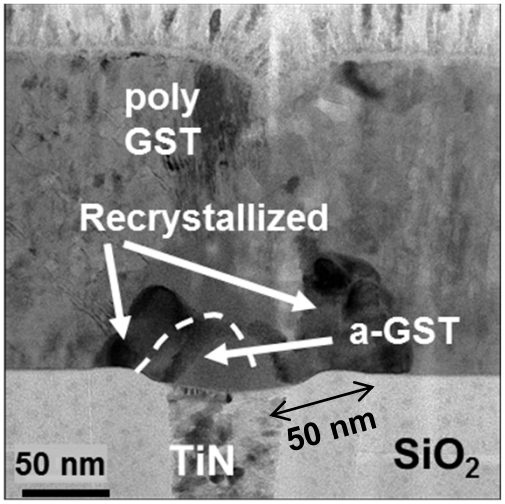
15th International Workshop on Computational Electronics
Phonon School May 21, 2012

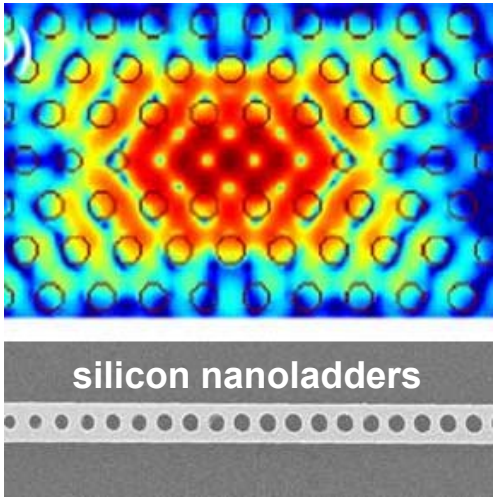
Phonons in NanoElectronics



With Wong Group,
Stanford EE

Ken Goodson
Mechanical Engineering
Stanford University

STANFORD nanoHeat



With Vuckovic Group,
Stanford EE

Electronics Thermal Challenges

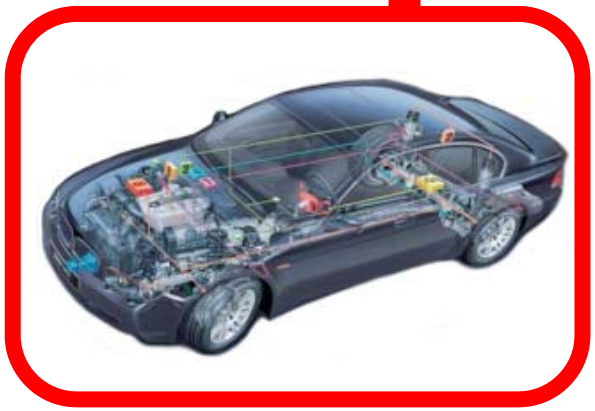
servers

portables

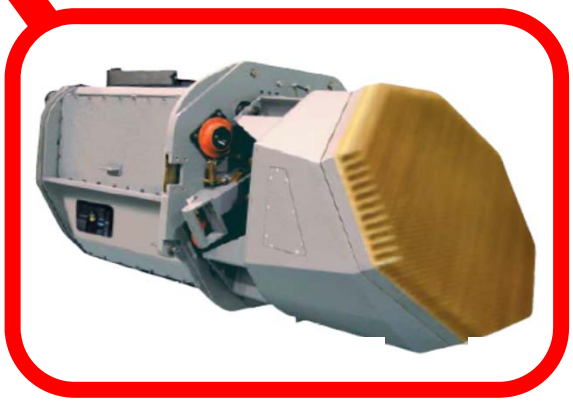
energy efficiency

hotspot mitigation

heterogeneous integration



transportation

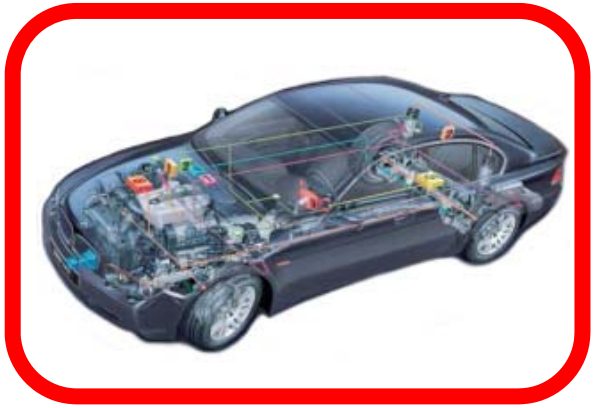


defense

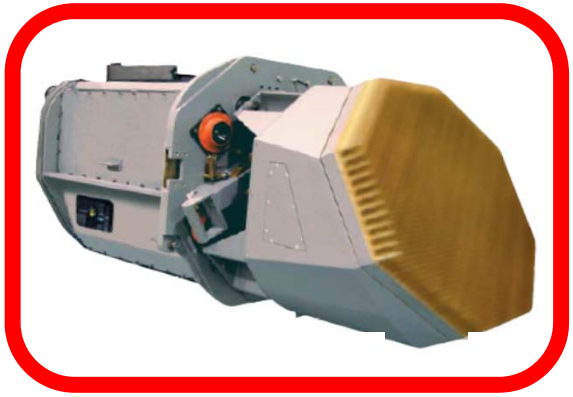
Electronics Thermal Challenges

servers

portables

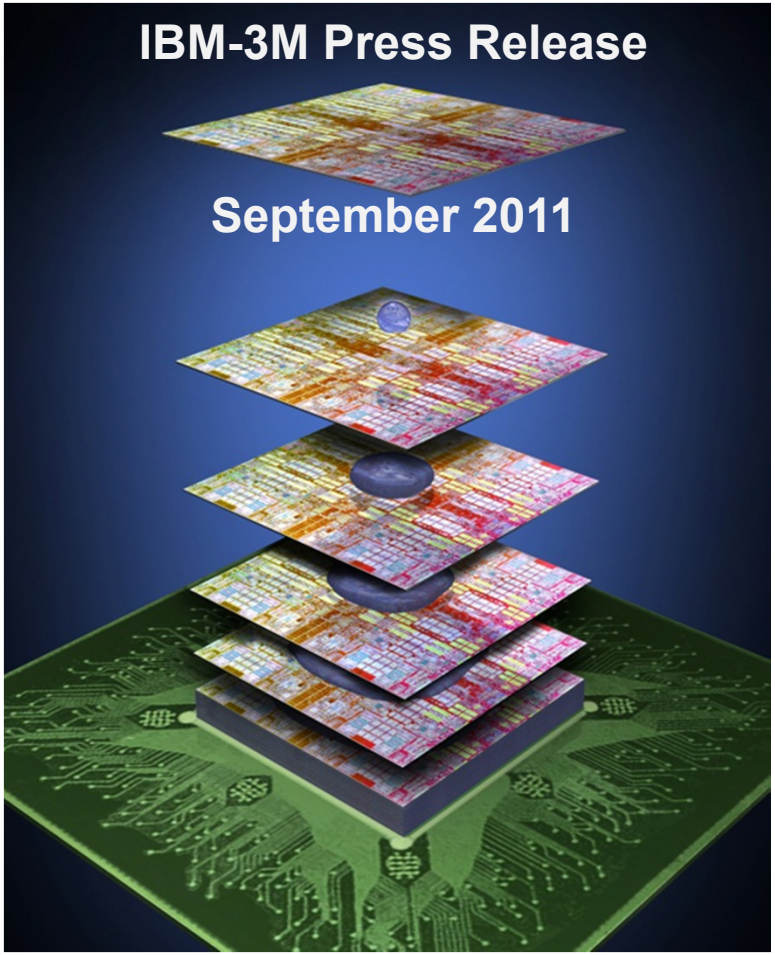


transportation



defense

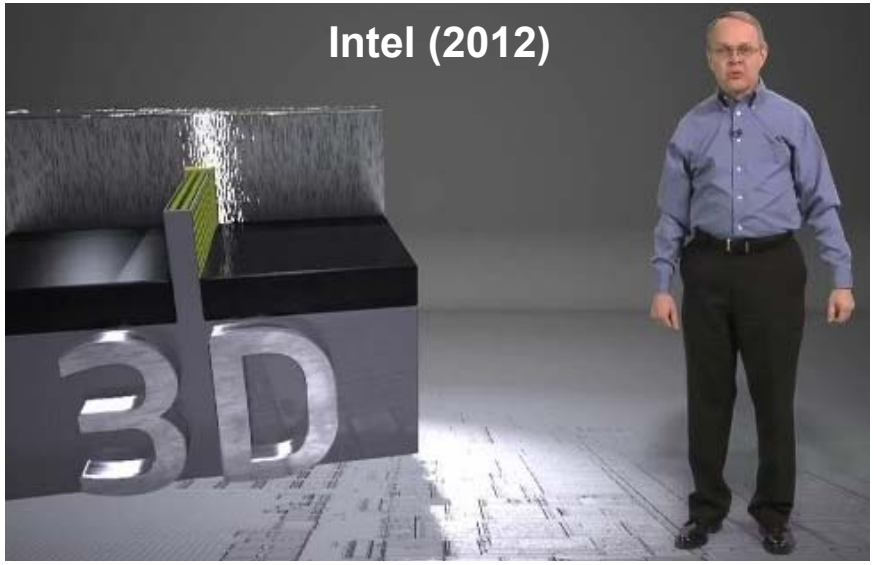
Electronics Cooling in the News



October 2012

Phonons in the News?

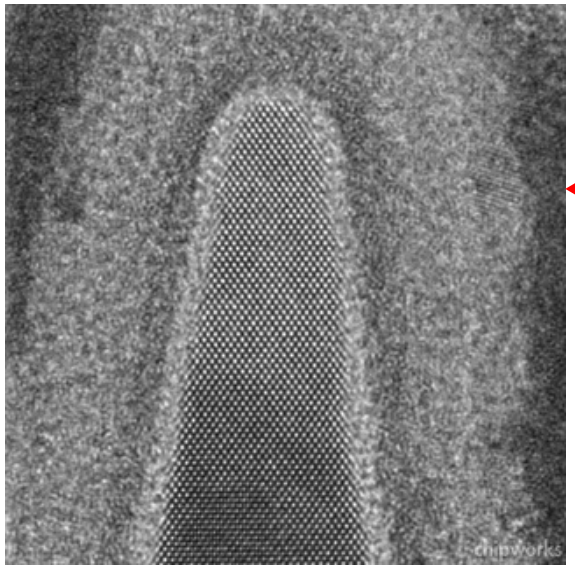
Finally, commercial finFETs

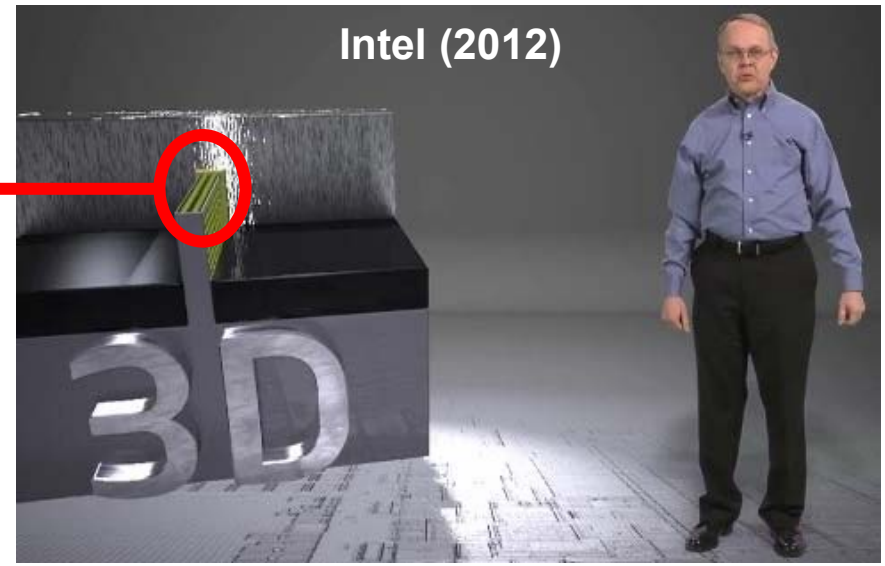


Samsung Cell Phone Memory, May 2011

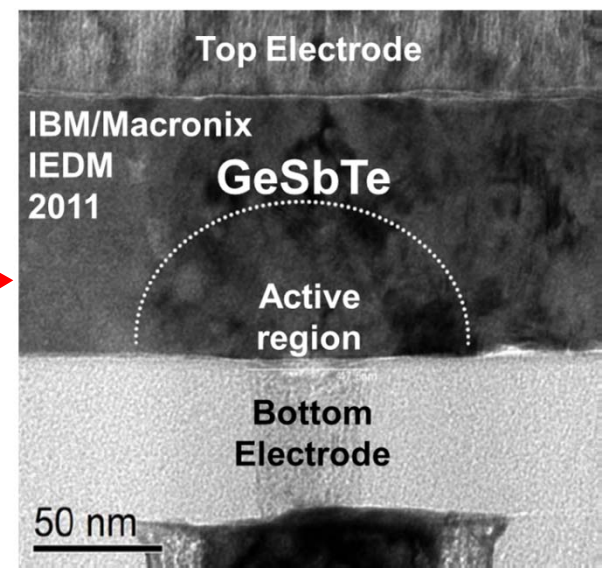
Finally, commercial phase change memory

Phonons in the News?

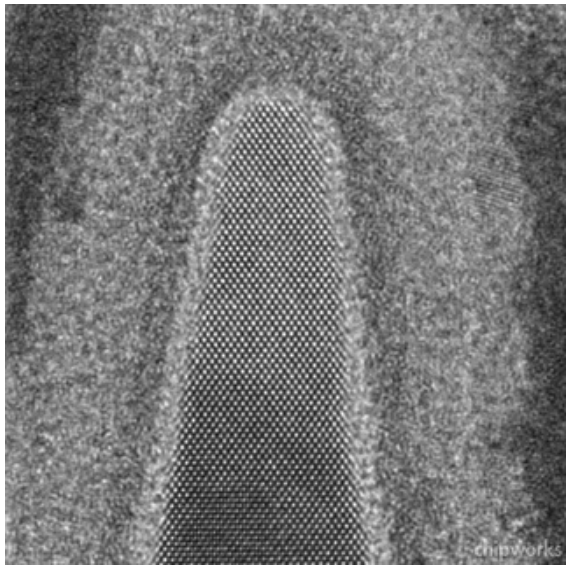


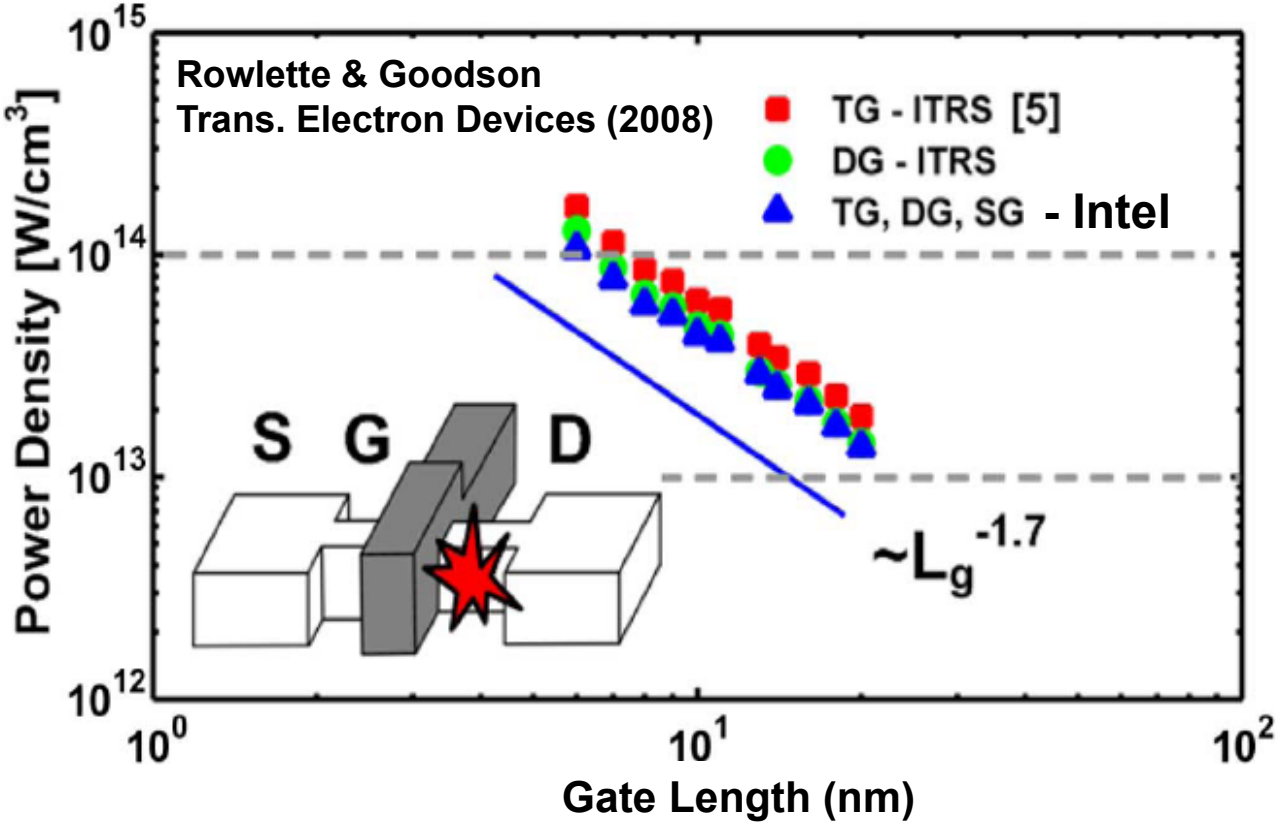


Samsung Cell Phone Memory, May 2011

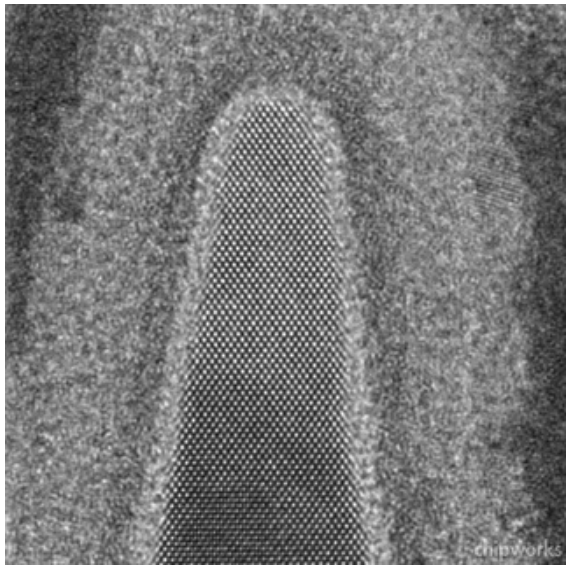


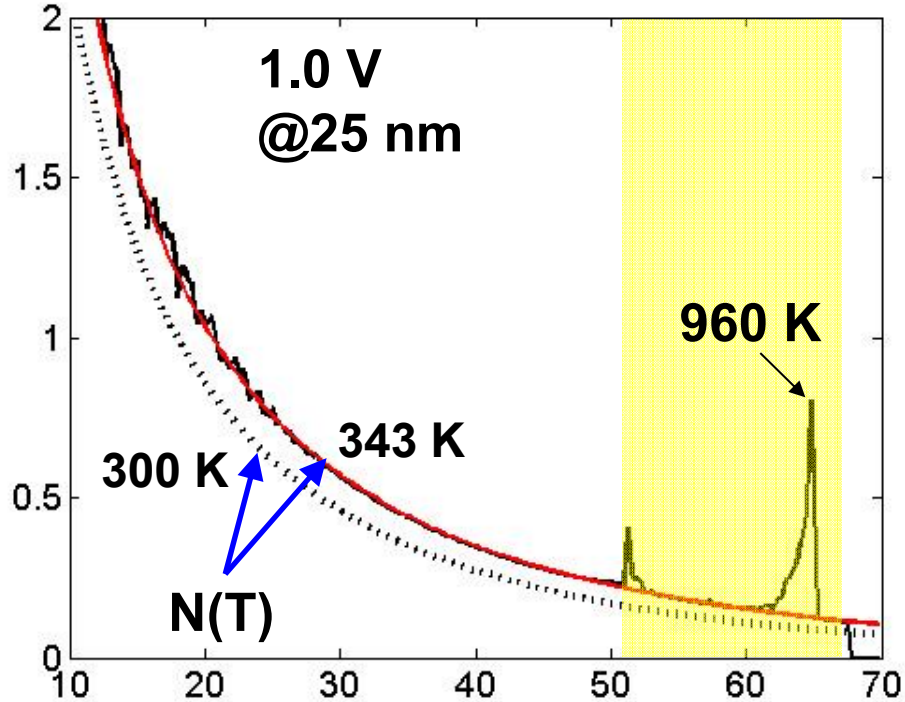
Phonons in the News?



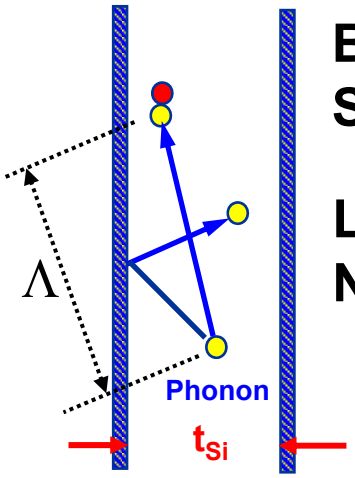


Phonons in the News?





Phonon Energy [meV]



Boundary Scattering

Local Phonon Nonequlibrium

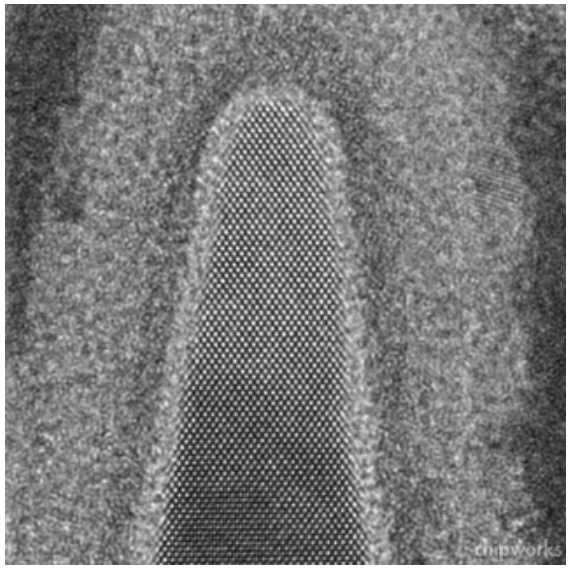
Proceedings of the IEEE

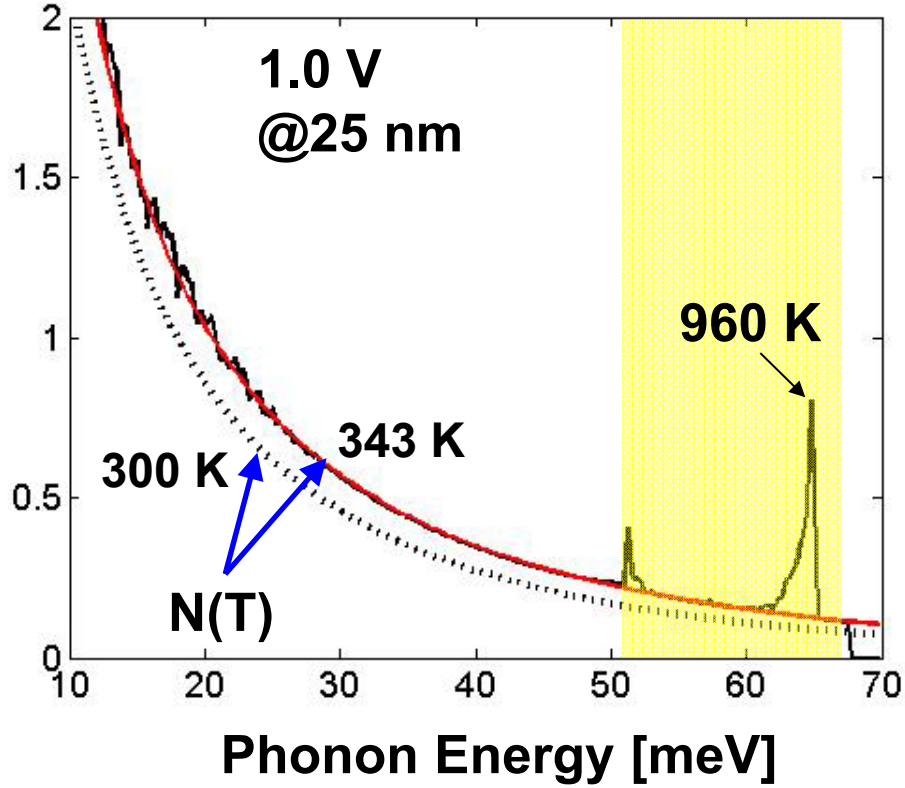
Heat Generation and Transport in Nanometer-Scale Transistors

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

Vol. 94 (2006)

Phonons in the News?





Branch Nonequilibrium (BTE Moments)

(Lai and Arun Majumdar 1996)

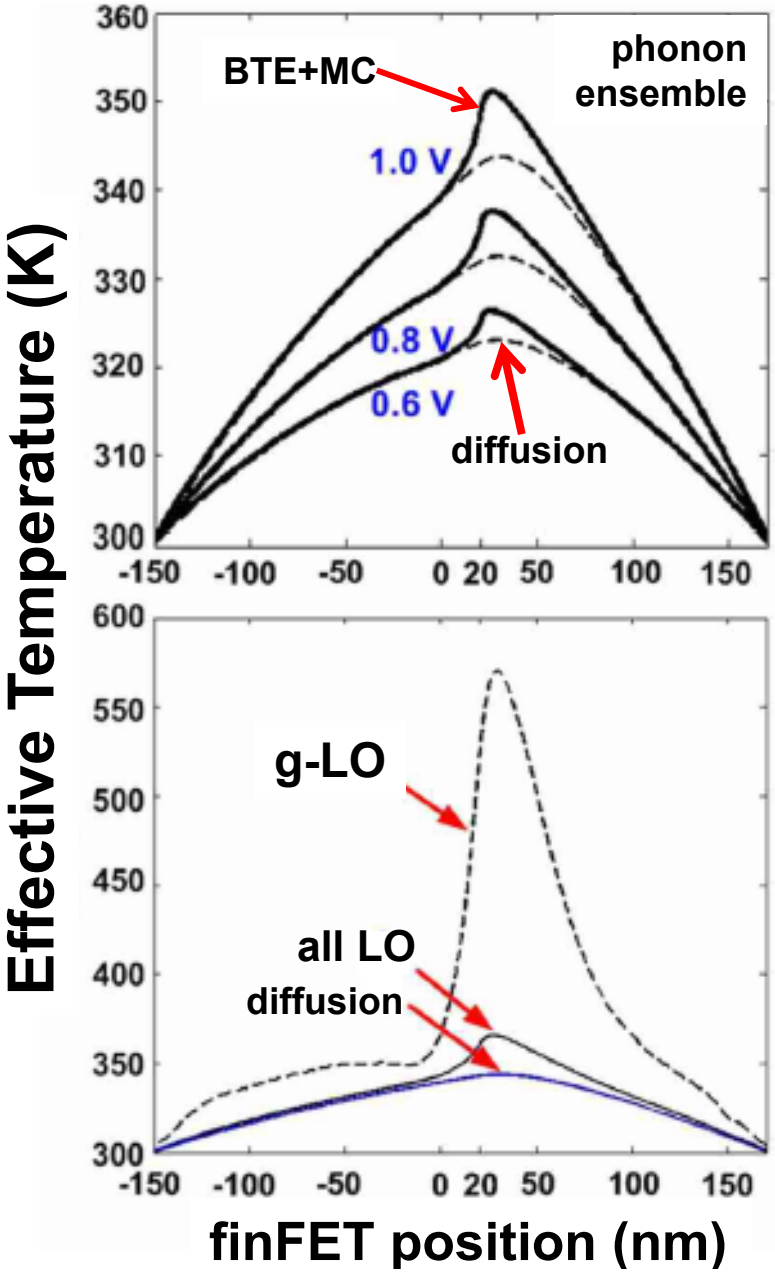
Hotspot Emission (BTE)

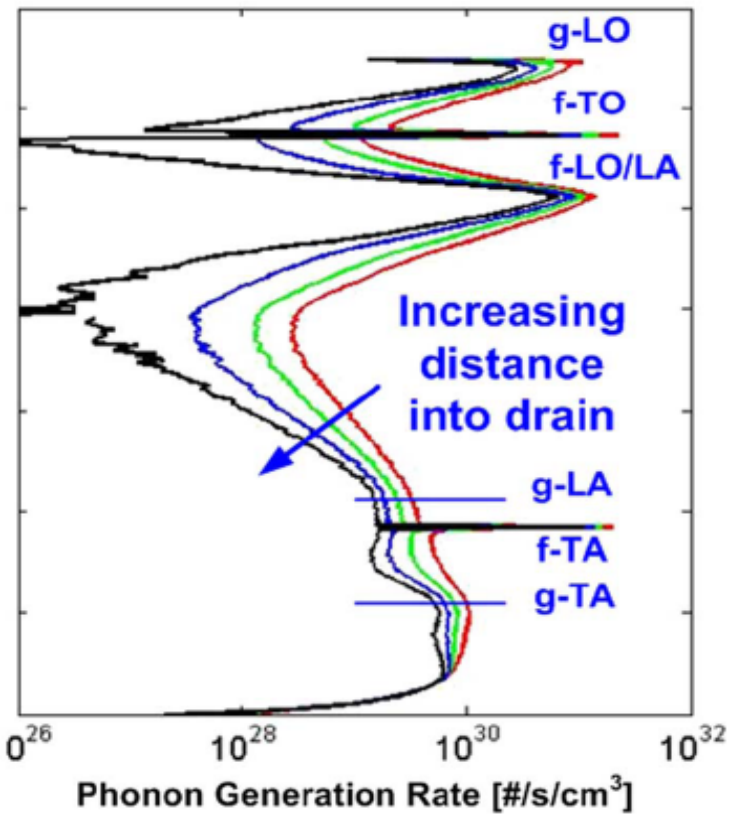
(Gang Chen 1996)

Boundary Scattering (SOI MOSFET)

(Goodson & Flik 1992; Sverdrup et al. 2001)

Phonons in the News?





Coupled Electron Monte Carlo & Phonon BTE in 20 nm finFET

IEEE TRANS. ELECTRON DEVICES (55) 2008

Jeremy A. Rowlette and Kenneth E. Goodson

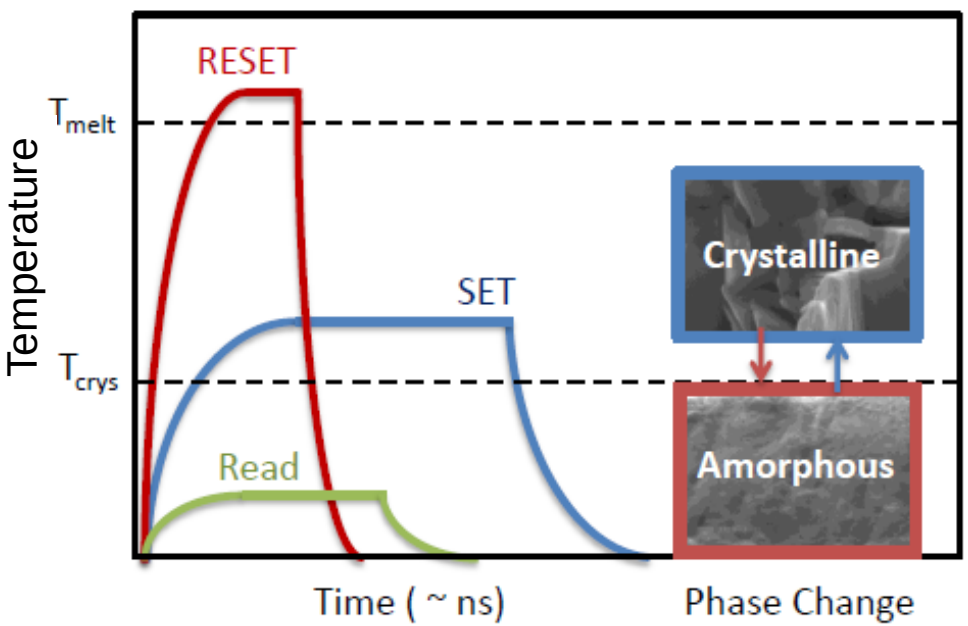
Phonons in the News?

Proceedings of the IEEE

Phase Change Memory

WONG, RAOUX, KIM, LIANG, REIFENBERG, RAJENDRAN, ASHEGHI, AND GOODSON

VOL. 98 (2010)



Phonons in the News?

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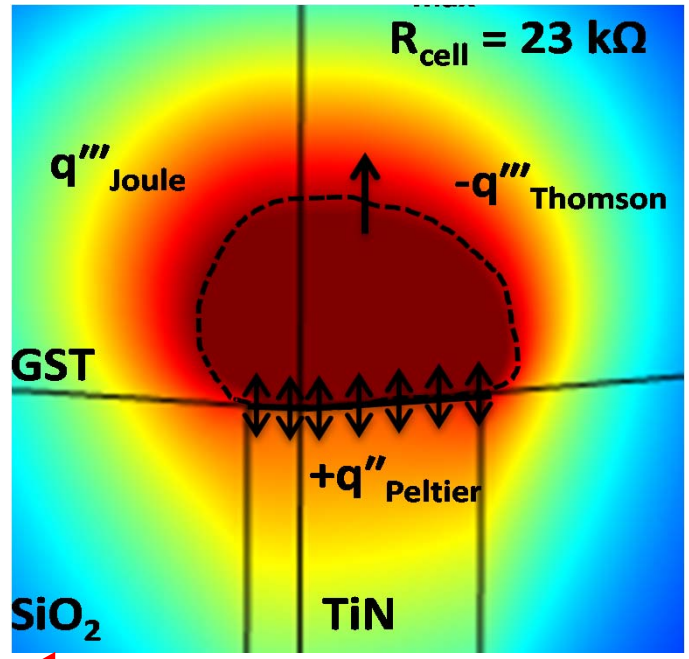
Phase Change Memory

WONG, RAOUX, KIM, LIANG, REIFENBERG, RAJENDRAN, ASHEGHI, AND GOODSON

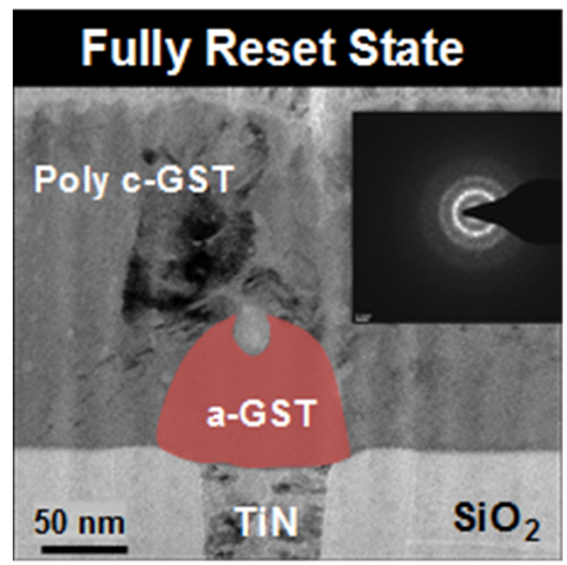
VOL. 98 (2010)

Lee, Asheghi, Goodson, *Nanotechnology* (2012)



Phonons in PCRAM

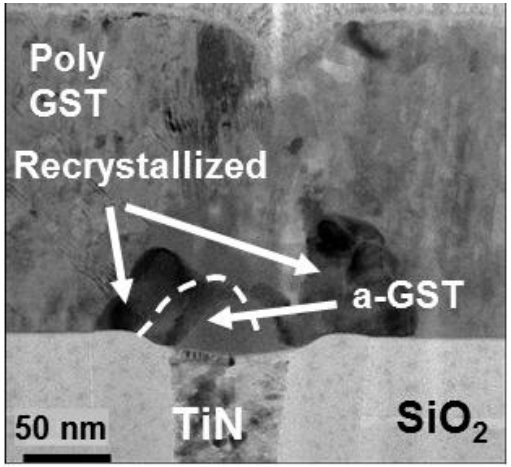
- **Electrode Interface**
  (Reifenberg et al., 2007 & 2008)
- **Phase Interfaces & Electrons**
  (Bozorg-Grayeli, 2011)
- **Thermoelectric Phenomena**
  (Lee et al., 2012)



(Kuzum, Wong, et al, 2011/2012)

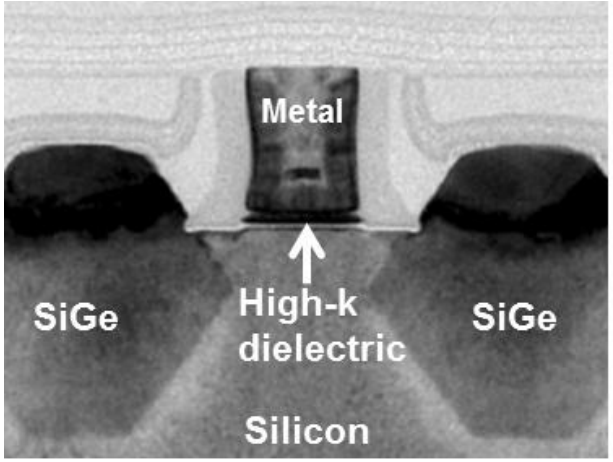
STANFORD nanoHeat

Phase Change NanoCells



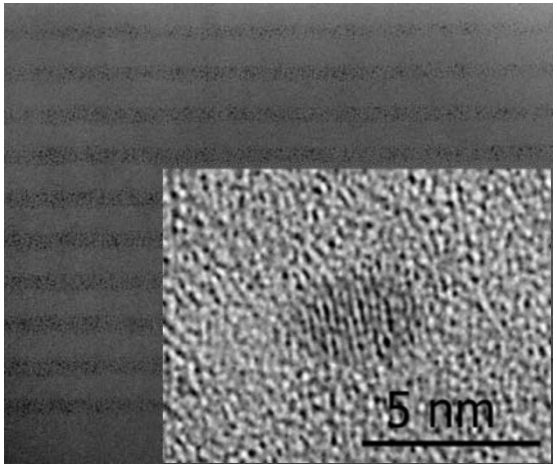
with Intel TMG, IBM (SRC) and Wong Group, Stanford EE

NanoFETs



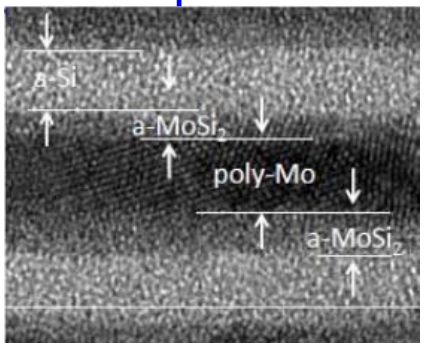
with Intel ATD (SRC)

Optical Nanocrystals



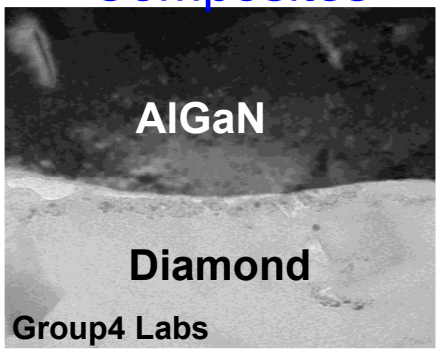
with Brongersma group, Stanford MSE

Extreme UV Optics



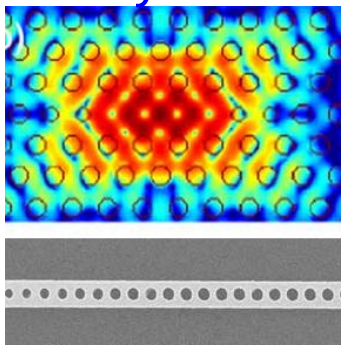
with KLA Tencor

GaN-Diamond Composites



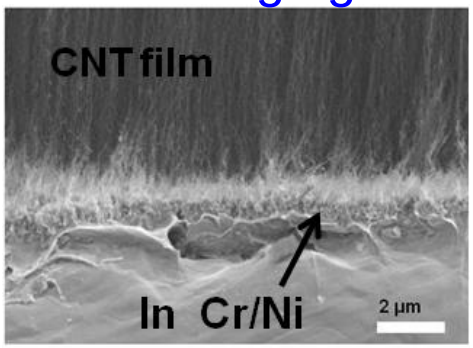
with Raytheon, Boeing, Boeing, BAE (DARPA NJTT)

Quantum Cavity Lasers



with Vuckovic group, Stanford EE

Nanostructured Packaging



with Bosch (NSF/DOE Partnership)

STANFORD nanoHeat

Current Group

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

Ken Goodson

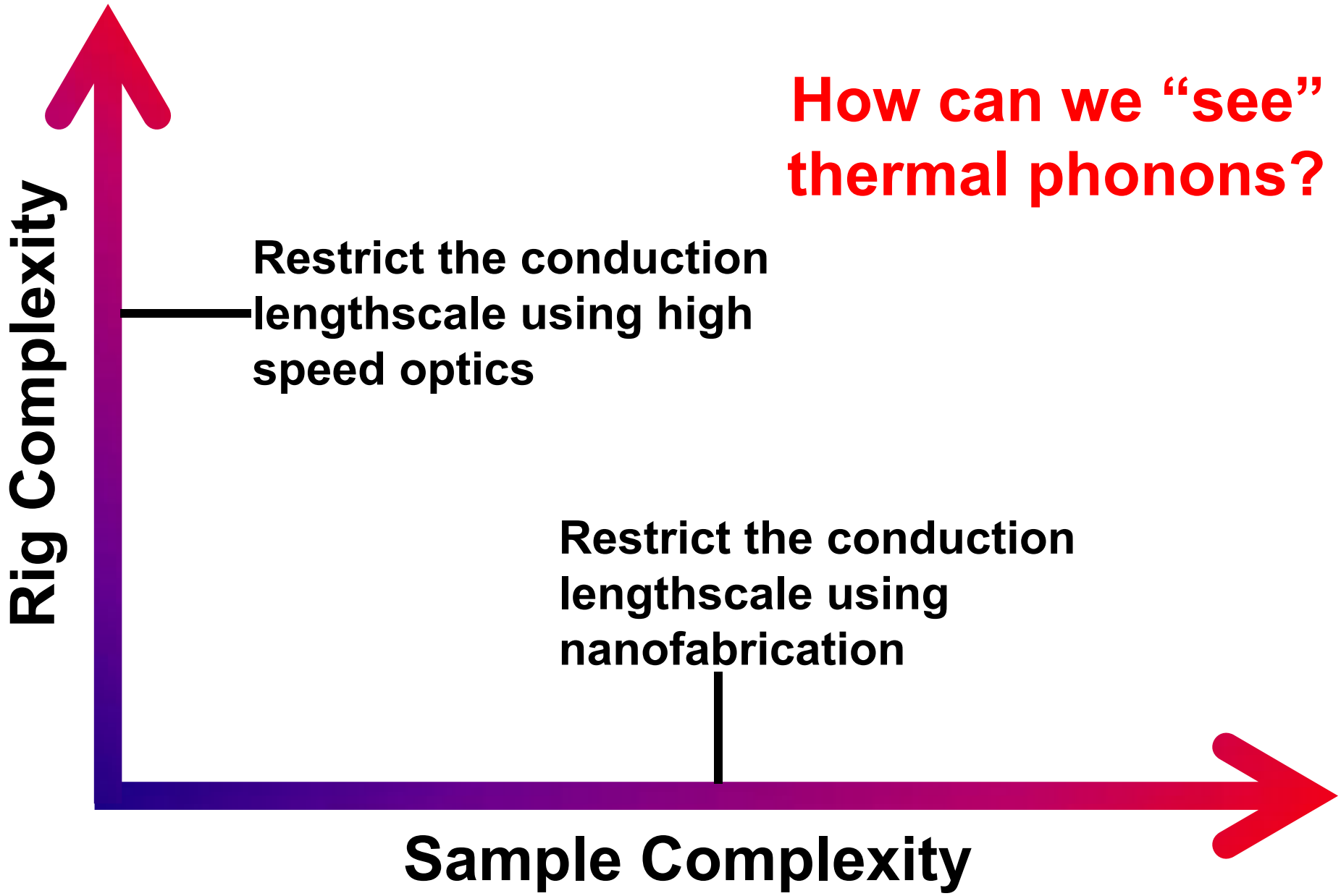
Lewis Hom
Aditja Sood (MSE)
Woosung Parc

Dr. Takashi Kodama
Dr. Yoonjin Won
Prof. Mehdi Asheghi

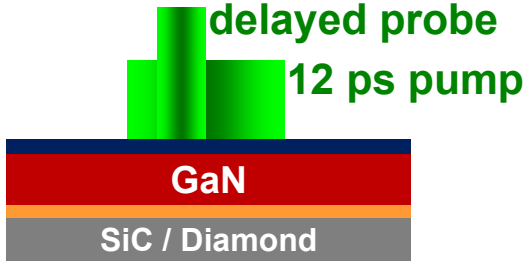
Selected Alumni

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 (EE)
Prof. Sanjiv Sinha	UIUC
Prof. Xeujiao Hu	Wuhan Univ.
Prof. Carlos Hidrovo	UT Austin
Prof. Kaustav Banerjee	UCSB (EE)
Prof. Ankur Jain	UT Arlington
Prof. Sarah Parikh	Foothill College
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	Intel
Dr. David Fogg	Creare
Dr. Matthew Panzer	KLA-Tencor

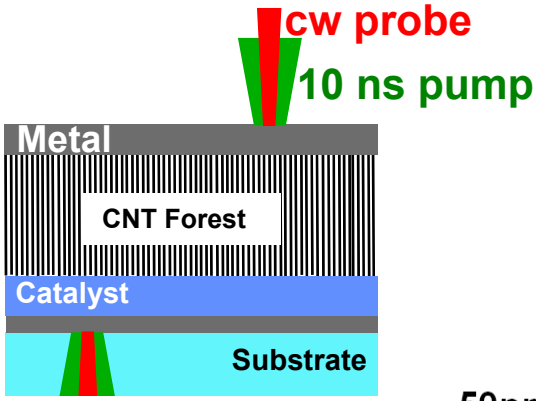
Nano Thermal Metrology



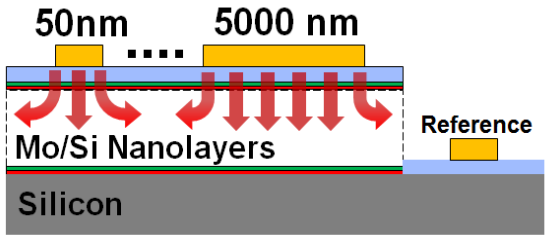
Nano Thermal Metrology



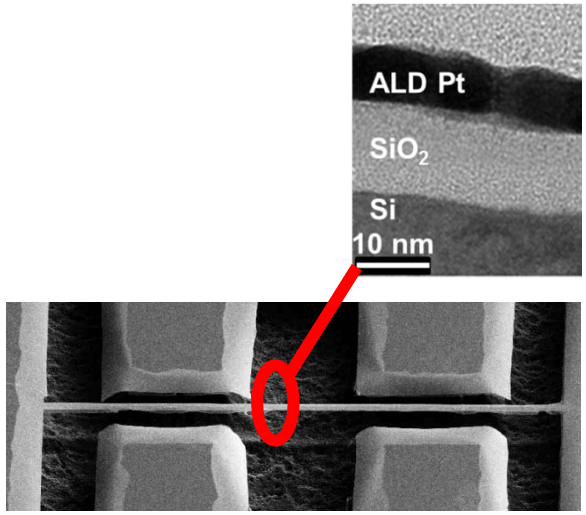
Students: Cho, Bozorg-Grayeli
Electron Device Letters (2012)



Students: Panzer, Gao
Nano Letters (2010)



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



Students: Yoneoka, Li, Kodama
Nano Letters (2012 in press)

Rig Complexity

Sample Complexity

Phonons in Nanowires & NanoTubes

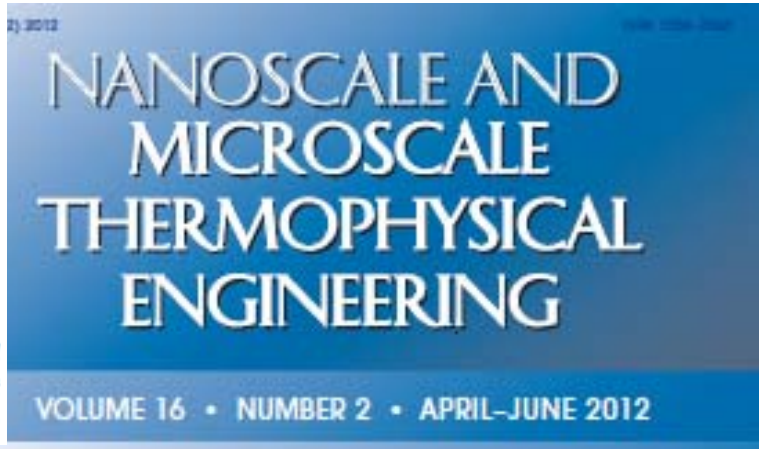
Appearing this month from Li Shi, UT Austin

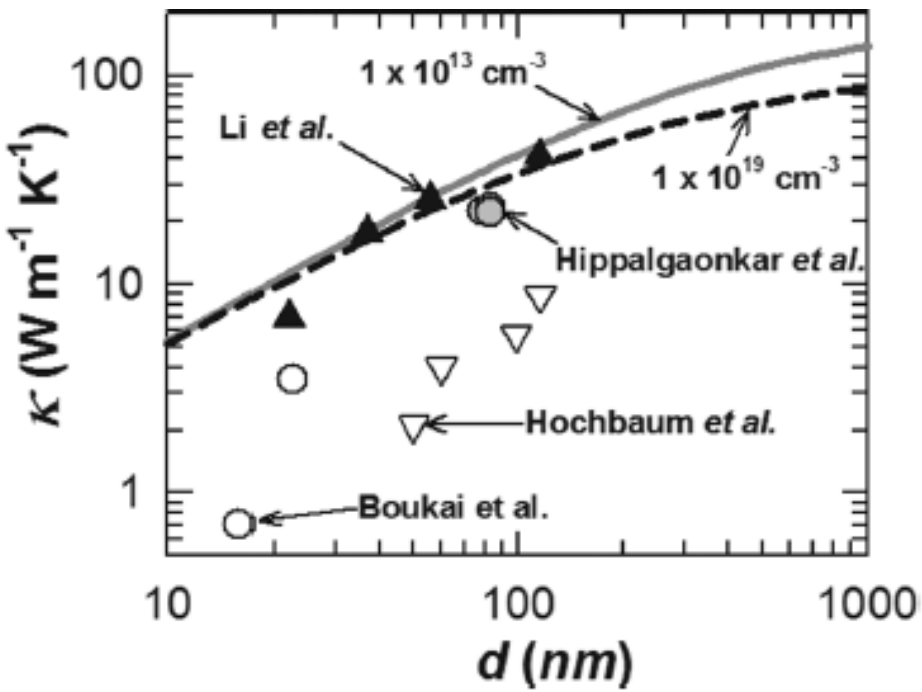
THERMAL AND THERMOELECTRIC TRANSPORT IN NANOSTRUCTURES AND LOW-DIMENSIONAL SYSTEMS

Li Shi

Department of Mechanical Engineering, Texas Materials Institute, The University of Texas at Austin, Austin, Texas

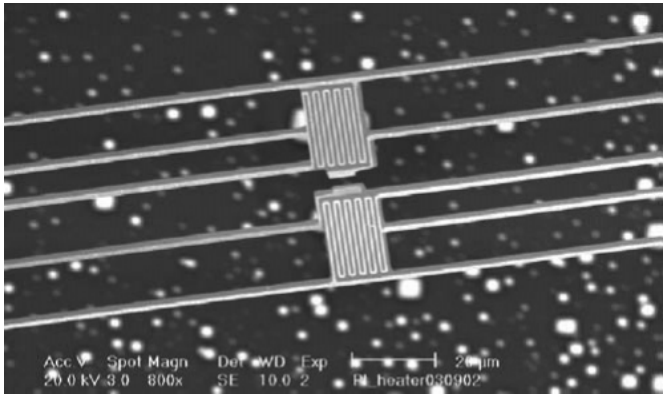
Significant progress has been made in recent studies of thermal and thermoelectric transport phenomena in nanostructures and low-dimensional systems. This article reviews several intriguing quantum and classical size effects on thermal and thermoelectric properties that have been predicted by theoretical calculations or observed in experiments. Attention is





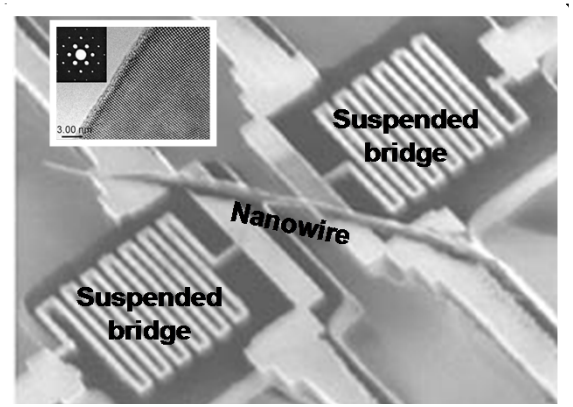
Phonons in Nanowires & NanoTubes

External Heating



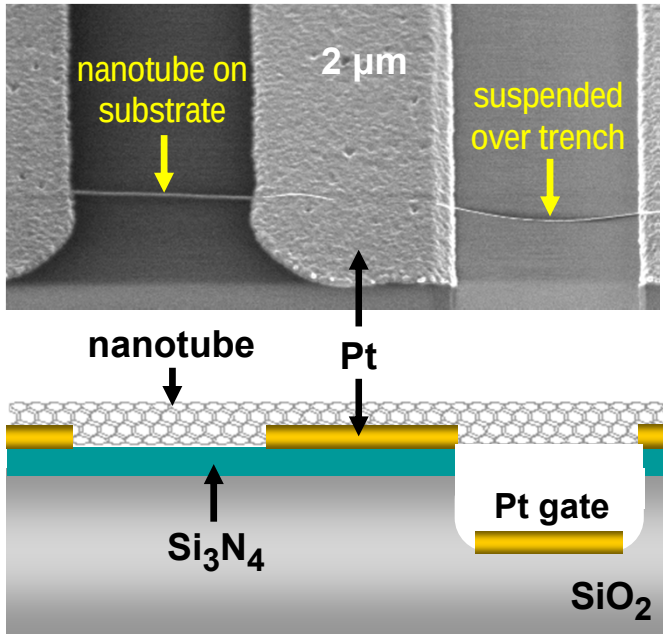
Shi and Li, JHT (2003)
Yu, Shi et al., Nanoletters (2005)

McConnell, Goodson et al. (2004)



Li, Majumdar, Yang, et al.
Applied Physics Letters (2003)

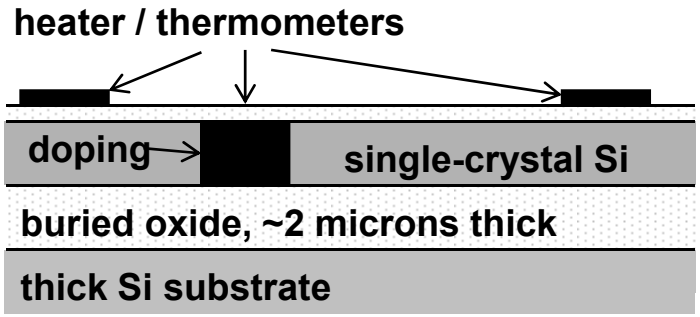
Internal Heating



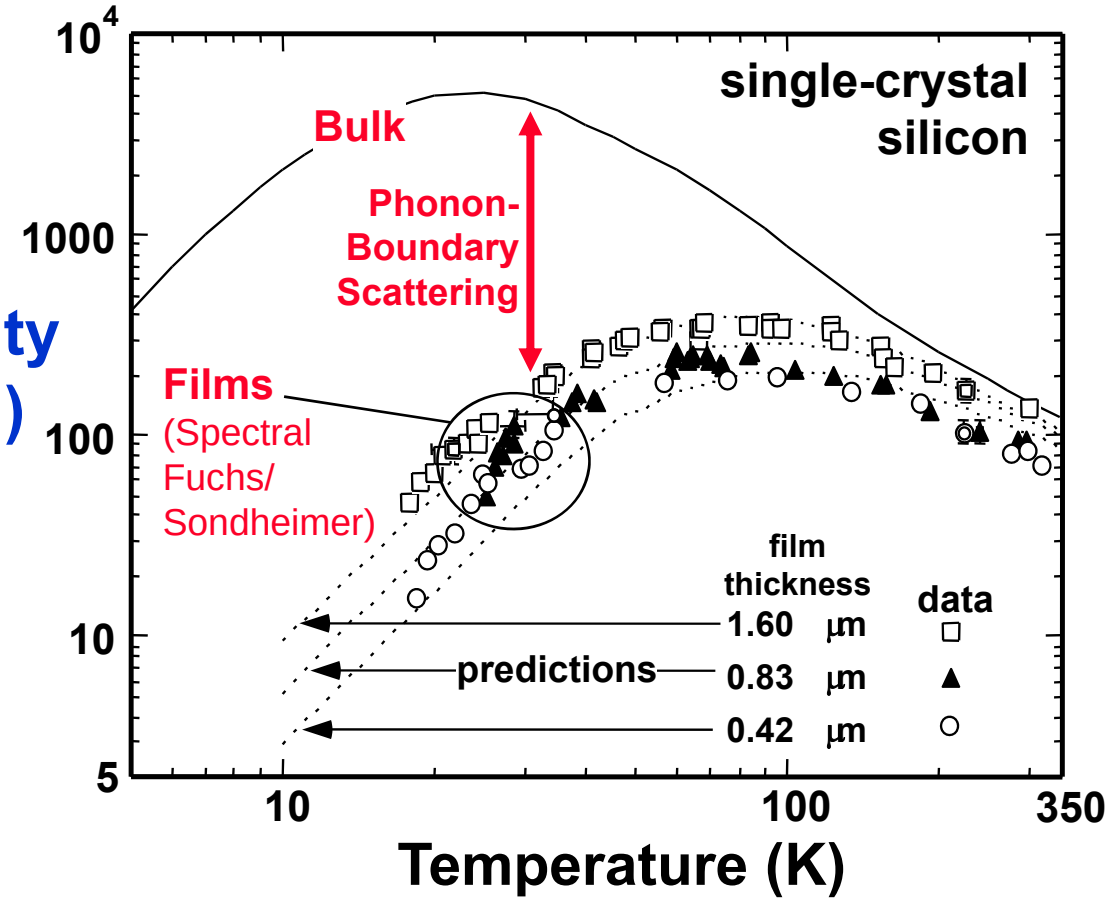
Pop, Goodson, Dai et al., *Nano Letters* (2006),
Pop, Goodson, Dai et al., *Physical Review Letters* (2005)

SOI-Enabled Phonon Studies 1994-

Measurement Structure



Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)

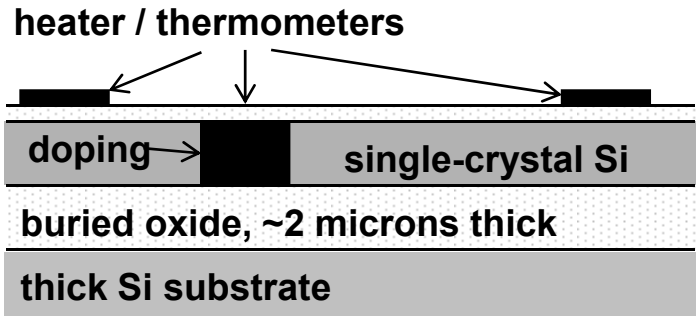


Asheghi, Goodson, et al., *Applied Physics Letters* 71 (1997)

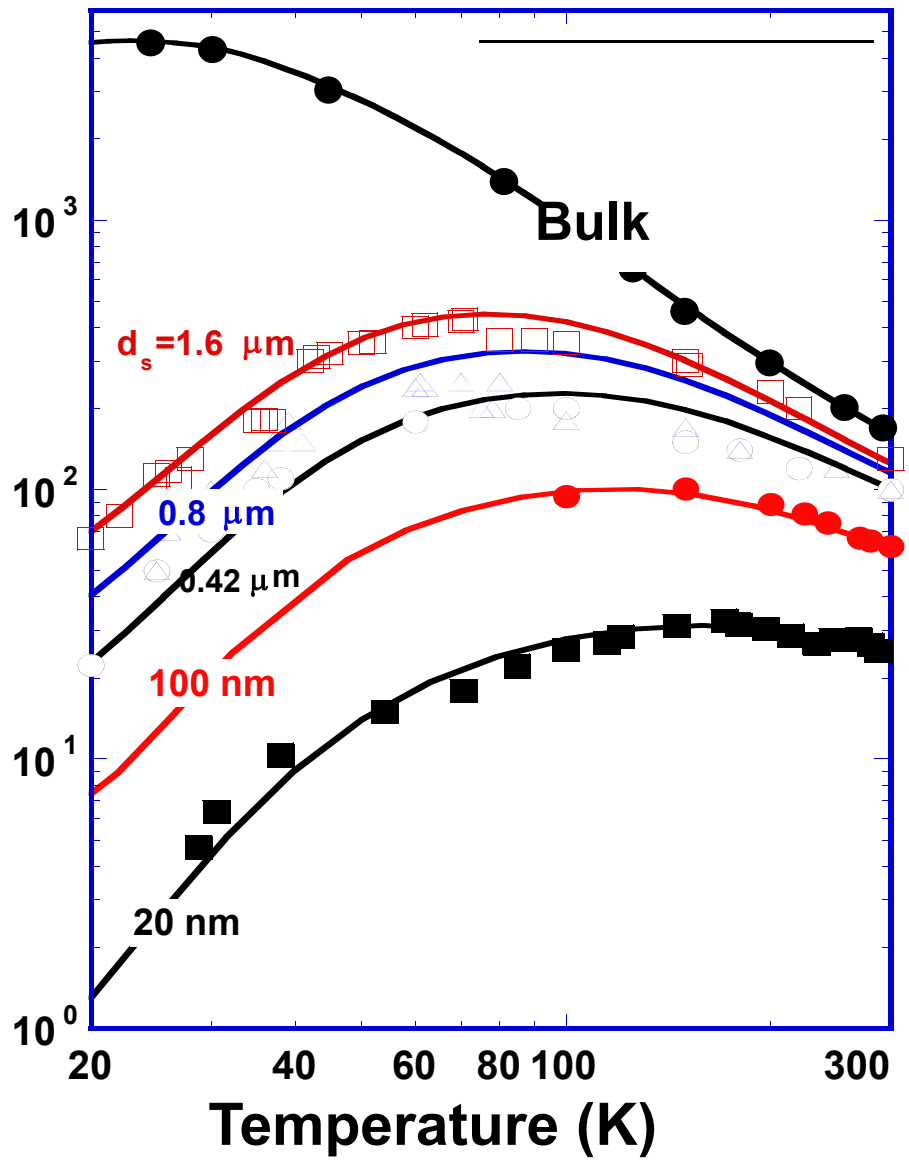
Asheghi, Goodson, et al., *J. Heat Transfer* 120 (1998)

SOI-Enabled Phonon Studies 1994-

Measurement Structure



Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)



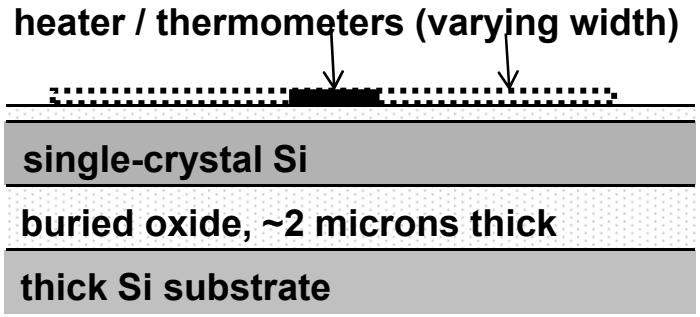
Asheghi, Goodson, et al.,
Applied Physics Letters 71 (1997)

Asheghi, Goodson, et al.,
J. Heat Transfer 120 (1998)

Liu and Asheghi
J. Heat Transfer 120 (2006)

SOI-Enabled Phonon Studies 1994-

Measurement Structure

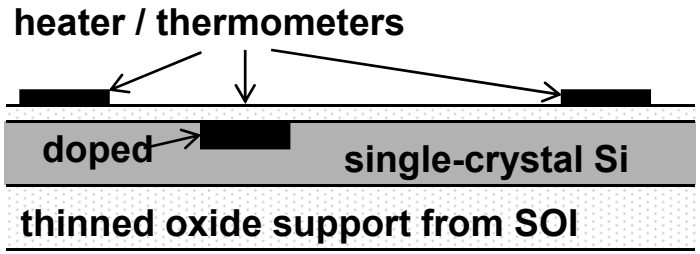


Y. Sungtaek Ju
now with UCLA MAE

Ju, Goodson
***Applied Physics Letters* 74 (1999)**

SOI-Enabled Phonon Studies 1994-

Measurement Structure

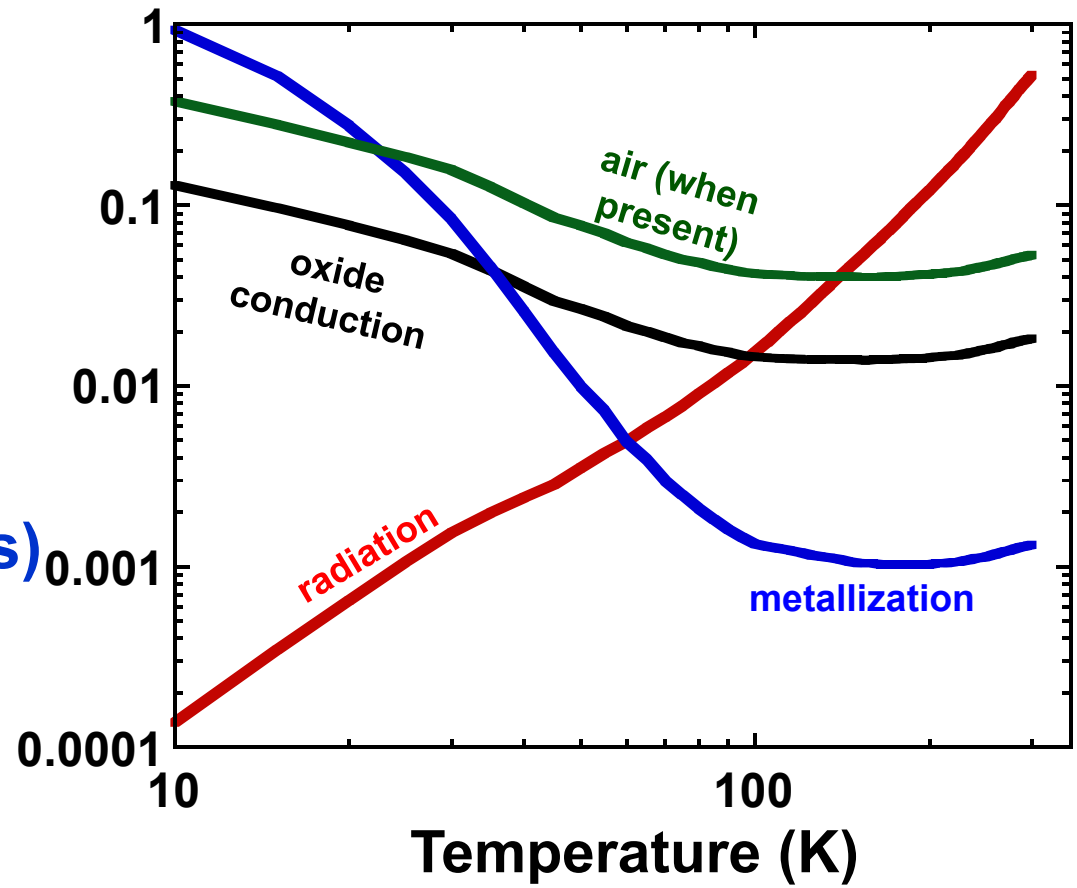


Vacuum
(suspended structure)

Thermal Resistance Ratio (SILICON / loss)

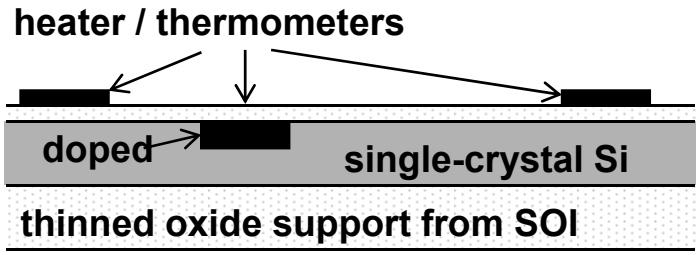
Sverdrup, Sinha, Goodson et al., *Applied Physics Letters* 78 (2001)

McConnell, Srinivasan, Goodson, et al., *JMEMS* 10 (2001)



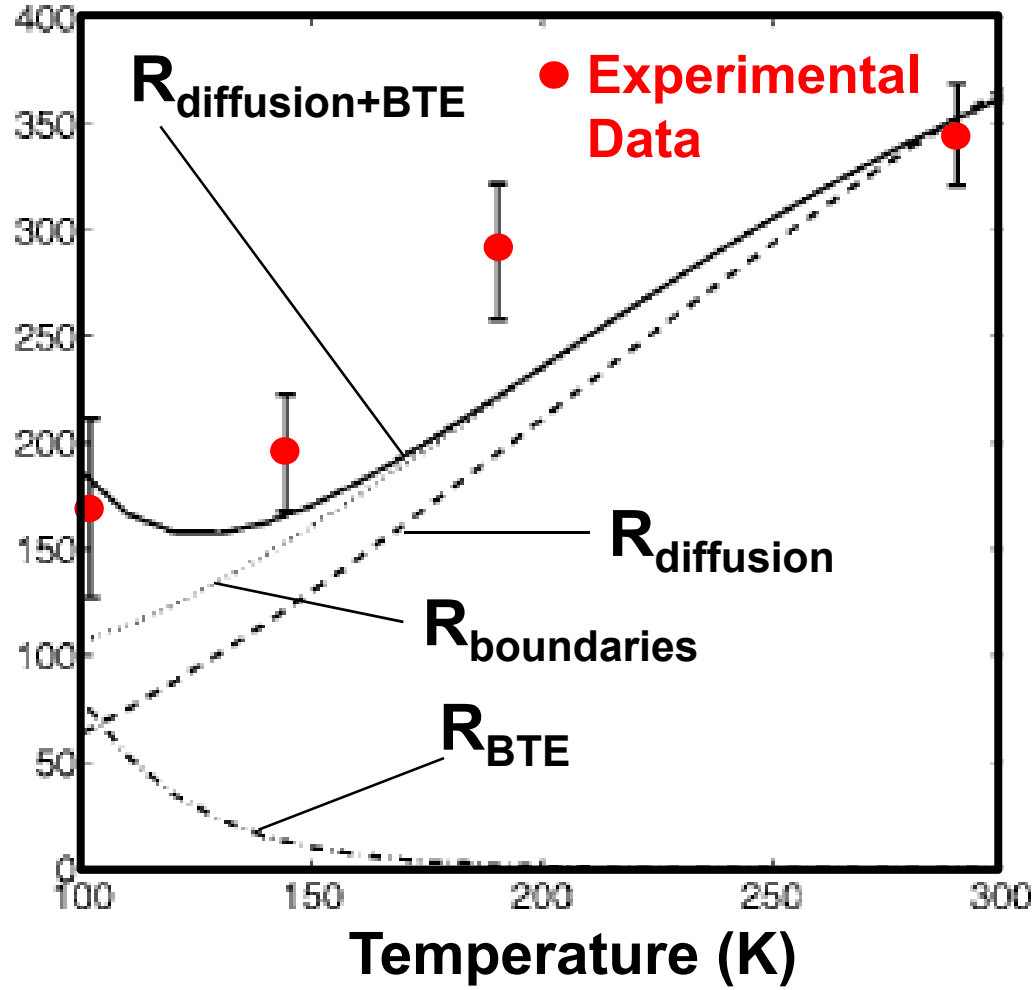
SOI-Enabled Phonon Studies 1994-

Measurement Structure



Vacuum
(suspended structure)

Thermal Resistance ($K\ W^{-1}$)

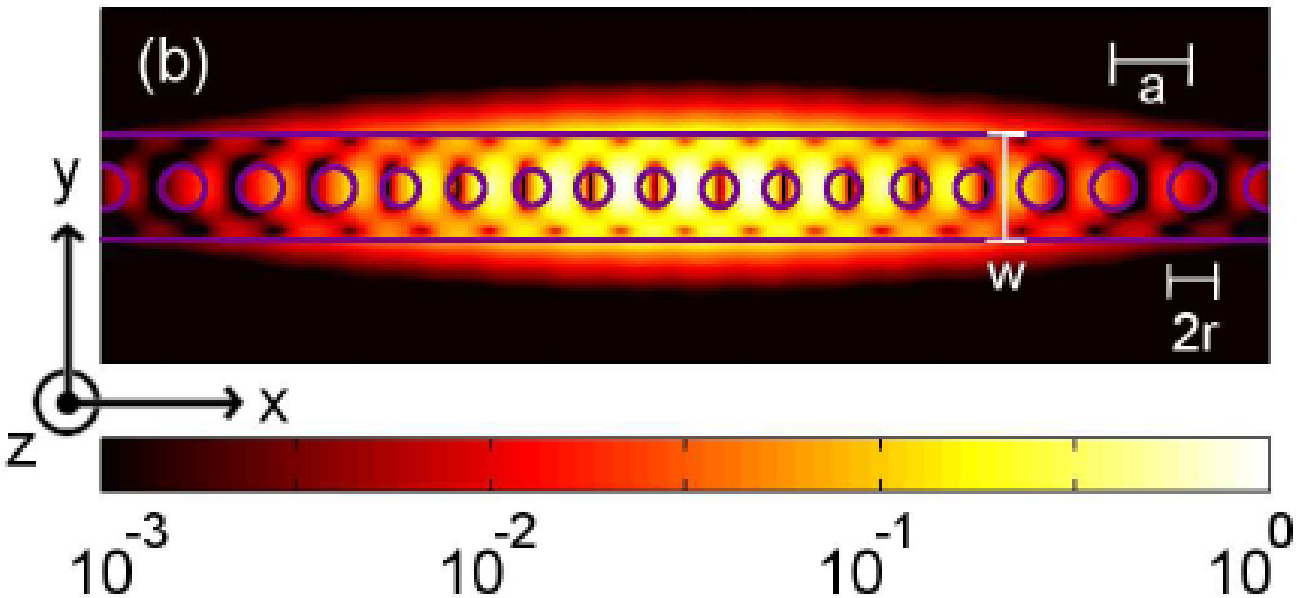


Sverdrup, Sinha, Goodson et al., *Applied Physics Letters* 78 (2001)

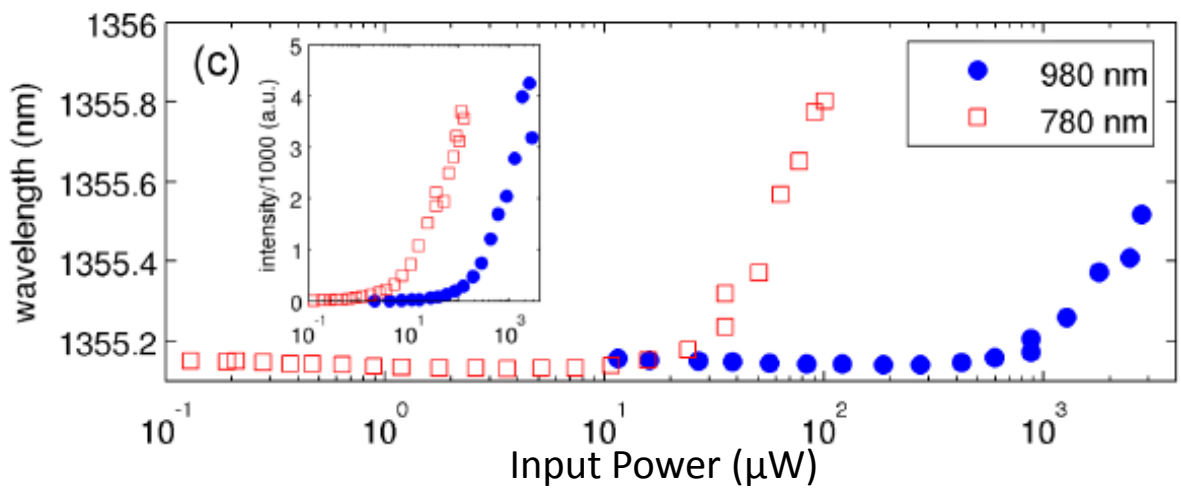
Model: Sinha, Pop, Dutton, Goodson, *J. Heat Transfer* (2006)

SOI-Enabled Phonon Studies

2010- (boundaries & nanoholes)

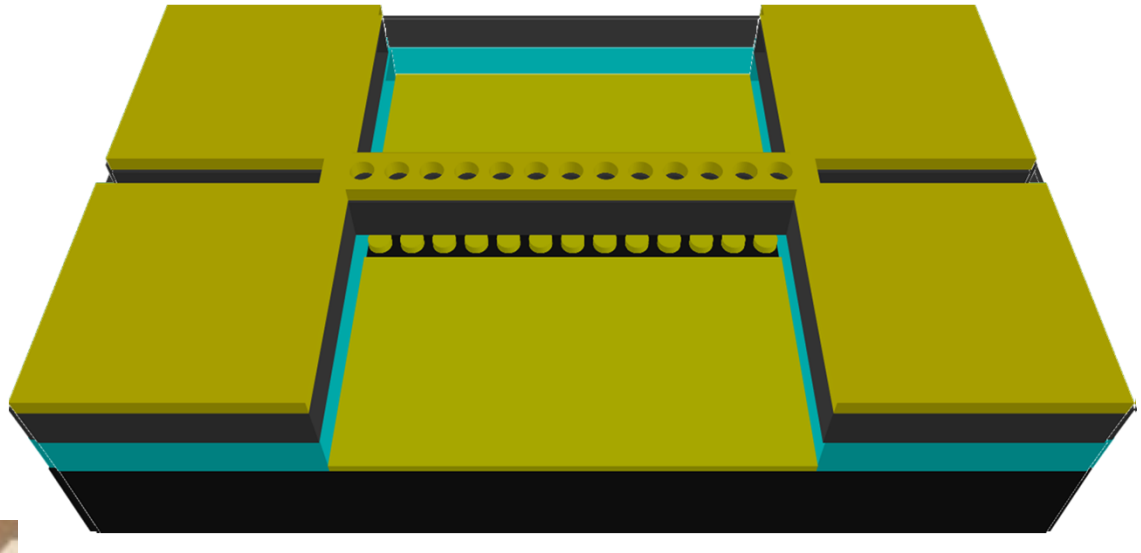


Quantum Cavity Lasers and Waveguides
Gong, Vuckovic, et al., Stanford EE



STANFORD nanoHeat

Nanoladder Device Fabrication



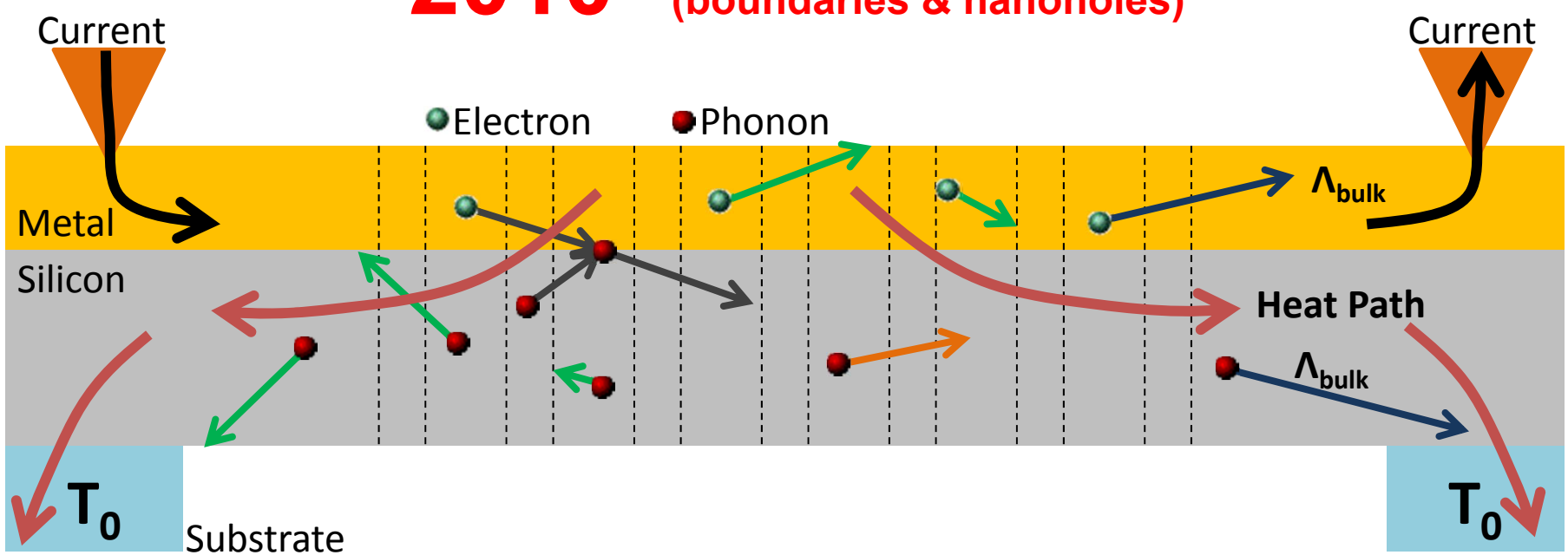
Dr. Taka Kodama

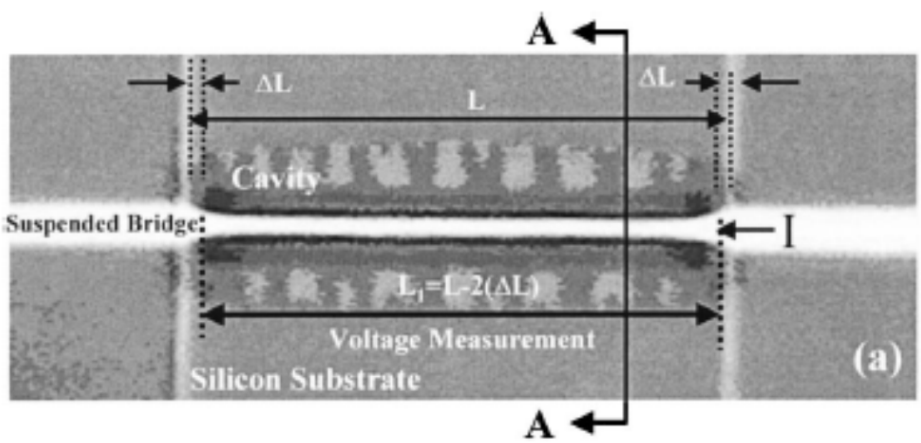
STANFORD nanoHeat

1. Silicon-On-Insulator Wafer
2. Deposit & Pattern (E-Beam Lithography) Photoresist
3. DRIE Etch Silicon Device Layer
4. Remove Oxide Layer To Suspend Device
5. Deposit Palladium Film

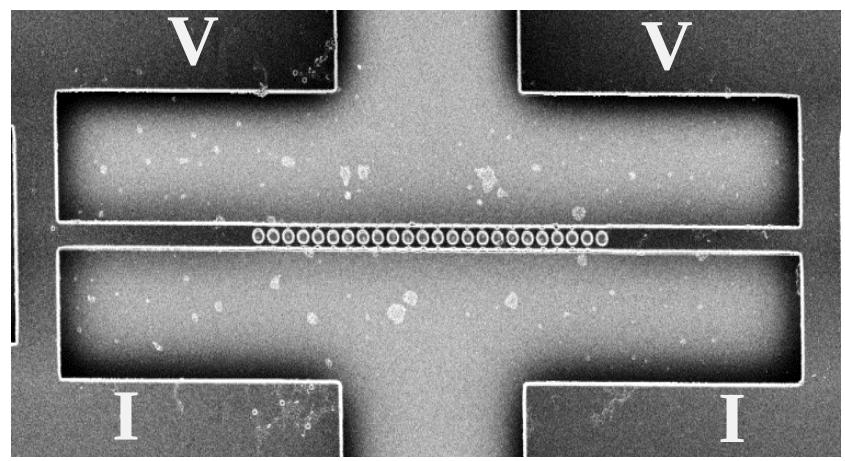
SOI-Enabled Phonon Studies

2010- (boundaries & nanoholes)





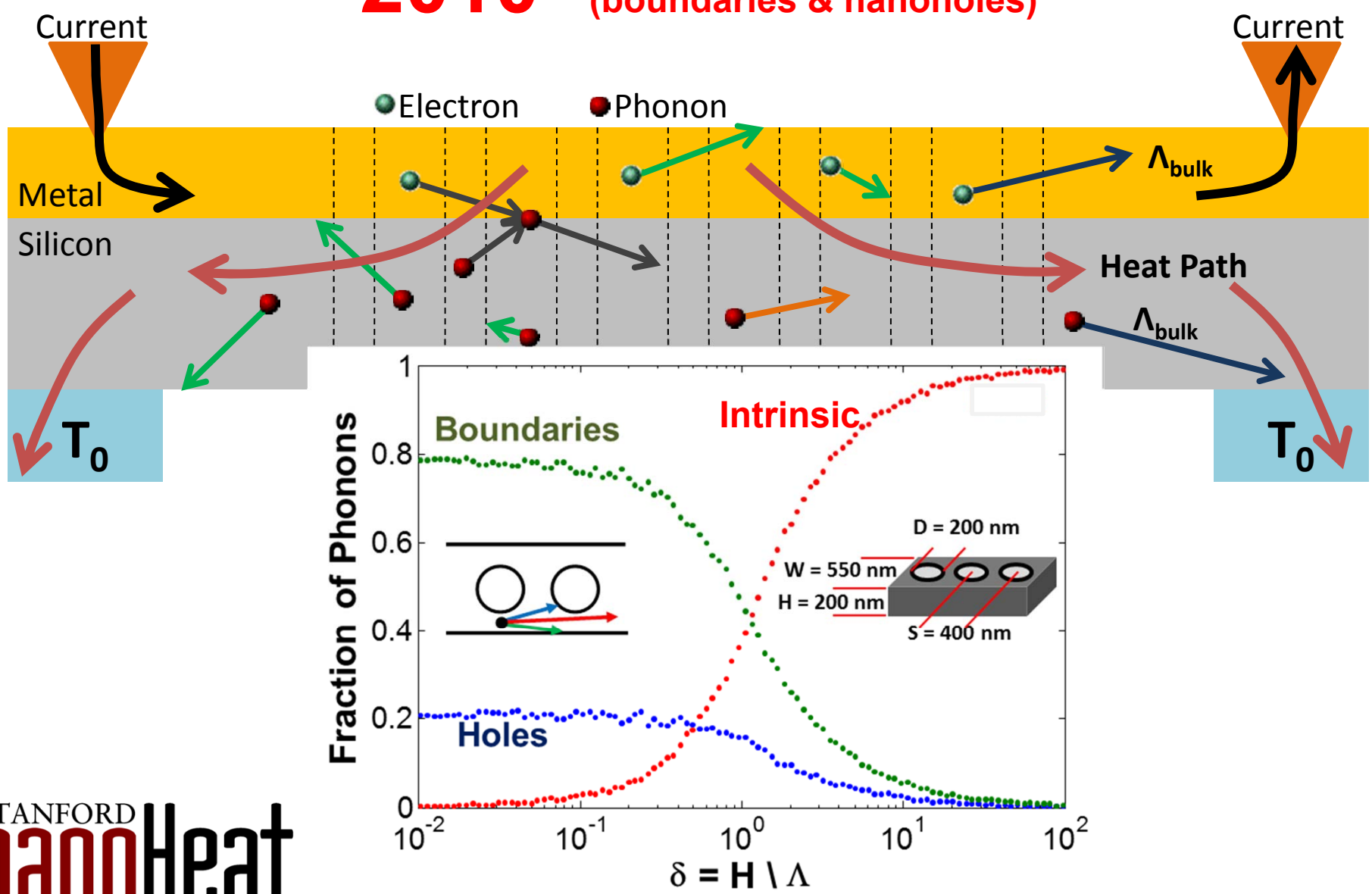
Liu and Asheghi
Applied Physics Letters (2004)



Marconnet, Kodama, Asheghi, Goodson, et al.
Nano & Microscale Thermophys. Eng. (2012)

SOI-Enabled Phonon Studies

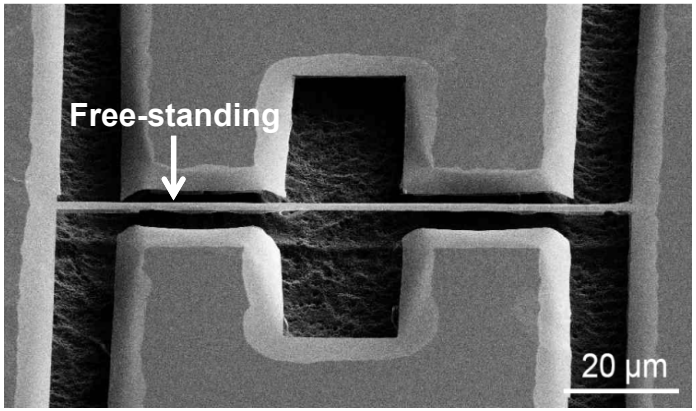
2010- (boundaries & nanoholes)

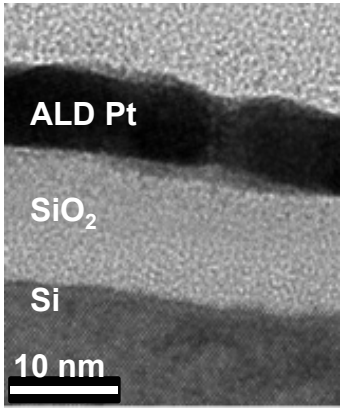


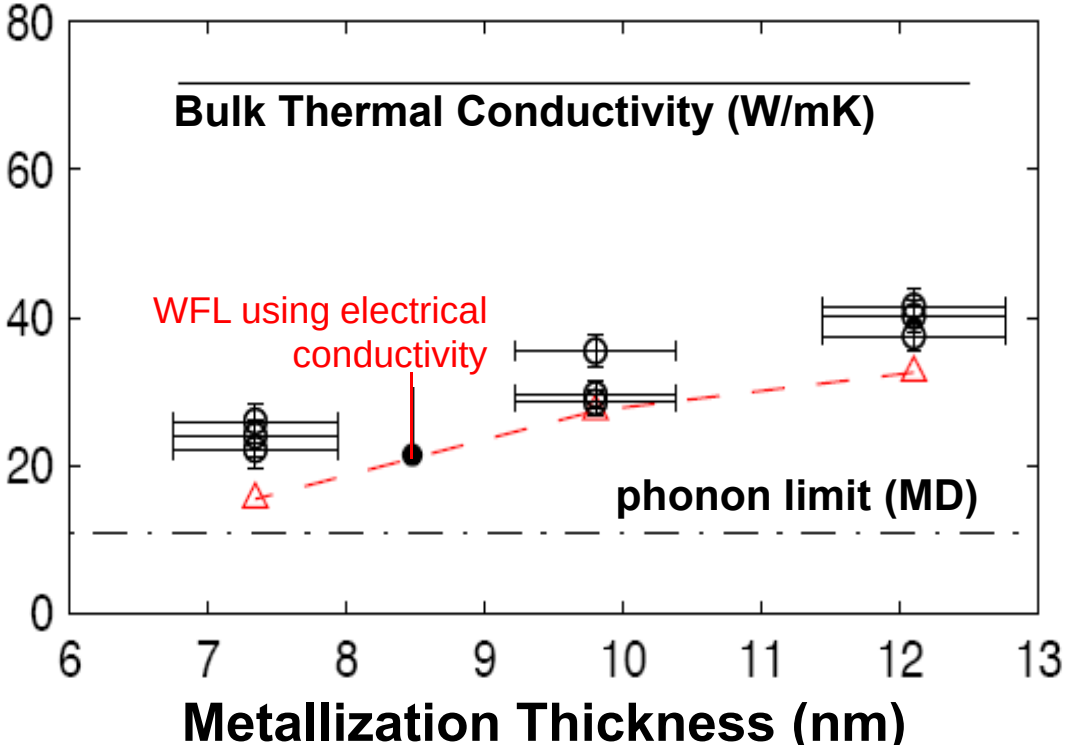
STANFORD nanoHeat

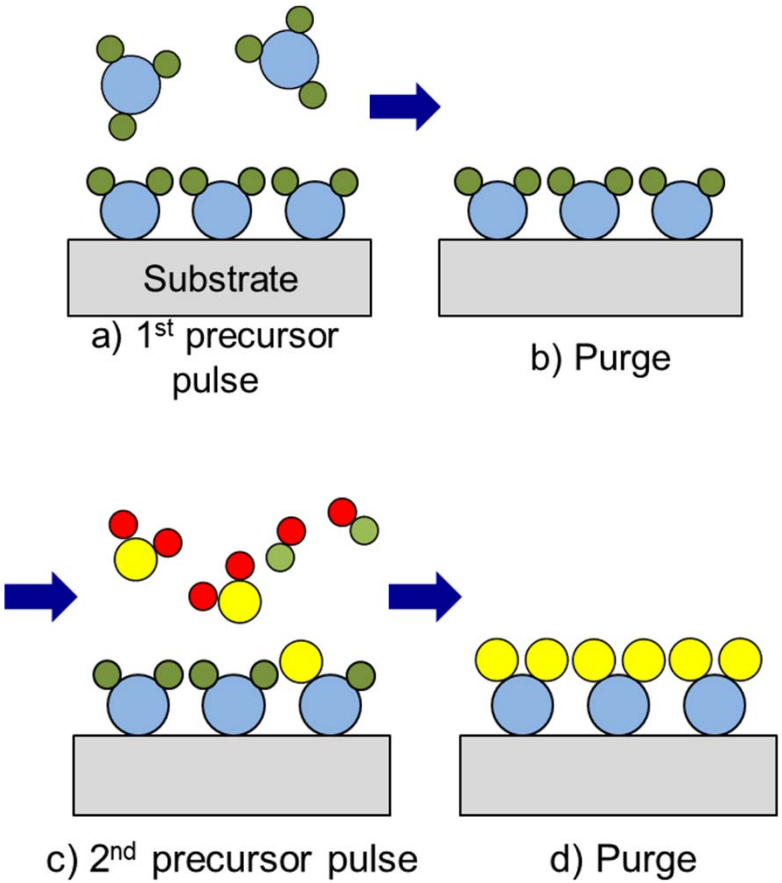
Probing the WFL at 7 nm

Yoneoka, Lee, Goodson, Kenny, et al., *Nano Letters* (2012)

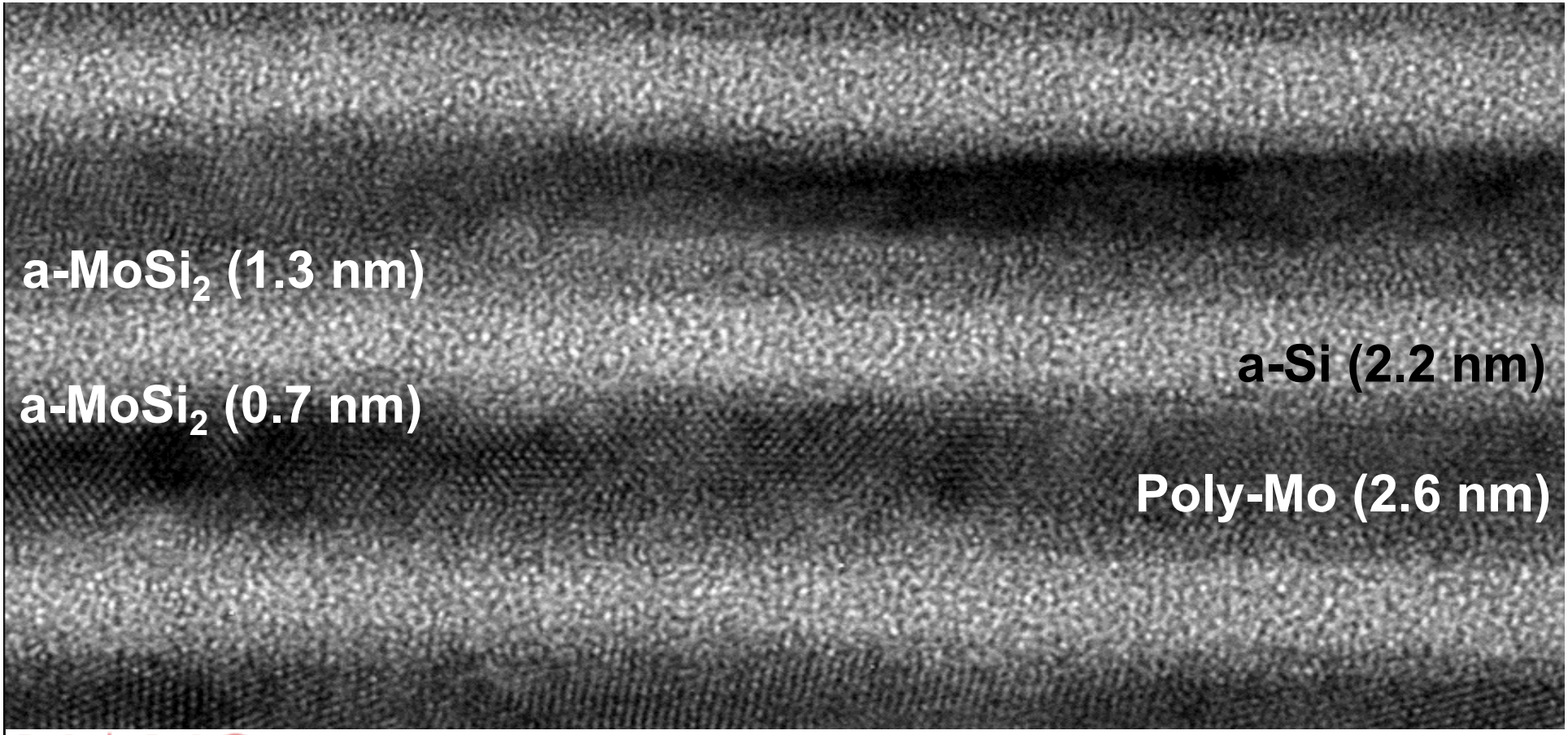








Atomic Layer Deposition



NANO LETTERS

Letter

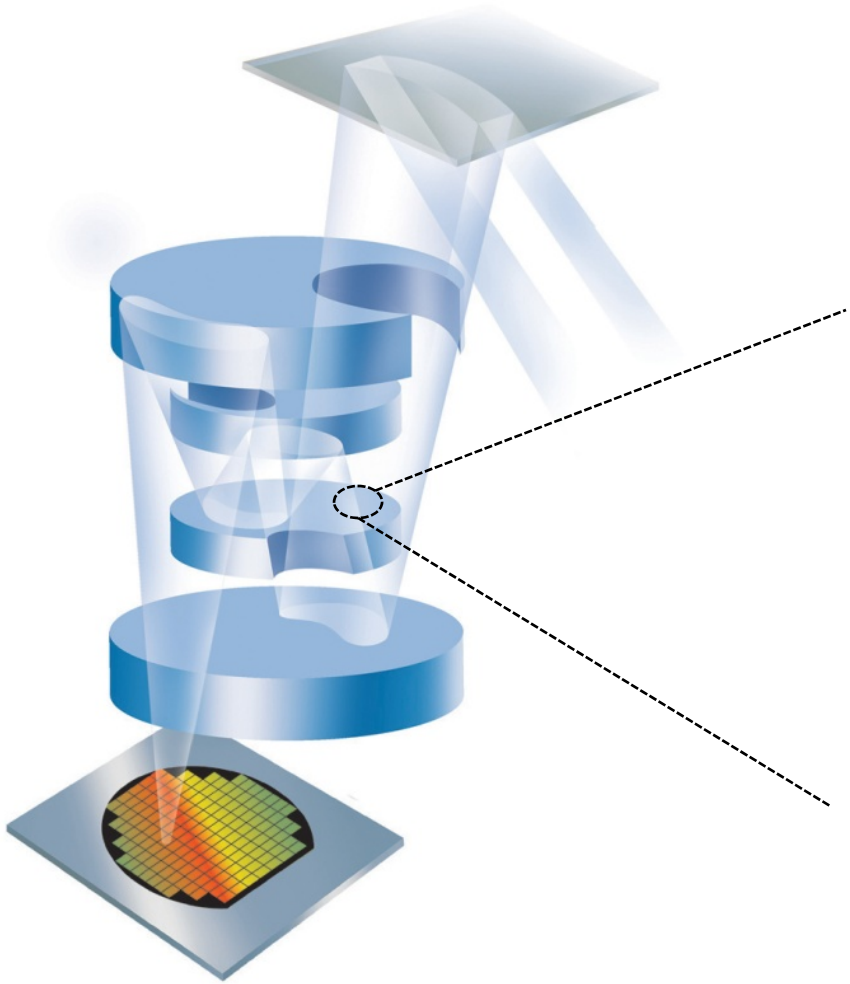
pubs.acs.org/NanoLett

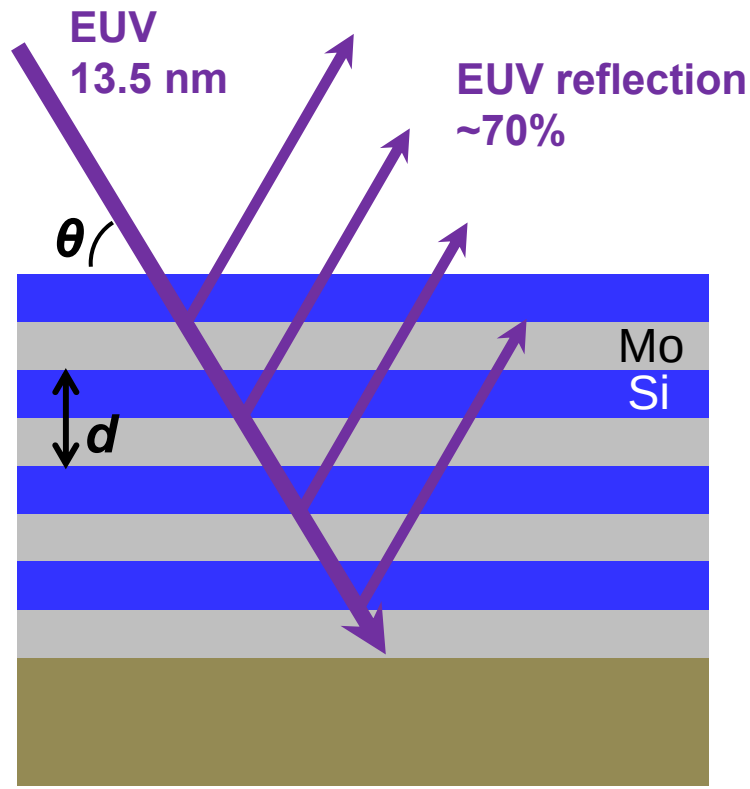
Phonon Dominated Heat Conduction Normal to Mo/Si Multilayers with Period below 10 nm

KLA Tencor

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

Extreme UV Optics

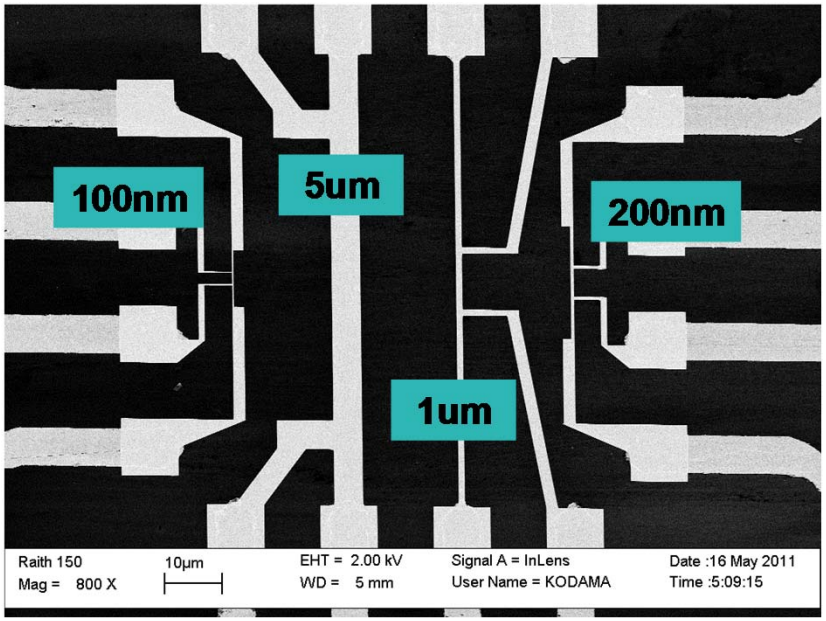


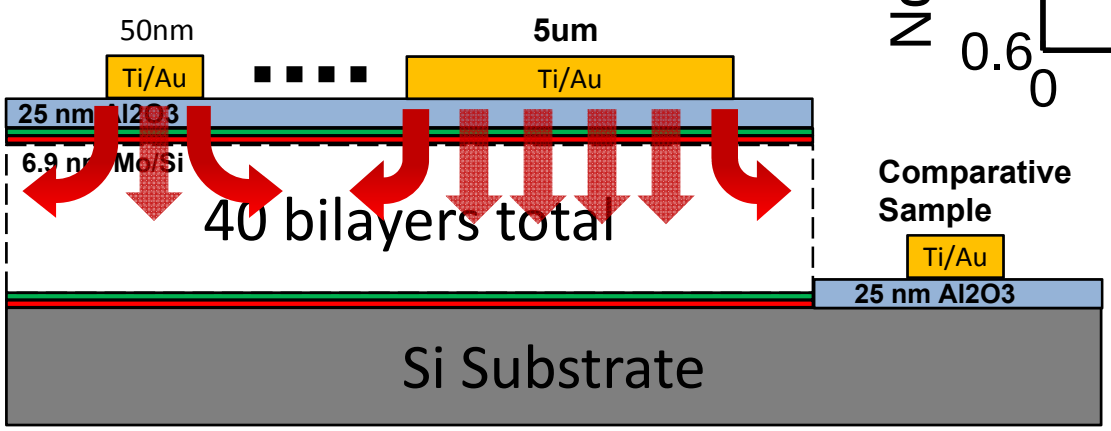


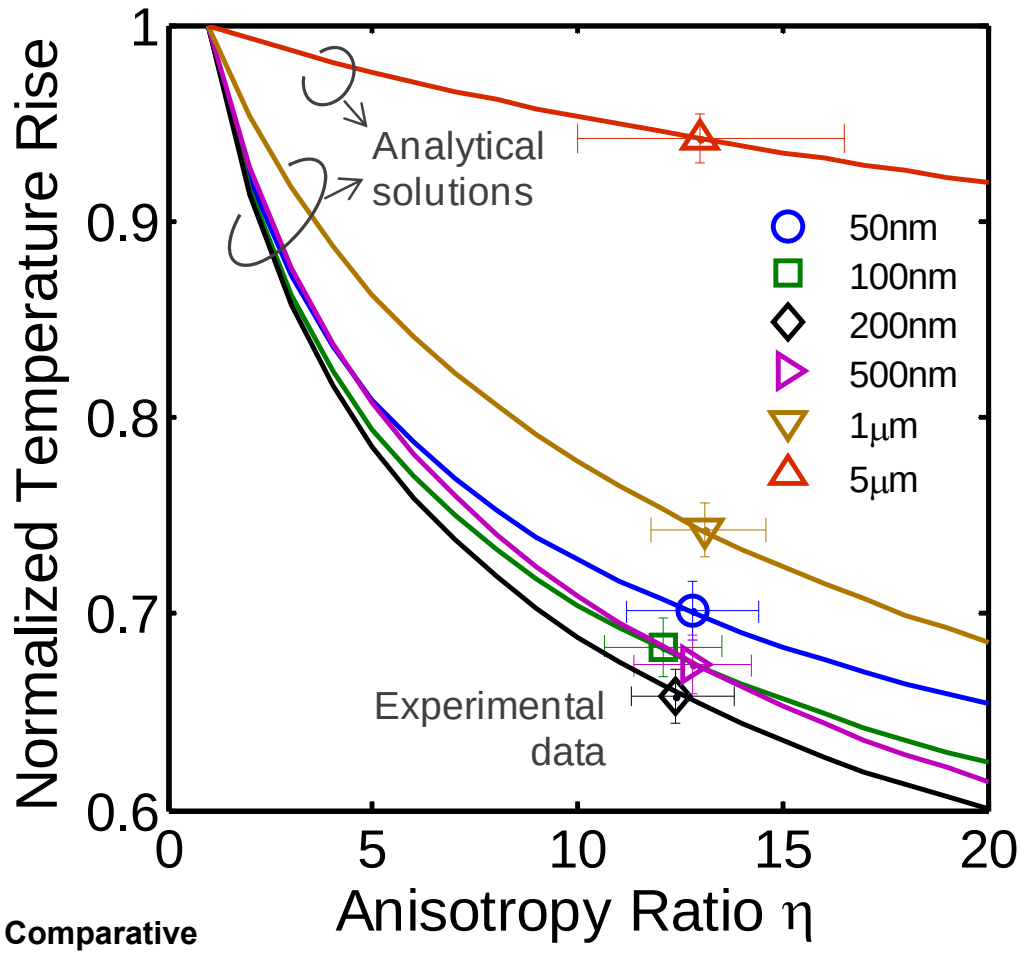
Carl Zeiss AG

Electrons & Phonons in Metal NanoLayers

Li, Goodson, et al., *Nano Letters* (2012), accepted and in press
Bozorg-Grayeli, Li, Goodson, et al., *Applied Physics Letters* (2011)







d_{Mo} = 2.8nm, d_{Si} = 4.1nm,
k_{Mo} ~ 14 W/mK (WFL)

Electrons & Phonons in Metal NanoLayers

Li, Goodson, et al., *Nano Letters* (2012), accepted and in press
Bozorg-Grayeli, Li, Goodson, et al., *Applied Physics Letters* (2011)

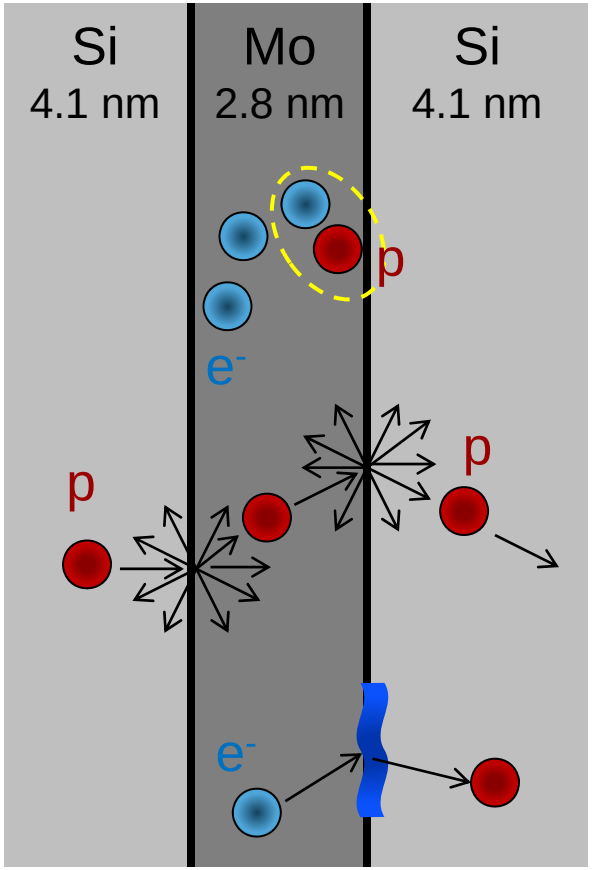
Anisotropy caused by:

- Series vs parallel film resistances
  η = 2-3

- Discrete interface resistances and
  ballistic electrons, η = 4-9

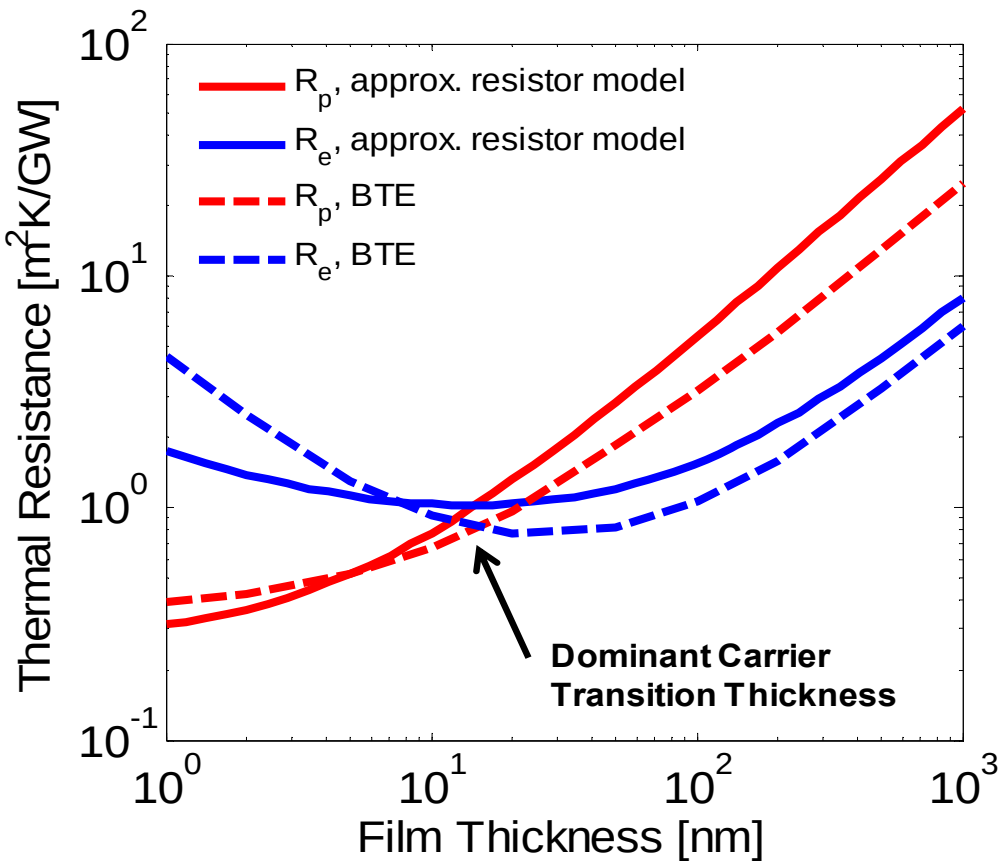
- Disorder and material interdiffusion at
  interfaces (smudging)

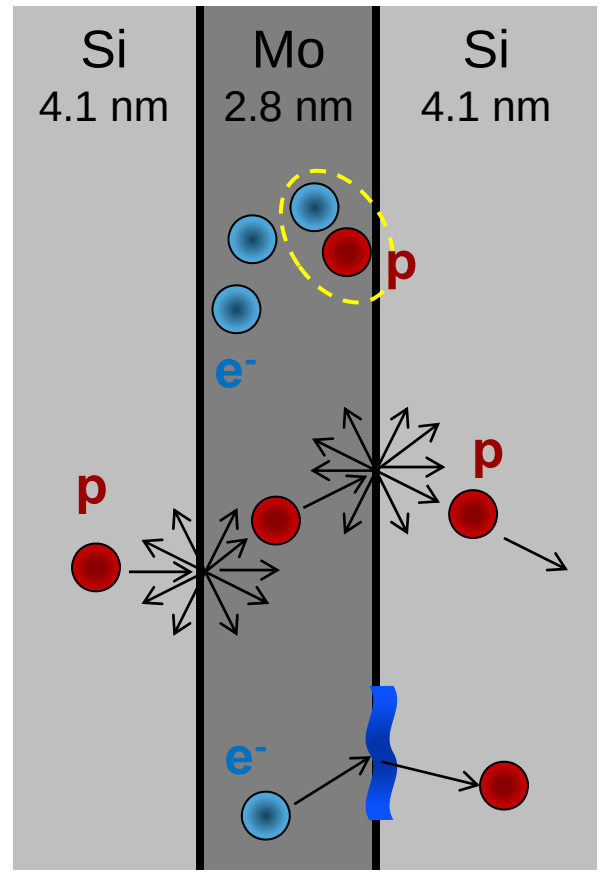
- Weak electron-phonon coupling and ballistic
  phonons?



Electrons & Phonons in Metal NanoLayers

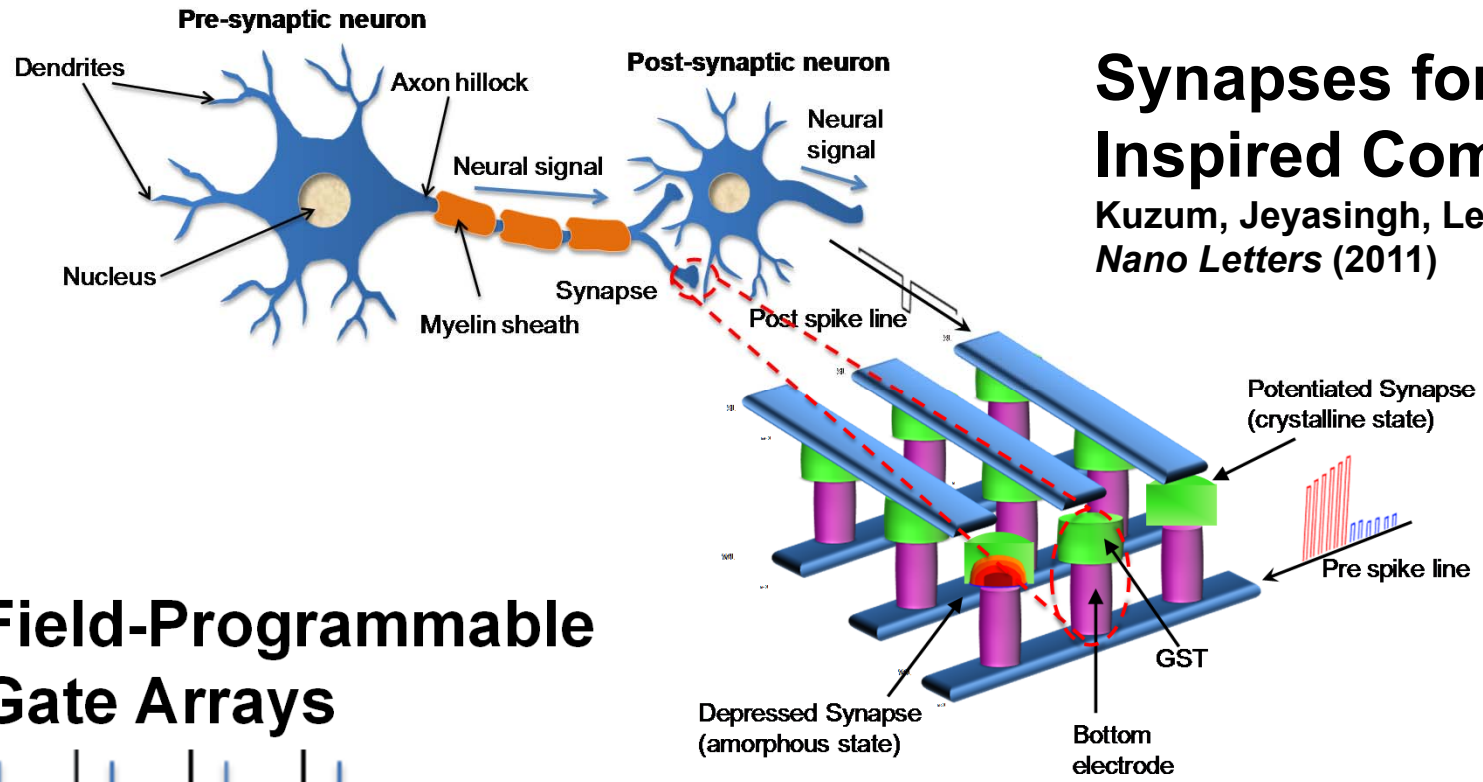
Li, Goodson, et al., *Nano Letters* (2012), accepted and in press
Bozorg-Grayeli, Li, Goodson, et al., *Applied Physics Letters* (2011)





$$d_{trans} = 2k_p k_e \,/\left[\sqrt{Gk_p}\left(k_e - k_p\right)\right]$$

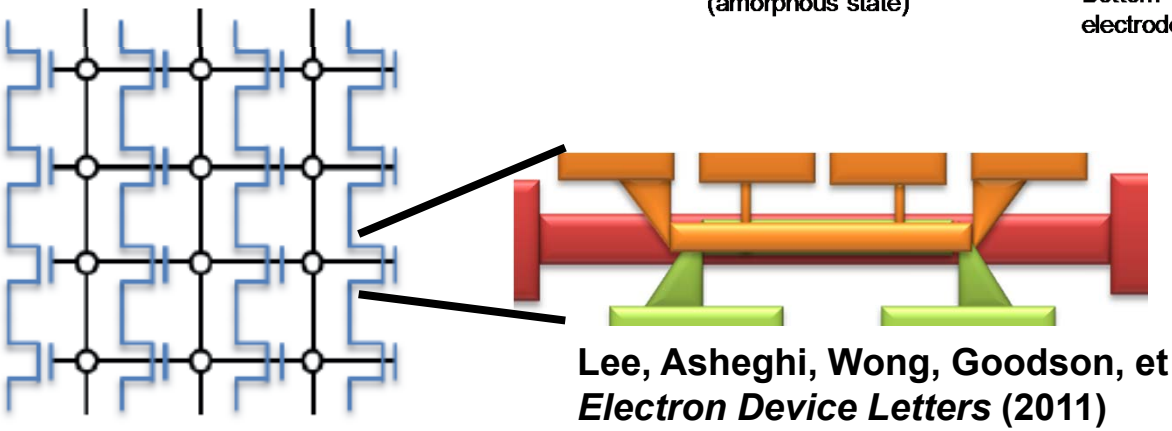
Future Phase Change Nanodevices



Synapses for Brain-Inspired Computing

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

Field-Programmable Gate Arrays



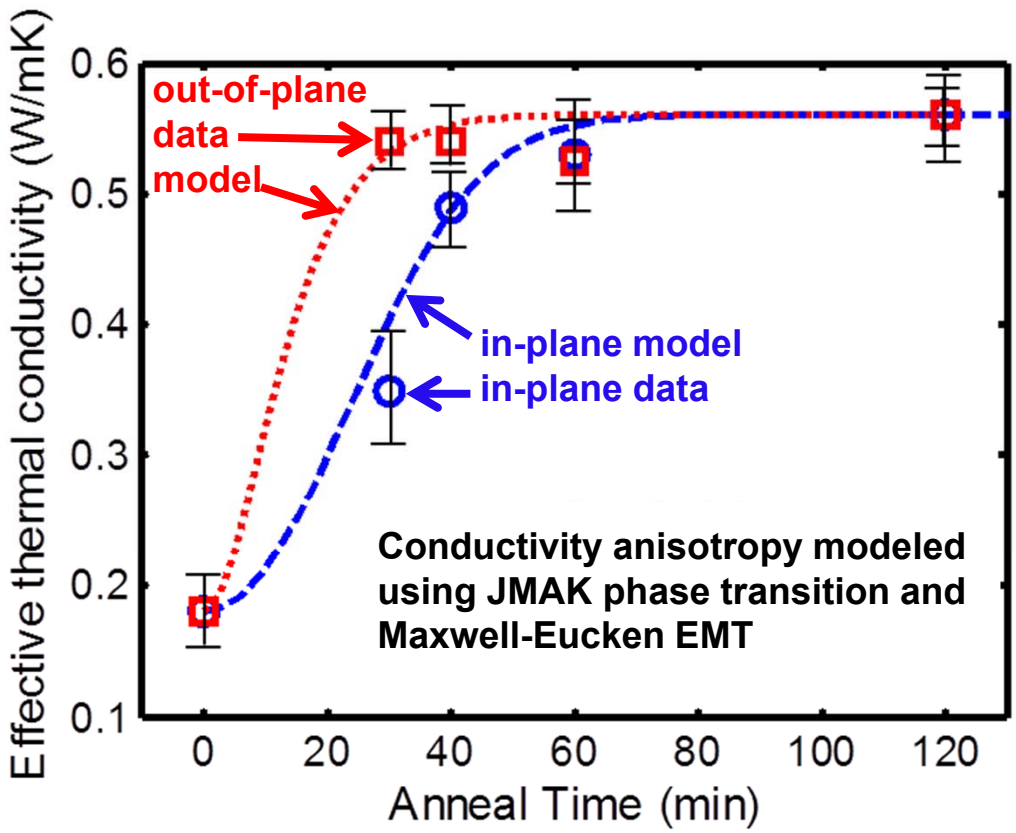
Lee, Asheghi, Wong, Goodson, et al.
***Electron Device Letters* (2011)**

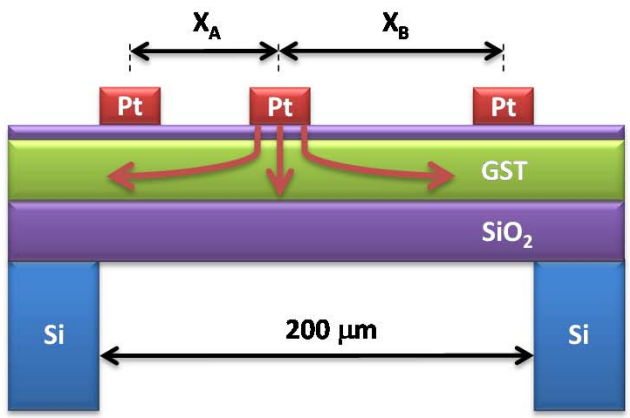
SyNAPSE

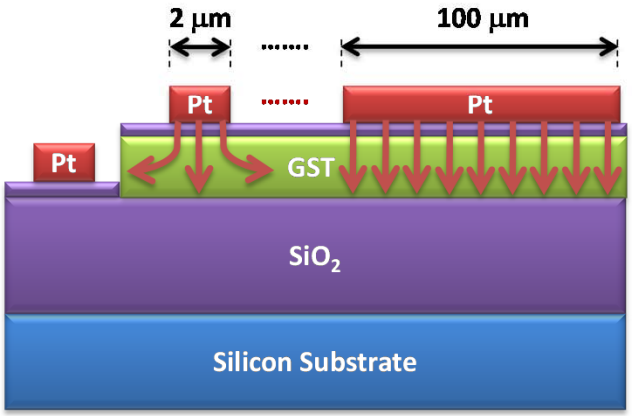
RF-FPGA

Phase Transition Complexity in $Ge_2Sb_2Te_5$

Lee, Li, Sinclair, Goodson, et al., Journal of Applied Physics (2011)
Li, Lee, Wong, Goodson et al., Electron Device Letters (2011)

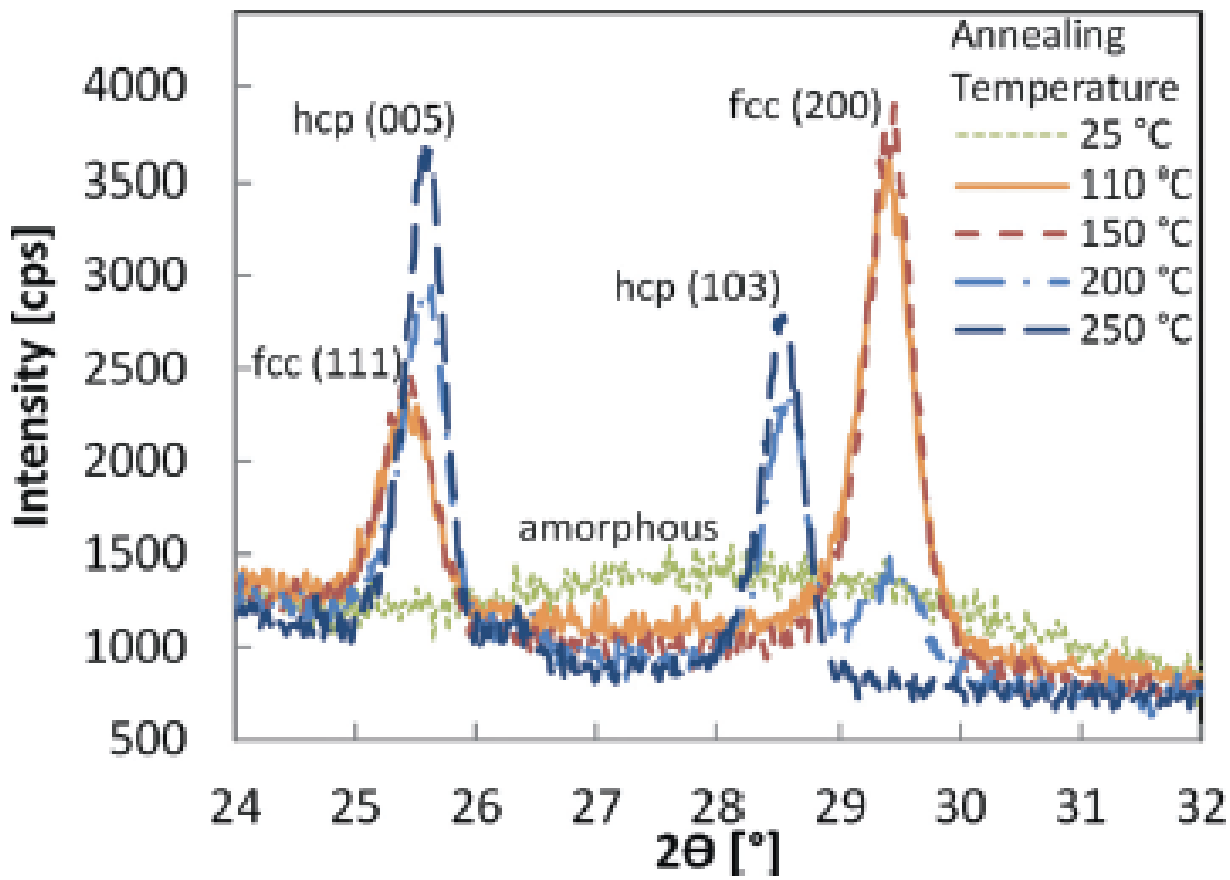


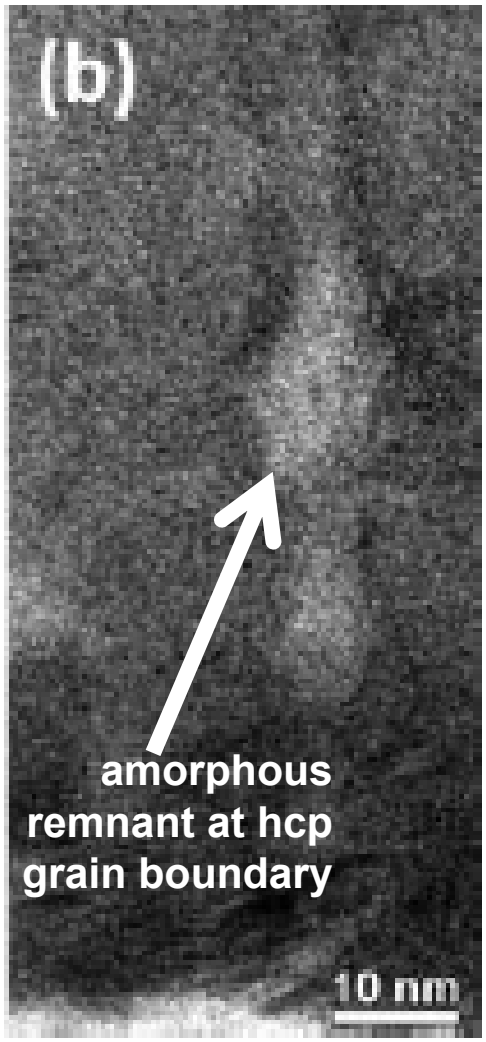




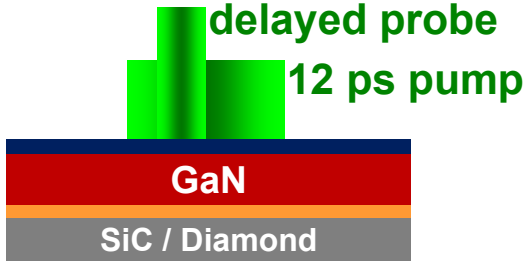
Phase Transition Complexity in $Ge_2Sb_2Te_5$

Lee, Li, Sinclair, Goodson, et al., Journal of Applied Physics (2011)
Li, Lee, Wong, Goodson et al., Electron Device Letters (2011)

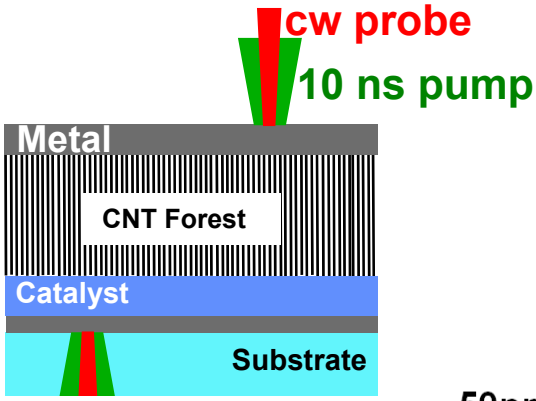




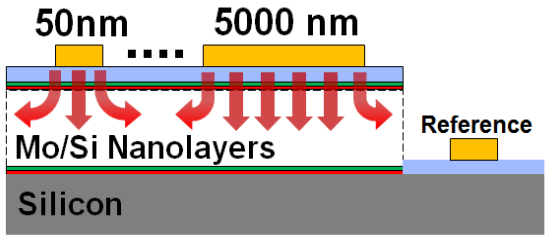
Nano Thermal Metrology



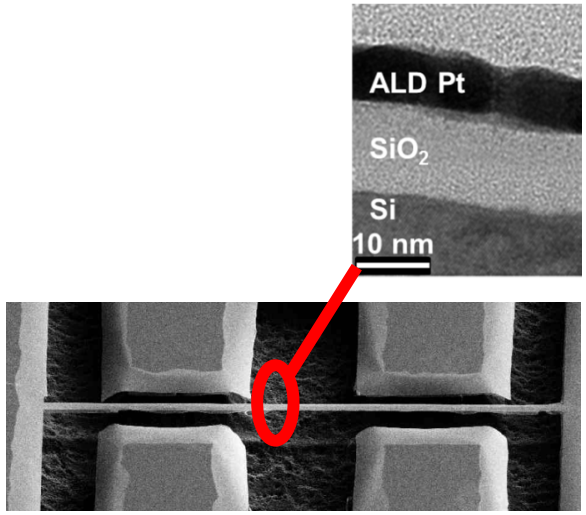
Students: Cho, Bozorg-Grayeli
Electron Device Letters (2012)



Students: Panzer, Gao
Nano Letters (2010)



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



Students: Yoneoka, Li, Kodama
Nano Letters (2012 in press)

Rig Complexity

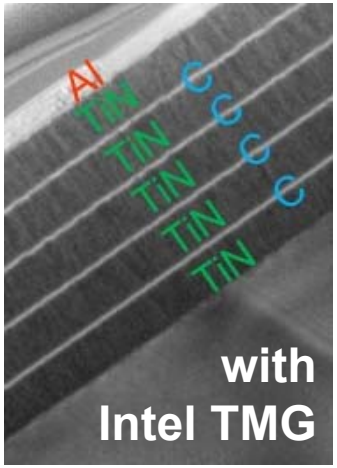
Sample Complexity

TDTR/TTR Sample Design

Phase Change Interfaces

Students: Bozorg-Grayeli, Li, Reifenberg

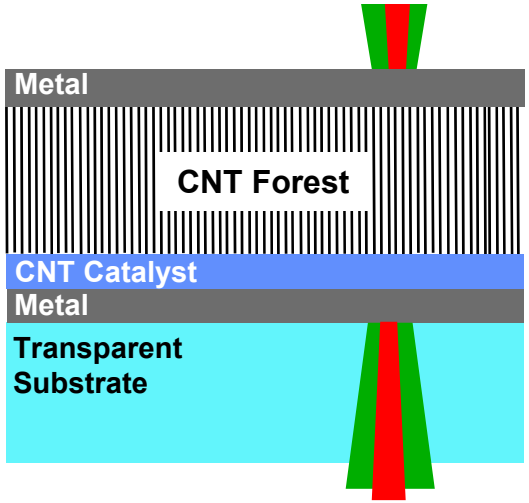
***Applied Physics Letters* (2007)**
***Electron Device Letters* (2008, 2010, 2011)**



CNT Forests

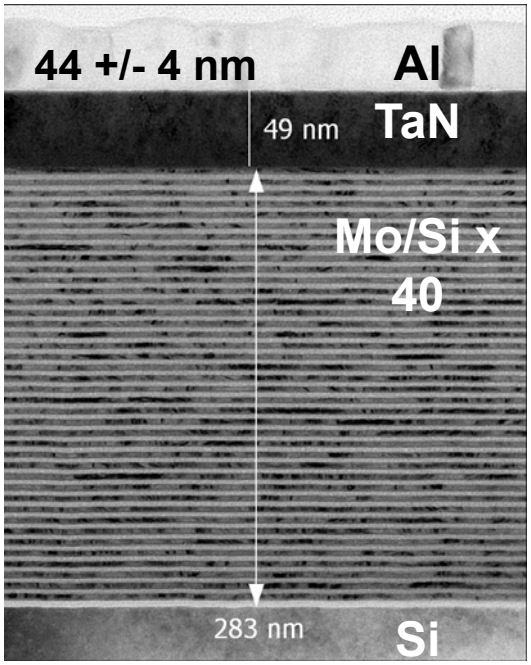
Students: Panzer, Gao, Marconnet

***ACS Nano* (2011)**
***Nanoletters* (2010)**
***J. Heat Transfer* (2008)**
***J. Electronic Materials* (2009)**



Extreme UV NanoOptics

Students: Bozorg-Grayeli, Li
***Applied Physics Letters* (2012)**
***Nano Letters* (2012)**

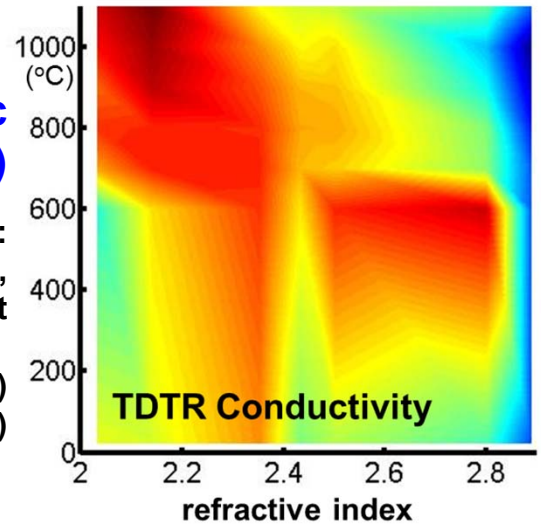


KLA Tencor

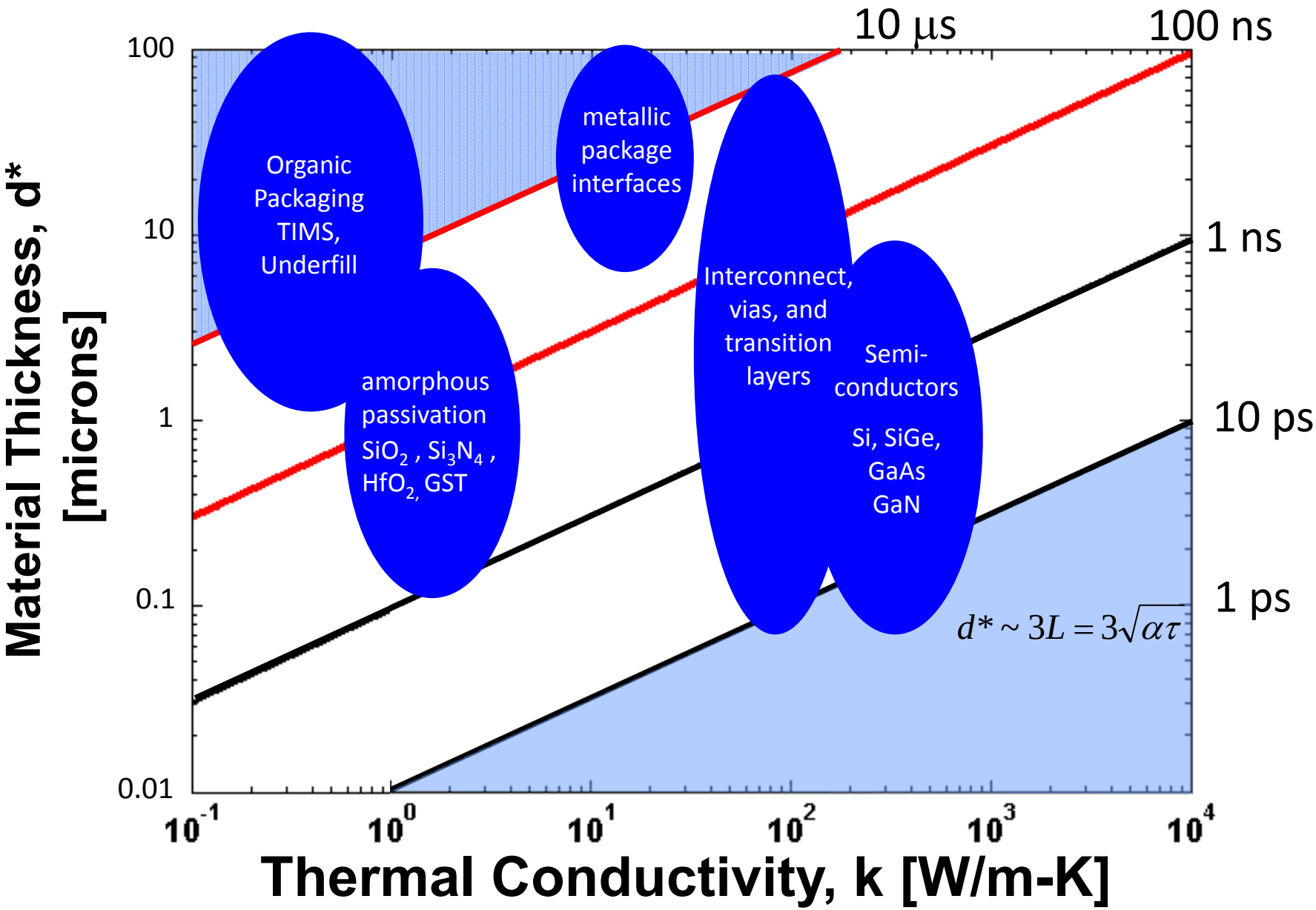
NanoPhotonic Crystals (SRO/SRN)

Students:
Rowlette, Kekatpure, Marconnet

***Physical Review B* (2009)**
***Applied Physics Lett.* (2012)**



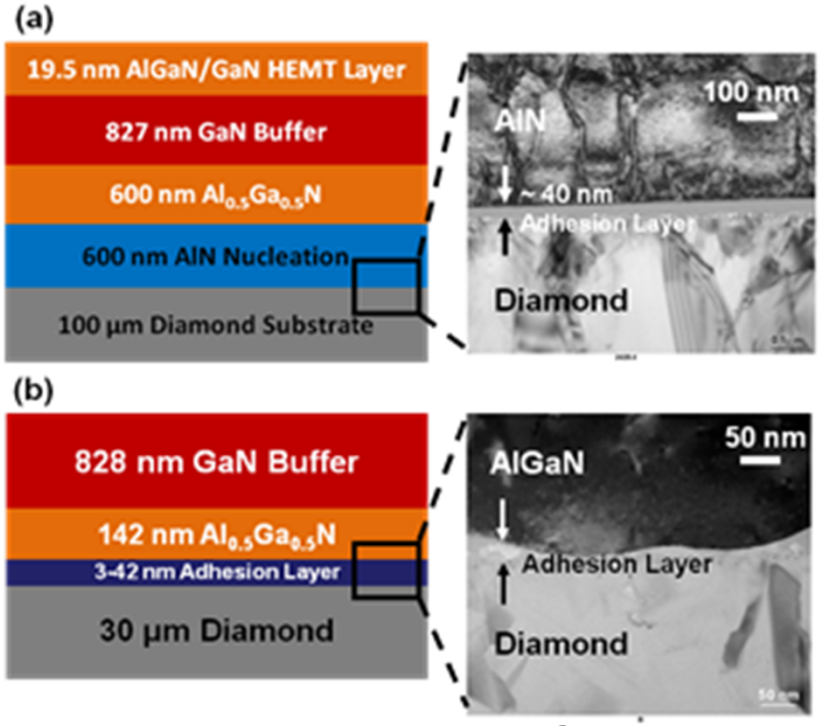
Required Measurement Timescales



Diamond Composite Substrates

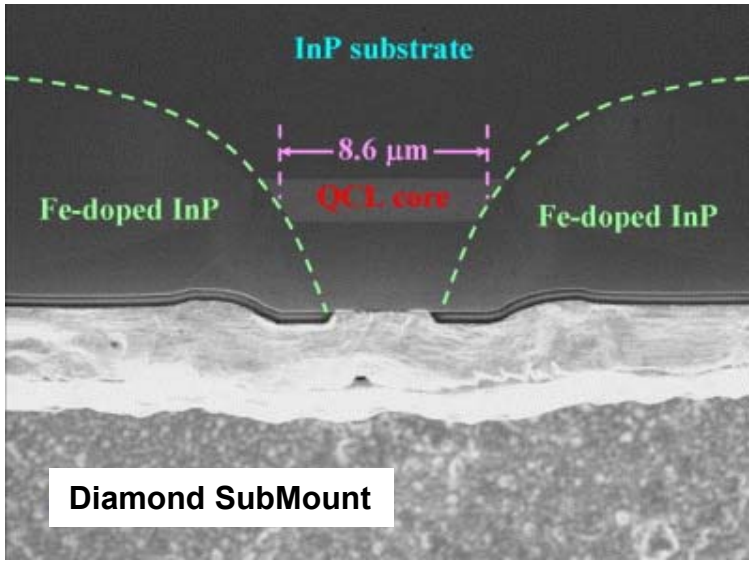
DARPA NJTT Programs

HEMT Composite Substrates



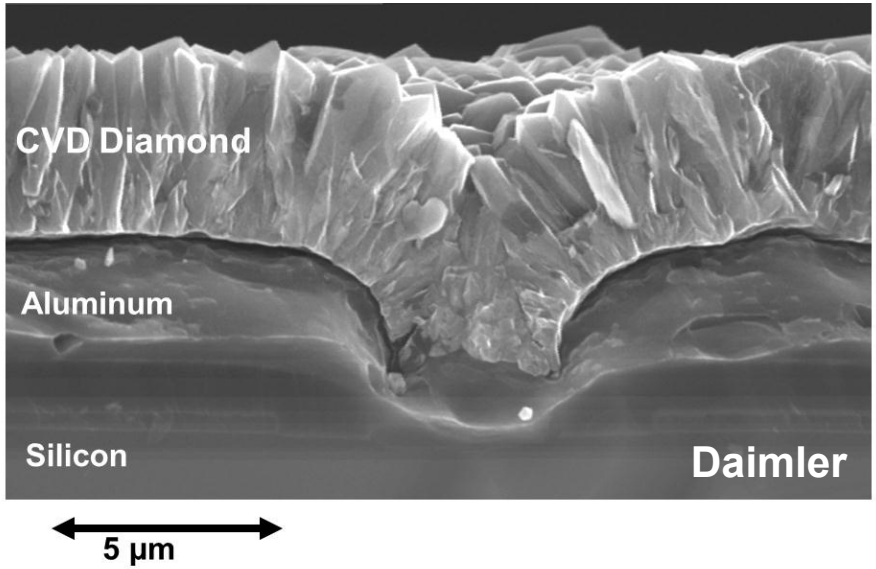
Proc. ITHERM 2012, with Group4 Labs

Quantum Cascade Laser SubMounts



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

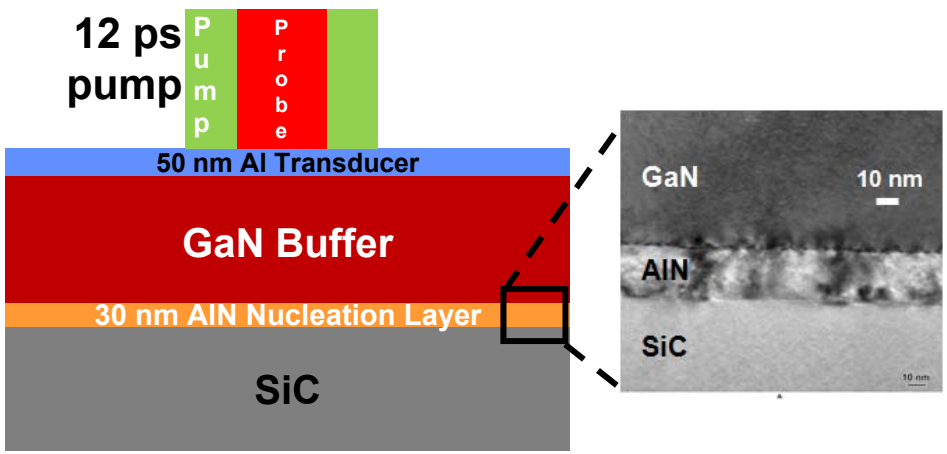
POWER FET Passivation

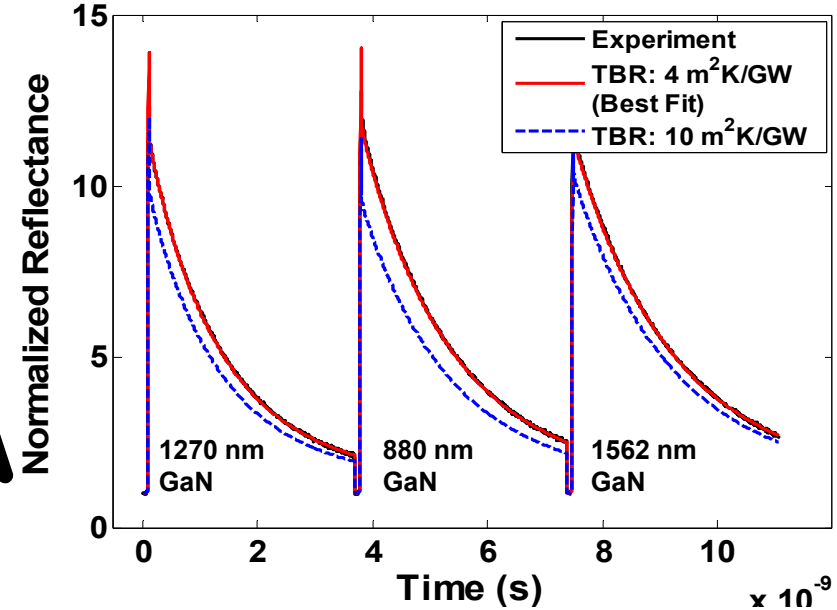


TDTR Boundary Resistance Extraction

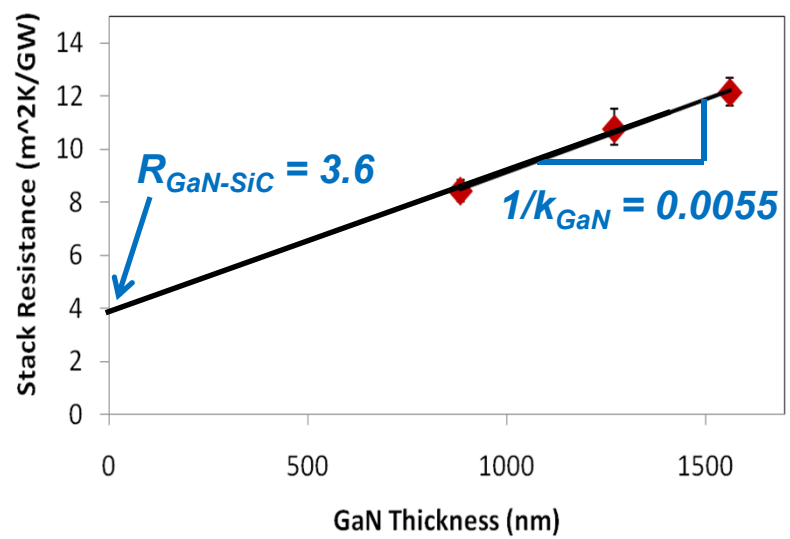
Stanford with Raytheon: Cho, Altman, Asheghi, Goodson, *Electron Device Letters* (2012)

GaN Composite Substrates





Sample	k_{GaN} W/m/K	$R_{GaN\text{-}SiC}$ m^2K/GW	AlN thickness nm
Raytheon HEMT ps TDTR simul-fit	157 ± 11	4.2 ± 0.6	27
Raytheon HEMT extrapolation	182 ± 33	3.6 ± 1.6	27

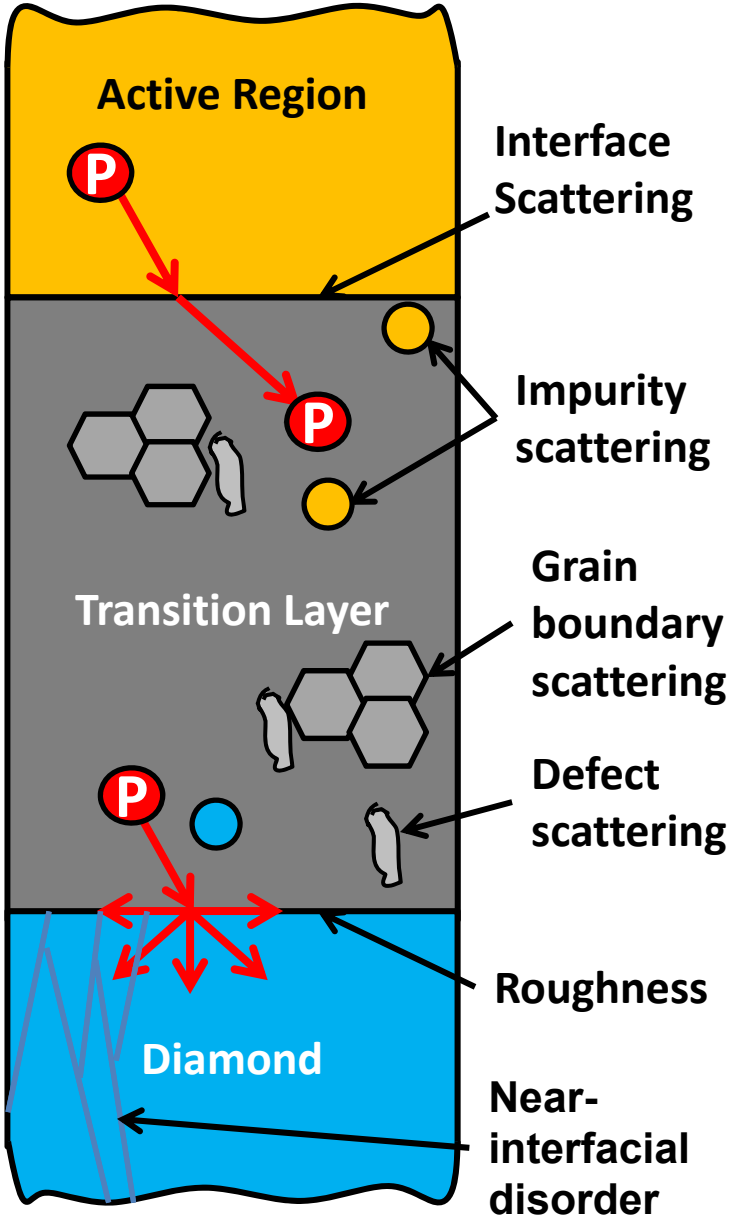


Thermal Resistance Mechanisms

Discrete carrier scattering at interfaces

Scattering on imperfections, stoichiometric impurities, and disorder in transition film

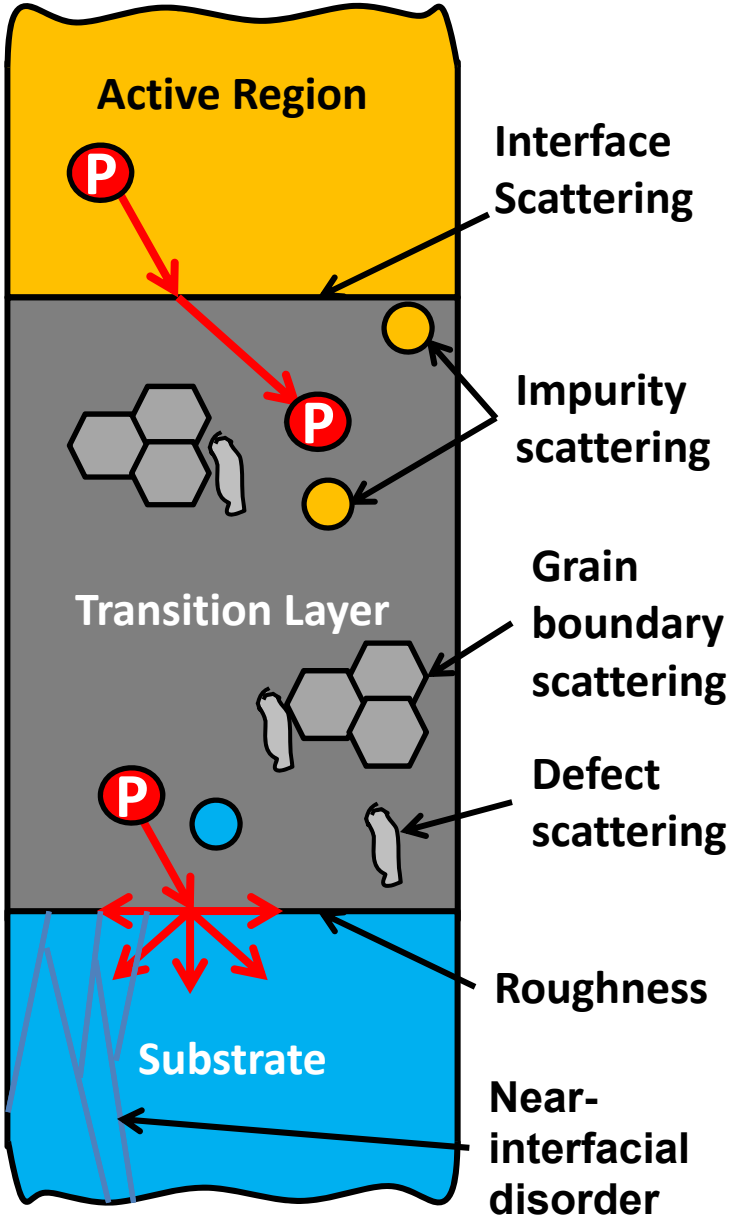
Near-interfacial disorder in primary composite substrate materials (GaN & Diamond)



Thermal Resistance Mechanisms

Discrete carrier scattering at interfaces

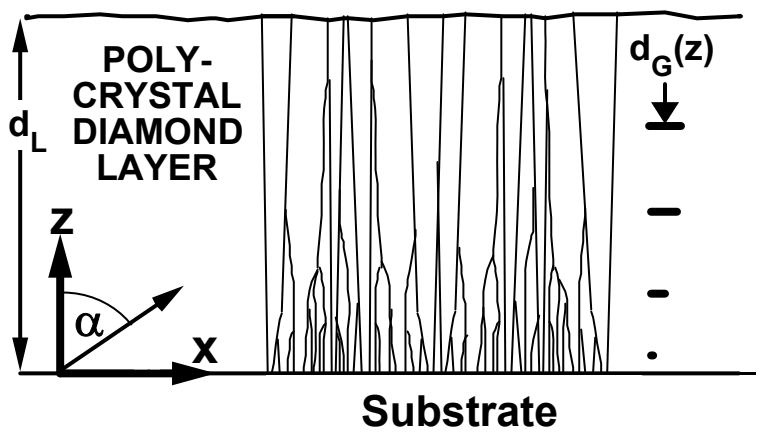
Scattering on imperfections, stoichiometric impurities, and disorder in transition film

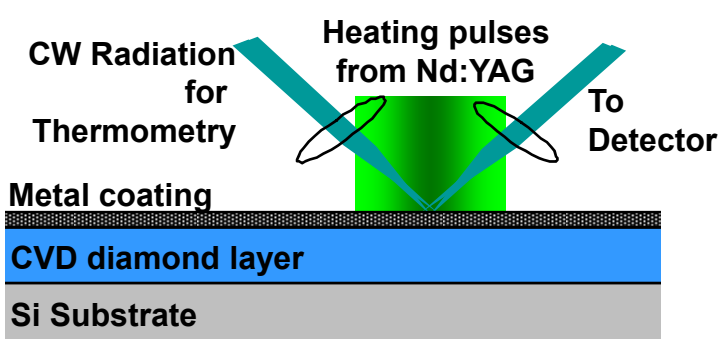


Near-Interfacial Diamond

Touzelbaev & Goodson, *Diamond & Related Materials* (1998)
Touzelbaev & Goodson, *J. Thermophysics & Heat Transfer* (1998)

Goodson, *ASME J. Heat Transfer* (1996)
Goodson et al., *Journal of Applied Physics* (1995)



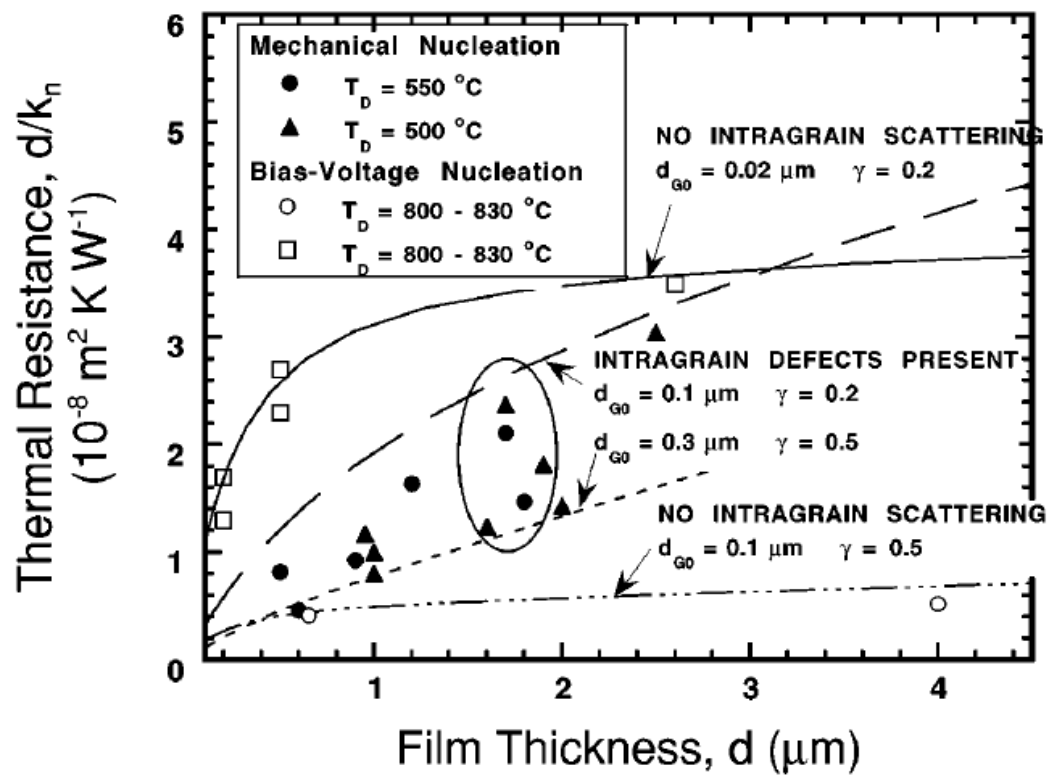


Mean free path

$$\Lambda^{-1} \cong \Lambda^{-1}_{phonon} + \Lambda^{-1}_{grain-boundary} \cong \Lambda^{-1}_{phonon} + \frac{d_G}{2\eta}$$

Grain-boundary scattering strength

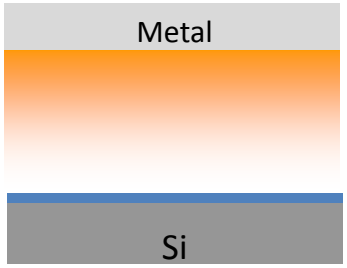
$$\eta \equiv \sum_{\substack{defect \\ types}} \sigma n(z)$$



Nanosecond Thermoreflectance

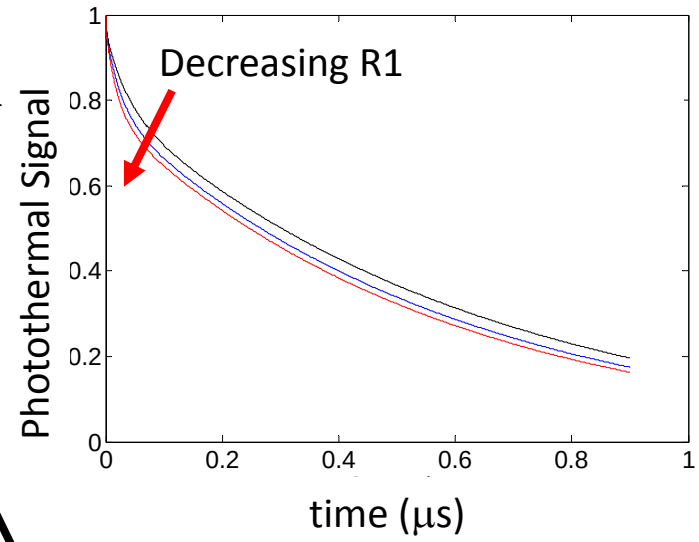
Panzer, Goodson, et al., *J. Heat Transfer* (2008), *NanoLetters* (2010)
Kaeding, Goodson, et al., *Applied Physics Letters* (1993)

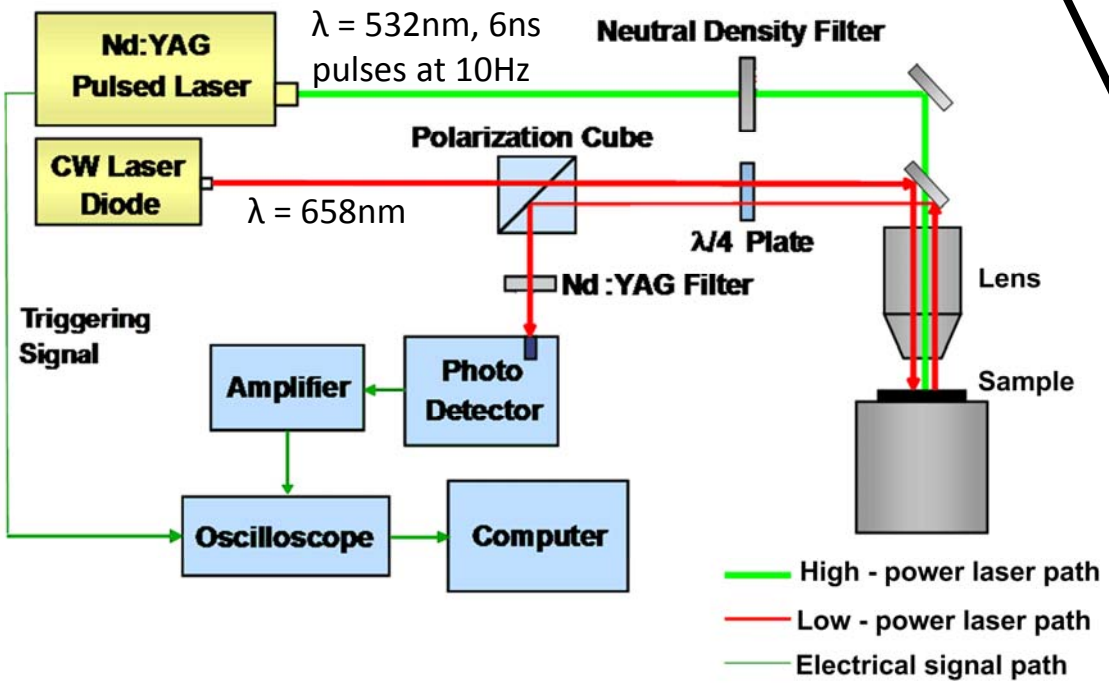
Rapid optical heating and thermometry allows vertical resistance contributions to be extracted independently

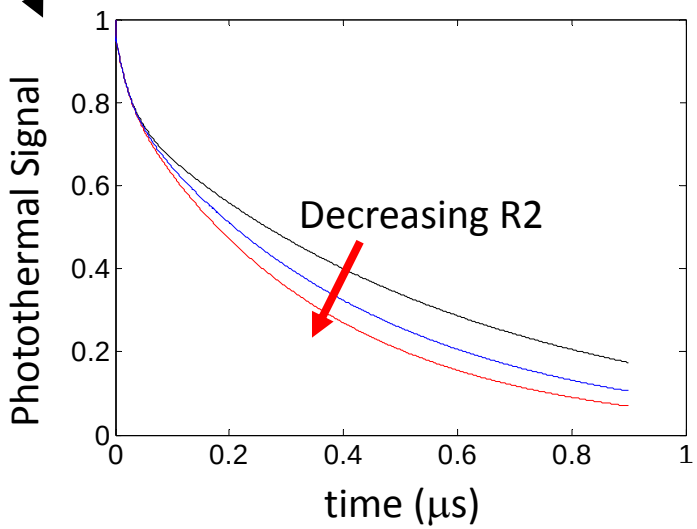


R1

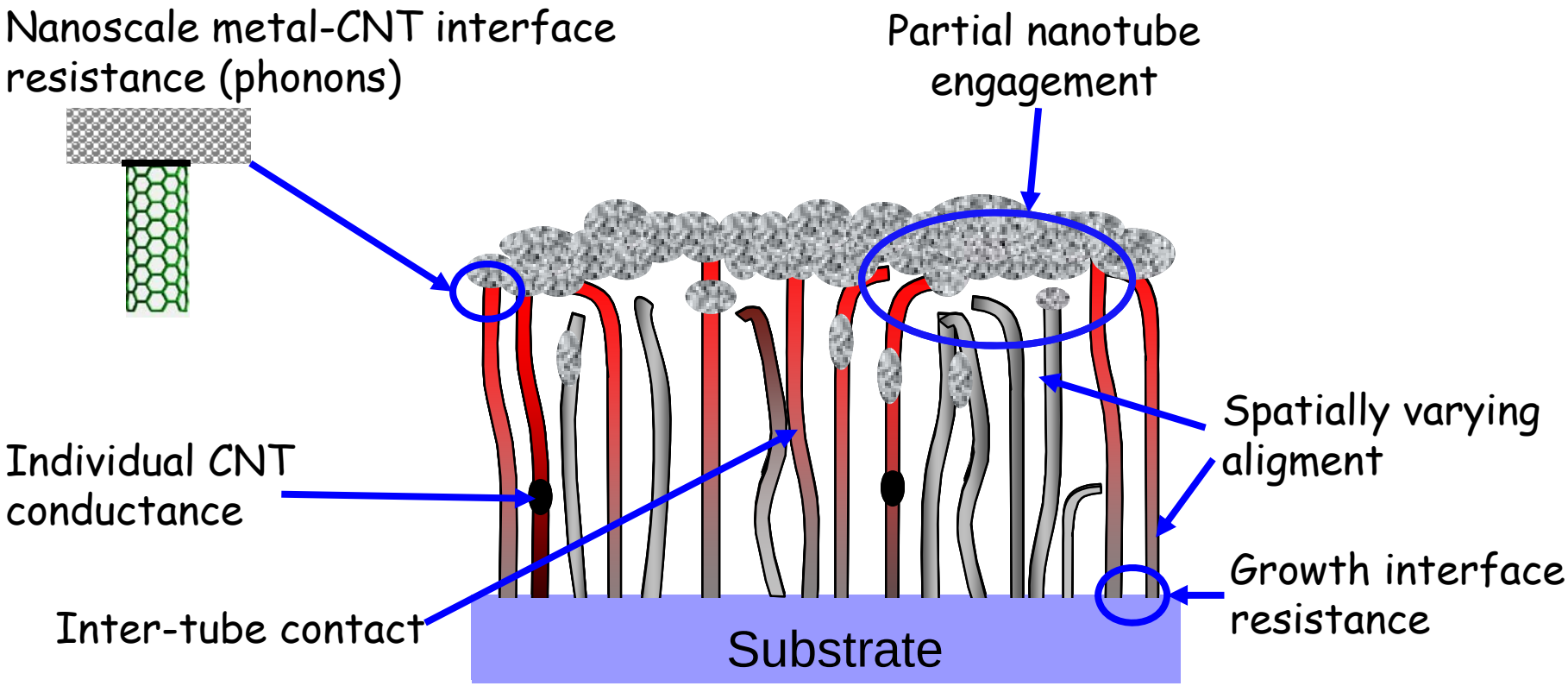
R2



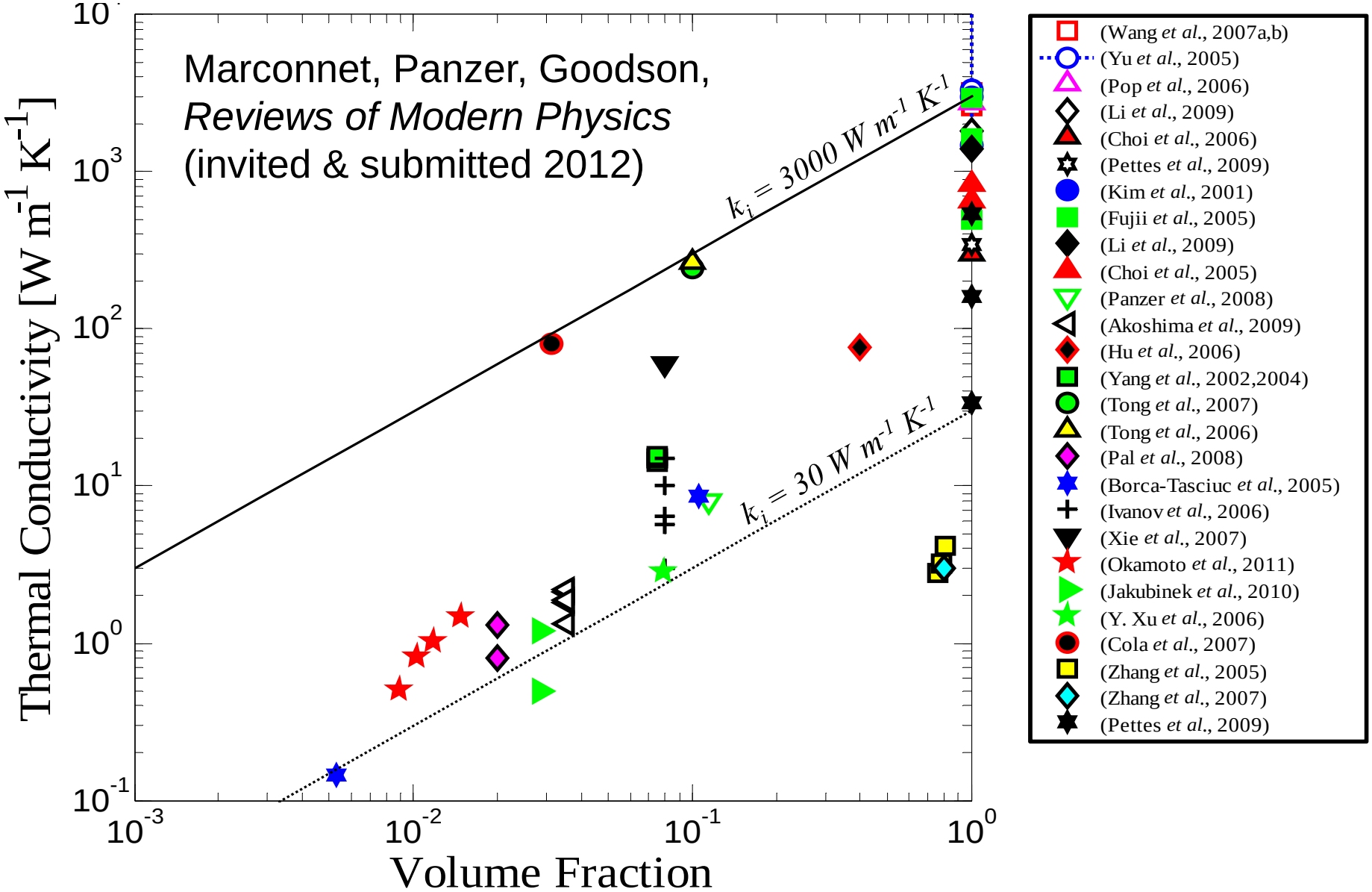




Conduction Physics in CNT Films

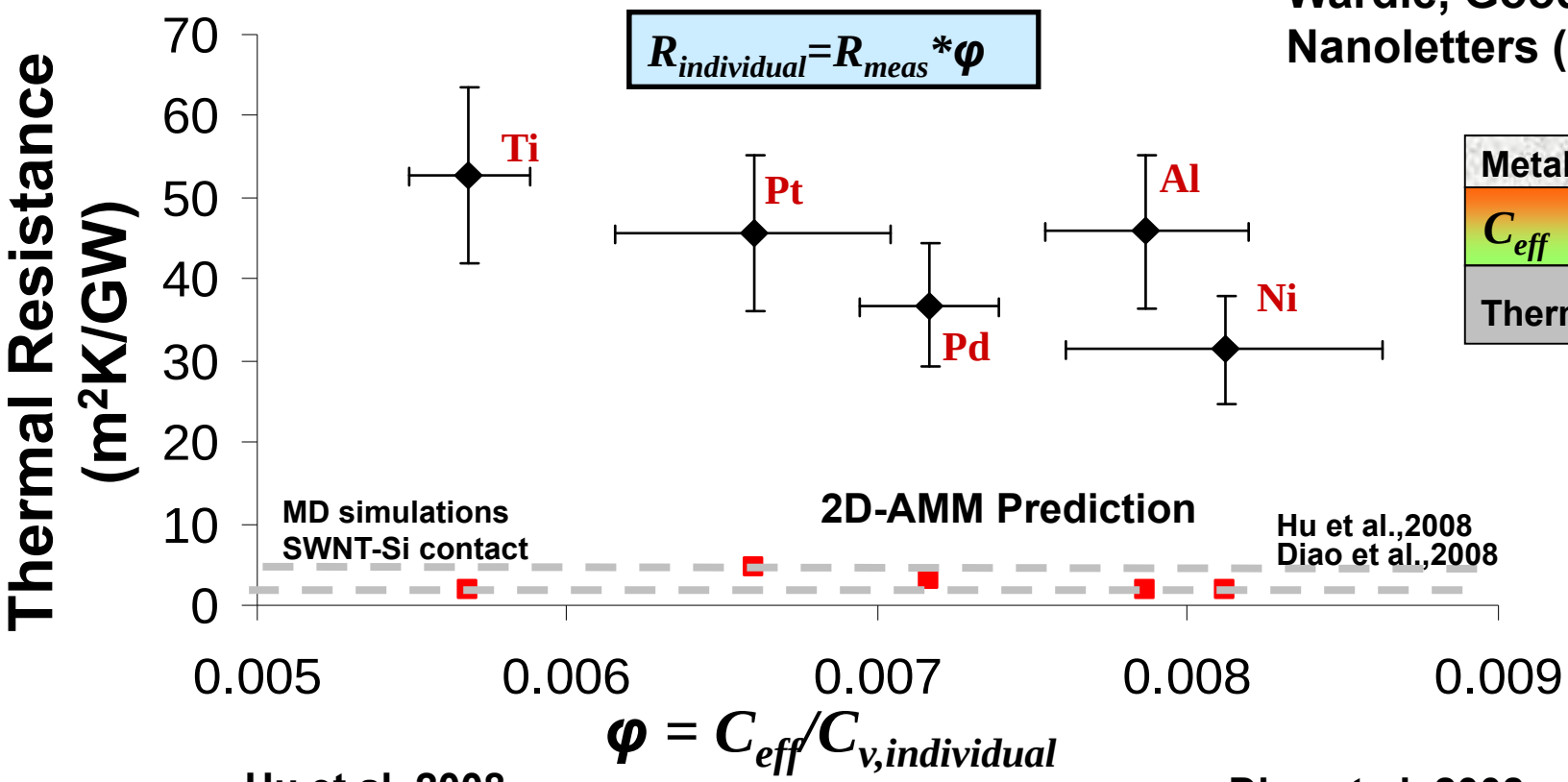


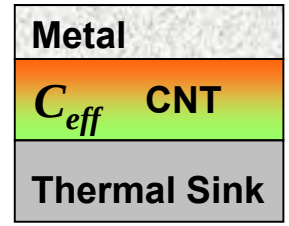
Thermal Conductivities of Individual CNTs and Aligned Arrays



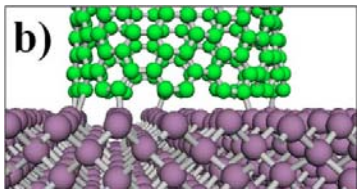
Data and Modeling for Individual SWNT-metal Interface Resistance

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



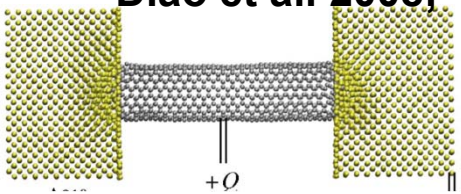


Hu et al.,2008

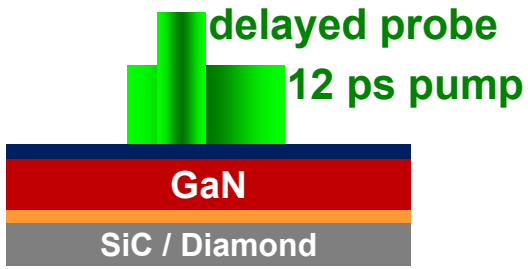


MD simulations SWNT-Si contact geometry

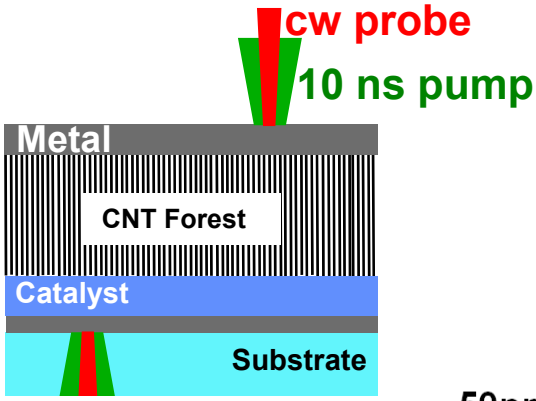
Diao et al. 2008;



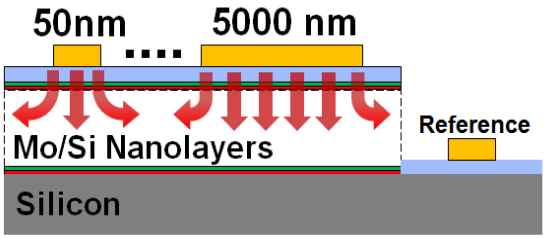
Nano Thermal Metrology



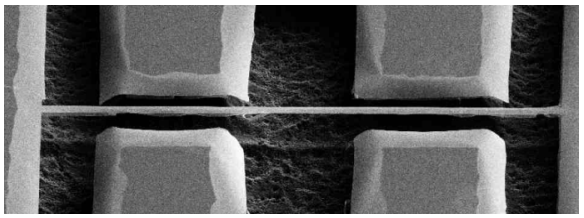
Students: Cho, Bozorg-Grayeli
Electron Device Letters (2012)



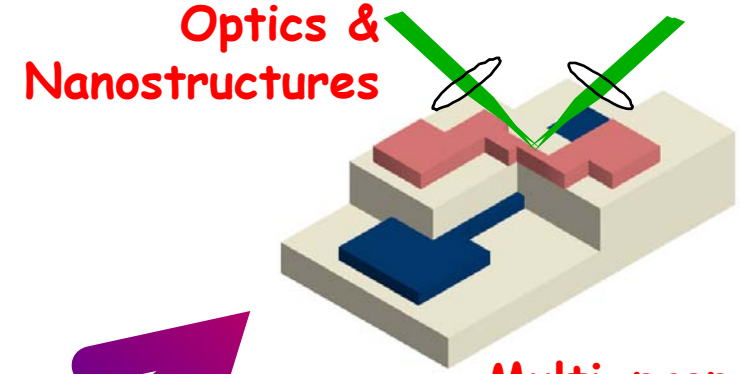
Students: Panzer, Gao
Nano Letters (2010)



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



Students: Yoneoka, Li, Kodama
Nano Letters (2012 in press)



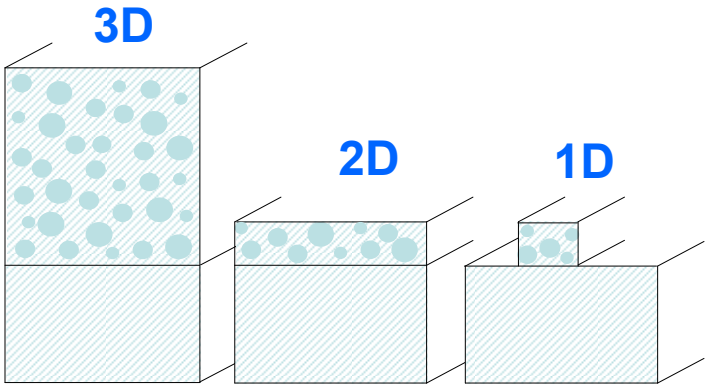
Multi-property

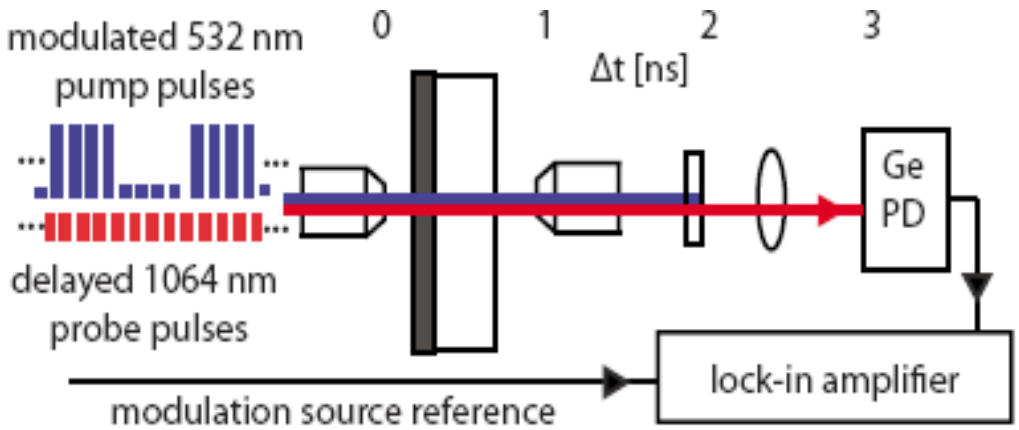
Rig Complexity

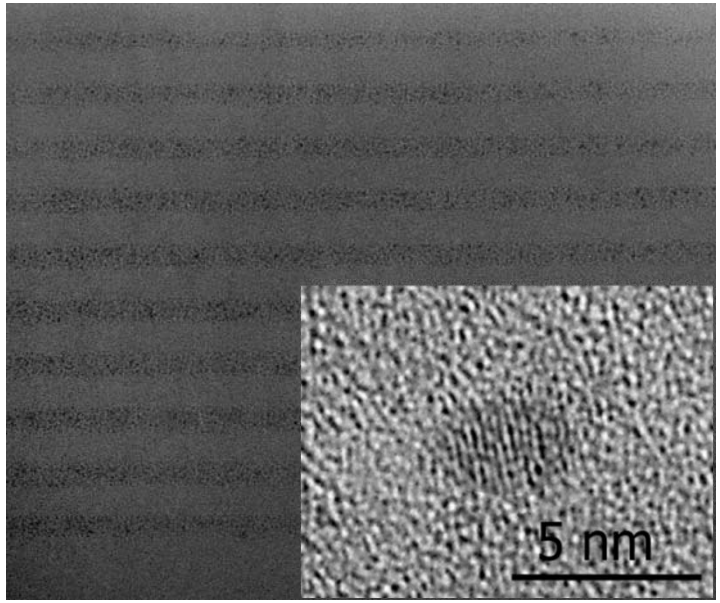
Sample Complexity

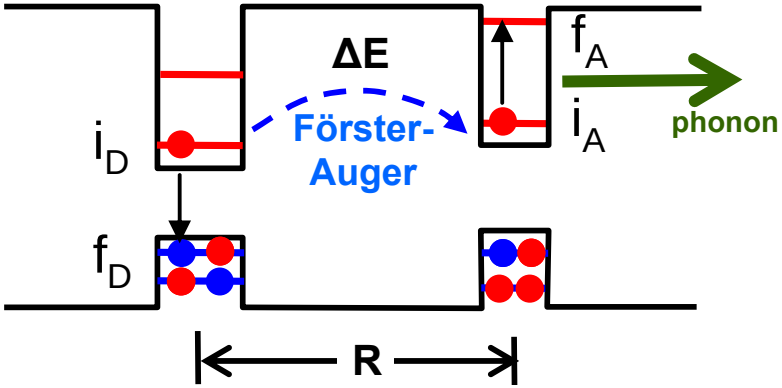
Thermal & Optical Properties of Silicon-Enriched Oxides & Nitrides

Rowlette, Kekatpure, Brongersma, Goodson, et al., *Physical Review B* (2009)
Marconnet, Yerci, Dal Negro, Goodson, et al., *Applied Physics Letters* (2012)









Thermal & Optical Properties of Silicon-Enriched Oxides & Nitrides

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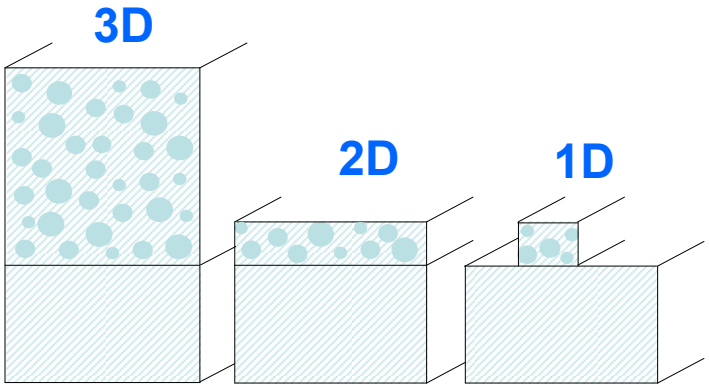
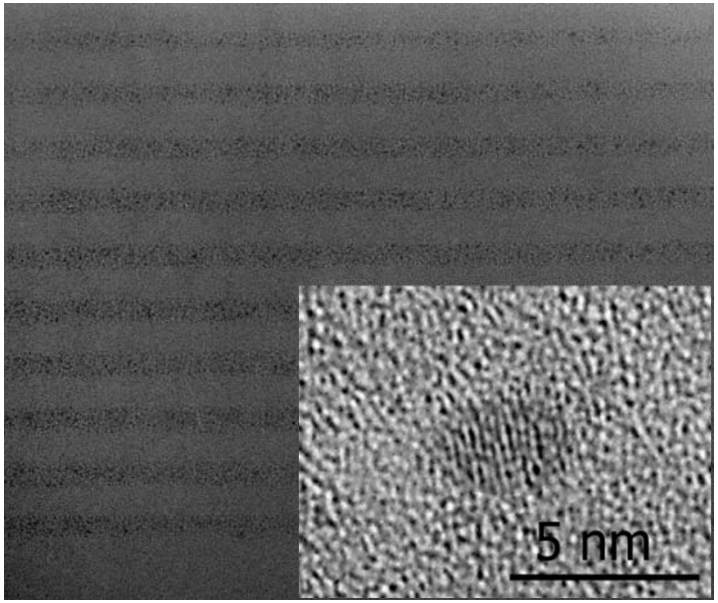
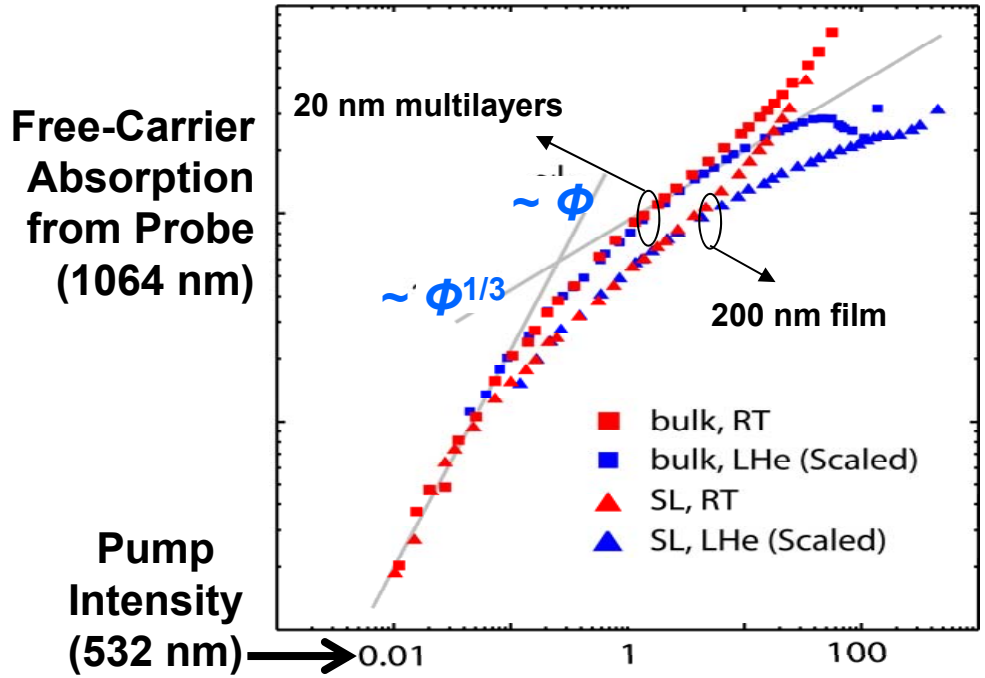
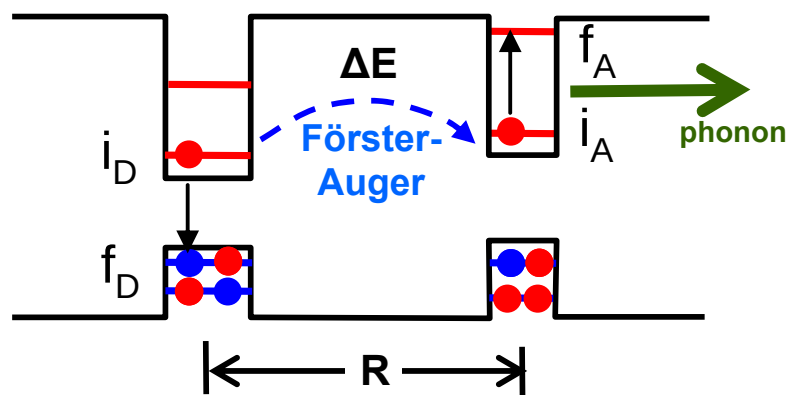
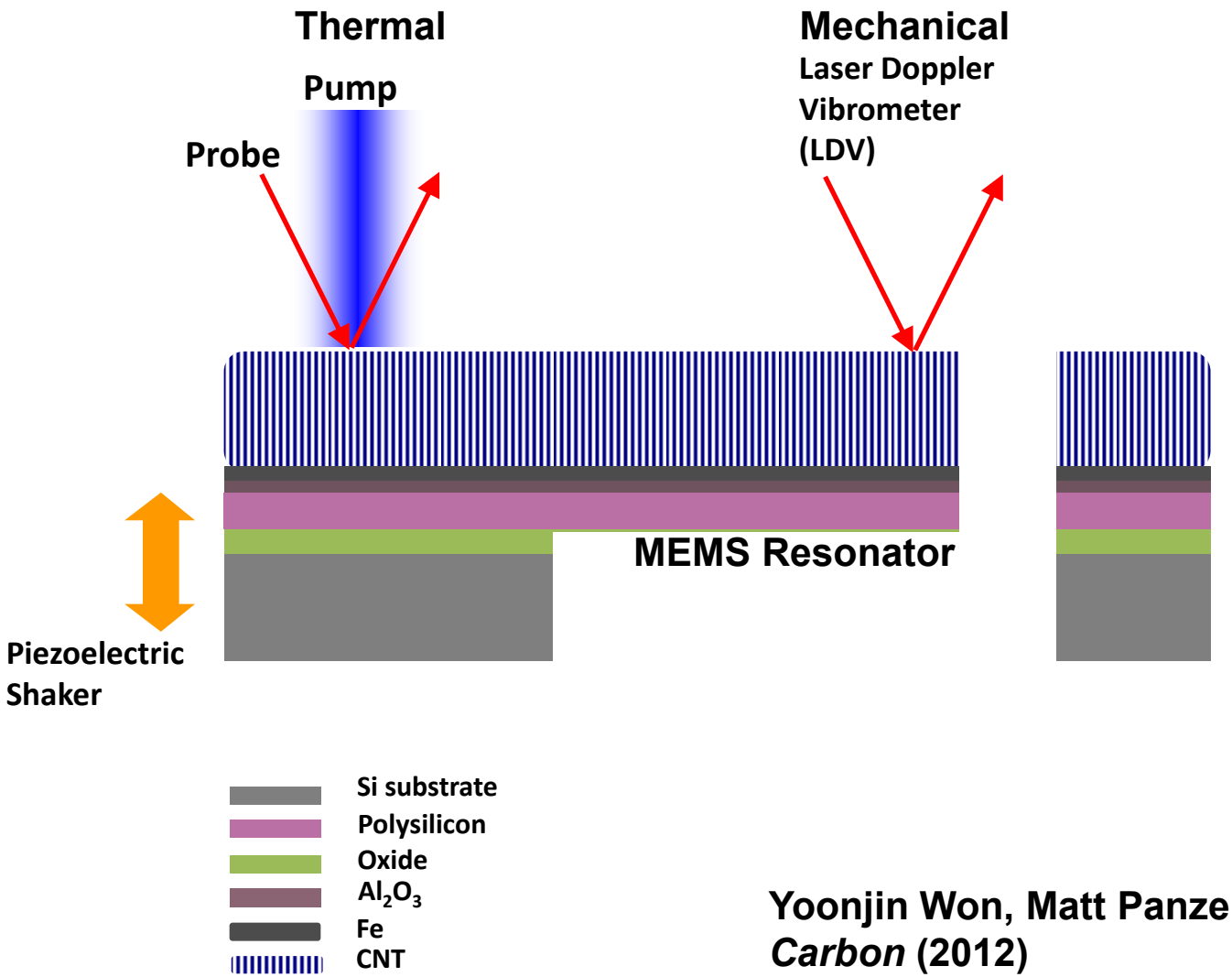


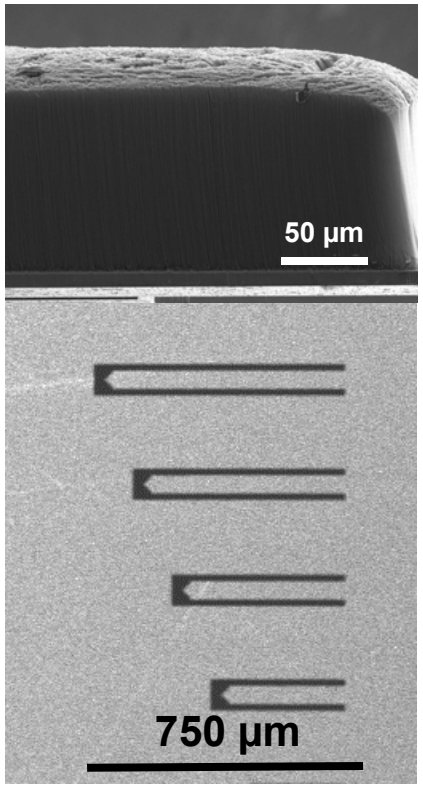






Mechanical & Thermal Properties of Aligned CNT Films

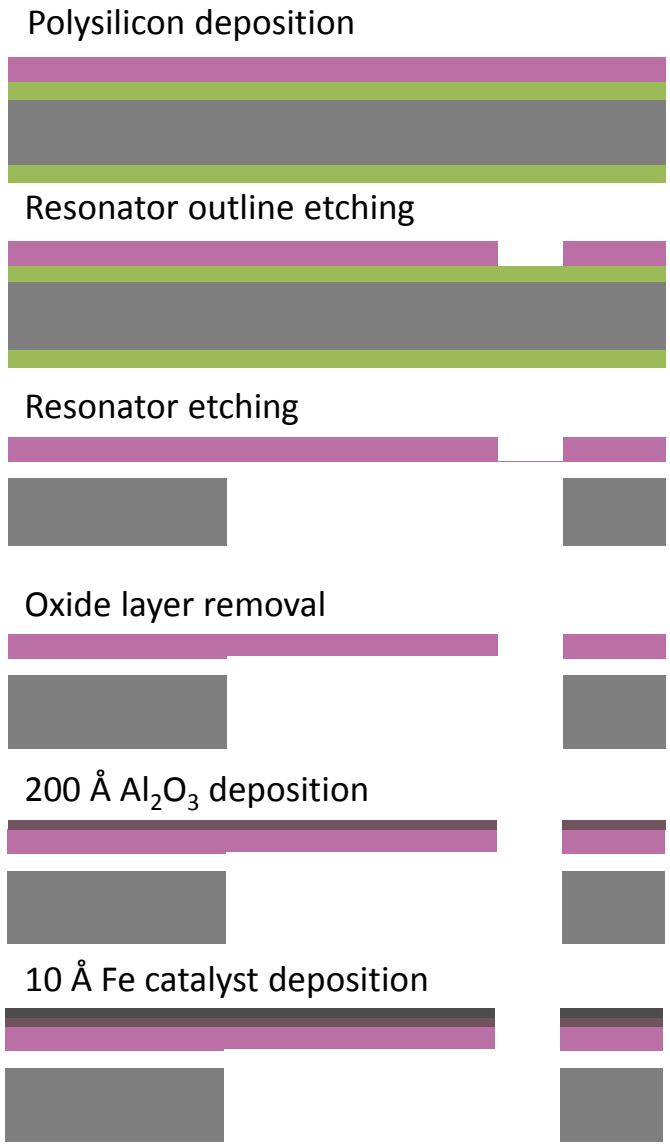




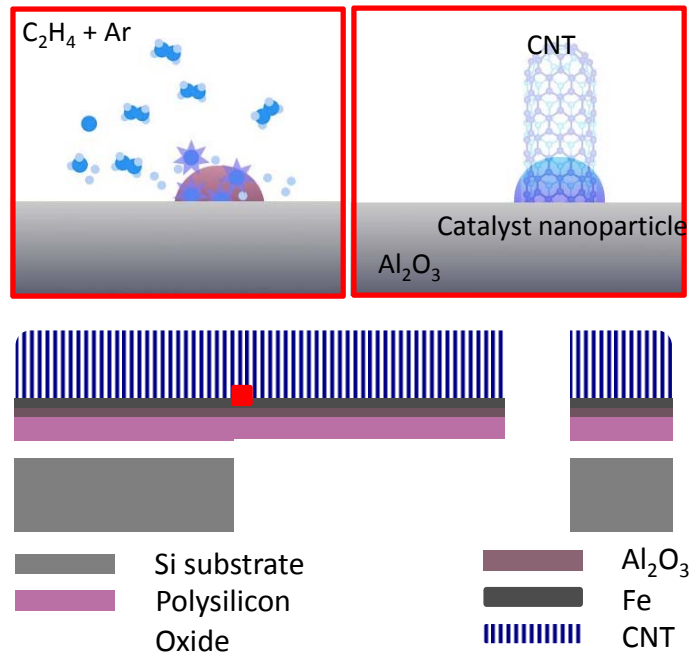
Yoonjin Won, Matt Panzer, Amy Marconnet, et al.
Carbon (2012)

Fabrication Process

Yoonjin Won, Matt Panzer, Amy Marconnet, et al., *CARBON* (2012)



CNT growth



<u>CNT growth process</u>

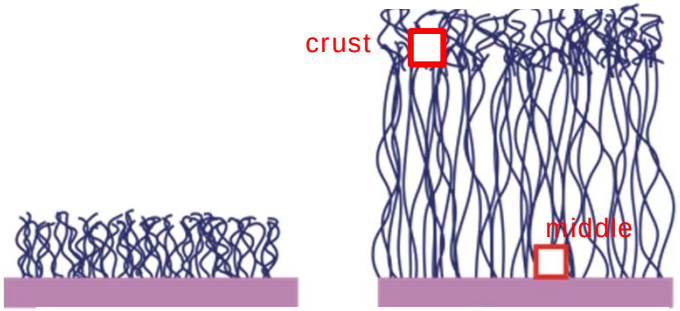
- A mixture of C_2H_4 and Ar gas flows through a tube furnace at 825°C
- The carbon atoms from C_2H_4 dissolve into the catalyst nanoparticles
- The carbons crystallize into stacks of flat sheets of hexagonally patterned carbon, which extrude as nanotubes

Modulus of Nonhomogeneous CNT Films

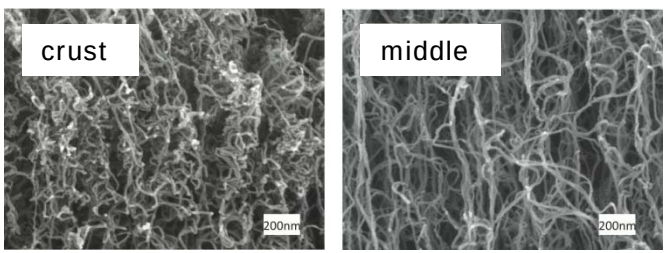
Yoonjin Won, Matt Panzer, Amy Marconnet, Goodson, et al. *CARBON* (2012a)
Yuan Gao, Takashi Kodama, Goodson, et al., *CARBON* (2012b)

Growth Stages

Stage 1 Stage 2



Self-organization Vertical-growth



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

Won, *Carbon* (2011)

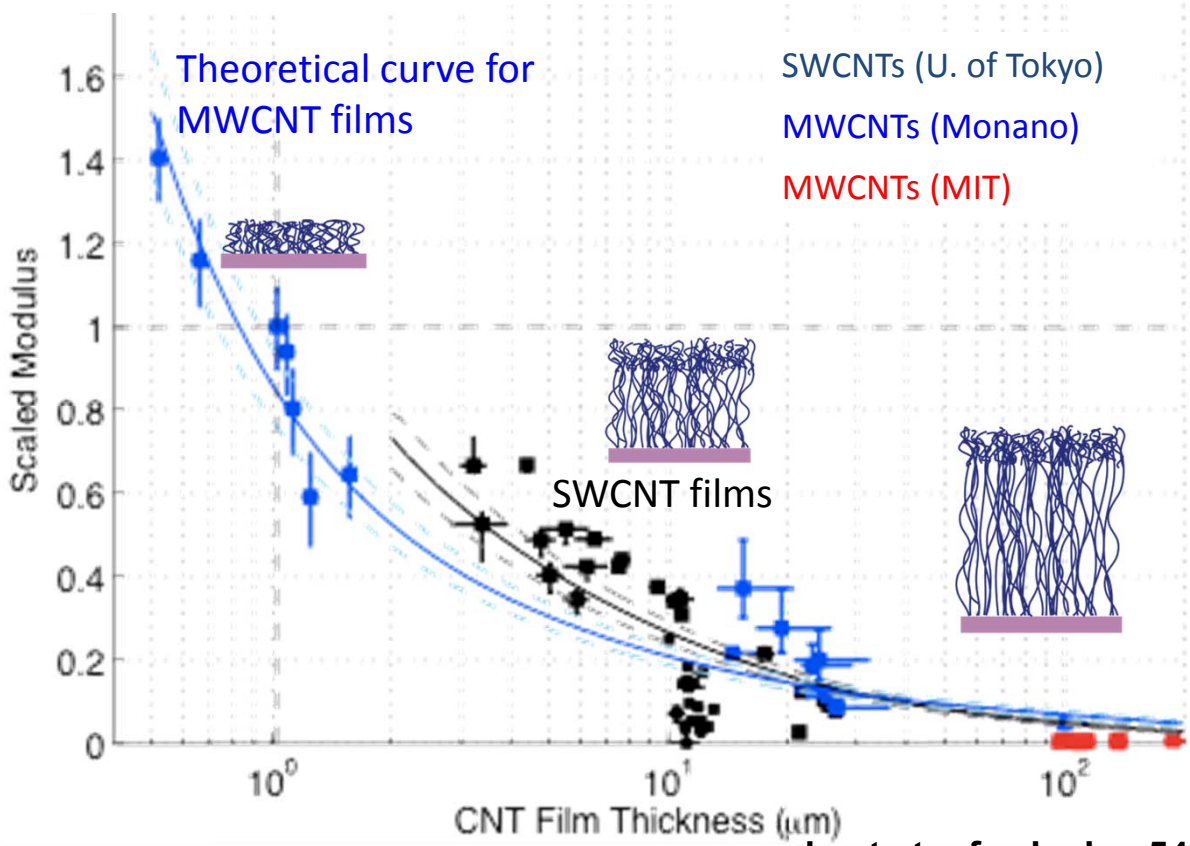
Three-layer Analysis

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



3D NanoPackaging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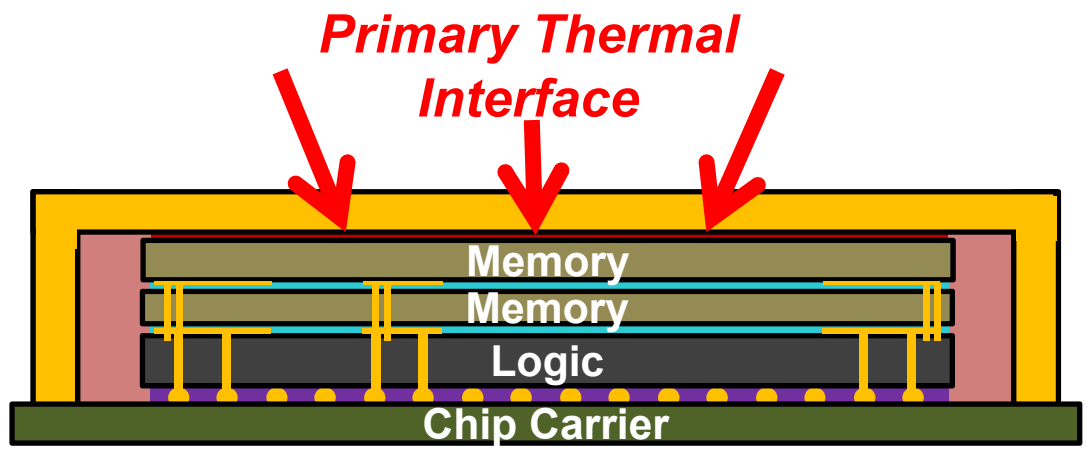
News & Analysis

Nanotape could make solder pads obsolete

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

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

By sandwiching thermally conductive carbon nanotubes between



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]

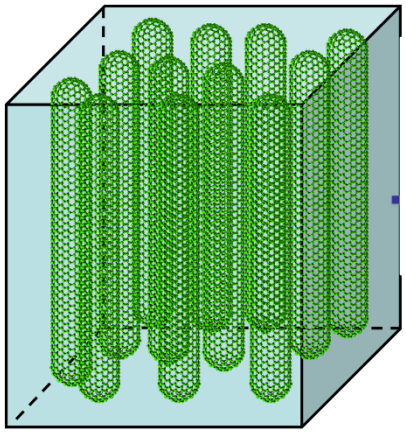
NANO LETTERS

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

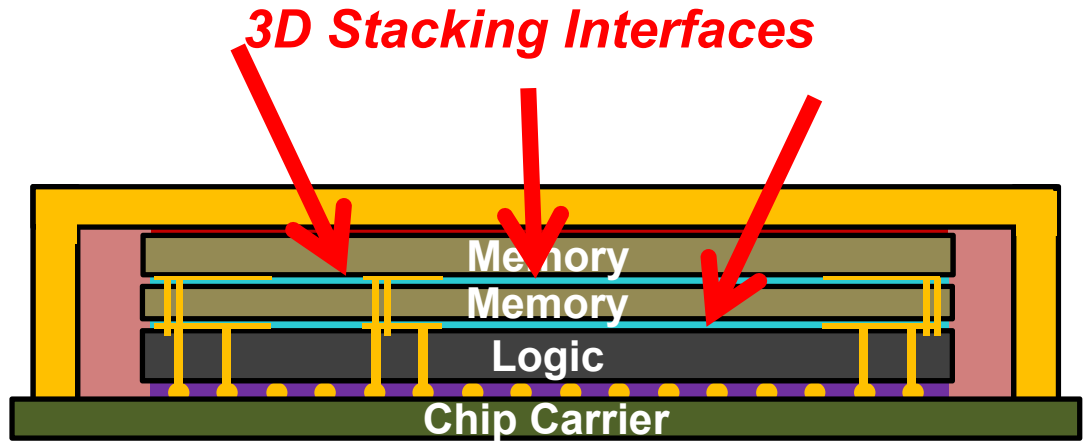
2010

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

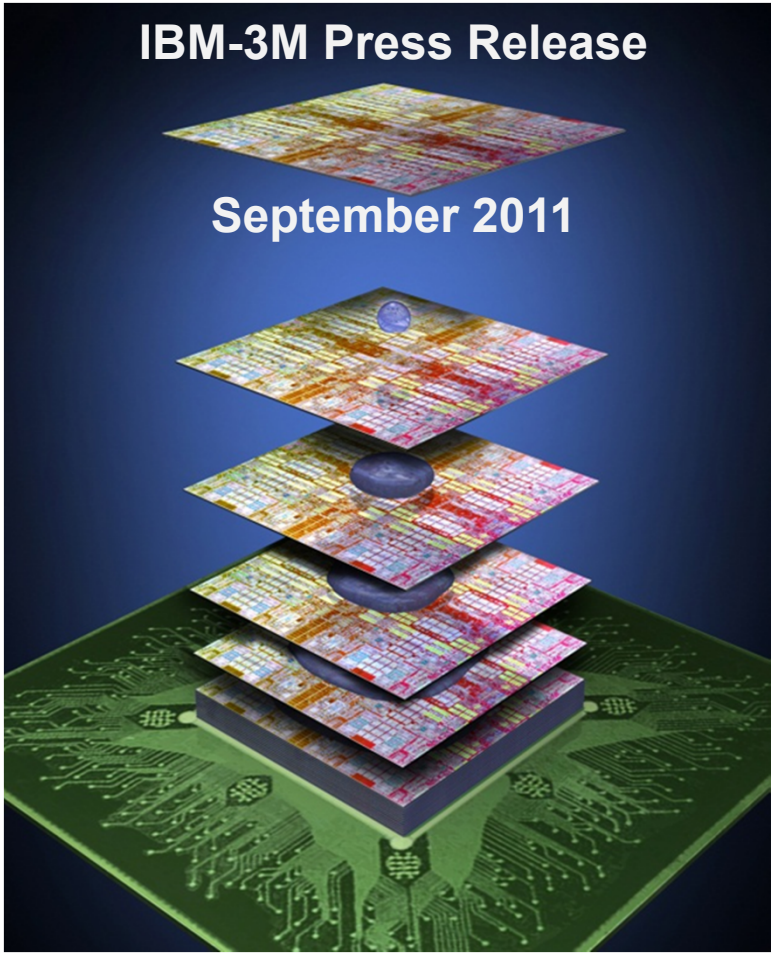
Thermal Conduction in Aligned Carbon Nanotube–Polymer Nanocomposites with High Packing Density

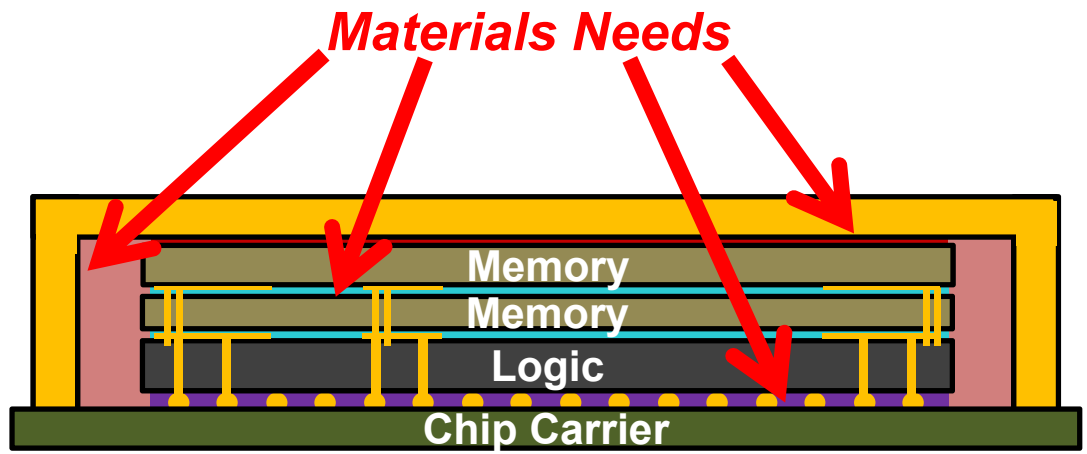
2011

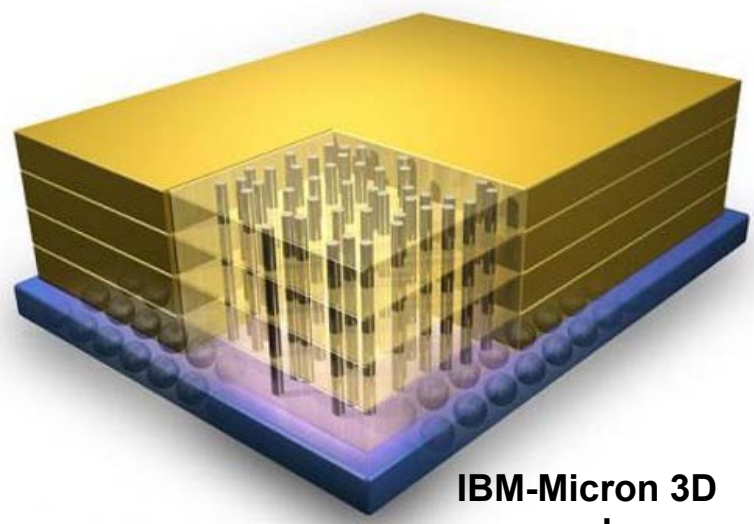
ARTICLE

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

3D NanoPackaging







IBM-Micron 3D press release, December 2011

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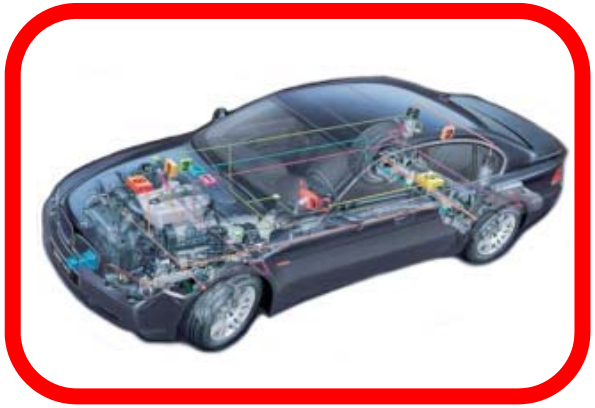
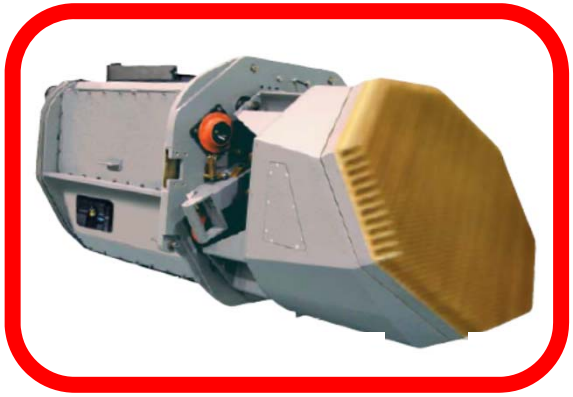


transportation



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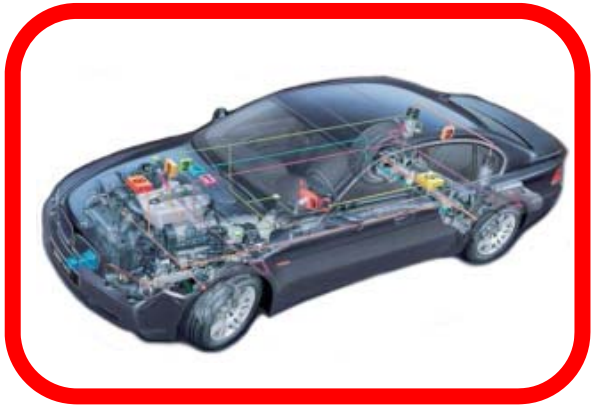

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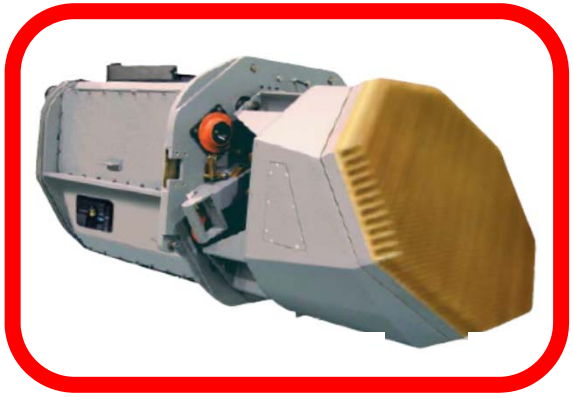

defense

STANFORD nanoHeat

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Sri Lingamneni
Saniya Leblanc
Jungwan Cho

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

Ken Goodson

Lewis Hom
Aditja Sood (MSE)
Woosung Parc

Dr. Takashi Kodama
Dr. Yoonjin Won
Prof. Mehdi Asheghi

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