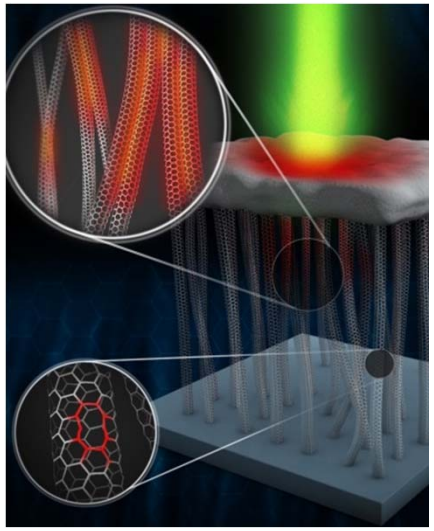
SF Bay Area Nanotechnology Council

September 17, 2013

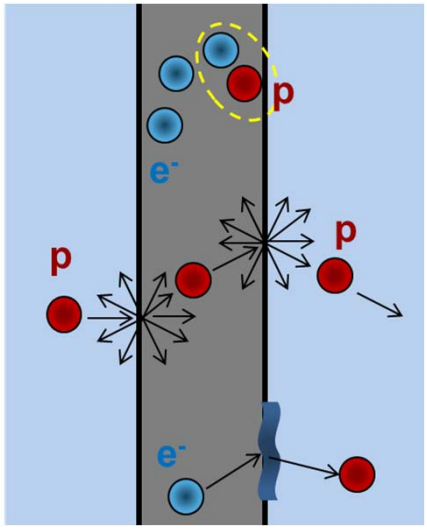
Thermal Management at the Extremes



Ken Goodson

Robert Bosch Department Chair

Stanford Mechanical Engineering



STANFORD nanoHeat

Stanford | ENGINEERING

“Hot” electronics are in the news…

ABC News October 2011

MacWorld June 2012

March 2012

NY Daily News 2010

Heat & Energy Challenges

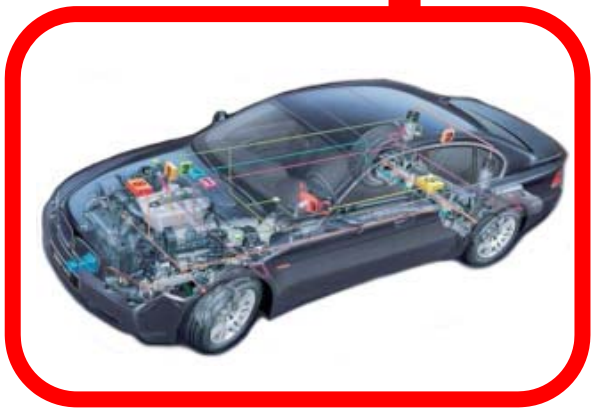
information

energy efficiency

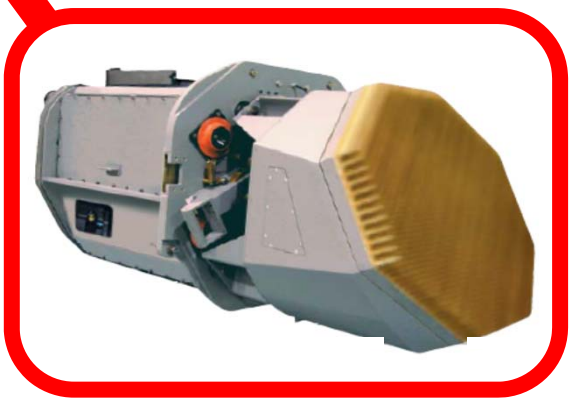
hotspot mitigation

materials integration

appliances



transportation



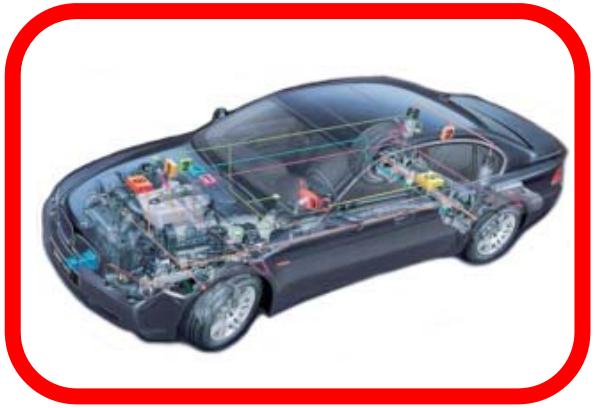
defense

STANFORD nanoHeat

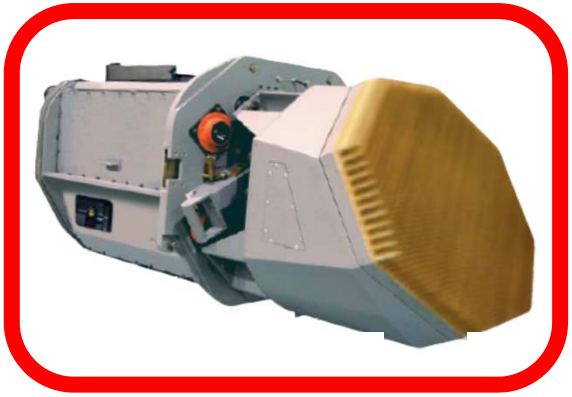
Heat & Energy Challenges

information

appliances



transportation

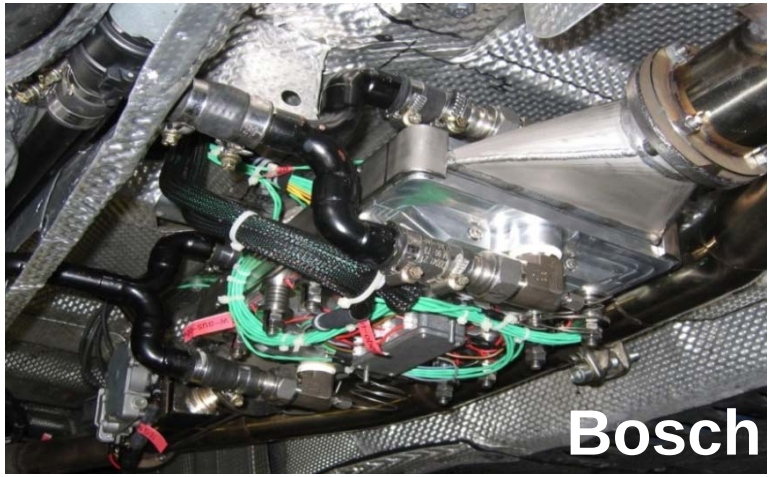


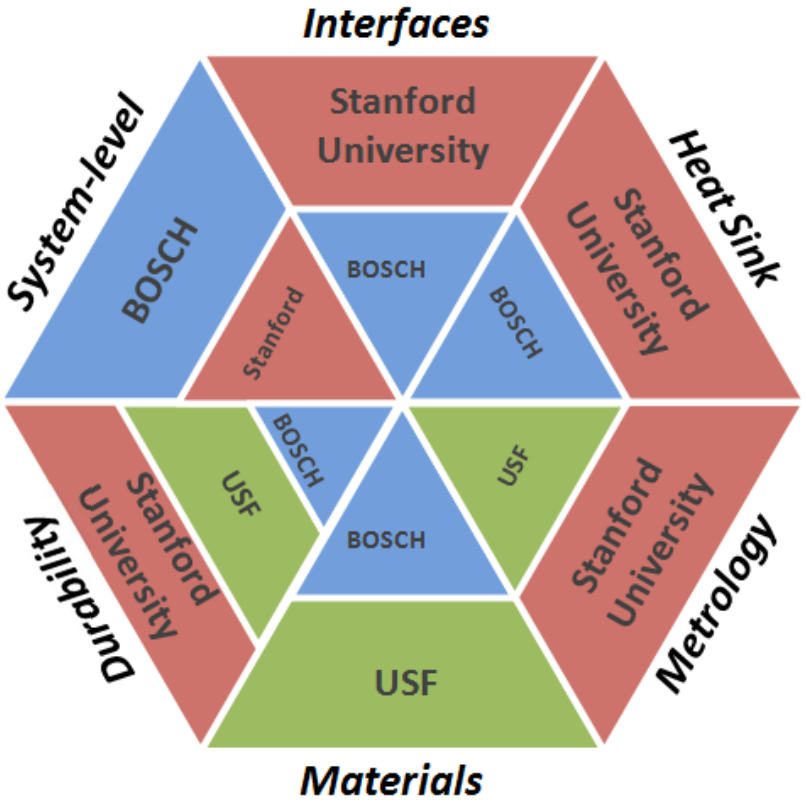
defense

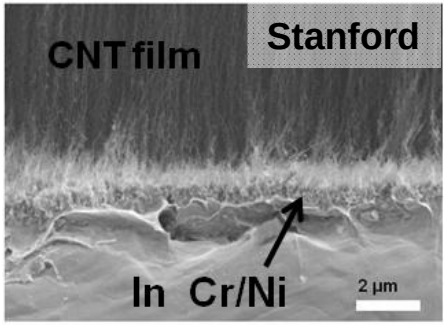
STANFORD nanoHeat

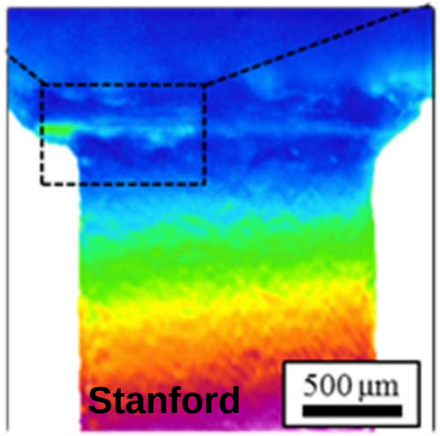
DOE-NSF Thermoelectrics Partnership

Vehicle Waste Heat Recovery









Faculty & Staff

Prof. Goodson (Stanford), PI
Prof. Nolas (USF)
Dr. Boris Kozinsky (Bosch)
Dr. Winnie Wong-Ng, NIST Functional Properties Group
Dr. Yongkwan Dong, USF Department of Physics

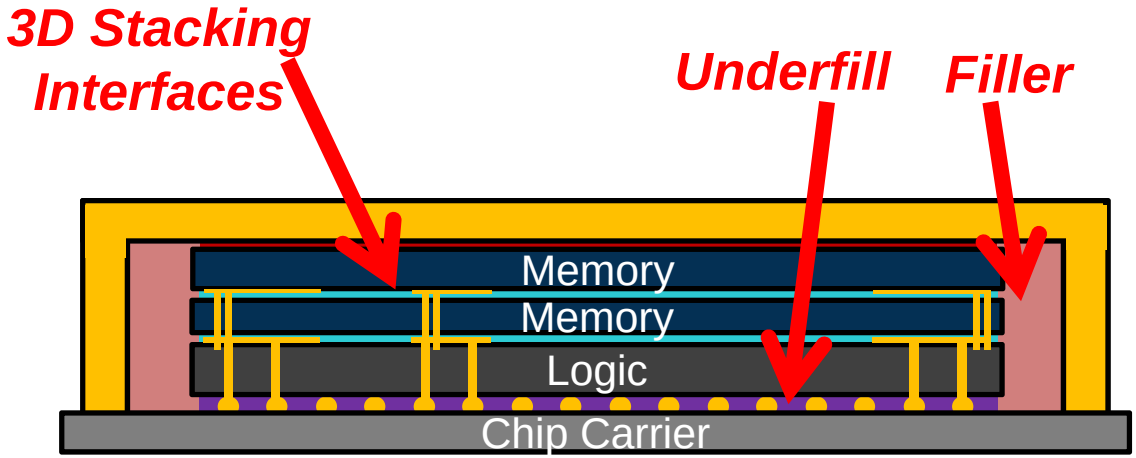
Students:

Michael Barako, Saniya Leblanc, Yuan Gao, Amy Marconnet

BOSCH

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

Nano Packaging Materials: From 3D to Portables

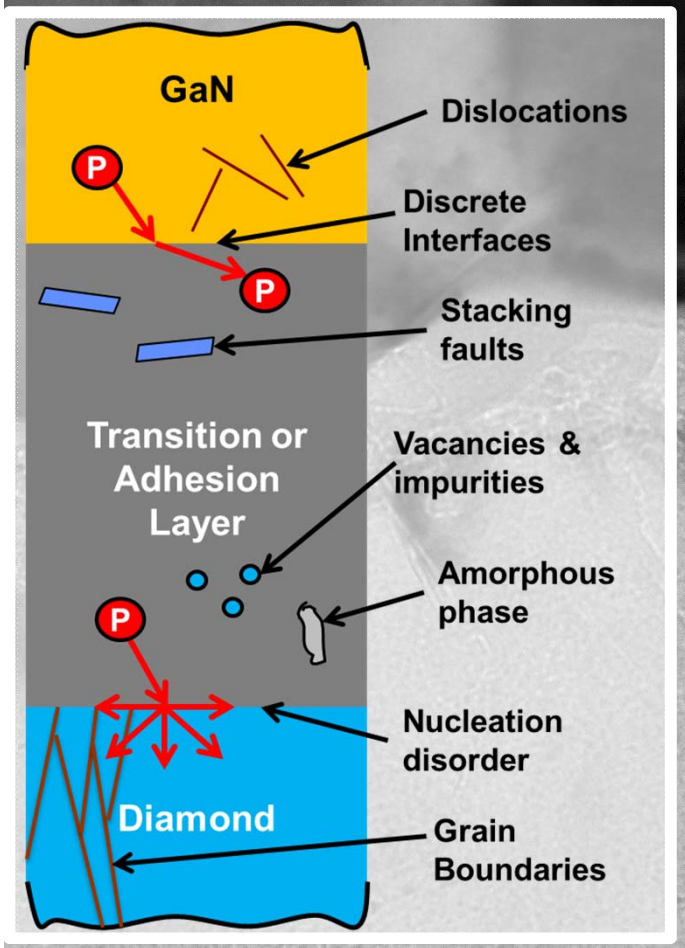


Nanostructured materials targeting unique combinations of electrical, thermal, mechanical properties

- **Mechanically Compliant Thermal & Electrical Conductors.**
- **Phase Change Energy Storage to Reduce Case Temperature.**
- **Controllable Anisotropic Electrical and Thermal Properties.**

DARPA Near Junction Thermal Transport (NJTT)

Extreme Conduction Cooling



50 nm

DARPA

Raytheon

BAE SYSTEMS

BOEING

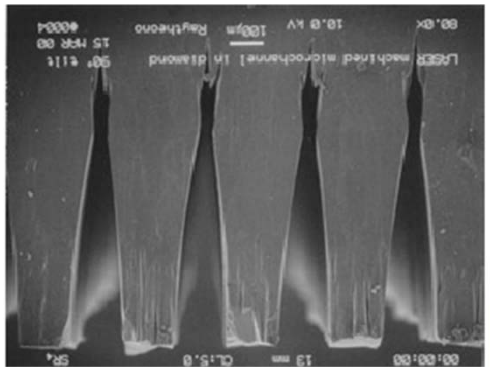
RF MICRO DEVICES

DARPA Convection Limits (ICECool 1 + 2)

Convection Cooling Limits

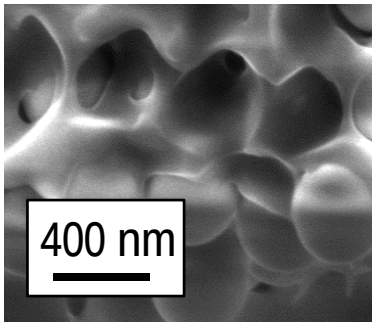
Raytheon

Spreading by Etched Diamond Channels

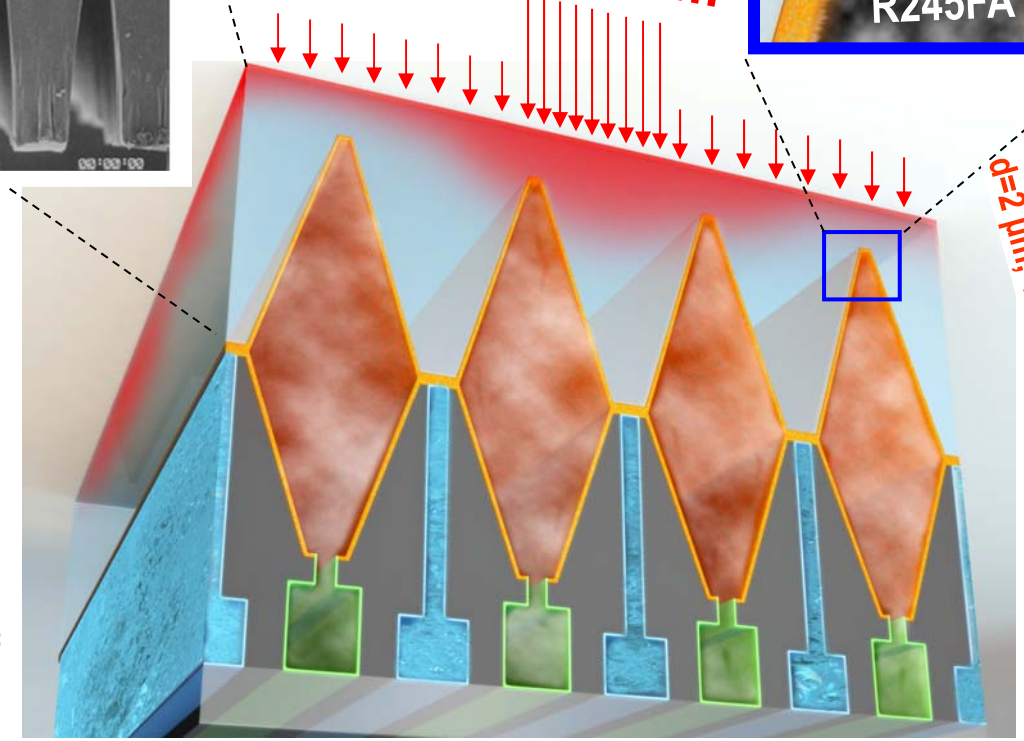


100µm

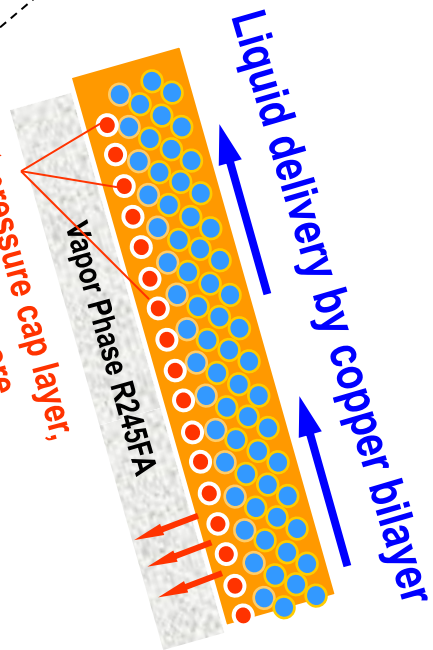
Phase Separation by Nanostructured Capping Film



50 kW/cm²

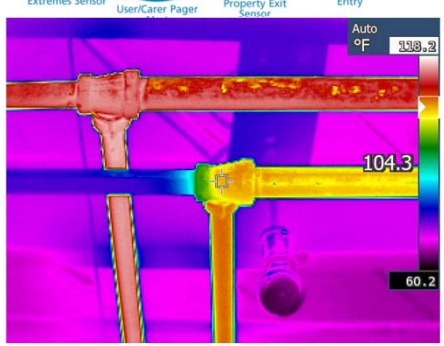


3D Routing of Liquid and Vapor

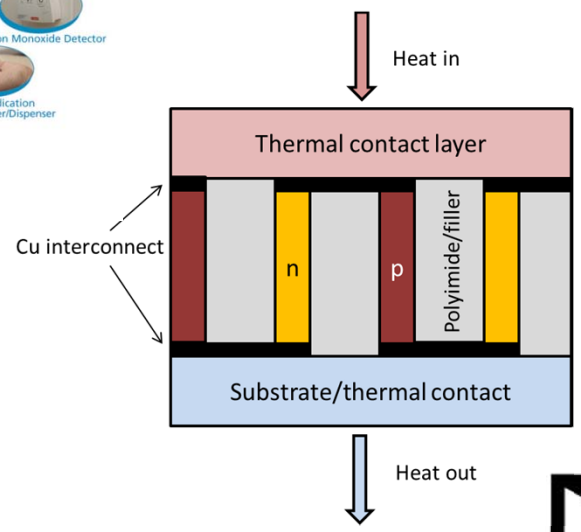


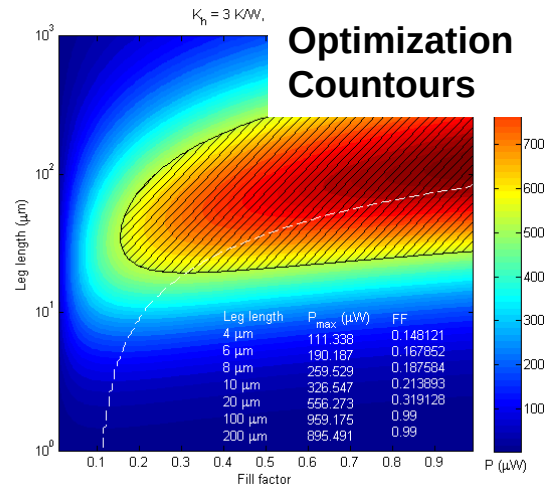
Analog Devices – Bosch – DOE - NSF

Energy Scavenging Sensors for Smart Buildings



- **Smart Buildings bring multitudes of sensors and wiring.**
- **TE energy scavenging from heat sources (HVAC, water, windows) allows "truly wireless" sensor networks.**
- **Low power, low temperature TE conversion demands revolutionary new materials and design.**





Faculty & Staff

Prof. Goodson (Stanford), PI

Prof. Martin Fisher (Stanford)

Students:

Marc Dunham, Michael Barako, Saniya Leblanc

ANALOG DEVICES

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

STANFORD nanoHeat

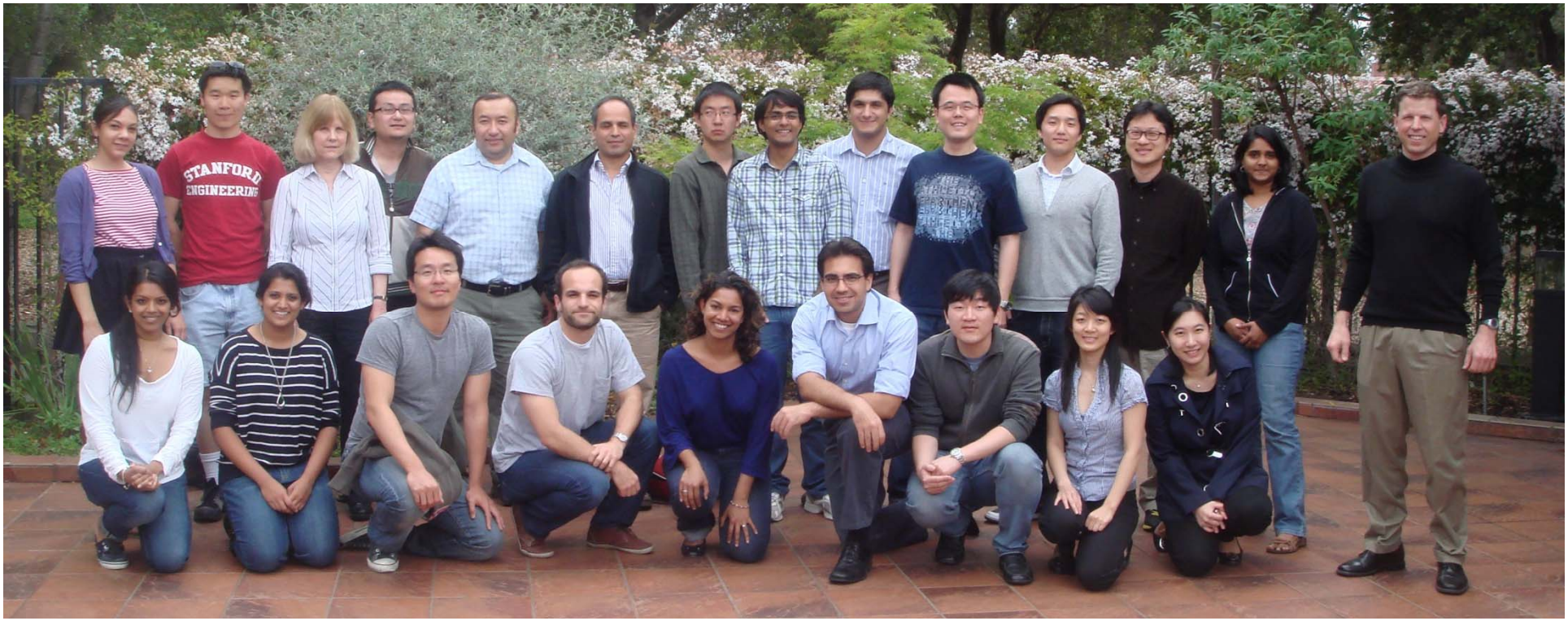
Current Group

Ken Goodson

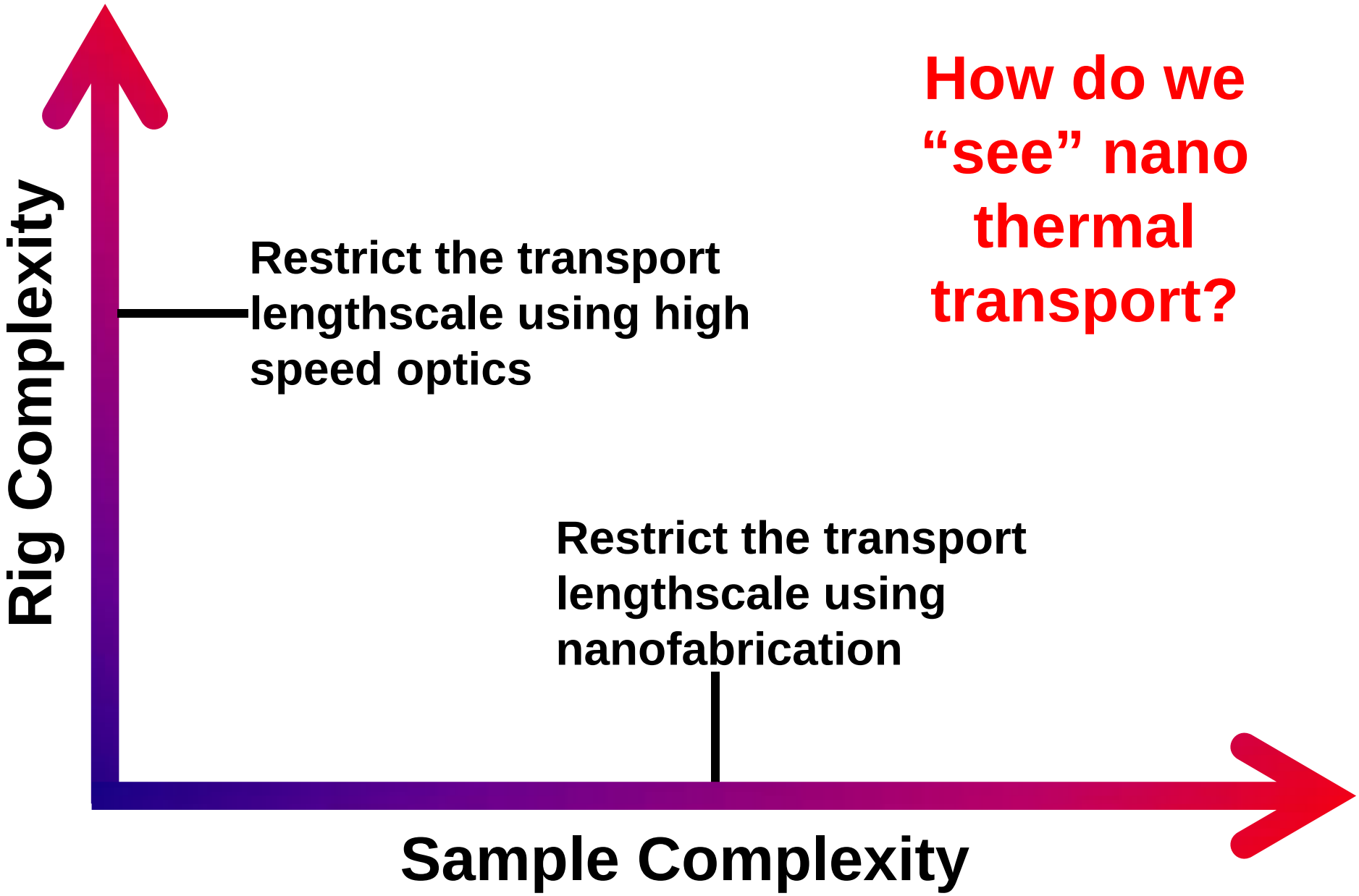
Woosung Park
Michael Barako
Shilpi Roy (EE)
Joe Katz (EE)
Jungwan Cho
Jena Barnes

Elah Bozorg-Grayeli
Tom Dessault
Sri Lingamneni
Aditya Sood (MSE)
Marc Dunham
Maneeshika Madduri

Ken Lopez
Matt Hoffman
Dr. Saniya LeBlanc
Dr. Takashi Kodama
Dr. Yoonjin Won
Dr. Damena Agonafer
Consulting Prof. Mehdi Asheghi



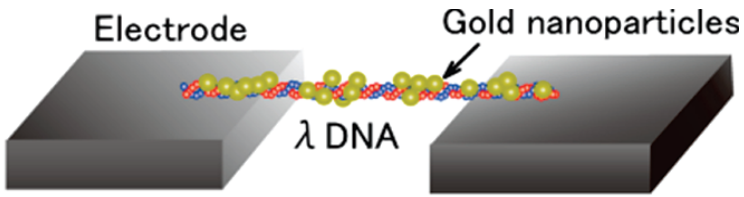
Nano Thermal Metrology



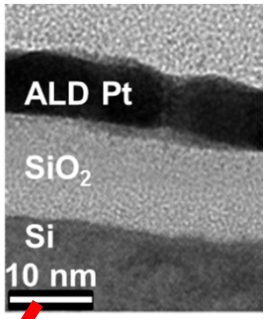
How do we "see" nano thermal transport?

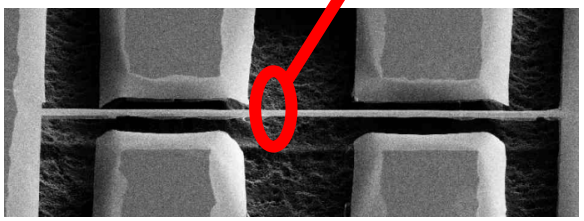
Nano Thermal Metrology

Rig Complexity



Kodama, Jain, Goodson,
Nano Letters 9 (2009)



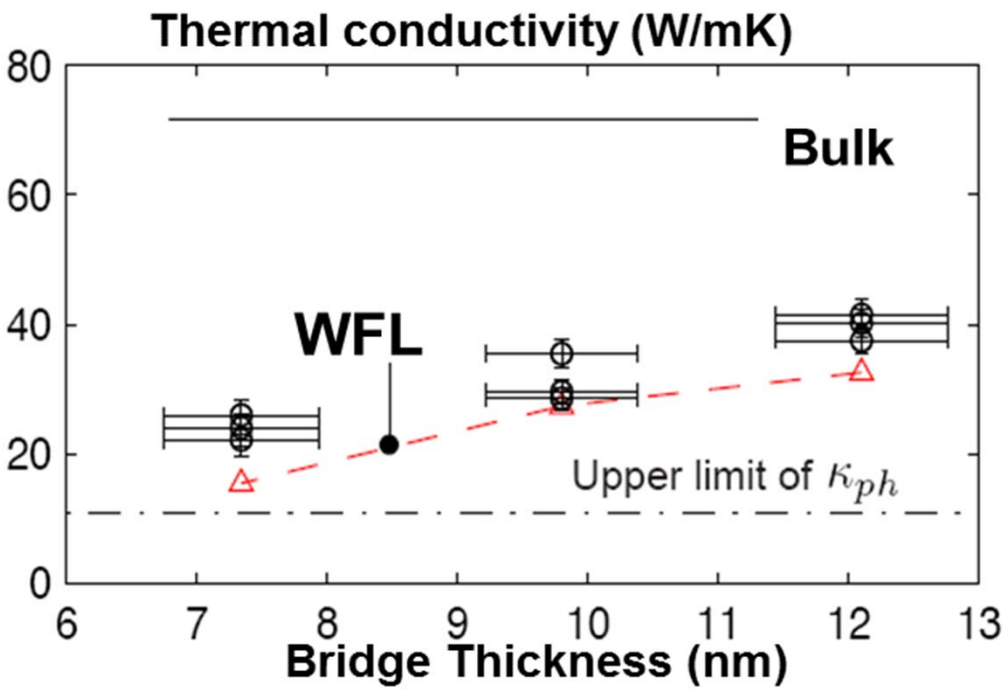


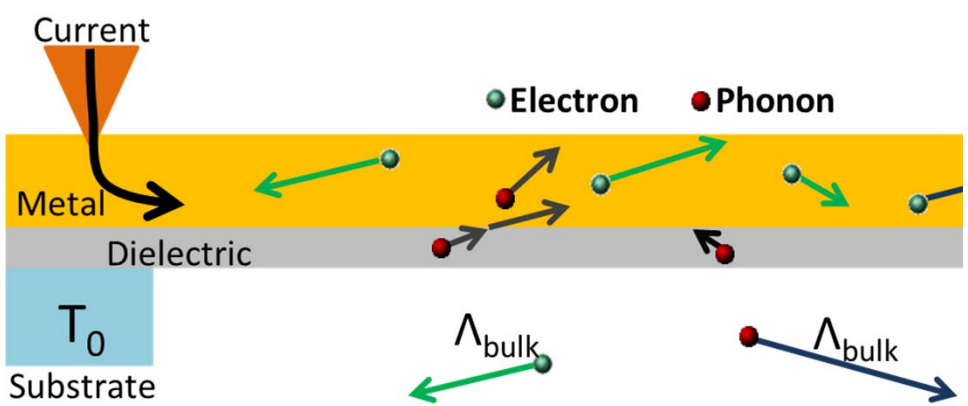
Students: Yoneoka, Li, Kodama
Nano Letters (2012b)

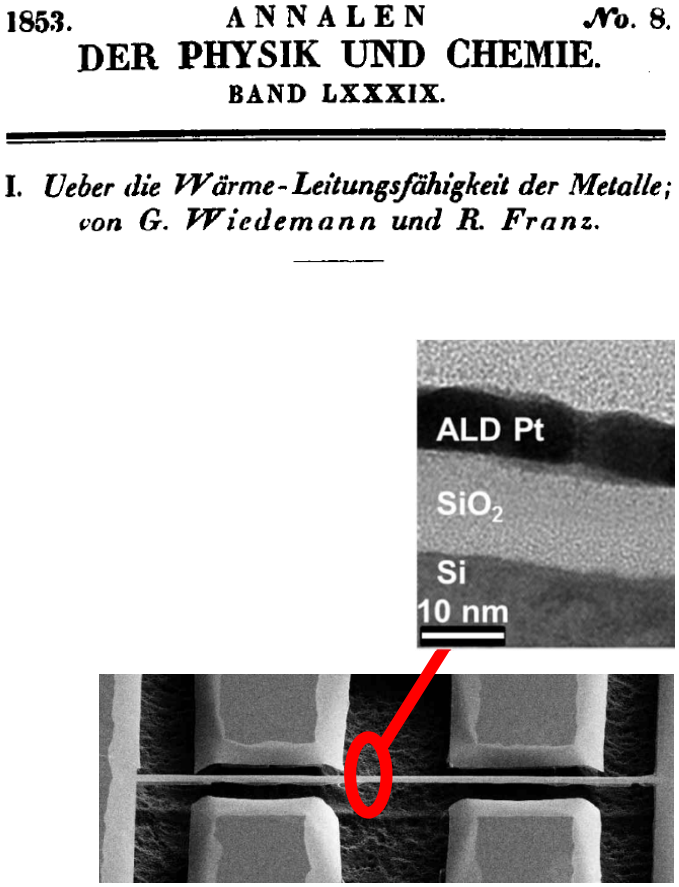
Sample Complexity

Electrons in Metal Nanofilms

Yoneoka, Lee, et al., 2012b, "Electrical and Thermal Conduction in ALD Nanobridges Down to 7-nm Thickness," *Nano Letters*, 12, 683-686.





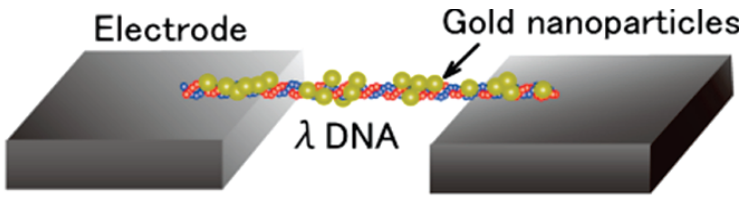

1853. ANNALEN No. 8.
DER PHYSIK UND CHEMIE.
BAND LXXXIX.

I. *Ueber die Wärme-Leitungsfähigkeit der Metalle;*
von G. Wiedemann und R. Franz.

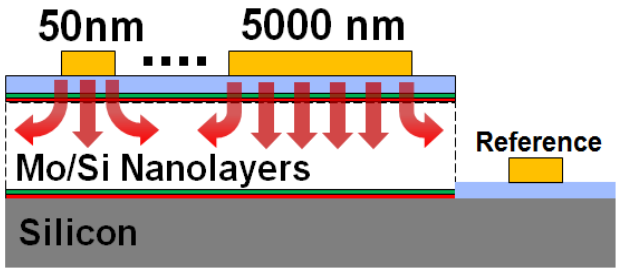
Students: Yoneoka, Li, Kodama
***Nano Letters* (2012b)**

Nano Thermal Metrology

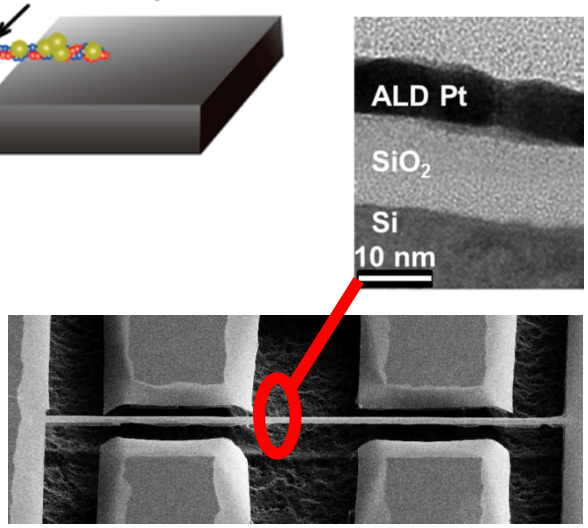
Rig Complexity



Kodama, Jain, Goodson,
Nano Letters 9 (2009)

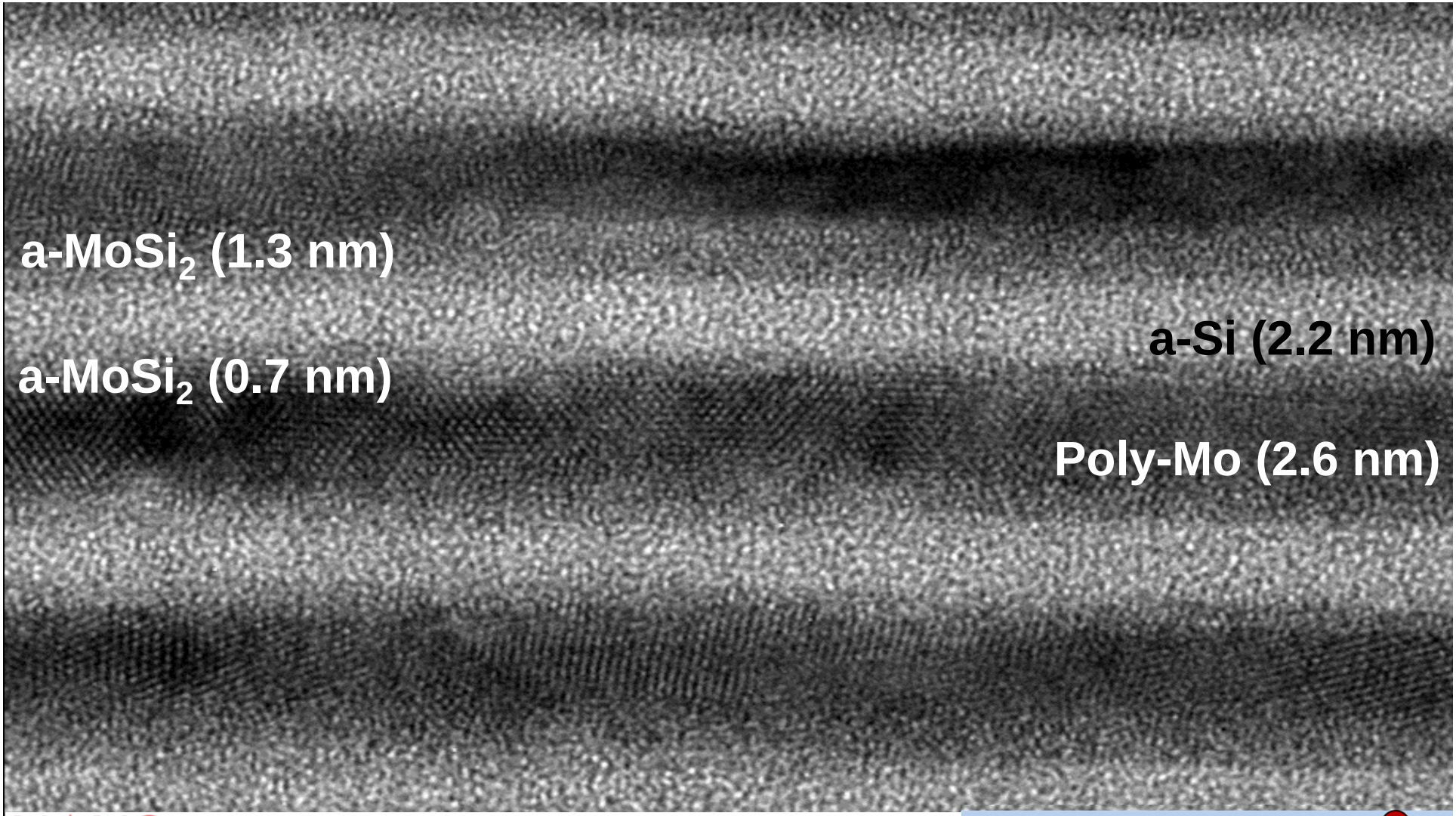


Students: Li, Lee, Kodama
Nano Letters (2012a)



Students: Yoneoka, Li, Kodama
Nano Letters (2012b)

Sample Complexity

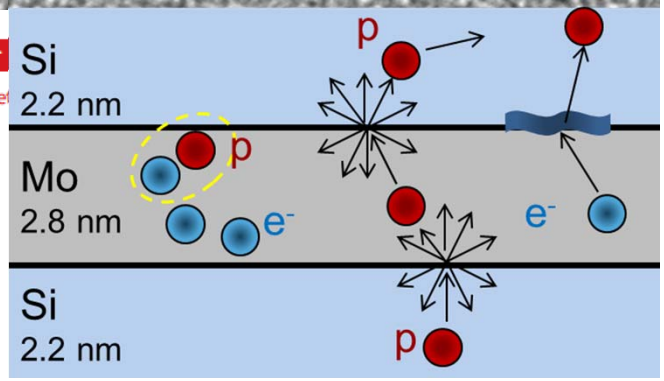


NANO LETTERS
Letter
pubs.acs.org/NanoLe

KLA Tencor

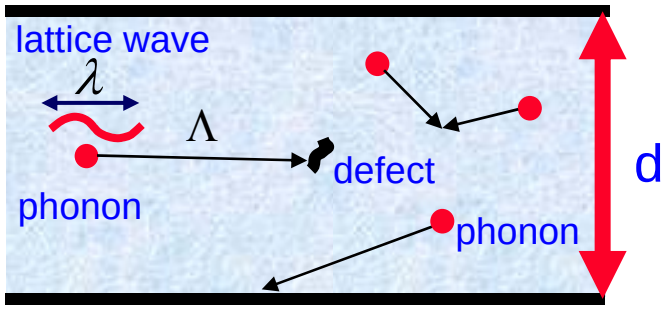
Phonon Dominated Heat Conduction Normal to Mo/Si Multilayers with Period below 10 nm

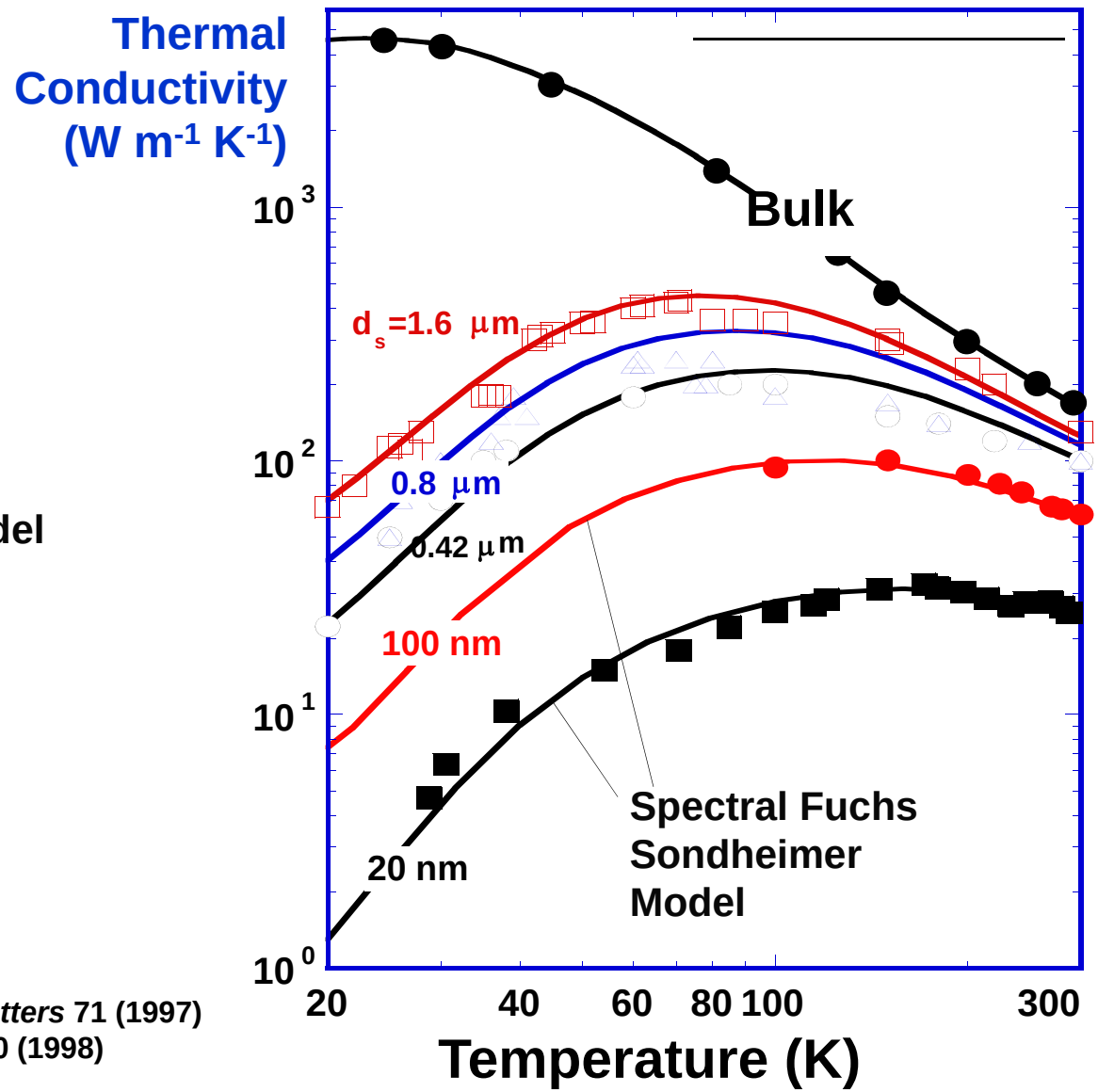
Zijian Li,[†] Si Tan,[†] Elah Bozorg-Grayeli,[†] Takashi Kodama,[†] Mehdi Asheghi,[†] Gil Delgado,[‡] Matthew Panzer,[‡] Alexander Pokrovsky,[‡] Daniel Wack,[‡] and Kenneth E. Goodson*[,†]



Phonons in Silicon Nanofilms

Marconnet, Asheghi, Goodson, "From the Casimir Limit to Phononic Crystals: 20 Years of Phonon Transport Studies using SOI Technology," *J. Heat Transfer* (2013)





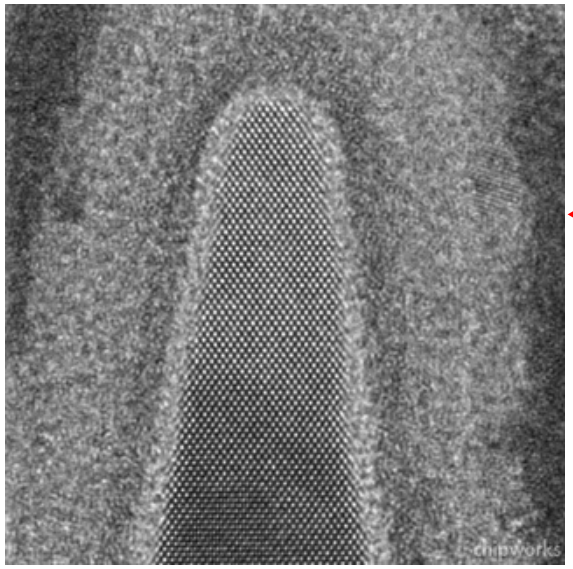
Spectral Fuchs-Sondheimer Model

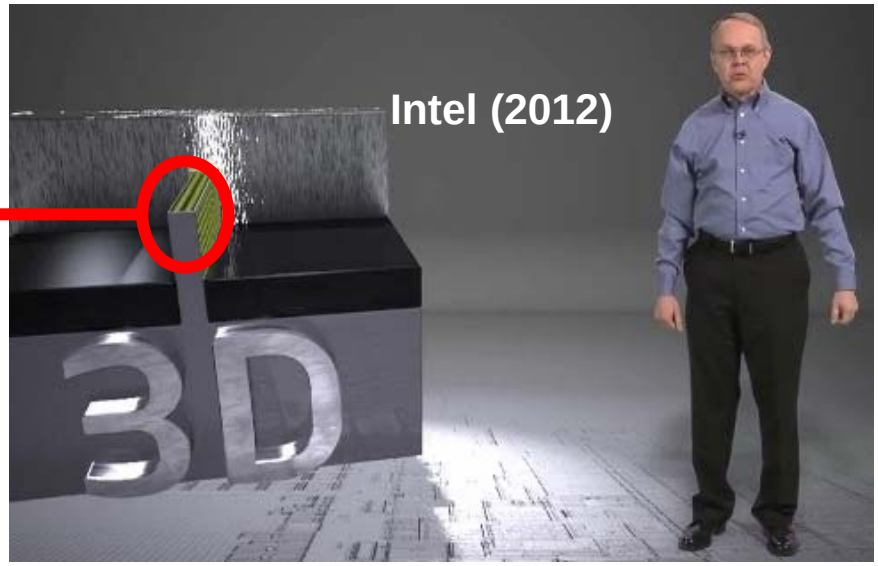
$$k \cong \sum_{modes} \frac{1}{3} \int C v^2 \tau_{bulk} \, dE$$

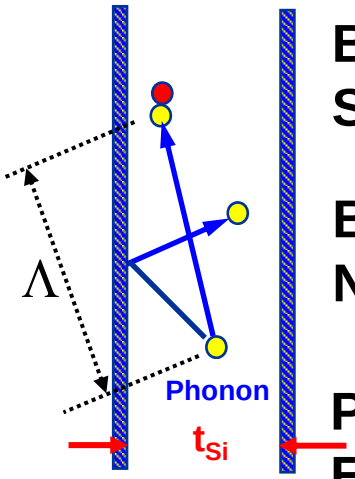
$$\tau_{film} = \tau_{bulk} F\left(d/\Lambda, \eta/\lambda \right)$$

Asheghi, Goodson, et al., *Applied Physics Letters* 71 (1997)
Asheghi, Goodson, et al., *J. Heat Transfer* 120 (1998)
Liu and Asheghi, *J. Heat Transfer* 120 (2006)

Electrons & Phonons in FinFETS







Boundary Scattering

Branch Nonequilibrium

Phonon Emission

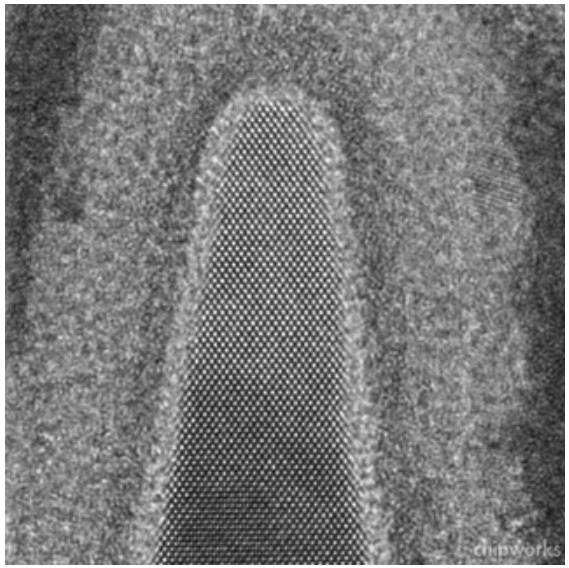
Proceedings of the IEEE

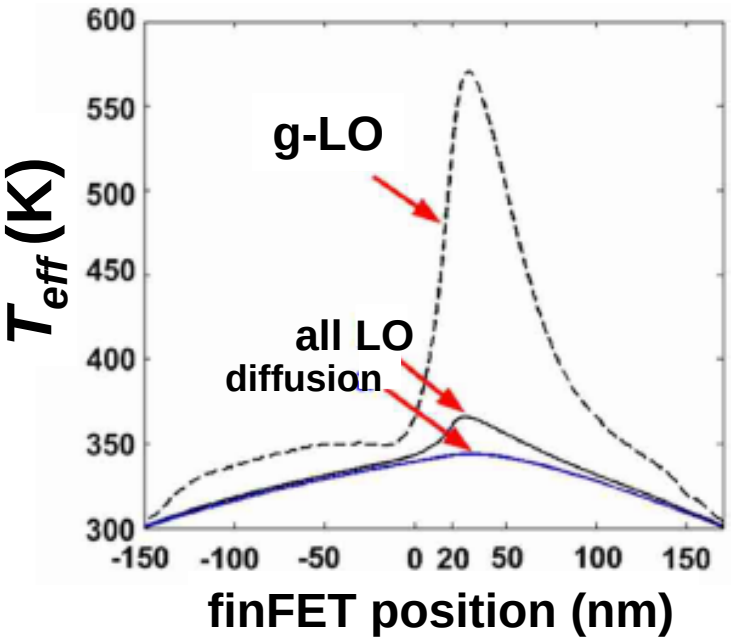
Heat Generation and Transport in Nanometer-Scale Transistors

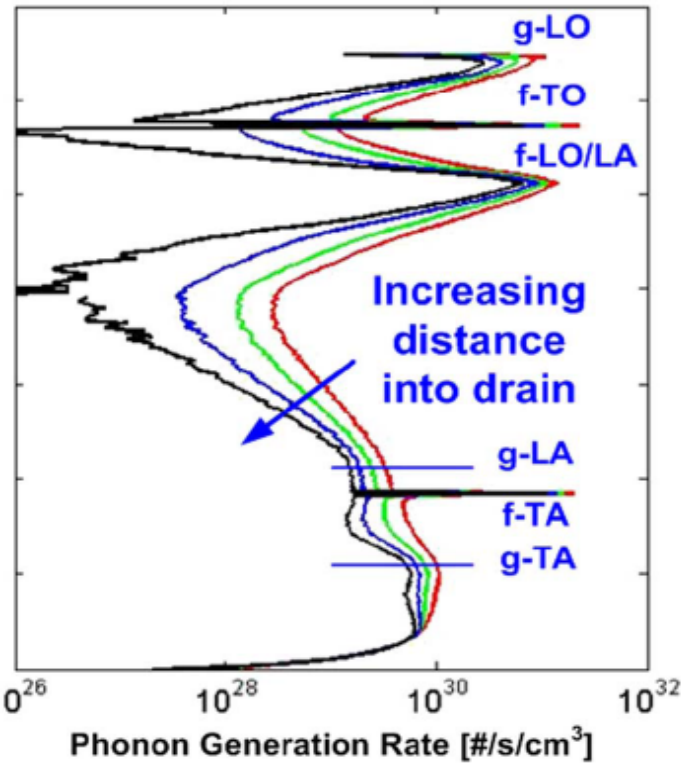
By Eric Pop, Sanjiv Sinha, and Kenneth E. Goodson

Vol. 94 (2006)

Electrons & Phonons in FinFETS





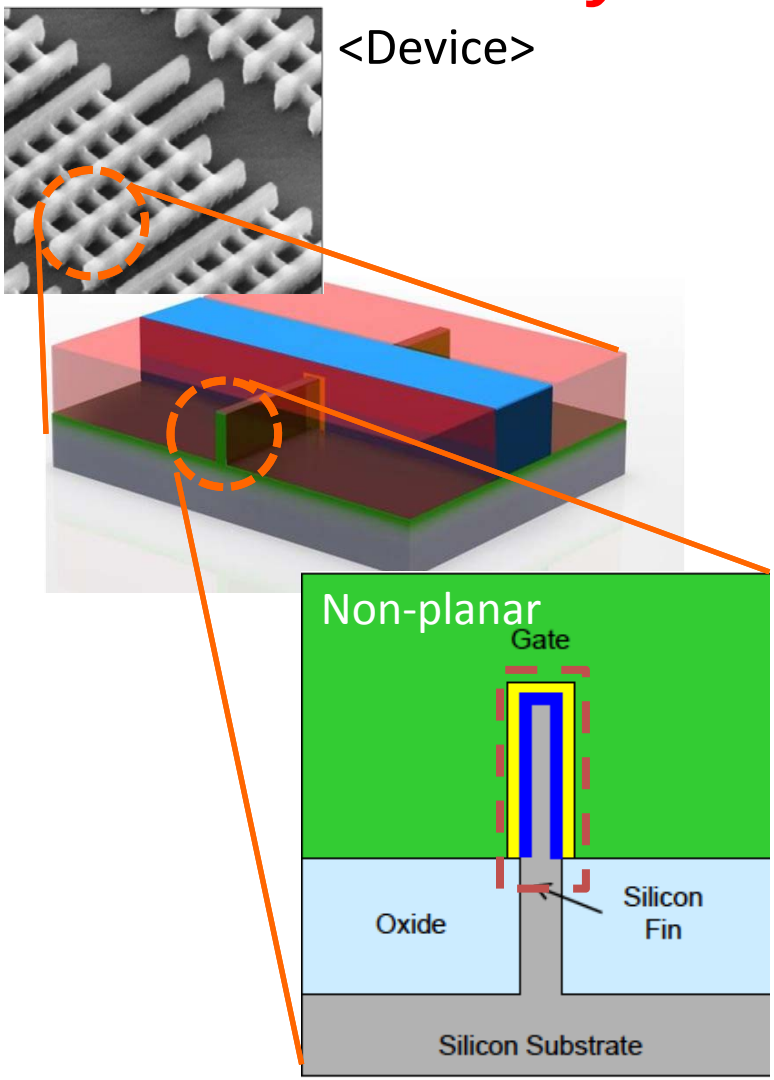


Coupled Electron Monte Carlo & Phonon BTE in 20 nm finFET

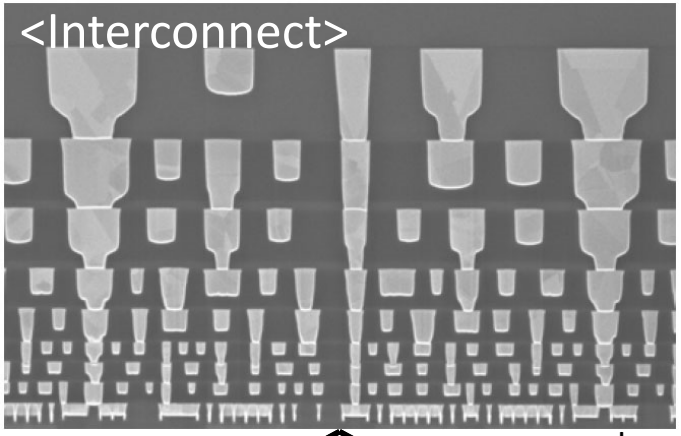
IEEE TRANS. ELECTRON DEVICES (55) 2008

Jeremy A. Rowlette and Kenneth E. Goodson

SRC Task 2308: Thermal Properties Beyond the 11nm Node



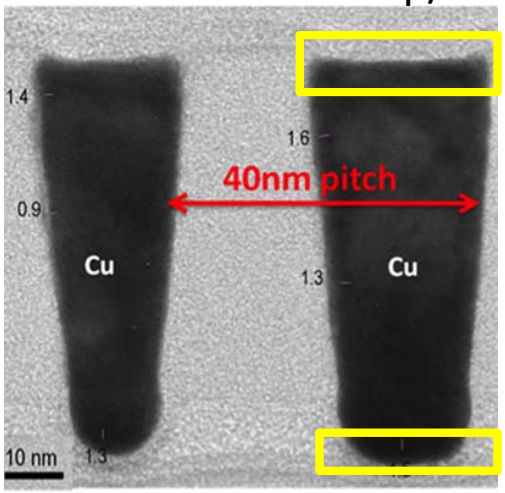
<http://www.intel.com>

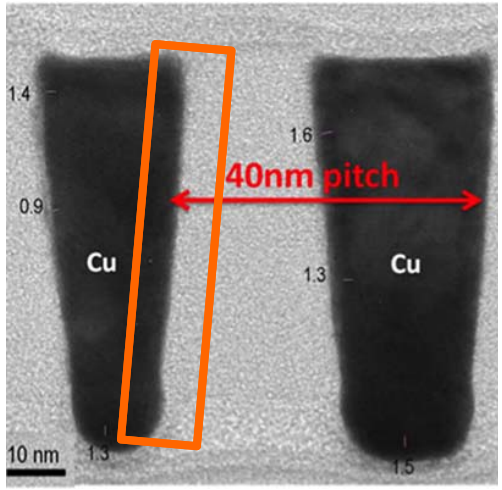


<www.realworldtech.com>

Top/Bottom

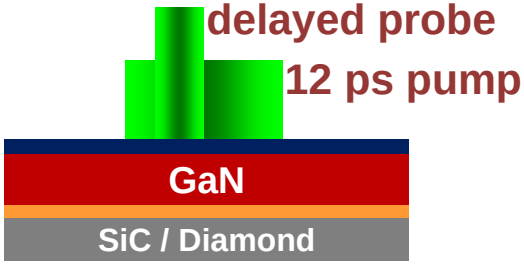
SideWall



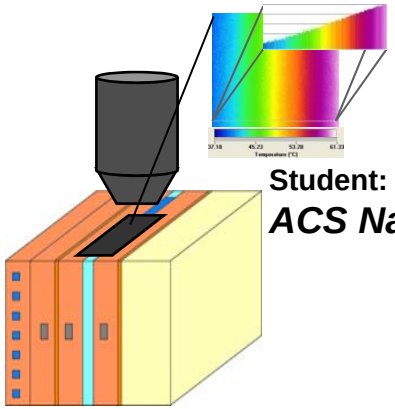


<http://www2.imec.be>

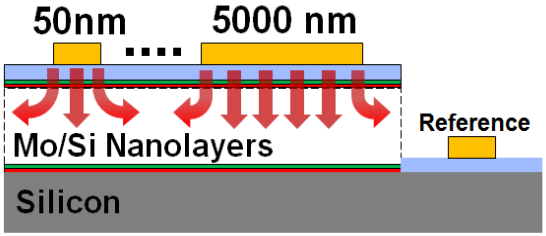
Nano Thermal Metrology



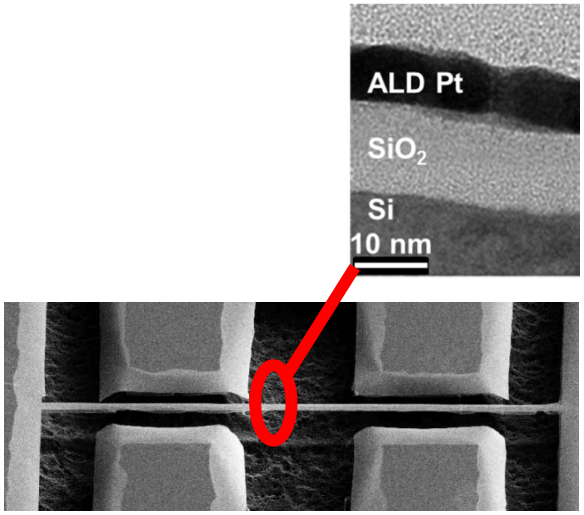
Students: Cho, Bozorg-Grayeli, Rowlette, Reifenberg
Physical Review B (2009)
Electron Device Letters (2010,2011,2012)



Student: Marconnet, Barako
ACS Nano (2011)



Students: Li, Lee, Kodama
Nano Letters (2012a)



Students: Yoneoka, Li, Kodama
Nano Letters (2012b)

Rig Complexity

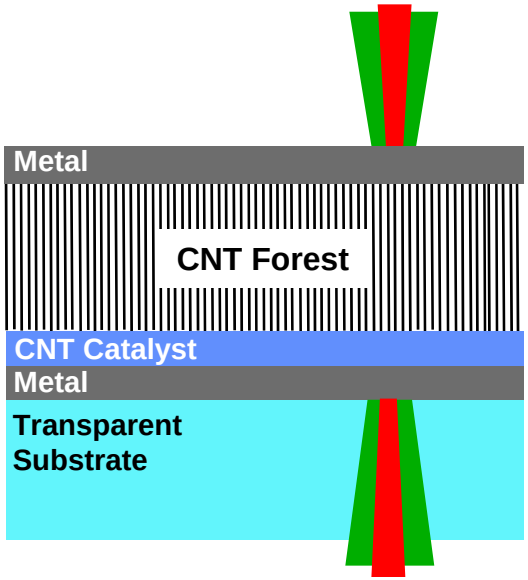
Sample Complexity

Thermal Pump-Probe Sample Design

Nanotube Films

Students: Panzer, Gao, Marconnet

Rev. Modern Physics (2013)
ACS Nano (2011)
Nanoletters (2010)

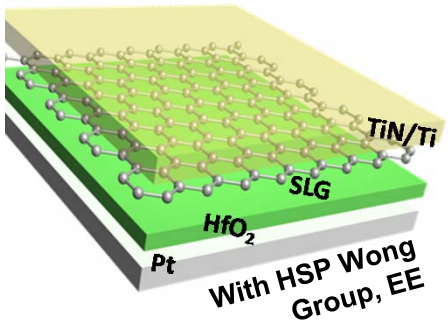


Electron-Phonon Interfaces

Students: Lee,Chen, Jeyasingh, Bozorg-Grayeli, Li, Reifenberg

Electron Device Letters (2008, 2010, 2011)

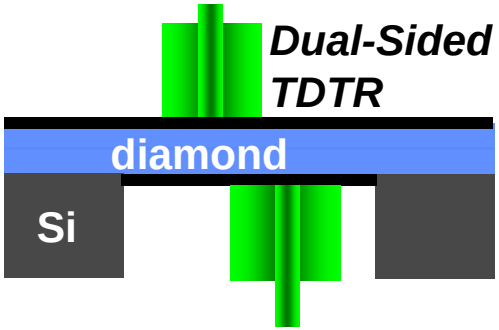
Proc. IEEE (2010)



Diamond Films

Students: Bozorg-Grayeli, Sood, Cho

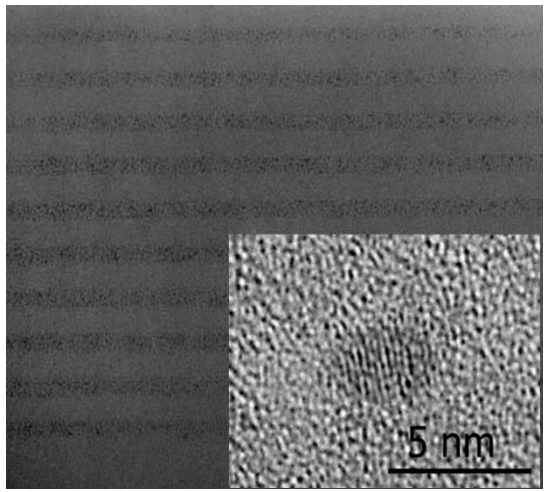
Applied Physics Letters (2013)
J. Applied Physics (1996)



NanoPhotonic Crystals

Students: Rowlette, Kekatpure, Marconnet

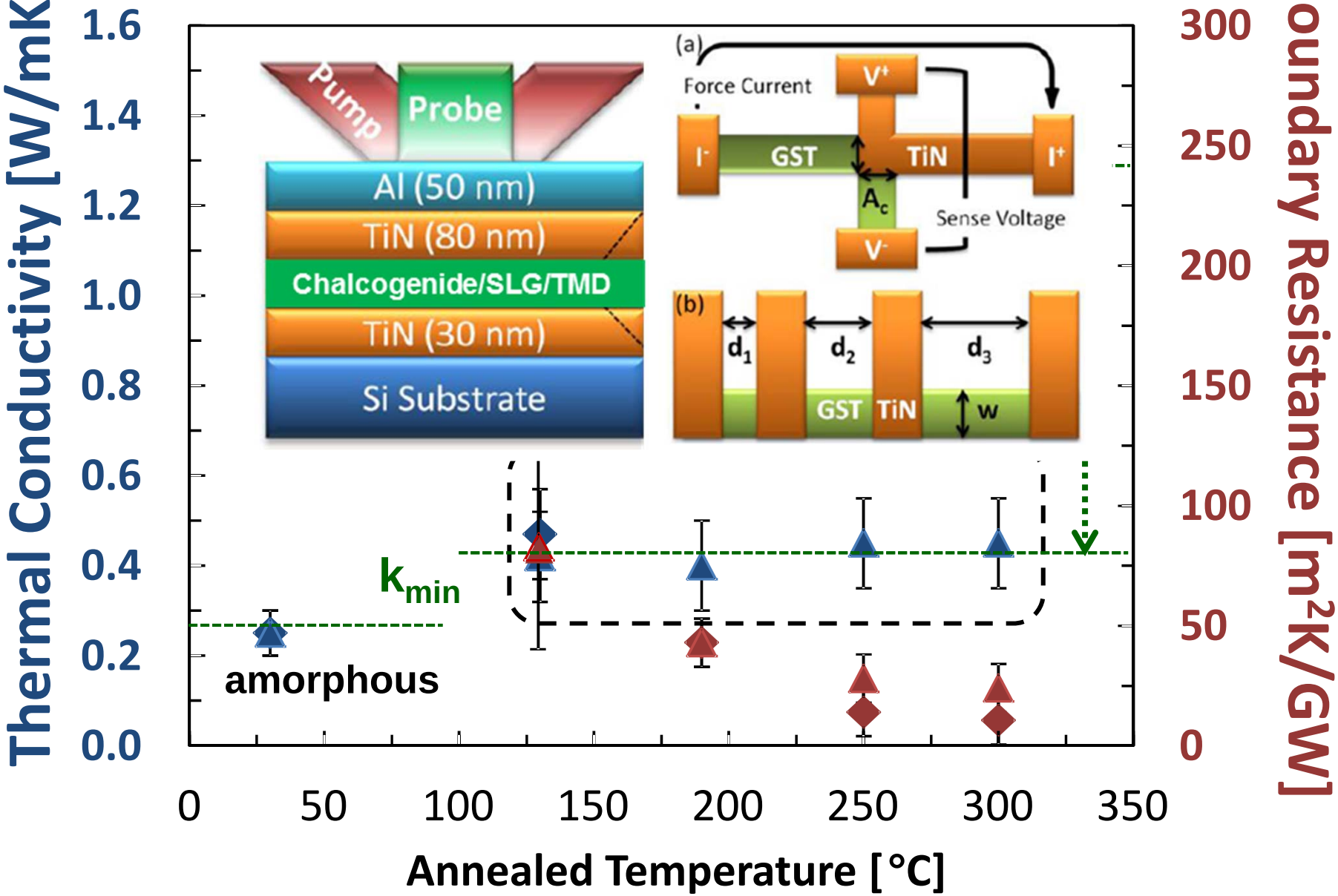
Physical Review B (2009)



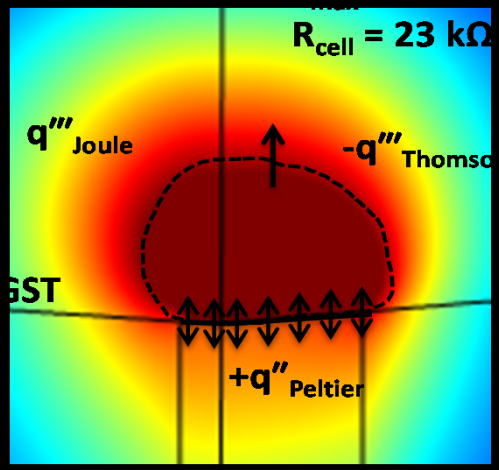
With Brongersma Group, MSE

Electrons & Phonons in GeSbTe

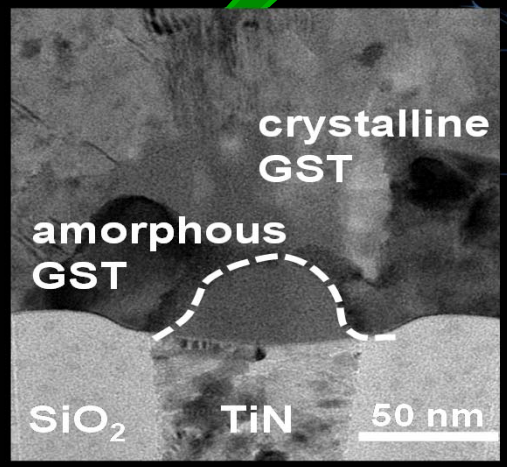
Lee, Wong, Goodson, et al., *Applied Physics Letters* 2013



Electrons, Phonons, and Neurons: Conversion with Chalcogenides

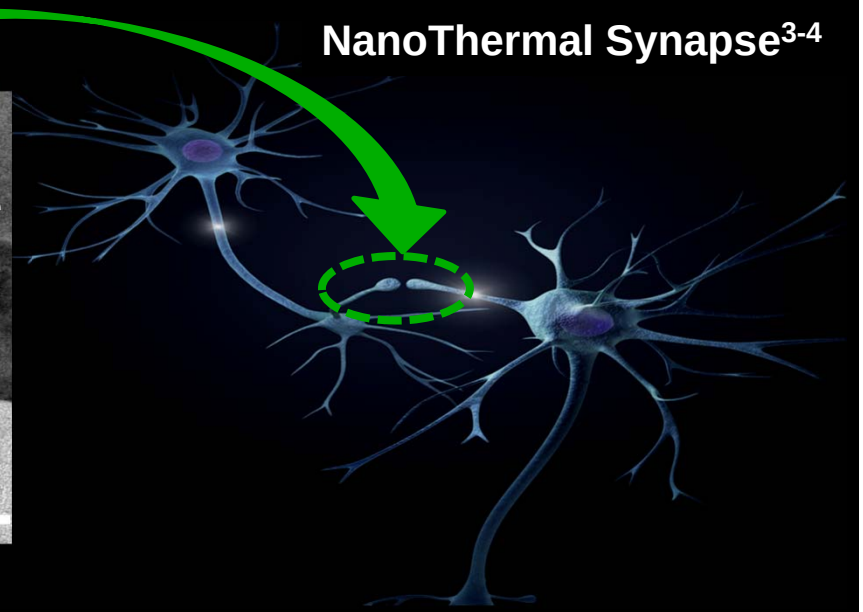


Thermoelectric conversion in a phase change cell[1,2,5]



Phase distributions in a phase change memory cell[2,3]

NanoThermal Synapse[3-4]

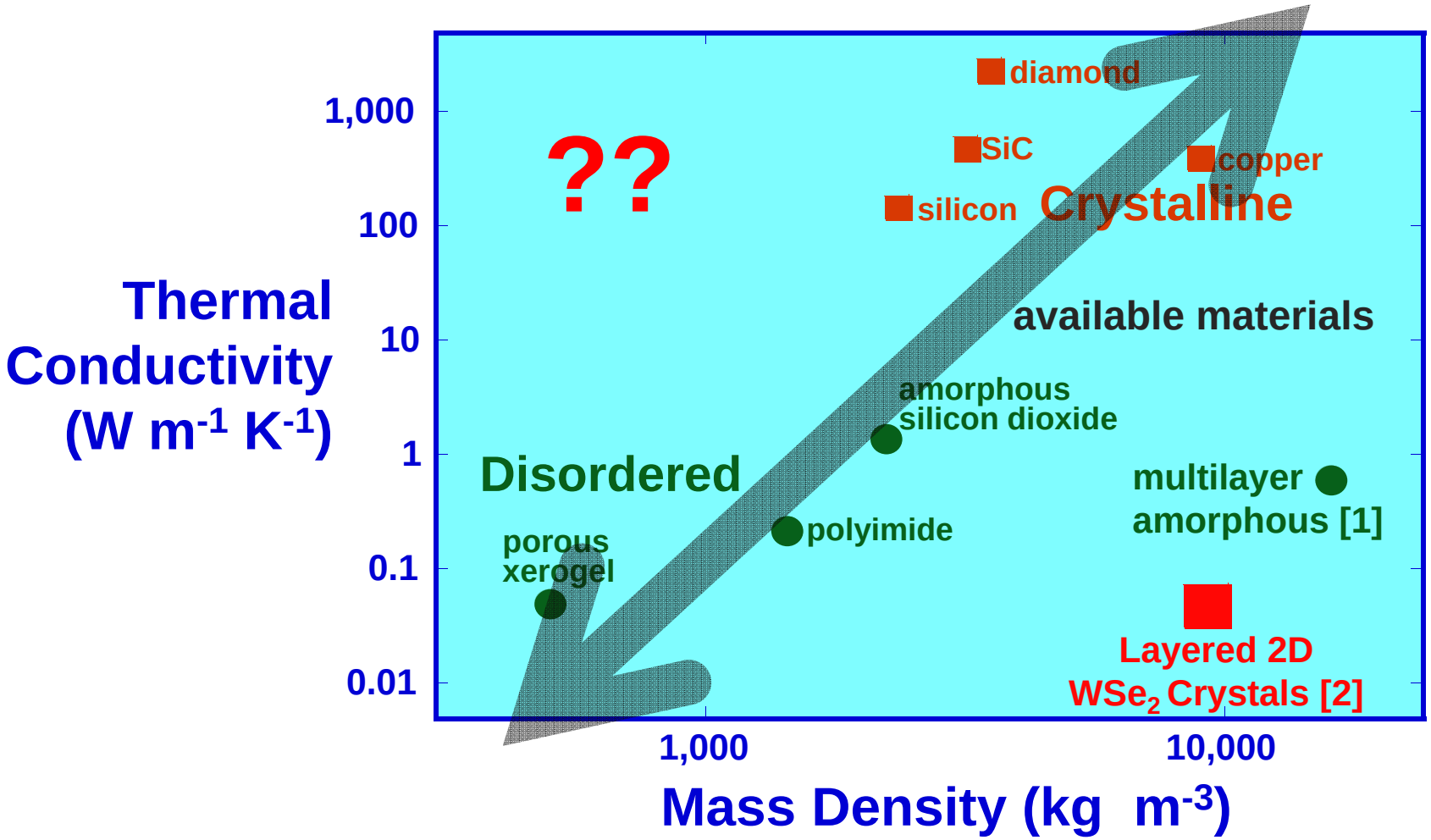


Philip Wong, Stanford EE

[1]Lee, Asheghi, Goodson *NANOTECHNOLOGY* (2012)
[2]Li, Wong, Goodson, et al., *TRANS. ELECTRON DEVICES* (2012)
[3]Kuzum, Jeyasingh, Wong, et al. *NANO LETTERS* (2012)
[4]Kuzum, Jeyasingh, Wong, et al. *TRANS. ELECTRON DEVICES* (2012)
[5]Wong, Asheghi, Goodson, et al. *PROCEEDINGS OF THE IEEE* (2010)
[6]Acharya et al., *MECHANICAL ENGINEERING* (2013)

Extreme Property Combinations

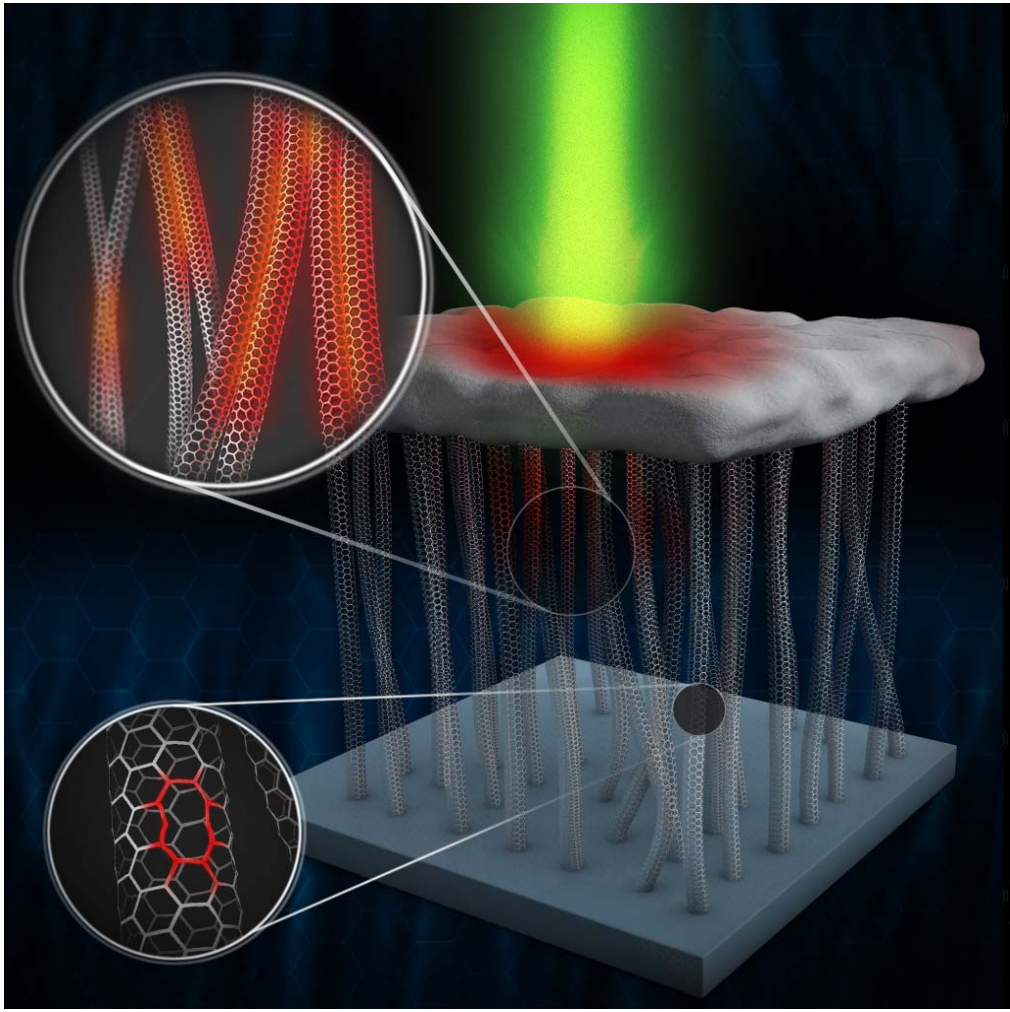
Goodson, *Science* 315 (2007)



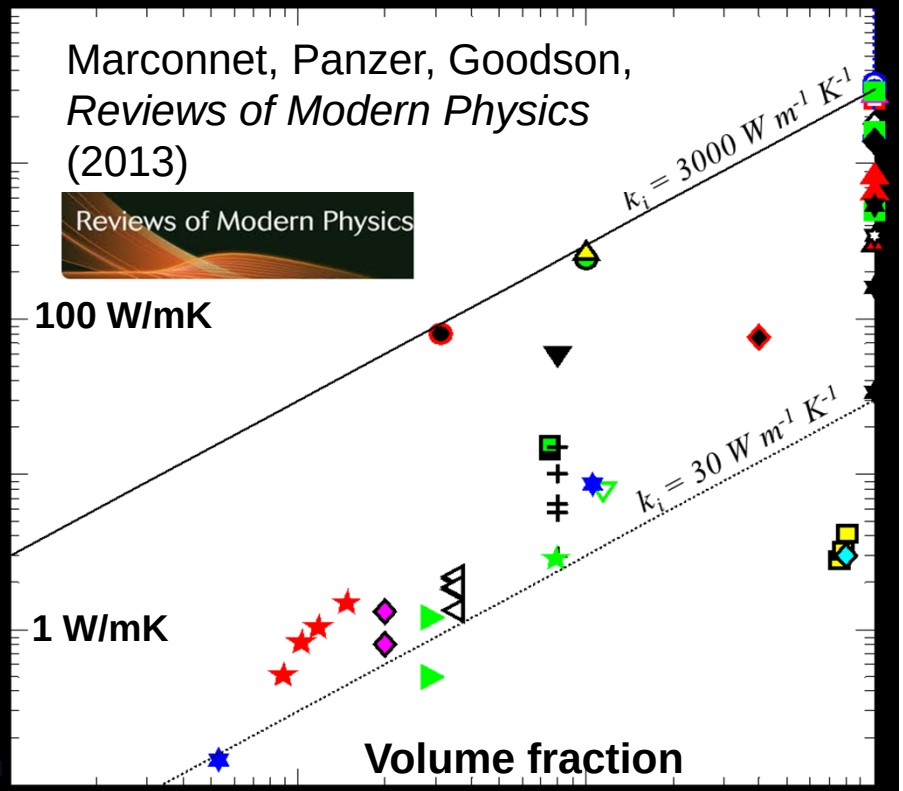
1. Costescu et al., *Science* 303 (2004)
2. Chiritescu et al., *Science* 315 (2007)

Thermal Properties of Aligned Carbon Nanotube Films

Amy Marconnet

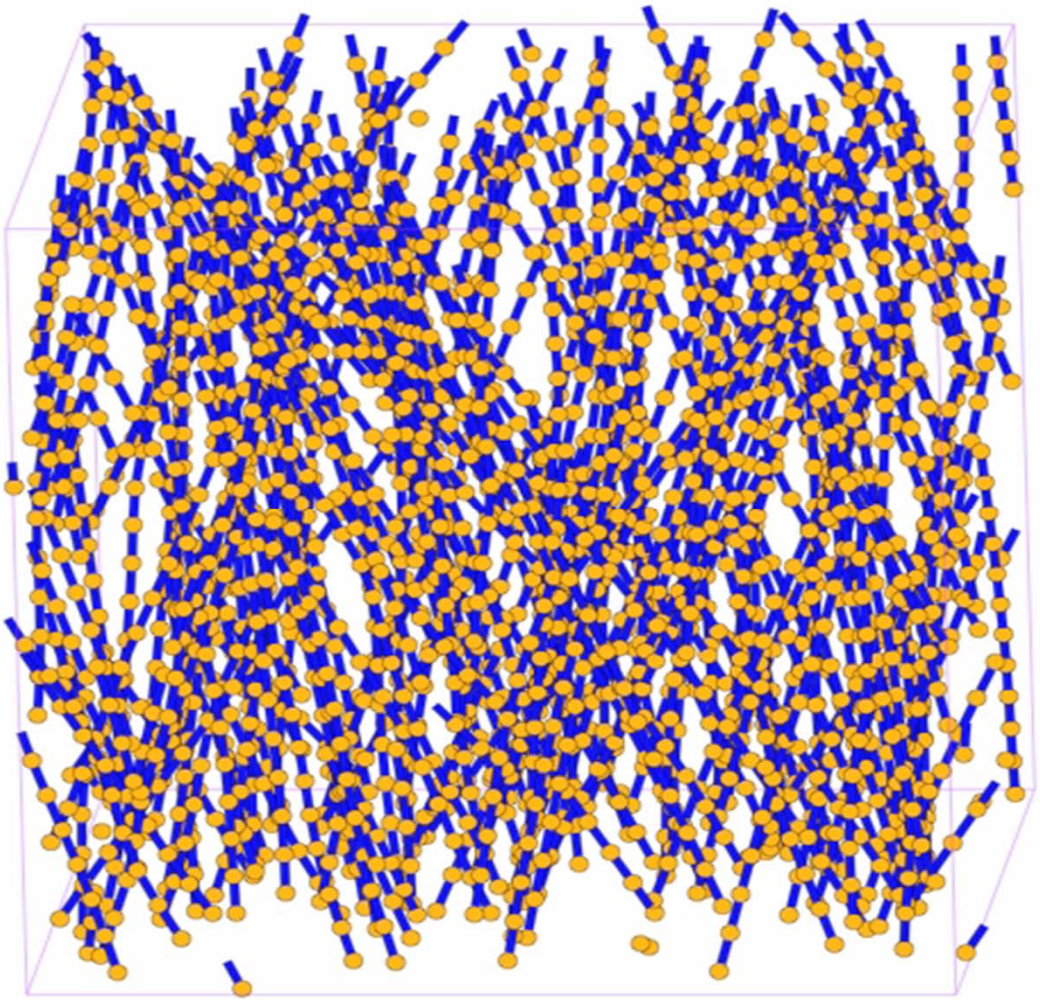


Thermal Conductivity

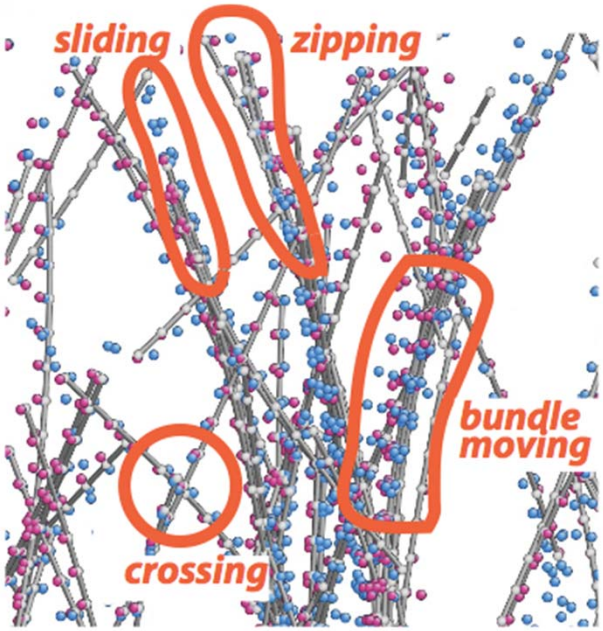


In Search of "Radically New Property Combinations"

Goodson, *Science* 315 (2007)

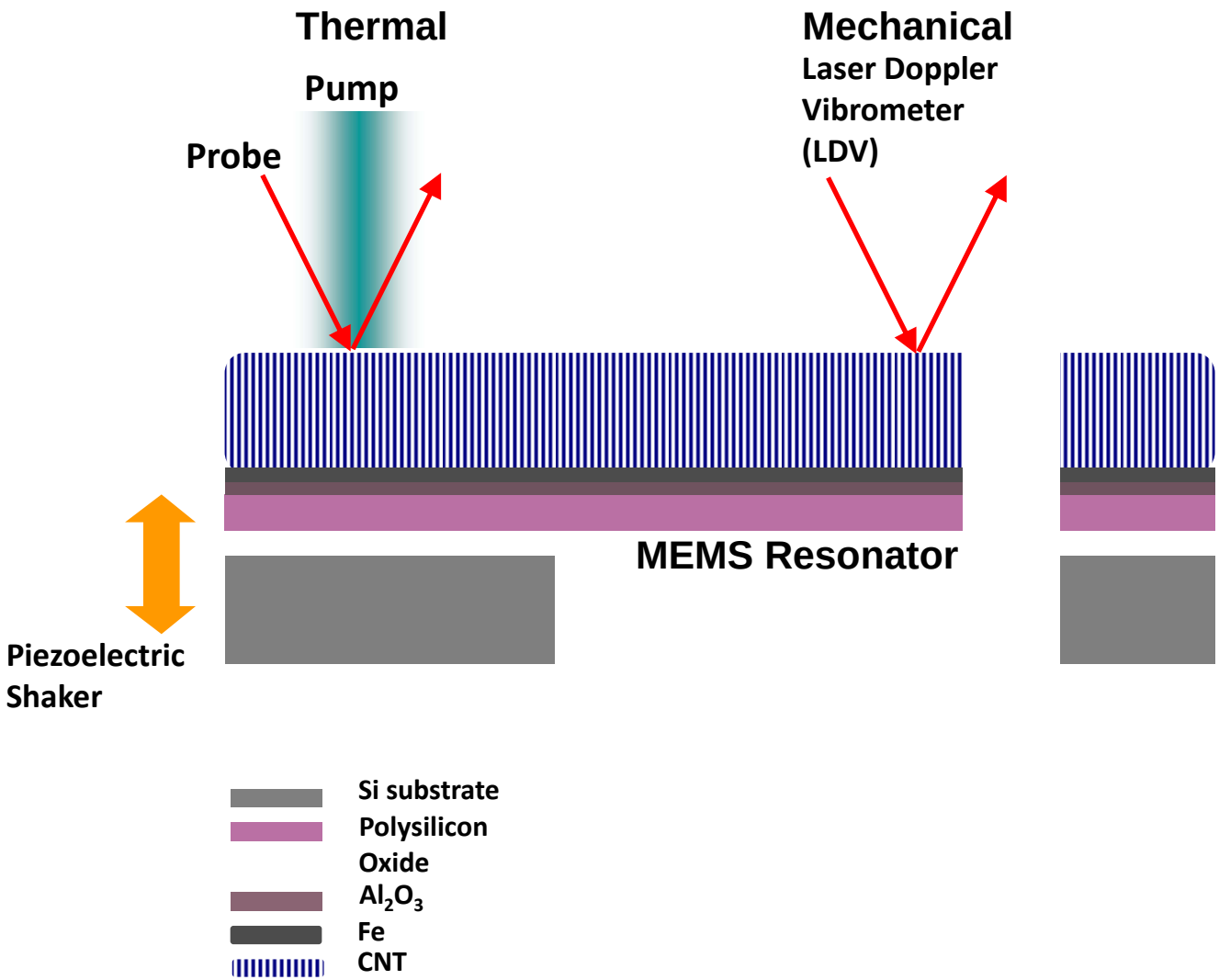


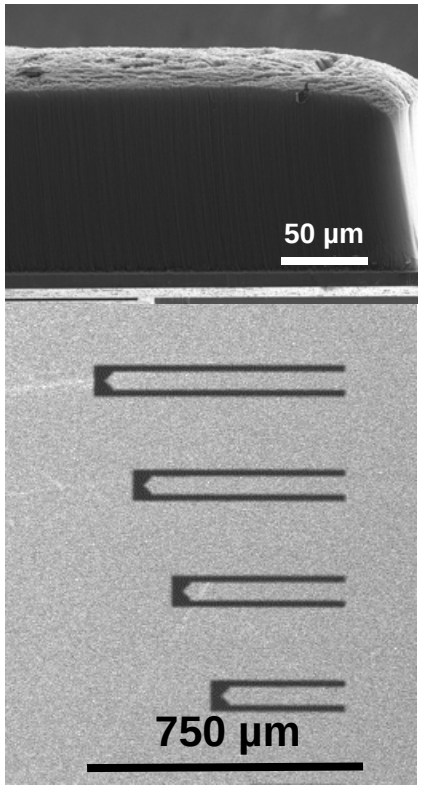
Molecular Simulation,
with Prof. Wei Cai,
Student: Yoonjin Won,
Stanford ME



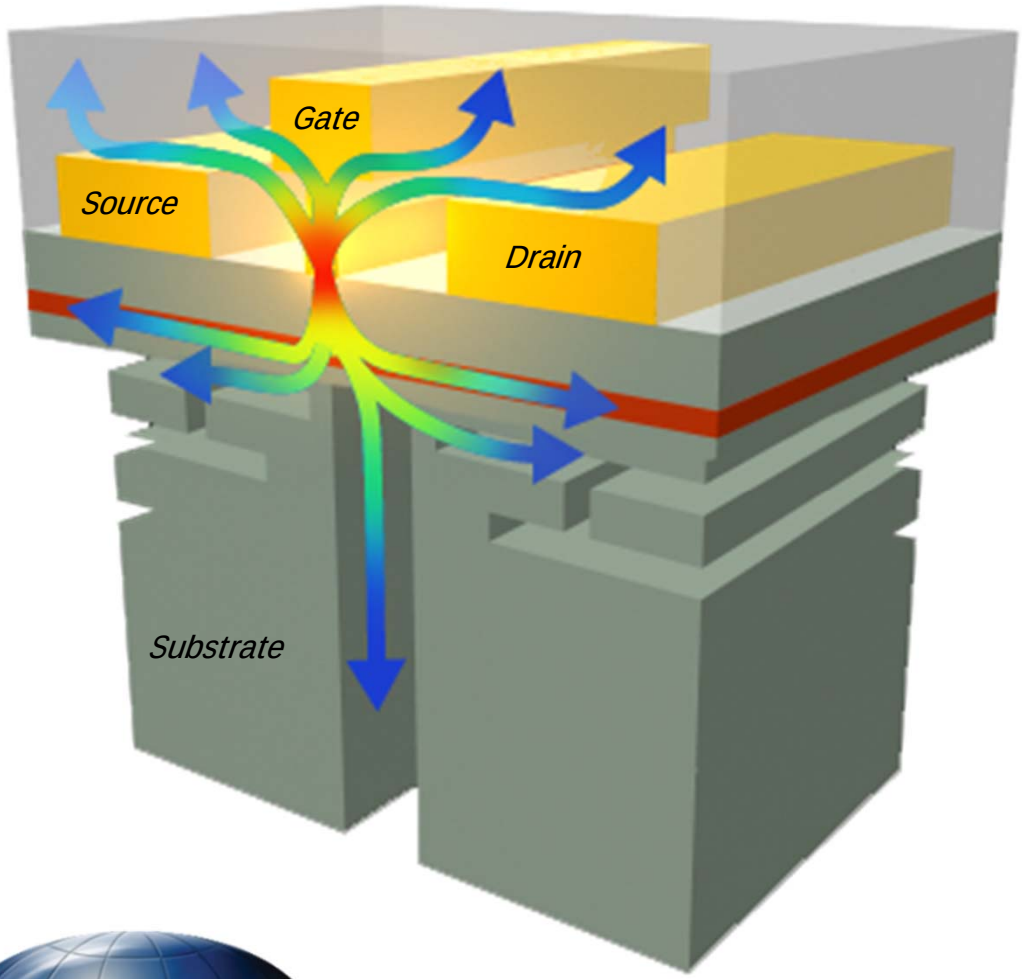
Mechanical & Thermal Properties of Aligned CNT Films

Students: Yoonjin Won, Yuan Gao, Matt Panzer, Amy Marconnet,
***PIs: Profs. Kenny & Goodson, Carbon* (2012)**





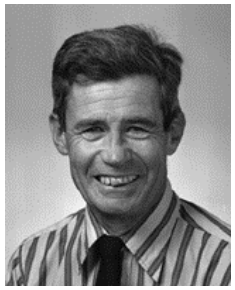
Towards 30kW/cm^2 for GaN HEMT Radar



What are the extreme limits of thermal management?

Special Thanks to Avi Bar-Cohen and Joe Maurer, DARPA MTO

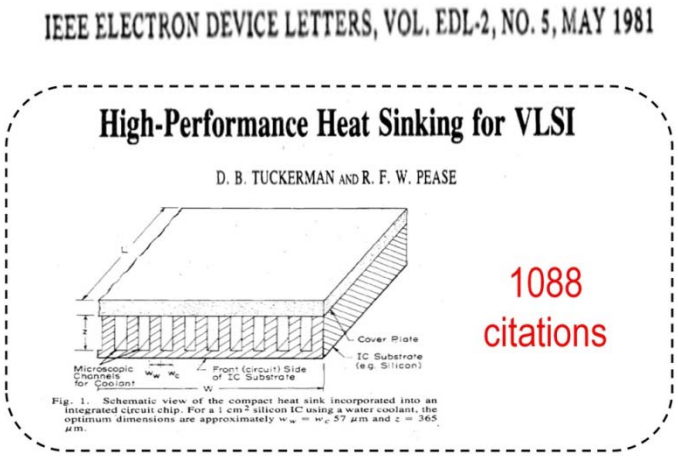
Stanford Compact Heat Exchanger History



Fabian Pease

Bill Kays

David Tuckerman



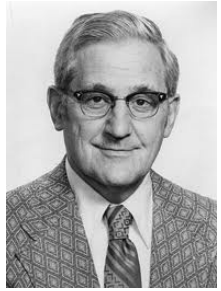
IEEE ELECTRON DEVICE LETTERS, VOL. EDL-2, NO. 5, MAY 1981

High-Performance Heat Sinking for VLSI

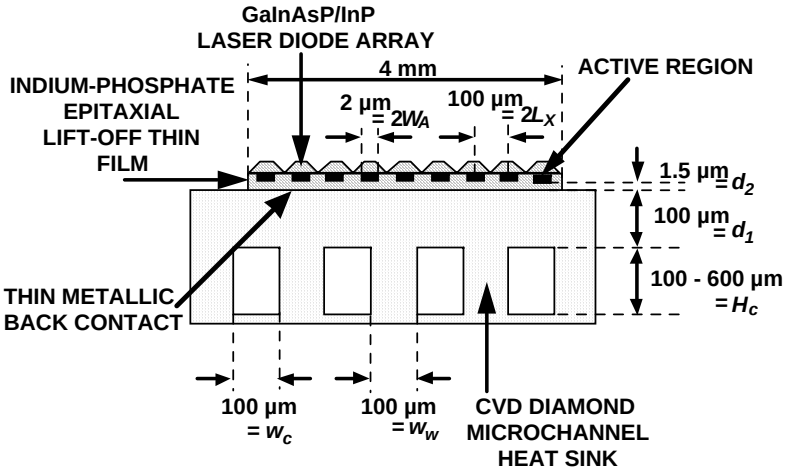
D. B. TUCKERMAN AND R. F. W. PEASE

Fig. 1. Schematic view of the compact heat sink incorporated into an integrated circuit chip. For a 1 cm² silicon IC using a water coolant, the optimum dimensions are approximately $w_w = w_c$ 57 μm and z = 365 μm.

1088 citations



Lou London

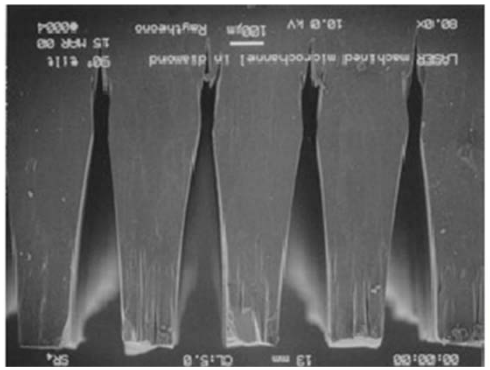


Goodson, Kurabayashi, and Pease,
***Trans. Components Packaging, Manufacturing Technology* B20 (1997)**

DARPA Convection Limits (ICECool 1 + 2)

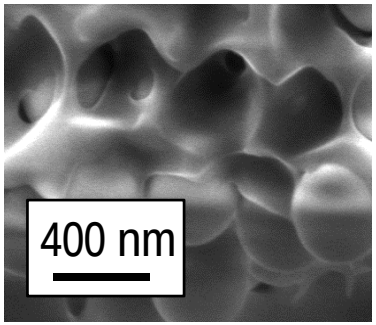
Nanostructured Heat Sinks

Spreading by Etched Diamond Channels

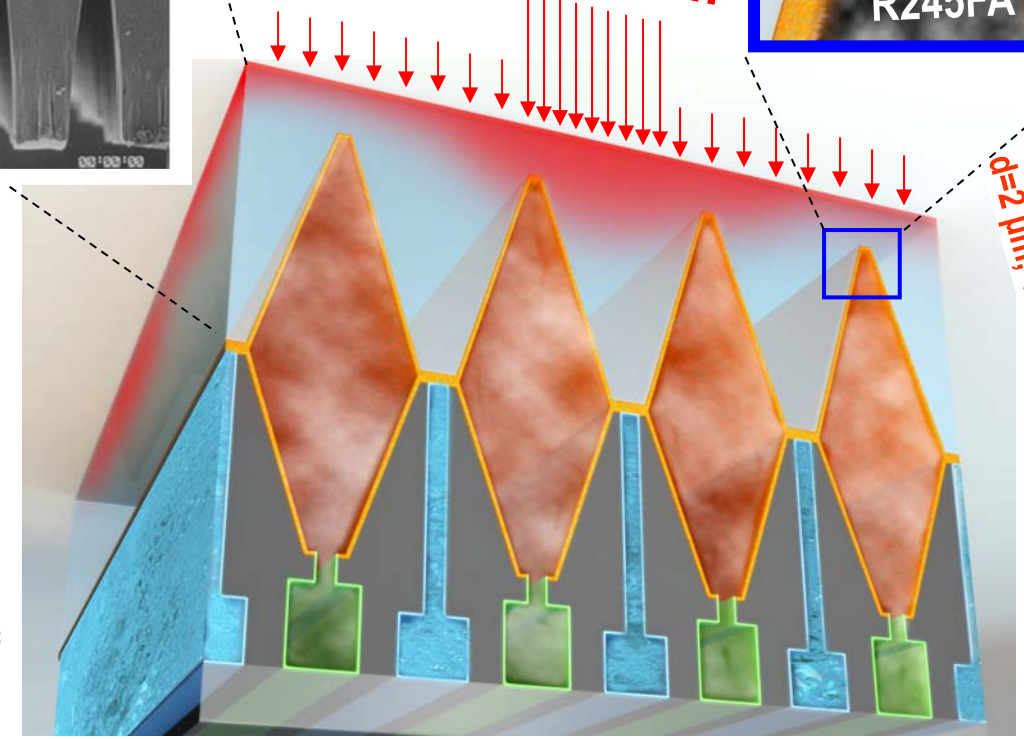


100µm

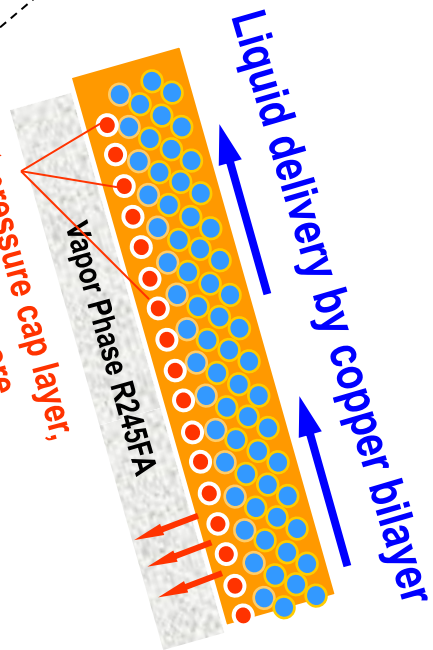
Phase Separation by Nanostructured Capping Film



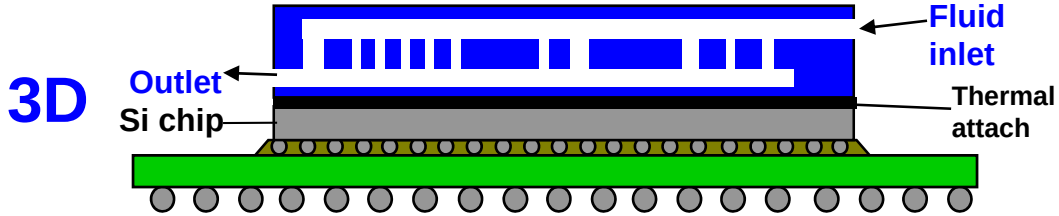
50 kW/cm²



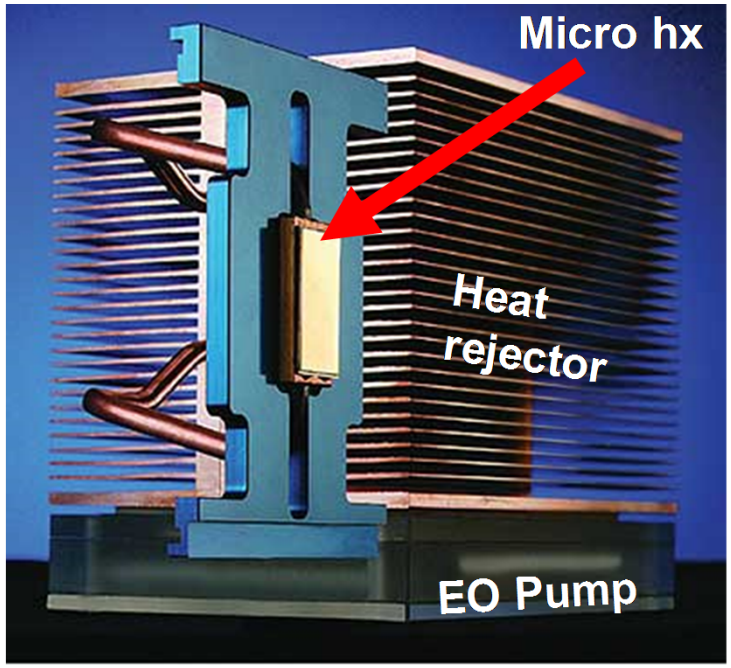
3D Routing of Liquid and Vapor



Trajectory of a Startup (Cooligy)



Liquid Cooling Challenge



Zhou et al., Proc. SEMITHERM 2004, Proc. ITHERM 2004

Research Background

DARPA funding
Intel
AMD
Apple

MicroCoolers for Computers

Cooligy Startup (VC funding)

Apple G5 Production run
100K+ Units

Acquisition By Emerson

~600W total

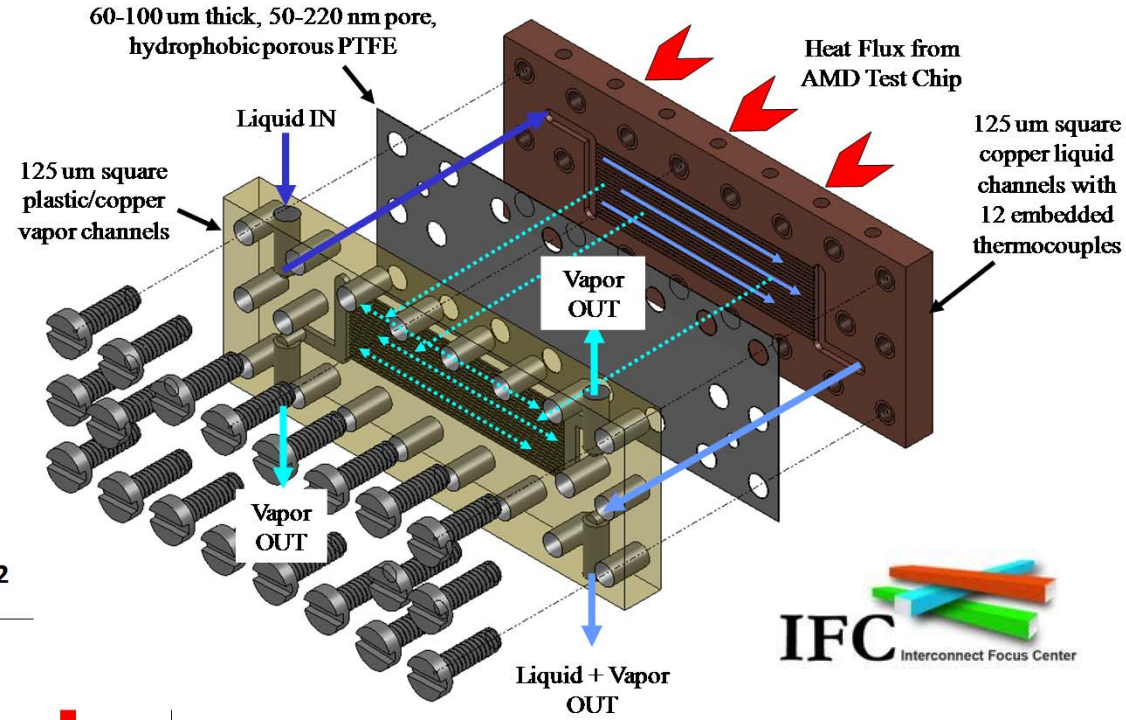
~ 1kW/cm^2

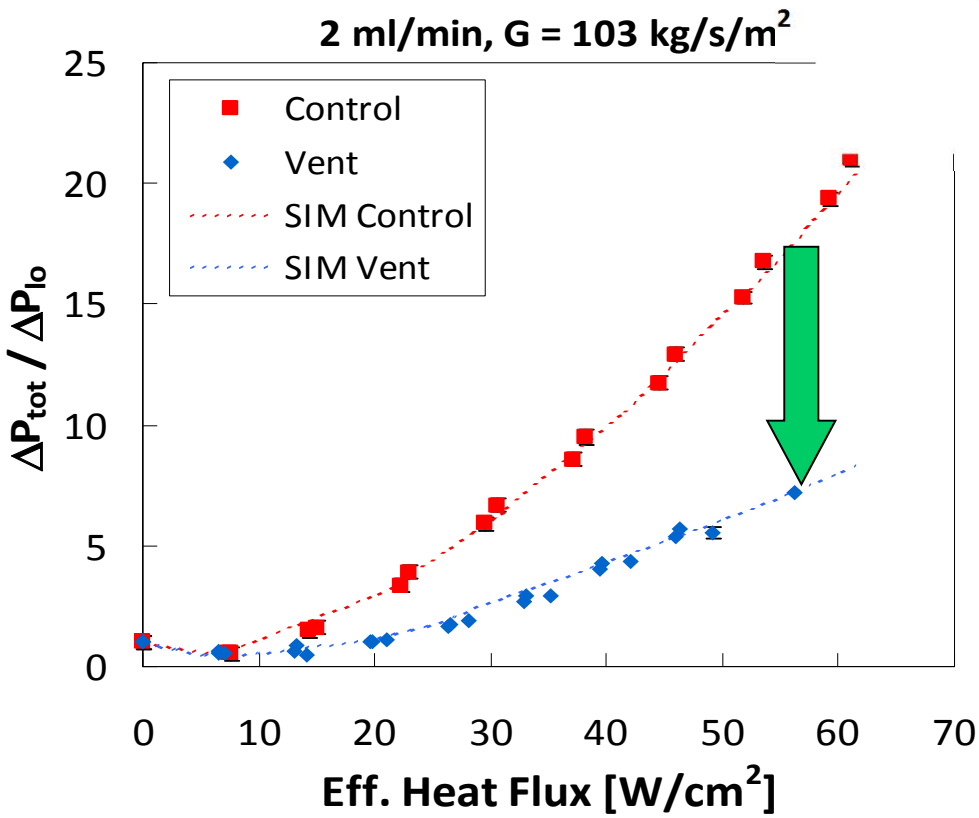
2000 2002 2004 2006 2008

Vapor Escape Microfluidic HX Prototype

International Journal of Heat and Mass Transfer (2011)

International Journal of Multiphase Flow (2011)



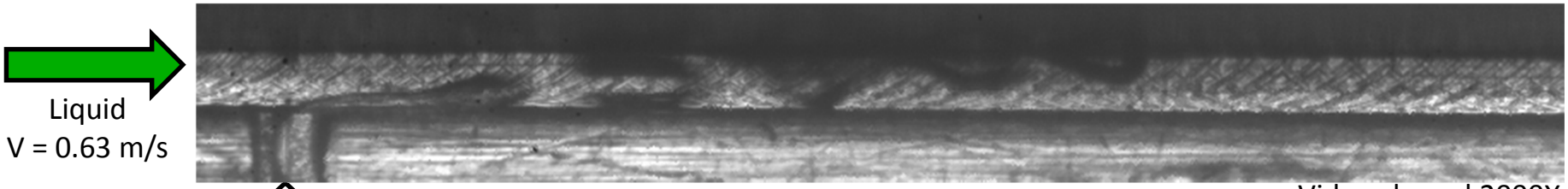


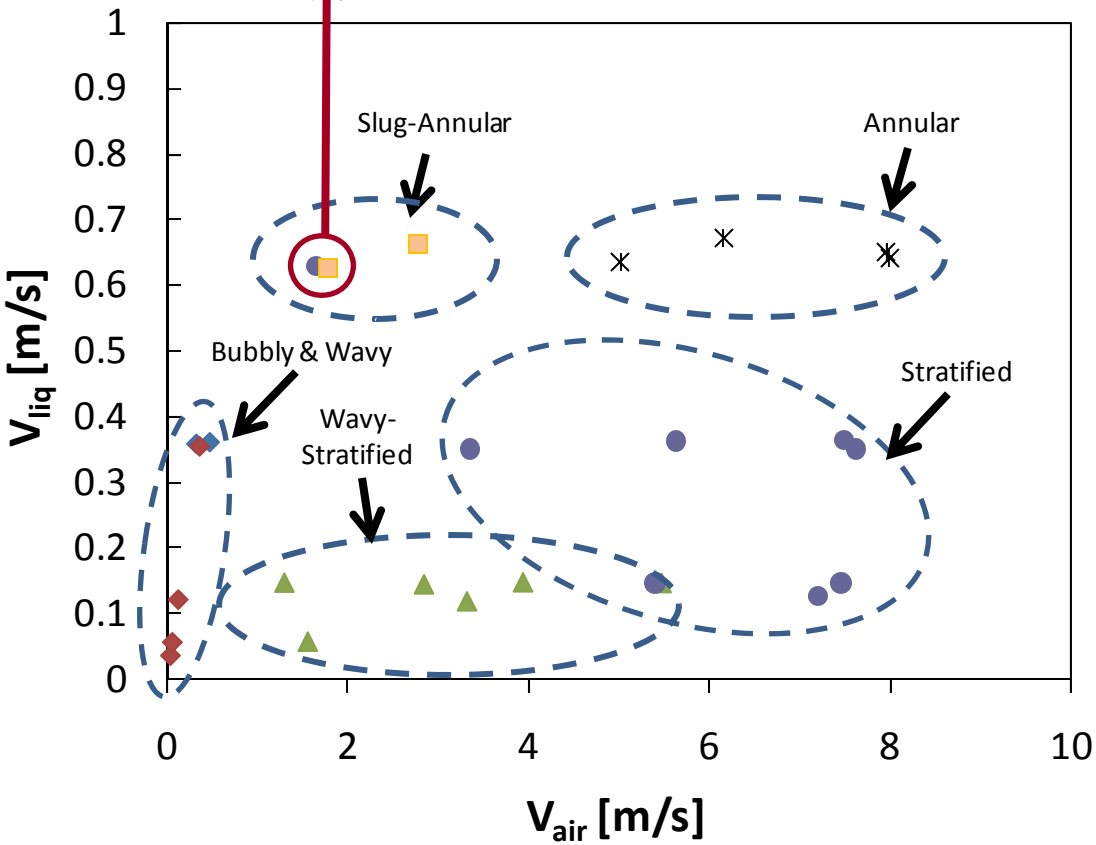
- **Vapor-transmitting membrane reduces pressure drop and instabilities along two-phase micro HX.**
- **Latest data show 60% pressure drop and nearly 50% drop in excess temperature over inlet saturation.**

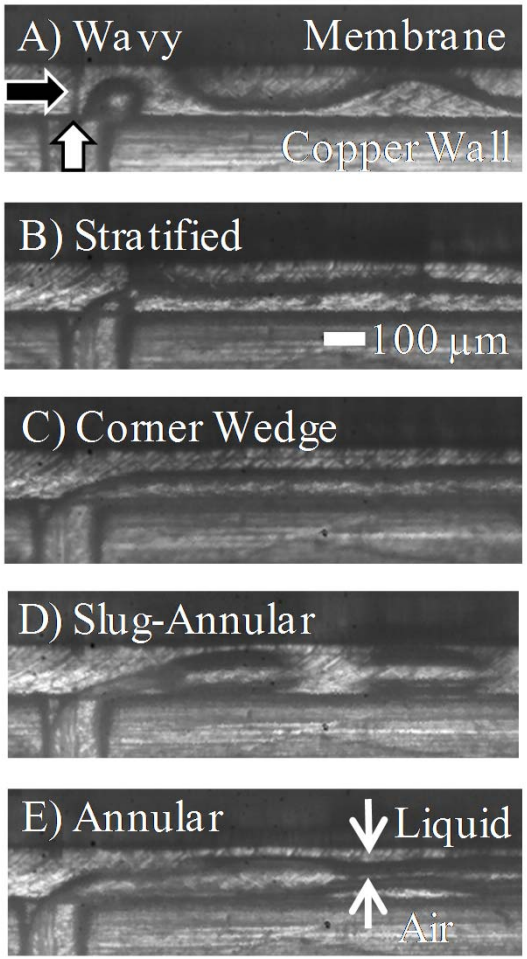
Students: Milnes David, Roger Flynn, Julie Steinbrenner, Chen Fang, Joe Miler

Vapor Escape I (2001-2010): Challenges

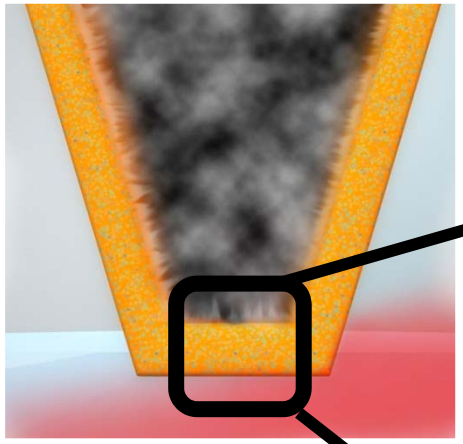
David, Miler, Steinbrenner, Goodson, et al., "Hydraulic and Thermal Characteristics of a Vapor Venting Two-phase Microchannel Heat Exchanger," *International Journal of Heat and Mass Transfer* (2011)

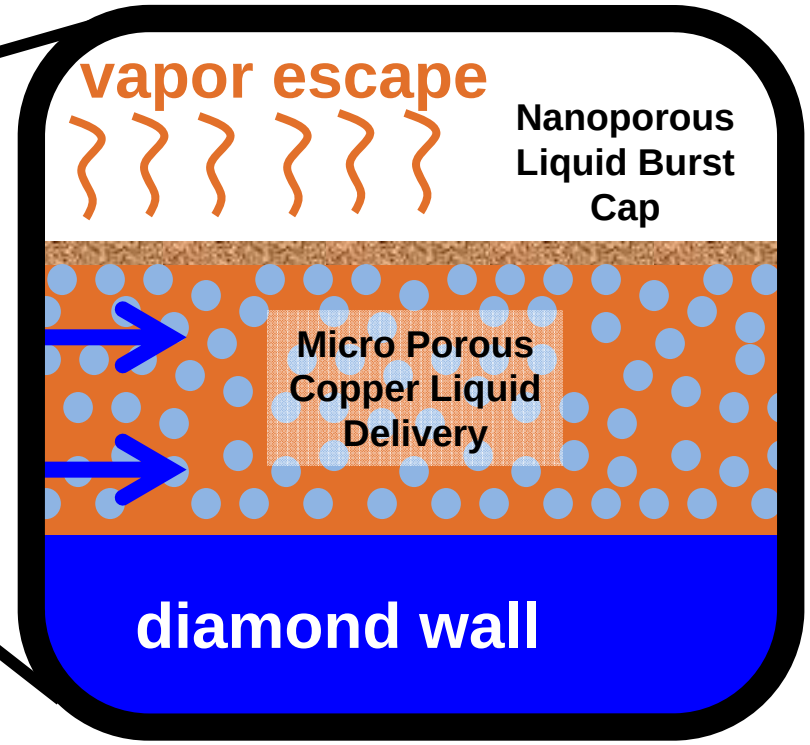


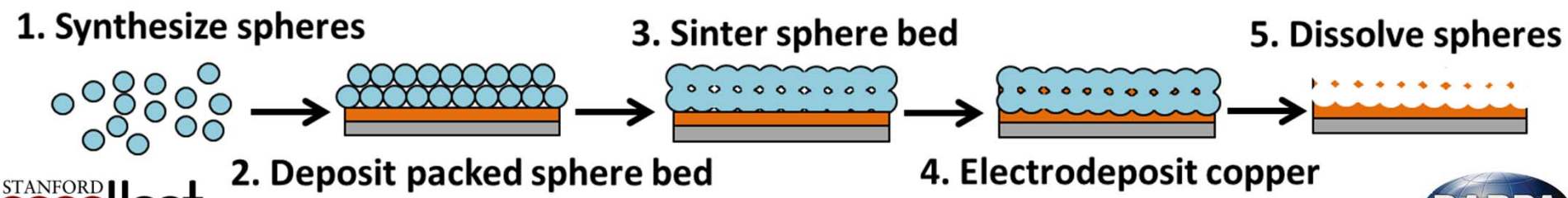




Vapor Escape II 2012 – Strict, Nanostructured Phase Separation







STANFORD nanoHeat

DARPA

Outreach to K-12 and Undergraduates

STANFORD nanoHeat

Undergraduates:

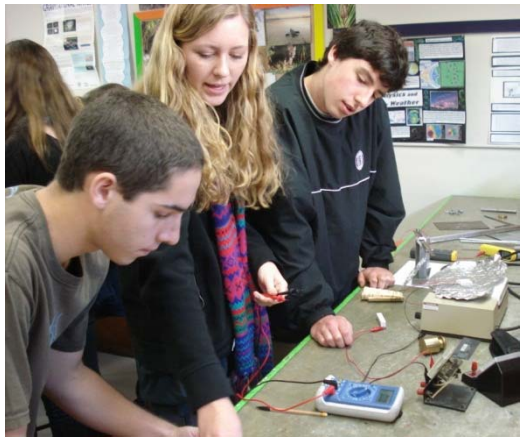
Jena Barnes
Materials Science & Engineering '13
Synthesis and Characterization of ZnO Nanowire Films

- Presented at national materials science conference
- Accepted fellowship to pursue PhD in materials science at Duke University

Maneeshika Madduri
Electrical Engineering '13
Thermal Characterization of ZnO Nanowire Films

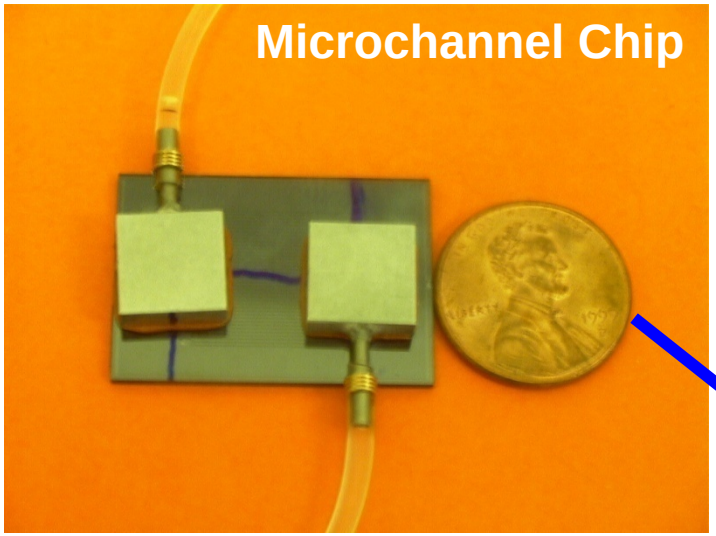
- Accepted into Sandia National Laboratory Master's Fellowship Program

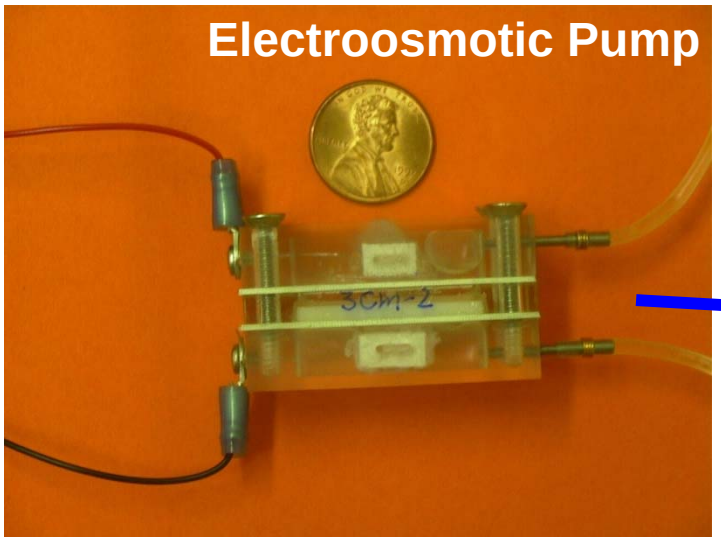
K-12 students & teachers:

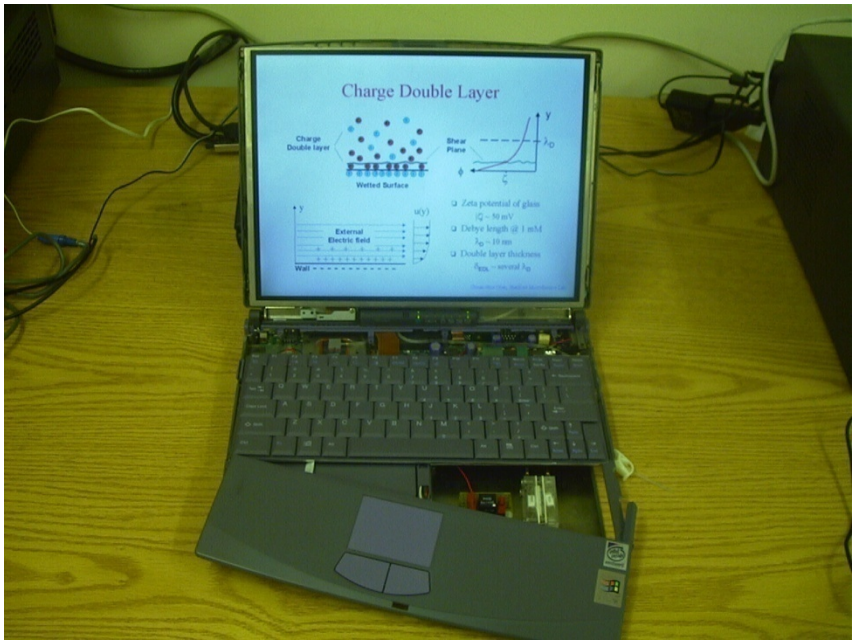


Partnering with public highschool to provide materials and mentors for design lab.

Last-Minute VC Demo, 2001





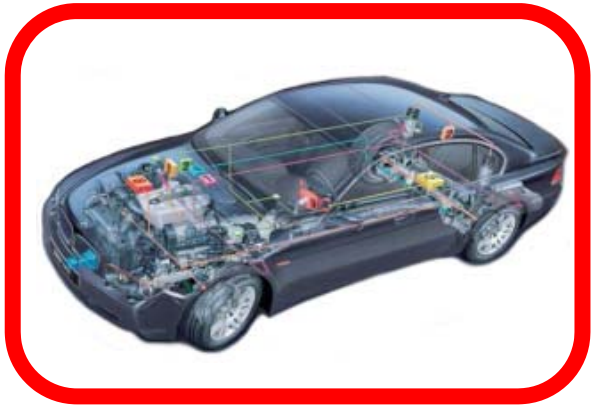


Shulin Zeng with help from Evelyn Wang, Linan Jiang, and Abdullahel Bari (Stanford)

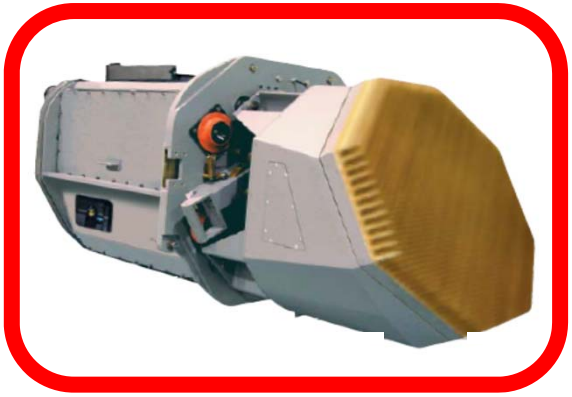
Heat & Energy Challenges

information

appliances



transportation



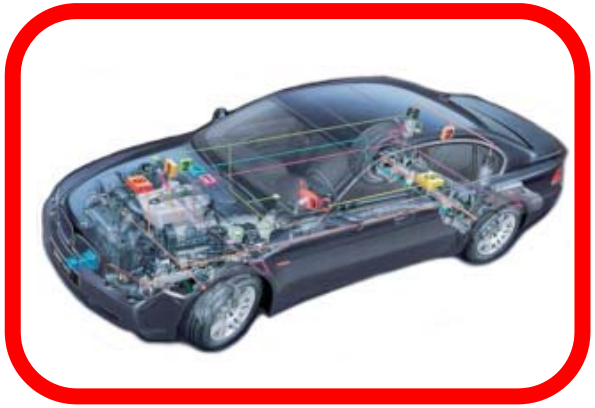
defense

STANFORD nanoHeat

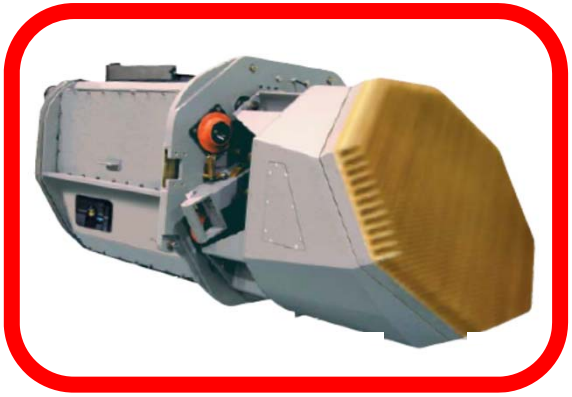
Heat & Energy Challenges

information

appliances



transportation



defense

STANFORD nanoHeat

STANFORD nanoHeat

Current Group

Ken Goodson

Woosung Park
Michael Barako
Shilpi Roy (EE)
Joe Katz (EE)
Jungwan Cho
Jena Barnes

Elah Bozorg-Grayeli
Tom Dessault
Sri Lingamneni
Aditya Sood (MSE)
Marc Dunham
Maneeshika Madduri

Ken Lopez
Matt Hoffman
Dr. Saniya LeBlanc
Dr. Takashi Kodama
Dr. Yoonjin Won
Dr. Damena Agonafer
Consulting Prof. Mehdi Asheghi

Selected Alumni

Prof. Dan Fletcher	UC Berkeley	Dr. Jeremy Rowlette	Daylight Solns
Prof. Evelyn Wang	MIT	Dr. Patricia Gharagozloo	Sandia Labs
Prof. Katsuo Kurabayashi	U. Michigan	Dr. Per Sverdrup	Intel
Prof. Sungtaek Ju	UCLA	Dr. Chen Fang	Exxon-Mobile
Prof. Amy Marconnet	Purdue	Dr. Milnes David	IBM
Prof. Bill King	UIUC	Dr. Saniya Leblanc	Alphabet En.
Prof. Eric Pop	UIUC (Stanford)	Dr. Roger Flynn	Intel
Prof. Sanjiv Sinha	UIUC	Dr. Julie Steinbrenner	Xerox Parc
Prof. Xeujiao Hu	Wuhan Univ.	Dr. John Reifenberg	Alphabet En.
Prof. Carlos Hidrovo	UT Austin	Dr. David Fogg	Creare
Prof. Kaustav Banerjee	UCSB (EE)	Dr. Matthew Panzer	KLA-Tencor
Prof. Ankur Jain	UT Arlington	Dr. Yuan Gao	Oracle
Prof. Sarah Parikh	Foothill College	Dr. Joe Miler	ARPA-E