goodson@stanford.edu
http://www.nanoheat.stanford.edu

Novel Thermal Interface Materials for 3D Chip Stacks

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Department of Mechanical Engineering, Stanford

IEEE SFBA Nanotechnology Council Talk

Oct 16, 2012

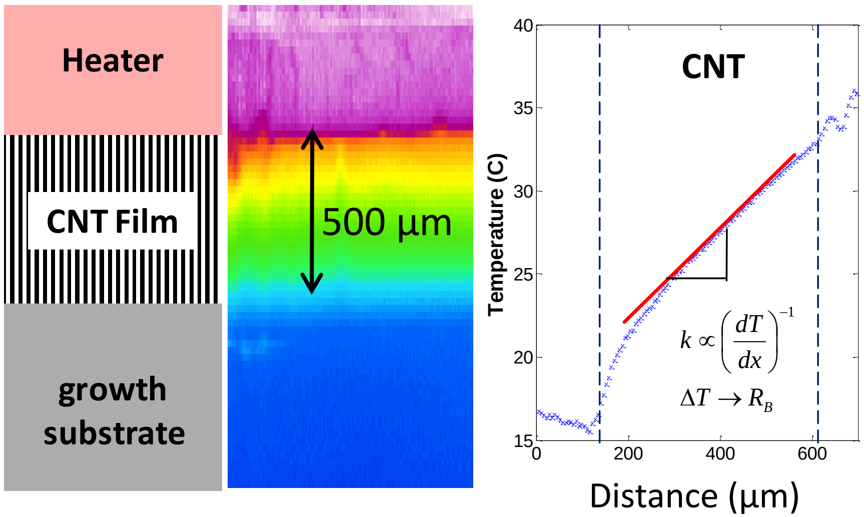
Outline

- **Stanford Nano Heat Lab**
  - Overview of Metrology and Materials

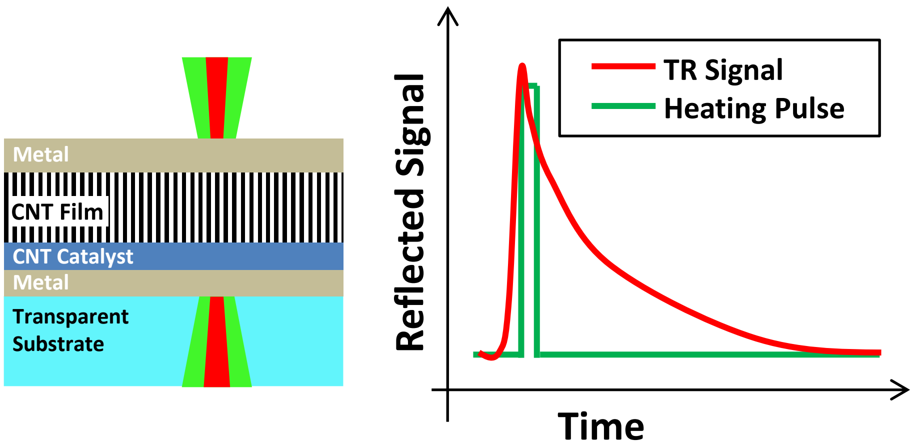
- **Materials for Thermal Management**
  - 3D chip attachments and conductive underfills
  - High density aligned CNT composites
  - Aligned CNT nanotape
  - Mechanical Characterization

Thermal and Mechanical Characterization

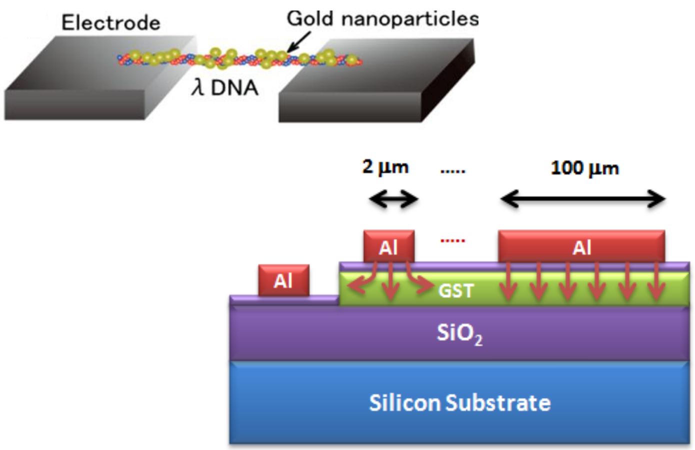
Cross-sectional IR Microscopy



Pico/Nanosecond Thermoreflectance

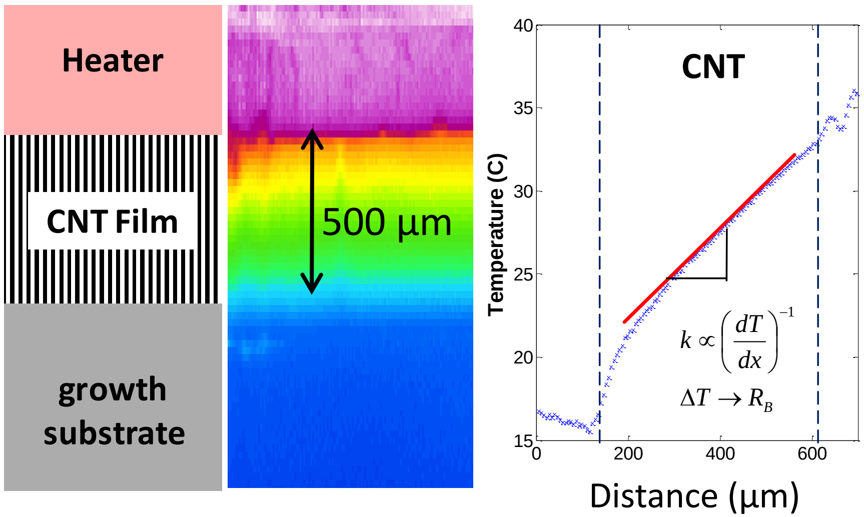


Electrothermal Characterization

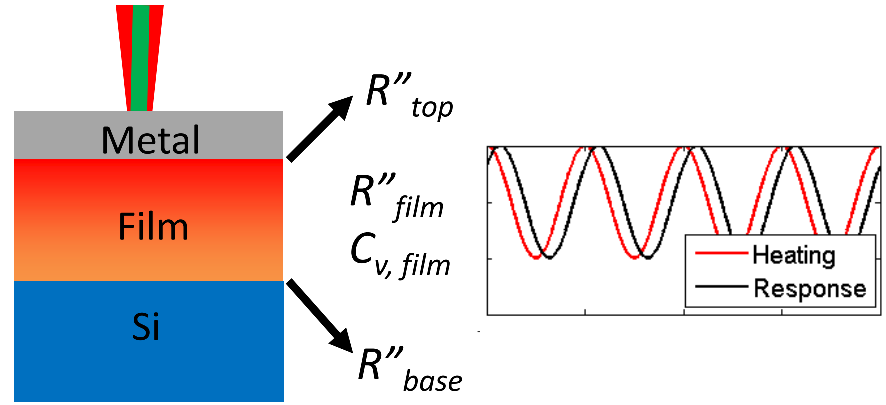


Thermal and Mechanical Characterization

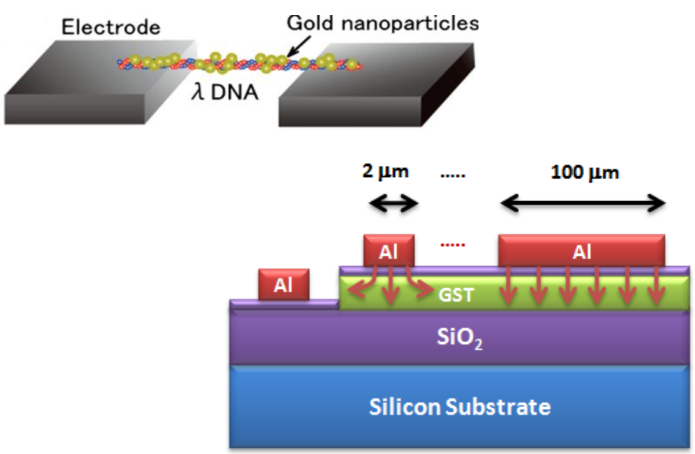
Cross-sectional IR Microscopy



Nanosecond Transient Thermoreflectance

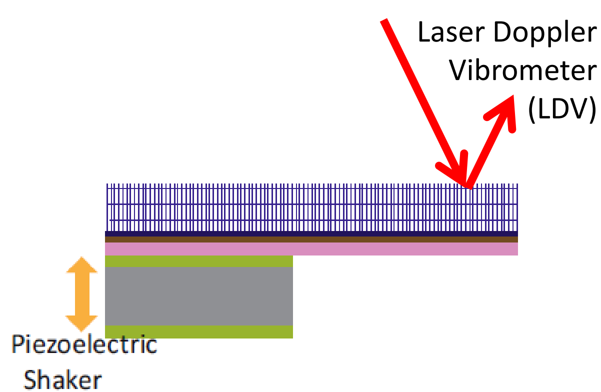


Electrothermal Characterization

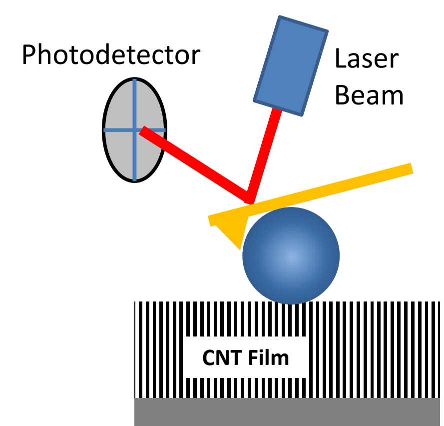


Mechanical Characterization

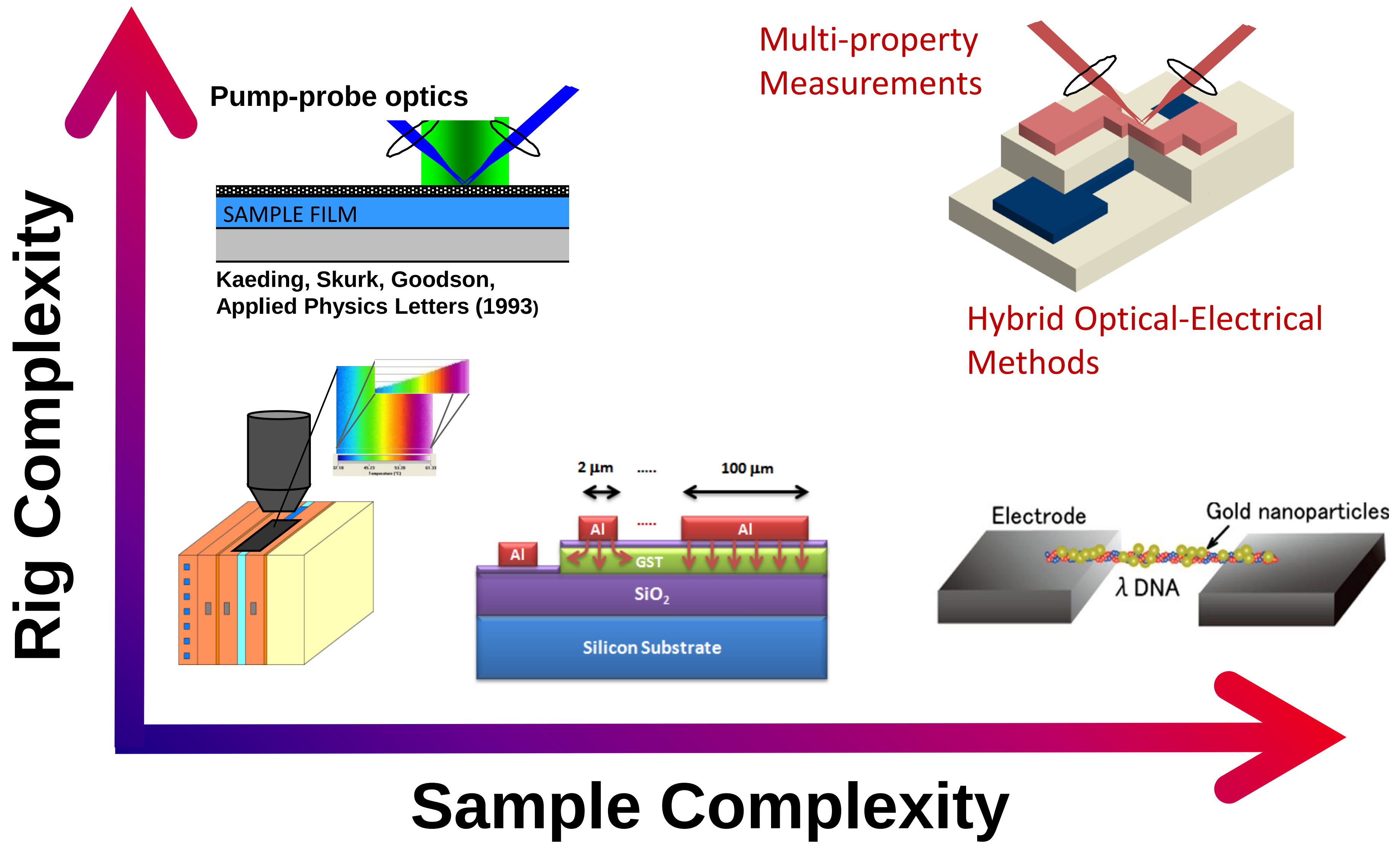
Microresonators (In-Plane)



Nanoindentation (Out-of-Plane)

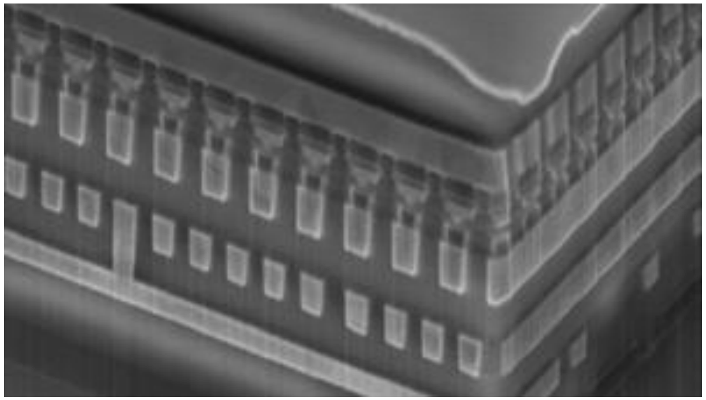


Metrology


Pump-probe optics
SAMPLE FILM
Kaeding, Skurk, Goodson,
Applied Physics Letters (1993)
Multi-property
Measurements
Hybrid Optical-Electrical
Methods
2 µm
100 µm
Al
Al
Al
GST
SiO2
Silicon Substrate
Electrode
Gold nanoparticles
λ DNA
Rig Complexity
Sample Complexity

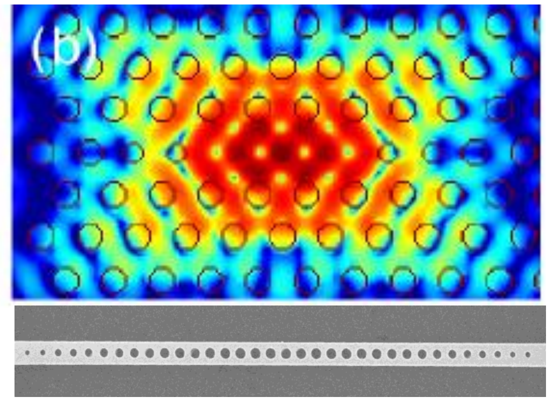
Nanodevices and Materials

Data Storage



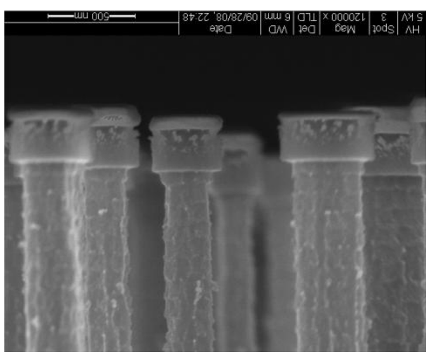
Numonyx/Intel

CMOS Lasers



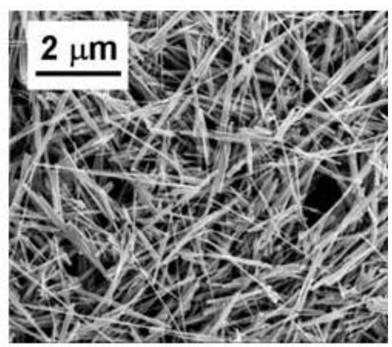
Vuckovic et al., Stanford

Thermoelectrics



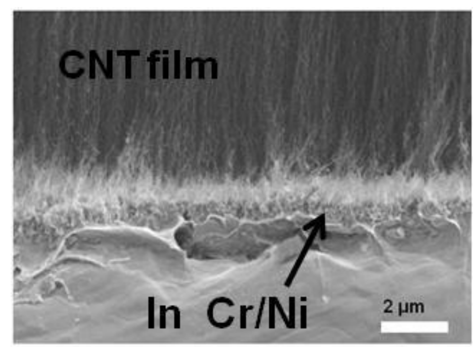
C. Xi, C-M Hsu
Cui group, Stanford

Solar Electrodes



R. Noriega and S. Phadke
Salleo group, Stanford

Thermal Interfaces



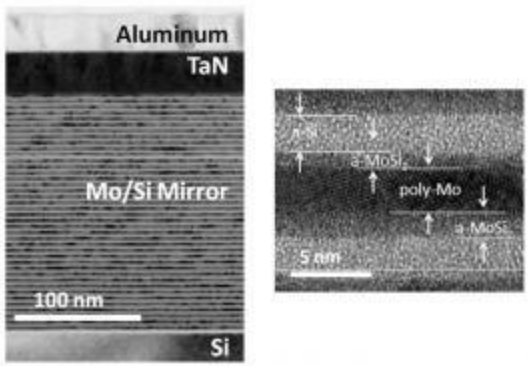
Goodson group, Stanford

Interface Physics

Zijian Li, Elah Bozorg-Grayeli, Jungwan Cho, Si Tan

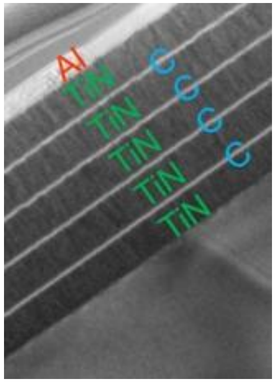
Extreme UV NanoOptics

Mo/Si Multilayer Structure



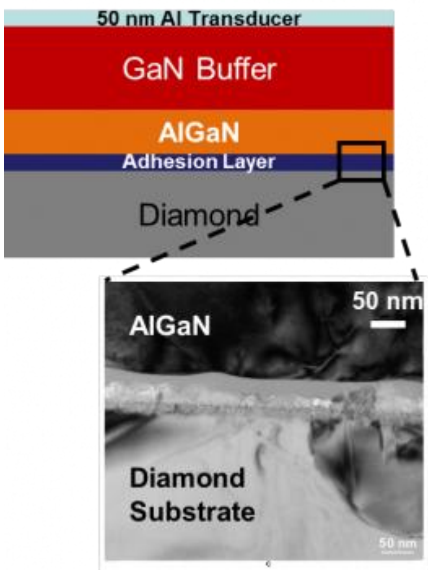
Phonon & Electron Nonequilibrium at Interfaces

Engineered multilayer interface for reducing thermal conductance in phase change memory devices

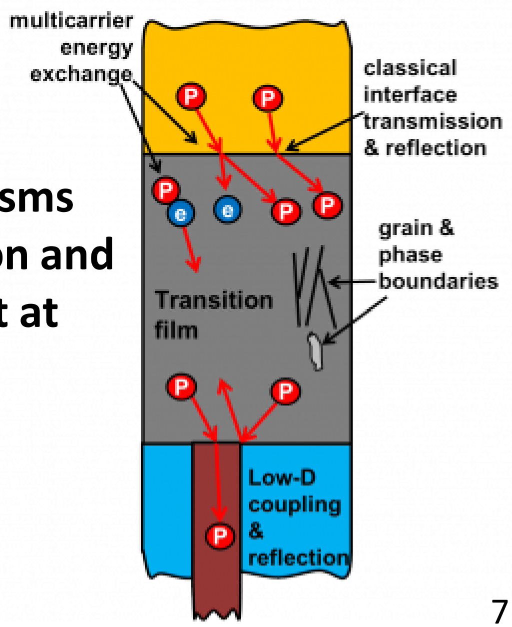


Novel Composite Substrates for Power Electronics and Photonics

GaN-diamond composite for power HEMTs (courtesy Group4 Labs)



Physical mechanisms governing electron and phonon transport at interfaces

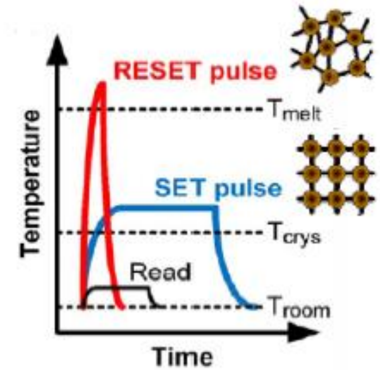


Phase Change Memory

Groups of H.S. Philip Wong (EE) and Kenneth E. Goodson (ME)

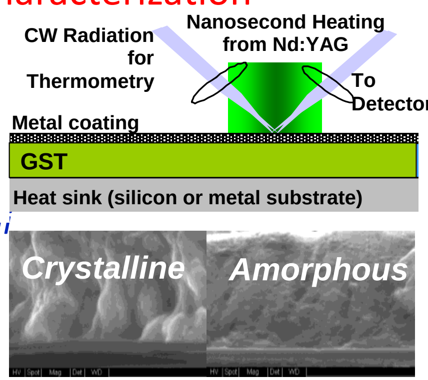
Sponsors & Collaborators:

Intel (D. Kau, K-W. Chang, Ilya V Karpov, G. Spandini)
NXP (F. Hurckx), Micron (John Smythe), IBM (Raoux, Krebs, et c
National Science Foundation (NSF),
Semiconductor Research Corporation (SRC)

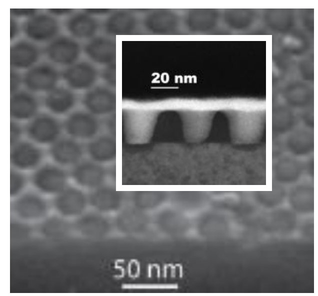


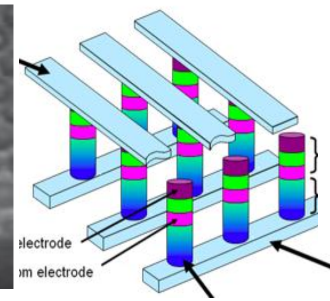
Thermal Characterization

Jaeho Lee
Zijian Li
Elah Bozorg-Grayeli
SangBum Kim
John Reifenberg



Novel Geometries, Synthesis, & Multibit

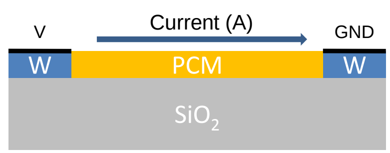




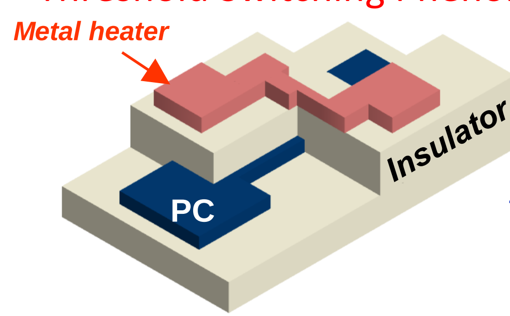
Yuan Zhang
Rakesh Gnana
Sangbum Kim
John Reifenberg

ThermoElectric Effect (Seebeck)

Jaeho Lee,
Rakesh Gnana,
Zijian Li



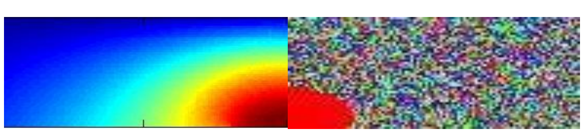
Threshold Switching Phenomena



MicroThermal Stage (MTS)

SangBum Kim
Rakesh Gnana,
John Reifenberg,
Jaeho Lee,
Zijian Li

Electrothermal/Crystallization Modeling



John Reifenberg
Zijian Lee

Key Challenges for TEs in Combustion Systems

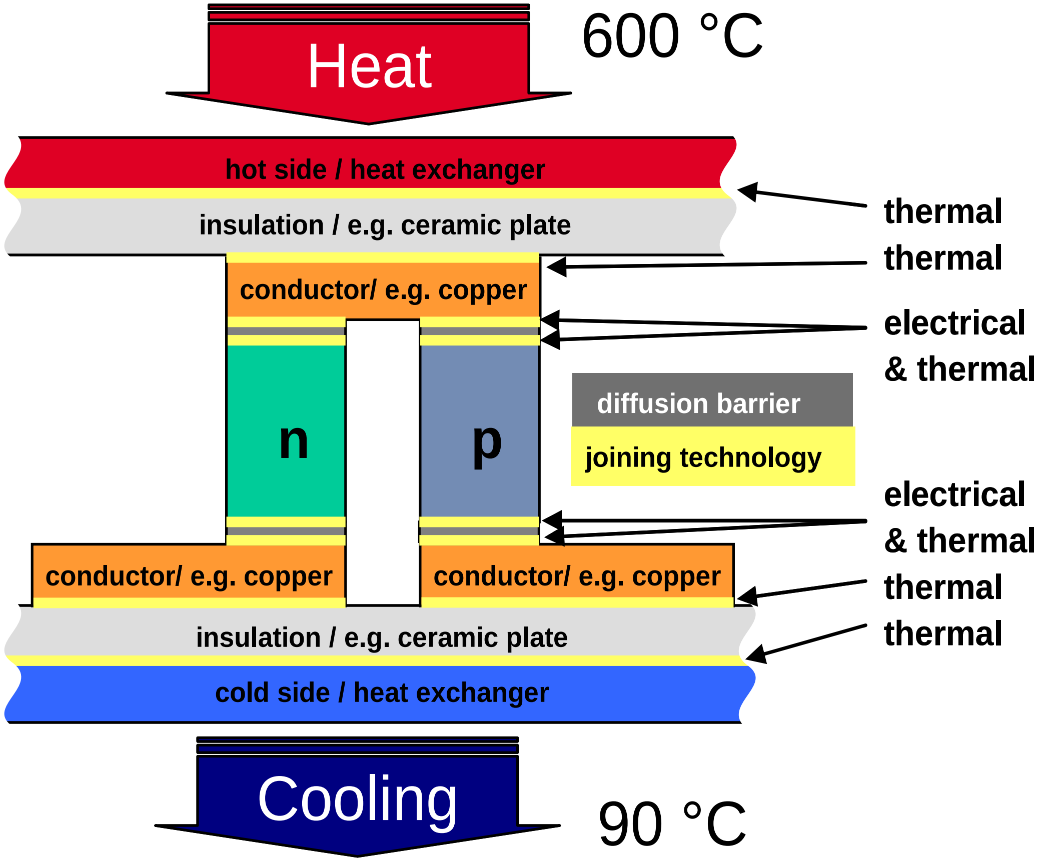
Improvements in the intrinsic ZT of TE materials are proving to be very difficult to translate into efficient, reliable power recovery systems.

Major needs include…

…Low resistance interfaces that are stable under thermal cycling.

…High-temperature TE materials that are stable and promise low-cost scaleup.

…Characterization methods that include interfaces and correlate better with system performance.



Automotive Waste Heat Recovery

Thermoelectric Modules and Electro-Thermo Interfaces

Michael Barako, Lewis Hom, Saniya Leblanc, Yuan Gao, Woosunng Park, Amir Aminfar, Amy Marconnet, Dr. Mehdi Asheghi

U.S. Department of Energy
Energy Efficiency and Renewable Energy

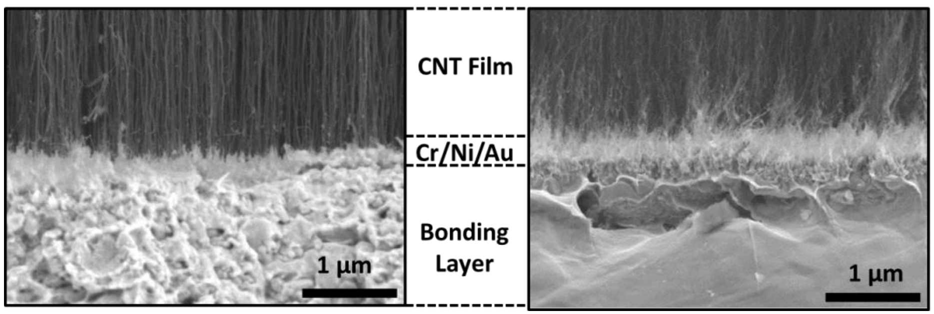
BOSCH

Novel Materials Laboratory
University of South Florida

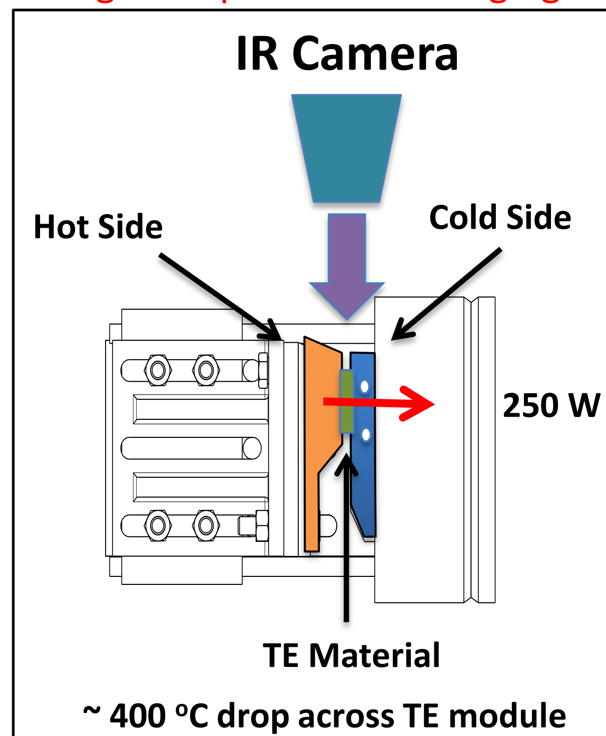
Solder Bonding

Nanofoil Bond

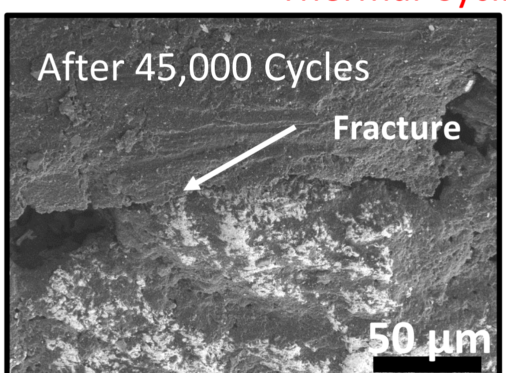
Indium Bond

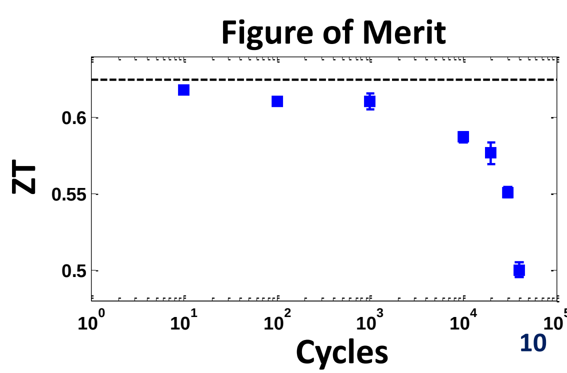


High Temperature IR Imaging



Thermal Cycling of TE Modules





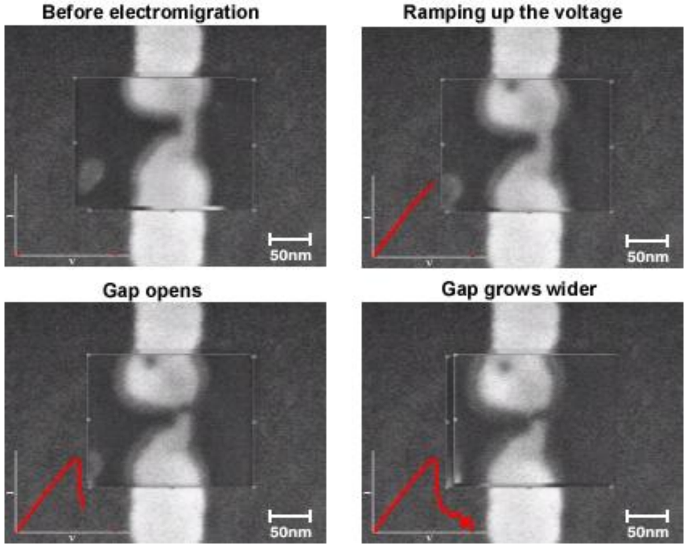
Thermal Management Challenges for Microprocessors

Importance of Hotspot Thermal Management

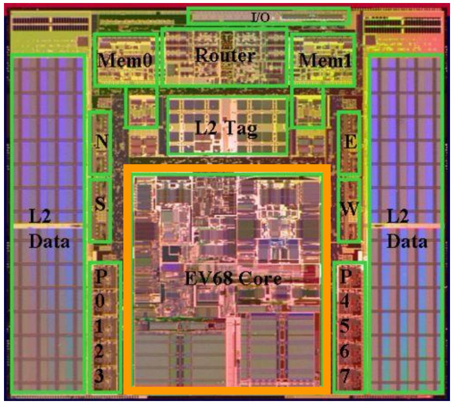
- Peak temperatures limit the reliability of interconnects
- Thermo-mechanical strains due to temperature non-uniformities can degrade packaging and interfaces

Challenges Ahead for Thermal Management

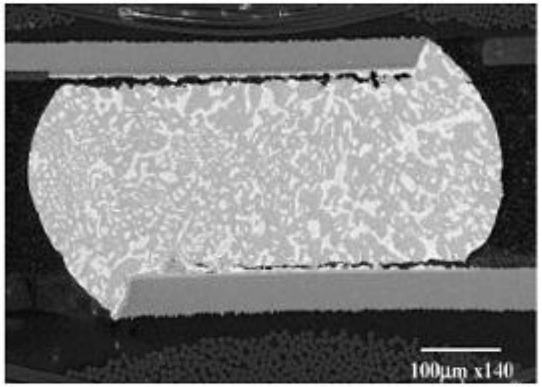
- Transistor scaling
- Increasing number of cores
- 3D integration
- Constraints of mobile applications



Images of Electromigration Failure
Ralph Group, Cornell University



Adapted from: http://en.wikipedia.org/wiki/Heat_sink



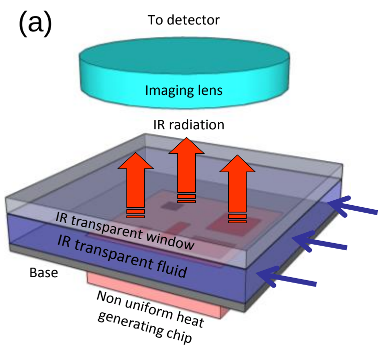
Solder joint failure due to thermomechanical stress
Ridgetop Group Inc.,

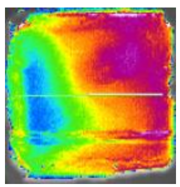
Hot Spot Detection and Thermal Management

To resolve transient chip hotspots with increased accuracy and cool them with high-heat flux cooling solutions

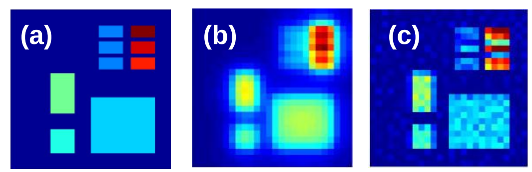
Milnes David, Joe Miler, Lewis Hom, Dr. Mehdi Asheghi

Through-Wafer Hotspot Imaging



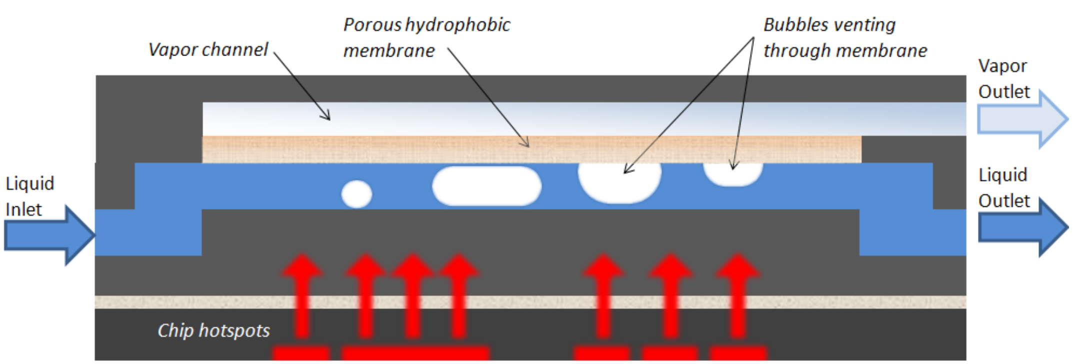


Rapid Hotspot Prediction & Power Distribution

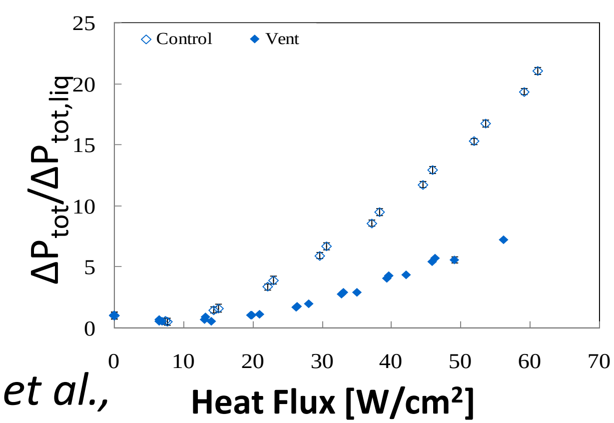


Power map | *Distributed Temperature Sensor Network* | *Reproduced power map*

Vapor-Venting Microfluidic Heat Exchangers



Side Profile of Heat Exchanger with Venting



David et al.,

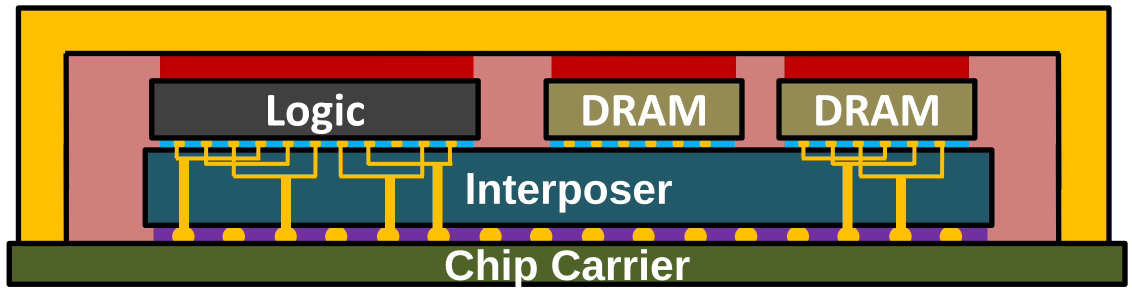
STANFORD nanoHeat
goodson@stanford.edu
http://www.nanoheat.stanford.edu

Thermal Interface materials

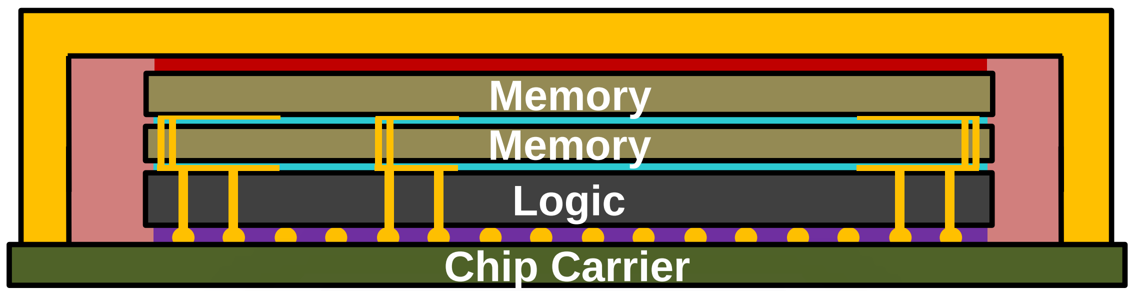
3D chips: Material Requirements

Goal: Discover and characterize advanced materials containing nanoscale inclusions (particles, platelets, tubes), targeting the unique property needs of packaging applications including TSV, interposer, and 3D

TIM 1 &2 (metal alloys, particle filled organics, aligned CNT films)
- High thermal conductivity
- Mechanical compliance



3D Chip Attachment (Adhesives, Thermal compression bonding)
- High thermal conductivity
- Electrically insulating
- Thermal cycling stability

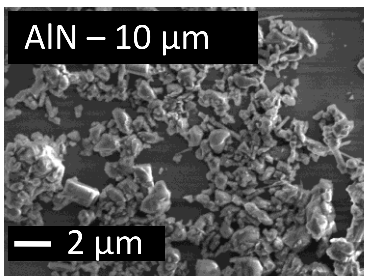


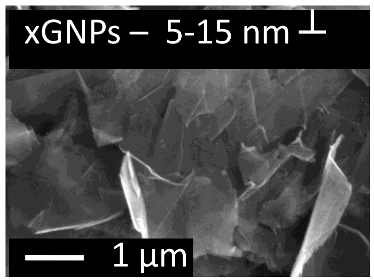
Encapsulation
- High thermal conductivity
- Electrically insulating (on the side facing the chip)
- Mechanical compliance

Flowable Underfill
- Electrically insulating
- Mechanical stiffness
- Viscosity and capillary forces
- High thermal conductivity

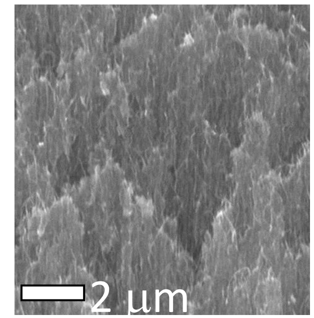
Thermal Interface Materials

AlN-(xGNP) Exfoliated Graphene nanoplatelet composites

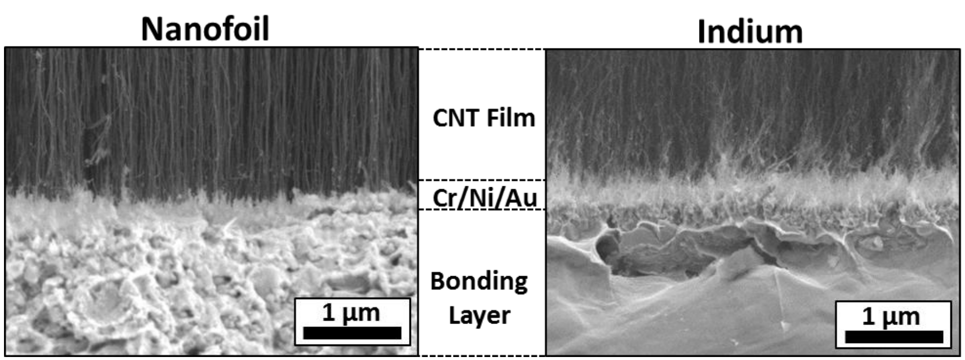




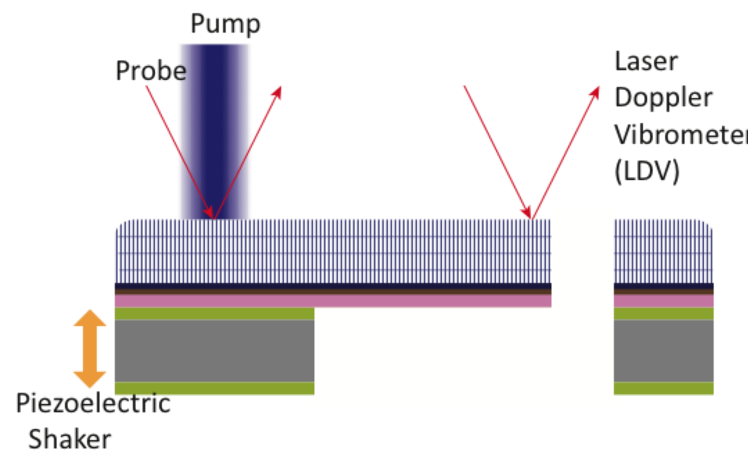
Aligned CNT Composites



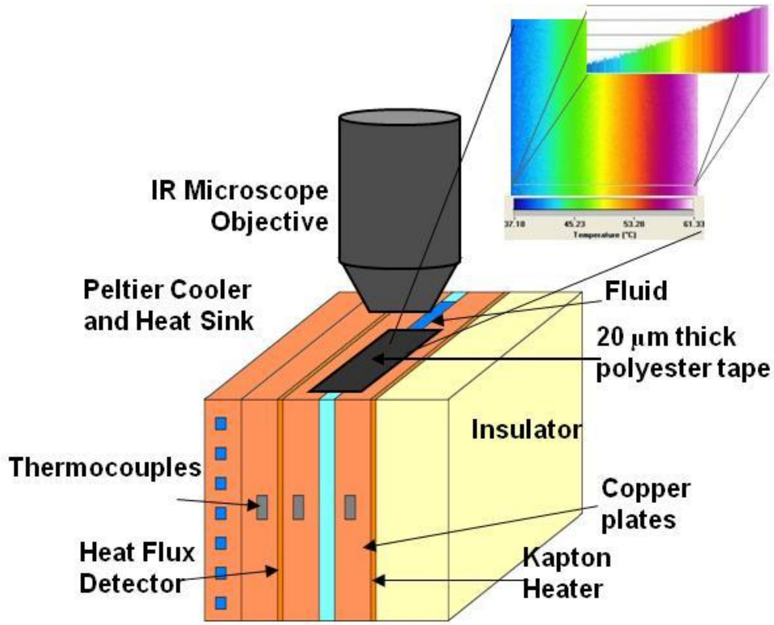
Nanotape to Replace Solder Pads

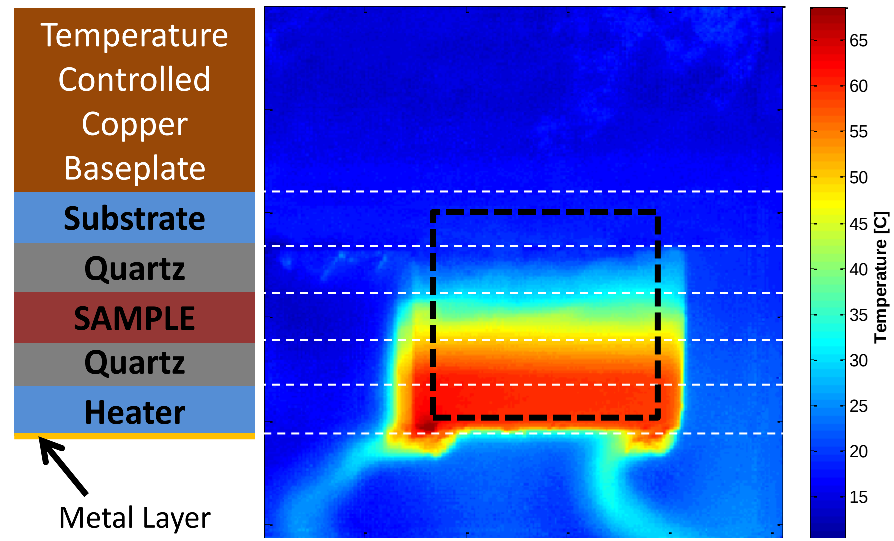


Thermal and Mechanical Characterization



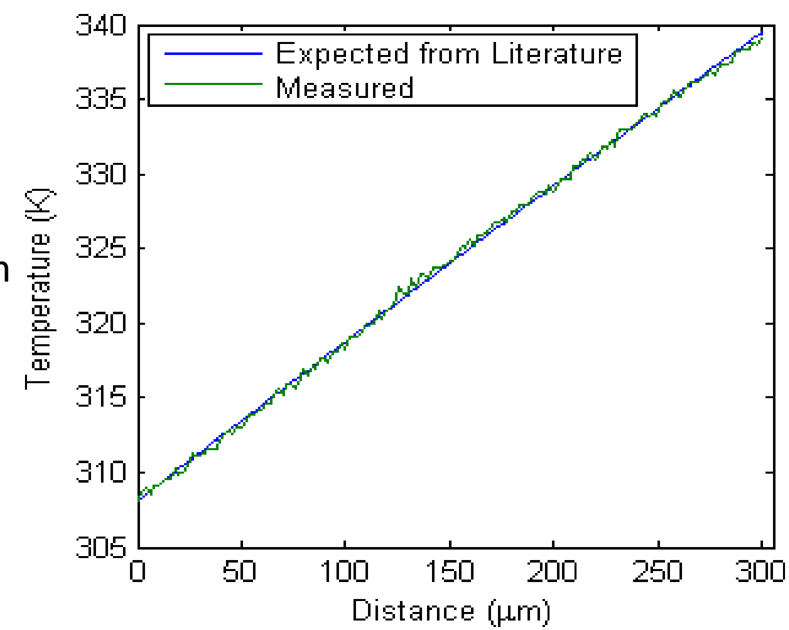
Thermal Conductivity Measurement – IR Imaging



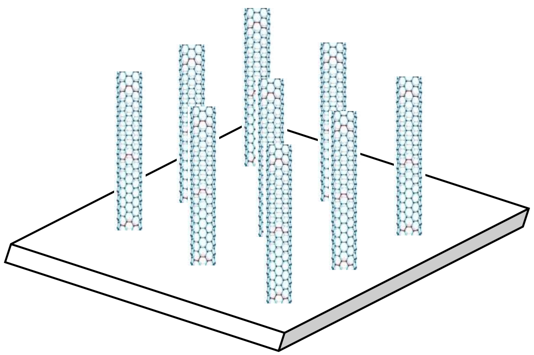


Calibration & Verification

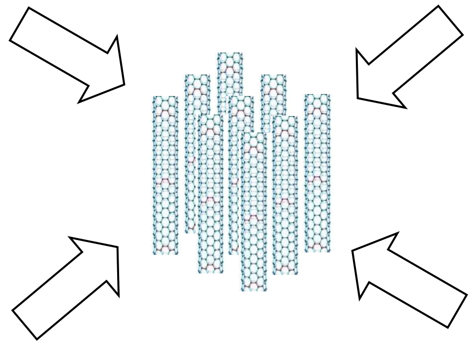
- Emitter tape defines measurement location and uniform emissivity
- Emissivity calibrated(@ 65-75 °C) using thermocouples
- Verification performed on known materials
- Dual heat flux measurement region quantify heat losses



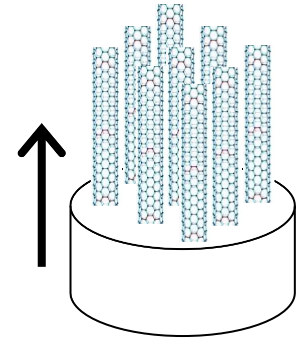
Aligned CNT Nanocomposites



Remove 1 vol.% CNT film from growth substrate

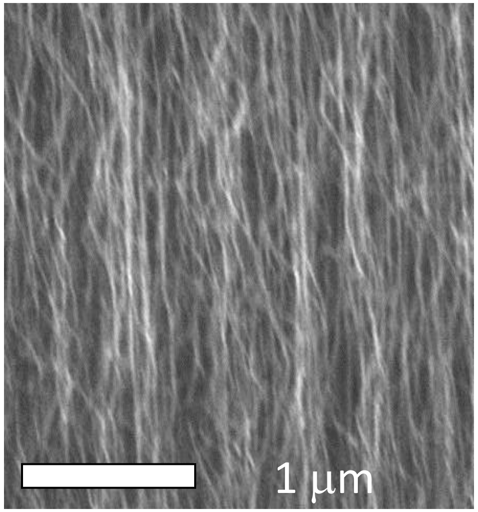


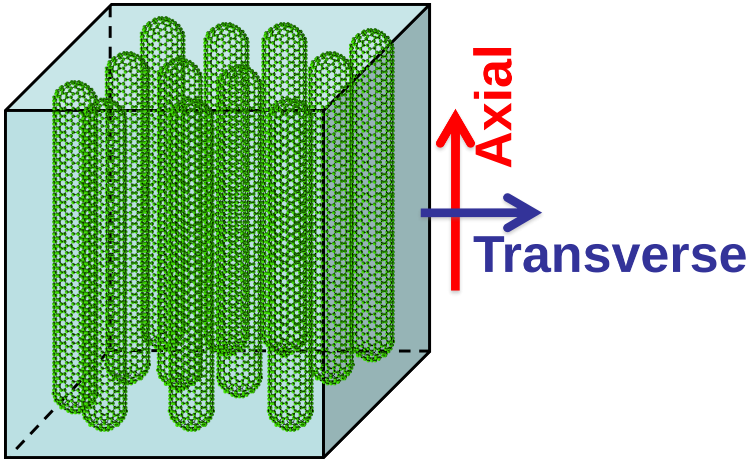
Biaxial compression to increase volume fraction



Infiltrate with epoxy (RTM-6)

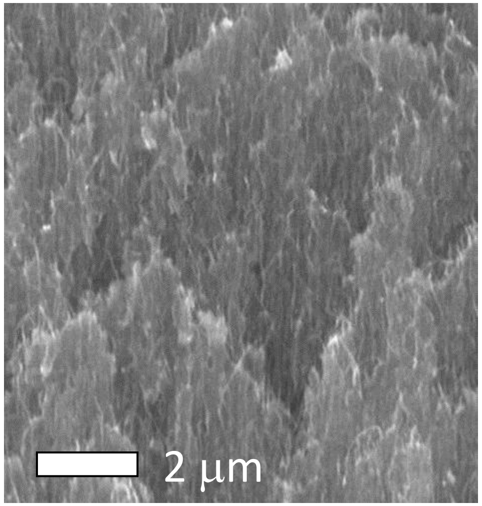
1 vol.% CNT film



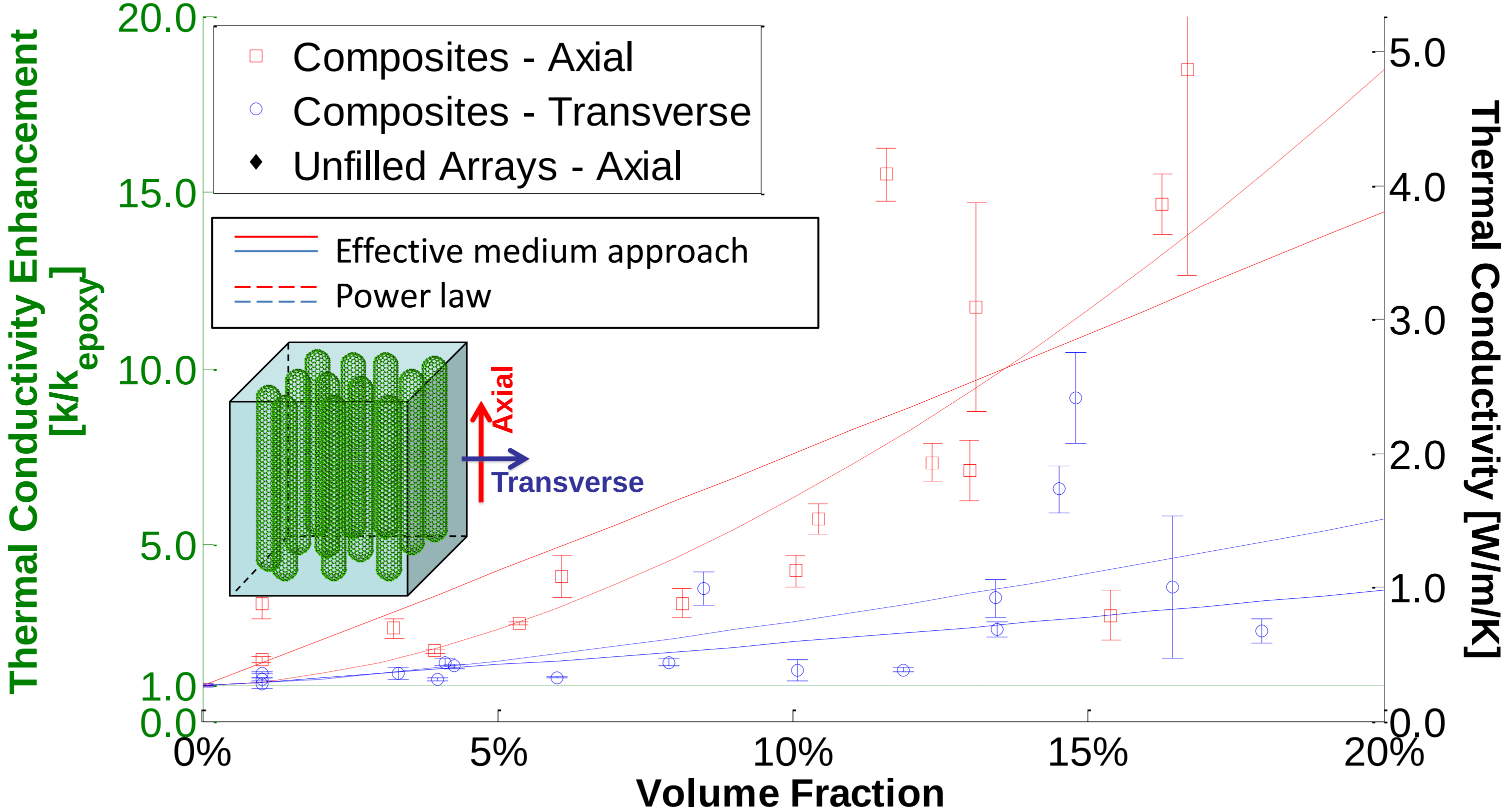


Marconnet et al, *ACS Nano* (2011)

1 vol.% CNT Composite



Thermal Conductivity of Aligned CNT Nanocomposites

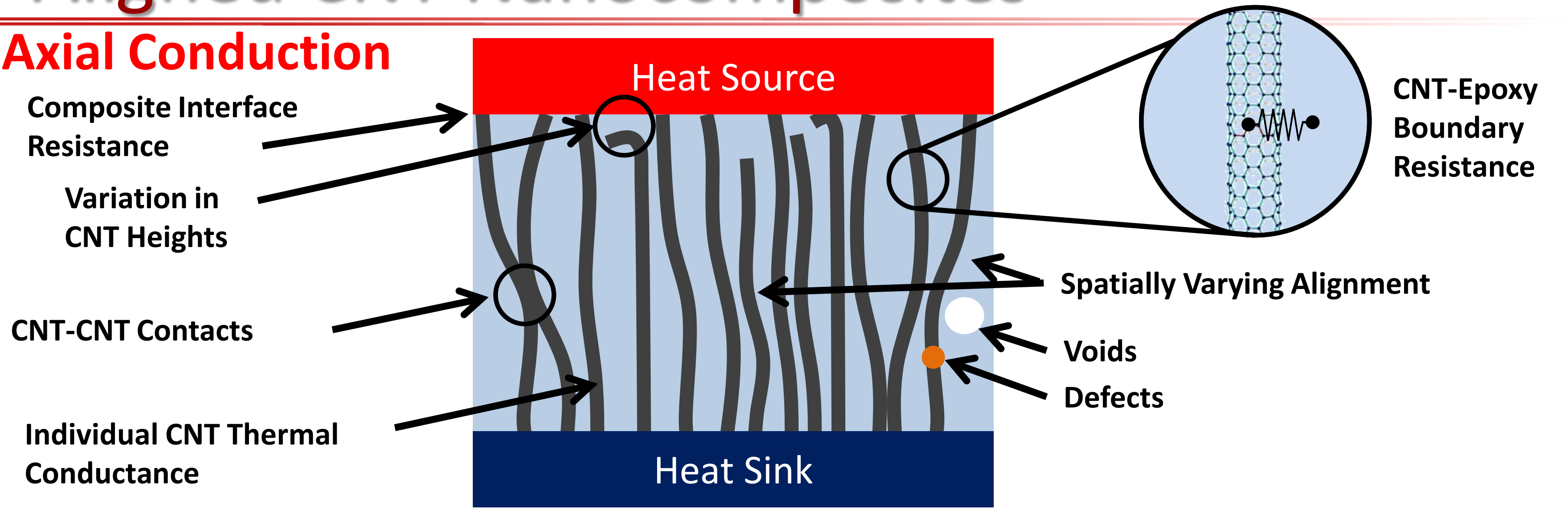


(Surfaces polished to ~3nm roughness and coated with 200 nm of Pt to ensure nearly identical contact conditions for all samples and improves contact between composite and reference layers)

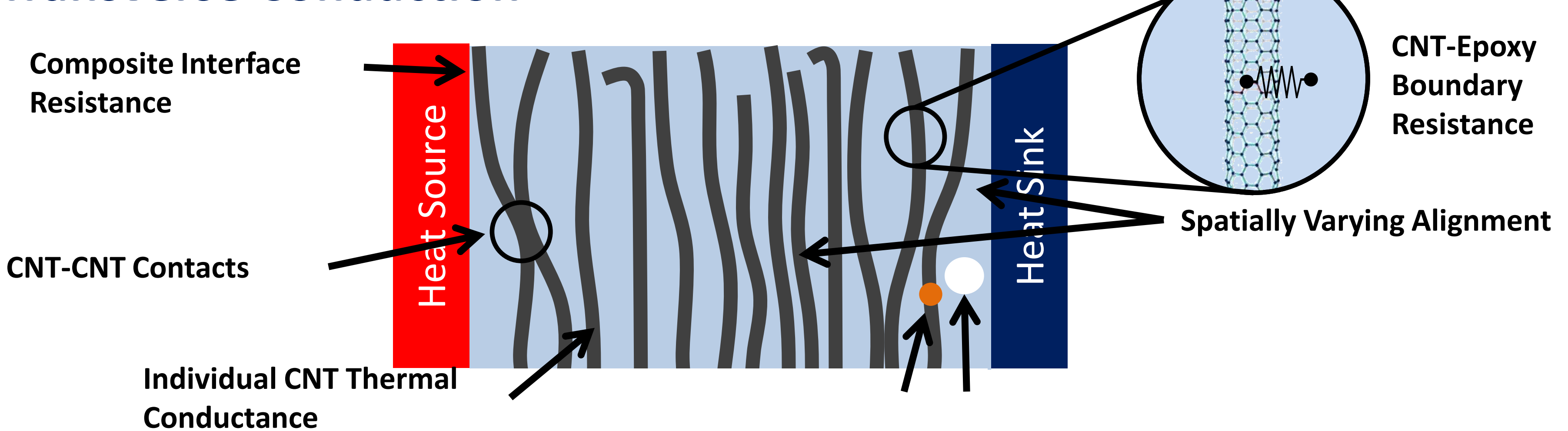
- **Non-linear increase at higher volume fraction suggests that CNT-CNT and CNT-polymer interactions are important to the thermal transport**
- **CNT's contribute at a rate of about 10 W/m/K per CNT at low volume fractions, much lower than expected.**

Aligned CNT Nanocomposites

Axial Conduction



Transverse Conduction



Nanotape to Replace Solder Pads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News & Analysis

Nanotape could make solder pads obsolete

R. Colin Johnson
1/24/2011 12:01 AM EST

PORTLAND, Ore.—Solder pads could soon be made obsolete by a ne
nanotape material created by the Semiconductor Research Corporatio
and Stanford University.

By sandwiching thermally conductive carbon nanotubes between thin r

SRC Patent: Hu, Jiang, Goodson, US Patent 7,504,453, issued 2009

SRC Patent: Panzer, Goodson, et al., 2009/0068387 (pending)

Panzer, Maruyama, Goodson et al., Nanoletters (2010)

Hu, Fisher, Goodson et al., J. Heat Transfer (2006)

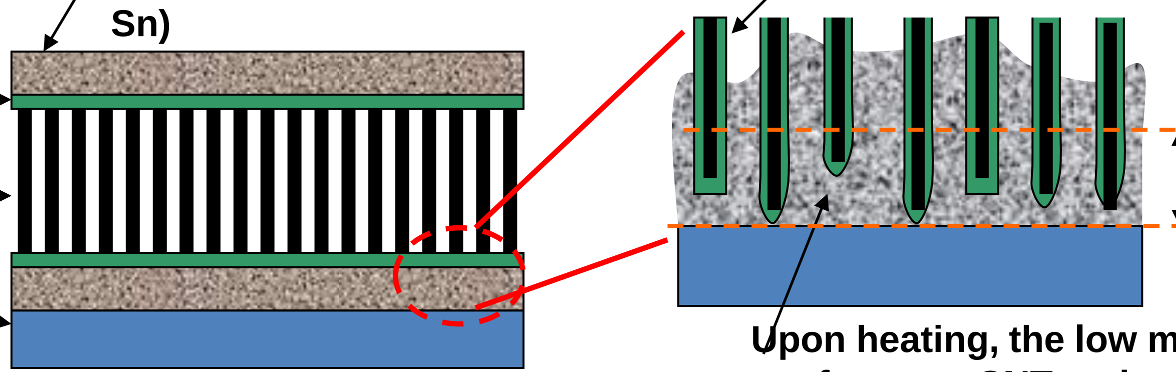
Low melting temperature binder (e.g. alloys of Ga, In, Sn)

Adhesion layer wets nanotubes and promotes adhesion of binder (Pd, Pt, or Ti).

Adhesion layer

Nanofibers

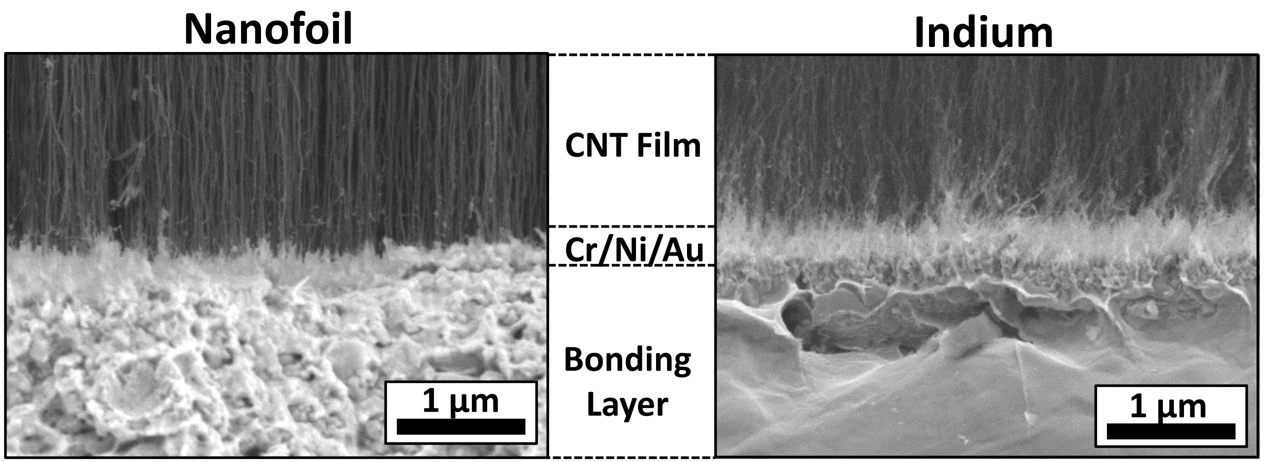
Removable mechanical backer

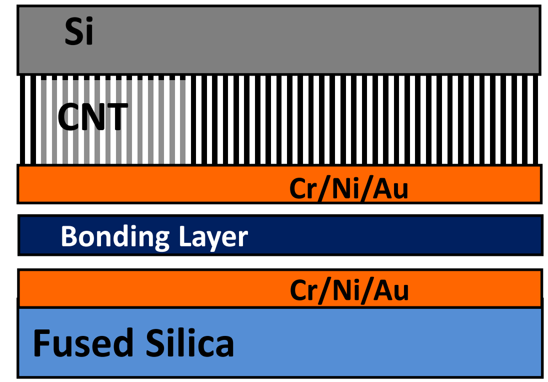


~100 nm is the typical variation in CNT height.

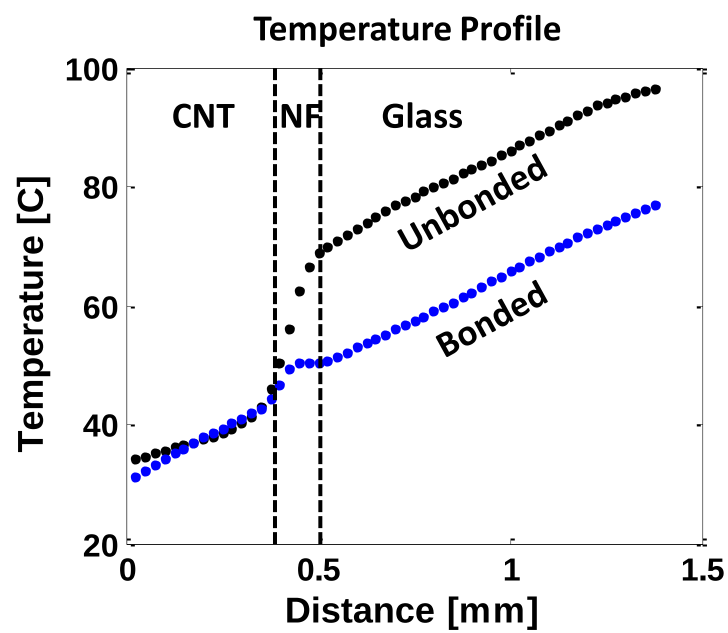
Upon heating, the low melting binder conforms to CNT and substrate topography.

Bonded CNT Thermal Properties





For constant q'', the interfacial temperature drop is reduced by an order of magnitude through solder bonding

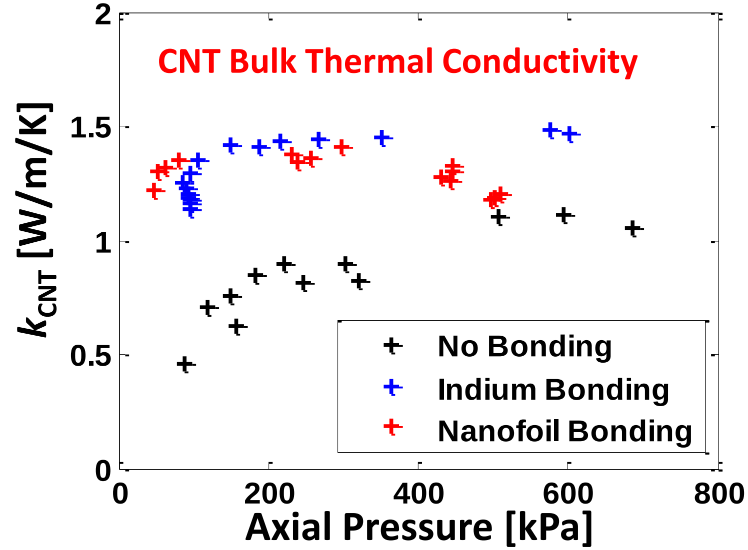


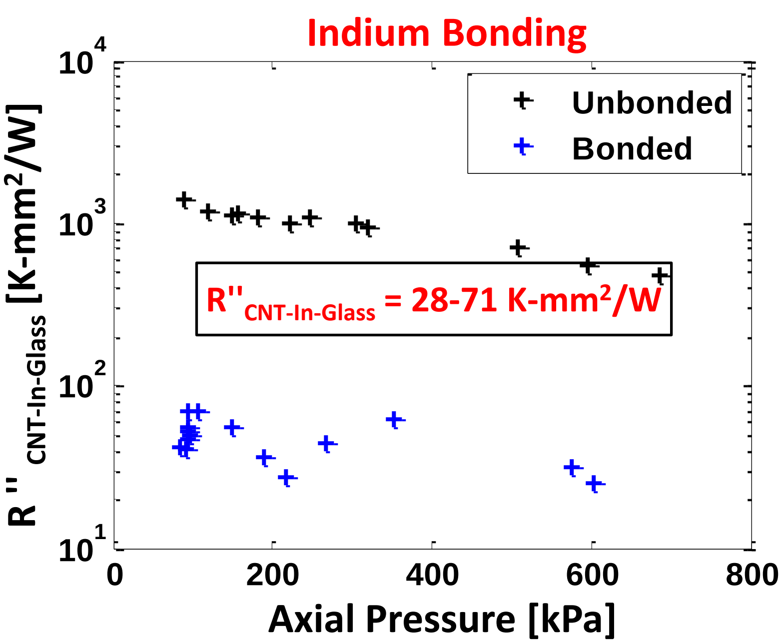
Barako et al, ITHERM 2012

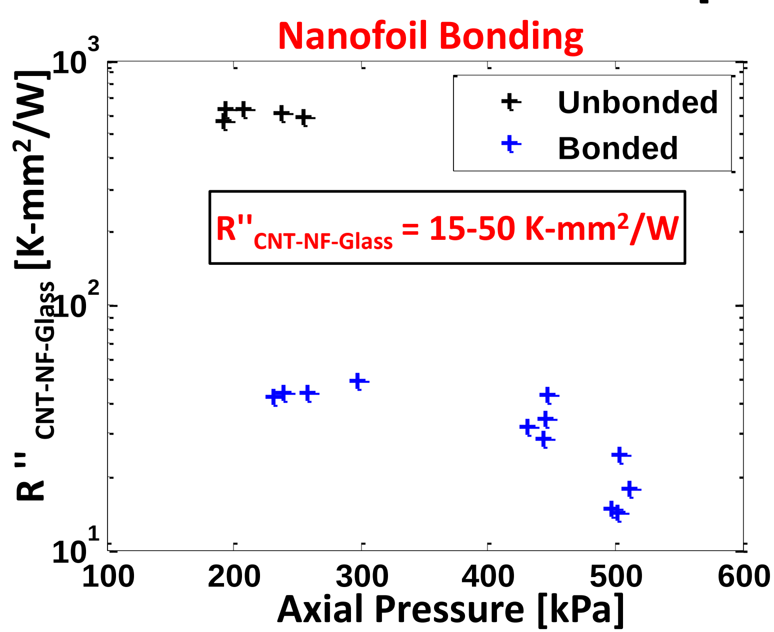
Bonded CNT Thermal Properties

- **Intrinsic Thermal Conductivity increases due to improved engagement of CNTs**
- **Thermal boundary resistance decreases significantly**

Barako et al, ITHERM 2012

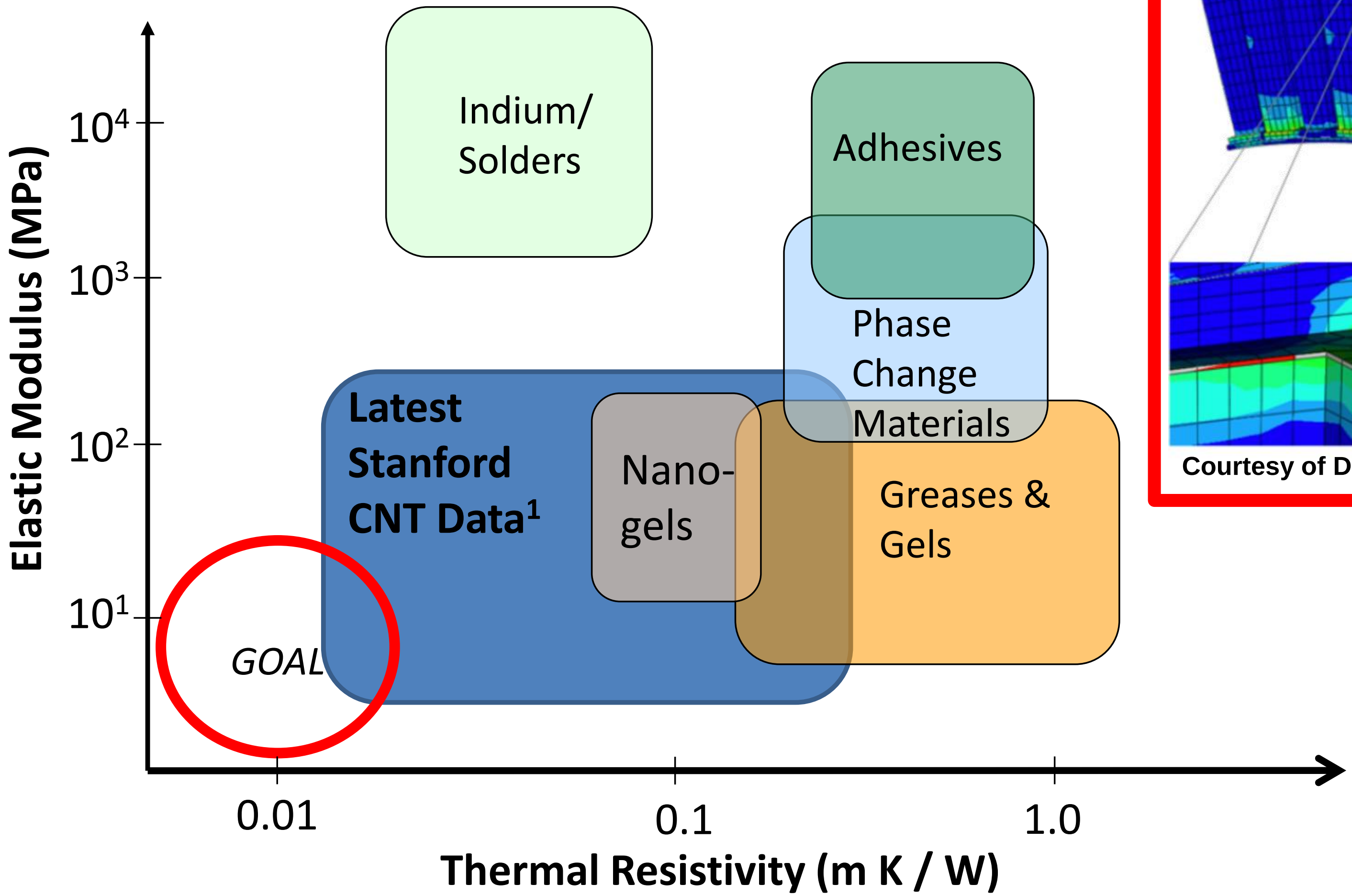




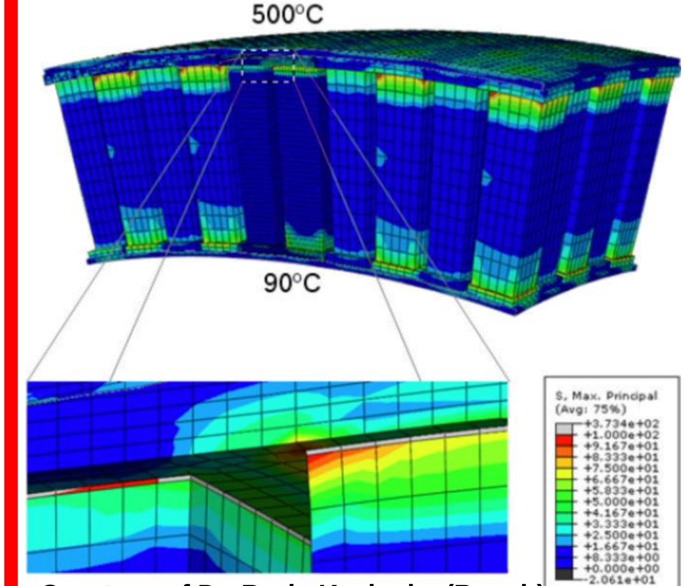


Thermal Interface Materials

GOAL: Thermal Conductivity + Mechanical Flexibility
Implication: Higher package form factor



Thermo-mechanical Stresses in TEs

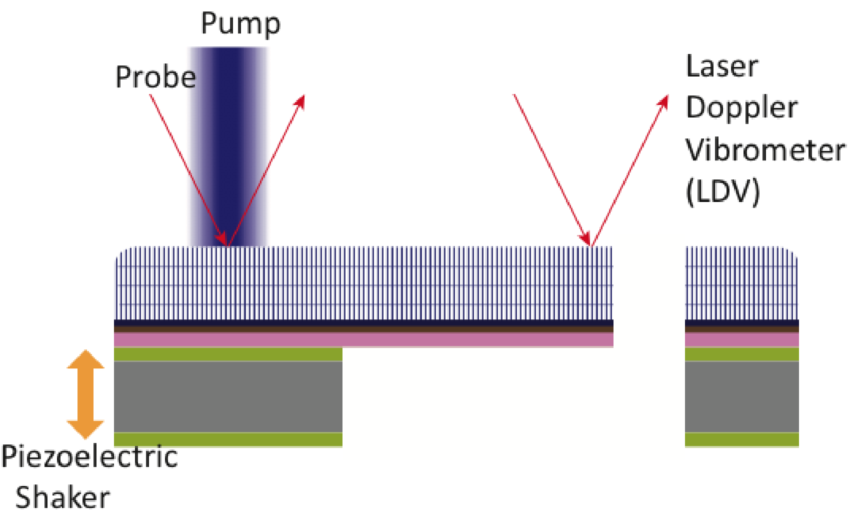


Courtesy of Dr. Boris Kozinsky (Bosch)

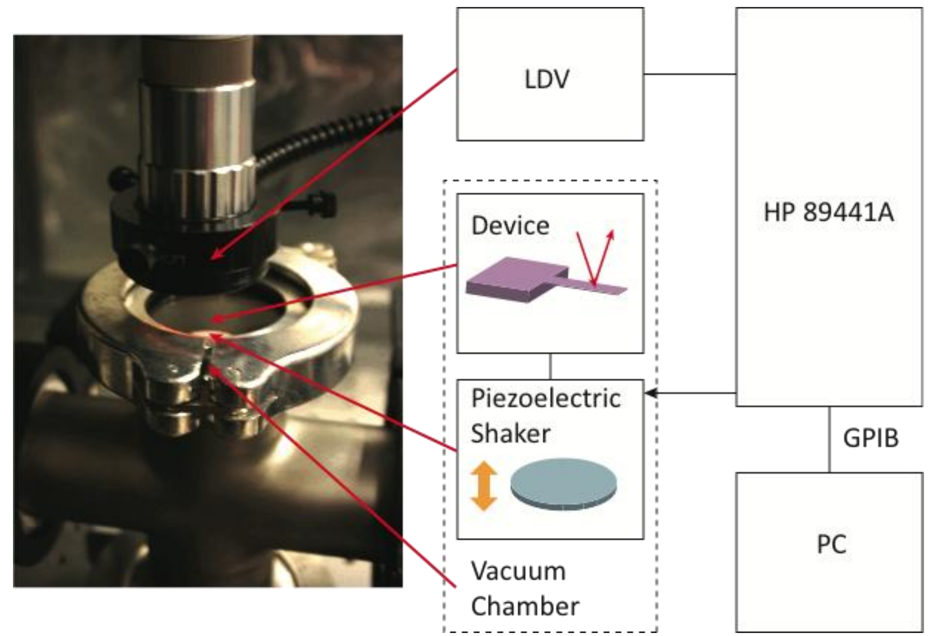
[1] *Gao, Goodson, et al., J. Electronic Materials* (2010).
Won, Goodson, et al., Carbon, submitted (2011).

Mechanical Properties of CNT Films
New Technique: Mechanical Resonators

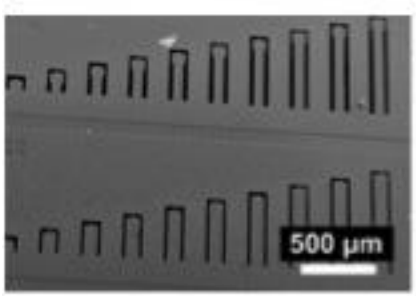
Thermal and Mechanical Characterization



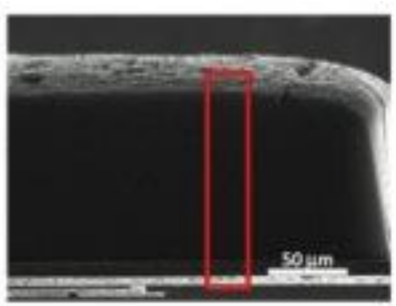
Experimental Setup



Resonator length and shape variation



CNT on a Cantilever



- LDV (laser Doppler velocimetry) experimental setup : resonant frequency of various thickness films.
- Resonant frequency shift : mechanical modulus
- Ring-down and fitting measurements : quality factors

Experimental Method and Data Interpretation

Euler-Bernoulli differential equation for multi-layer beam

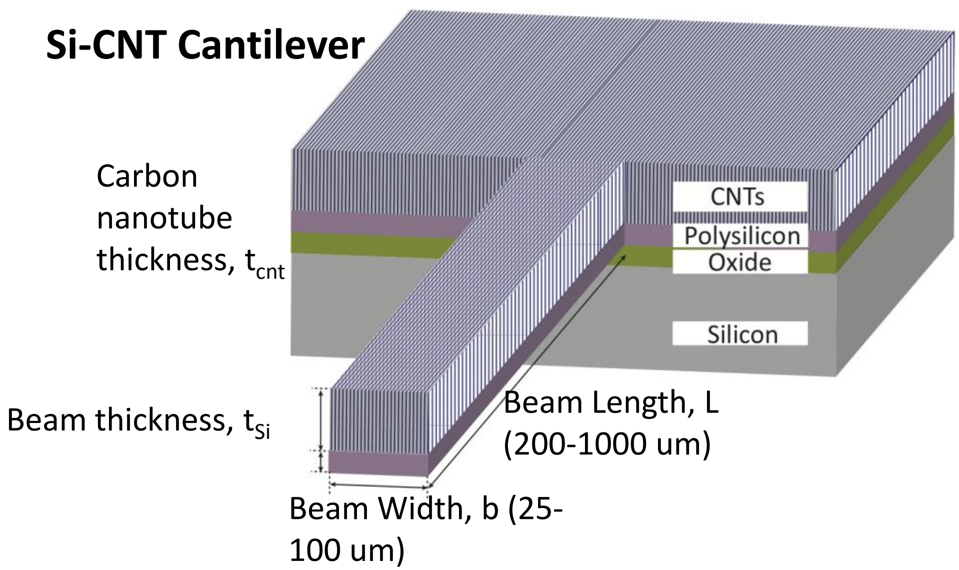
$$\overline{\rho A}\frac{\partial^2 w}{dt^2}+\overline{EI}\frac{\partial^4 w}{\partial x^4}=0 \qquad \overline{\rho A}=\sum_i \rho_i A_i \quad \overline{EI}=\sum_i E_i I_i$$

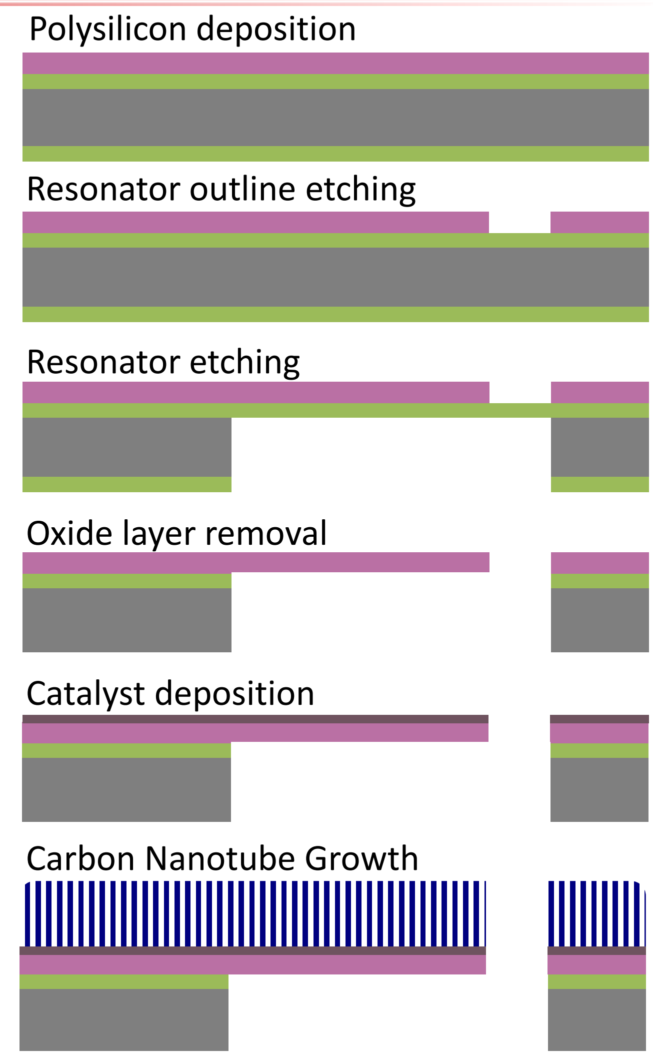
Transformed section method

$$\frac{\Delta w_n}{w_{n,o}}=\sqrt{\frac{E_{Si}I_{Si}+E_{cnt}I_{cnt}}{\rho_{Si}A_{Si}+\rho_{cnt}A_{cnt}}}\sqrt{\frac{\rho_{Si}A_{Si}}{E_{Si}I_{Si,o}}}-1$$

$$E_{CNT}=\frac{E_{si}}{I_{CNT}}\cdot\left(\left(1+\frac{\rho_{CNT}A_{CNT}}{\rho_{Si}A_{Si}}\right)\cdot\left(1+\left(\frac{\Delta w_n}{w_{n,Si,0}}\right)\right)^2 I_{Si,0}-I_{Si}\right)$$

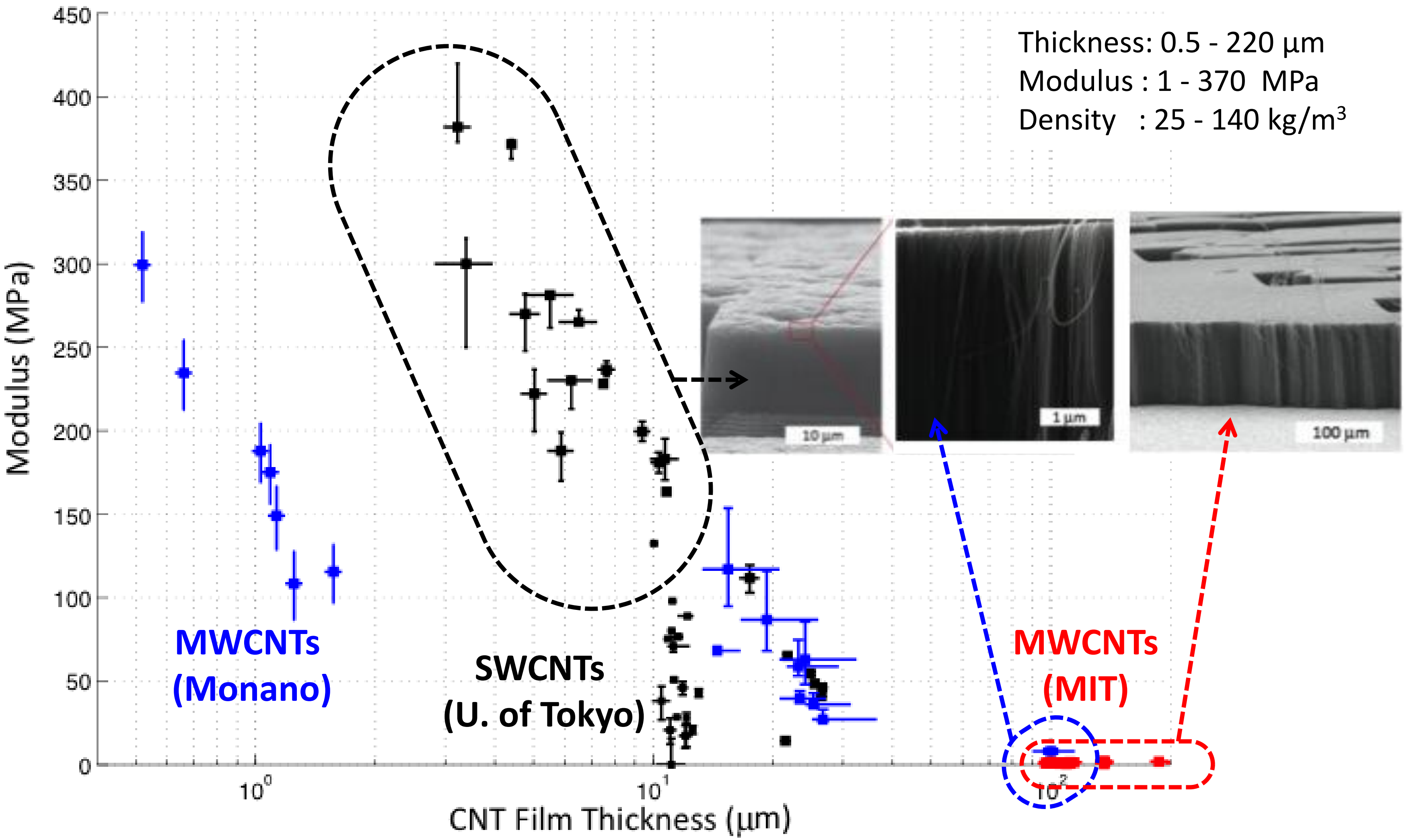
Si-CNT Cantilever





Won et al, *Carbon* (2011)

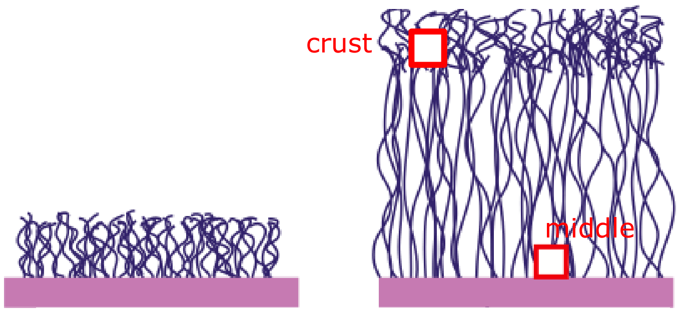
Mechanical Behavior of CNT Films



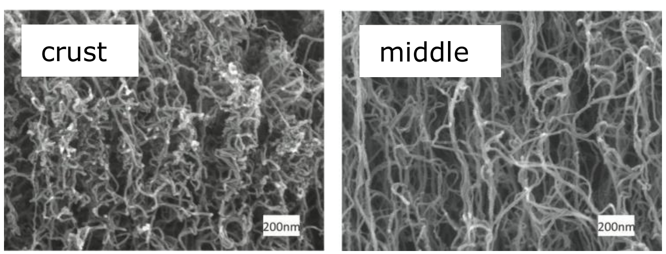
Mechanical Behavior of Nonhomogeneous CNT Films

Growth Stages

Stage 1 Stage 2



Self-organization Vertical-growth



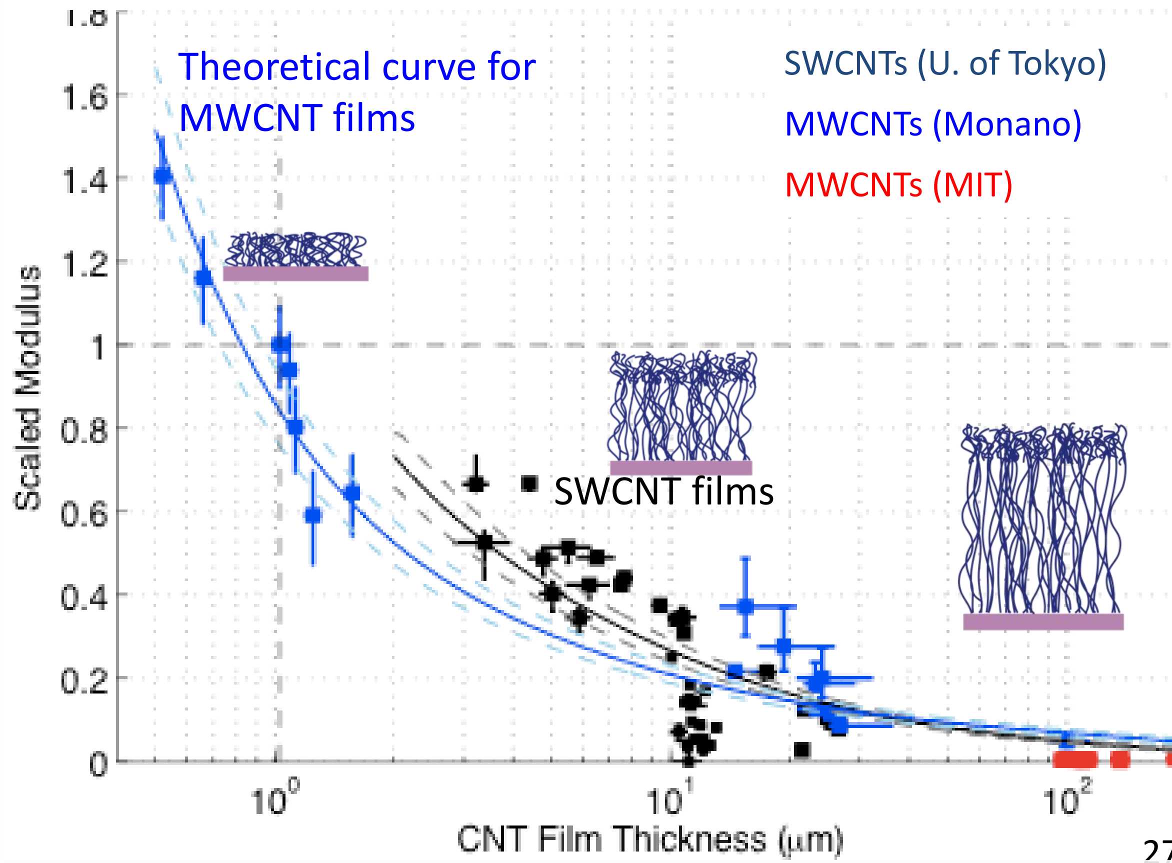
- Interweaving of a thin layer of entangled and randomly oriented nanotubes
- Vertical-aligned growth
- Density decay

Three-layer Analysis

Two-layer analysis → Three-layer analysis

$$\frac{\Delta w_n}{w_{n,Si,0}} = \sqrt{\frac{E_{Si}I_{Si,1} + E_{Middle}I_{Middle} + E_{Top}I_{Top}}{\rho_{Si}A_{Si} + \rho_{Middle}A_{Middle} + \rho_{Top}A_{Top}}} \cdot \sqrt{\frac{\rho_{Si}A_{Si}}{E_{Si}I_{Si,0}}} - 1$$

Dimensionless Effective Modulus : Moduli are scaled by reference sample and volume fraction



Conclusions - Materials for Thermal Management

- Development of novel thermal interface materials is crucial for 3D circuits performance
- Nano tape is a promising replacement to solder pads
- Measurements of aligned CNT films and composites showed thermal conductivity and elastic modulus comparable to or better than commercial TIMs
- Thermal conductivity data of AlN-xGNP nanocomposites showed promising trends and are potential candidates for underfill materials

Questions & Comments

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