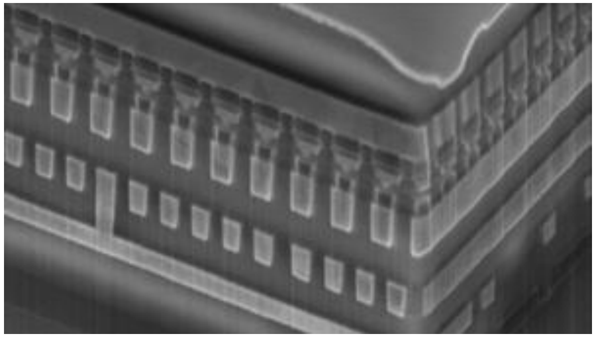
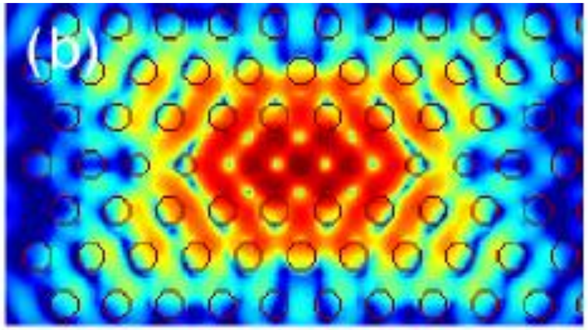
Nano Thermal Management for Electronics

MEPTEC 2012

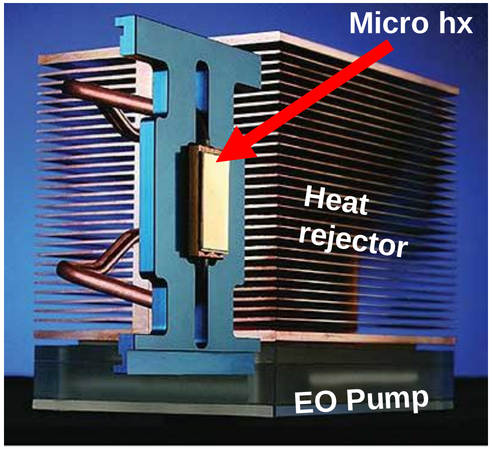
March 19, 2012



Intel/Numonyx



Vuckovic Group, Stanford

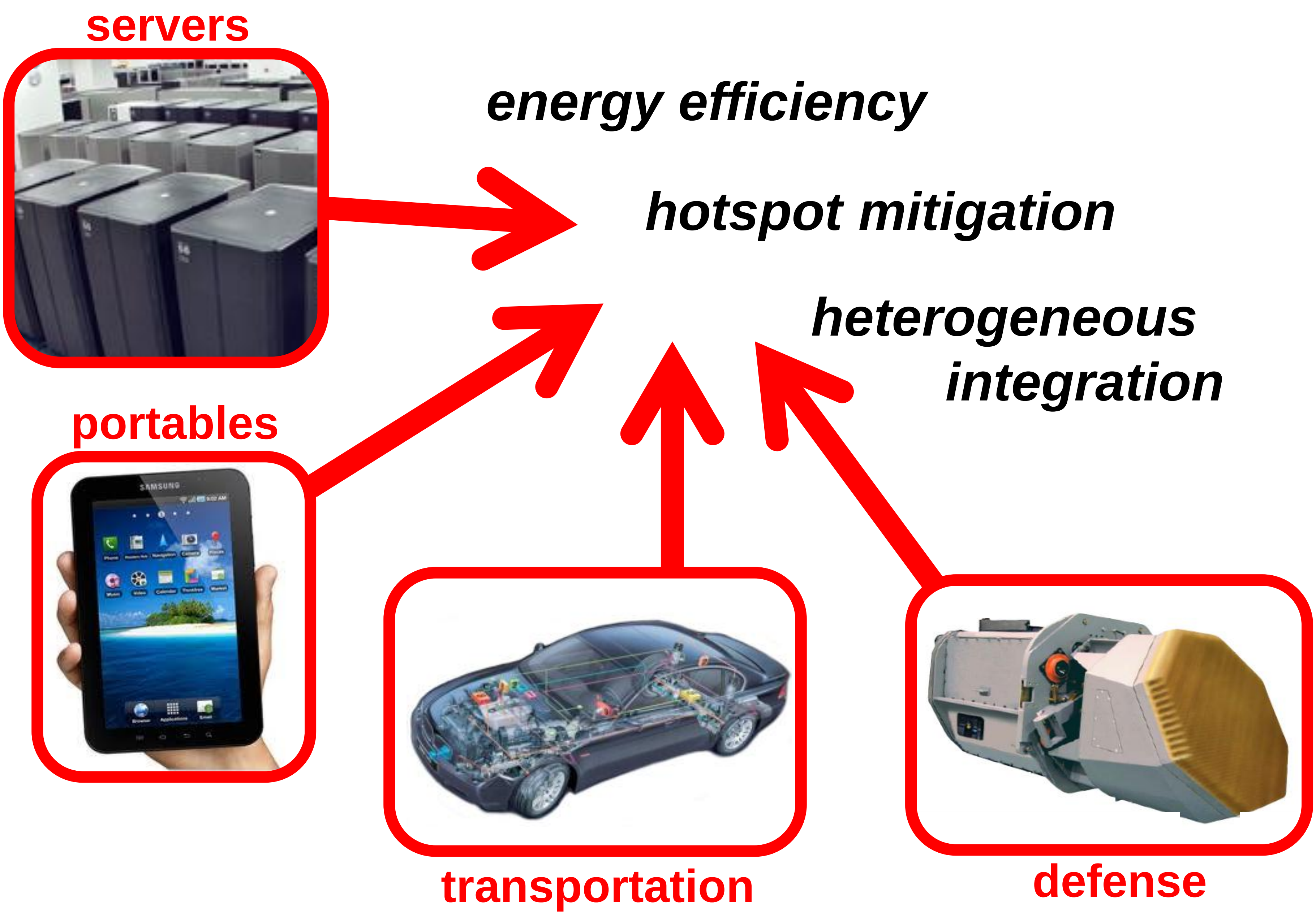


Ken Goodson
Professor & Vice Chair
Mechanical Engineering
Stanford University

STANFORD nanoHeat

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

Electronics Thermal Challenges



Electronics Thermal Challenges

servers

intel AMD Texas Instruments Raytheon

SAMSUNG BAE SYSTEMS

KLA Tencor NORTHROP GRUMMAN

BOSCH RFMD GROUP4 LABS AN EXTREME MATERIALS COMPANY

portables

transportation

defense

Electronics Thermal Challenges

servers

portables

SRC

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

NSF

IFC Interconnect Focus Center

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

DEPARTMENT OF THE NAVY
ONR
Science & Technology

DARPA

transportation

defense

STANFORD nanoHeat

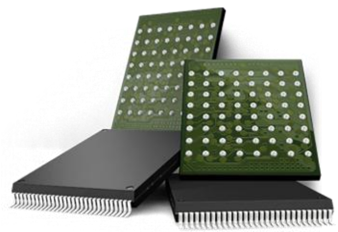
Our Research

thermoelectric harvesting

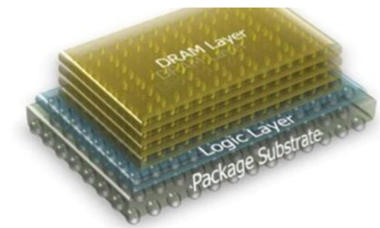
heat & power for computation

heat & power in portables

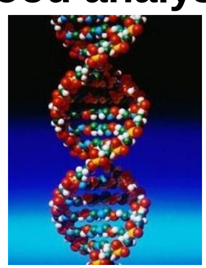
nonvolatile memory



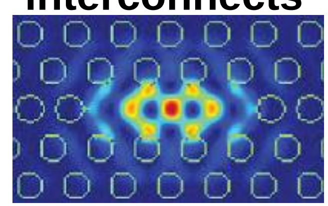
3D integration



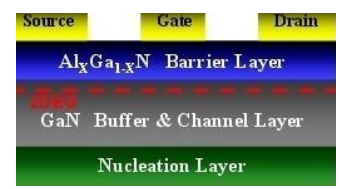
rapid PCR & blood analysis



optical interconnects



RF electronics



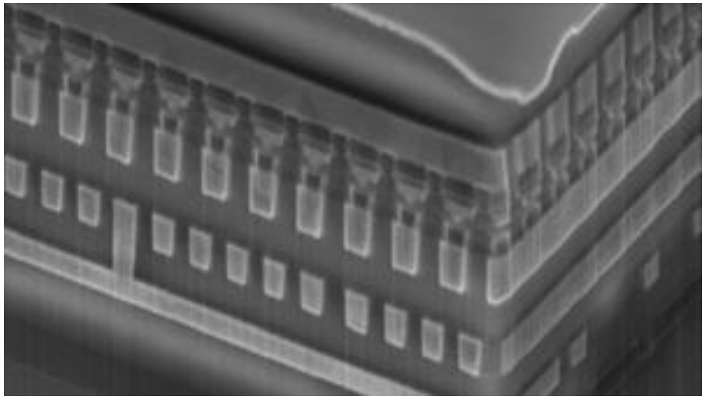
Energy Efficiency

Performance

STANFORD nanoHeat

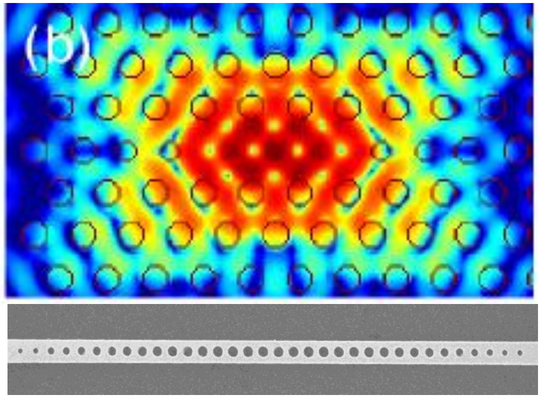
NanoMaterials

PCRAM Data Storage



with Intel TMG

QC Lasers/Guides

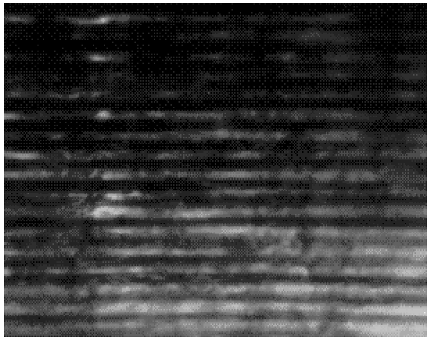


with Vuckovic et al. Stanford

Composite Substrates

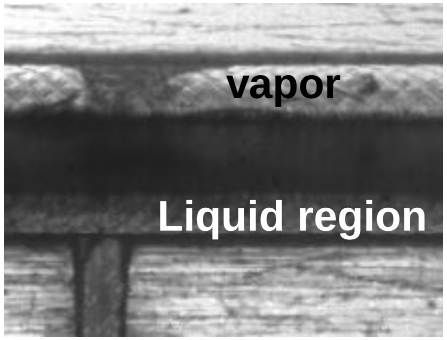
with Group4 Labs

nanoThermo-electrics



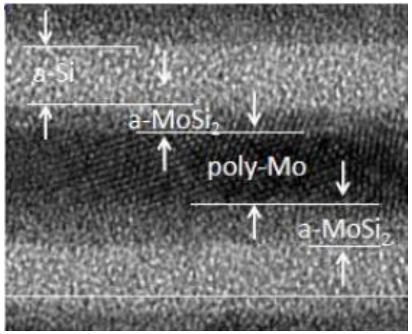
with RTI

Micro HX Membranes



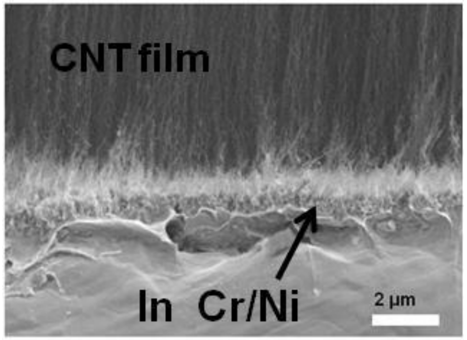
Milnes David, Goodson group, Stanford

EUV Nano Mirrors



with KLA Tencor

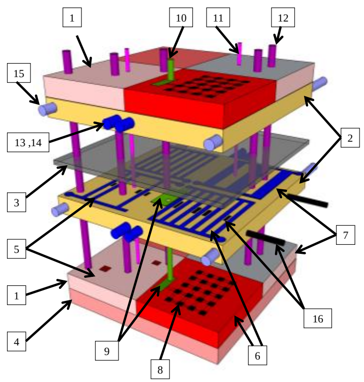
Thermal Interfaces

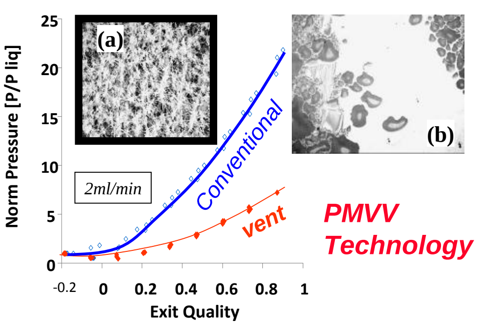


Goodson group & Monano collaborators, Stanford

Heat & Power Management for Computation

Microfluidic Cooling

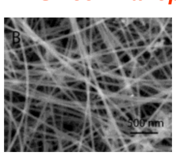


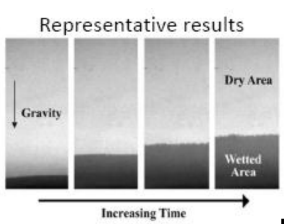


PMVV Technology

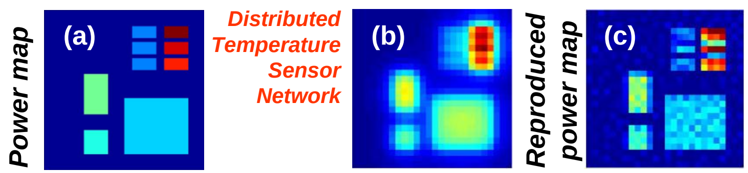
Advanced Vapor Chambers

Silicon Nanopillar Hydrophilic Layer



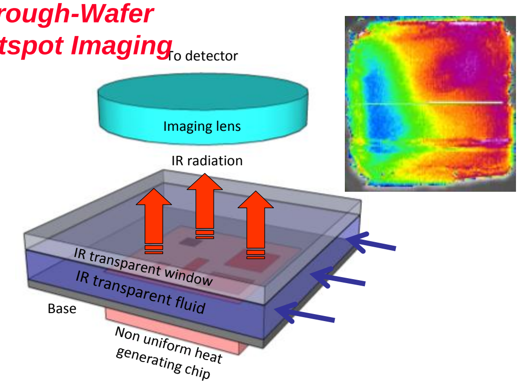


Rapid Hotspot Prediction & Power Distribution

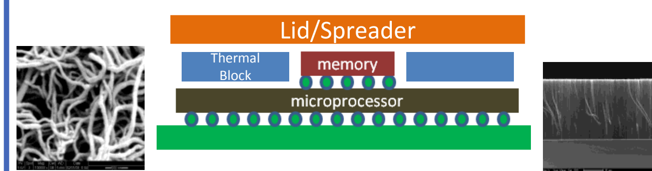


- *Real-time power and hotspot mapping for temp/power–aware computing and energy saving.*
- *Microfluidic cooling including Porous Membrane Vapor Venting and 3D in-situ extraction (MCCI)*
- *Nanostructured underfill and thermal interface materials (TIM)*
- *Low-power nonvolatile memory technologies including PCRAM*

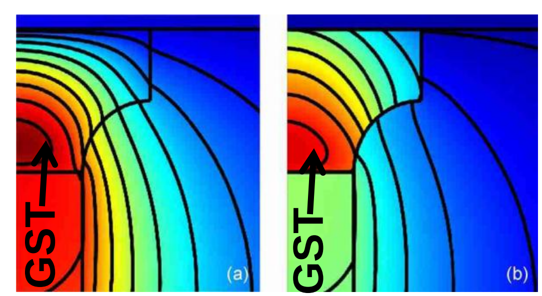
Through-Wafer Hotspot Imaging



Nanostructured Underfill and Interface Materials



Nonvolatile Memory including PCRAM



http://www.stanford.edu/group/microheat/

STANFORD nanoHeat

Current Group

Ken Goodson

Josef Miler
Michael Barako
Jaeho Lee
Sri Lingamneni
Saniya Leblanc
Jungwan Cho

Elah Bozorg-Grayeli
Amy Marconnet
Shilpi Roy (EE)
Yuan Gao
Yiyang Li (MSE)
Zijian Li

Lewis Hom
Aditja Sood (MSE)
Woosung Parc

Dr. Takashi Kodama
Dr. Yoonjin Won
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. Mehdi Asheghi	Stanford	Dr. Milnes David	IBM
Prof. Bill King	UIUC	Dr. Max Touzelbaev	AMD
Prof. Eric Pop	UIUC (EE)	Dr. Roger Flynn	Intel
Prof. Sanjiv Sinha	UIUC	Dr. Julie Steinbrenner	Xerox Parc
Prof. Xeujiao Hu	Wuhan Univ.	Dr. John Reifenberg	Intel
Prof. Carlos Hidrovo	UT Austin	Dr. David Fogg	Creare
Prof. Kaustav Banerjee	UCSB (EE)	Dr. Matthew Panzer	KLA-Tencor
Prof. Ankur Jain	UT Arlington		
Prof. Sarah Parikh	Foothill College		

Outline

Metrology

GaN-Diamond HEMTs

Phase Change Memory

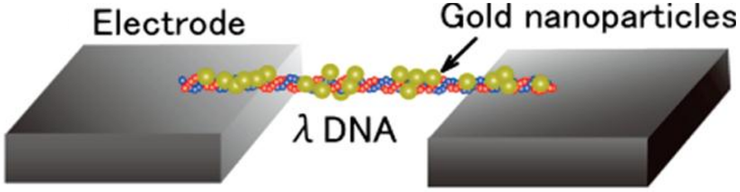
3D NanoPackaging

Microfluidic Cooling

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

Nano Thermal Metrology

Rig Complexity



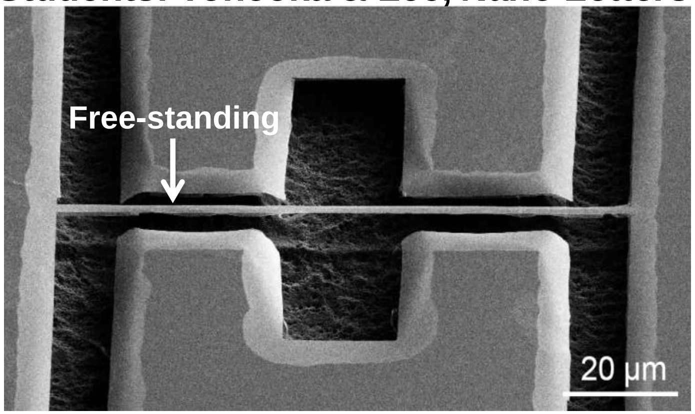
Kodama, Jain, Goodson, Nano Letters 9 (2009)

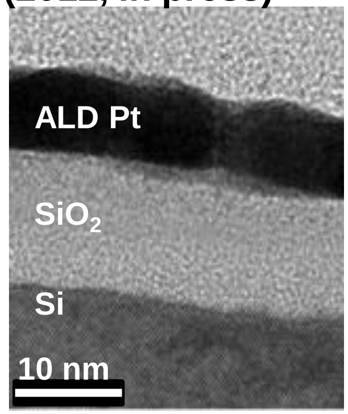
Sample Complexity

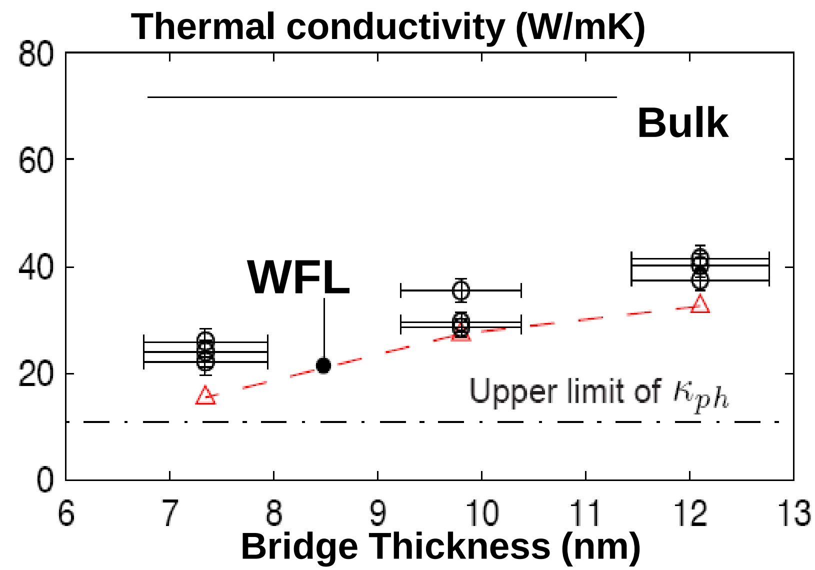
Nanobridge Samples

Metal Interconnects down to 7.3 nm

Students: Yoneoka & Lee, *Nano Letters* (2012, in press)

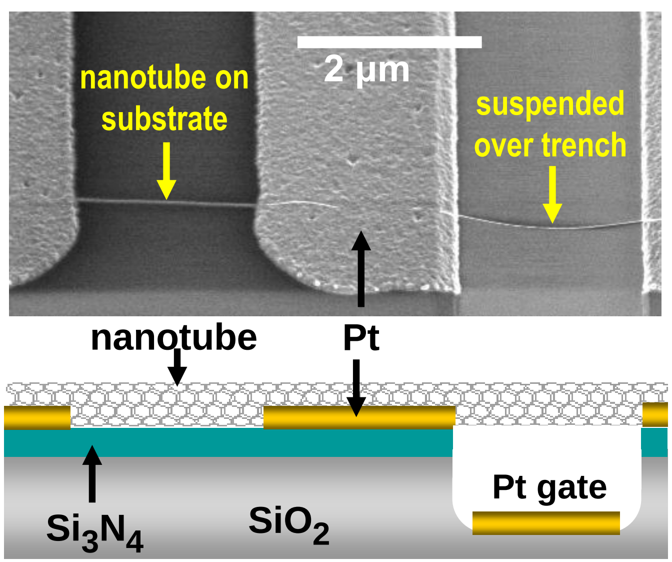


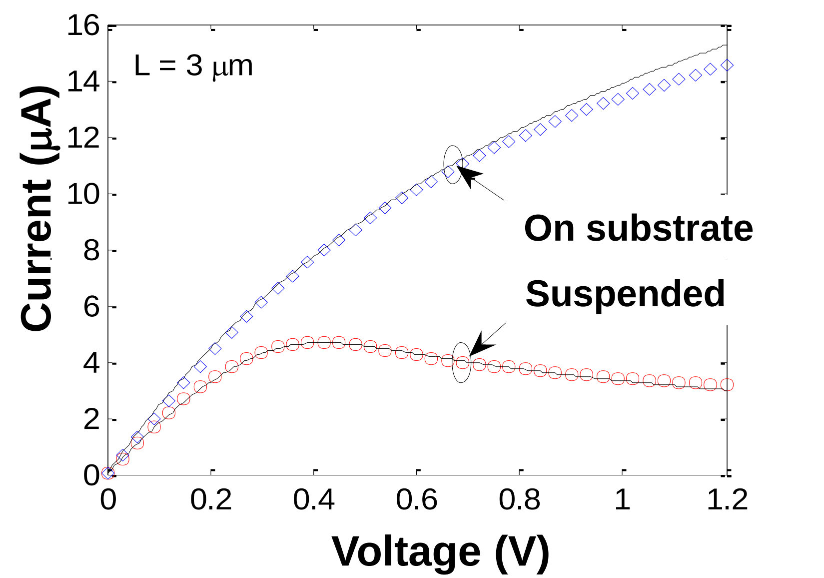




Single Wall Carbon Nanotube FETs

Pop, Dai, Goodson, et al., *Physical Review Letters* (2005), *Nano Letters* (2006)





Nano Thermal Metrology

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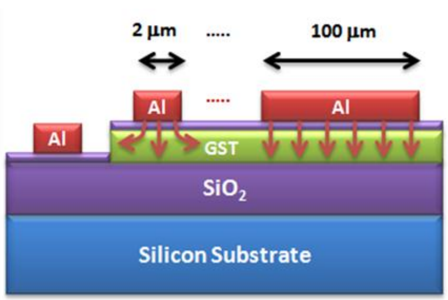
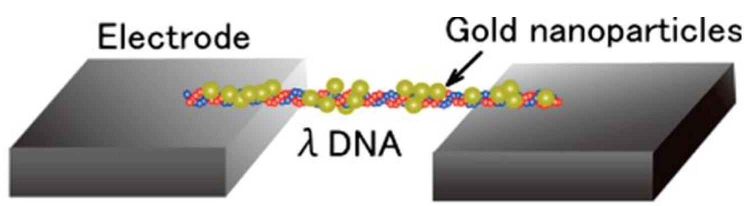


Ju, Kurabayashi, Goodson, *Thin Solid Films* (1999)
Lee et al., Journal of Applied Physics, (2011)

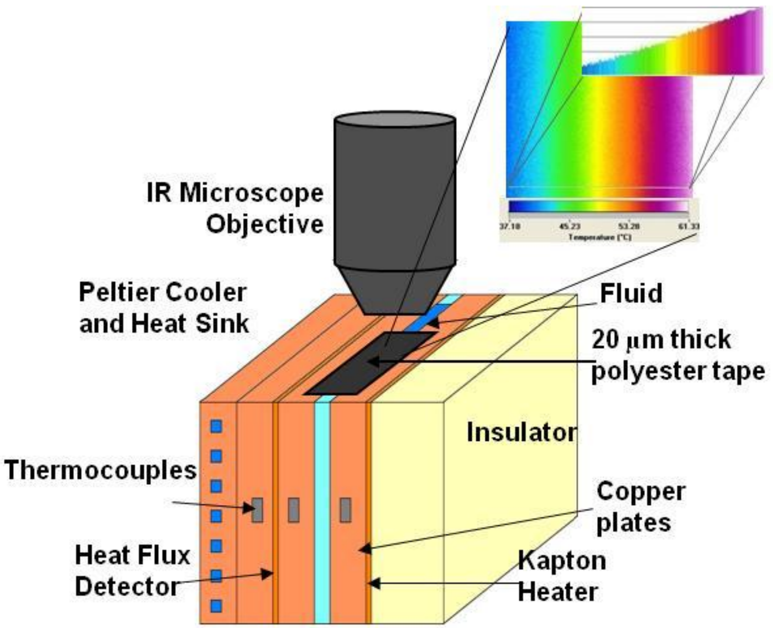


Kodama, Jain, Goodson, Nano Letters 9 (2009)

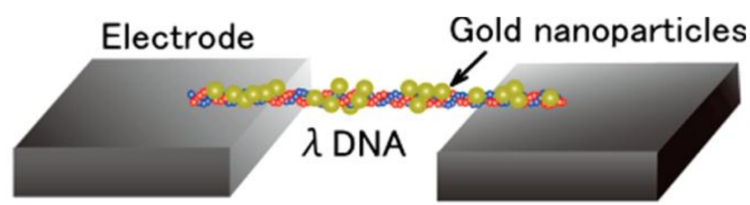
Sample Complexity

Nano Thermal Metrology

Rig Complexity



Marconnet, Wardle, Goodson, et al., ACS Nano (2011)



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

Sample Complexity

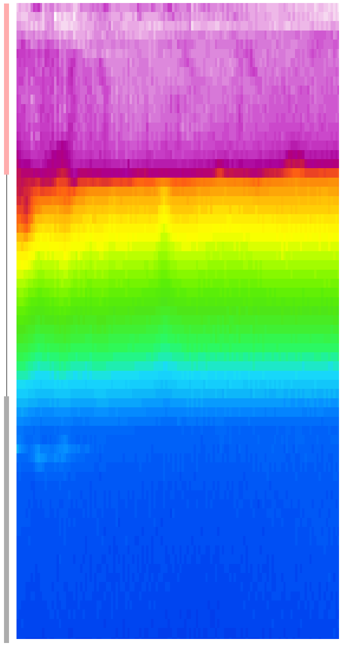
IR Imaging

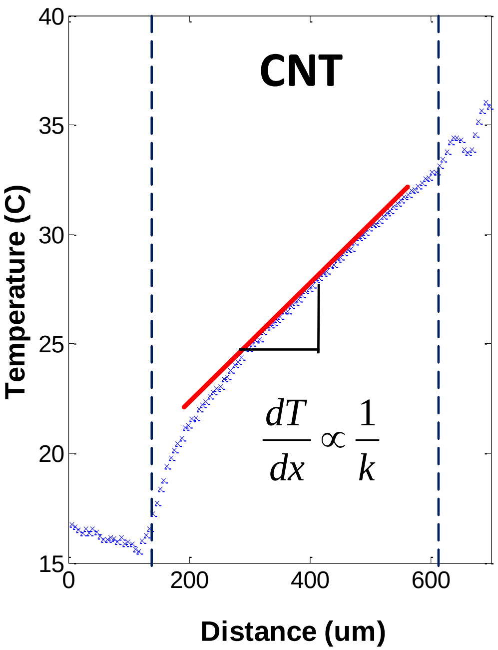
Nanostructured TIMs

Volume & boundary resistance separation

Xuejiao Hu, Amy Marconnet, Sri Lingamneni

Opposing CNT arrays up to 80 W/mK
(J. Heat Transfer 2006, 2007)
CNT-epoxy nanocomposites up to 5 W/mK
(ACS Nano 2011)
Graphene nanocomposites
(work in progress for SRC)





IR Imaging

Nanostructured TIMs

Volume & boundary resistance separation

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- **Graphene nanocomposites**
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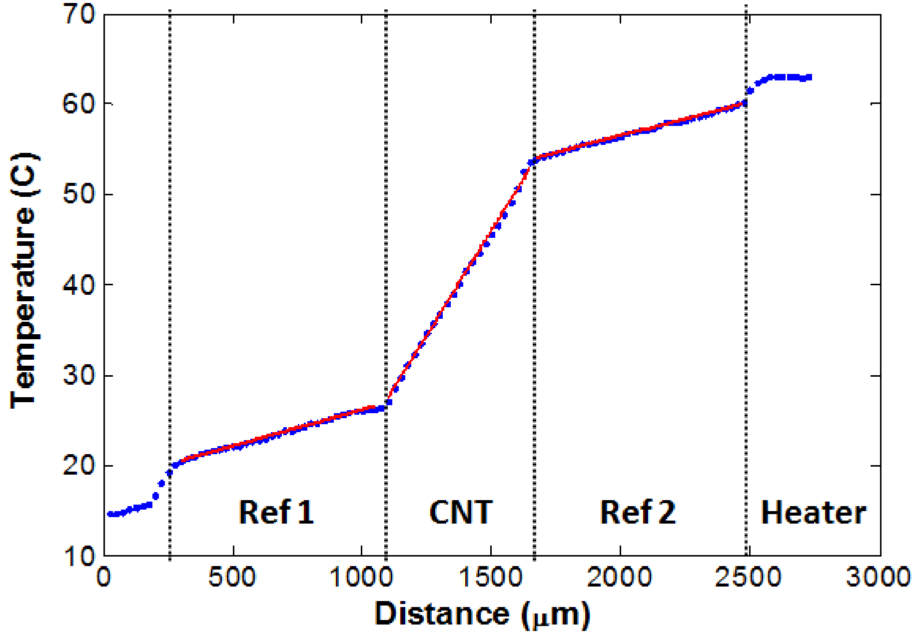
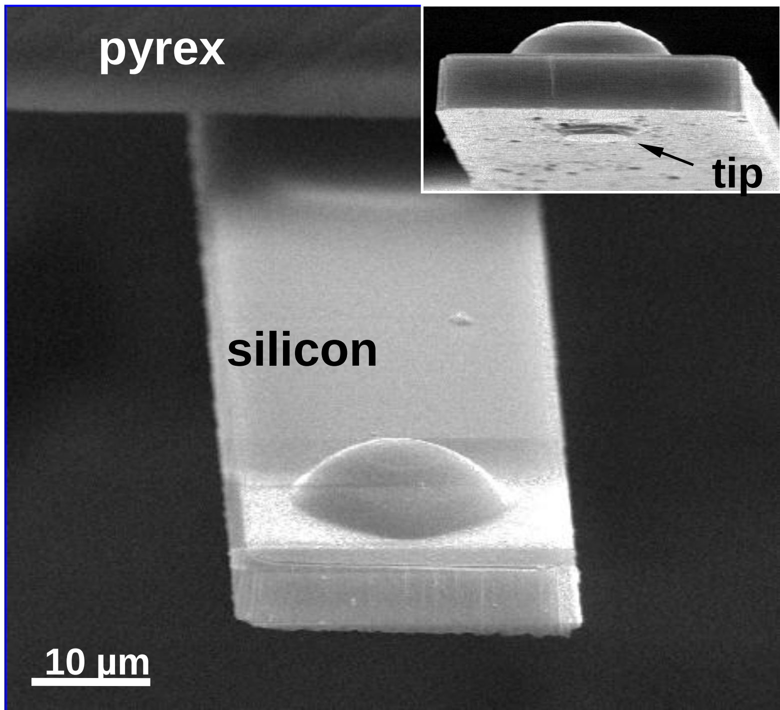


IR Solid Immersion Lens

Submicron resolution with microcantilever

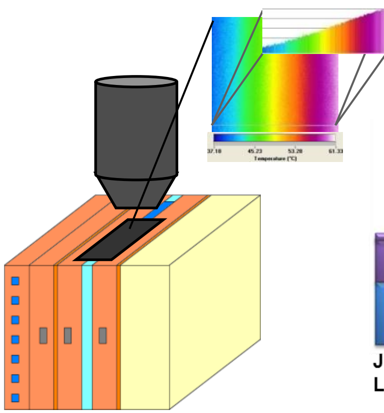
Daniel Fletcher

- **First thermal microscopy demonstration**
  (Microscale Thermophysical Engineering 2003)
- **Electromagnetic simulations and optimization**
  (Optics Letters 2001)
- **Microfabrication details**
  (J. MicroElectroMechanical Systems 2001)
- **Resolution demonstration**
  (Applied Physics Letters 2000)

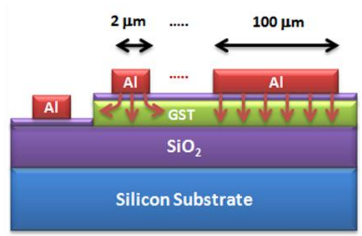


Nano Thermal Metrology

Rig Complexity



Marconnet, Wardle, Goodson, et al., *ACS Nano* (2011)



Ju, Kurabayashi, Goodson, *Thin Solid Films* (1999)
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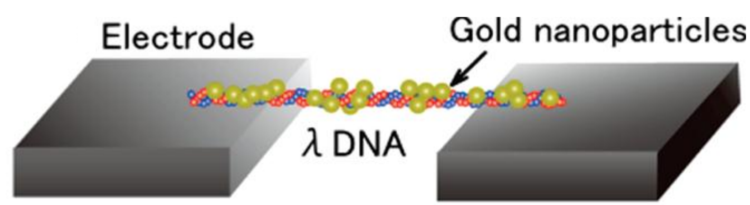
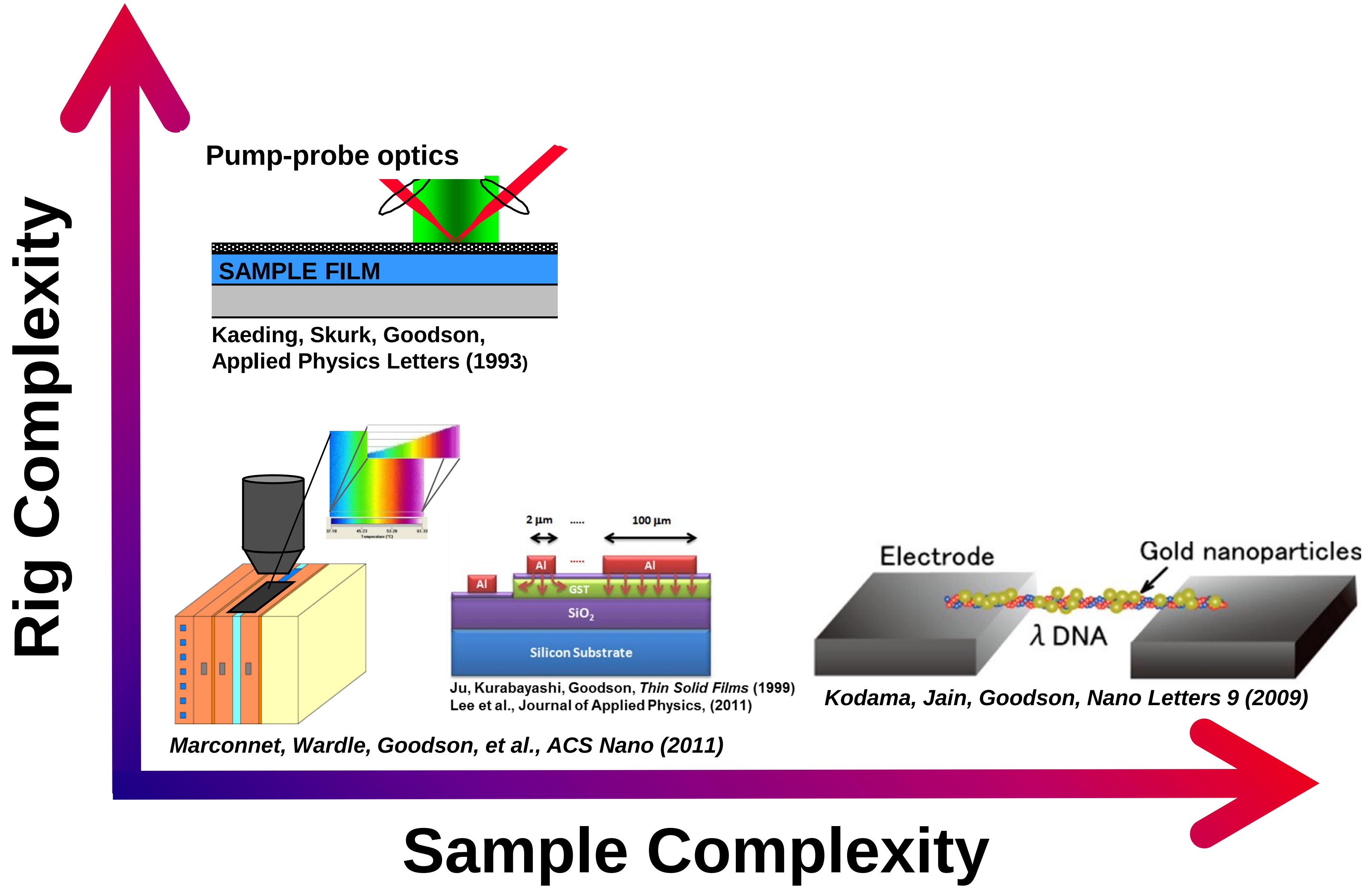


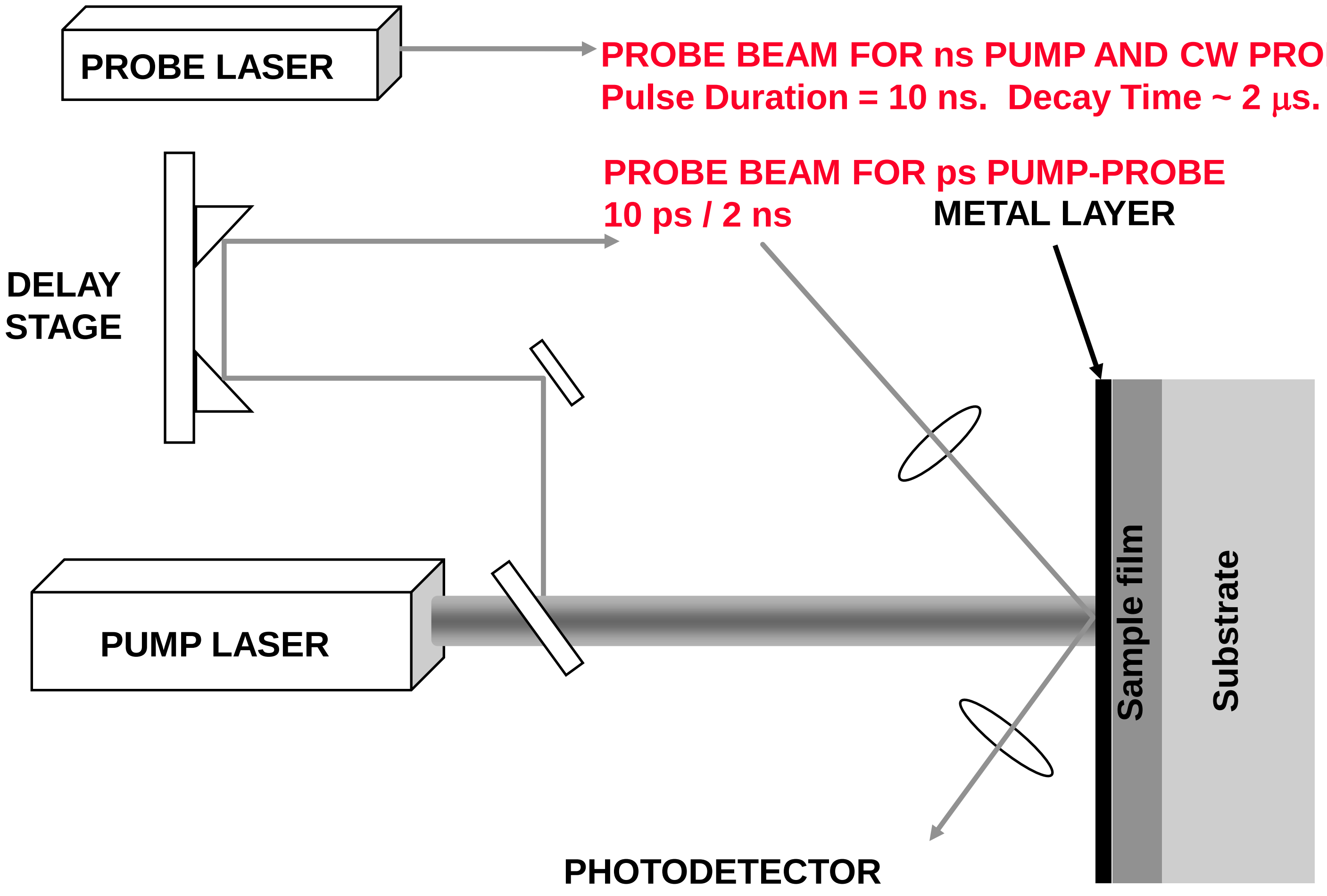
Kodama, Jain, Goodson, Nano Letters 9 (2009)

Sample Complexity

Nano Thermal Metrology



Short-Timescale Photothermal Characterization of Packaging Properties



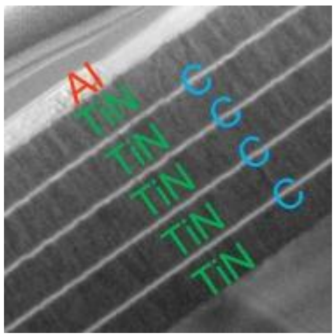
Kaeding, Skurk, and Goodson, *Applied Physics Letters* 65 (1994)
Goodson & Ju, *Annual Review of Materials Science* 29 (1999)
Panzer et al., *Journal of Heat Transfer* (2008)

Applications

PCRAM Materials and Interfaces

Elah Bozorg-Grayeli & John Reifenberg

Applied Physics Letters (2007)
Electron Device Letters (2008, 2010, 2011x3!)



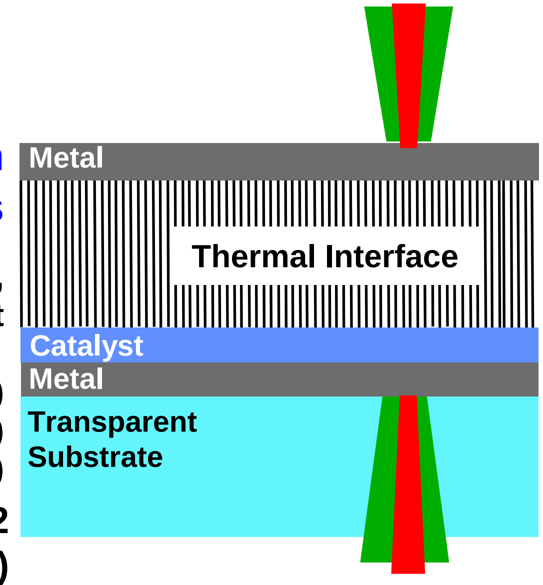
Intel SRS
SRC DS Task 1996

Die Attach Distributions

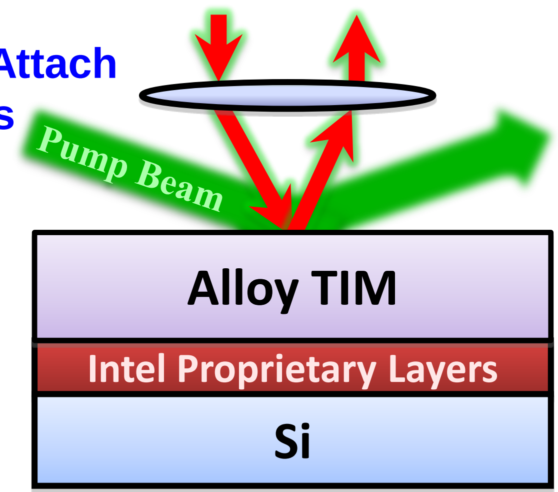
Matt Panzer, Yuan Gao, Amy Marconnet

Nanoletters (2010)
J. Heat Transfer (2008)
J. Electronic Materials (2009)

SRC IPS Task 1392 (2009-2011)

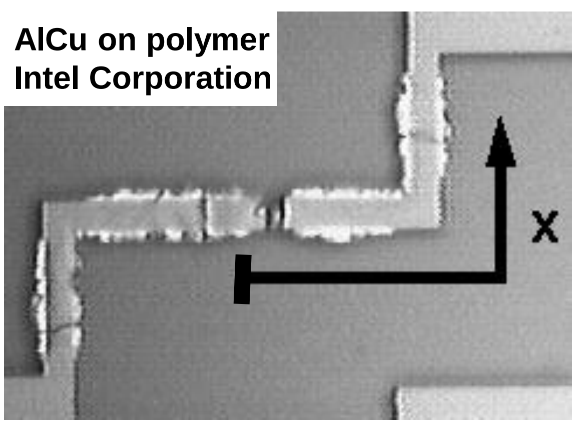


Alloy Die Attach Multilayers



Jungwan Cho, Matt Panzer

SRC/Intel IPS Task 1640 (2009)



AlCu on polymer
Intel Corporation

SRC Tasks 357 & 754 (1998)

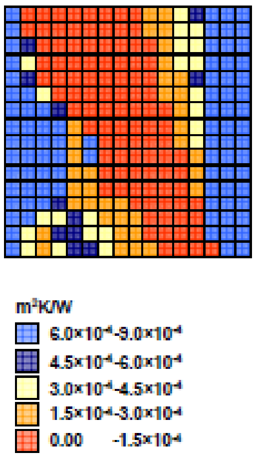
Interconnects & Low-K Dielectrics

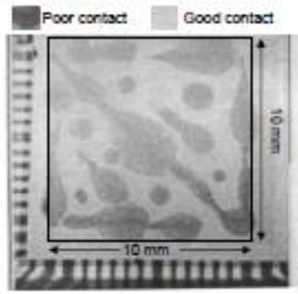
Sungtaek Ju, Olaf Kaeding, Katsuo Kurabayashi

Journal of Heat Transfer (1998)
Electron Device Letters (1997a, 1997b)
Thin Solid Films (1999)
JMEMS (1999)

Applications

Die Attach Scanning





Katsuo Kurabayashi

IEEE Transactions on Components, Packaging, & Manufacturing Technology (1998)

SRC Task 357 (1998)

Die Attach Distributions

Matt Panzer, Yuan Gao, Amy Marconnet

Nanoletters (2010)
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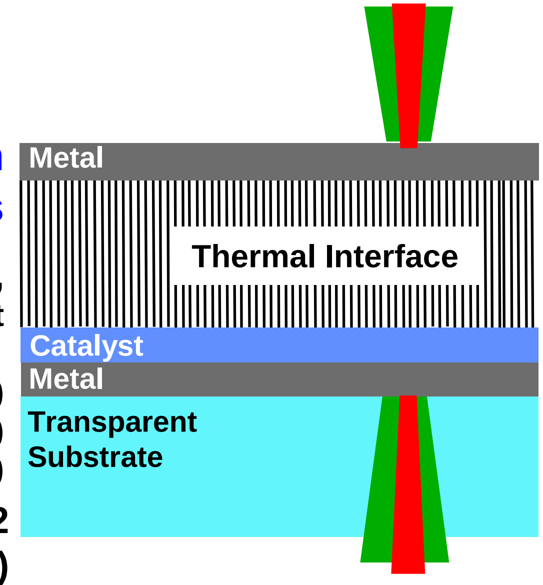
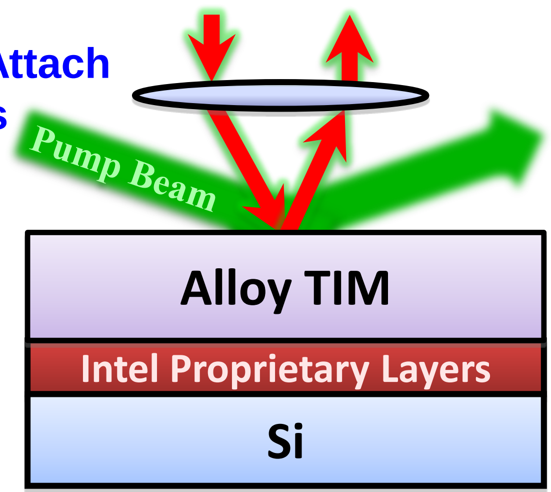
J. Electronic Materials (2009)

SRC IPS Task 1392 (2009-2011)



Alloy Die Attach Multilayers



Jungwan Cho, Matt Panzer

SRC/Intel IPS Task 1640 (2009)

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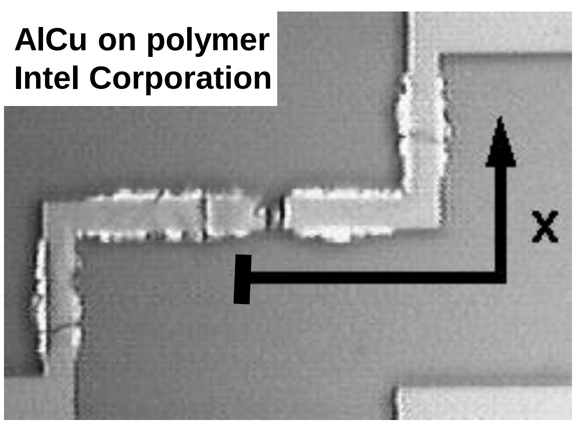

SRC Tasks 357 & 754 (1998)

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JMEMS (1999)

Outline

Metrology

GaN-Diamond HEMTs

Phase Change Memory

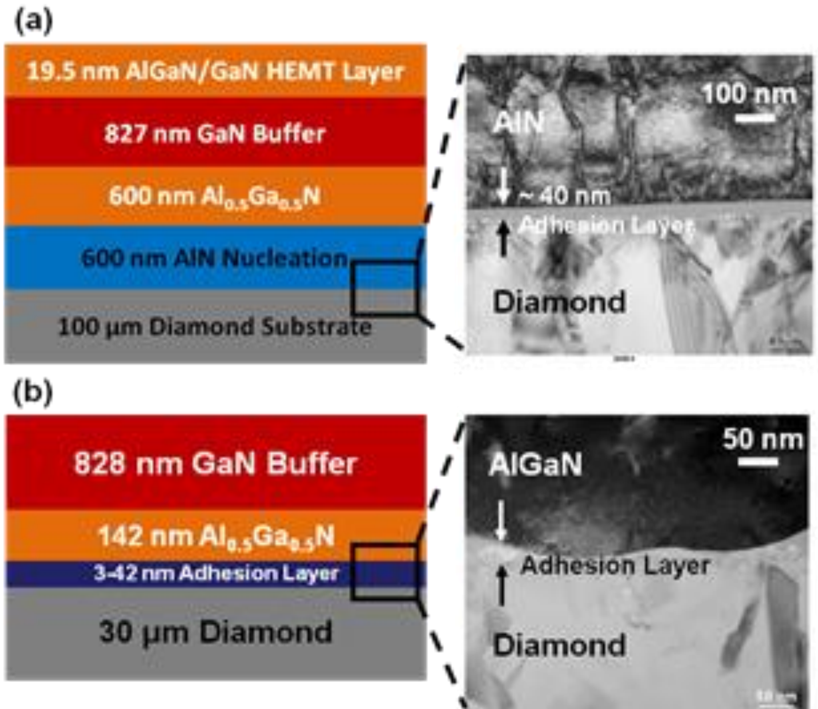
3D NanoPackaging

Microfluidic Cooling

Diamond Examples

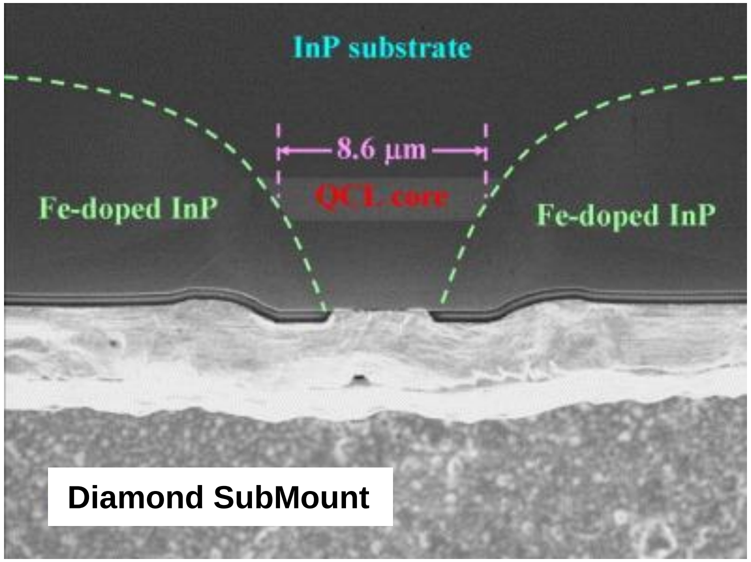
Close proximity demands low thermal resistances at and near the diamond interface

HEMT Composite Substrates



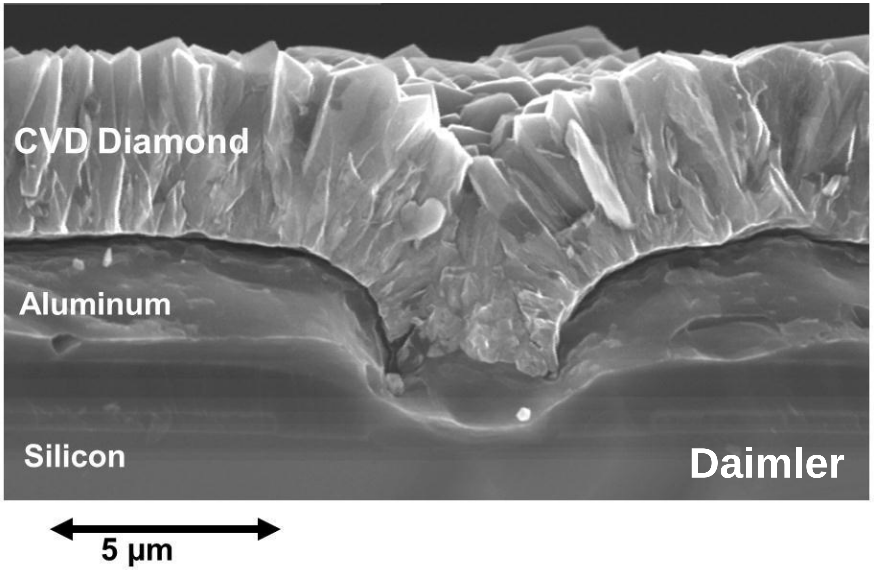
Proc. ITHERM 2012, with Group4 Labs

Quantum Cascade Laser SubMounts

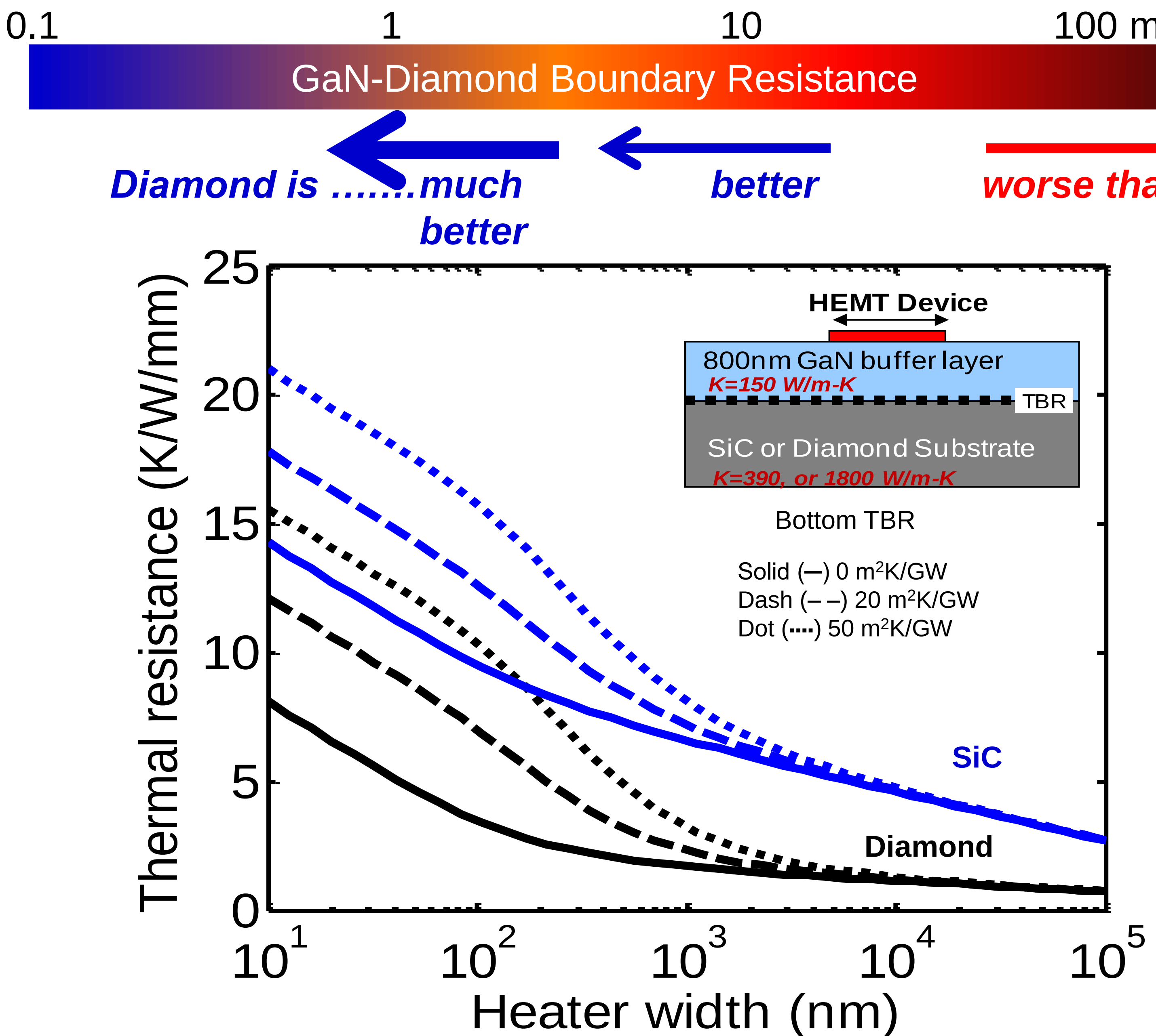


Razeghi et al., *N. J. Phys.* (2009)

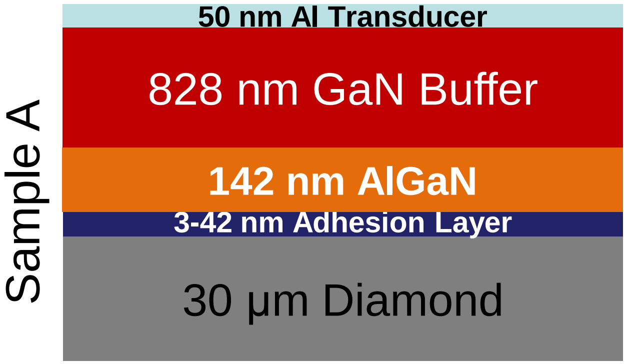
POWER FET Passivation

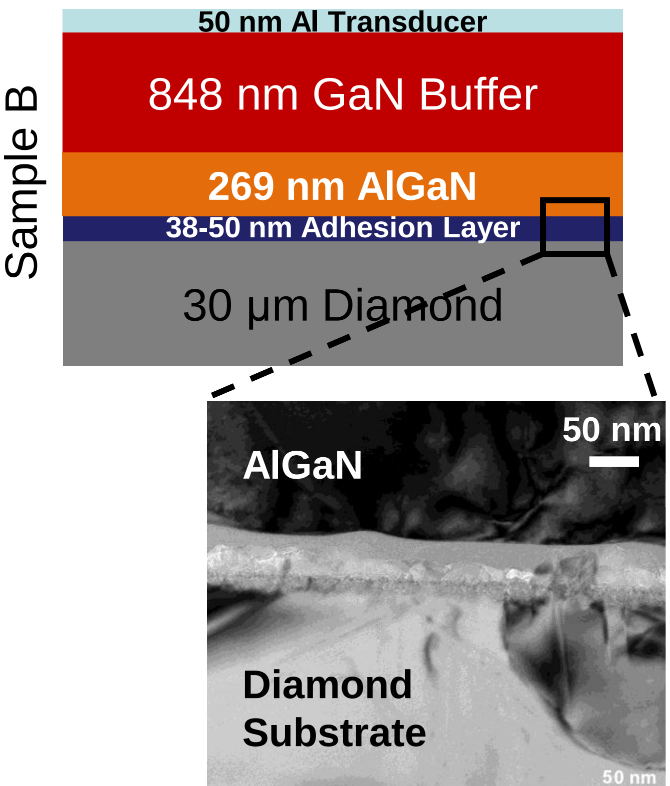


Resistance Targets for GaN HEMTs

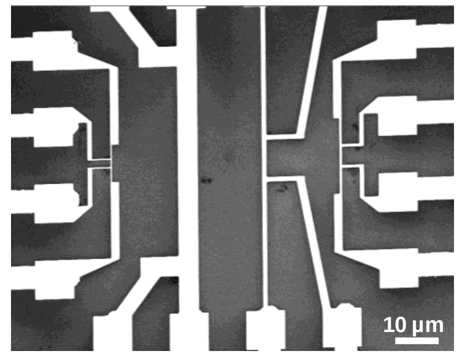


Picosecond & DC Joule Heating for GaN-on-Diamond Multilayers

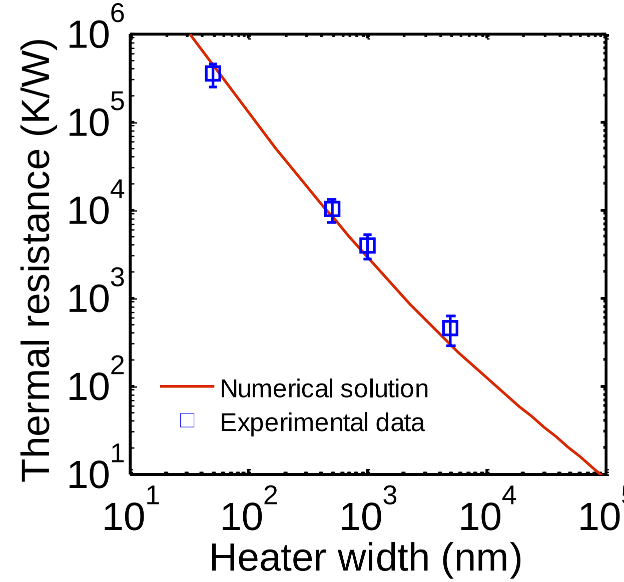




Stanford with Group4 Labs



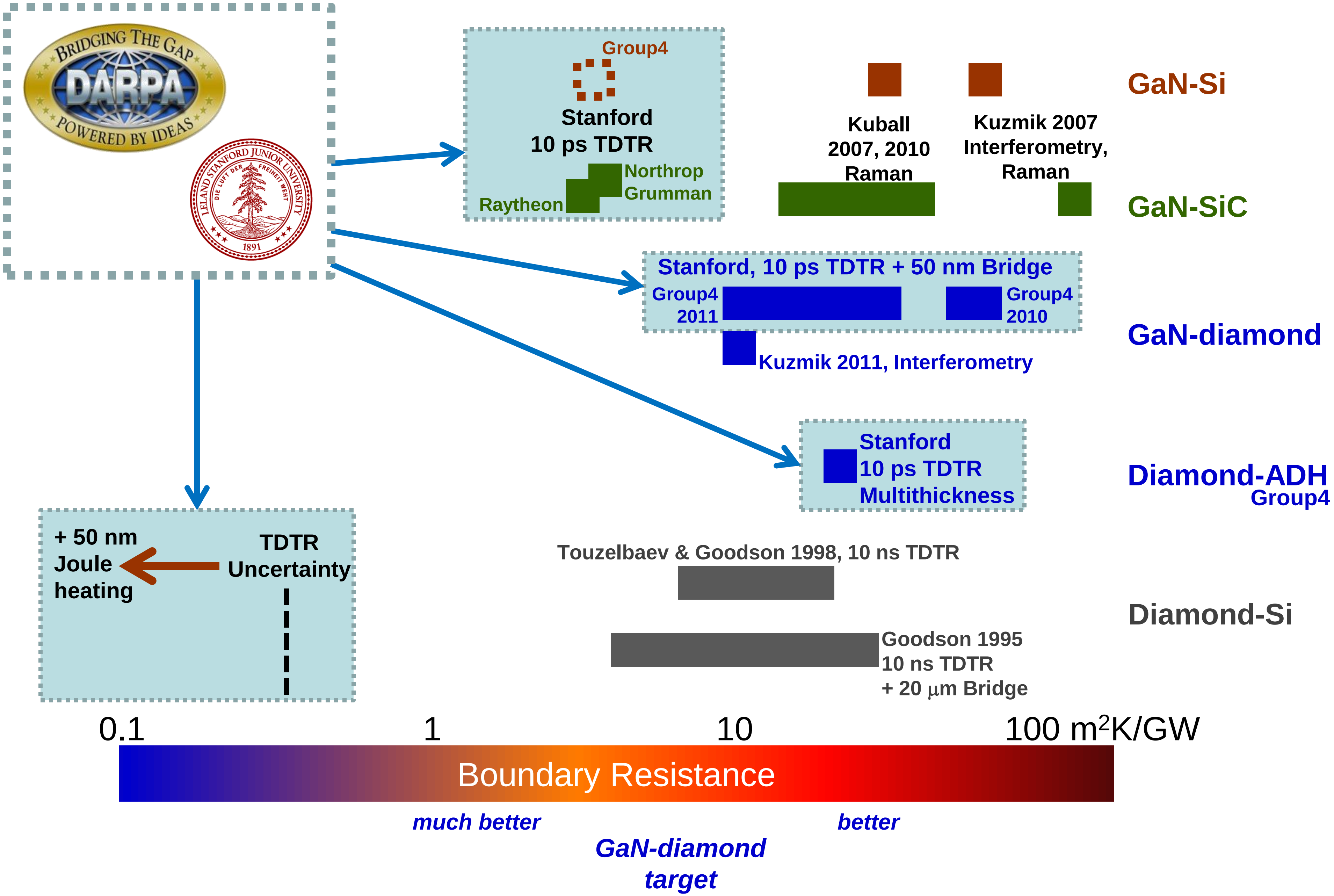
Patterned bridges, 50nm-5mm width



- $R_{GaN\text{-}Diamond} = R_{AlGaN\text{-}ADH} + R_{ADH} + R_{ADH\text{-}Diamond}$
- k_{GaN} and k_{AlGaN} measured using independent sample sets yielding 90 and 16.6 W/mK, respectively

Measurement Technique	$R_{GaN\text{-}Diamond,\,A}$ [m²K/GW]	$R_{GaN\text{-}Diamond,\,B}$ [m²K/GW]
Picosecond	22 ± 9	25 ± 13
DC Joule heating	25 ± 11	29 ± 12

Diamond & GaN in Composite Substrates



Outline

Metrology

GaN-Diamond HEMTs

Phase Change Memory

3D NanoPackaging

Microfluidic Cooling

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

INVITED PAPER

Pop, Sinha, Goodson, Proceedings IEEE (2006)
Rowlette, Goodson, IEEE Trans. Electron Devices (2008)

Heat Generation and Transport in Nanometer-Scale Transistors

Heat problems in ever-smaller integrated circuits include hot-spots at transistor drain areas, reduced heat conduction in new devices and higher thermal resistance at material boundaries.

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

ABSTRACT | As transistor gate lengths are scaled towards the 10-nm range, thermal device design is becoming an important part of microprocessor engineering. Decreasing dimensions lead to nanometer-scale hot spots in the transistor drain

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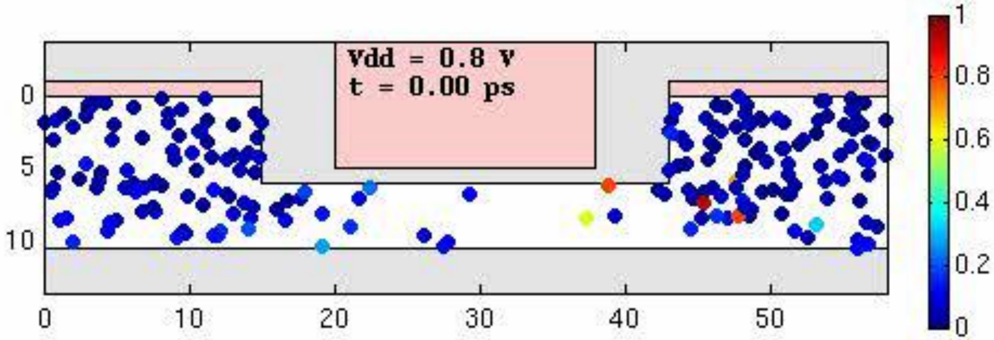
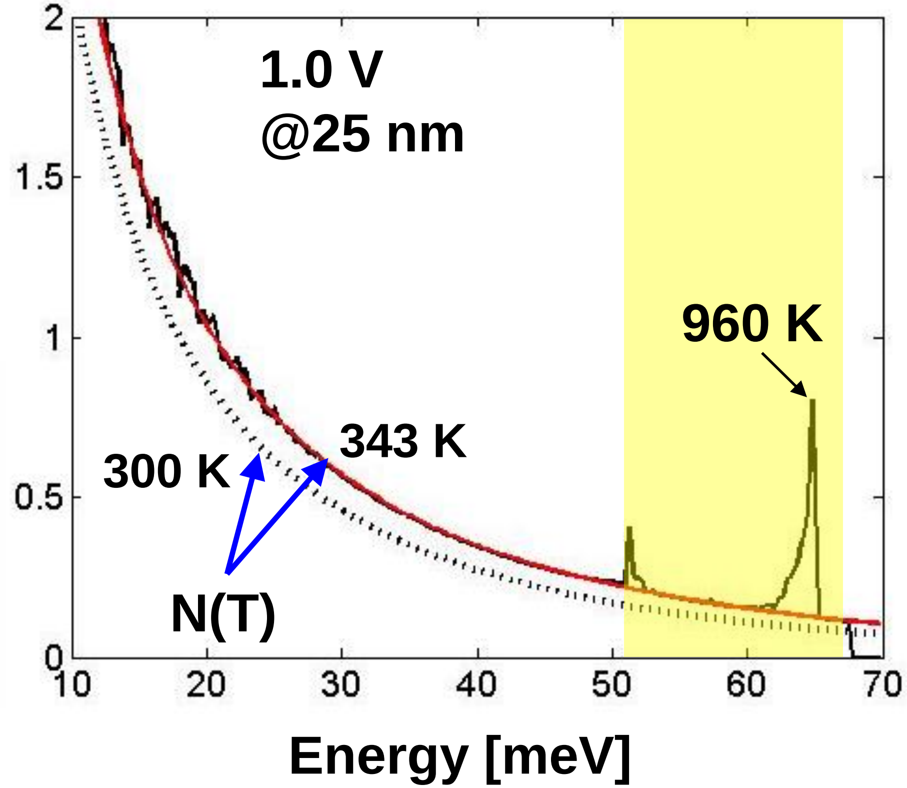
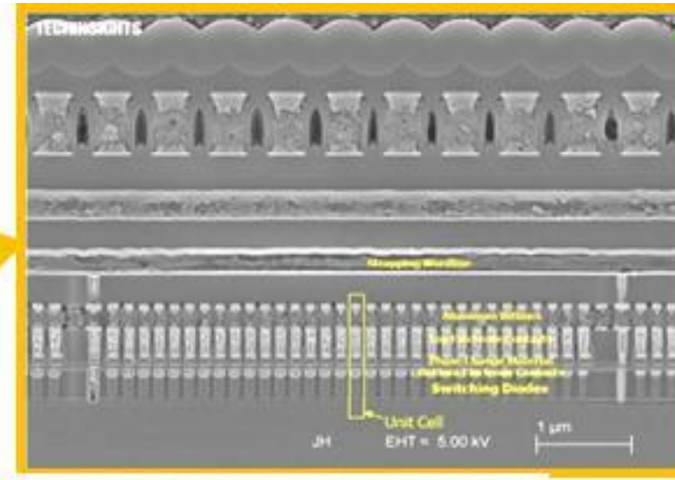
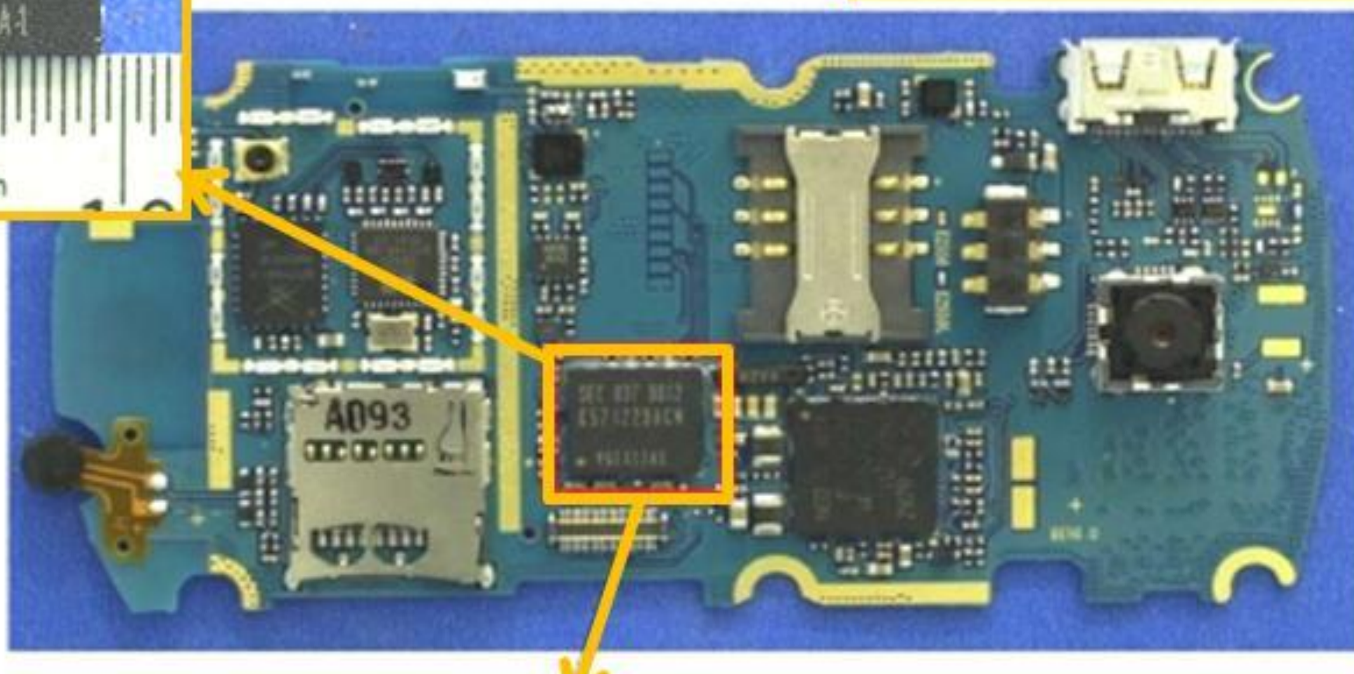


Hot Phonons



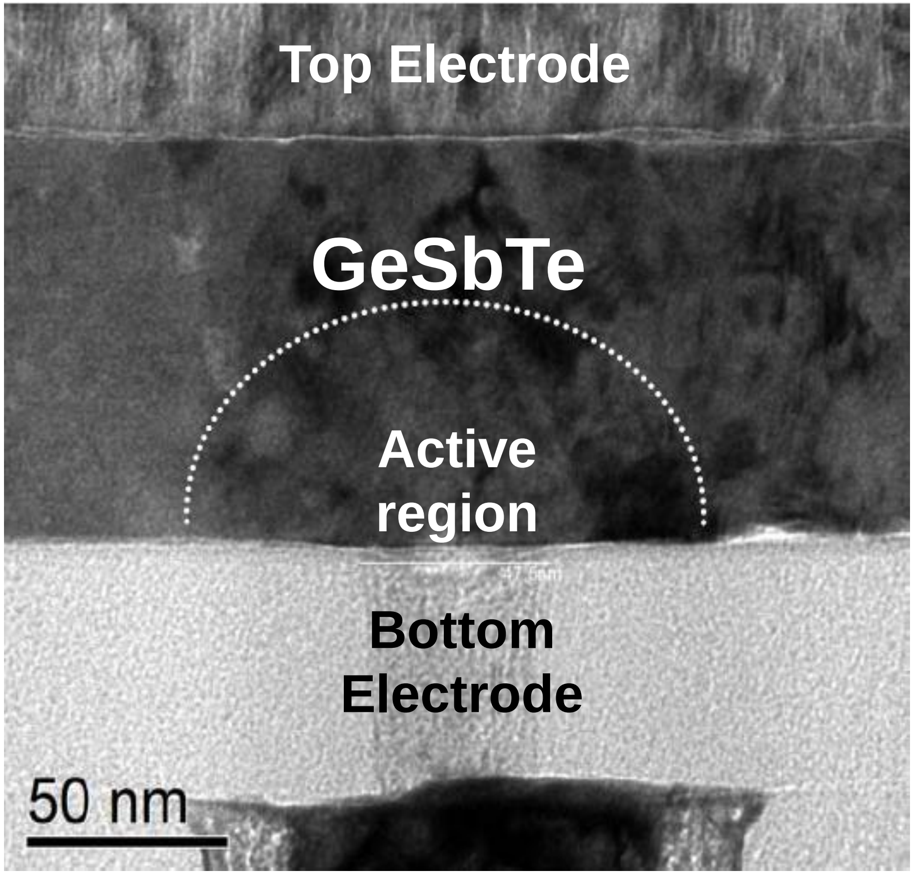
Phase Change Memory



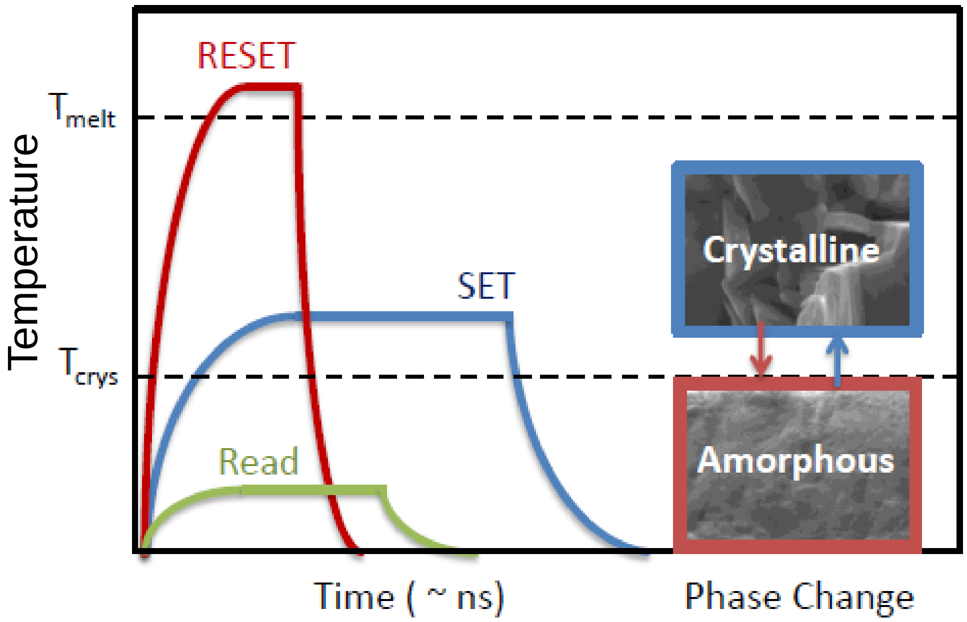


K571229ACM (MCP with PRAM and UtRAM)

Phase Change Memory



Cheng et al., IBM/Macronix, Proc IEDM 2011



Research Challenges

- Multibit data storage (holy grail)
- Drift of reset resistance
  & threshold voltage
- Interface transport
- Energy consumption (reset)

Phase Change Nanodevice Group

Sponsors & Collaborators: *H.S.P Wong group (Stanford EE), Intel (Kau, Chang, Spandini), NXP (Hurckx), Micron (Smythe), IBM (Raoux, Krebs)*
National Science Foundation, Semiconductor Research Corporation

Thermal Characterization

Multibit Strategies and Novel Synthesis

INVITED PAPER
Vol. 98, No. 12, December 2010 | PROCEEDINGS OF THE IEEE

Phase Change Memory

A comprehensive and thorough review of PCM technologies, including a discussion of material and device issues, is provided in this paper.

By H.-S. PHILIP WONG, *Fellow IEEE*, SIMONE RAOUX, *Senior Member IEEE*, SANGBUM KIM, JIALE LIANG, *Student Member IEEE*, JOHN P. REIFENBERG, BIPIN RAJENDRAN, *Member IEEE*, MEHDI ASHEGHI, AND KENNETH E. GOODSON

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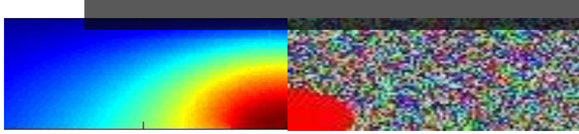
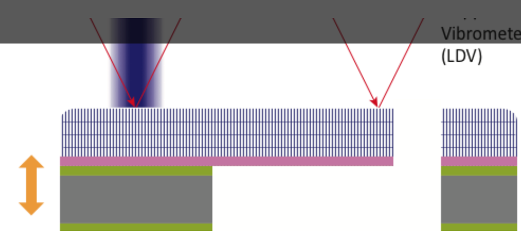
Thermomechanics



Jaeho Lee
Zijian Li



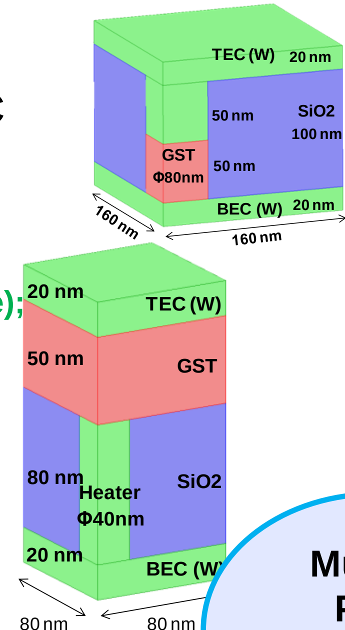
Yoonjin Won
Jaeho Lee

PCRAM Multibit Design Geometries

Wong, Goodson, Asheghi, et al., *Proceedings of the IEEE* (2011)

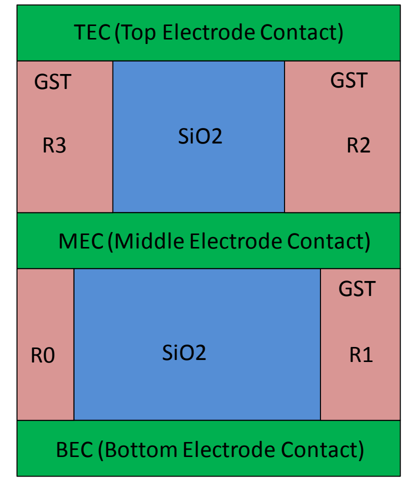
Pulse-controlled MLC

- Standard manufacturing;
- Multiple programming schemes available (tail duration and pulse amplitude);
- Capable of more than 4 levels;
- Need write-and-verify;
- Subject to resistance drift.



Stacked Vertical Cell

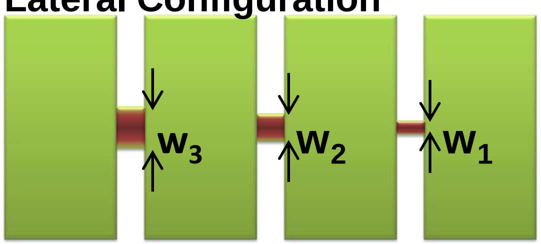
- Four distinct resistance levels;
- Low programming current;
- Precise control of dimensions;
- Fabrication complexity;



Multibit PCM Design Strategies

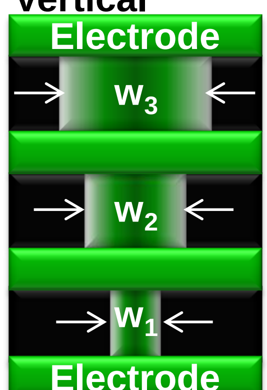
Varying Width PC Structures

Lateral Configuration



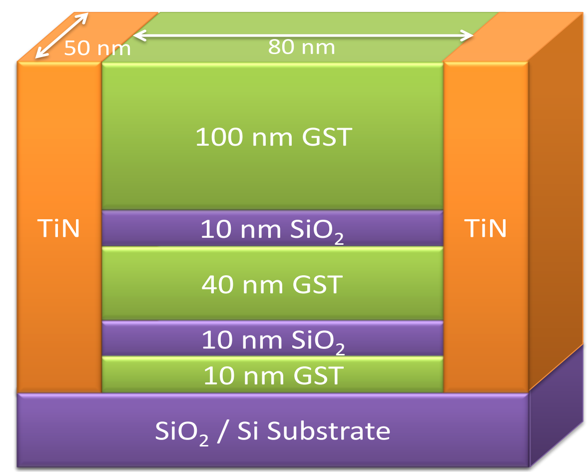
- Programming control with variable width w3 > w2 > w1
- Susceptible to resistance drift

Vertical

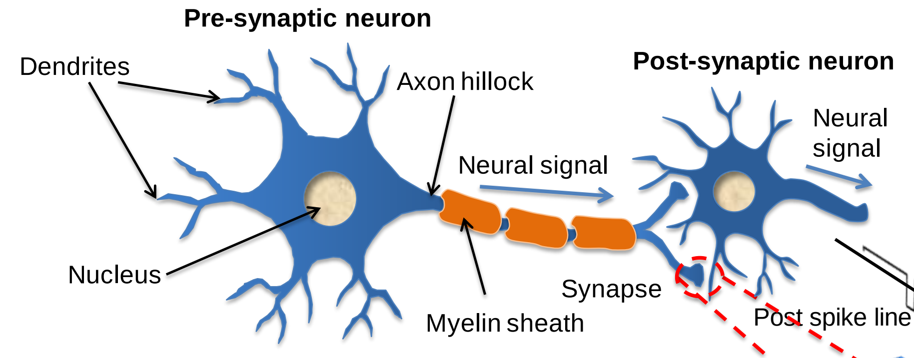


Multilayer Stacked Design

- Distinct levels of resistance
- Thermally efficient programming
- Fabrication complexity

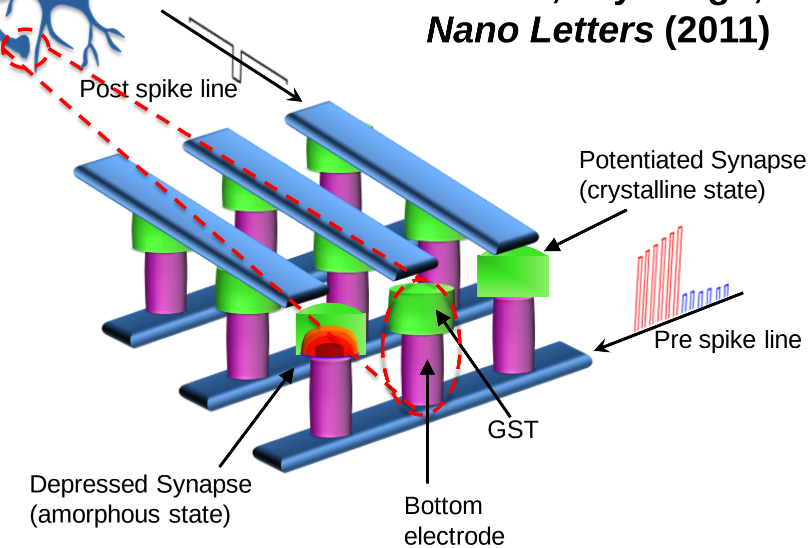


Future Phase Change Nanodevices

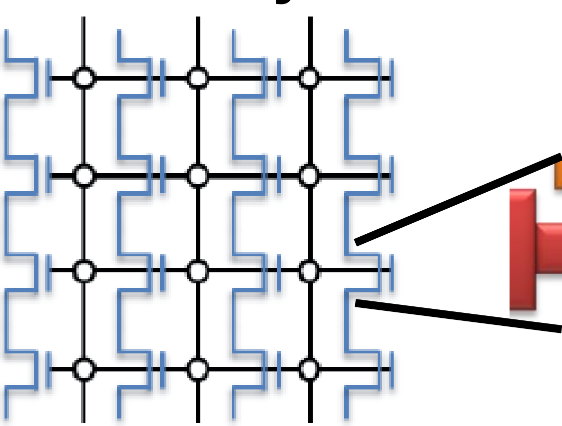


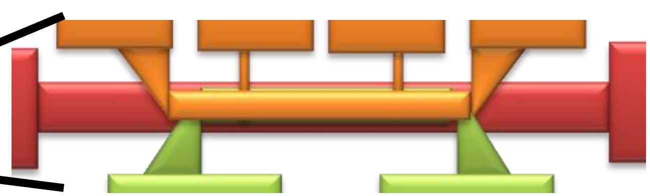
Synapses for Brain-Inspired Computing

Kuzum, Jeyasingh, Lee, Wong,
***Nano Letters* (2011)**



Field-Programmable Gate Arrays





Lee, Asheghi, Wong, Goodson, et al.
***Electron Device Letters* (2011)**

SyNAPSE

DARPA

RF-FPGA

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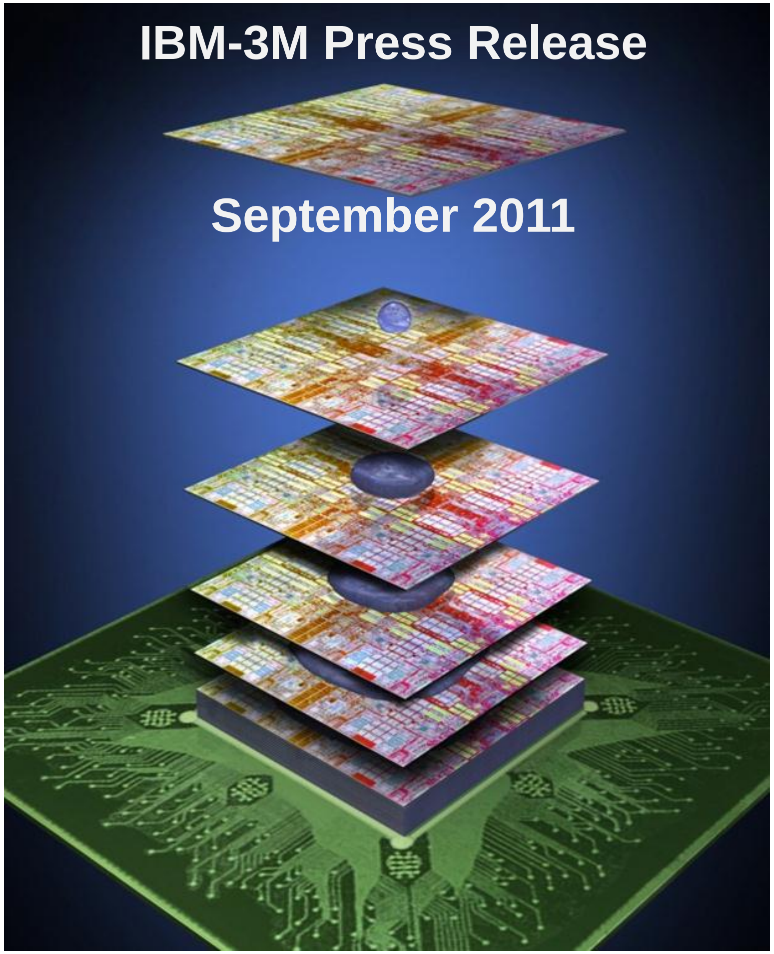
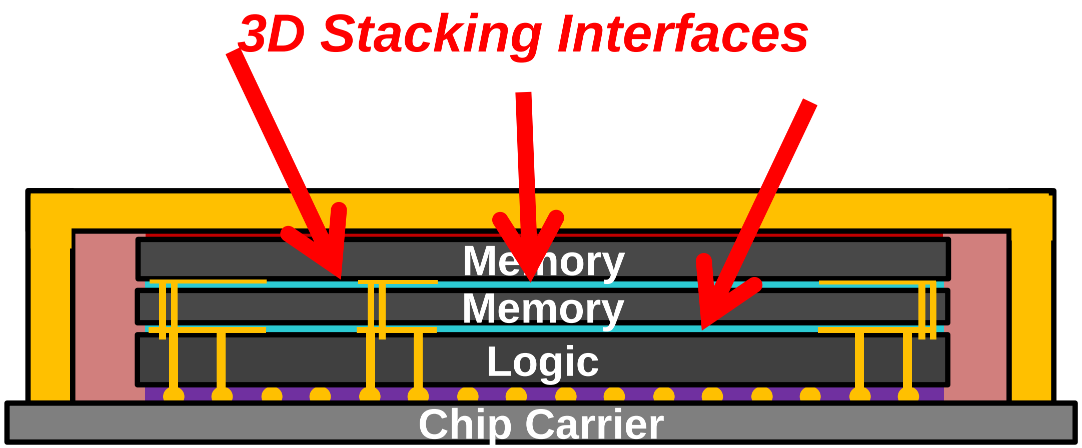
goodson@stanford.edu
http://www.nanoheat.stanford.edu

3D NanoPackaging





3D NanoPackaging

EE Times Home > News and Analysis

News & Analysis

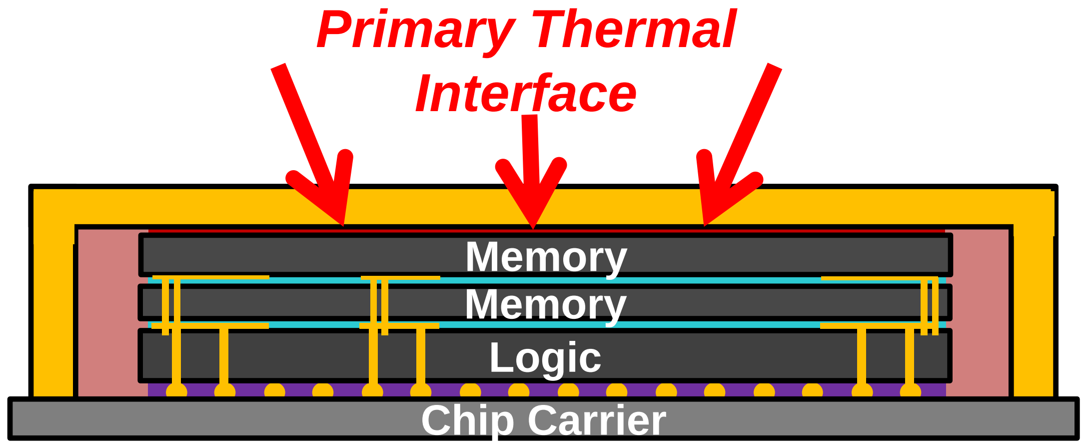
Nanotape could make solder pads obsolete

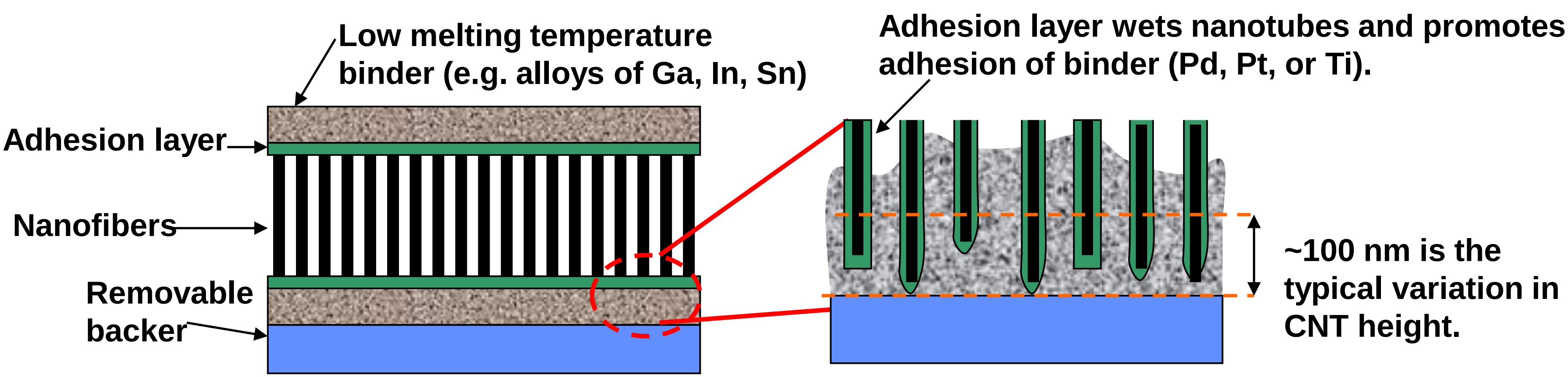
R. Colin Johnson

1/24/2011 12:01 AM EST

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

By sandwiching thermally conductive carbon nanotubes between





Hu, Fisher, Goodson, et al., *J. Heat Transfer* (2006)
SRC Patent: Hu, Jiang, Goodson, US Patent 7,504,453, issued 2009
SRC Patent: Panzer, Goodson, et al., 2009/0068387 (pending)

3D NanoPackaging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News & Analysis

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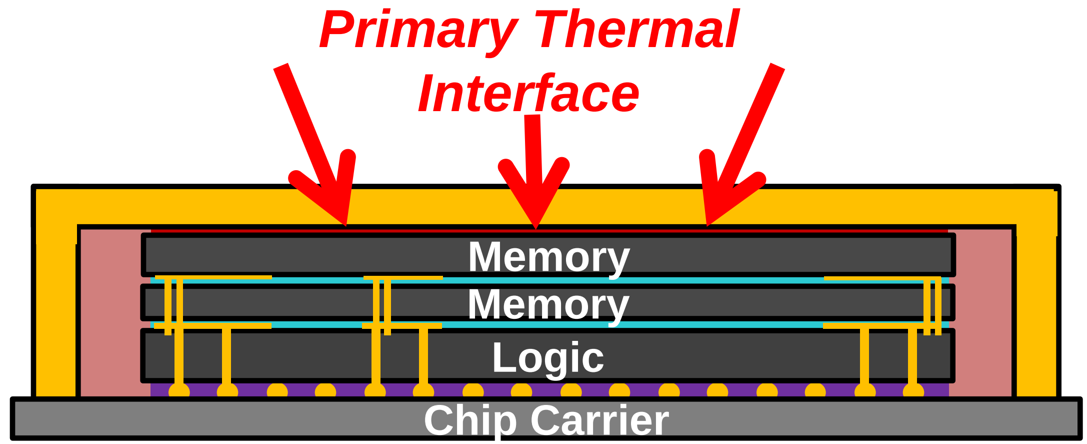


Carbon

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]

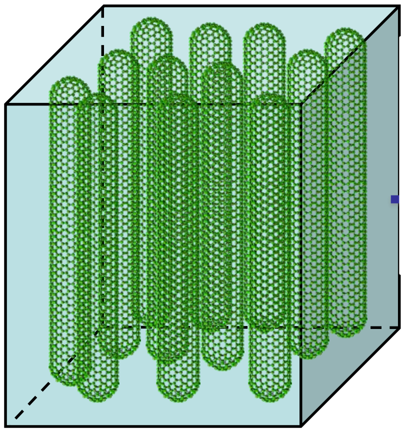
NANO LETTERS

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

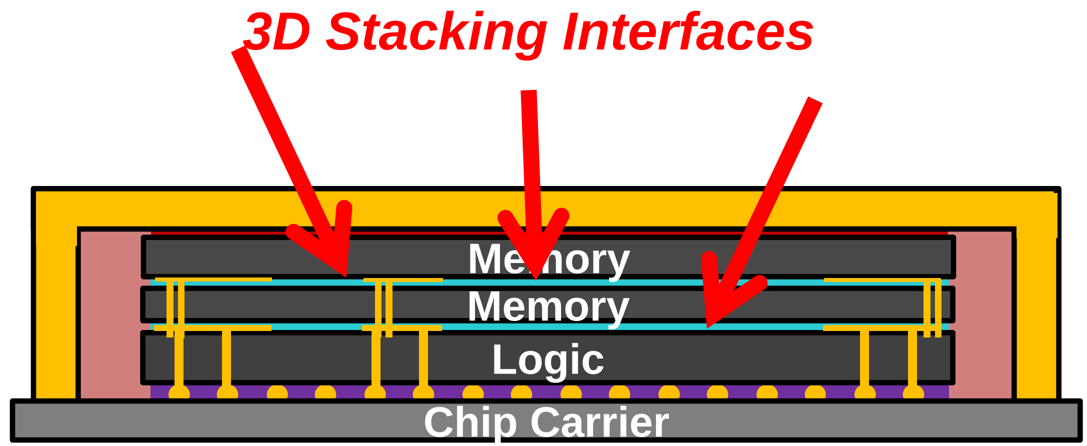
2010

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

3D NanoPackaging



CNT Composites



ACS NANO

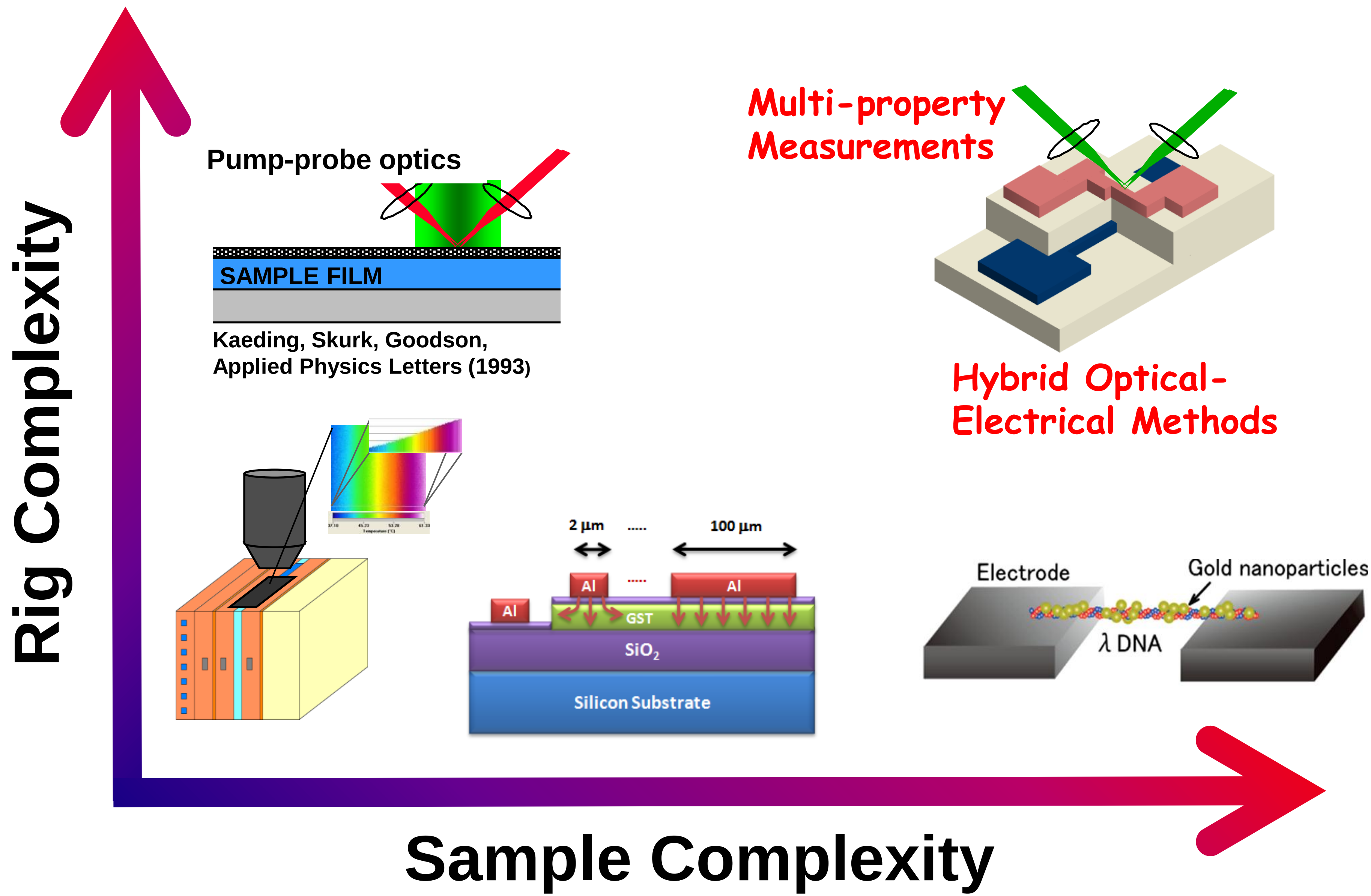
ARTICLE

Thermal Conduction in Aligned Carbon Nanotube–Polymer Nanocomposites with High Packing Density

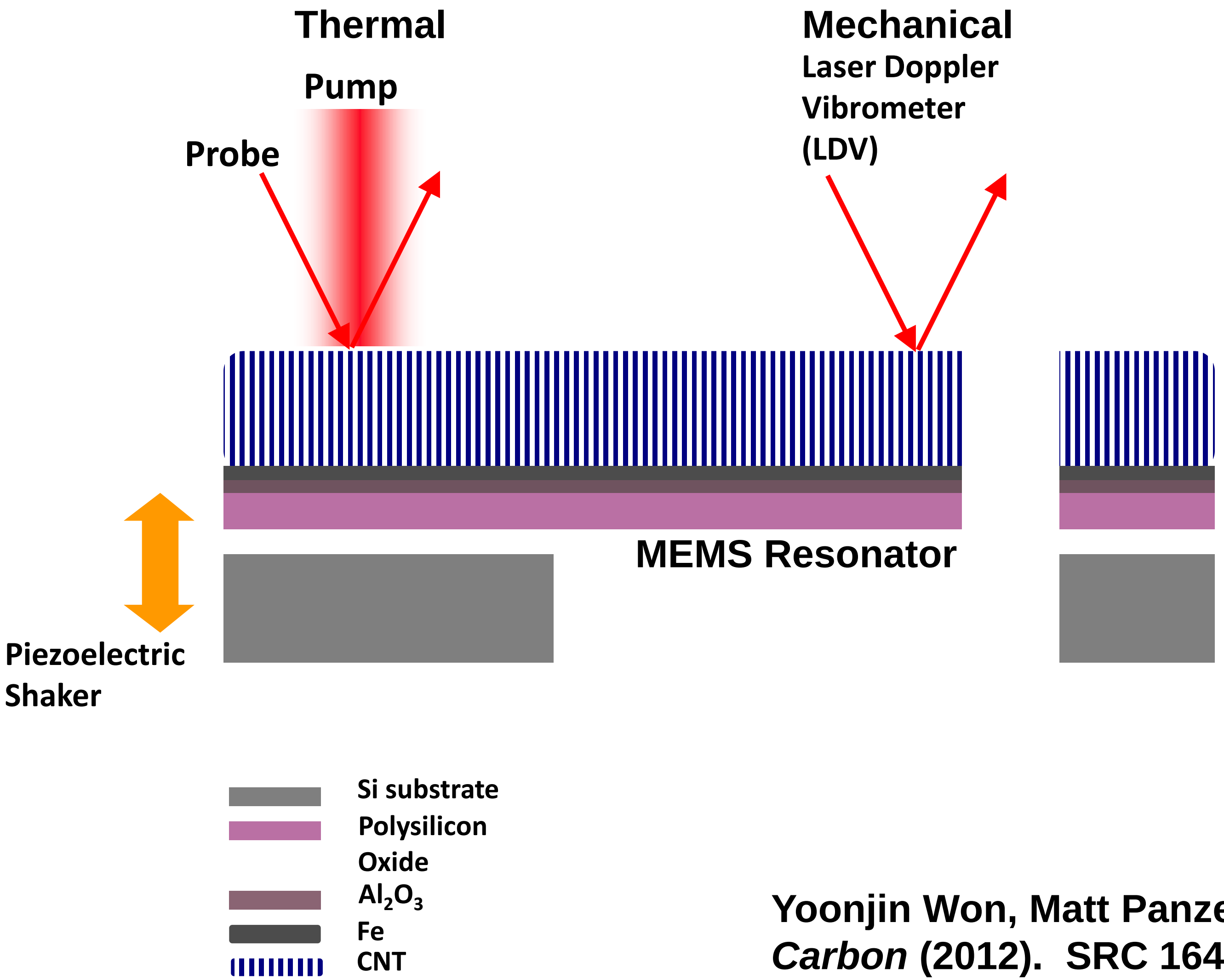
2011

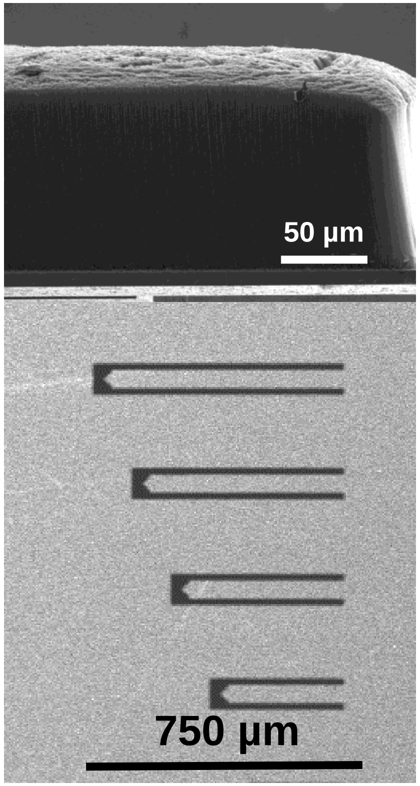
Amy M. Marconnet,[†] Namiko Yamamoto,[‡] Matthew A. Panzer,[†] Brian L. Wardle,[‡] and Kenneth E. Goodson[†,*]

Nano Thermal Metrology



Mechanical & Thermal Properties of Aligned CNT Films

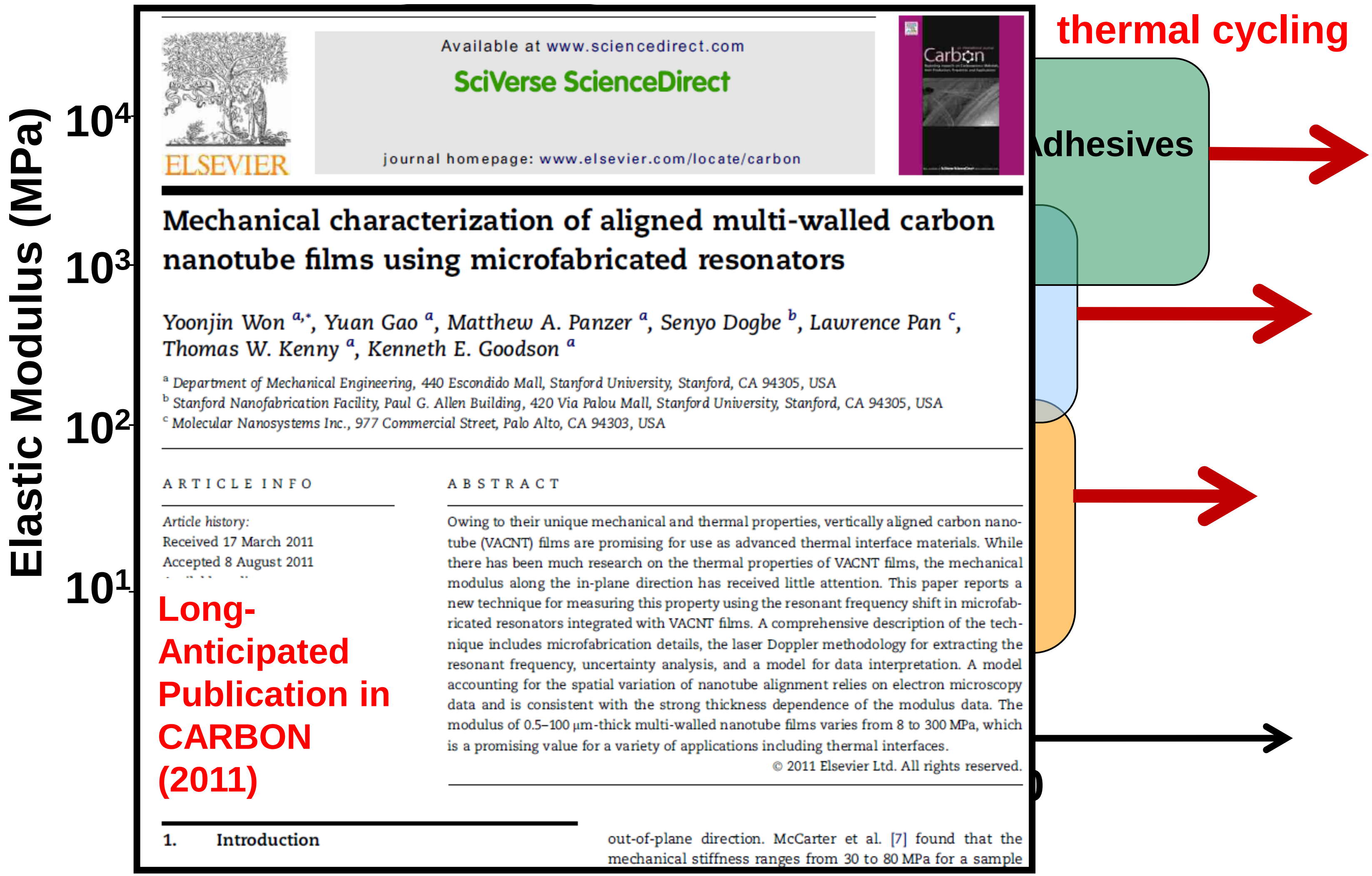




Yoonjin Won, Matt Panzer, Amy Marconnet
***Carbon* (2012). SRC 1640 (ended), 1966**

Thermal Interface Materials (TIM) Properties

Lifetime thermal cycling



Available at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/carbon

ELSEVIER

Carbon

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

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

[a] Department of Mechanical Engineering, 440 Escondido Mall, Stanford University, Stanford, CA 94305, USA
[b] Stanford Nanofabrication Facility, Paul G. Allen Building, 420 Via Palou Mall, Stanford University, Stanford, CA 94305, USA
[c] Molecular Nanosystems Inc., 977 Commercial Street, Palo Alto, CA 94303, USA

ARTICLE INFO

Article history:
Received 17 March 2011
Accepted 8 August 2011

ABSTRACT

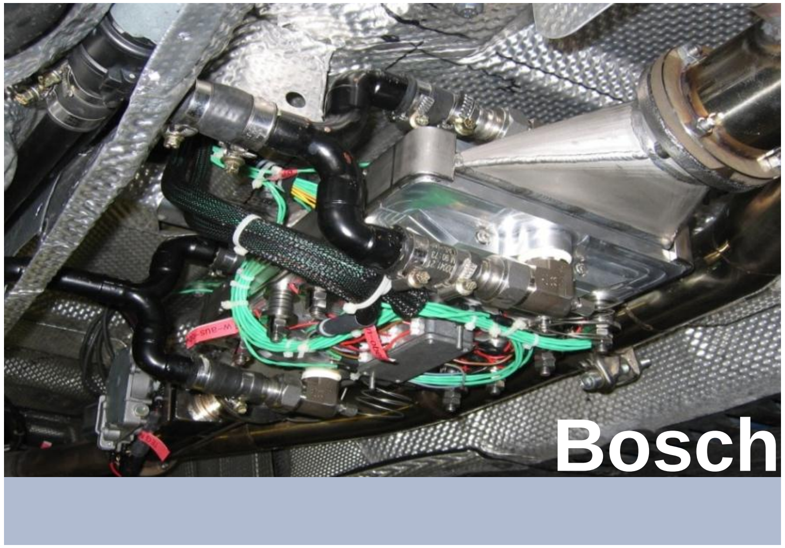
Owing to their unique mechanical and thermal properties, vertically aligned carbon nanotube (VACNT) films are promising for use as advanced thermal interface materials. While there has been much research on the thermal properties of VACNT films, the mechanical modulus along the in-plane direction has received little attention. This paper reports a new technique for measuring this property using the resonant frequency shift in microfabricated resonators integrated with VACNT films. A comprehensive description of the technique includes microfabrication details, the laser Doppler methodology for extracting the resonant frequency, uncertainty analysis, and a model for data interpretation. A model accounting for the spatial variation of nanotube alignment relies on electron microscopy data and is consistent with the strong thickness dependence of the modulus data. The modulus of 0.5–100 μm-thick multi-walled nanotube films varies from 8 to 300 MPa, which is a promising value for a variety of applications including thermal interfaces.

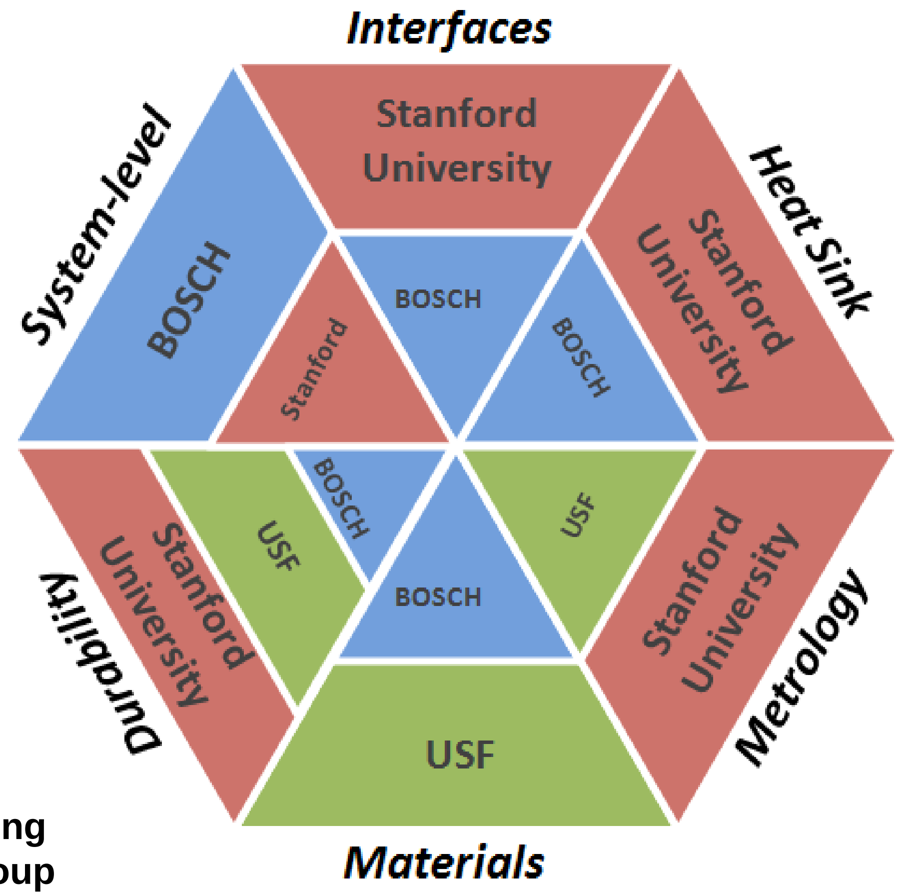
1. Introduction

out-of-plane direction. McCarter et al. [7] found that the mechanical stiffness ranges from 30 to 80 MPa for a sample

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

NSF-DOE Thermoelectrics Partnership
Automotive Thermoelectric Modules





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Dr. Boris Kozinsky (Bosch)
Prof. Mehdi Asheghi, Stanford Mechanical Engineering
Dr. Winnie Wong-Ng, NIST Functional Properties Group
Dr. Yongkwan Dong, USF Department of Physics

Students:

Michael Barako, Lewis Hom, Saniya Leblanc, Yuan Gao, Amy Marconnet

Leveraged Support:

Northrop Grumman, AMD/SRC, NSF Graduate Fellowships, Stanford Graduate Fellowship, Stanford DARE Fellowship, Sandia National Labs Fellowship

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

Outline

STANFORD nanoHeat

Metrology

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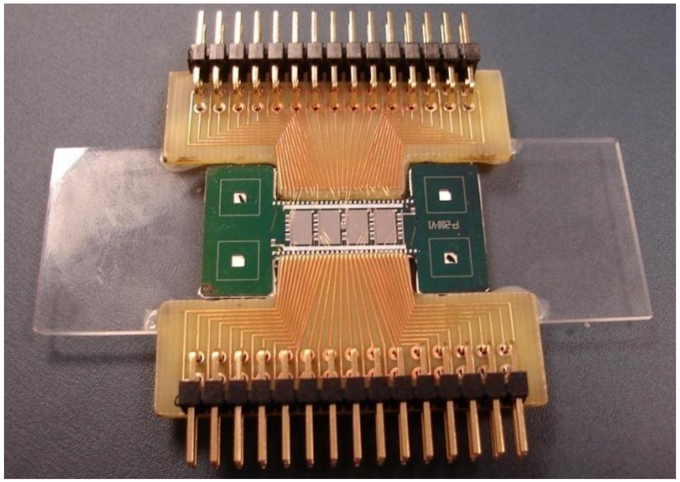
Microfluidic Cooling

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

Microfluidics Cooling Trajectory



IBM Thermal conduction module

Tuckerman & Pease microchannel demonstration

Microchannel implementation in laser diode cooling

Extensive single/two-phase flow research

Toshiba & Hitachi Laptops

DARPA Programs

Apple G5

100 W/Cm^2 → 300+ W/Cm^2

Multicore

3D microfluidics

Two-phase flow

Fluid Design

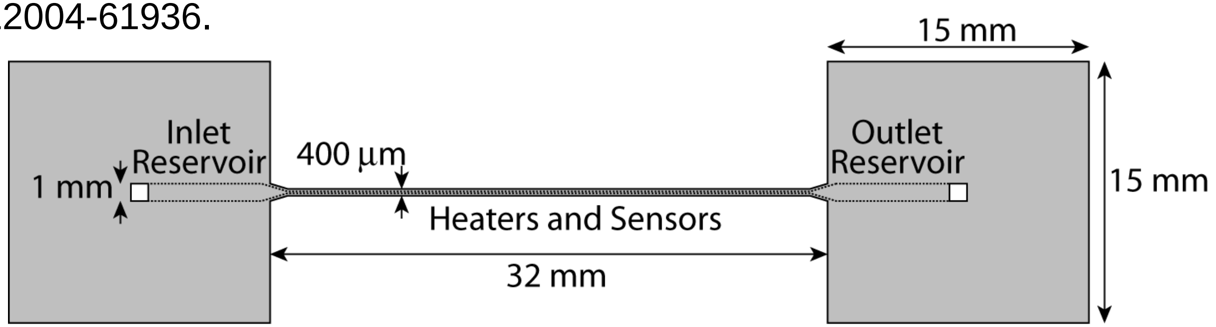
Nano Surfaces

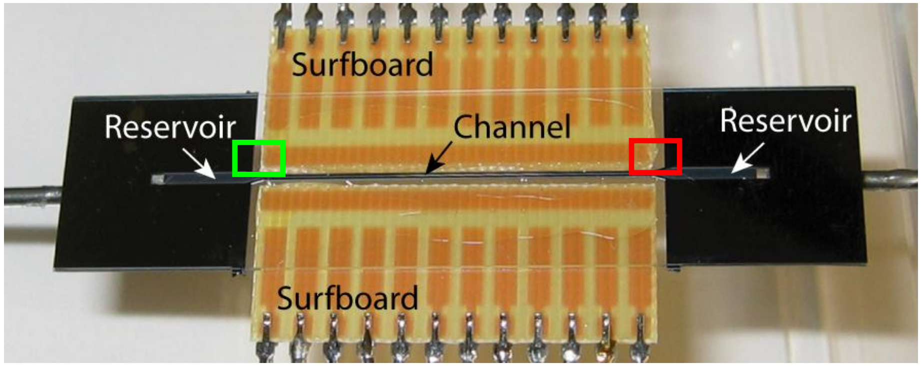
Liquid Cooling goes primetime

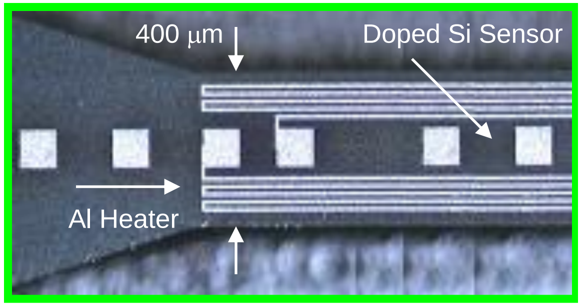
1985 **1990** **2000** **2005** **2010**

Instrumented Microfluidic Platform

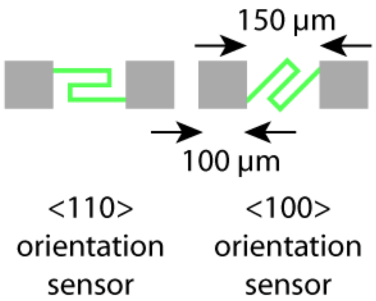
Kramer, Flynn, Fogg, Wang, Hidrovo, **Prasher, Chau, Narasimhan**, Goodson. "Microchannel Experimental Structure for Measuring Temperature Fields During Convective Boiling," *ASME International Mechanical Engineering Congress & Exposition*, Anaheim, CA, USA, November 13-19, 2004, IMECE2004-61936.

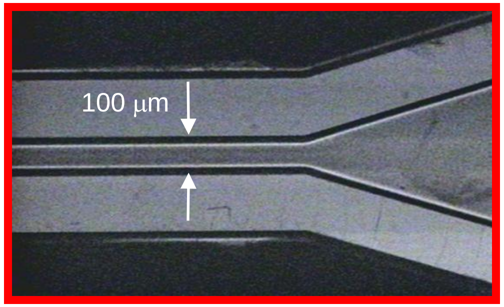






Back Side





Front Side

Trajectory of a Startup (Cooligy)

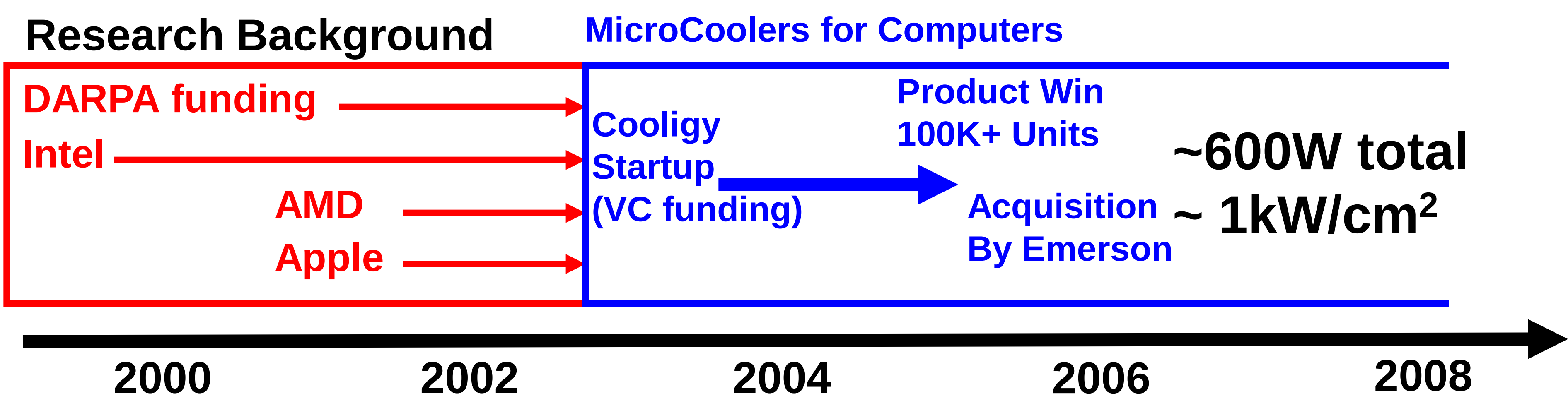
IEEE Transactions on Components and Packaging Technology (2002)
Best Paper at SEMITHERM 2001

Closed-Loop Electroosmotic Microchannel Cooling System for VLSI Circuits

Linan Jiang, James Mikkelsen, Jae-Mo Koo, David Huber, Shuhuai Yao, Lian Zhang, Peng Zhou, James G. Maveety, Ravi Prasher, Juan G. Santiago, Thomas W. Kenny, and Kenneth E. Goodson

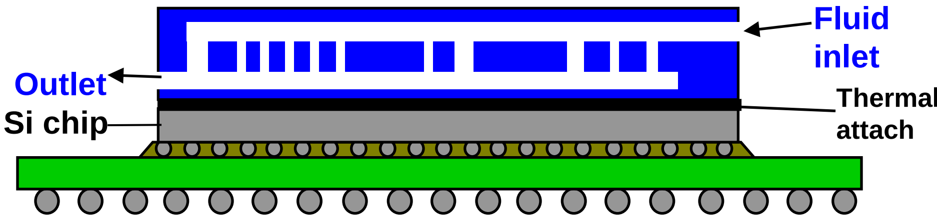
***Abstract*—The increasing heat generation rates in VLSI circuits motivate research on compact cooling technologies with low thermal resistance. This paper develops a closed-loop two-phase microchannel cooling system using electroosmotic pumping for the**

[3]. However, these capillary-driven devices are not optimal for chip powers exceeding a few tens of Watts because of the associated increases in heat pipe cross-sectional area and the limitations in the wick thickness. Recent research on

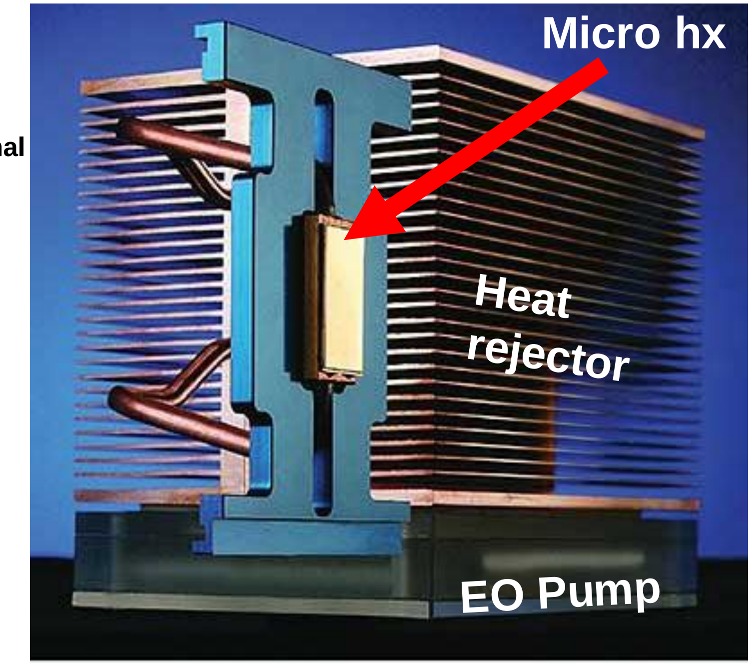


Trajectory of a Startup (Cooligy)

3D



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) → Product Win 100K+ Units; Acquisition By Emerson

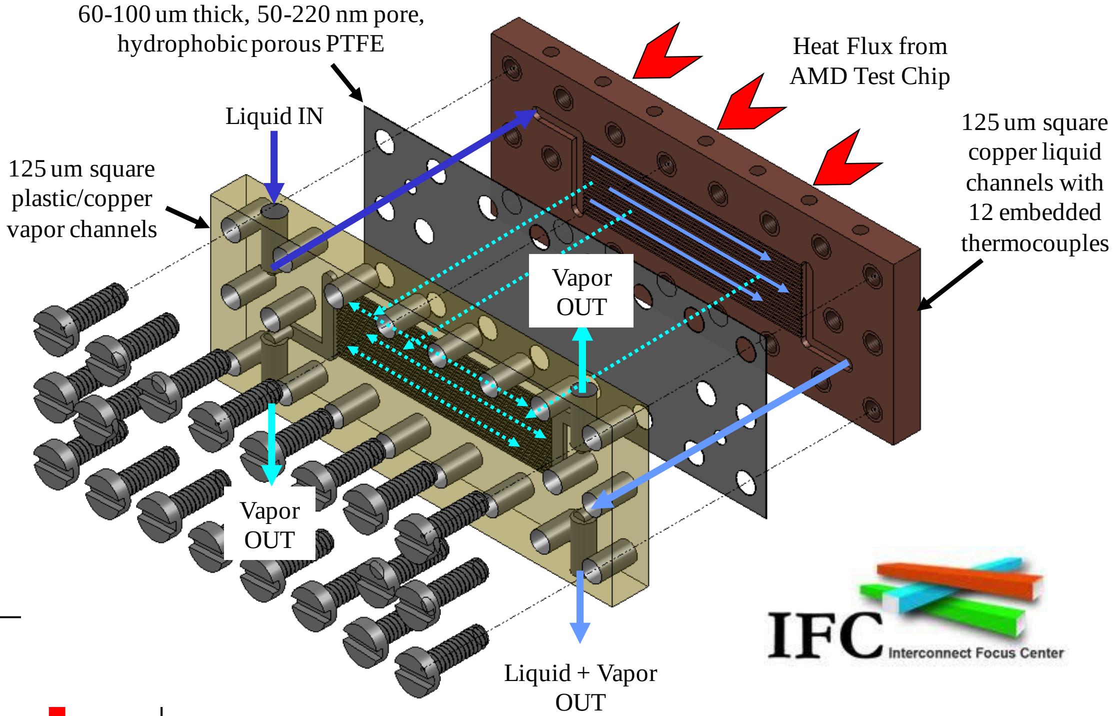
~600W total
~ 1kW/cm^2

2000 | 2002 | 2004 | 2006 | 2008

Vapor Escape Microfluidic HX Prototype

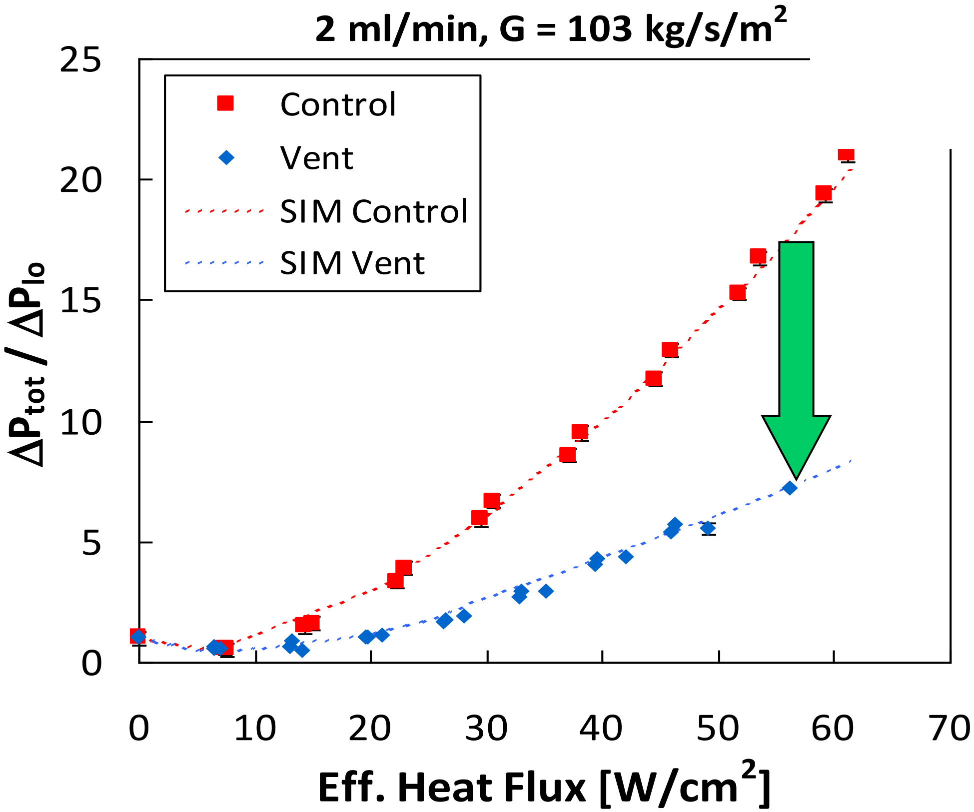
International Journal of Heat and Mass Transfer (2011)

International Journal of Multiphase Flow (2011)



IFC Interconnect Focus Center

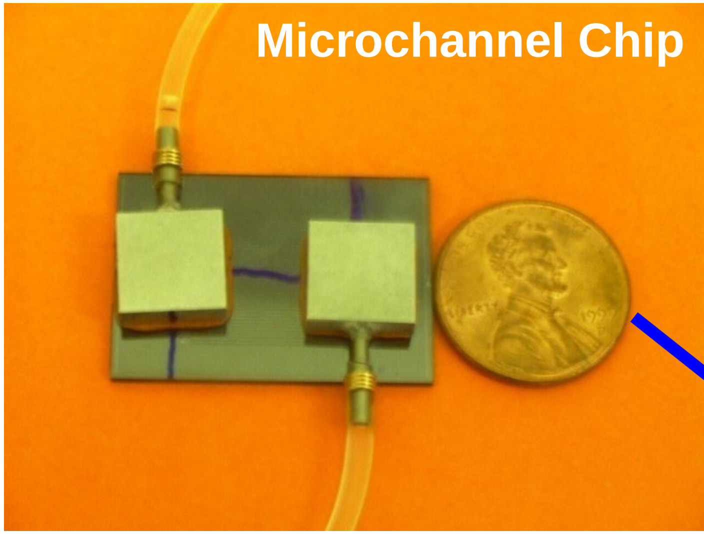
AMD

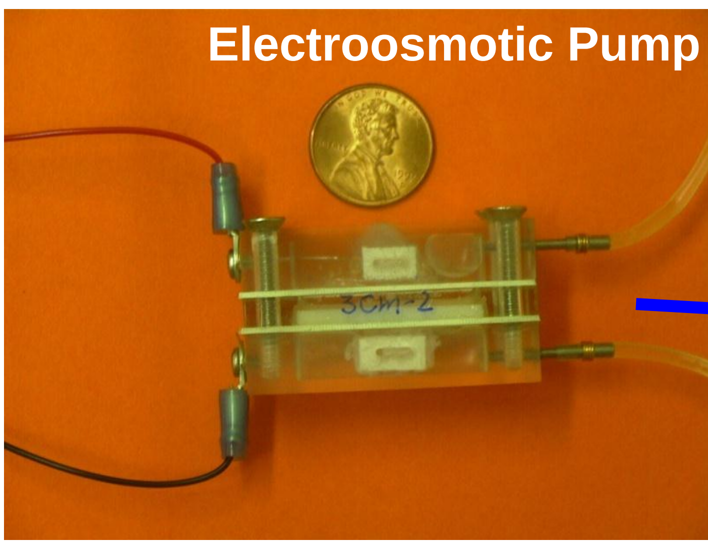


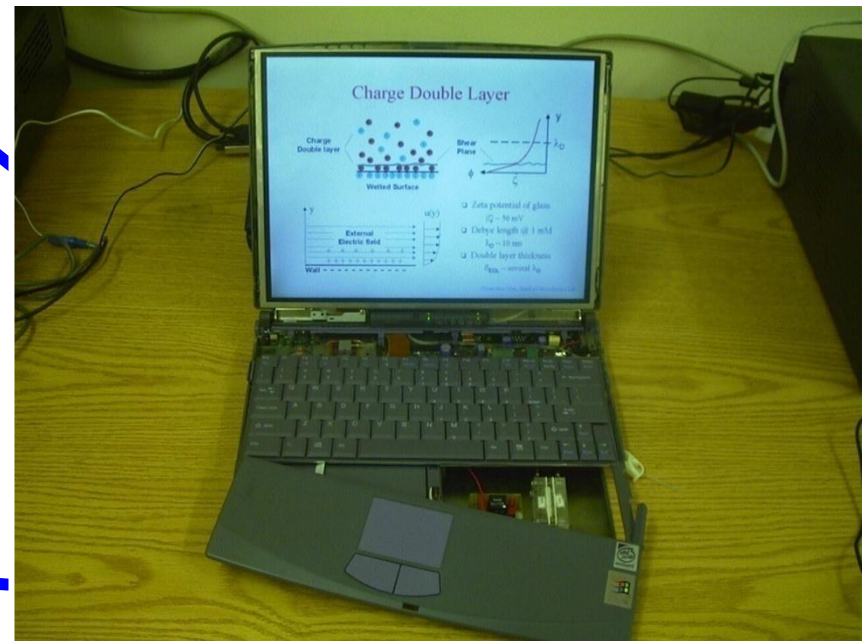
- **Vapor-transmitting membrane reduces pressure drop and instabilities along two-phase micro HX.**
- **Latest data show 60% pressure drop and nearly 50% drop in excess temperature over inlet saturation.**

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

Last-Minute VC Demo, 2001







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

STANFORD nanoHeat

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