STANFORD nanoHeat

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

3D Chip Stacks
Novel Thermal Interface Materials

Srilakshmi Lingamneni
sril@stanford.edu
PI: Prof. Ken Goodson
Department of Mechanical Engineering
IEEE CPMT Society
March 14, 2012

Outline

- **Stanford Nano/Micro Heat Lab**
  – Overview of Metrology and Materials
- **Materials for Thermal Management**
  – Aligned CNT nanotape
  – High density aligned CNT composites
  – Mechanical Characterization
  – 3D chip attachments and conductive underfills

Nano Heat Transfer Lab

Current Group

Josef Miler
Yuan Gao
Jaeho Lee
Sri Lingamneni
Saniya Leblanc
Jungwan Cho
Elah Bozorg-Grayeli
Amy Marconnet
Shilpi Roy (EE)
Michael Barako
Lewis Hom
Zijian Li
Woosung Park
Prof. Mehdi Asheghi
Dr. Yoonjin Won
Dr. Takashi Kodama

Alumni

Prof. Dan Fletcher UC Berkeley
Prof. Evelyn Wang MIT
Prof. Katsuo Kurabayashi U. Michigan
Prof. Sungtaek Ju UCLA
Prof. Mehdi Asheghi Stanford
Prof. Bill King UIUC
Prof. Eric Pop UIUC
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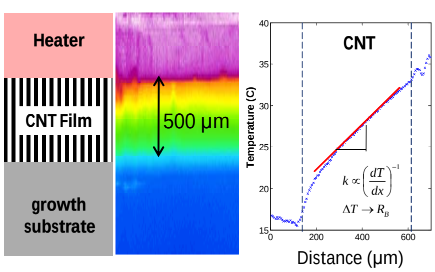
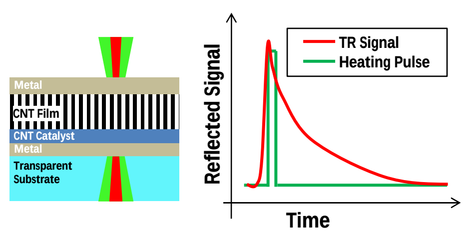
Prof. Xeujiao Hu Wuhan Univ.
Prof. Carlos Hidrovo UT Austin
Prof. Kaustav Banerjee UCSB
Prof. Sarah Parikh Foothill College
Prof. Ankur Jain UT Arlington
Dr. Jeremy Rowlette Daylight Solns
Dr. Patricia Gharagozloo Sandia Labs
Dr. Per Sverdrup Intel
Dr. Chen Fang Exxon-Mobile
Dr. Milnes David IBM
Dr. Max Touzelbaev AMD
Dr. Roger Flynn Intel
Dr. Julie Steinbrenner Xerox Parc
Dr. John Reifenberg Alphabet Energy
Dr. David Fogg Creare
Dr. Matthew Panzer KLA-Tencor

Thermal and Mechanical Characterization

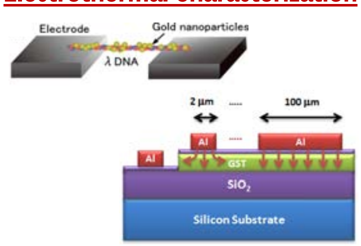
Cross-sectional IR Microscopy



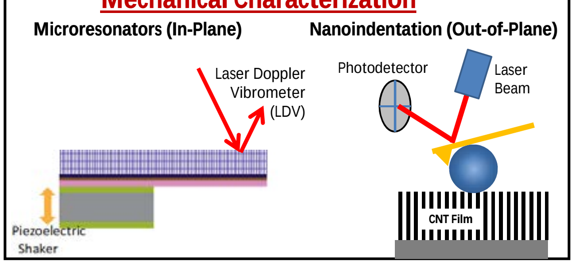
Pico/Nanosecond Thermoreflectance

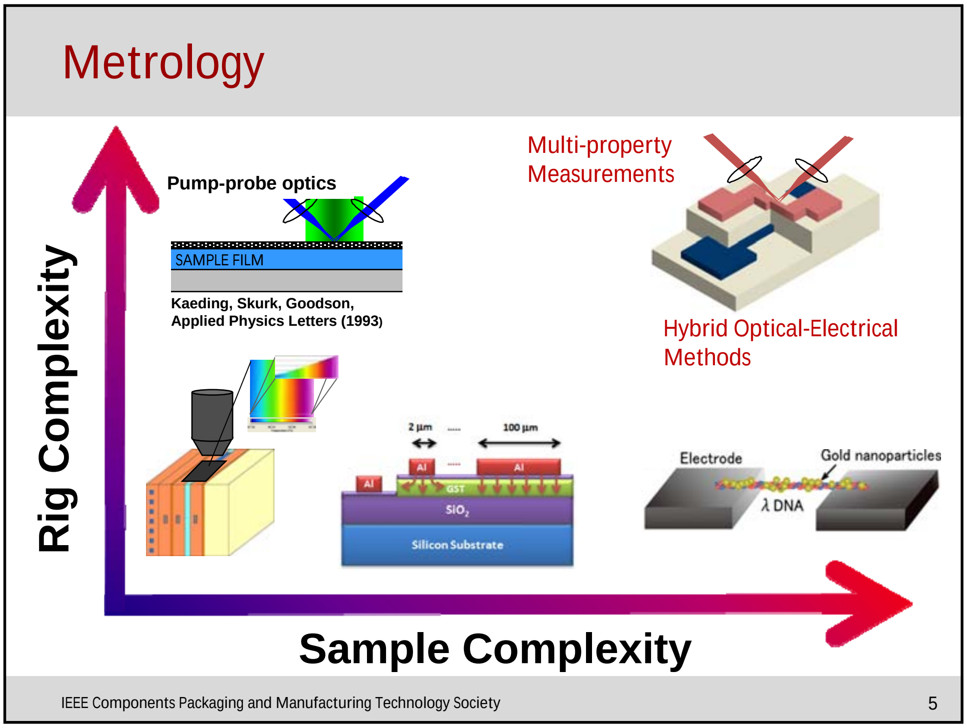


Electrothermal Characterization



Mechanical Characterization




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
IEEE Components Packaging and Manufacturing Technology Society
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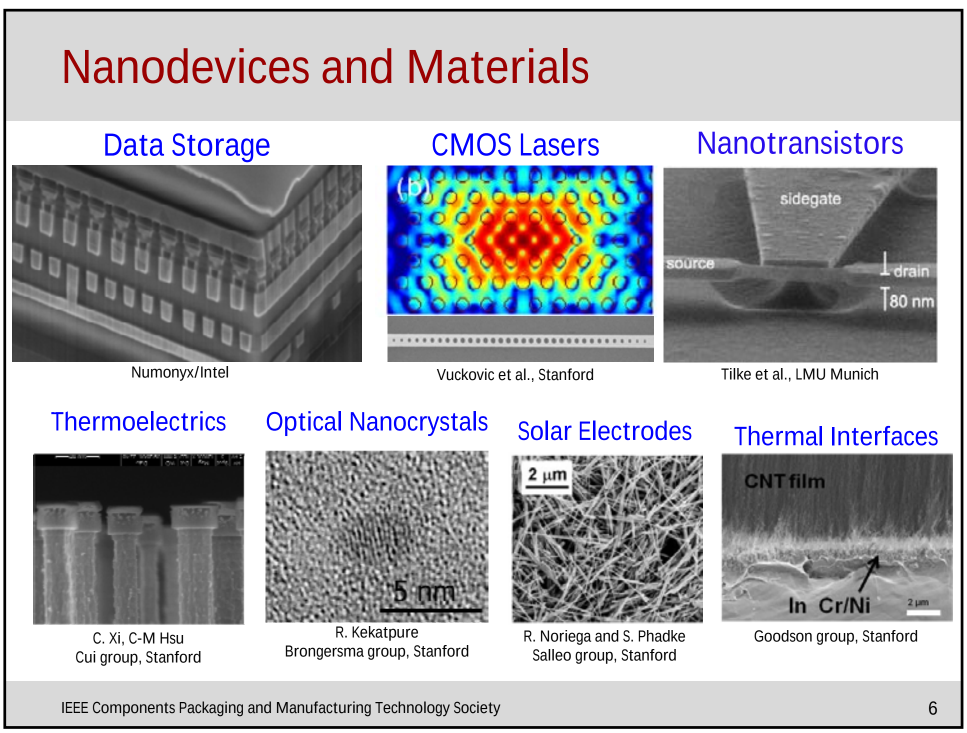
Nanodevices and Materials
Data Storage
CMOS Lasers
Nanotransistors
Numonyx/Intel
Vuckovic et al., Stanford
sidegate
source
drain
80 nm
Tilke et al., LMU Munich
Thermoelectrics
Optical Nanocrystals
Solar Electrodes
Thermal Interfaces
5 nm
2 µm
CNT film
In Cr/Ni
C. Xi, C-M Hsu
Cui group, Stanford
R. Kekatpure
Brongersma group, Stanford
R. Noriega and S. Phadke
Salleo group, Stanford
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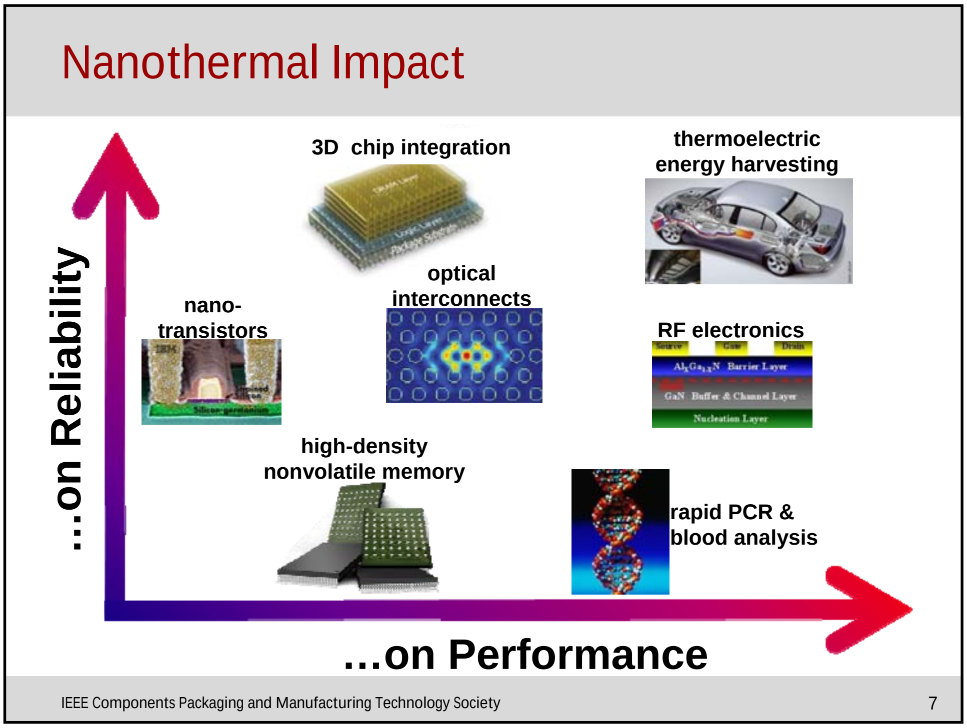
Nanothermal Impact
3D chip integration
thermoelectric
energy harvesting
nano-
transistors
optical
interconnects
RF electronics
high-density
nonvolatile memory
rapid PCR &
blood analysis
…on Reliability
…on Performance
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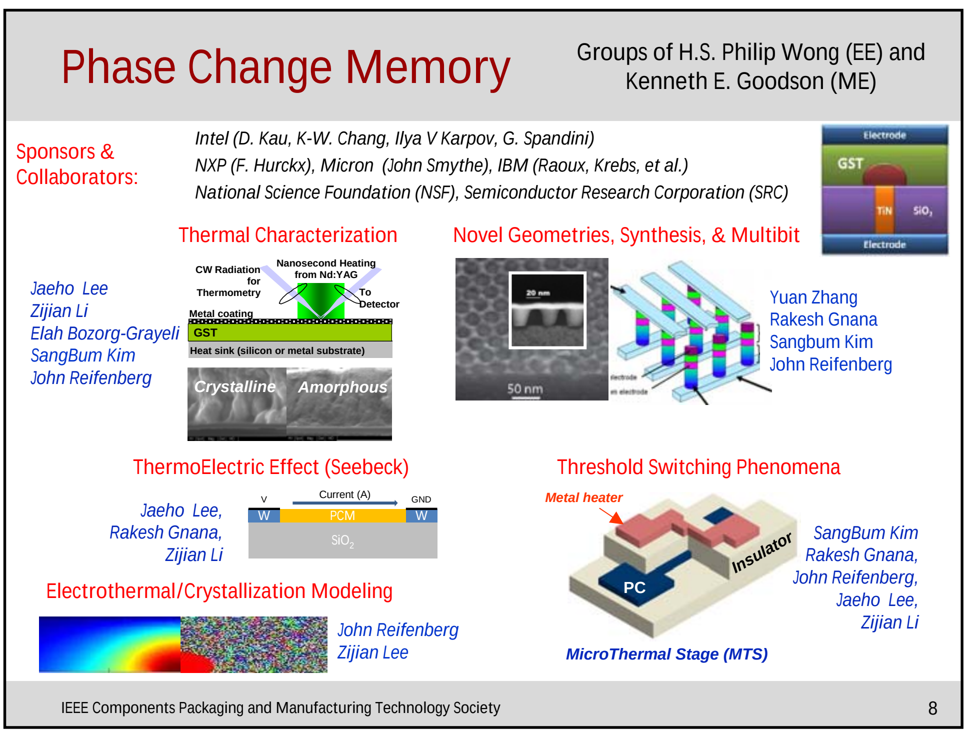
Phase Change Memory
Groups of H.S. Philip Wong (EE) and
Kenneth E. Goodson (ME)
Sponsors &
Collaborators:
Intel (D. Kau, K-W. Chang, Ilya V Karpov, G. Spandini)
NXP (F. Hurckx), Micron (John Smythe), IBM (Raoux, Krebs, et al.)
National Science Foundation (NSF), Semiconductor Research Corporation (SRC)
Electrode
GST
TiN
Electrode
Thermal Characterization
Jaeho Lee
Zijian Li
Elah Bozorg-Grayeli
SangBum Kim
John Reifenberg
CW Radiation for Thermometry
Nanosecond Heating from Nd:YAG
To Detector
Metal coating
GST
Heat sink (silicon or metal substrate)
Crystalline
Amorphous
Novel Geometries, Synthesis, & Multibit
20 nm
50 nm
Yuan Zhang
Rakesh Gnana
Sangbum Kim
John Reifenberg
ThermoElectric Effect (Seebeck)
Jaeho Lee,
Rakesh Gnana,
Zijian Li
Current (A)
V
GND
W
PCM
W
Threshold Switching Phenomena
Metal heater
Insulator
PC
SangBum Kim
Rakesh Gnana,
John Reifenberg,
Jaeho Lee,
Zijian Li
MicroThermal Stage (MTS)
Electrothermal/Crystallization Modeling
John Reifenberg
Zijian Lee
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Key Challenges for TEs in Combustion Systems

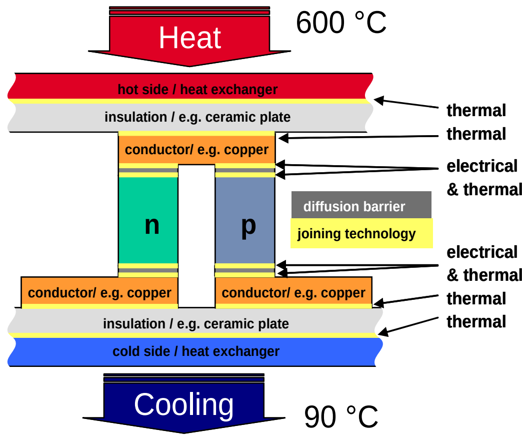
Improvements in the intrinsic ZT of TE materials are proving to be very difficult to translate into efficient, reliable power recovery systems.

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

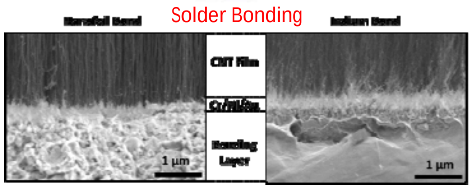
U.S. Department of Energy Energy Efficiency and Renewable Energy

NSF

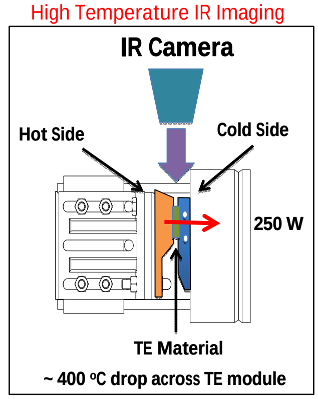
BOSCH

Novel Materials Laboratory
University of South Florida

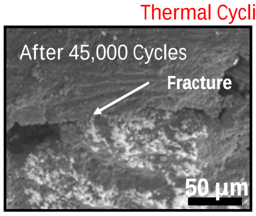
Solder Bonding

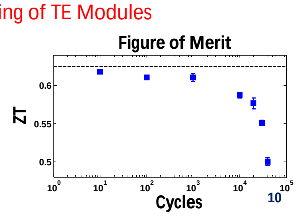


High Temperature IR Imaging



Thermal Cycling of TE Modules





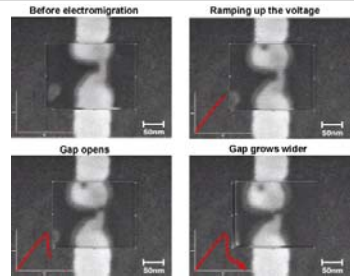
Thermal Management Challenges for Microprocessors

Importance of Hotspot Thermal Management

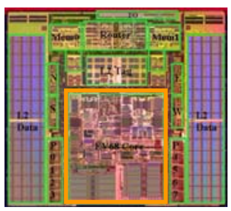
- Peak temperatures limit the reliability of interconnects
- Thermo-mechanical strains due to temperature non-uniformities can degrade packaging and interfaces

Challenges Ahead for Thermal Management

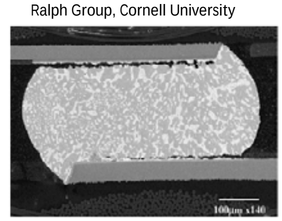
- Transistor scaling
- Increasing number of cores
- 3D integration
- Constraints of mobile applications



Images of Electromigration Failure
Ralph Group, Cornell University



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

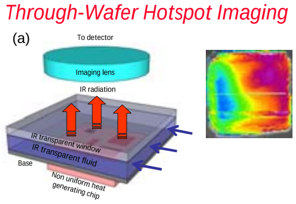


Solder joint failure due to thermomechanical stress
Ridgetop Group Inc.,

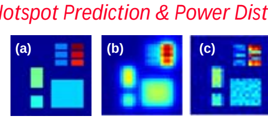
Hot Spot Detection and Thermal Management

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



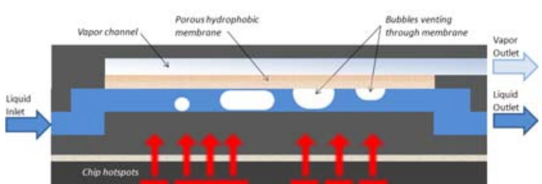
Rapid Hotspot Prediction & Power Distribution



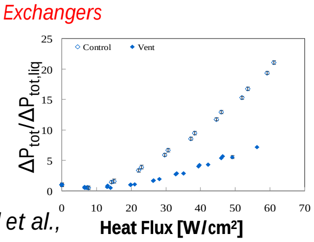
Power map *Distributed Temperature Sensor Network* *Reproduced power map*

AMD SRC CISCO

Vapor-Venting Microfluidic Heat Exchangers



Side Profile of Heat Exchanger with Venting



David et al.,

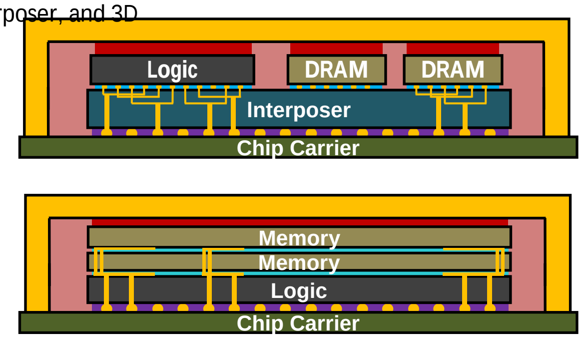
Outline

- Stanford Nano/Micro Heat Lab
  - Overview of Metrology and Materials
- **Materials for Thermal Management**
  - Aligned CNT nanotape
  - High density aligned CNT composites
  - Mechanical Characterization – Resonator
  - 3D chip attachments and conductive underfills

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

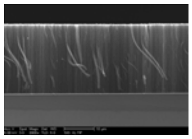


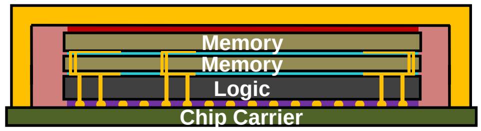
3D Chip Attachment (Adhesives, Thermal compression bonding)
- High thermal conductivity
- Electrically insulating
- Thermal cycling stability

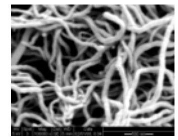
Encapsulation
- High thermal conductivity
- Electrically insulating (on the side facing the chip)
- Mechanical compliance

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

Challenges Posed by Material Requirements







- Problem: **Heat removal from 3D stacked circuits** is severely limited by low conductivities of the underfill/BGA and the thermal interface.
- Solution: **Nanostructured organics** promise high thermal conductivity with the mechanical and viscoelastic properties required for manufacturing and lifetime reliability.
- Application:
  - Passivation layer during the BEP of the wafer
  - Non-conductive adhesive as a replacement to under-fill

Challenges:

- Maintaining nanostructure **during dispensing** and CMP
- Minimizing negative impact from **contacting** the nanostructure to the **adjacent materials**
- Impact of **thermal pressure bonding** during assembly process
- **Thermo-mechanical stresses** between the polymer and the micro-bump/Cu pillar
- Effects of **reflow process**

IBM and 3M collaboration

High thermal conductivity underfill adhesives for building silicon skyscrapers

IBM United States [change]

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3M and IBM to Develop New Types of Adhesives to Create 3D Semiconductors

Innovation leading to the creation of 'Silicon Skyscrapers'

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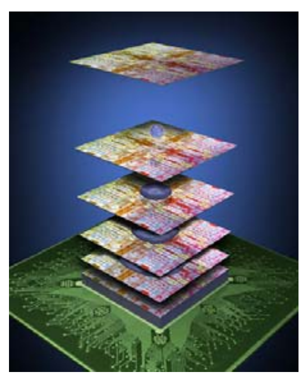
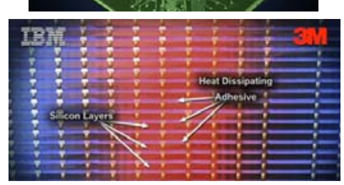
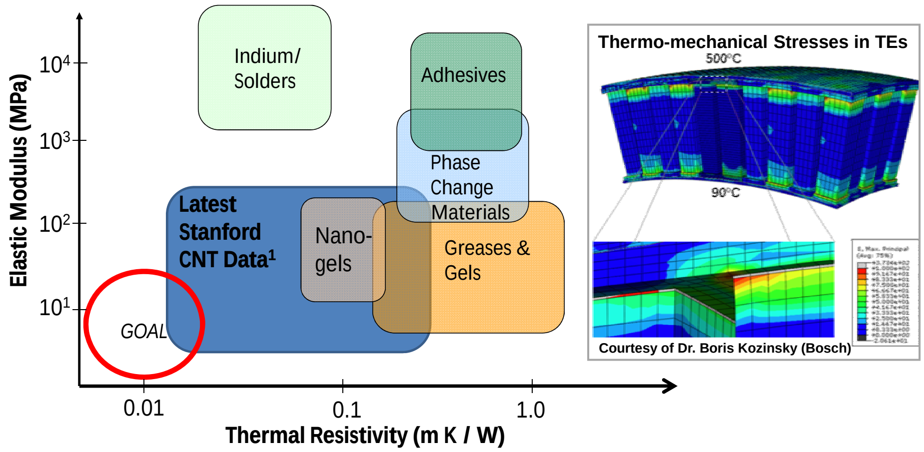
ST. PAUL, Minn. & ARMONK, N.Y. - 07 Sep 2011: 3M and IBM (NYSE: IBM) today announced that the two companies plan to jointly develop the first adhesives that can be used to package semiconductors into densely stacked silicon "towers." The companies are aiming to create a new class of materials, which will make it possible to build, for the first time, commercial microprocessors composed of layers of up to 100 separate chips.



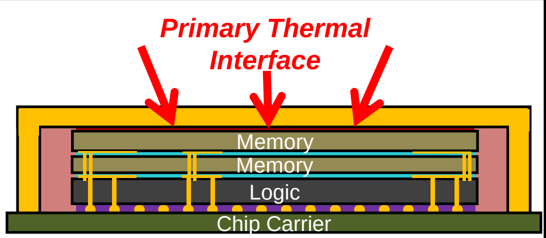


Thermal Interface Materials

Goal: Engineer materials with high thermal conductivity and low elastic modulus



CNT Die Attachment



Carbon

Mechanical characterization of aligned multi-walled carbon nanotube films using microfabricated resonators 2012

Yoonjin Won [a,], Yuan Gao [a], Matthew A. Panzer [a], Senyo Dogbe [b], Lawrence Pan [c], Thomas W. Kenny [a], Kenneth E. Goodson [a]*

Temperature-Dependent Phonon Conduction and Nanotube Engagement in Metalized Single Wall Carbon Nanotube Films 2010

Matthew A. Panzer,[†] Hai M. Duong,[‖] Jun Okawa,[§] Junichiro Shiomi,[§] Brian L. Wardle,[†] Shigeo Maruyama,[§] and Kenneth E. Goodson[†,*]

NANO LETTERS

Nanotape to Replace Solder Pads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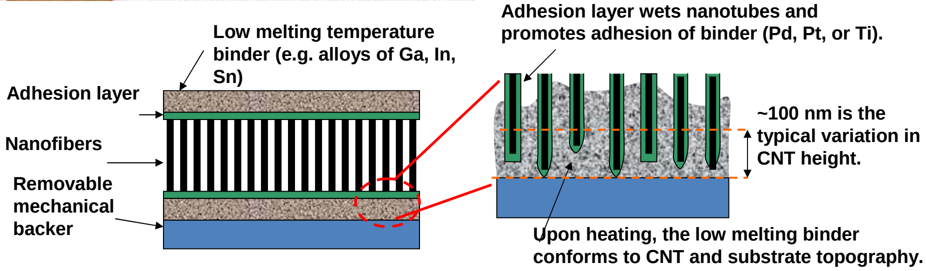
Nanotape could make solder pads obsolete

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

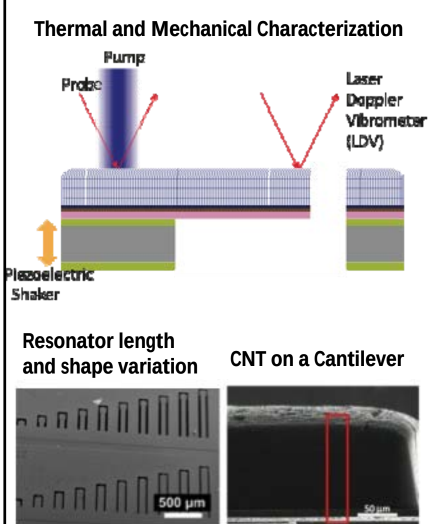
PORTLAND, Ore.—Solder pads could soon be made obsolete by a ne
nanotape material created by the Semiconductor Research Corporatio
and Stanford University.

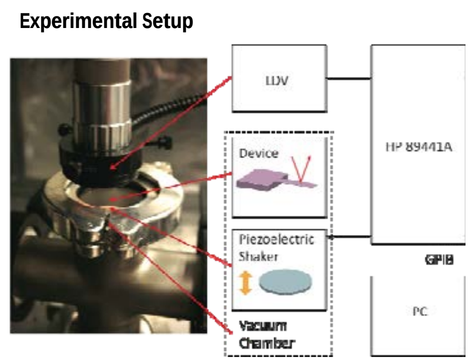
By sandwiching thermally conductive carbon nanotubes between thin

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)



Mechanical Properties of CNT Films
New Technique: Mechanical Resonators





- 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

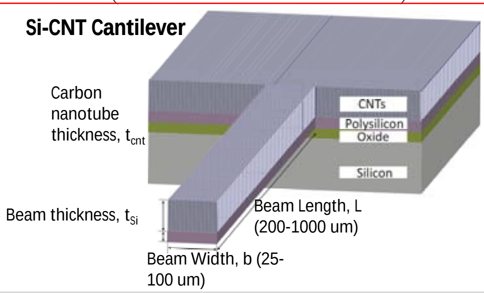
Euler-Bernoulli differential equation for multi-layer beam

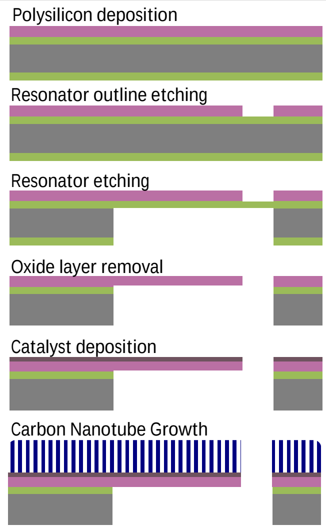
$$\overline{\rho A}\frac{\partial^2 w}{dt^2} + \overline{EI}\frac{\partial^4 w}{\partial x^4} = 0 \qquad \overline{\rho A} = \sum_i \rho_i A_i \quad \overline{EI} = \sum_i E_i I_i$$

Transformed section method

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

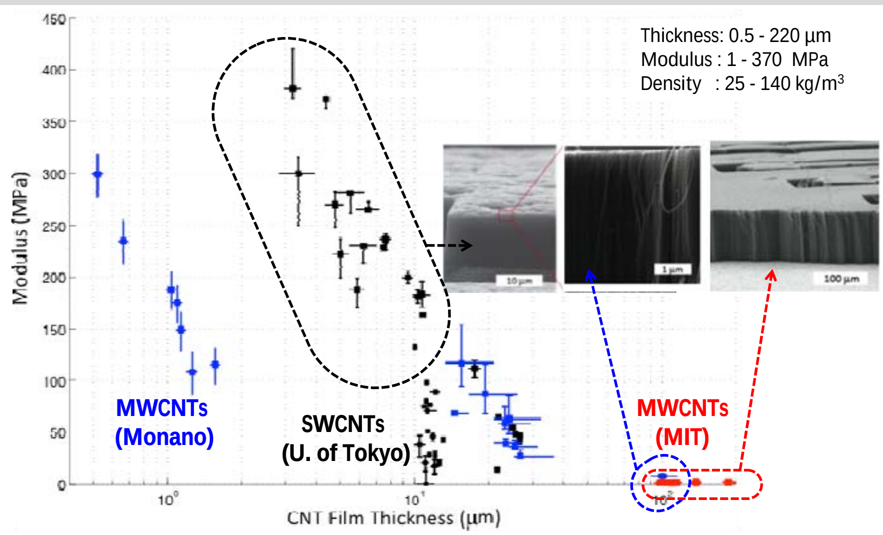
$$E_{CNT} = \frac{E_{Si}}{I_{CNT}}\cdot\left(\left(1+\frac{\rho_{CNT}A_{CNT}}{\rho_{Si}A_{Si}}\right)\cdot\left(1+\left(\frac{\Delta w_n}{w_{n,Si,0}}\right)\right)^2 I_{Si,0} - I_{Si}\right)$$





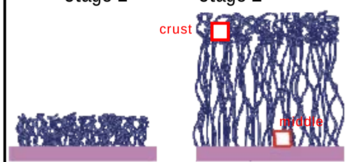
Won et al, *Carbon* (2011)

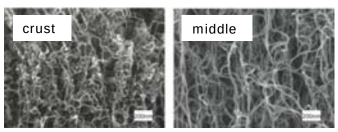
Mechanical Behavior of CNT Films



Mechanical Behavior of Nonhomogeneous CNT Films

Growth Stages





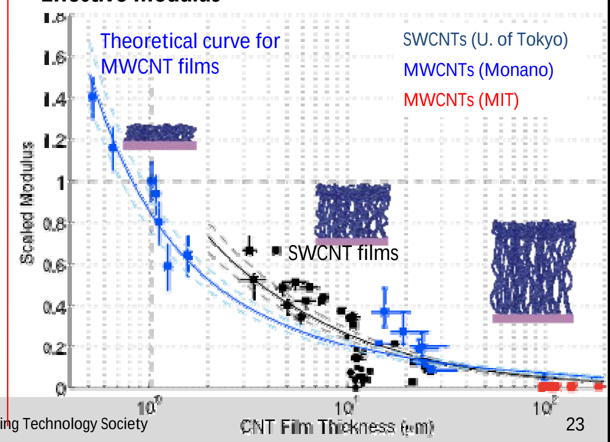
- Interweaving of a thin layer of entangled and randomly oriented nanotubes
- Vertical-aligned growth
- Density decay

Three-layer Analysis

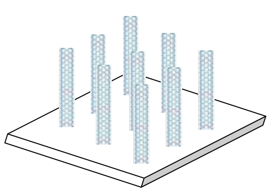
Two-layer analysis → Three-layer analysis

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

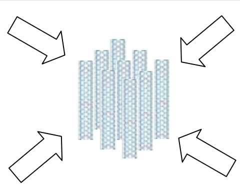
Dimensionless Effective Modulus : Moduli are scaled by reference sample and volume fraction



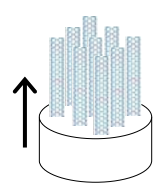
Aligned CNT Nanocomposites



Remove 1 vol.% CNT film from growth substrate

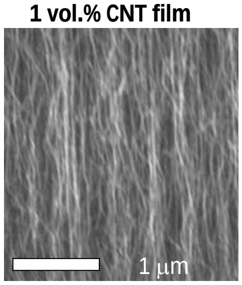


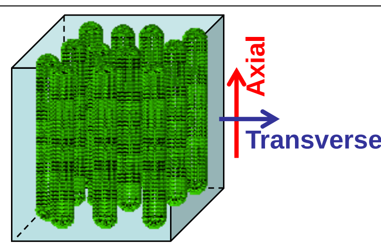
Biaxial compression to increase volume fraction



Infiltrate with epoxy (RTM-6)

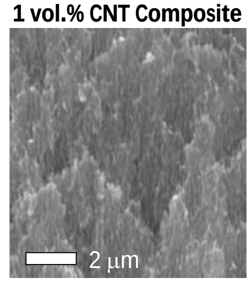
1 vol.% CNT film



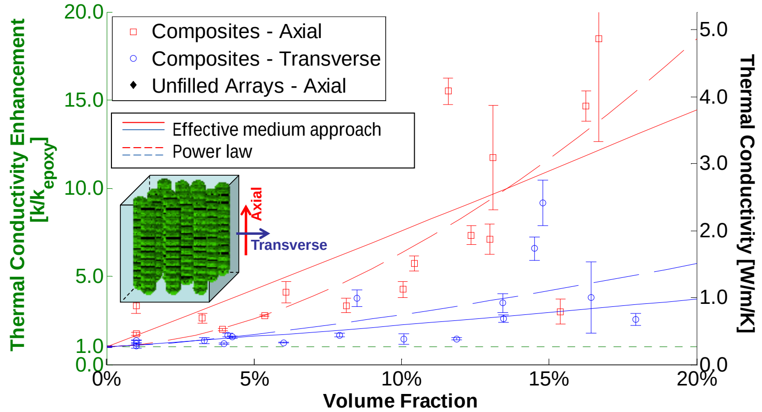


Marconnet et al, *ACS Nano* (2011)

1 vol.% CNT Composite



Thermal Conductivity of Aligned CNT Nanocomposites

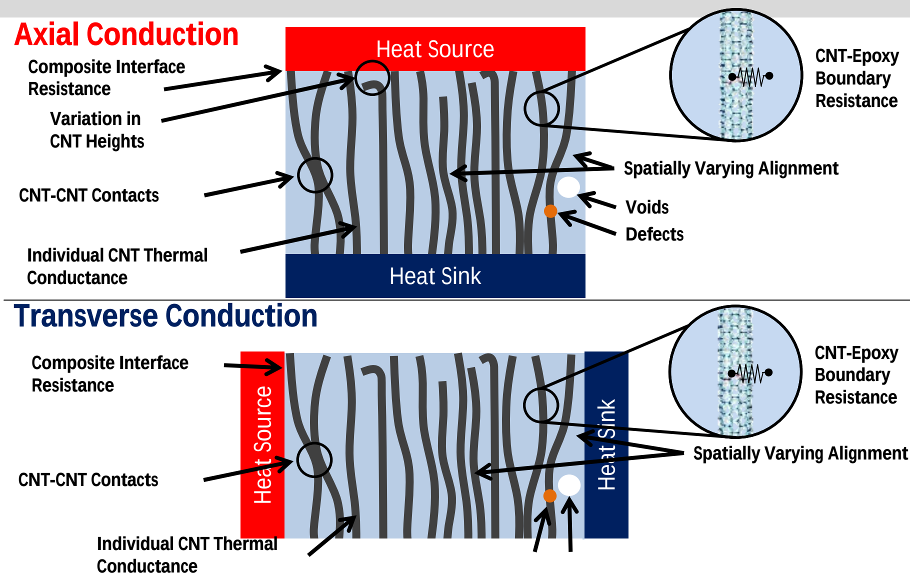


(Surfaces polished to ~3nm roughness and coated with 200 nm of Pt to ensure nearly identical contact conditions for all samples and improves contact between composite and reference layers)

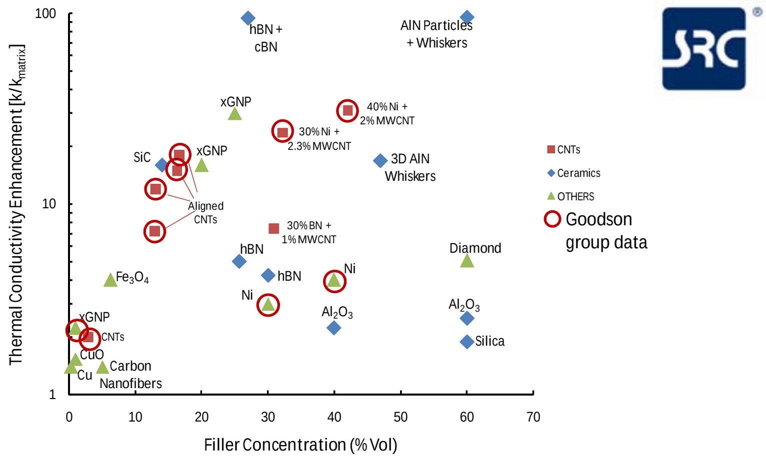
•Non-linear increase at higher volume fraction suggests that CNT-CNT and CNT-polymer interactions are important to the thermal transport

•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



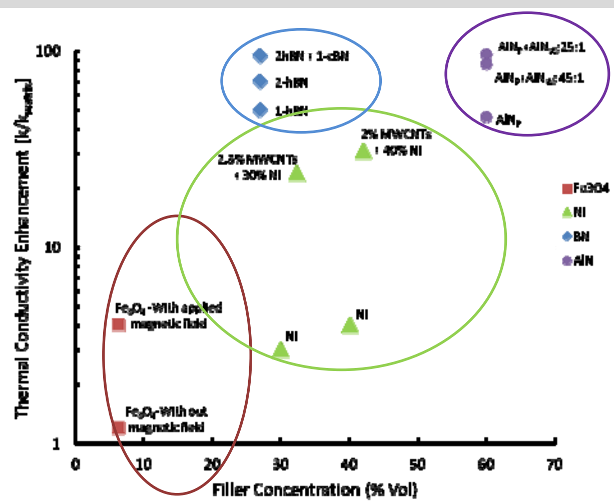
Nanoparticle Based Composite Packaging



Cu - Eastman et al, 2001; Carbon Nanofibers - Sui et al, 2008; CuO – Karthikeyan et al, 2008; Fe_3O_4 - Philip et al, 2008; SiC – Zhou et al, 2008; xGNP – Fukushima et al, 2006 and Yu et al, 2007; hBN – Hsuan et al, 2006; hBN+cBN – Yung et al, 2007; hBN, Daimond, Silica – Lee et al, 2005; BN+MWCNT – Teng et al, 2011; Al_2O_3 – Fu et al, 2011 and Lee et al, 2005; 3D AlN – Shi et al, 2009; AlN Particles + Whiskers – Xu et al, 2001.

Key Notes from Literature – Percolation Pathways

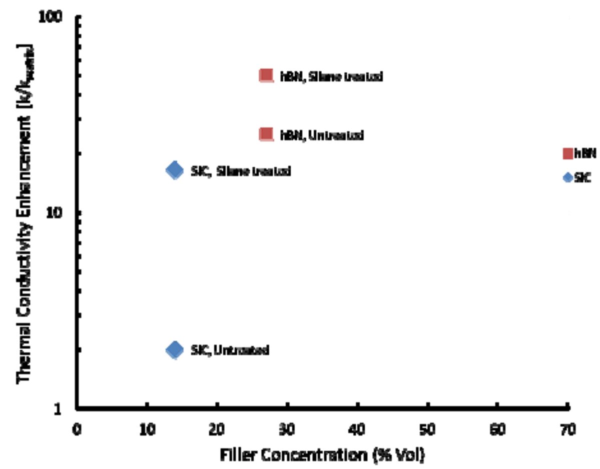
- Application of magnetic field in the direction parallel to the temperature gradient
- CNT inclusions to form conductive pathways
- Multimodal particle size mixing
- Combination of different crystalline forms
- Distribution in particle shapes to form better networks



Fe_3O_4 - Philip et al, 2008; Ni - Hu et al, 2004; BN - Yung et al, 2007; AlN - Xu et al, 2001.

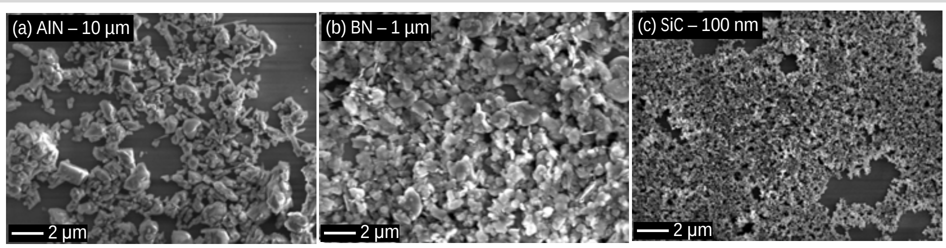
Key Notes from Literature – Chemical Treatment

Silane surface treatment of particles to form particle-resin interface structures

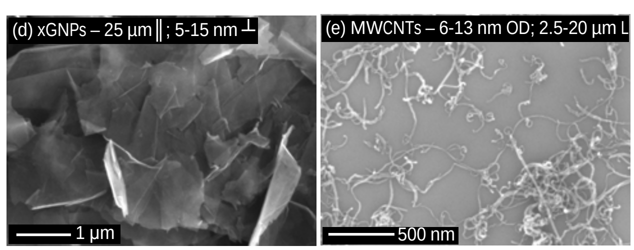


SiC – Zhou et al, 2008; hBN - Yung et al, 2007.

Candidate Filler Micro/Nano Particles



Material	Thermal Conductivity (W/mK)	Electrical Resistivity (Ω-cm)
Aluminum Nitride	285 (single) 70–210 (poly)	> 10^{14}
h-Boron Nitride	600 ‖ ; 30 ⊥	> 10^{14}
Silicon Carbide	120	10^{2}–10^{6}
xGNP	3000 ‖ ; 6 ⊥	10^{-5} ‖ ; 1 ⊥
MWCNTs	100-3000 ‖	



Preliminary Thermal Conductivity Data

Samples: particles dispersed in silicone oil
Technique : IR imaging

•1% xGNP performed better than 1% MWCNT

• 1% xGNP and 1% MWCNT performed better that 10% AlN

• 1% xGNP addition to 10% AlN showed promising enhancement

Particle Composition (Vol %)	Thermal Conductivity Enhancement (k/k_{matrix})
1 % xGNP	2.1
1% MWCNT	1.5
10% AlN	1.3
10% AlN + 1% xGNP	2.8

Ongoing Work and Future Directions

- Ongoing work
  - Cured polymer nanocomposites
  - Various surface treatments of filler particles
  - Electrical characterization of polymer nanocomposites
  - Compare thermal and electrical conductivity data against existing effective medium theories
- Future directions
  - Bonding of composite materials to Si
  - CTE measurement of composite materials bonded to mechanical resonator
  - Real-time evolution of interfacial adhesion, fatigue, debonding

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
- Preliminary thermal conductivity data of nanosuspensions in silicone oil showed promising trends, and this work is being extended to nanocomposites

Questions & Comments