transport in Single Wall Nanotubes

Low Bias:

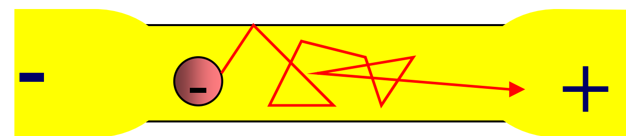
$E_{electron} < E_{optical\ phonon}$

Ballistic (long *mfp*)

High Bias:

$E_{electron} > E_{optical\ phonon}$

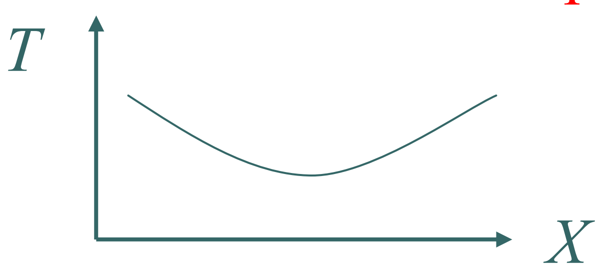
Diffusive (short *mfp*)



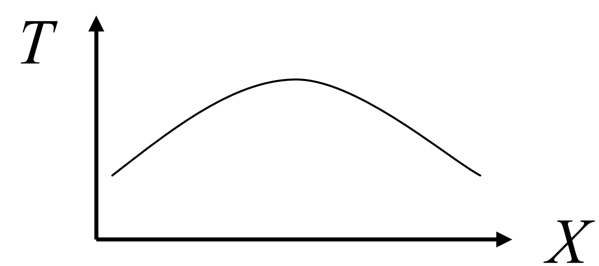
mfp: mean free path before scattered by boundary, defects, phonons

Lattice vibration

Ballistic – Junction Dissipation

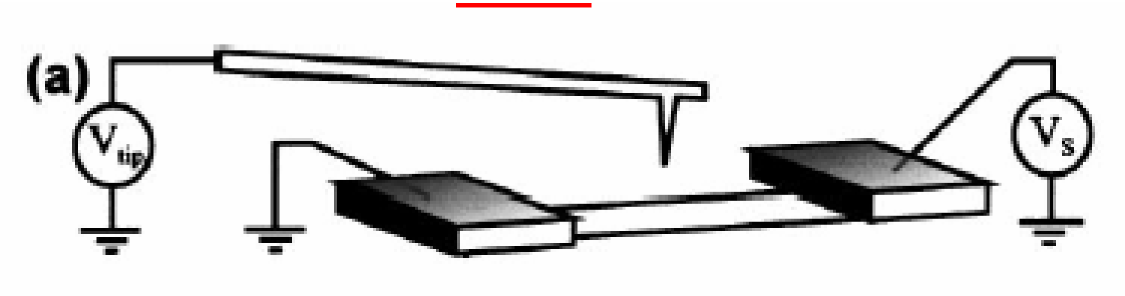


Diffusive – Bulk Dissipation



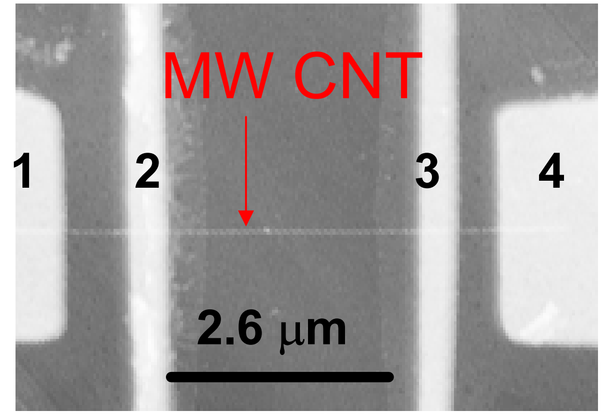
Electrostatic Force Microscopy (EFM)

EFM

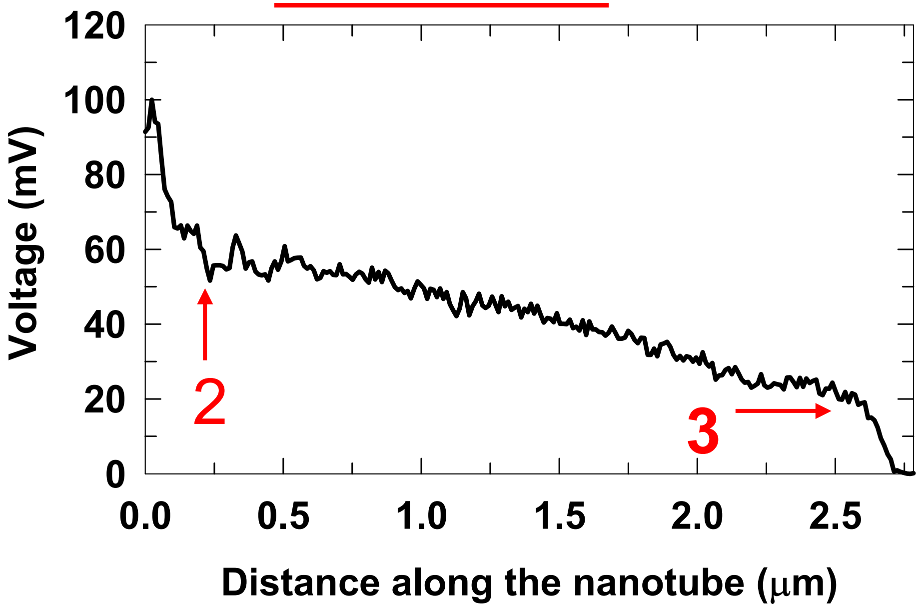


Amplitude and phase of AFM cantilever oscillation depend on tip-sample electric filed

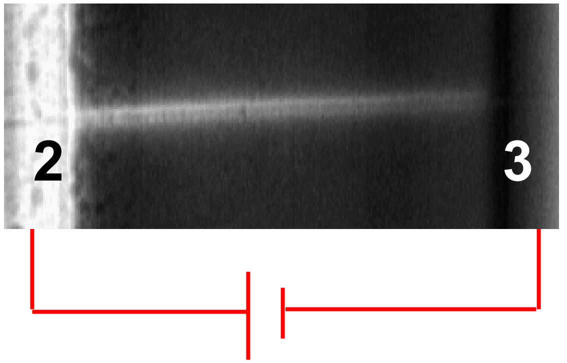
AFM Image



EFM Profile

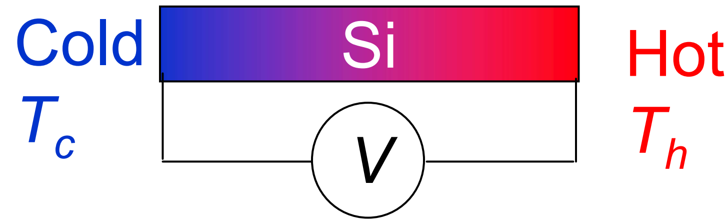


EFM Image

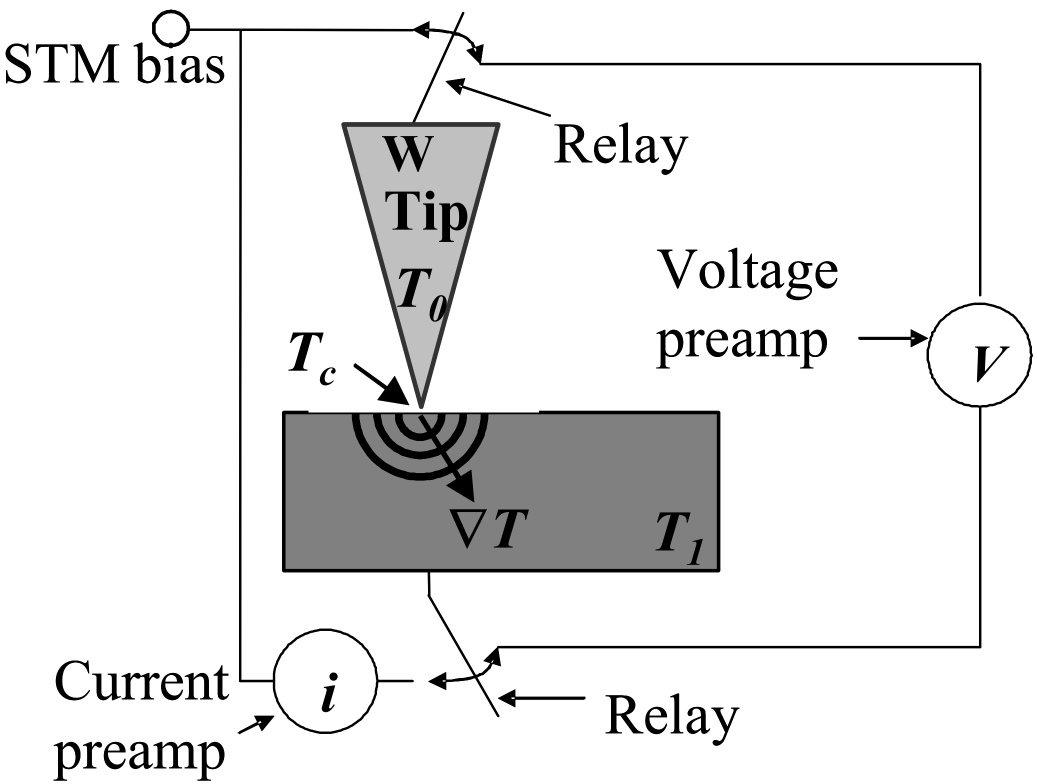


UHV Scanning Thermoelectric Microscopy

- Nanoscale Profiling Seebeck Coefficient (S, or Thermoelectric Power)
- Origins from the hot-probe method for determining doping type



$$V = S(T_h - T_c)$$



- Establish a nano-contact between the STM tip and the heated sample

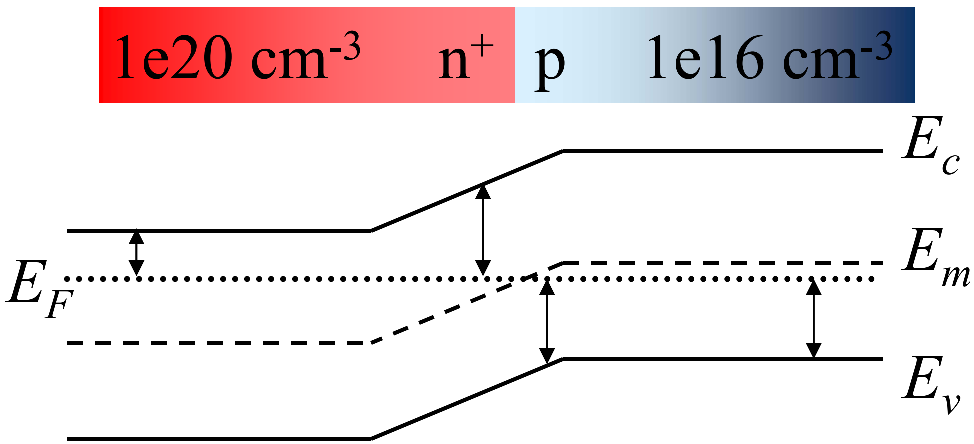
$$T_1 > T_c > T_0$$

- ∇T in the sample is localized at the contact
- Measure local thermoelectric voltage

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

Collaboration: C. K. Ken Shih, UT Physics

Profiling Carrier Concentration of p-n Junctions

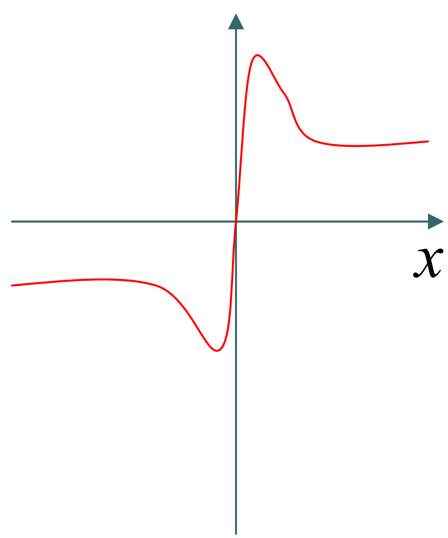


$$S = \frac{nS_{electron} + pS_{hole}}{n+p}$$

n-doped

$$S \approx S_{electron} = \frac{1}{-eT}\left(E_c - E_F + \frac{3}{2}k_B T\right) = -\frac{k_B}{e}\left(\ln\frac{N_v}{n} + \frac{3}{2}\right) < 0$$

Electron concentration

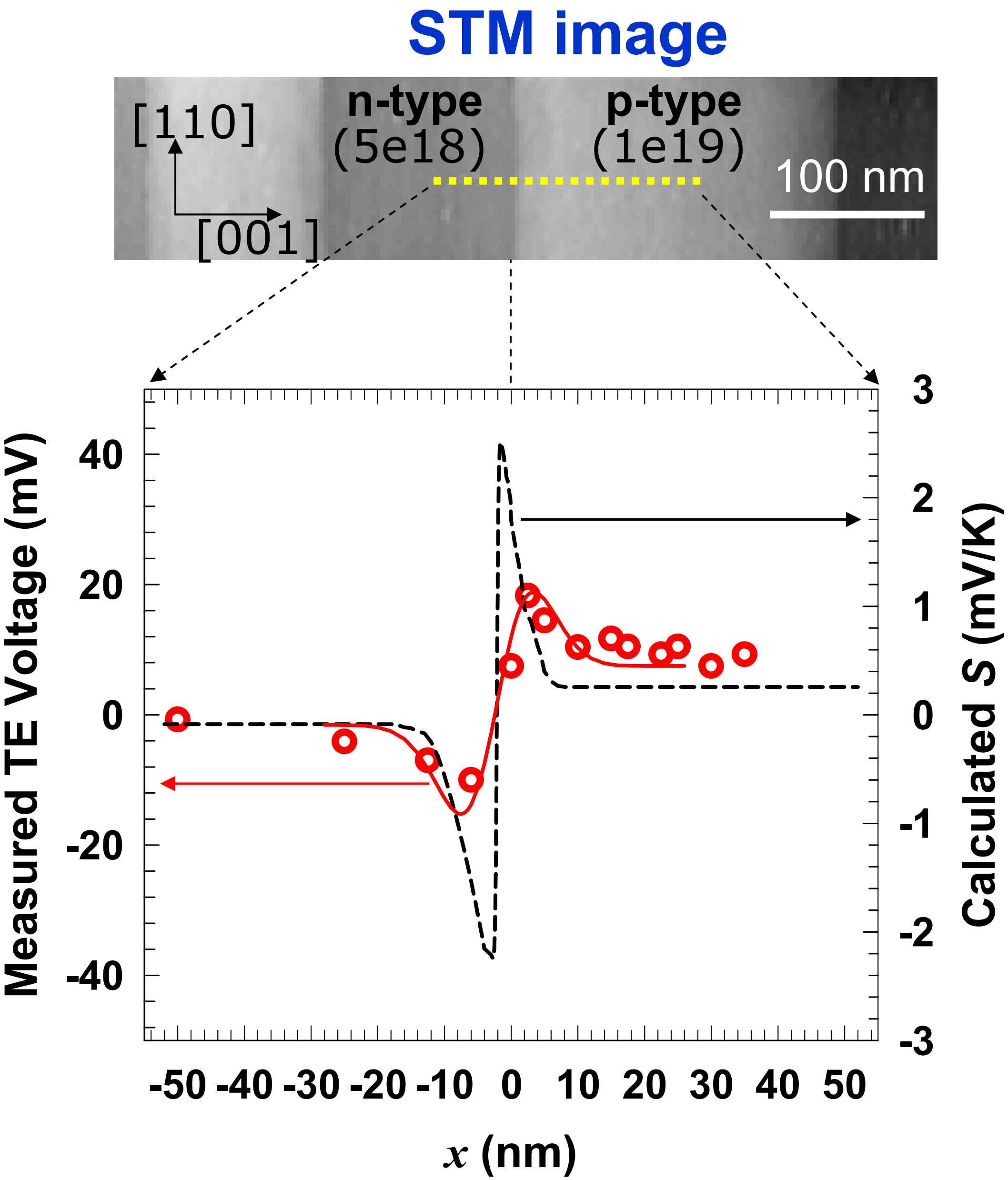


p-doped

$$S \approx S_{hole} = \frac{1}{eT}\left(E_F - E_v + \frac{3}{2}k_B T\right) = \frac{k_B}{e}\left(\ln\frac{N_c}{p} + \frac{3}{2}\right) > 0$$

Hole concentration

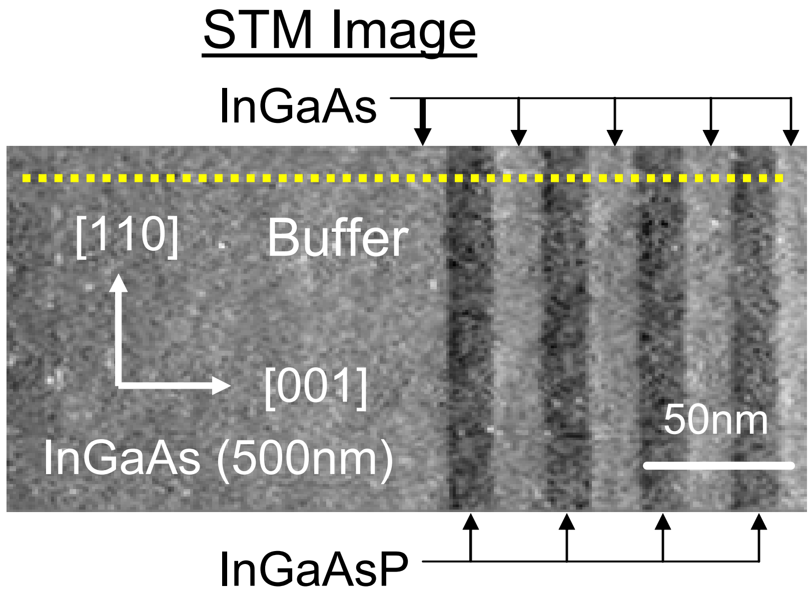
Thermoelectric Profiling of a GaAs p-n Junction

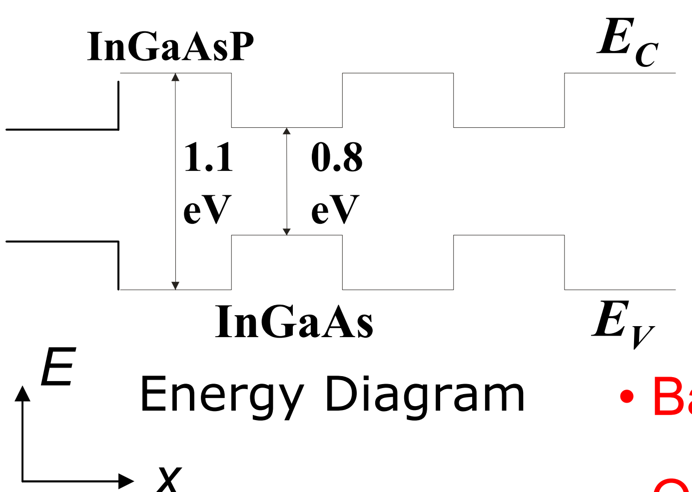


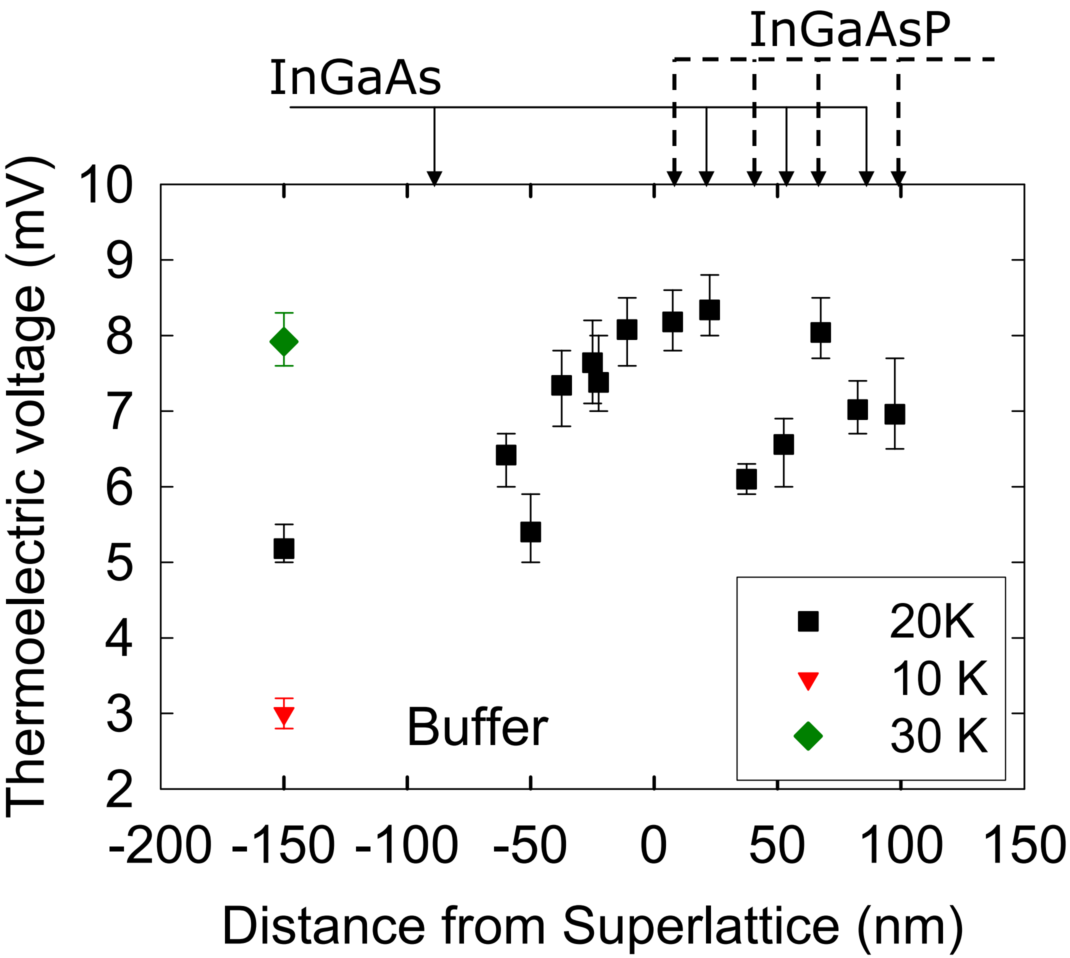
- ❑ Spatial resolution ~ 5 nm
- ❑ Measure both carrier concentration and type
- ❑ Sharp discontinuity at the interface → accurate junction delineation
- ❑ Promising for meeting the roadmap requirements on carrier profiling

PhD Student: Ho-Ki Lyeo

Profiling Seebeck Coefficient of a Superlattice



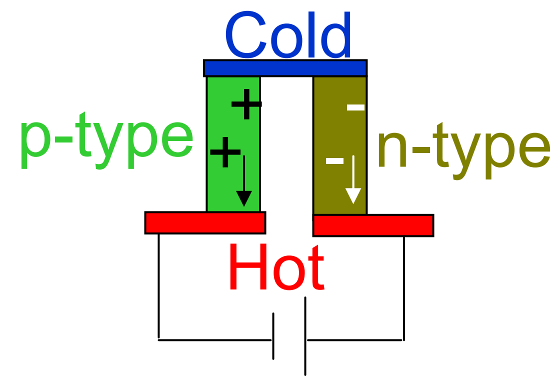




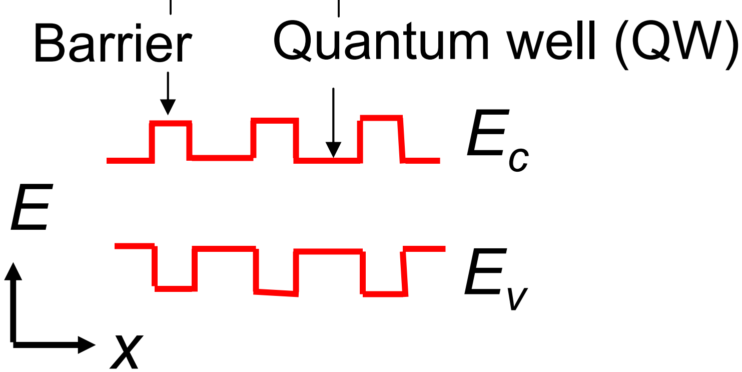
- Band Bending in the buffer near the 1st barrier
- Quantum wells show larger S values than the buffer with the same chemical composition

Samples grown in Shakouri/Bower's group, provided by Shakouri & Huxtable

Superlattice Thermoelectric Coolers

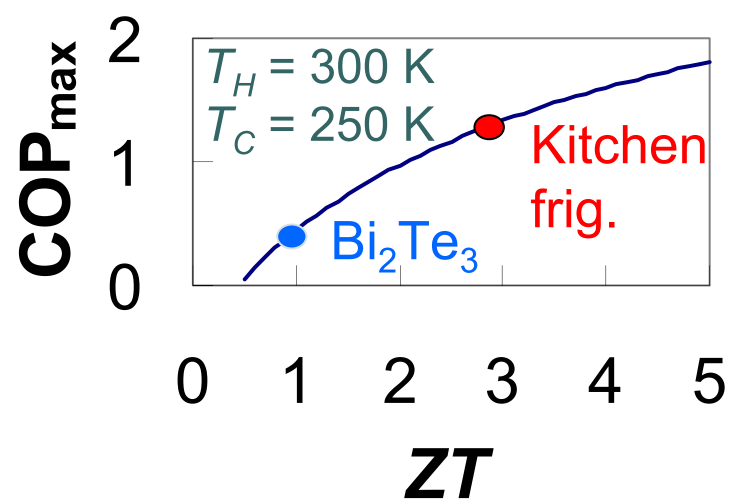


- Superlattices based on Bi_2Te_3, Si/Ge, GaAs/AlAs



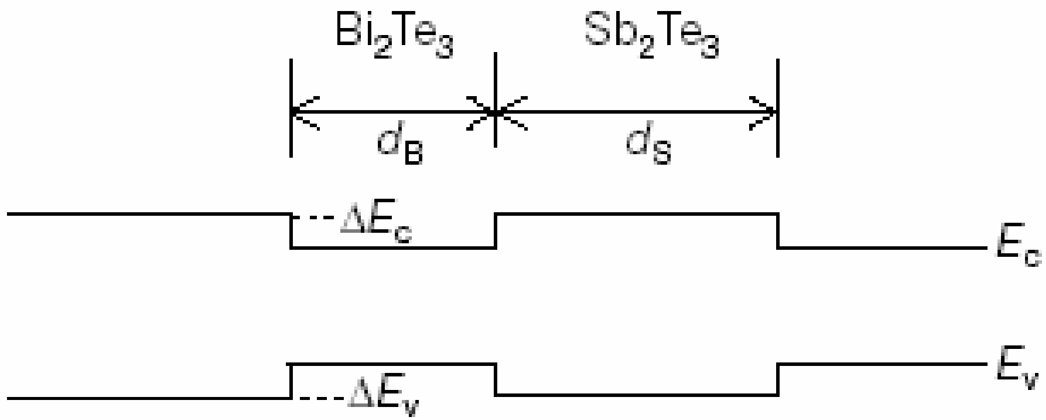
- Large electron density of states near the Fermi Level → Increased S and σ (electrical conductivity)
- k (thermal conductivity) is reduced due to phonon-boundary scattering

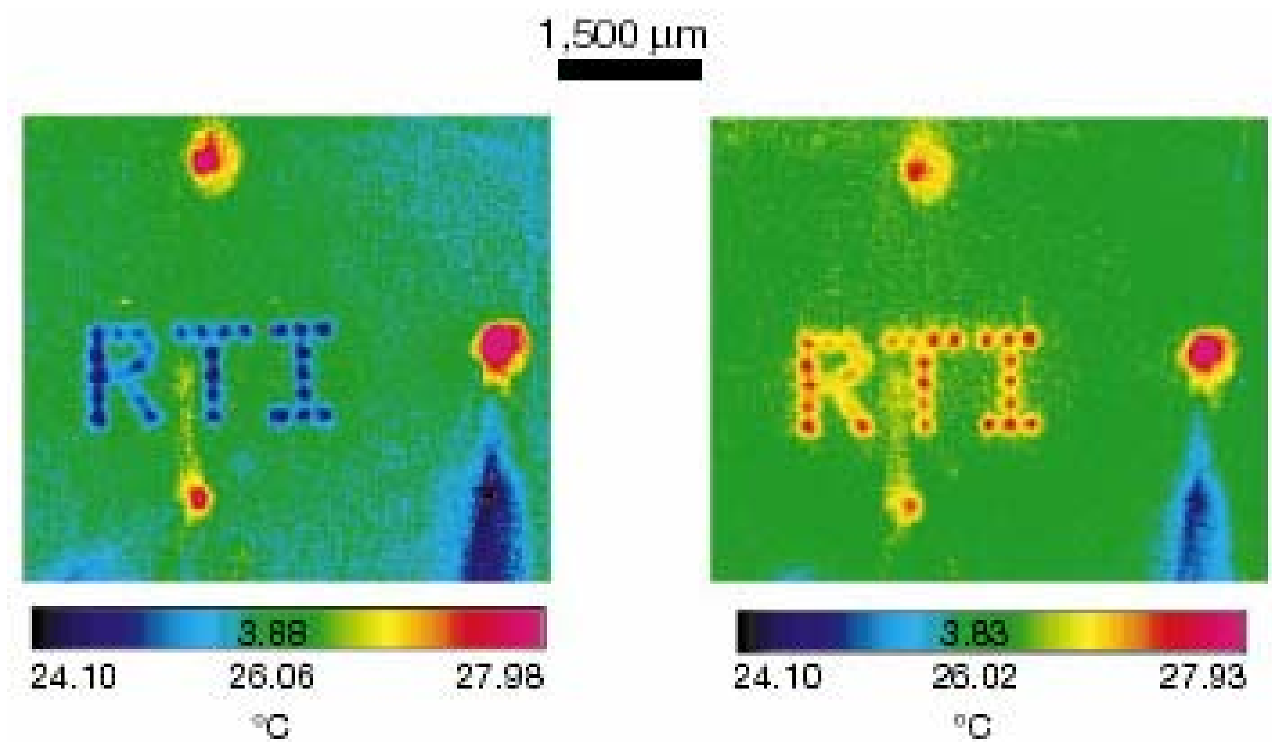
- Efficiency (COP) depends on thermoelectric figure of merit: $ZT = (S^2\sigma/k)T$



Spot Cooling using Superlattices

Ref: Venkatasubramanian et al, *Nature* 413, P. 597 (2001)





Summary

- **Scanning Thermal Microscopy (SThM):**

  Map temperature distribution with 50 nm spatial resolution

- **Electrostatic Force Microscopy (EFM):**

  Map voltage distribution with 10 nm spatial resolution

- **Scanning Thermoelectric Microscopy (SThEM):**

  Map Seebeck coefficient, carrier concentration, band structure with 5 nm resolution

Acknowledgment

Graduate Students:

Jianhua Zhou, Choongho Yu, Qing Hao

Collaborations:

UT Austin: Paul S. Ho, C. K. Ken Shih & Ho-Ki Lyeo

UC Berkeley: Arun Majumdar & Deyu Li, Paul McEuen, Philip Kim

UCSC: Ali Shakouri

MIT: Rajeev Ram & Kevin Pipe

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DOD