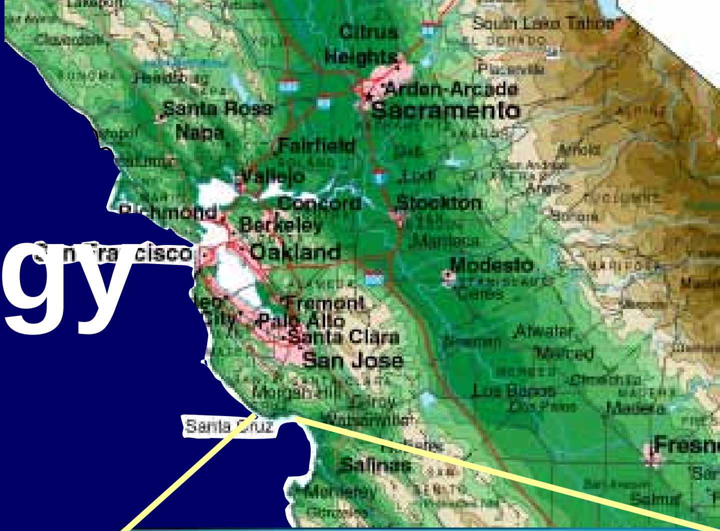
Ultrafast Nanoscale Electrothermal Energy Conversion Devices and Measurements



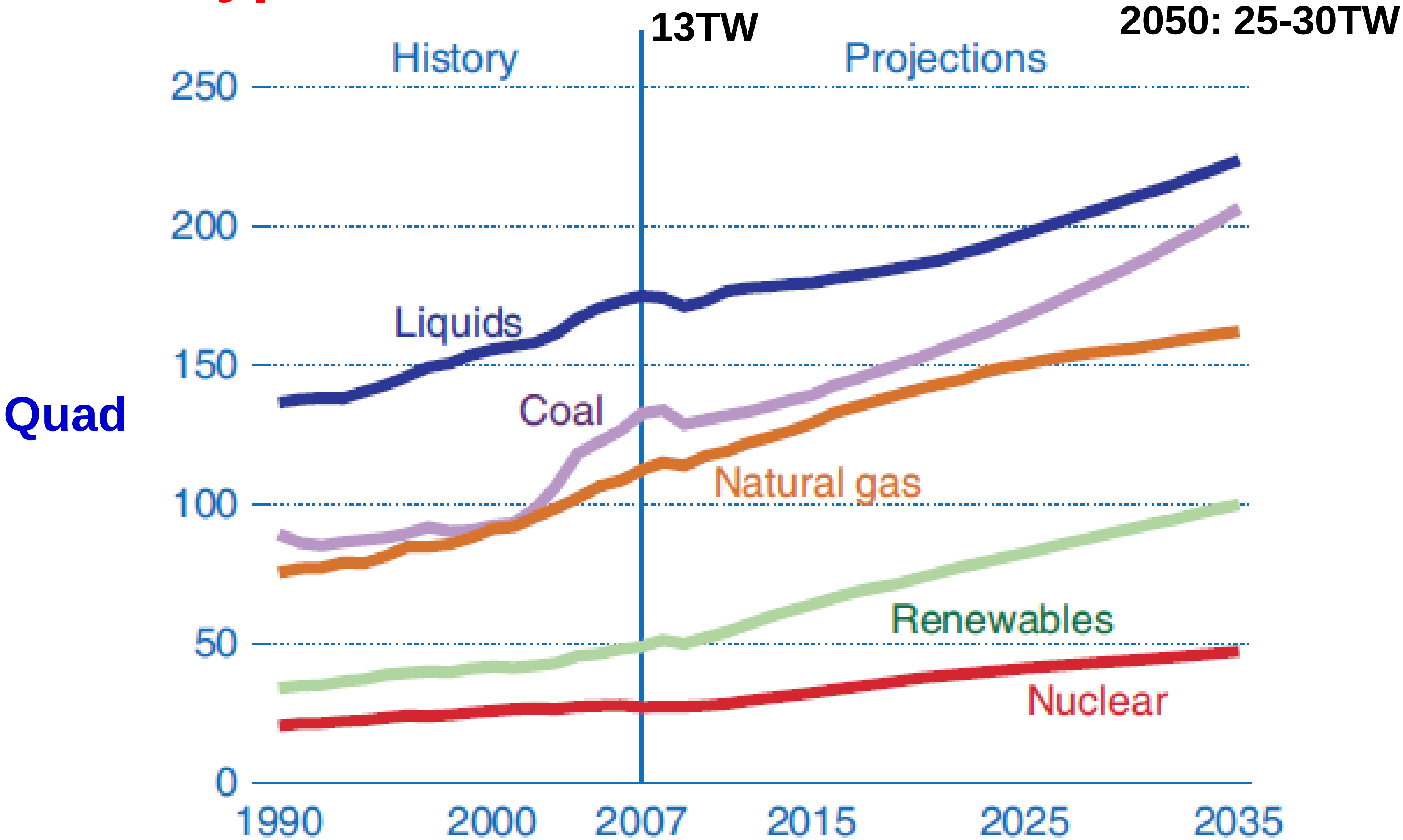
Ali Shakouri
Baskin School of Engineering
University of California Santa Cruz

Acknowledgement: **ONR, DARPA, AFOSR, CEA, NSF, DOE/EFRC, NASA/UCSC National Semiconductor, Intel, Canon, Wyle Lab, SRC-IFC**

IEEE Power Electronics Society, Santa Clara Valley Chapter; 16 Feb. 2011

World Marketed Energy Use by Fuel Type 1990-2035

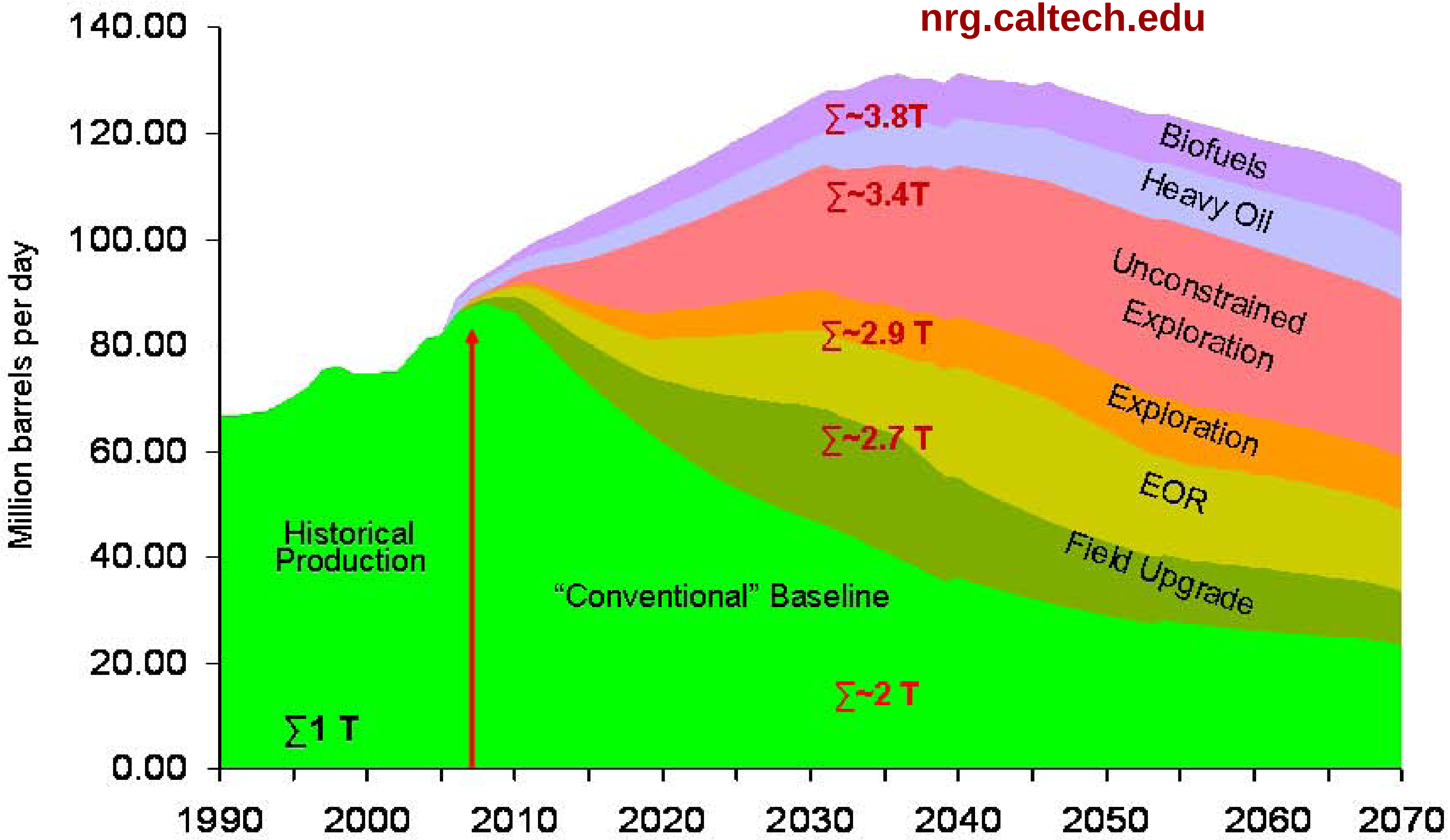
A. Shakouri 2/16/2011



US Department of Energy; Energy Information Administration (2010)

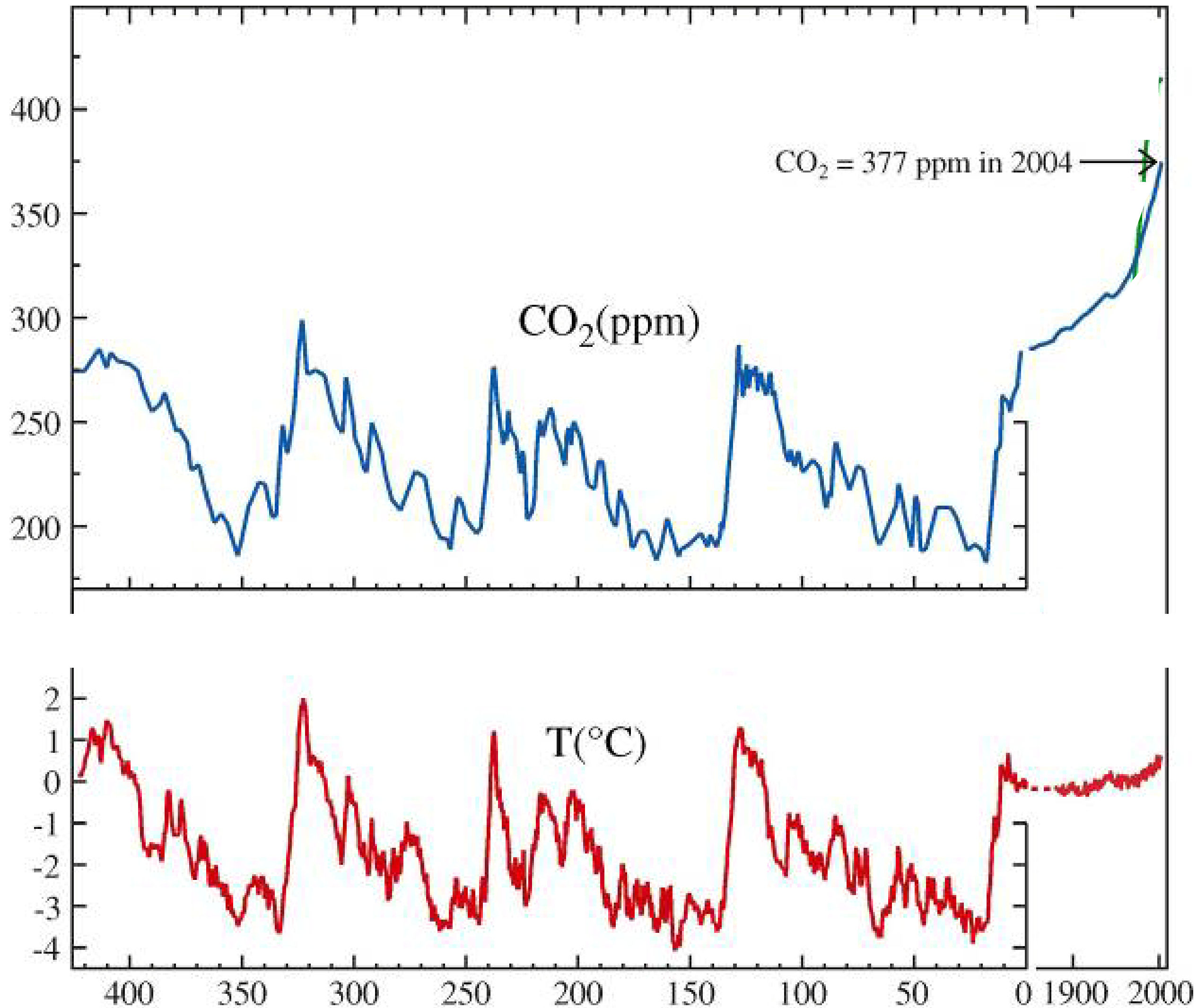
A Future: ~ 3.5 Trillion bbls **Oil Resources**

S. Koonin, Former Chief Scientist BP
nrg.caltech.edu



ɔurce: Modified from Cambridge Energy Research Associates, Inc. (CERA). The use of this graphic was authorized in 'ance by CERA. No other use, or redistribution of this information is permitted without written permission by CERA."

400,000 years of greenhouse-gas & temperature history based on bubbles trapped in Antarctic ice



Last time CO_2 >300 ppm was 25 million years ago.

Source: Hansen, *Clim. Change*, **68**, 269, 2005.

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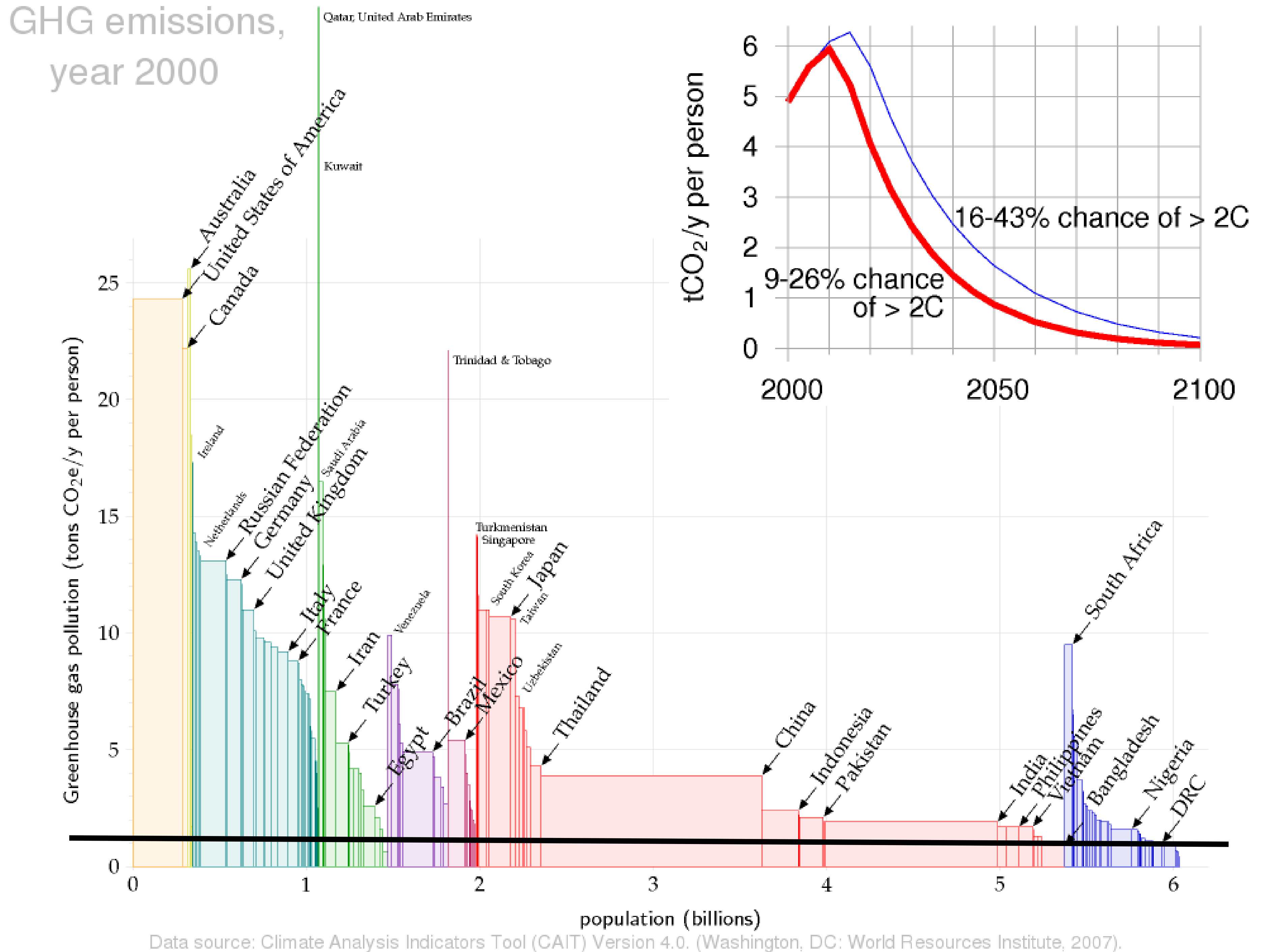
John P. Holdren, 2006

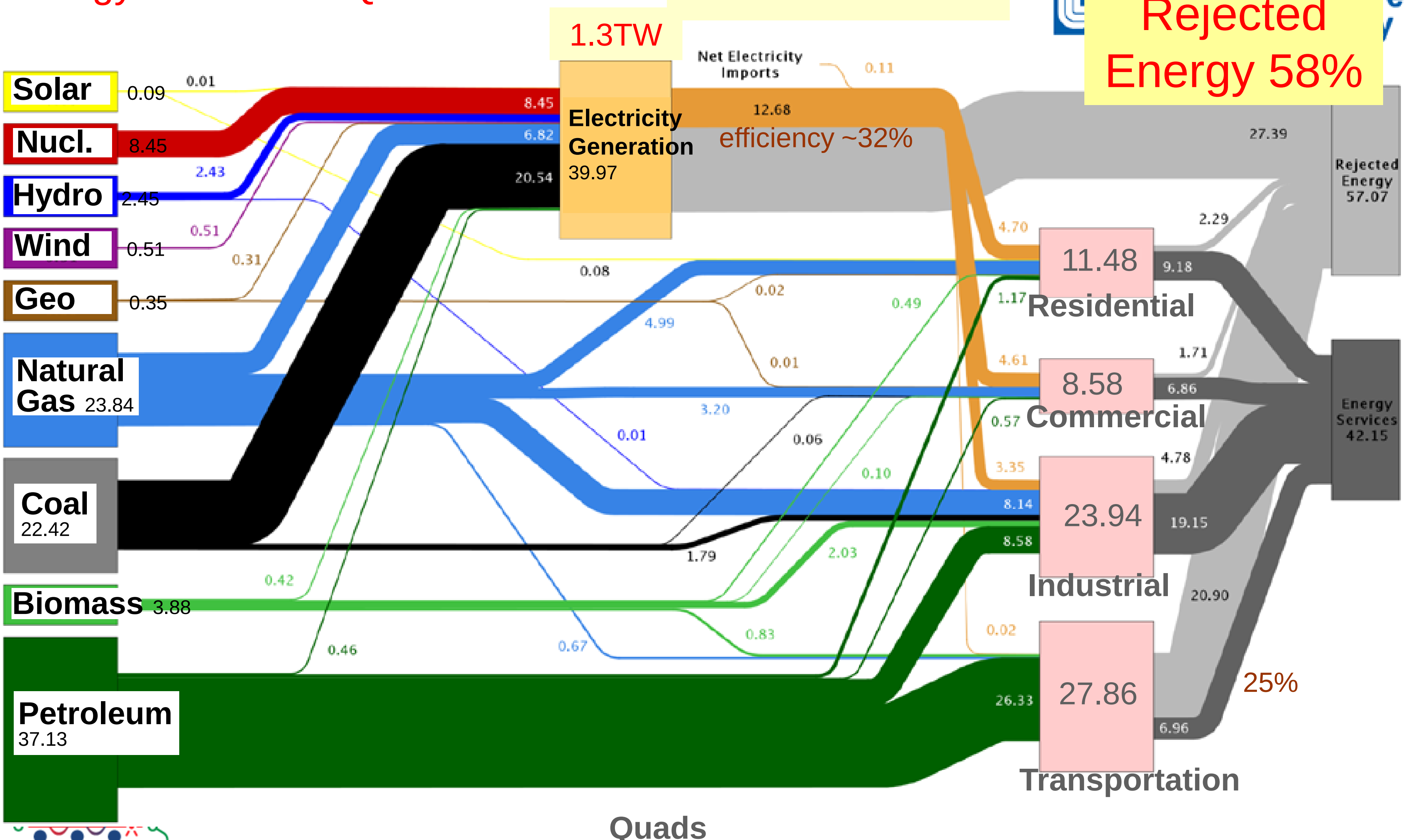


GHG emissions, year 2000
Qatar, United Arab Emirates
Kuwait
Australia
United States of America
Canada
Trinidad & Tobago
Ireland
Netherlands
Russian Federation
Germany
United Kingdom
Saudi Arabia
Italy
France
Iran
Turkey
Egypt
Venezuela
Brazil
Mexico
Turkmenistan
Singapore
South Korea
Japan
Taiwan
Uzbekistan
Thailand
China
Indonesia
Pakistan
India
Philippines
Vietnam
Bangladesh
Nigeria
DRC
South Africa
Greenhouse gas pollution (tons CO_2e/y per person)
population (billions)
tCO_2/y per person
16-43% chance of > 2C
9-26% chance of > 2C
2000
2050
2100
Data source: Climate Analysis Indicators Tool (CAIT) Version 4.0. (Washington, DC: World Resources Institute, 2007).

US Energy Flow 2008

A. Shakouri 2/16/2011

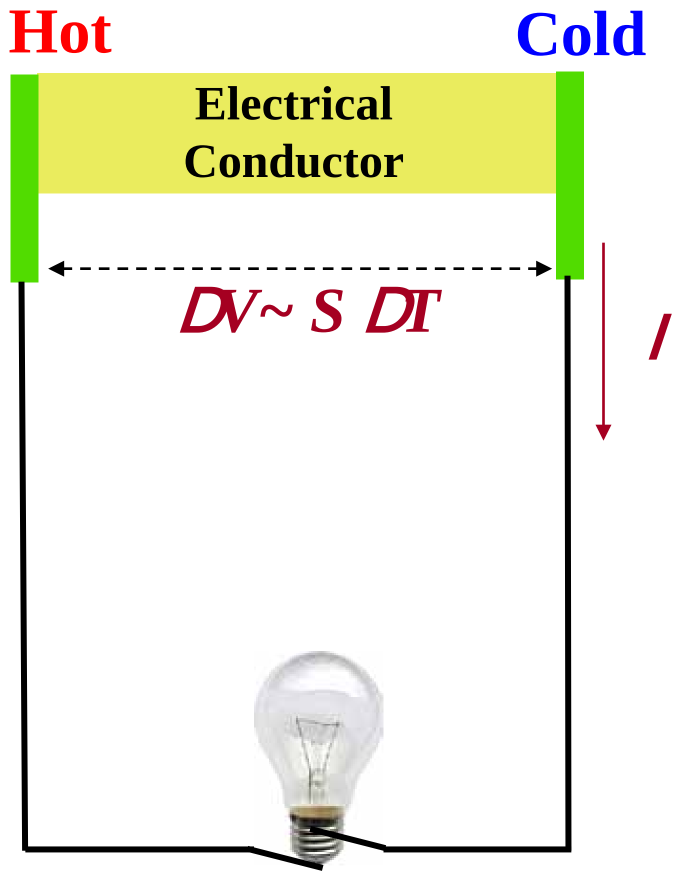
Energy Use = 99.2 Quad = 105 EJ → Power ~3.3 TW



http://eed.llnl.gov/flow

Direct Conversion of Heat into Electricity

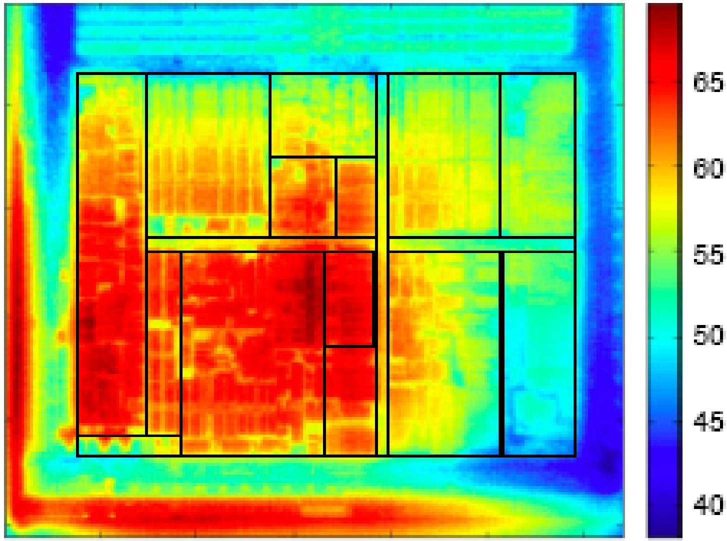
Seebeck
(1821)

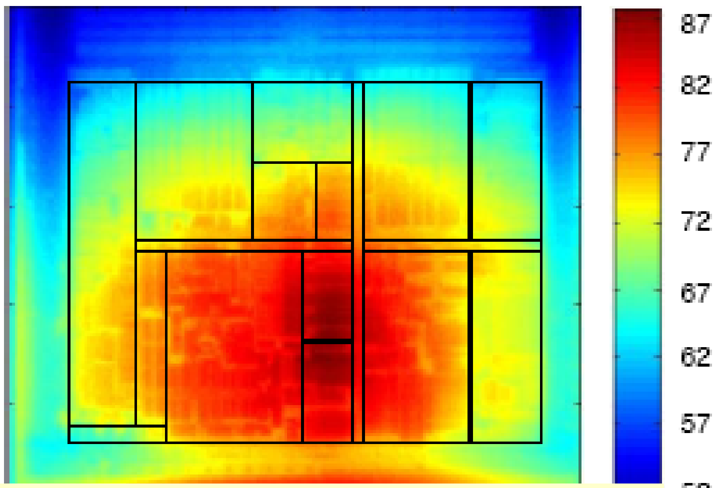


Impact of 15ºC temperature increase on IC performance

- Leakage power exponential increase with temperature
  - 60nm→50-70% of total power
  - Potential thermal runaway
- Lifetime exponential decrease with temperature (x ¼) – e.g. electromigration, oxide breakdown
- Interconnect delay (10-15%)
- Crosstalk noise (↑up to 25%)

Thermal integrity: a must for low-power-IC digital design, EDN 15 Sept. 2005





http://masc.cse.ucsc.edu

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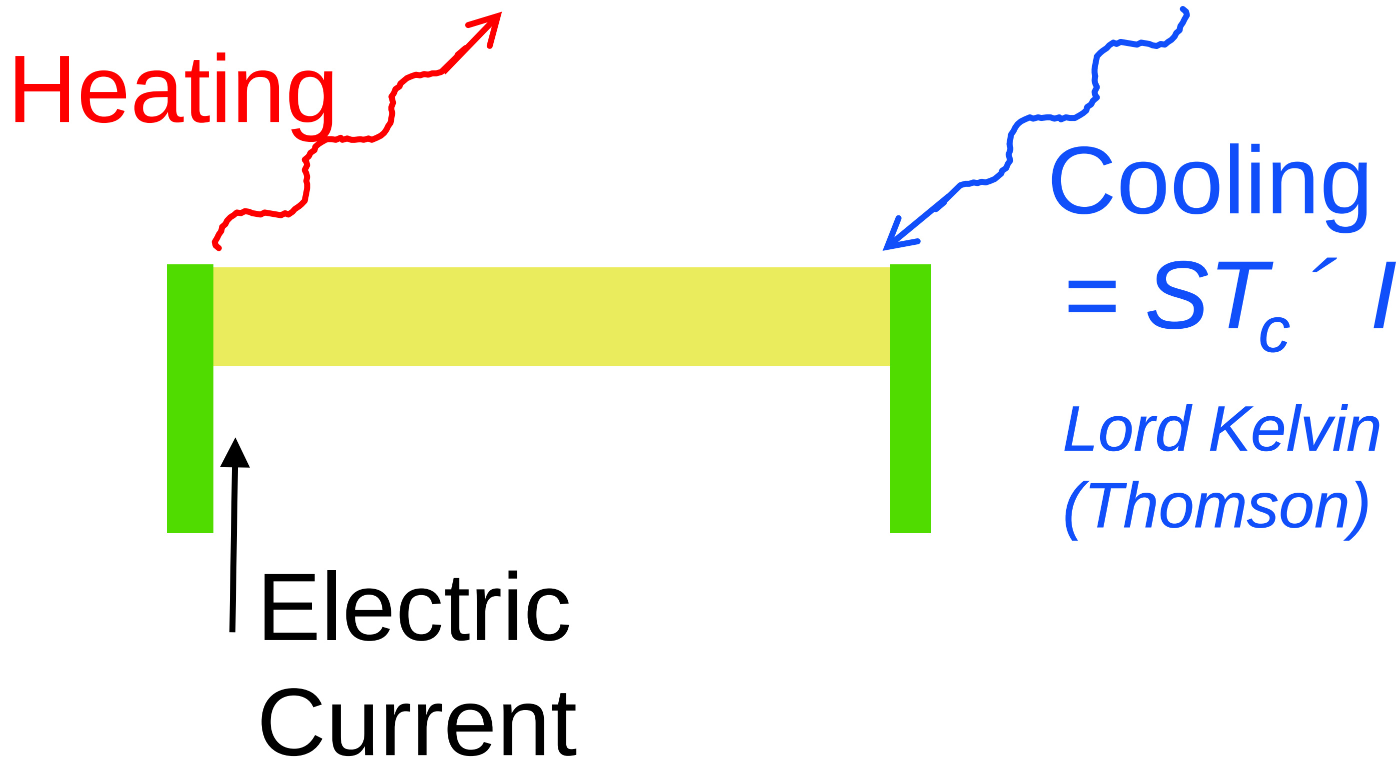
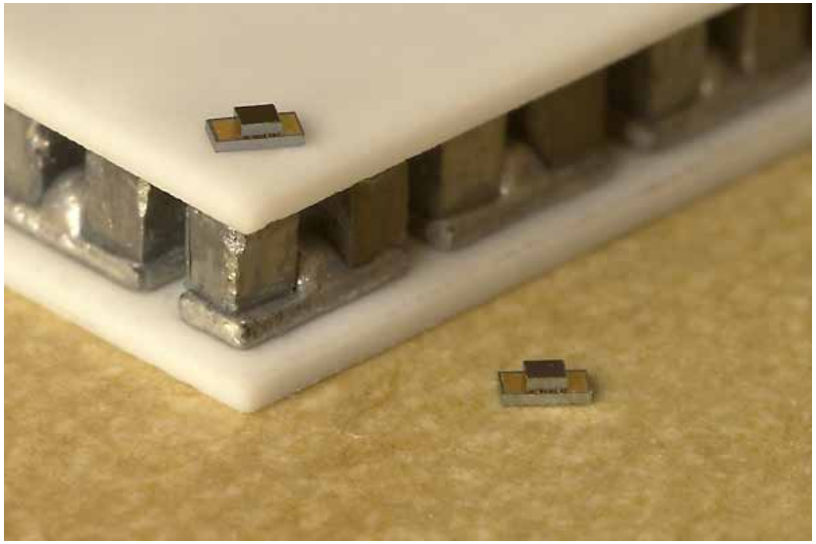
Measuring Power and Temperature from Real Processors, Javi Martinez, Jose Renau, et al.
*The Next Generation Software (NGS) Workshop (**NGS08**)*, April 2008

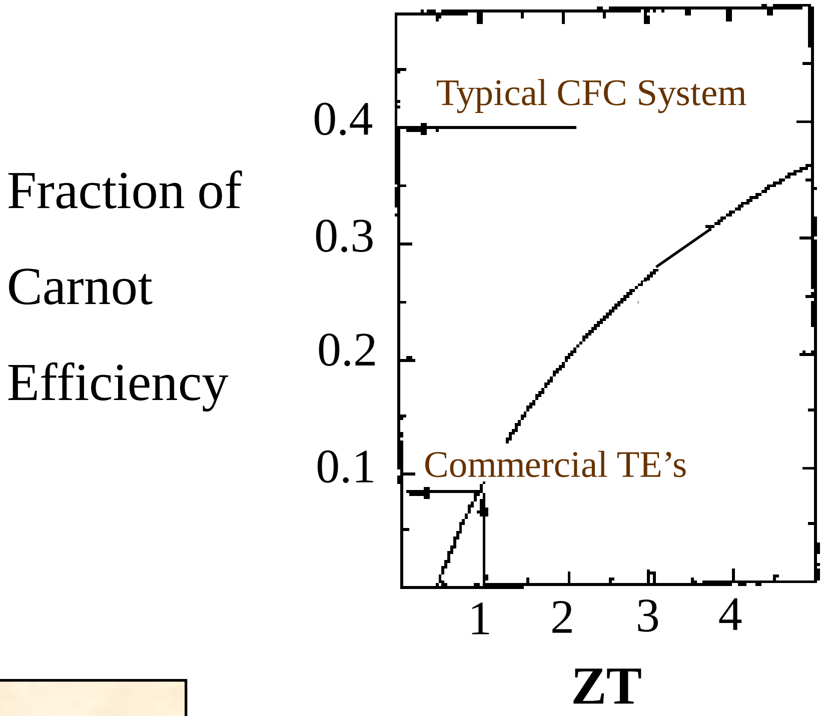
Peltier Effect (1834)



Reverse of Seebeck effect (electric current produces cooling/heating)

Thermoelectric (Peltier) Coolers





$$Z = \frac{S^2 s}{k}$$

$$Z = \frac{(Seebeck)^2 (electrical\ \ conductivity)}{(thermal\ \ conductivity)}$$

Conventional thermoelectrics have low efficiencies and low cooling power density <50-100W/cm².

TEs for Telecom Cooling

- Melcor, Marlow and many other TE manufacturers provide coolers specifically designed for Telecom laser-cooling applications

Typical Distributed Feedback Laser:

$\Delta\lambda/\Delta T$= <u>0.1 nm/°C</u>

Heat generation <u>kW/cm^2</u>

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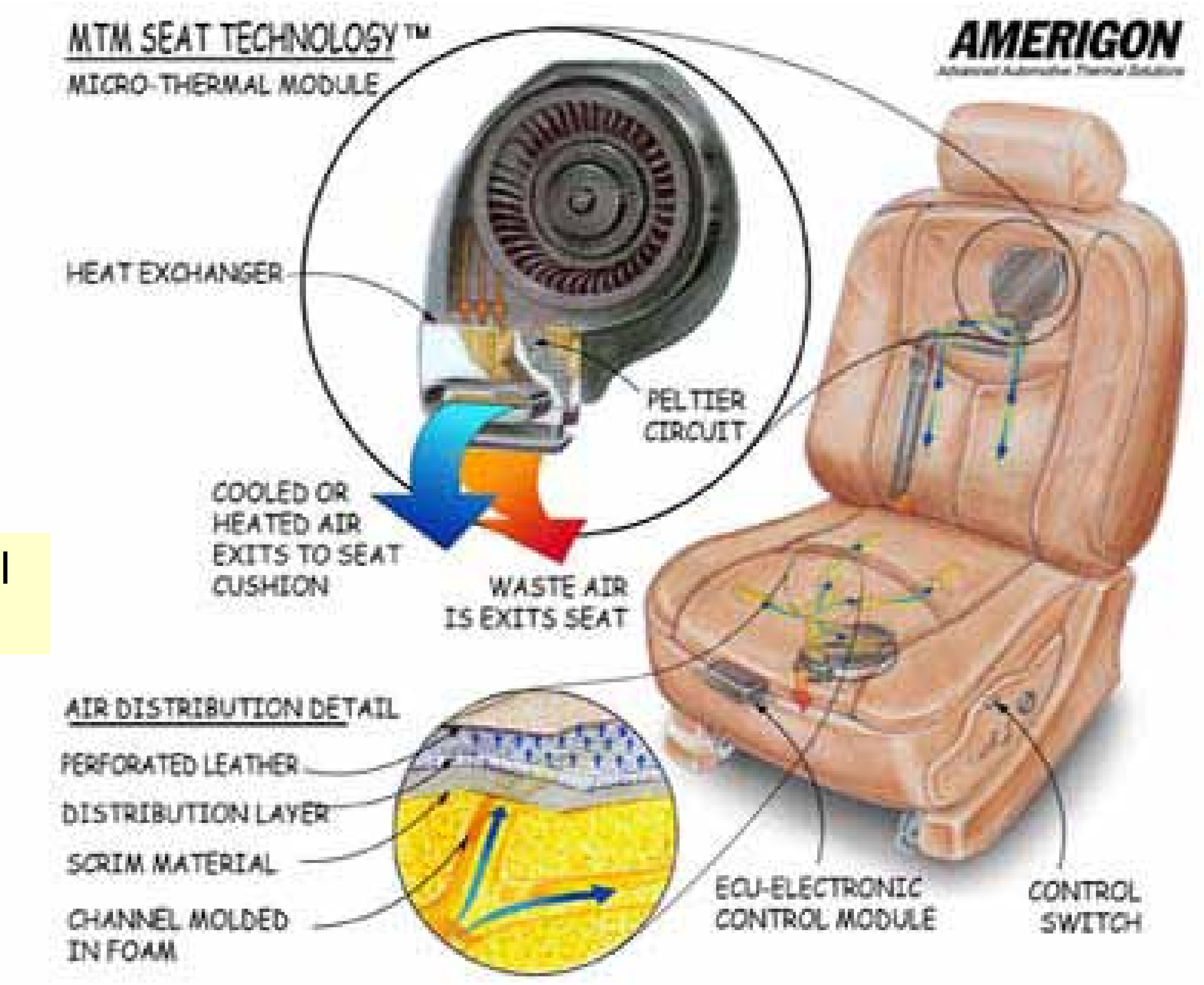
Cronin Vining, ZT Services

Thermoelectrically-Cooled/Heated Car Seat



Lon Bell
BSST

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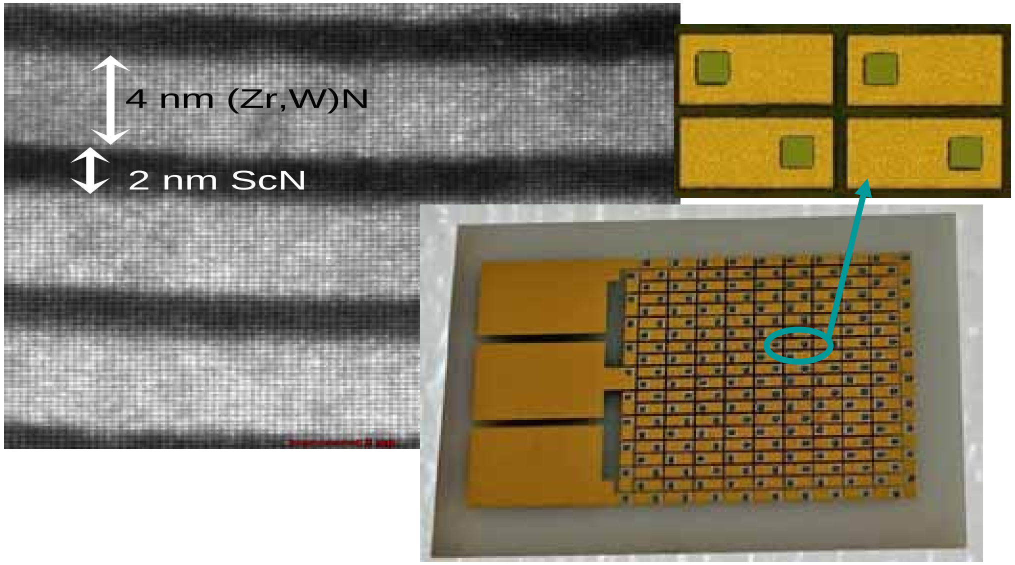
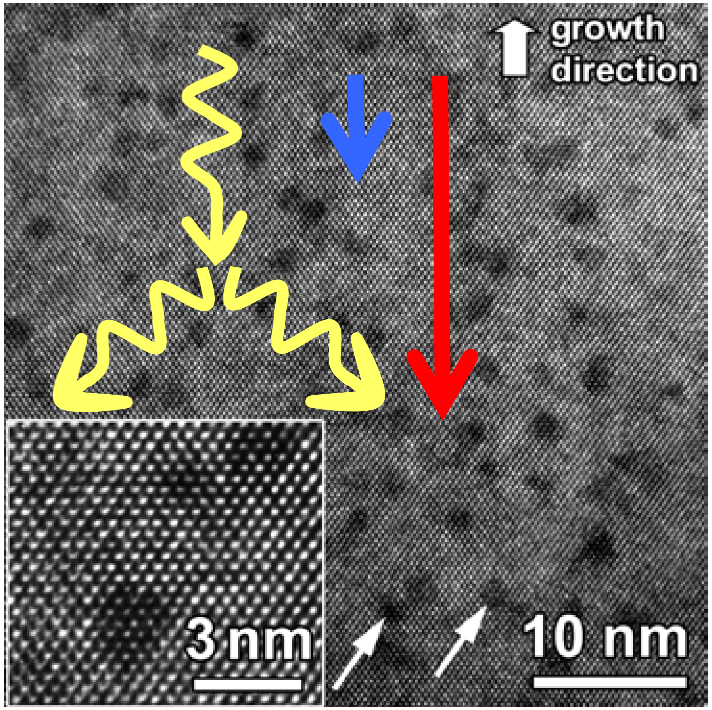
Solid-State Thermoelectric Energy Conversion using Nanostructured Materials

Thermionic Energy Conversion Center

Ali Shakouri, Director





Engineering current and heat flow using nanostructures

Goal: direct conversion of heat into electricity with > 20-30% efficiency

UCSC (Bian, Kobayashi), **Berkeley** (Majumdar), **BSST Inc.** (Bell), **Delaware** (Zide), **MIT** (Ram), **Purdue** (Sands), **UCSB** (Bowers, Gossard)

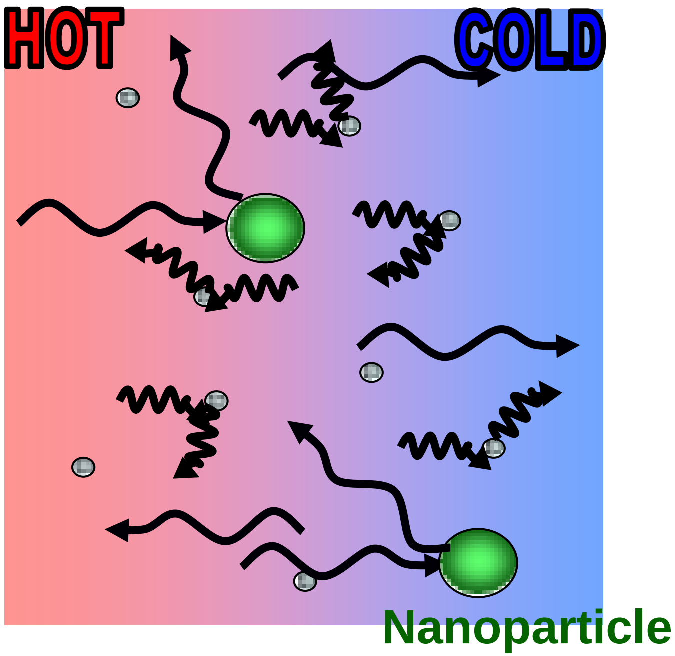
Funding: DARPA, ONR, DOE, NSF

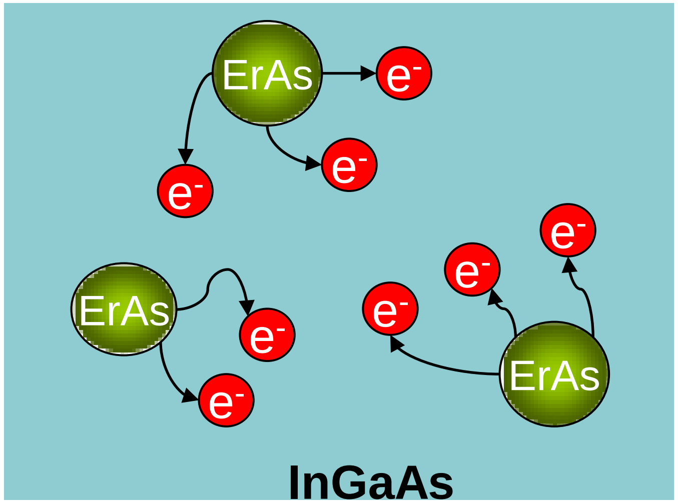
Two beneficial effects of metal nanoparticles on thermoelectric performance

Metal nanoparticles ***scatter phonons***
Æ reduced thermal conductivity

Metal nanoparticles ***donate electrons***
Æ enhanced electrical conductivity by increasing electron density in the semiconductor matrix

$$Z = \frac{(\text{Seebeck})^2(\textit{electrical conductivity})}{(\textit{thermal conductivity})}$$

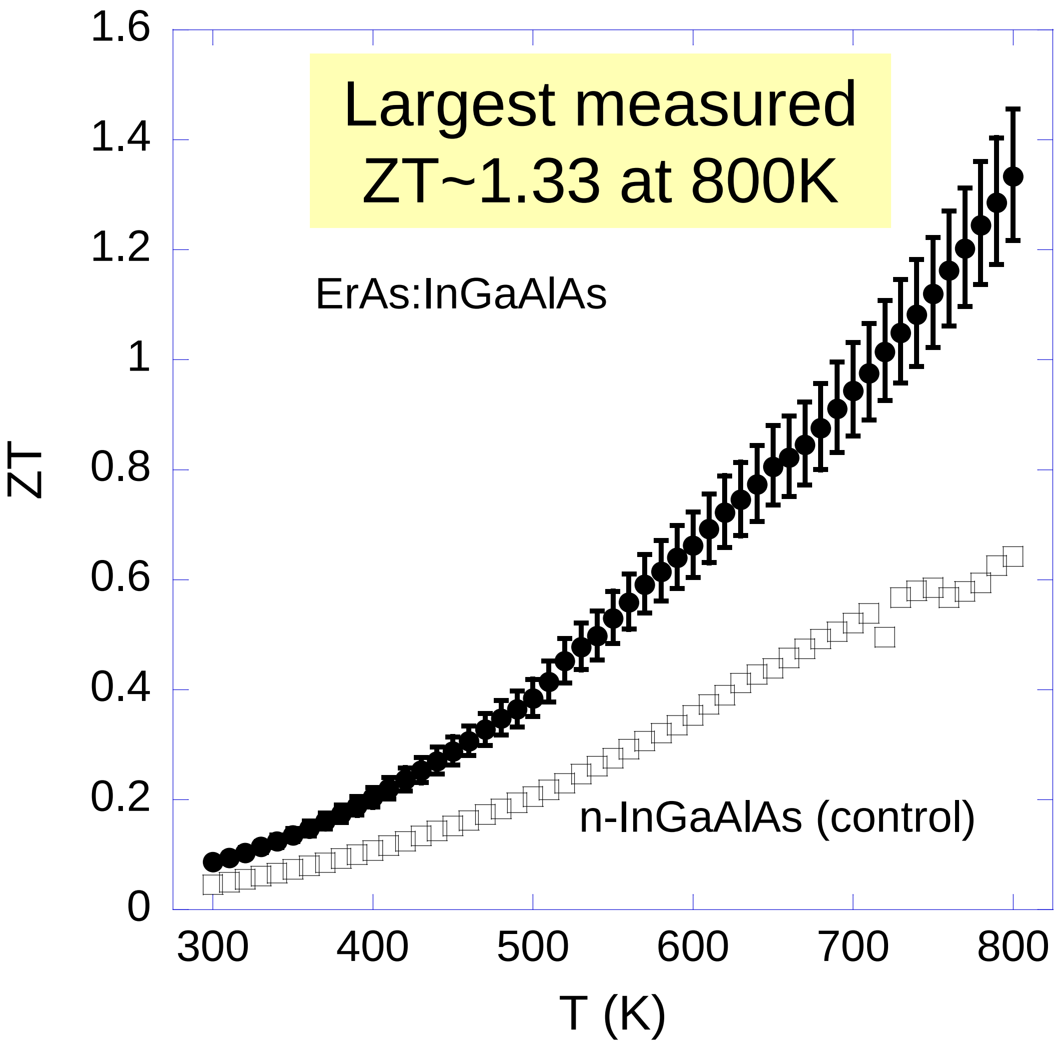




D. Vashaee and A. Shakouri, ***Phys. Rev. Lett.*** **92**, 106103/1 (2004)

C. Vineis et al. Nano. Thermoelectrics: big efficiency gains from small features, ***Advanced Materials*** (2010)

Thermoelectric figure-of-merit

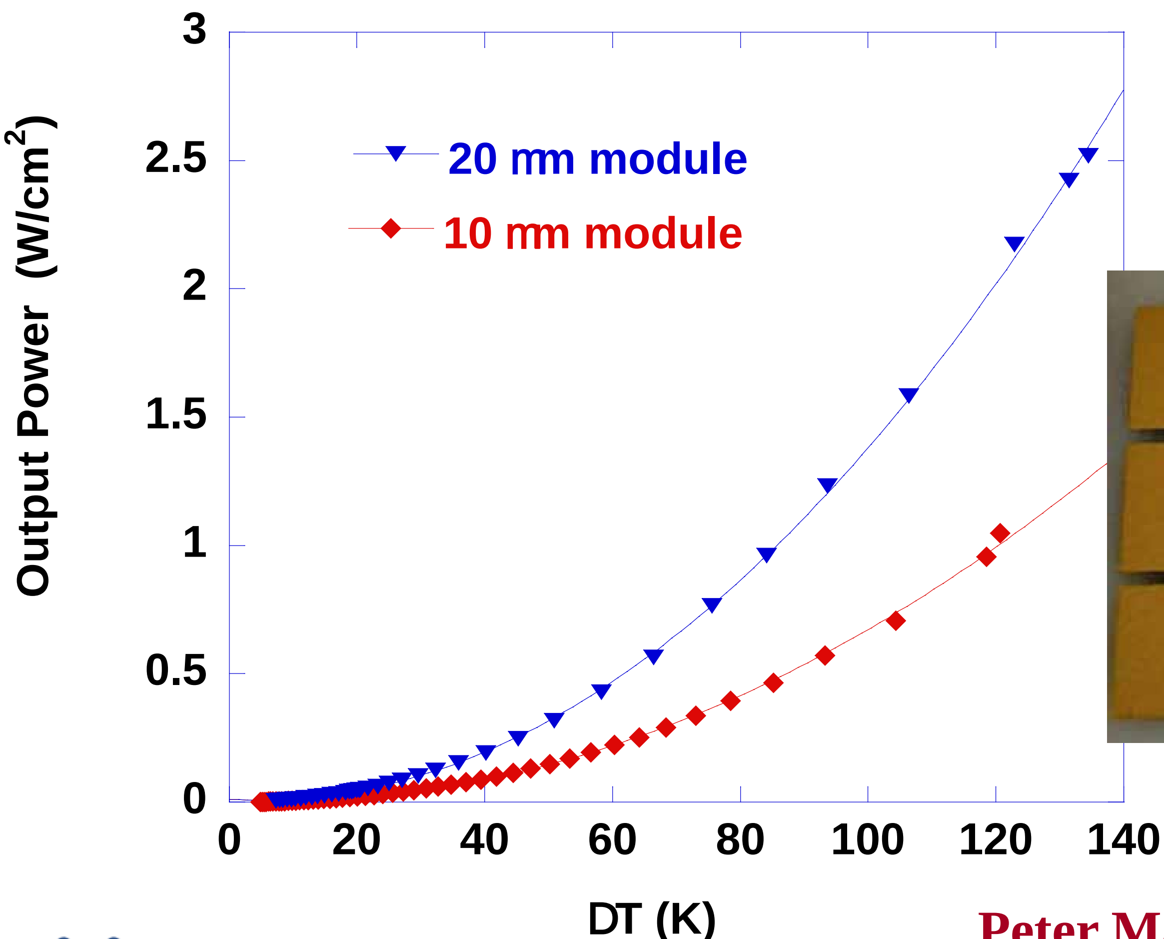


J. Zide et al. Journal of Applied Physics (Dec. 2010)

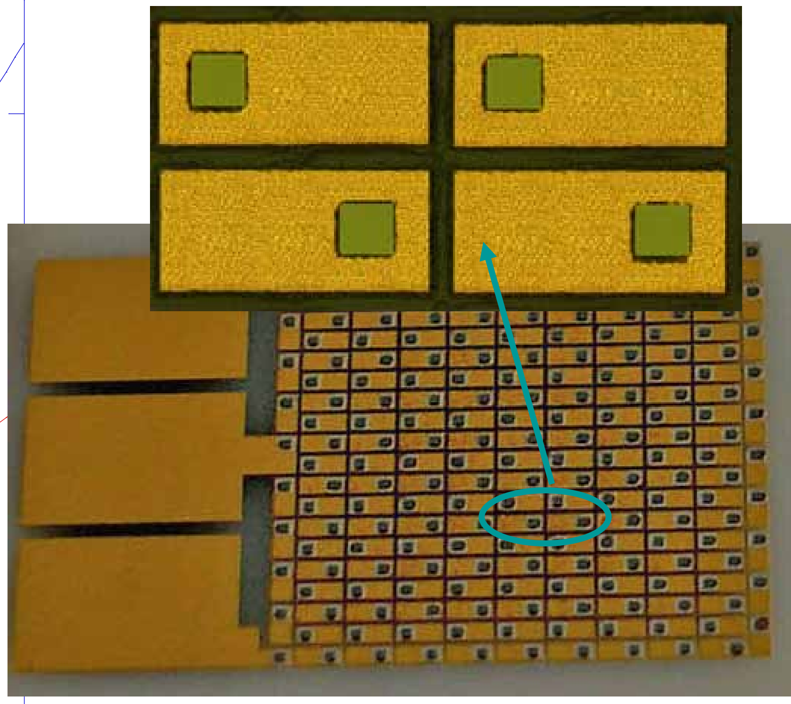
The majority of ZT enhancement is from thermal conductivity reduction.
5% power factor enhancement at 800K.

Module power generation results

400 elements (10-20 microns ErAs:InGaAlAs thin films, 120x120mm^2), array size 6x6 mm^2



140 mm/140 mm AlN



Peter Mayer and Rajeev Ram MIT
TE module requirements

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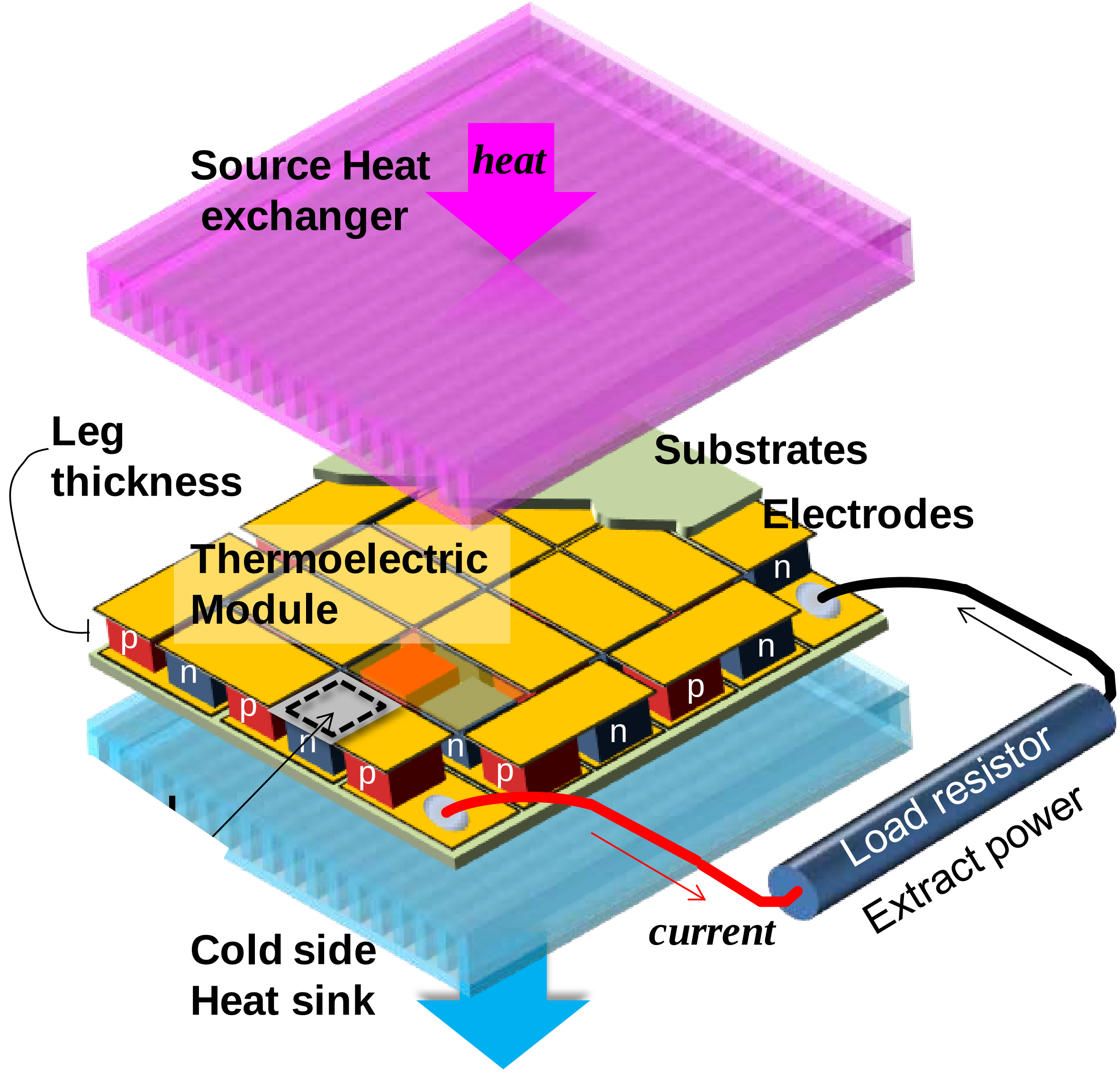
Co-optimization of thermo-electric module with heat sinks



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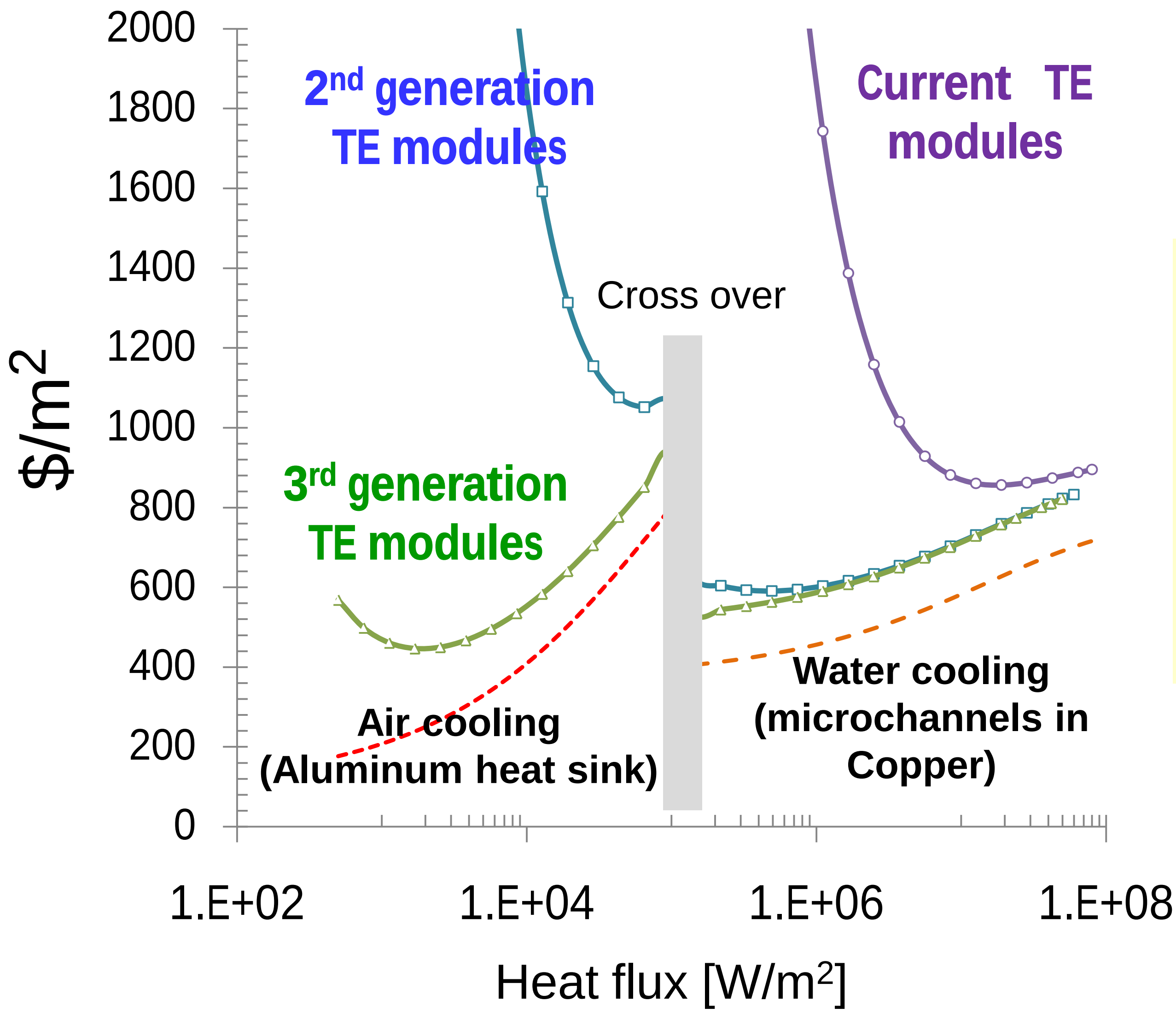
K. Yazawa and A. Shakouri, Int. Conf. on Thermoelectrics 2010, IMECE 2010

Material cost of TE power generation system

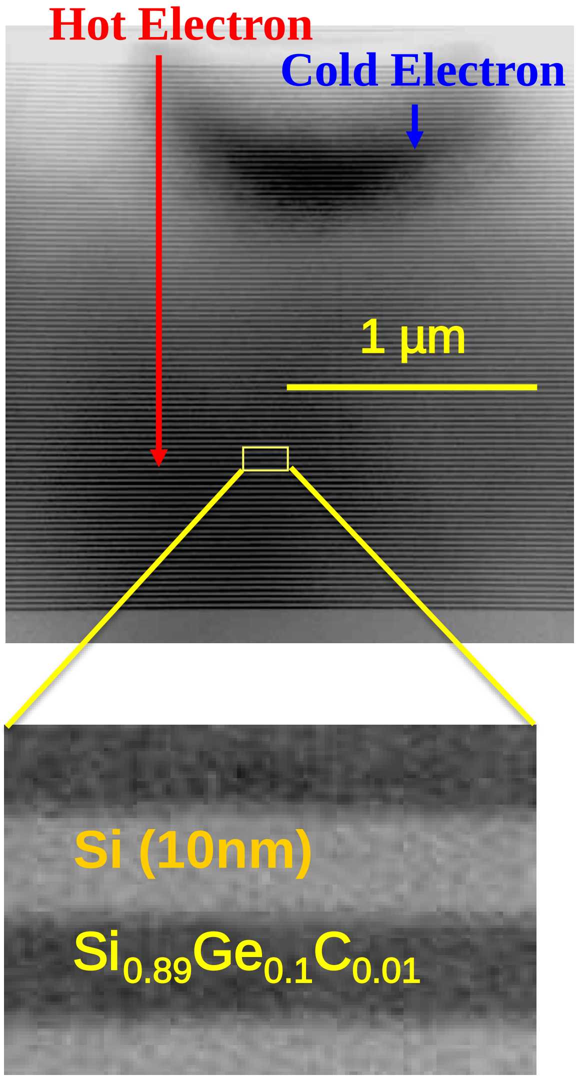


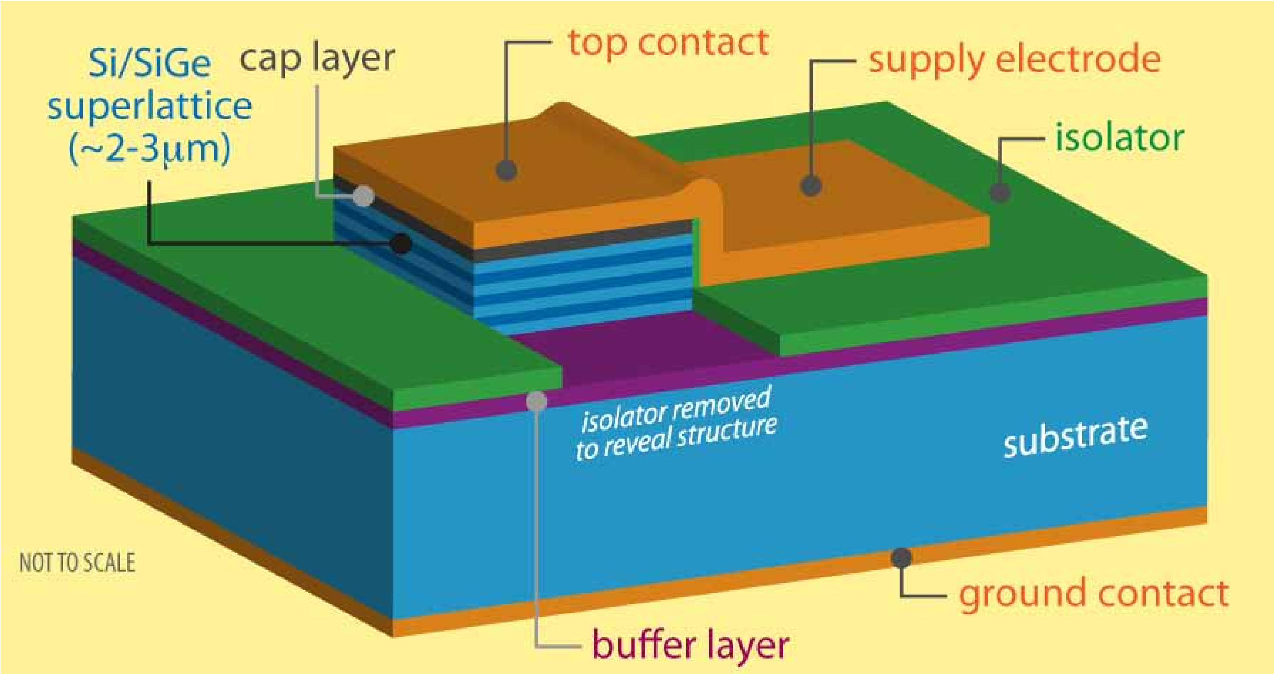
Today's TE power generation cost: $1-2/W

Potential to bring this down to: $0.1/W

K. Yazawa and A. Shakouri, International Mechanical Engineering Congress Nov. 2010

Microrefrigerators on a chip





Heterostructure Integrated Thermionic Coolers; A. Shakouri and John Bowers, **Appl. Phys. Lett.** 1997

Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, **Proceedings of IEEE**, July 2006

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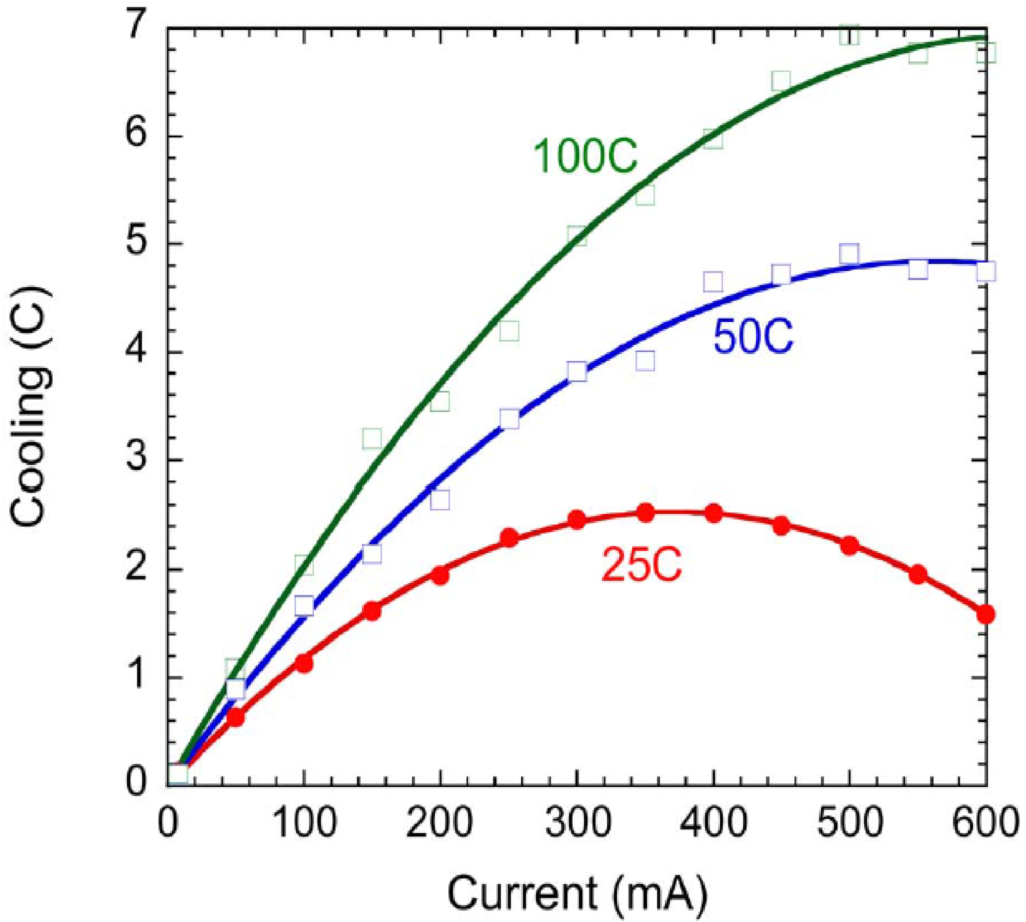
Microrefrigerators on a chip

- Monolithic integration on silicon
- DT_{max}~4C at room temp. (7C at 100C)

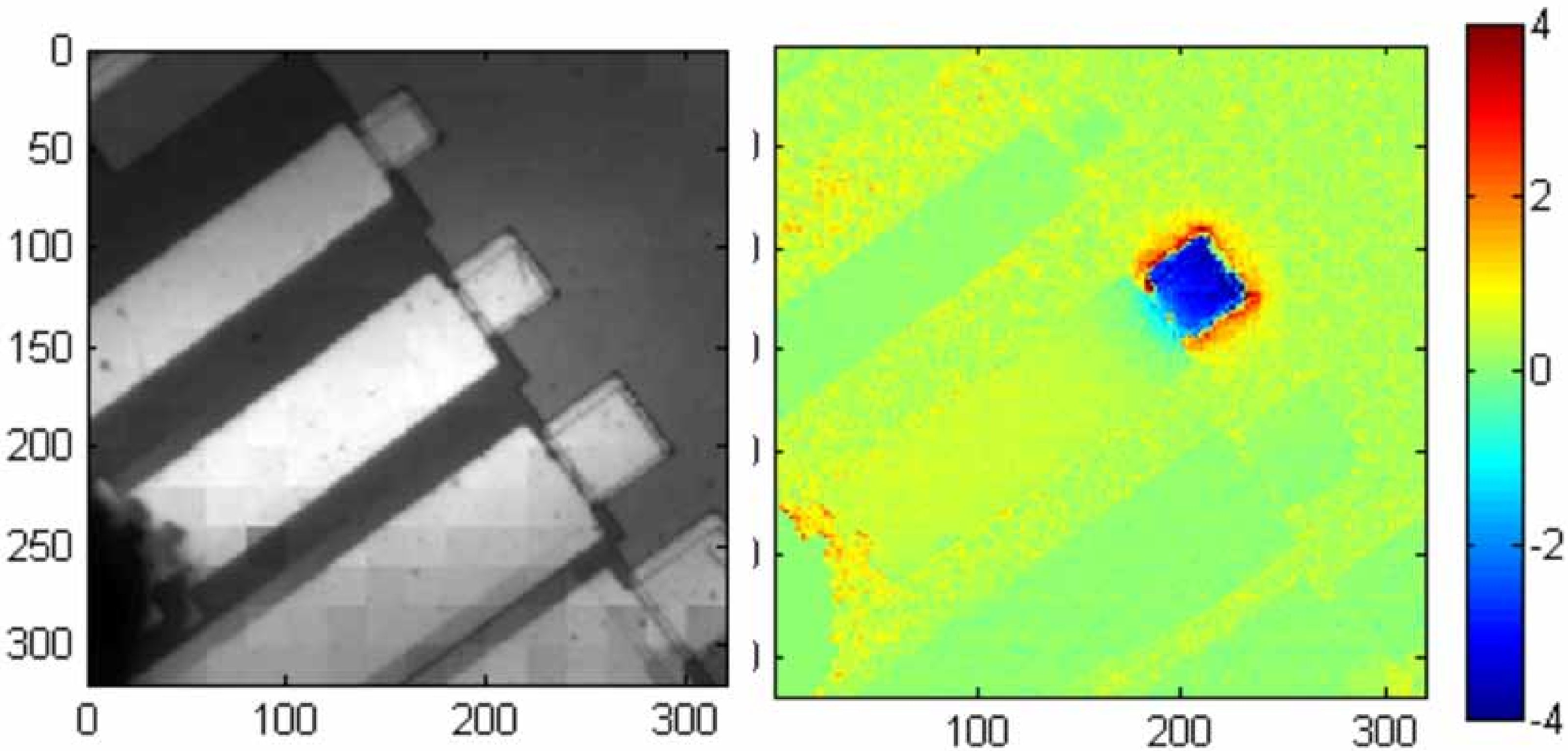


Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, **Proceedings of IEEE**, July 2006

Featured in Nature Science Update, Physics Today, AIP April 2001

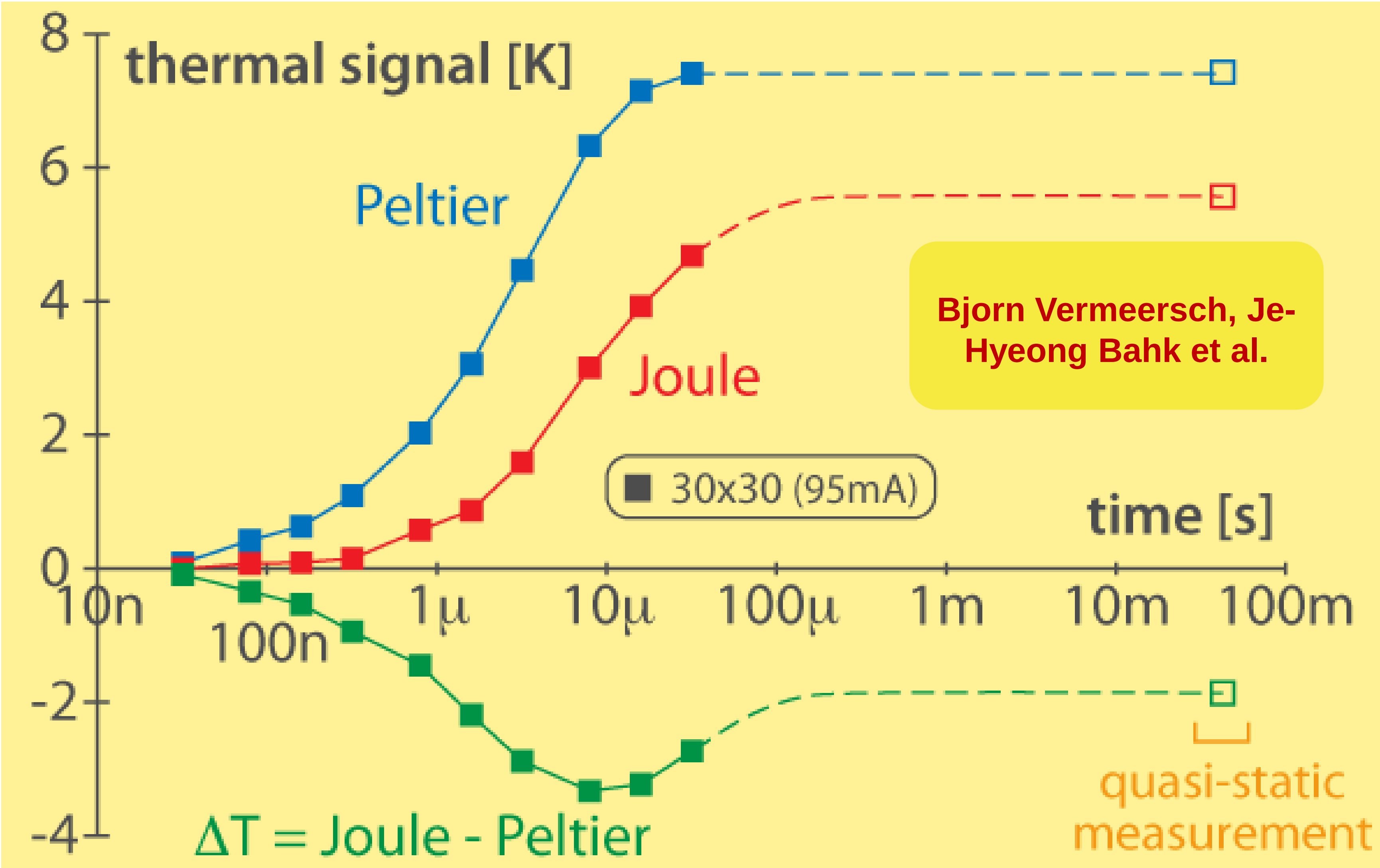
High resolution thermal imaging of microcoolers

- Temperature resolution: 0.006ºC
- Spatial resolution: submicron
- 256 channel lock-in camera <20kHz, 123dB (1sec)



J. Christofferson and A. Shakouri, Review of Scientific Instruments, 2005

Transient thermal imaging



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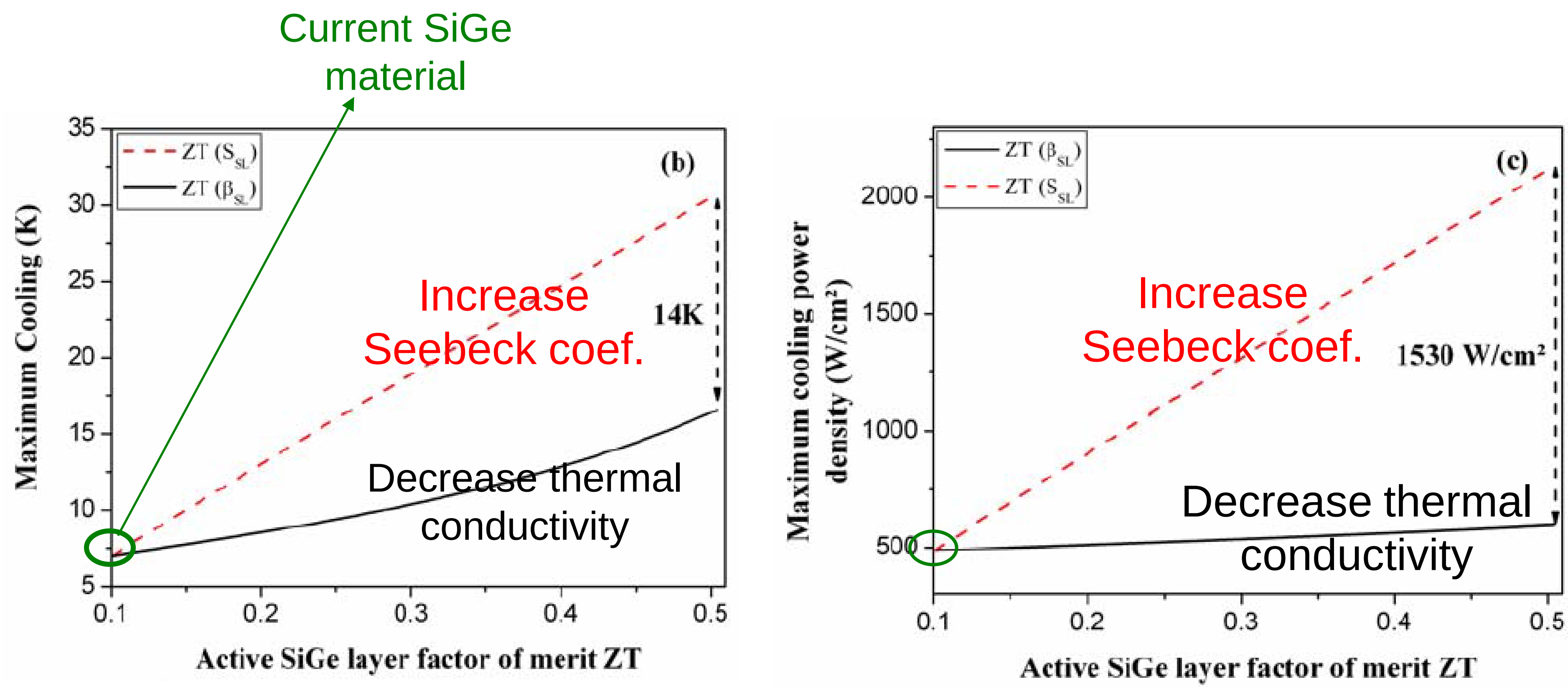
- Maximum cooling can be increased under pulsed operation
- Reason: <u>Interface</u> Peltier cooling and <u>distributed</u> Joule

Thin Film Microrefrigerator Optimization

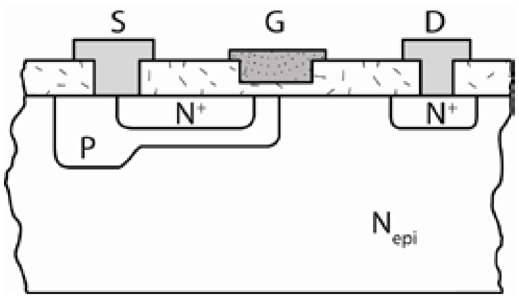
- 10 microns thick, 50x50mm^2 monolithic microrefrigerator with ZT~0.5 can cool a 1000W/cm^2 hot spot by >15C.

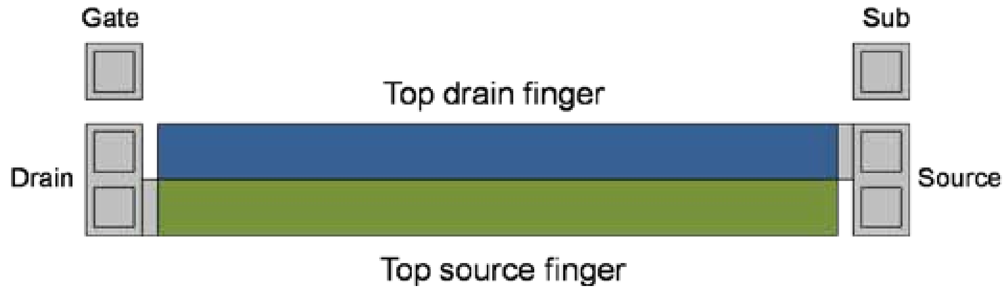


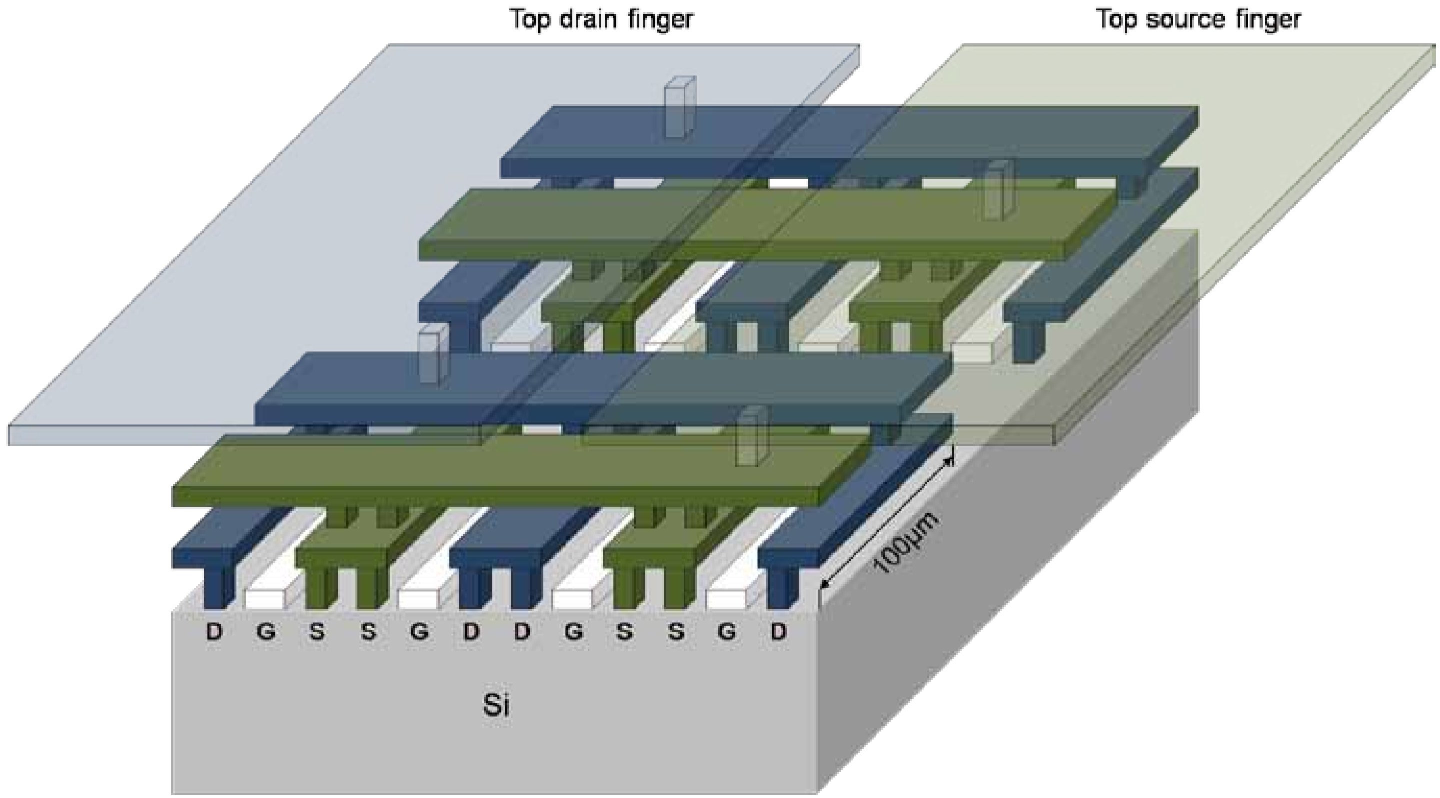
Younes Ezzahri, Ali Shakouri et al. InterPACK07, Vancouver, Canada

Ultrafast Thermal Characterization and Simulations Techniques

High Power MOSFET Transistor Array



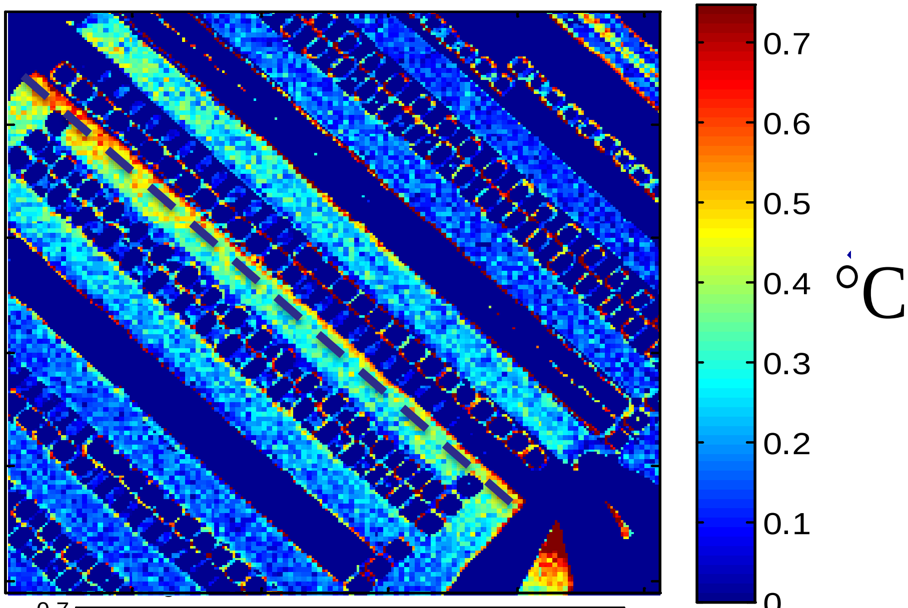


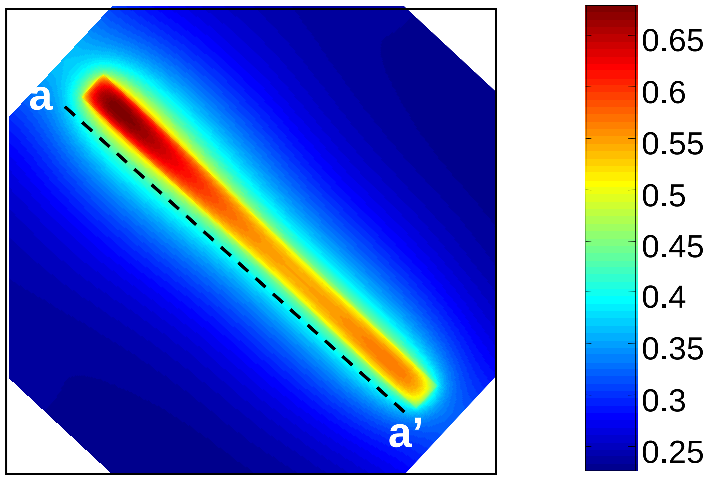


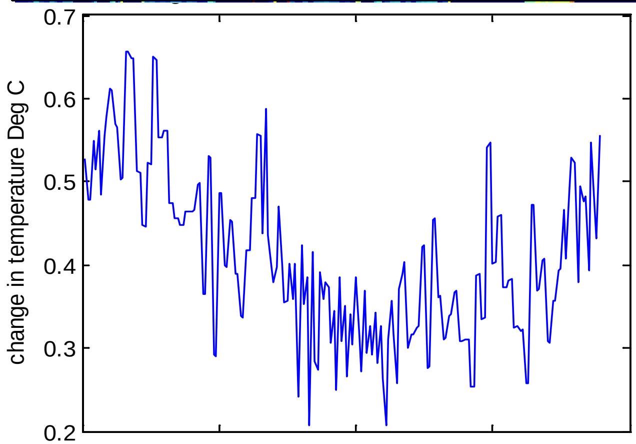
"Thermal Characterization of High Power Transistor Arrays", K. Maize et al, *25th IEEE SEMI-THERM Symposium*, 2009.

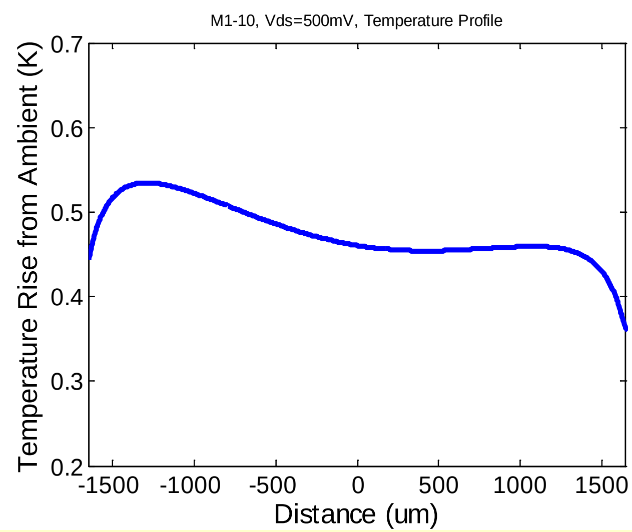
Thermal image *vs.* ***simulation*** at **low** bias

Vd = 0.5V, Id ≈0.5A 6 amps/mm^2









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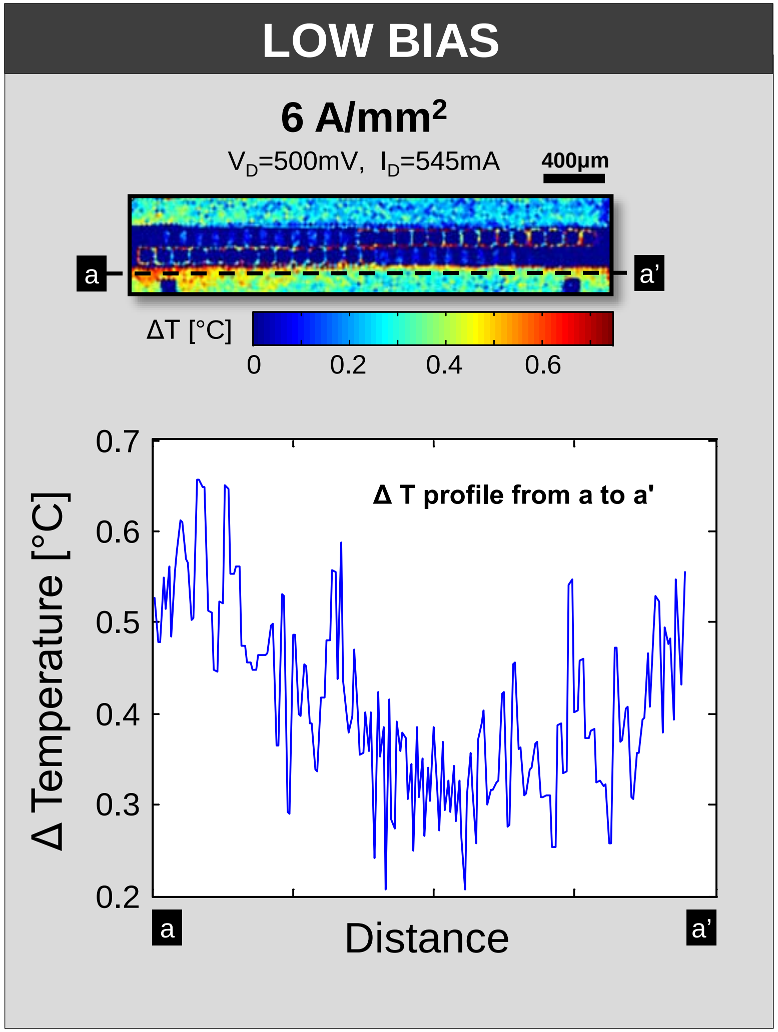
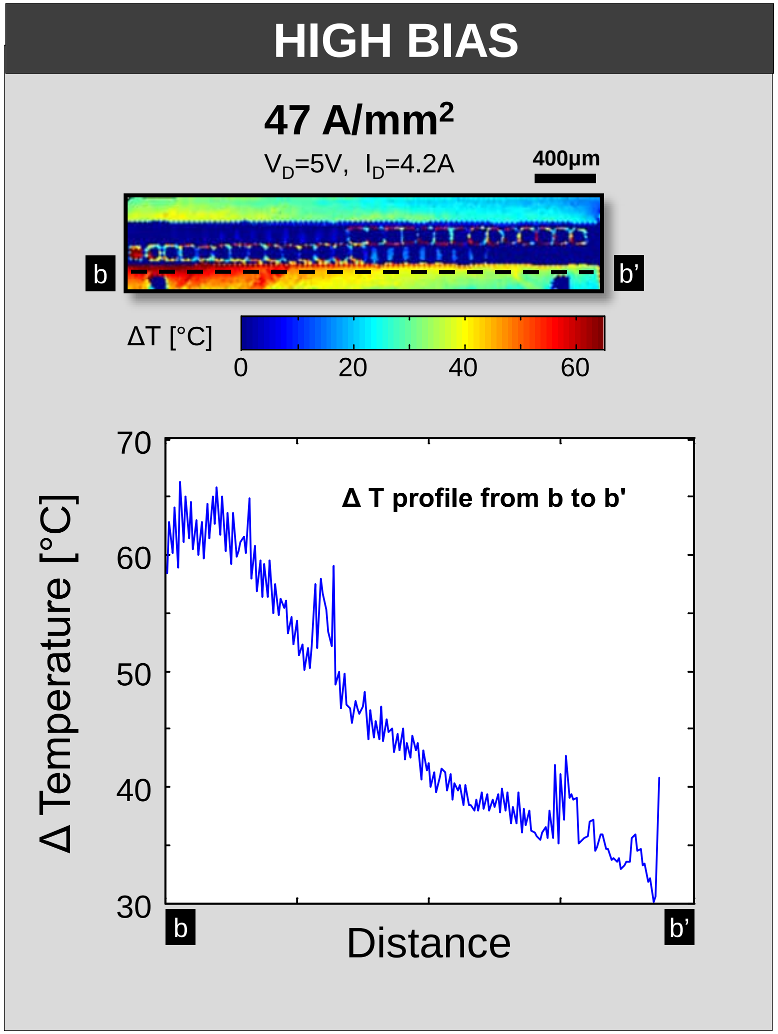
The magnitudes of temperature rise at both ends (source and drain) are in a good agreement. Potential role of the probe tips.

Thermo-reflectance thermal images

Tempera-ture profile along array





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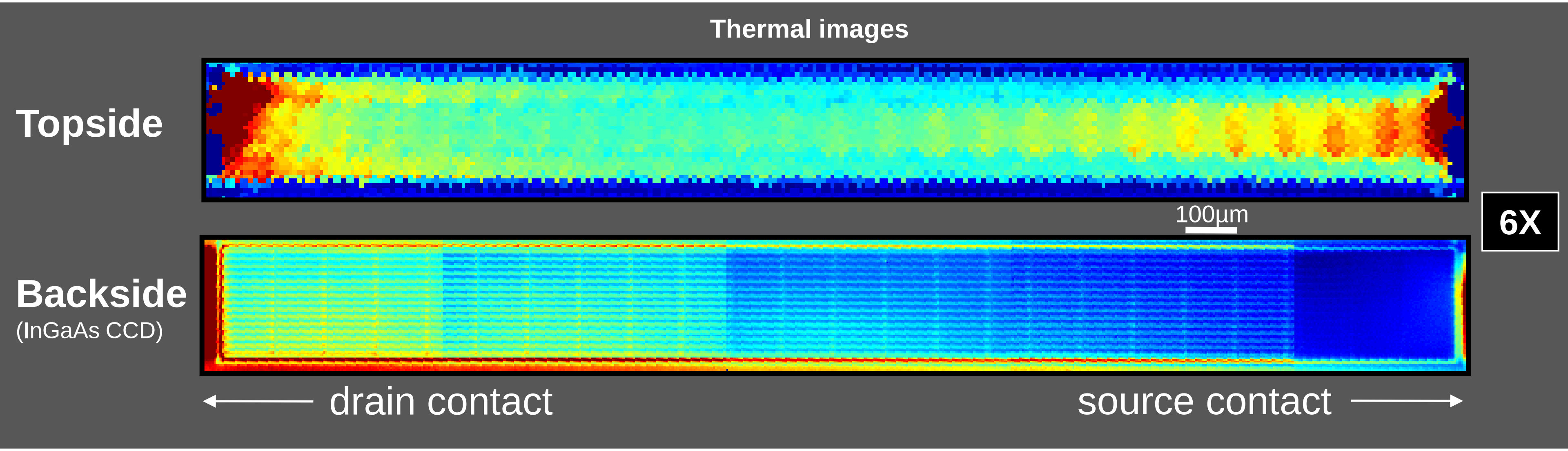
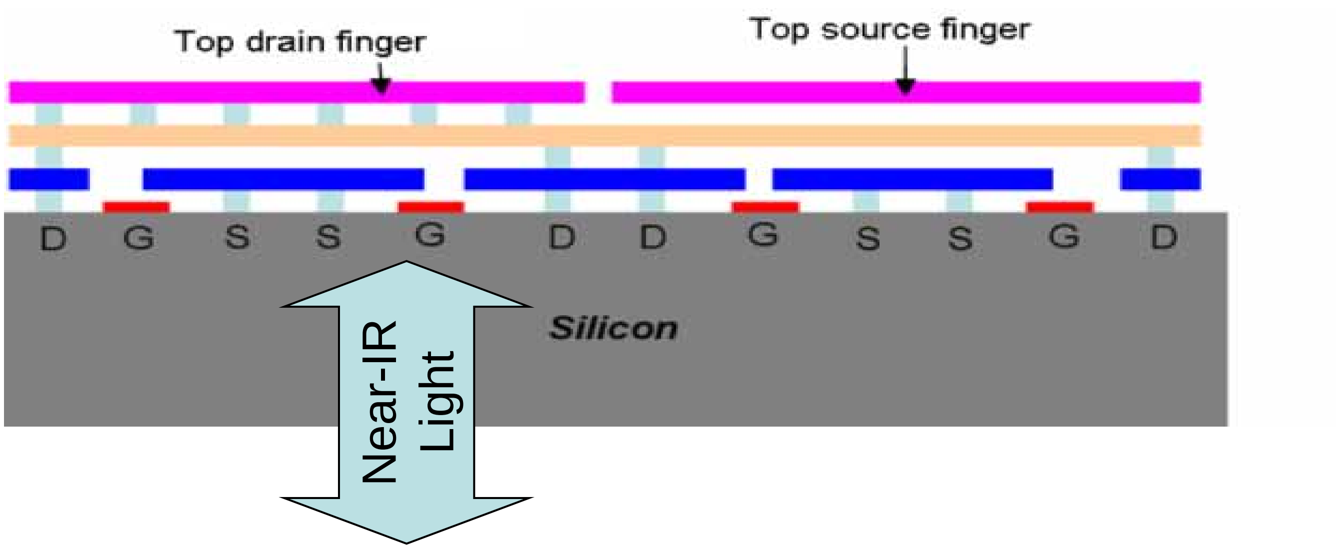
“Thermal Characterization of High Power Transistor Arrays”, K. Maize et al, *25th IEEE SEMI-THERM Symposium*, 2009.

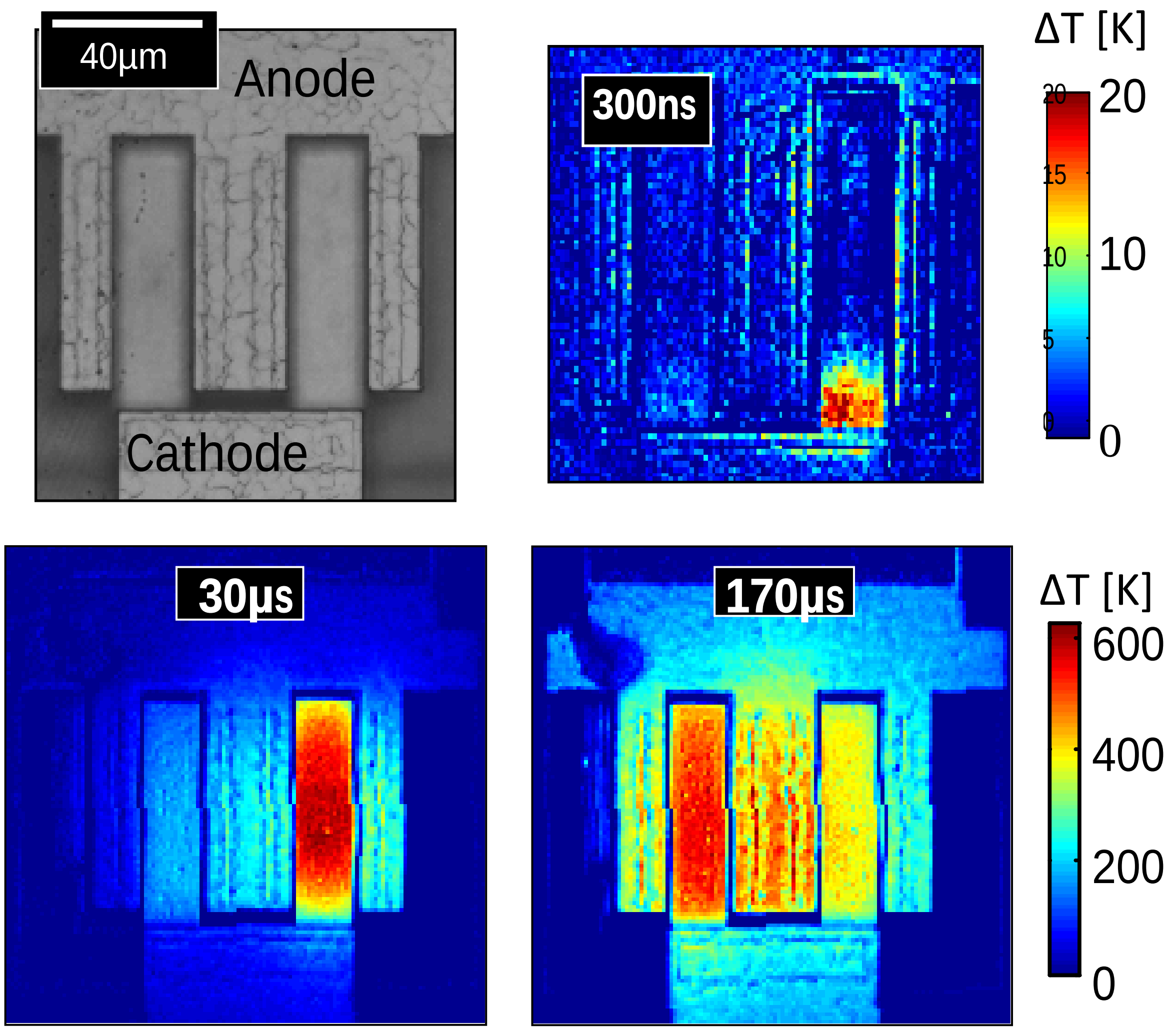
Through-substrate thermoreflectance – Comparing topside and backside heating





K. Maize et al, *SemiTHERM 2010 and IHTC* 2010.

Heating in Electro Static Discharge Devices



Snapback current =1.22A.

K. Maize, V. Vashchenko et al, *To be presented at IRPS*, 2011.

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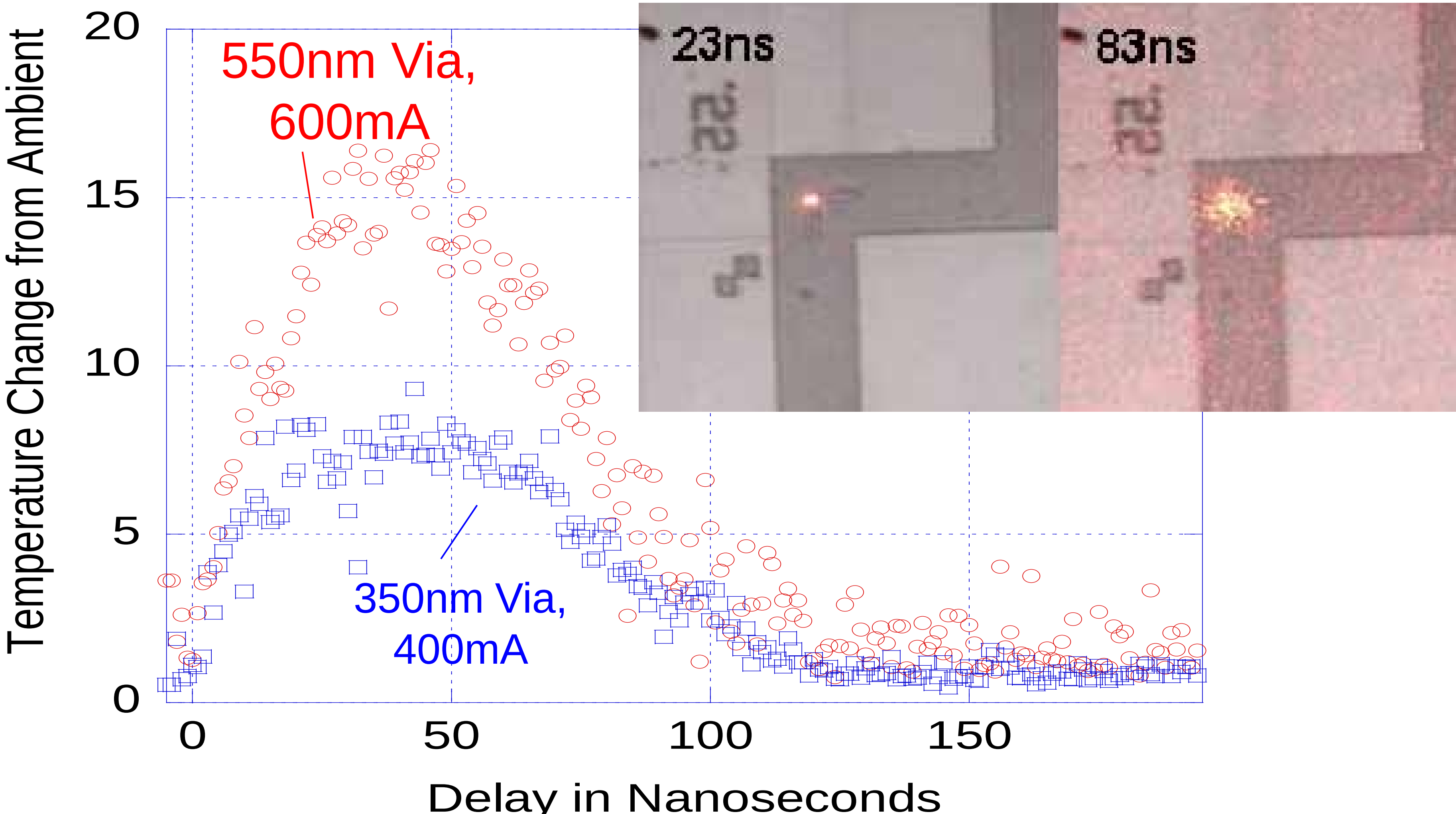
High Speed Thermal Imaging (800ps)

Study of heating in submicron interconnect vias



J. Christofferson et al., *Proceedings of Int. Heat Transfer Conf., August 2010*

Thermoreflectance Imaging for Reliability Characterization of Copper Vias

Shila Alavi, Glenn B Alers, Kaz Yazawa and Ali Shakouri

Department of Electrical Engineering
University of California, Santa Cruz

Advanced Studies Laboratory
University of California, Santa Cruz

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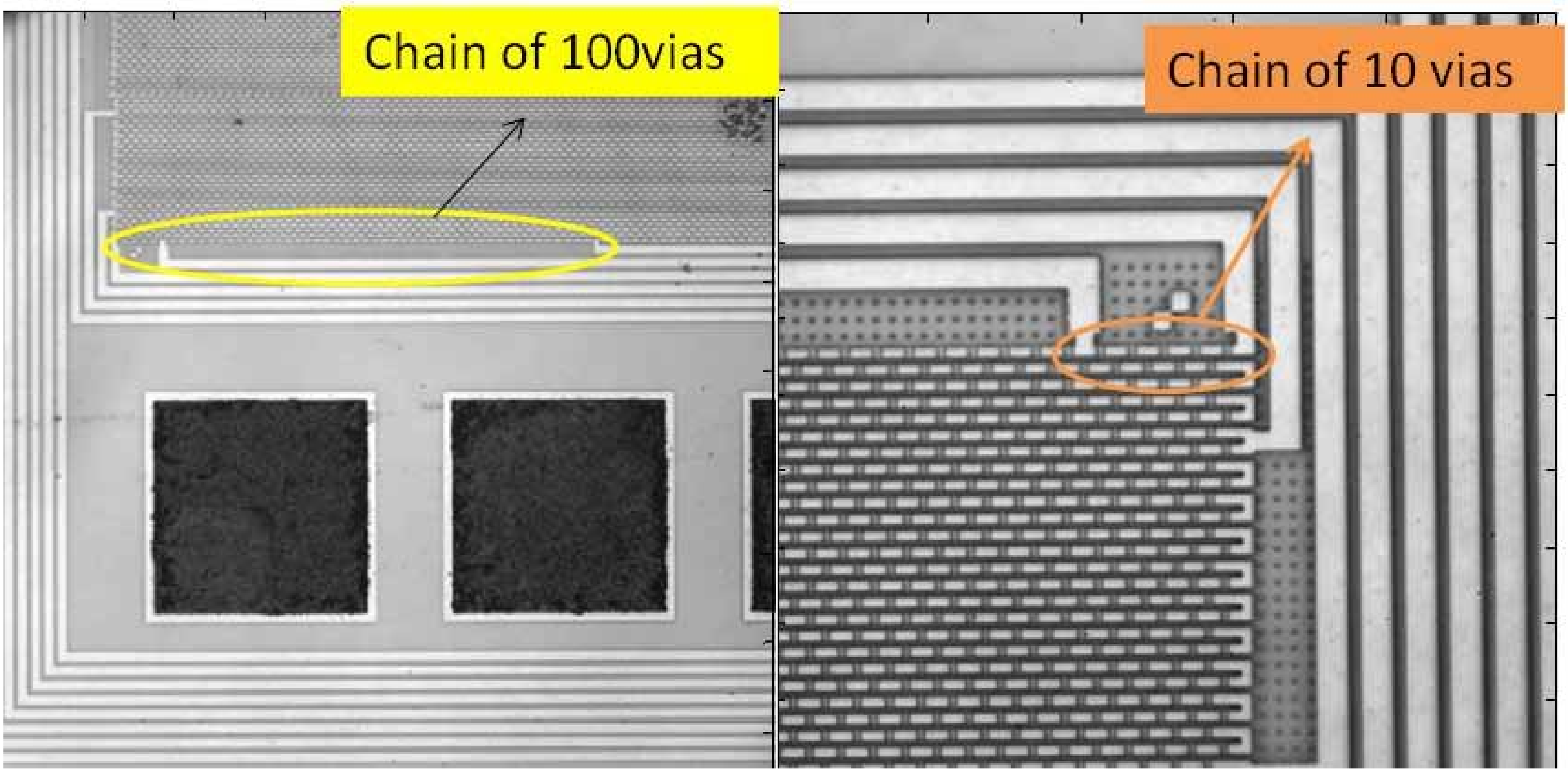
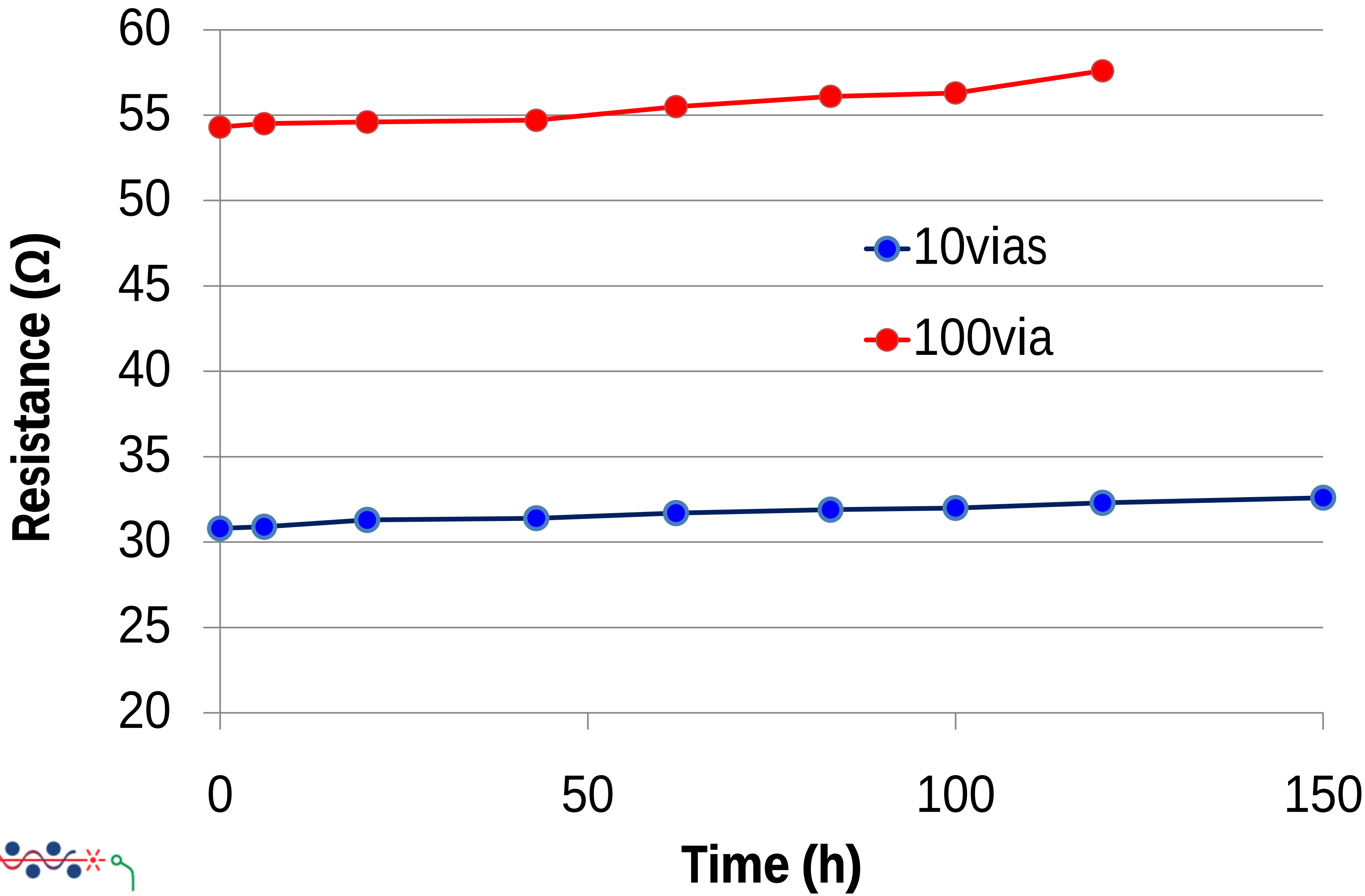
Copper via chains



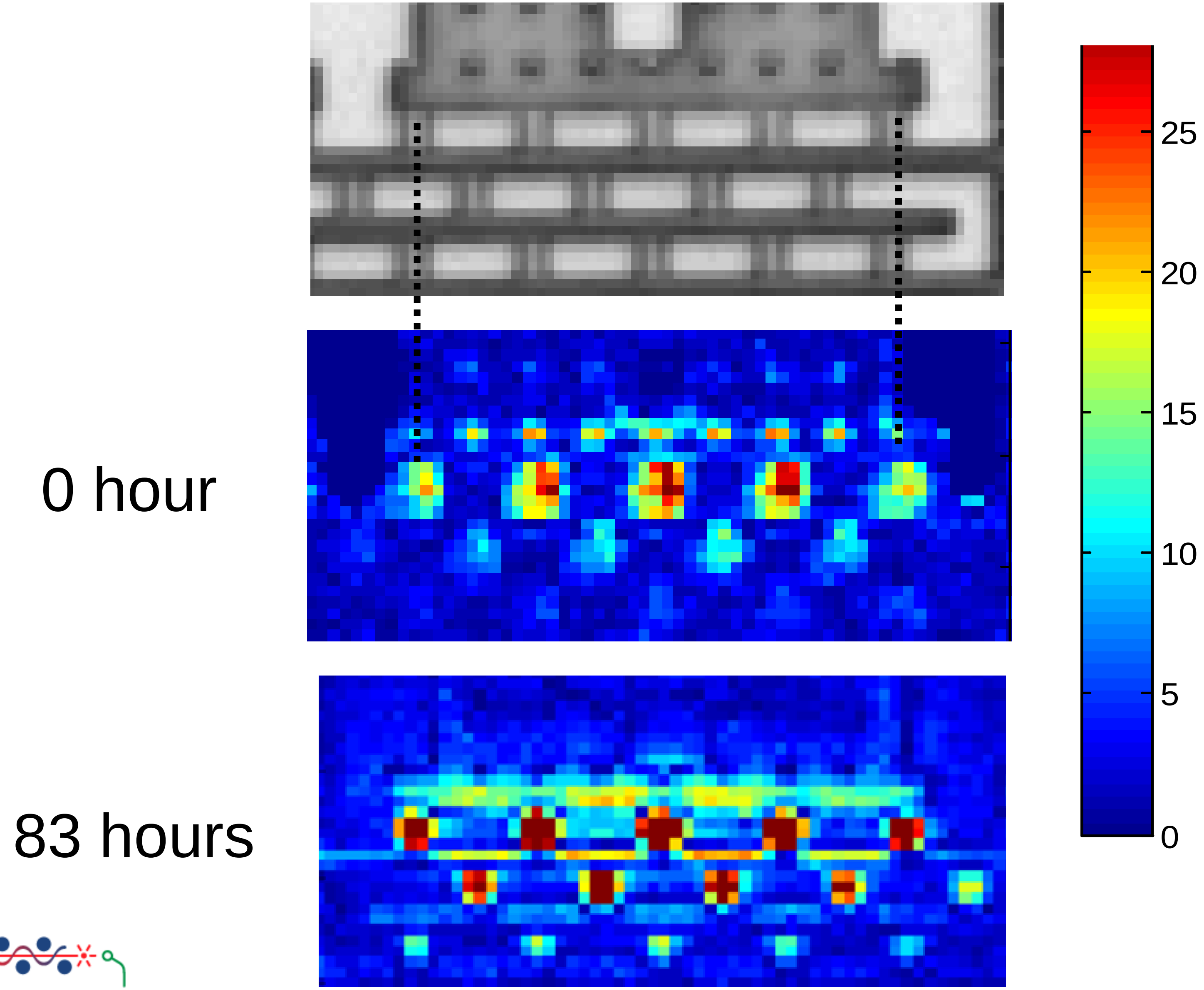
S. Alavi et al, *To be presented at SemiTHERM*, 2011.

Resistance shift for different via chains after aging at 200C

A. Shakouri 2/16/2011



Thermal map of 10 via chain under bias

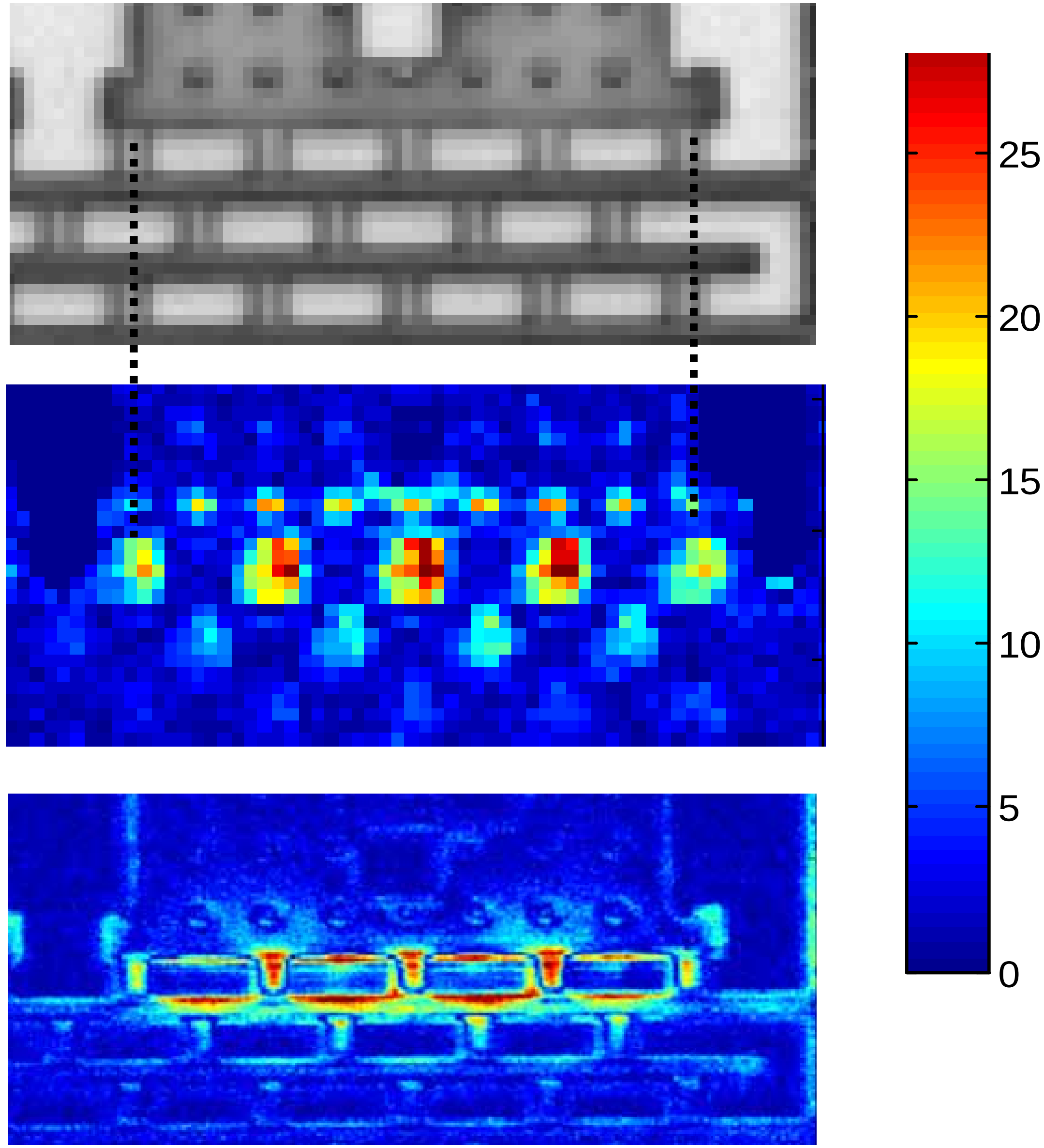


S. Alavi et al, *SemiTHERM*, 2011.

Thermal map of 10 via chain under bias

0 hour

120 hours



S. Alavi et al, *SemiTHERM*, 2011.

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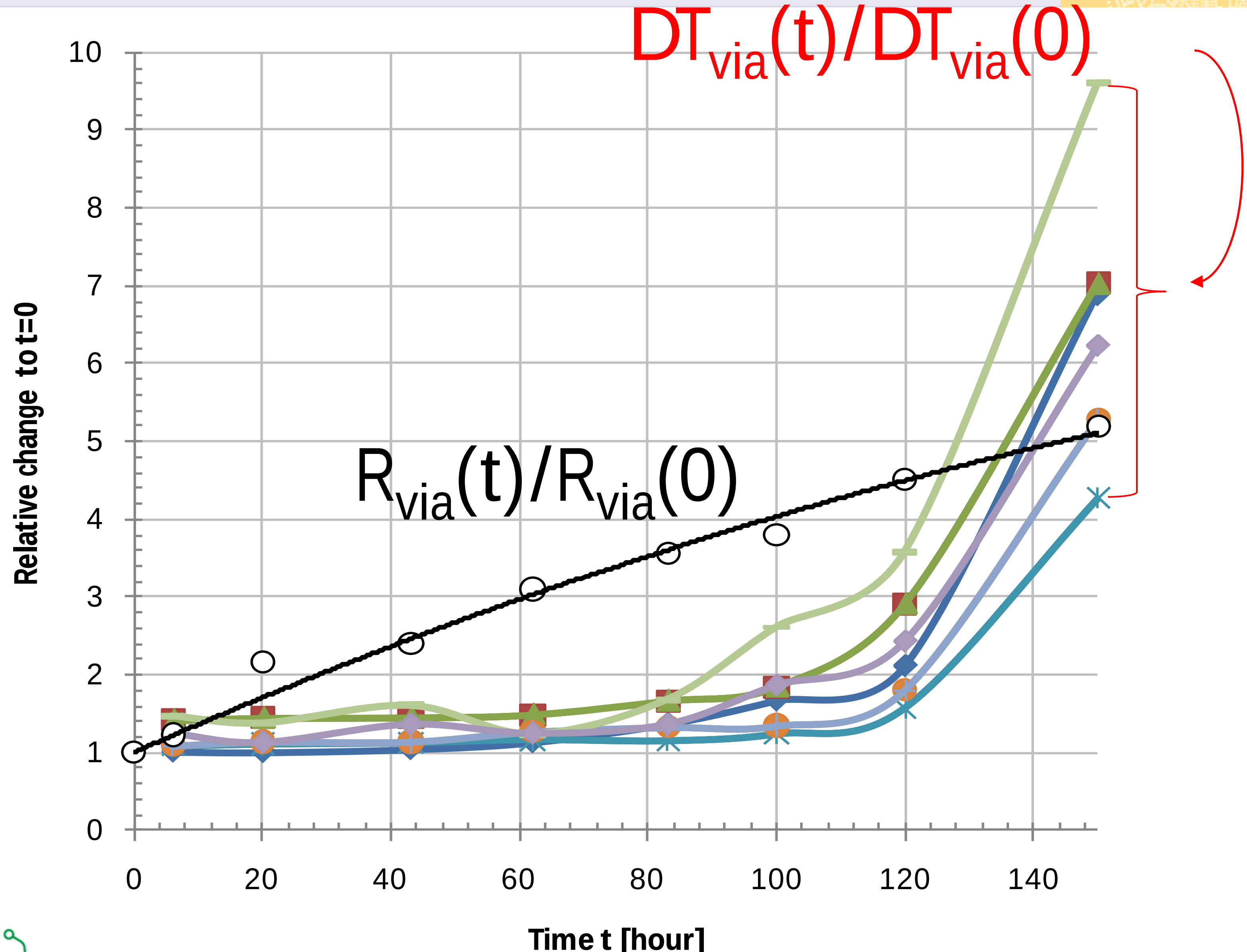
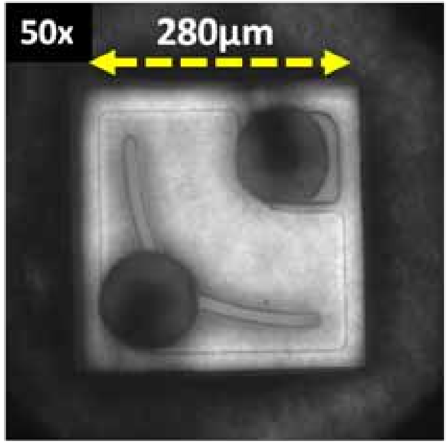
Relative change in R and DT

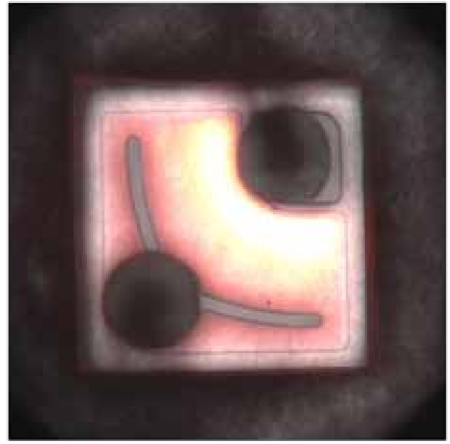


S. Alavi et al, *SemiTHERM*, 2011.

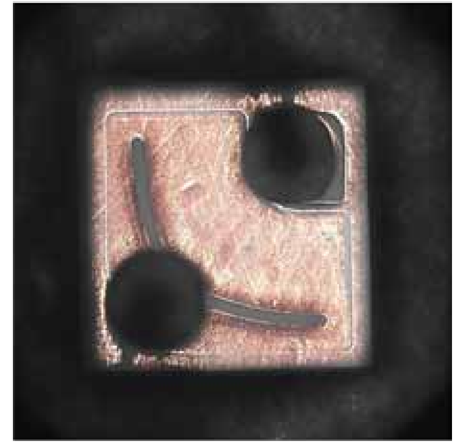
Thermal/ electroluminescence imaging of LEDs



Optical

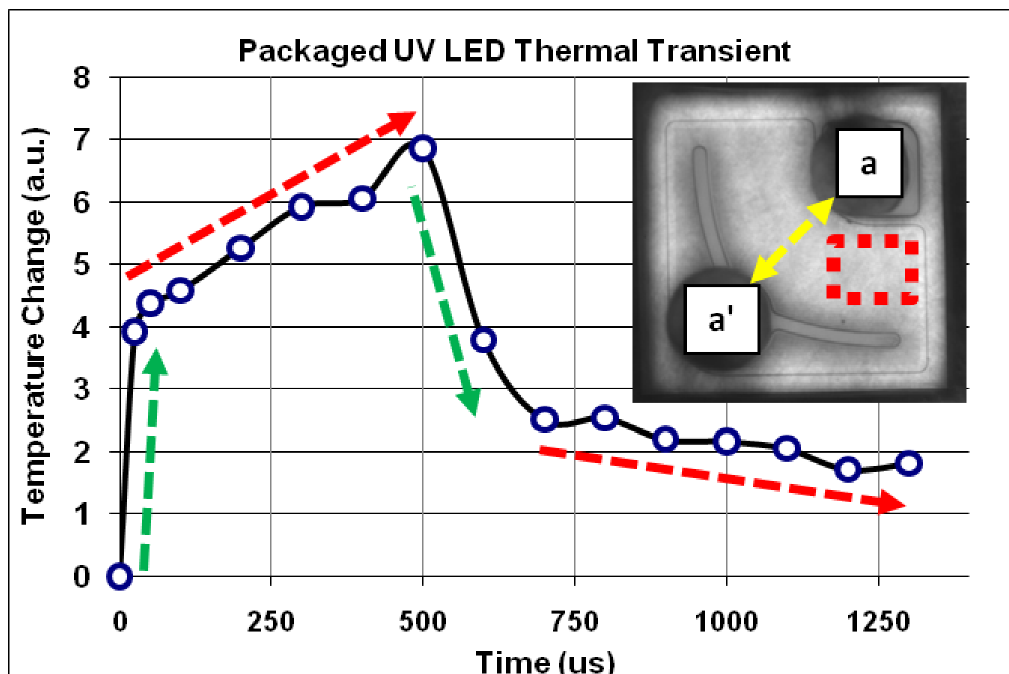


Electroluminescence/ Optical



Thermal/Optical

D. Kendig et al, *To be presented at SemiTHERM*, 2011



Thermal/ electroluminescence imaging of Solar cells

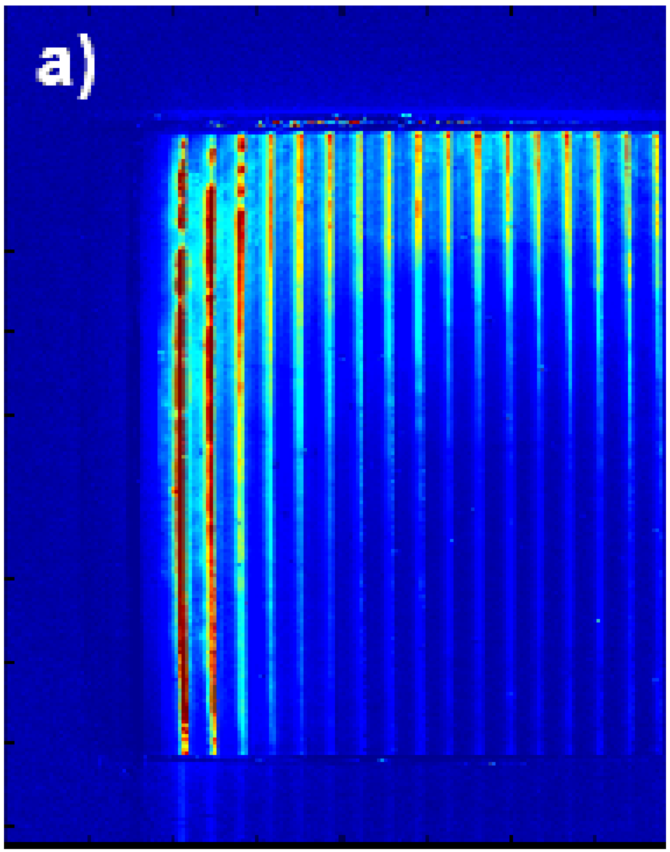


Figure 4. a) forward and b) rev
solar cell mini-r

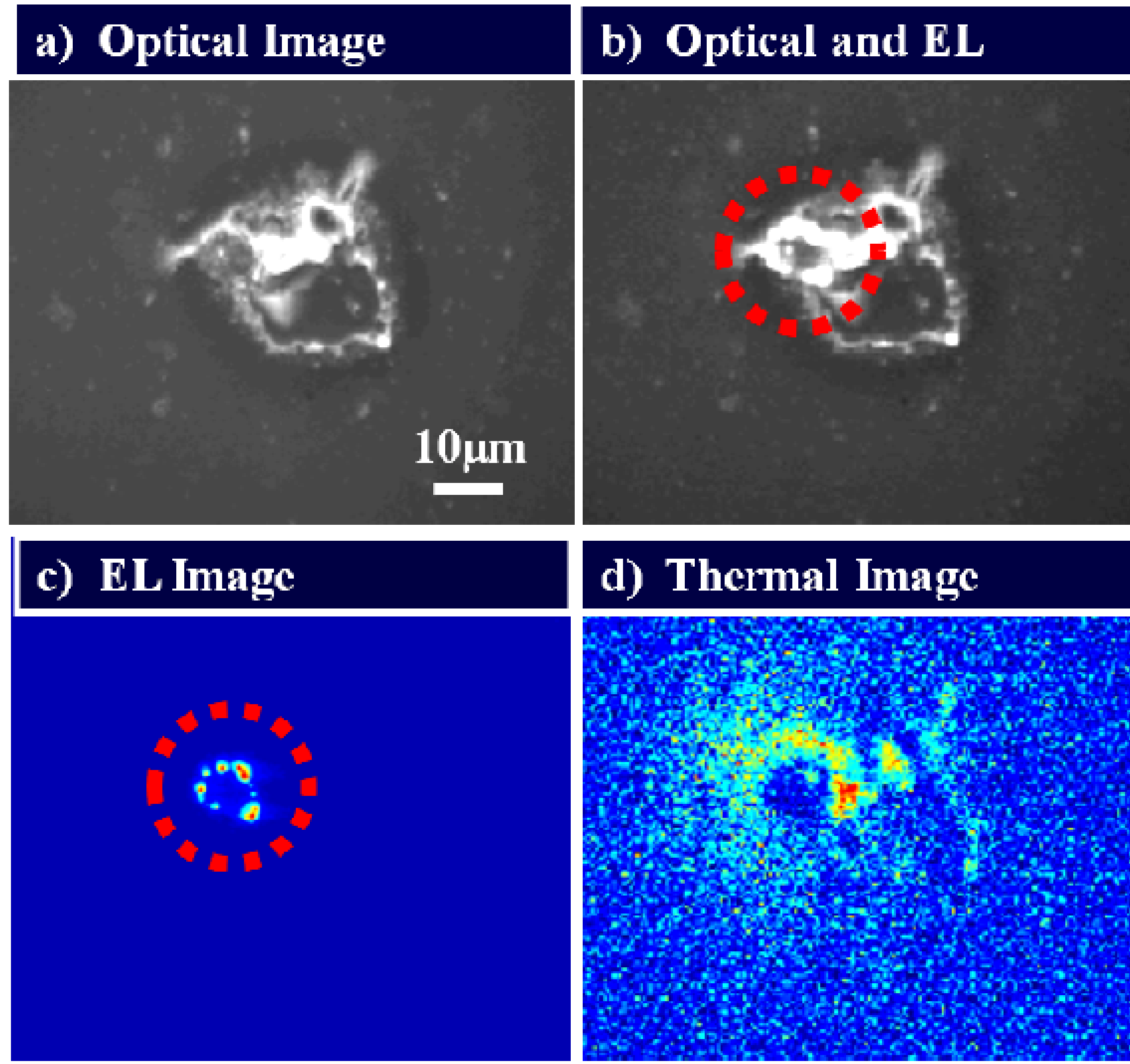


Figure 6. a) optical image of a defect in poly-Si, b) optical image with EL combined to show the location of the EL on the defect, c) EL signal in reverse bias, d) Thermal image of defect at 30V reverse bias

D. Kendig et al, *IPRS 2010*

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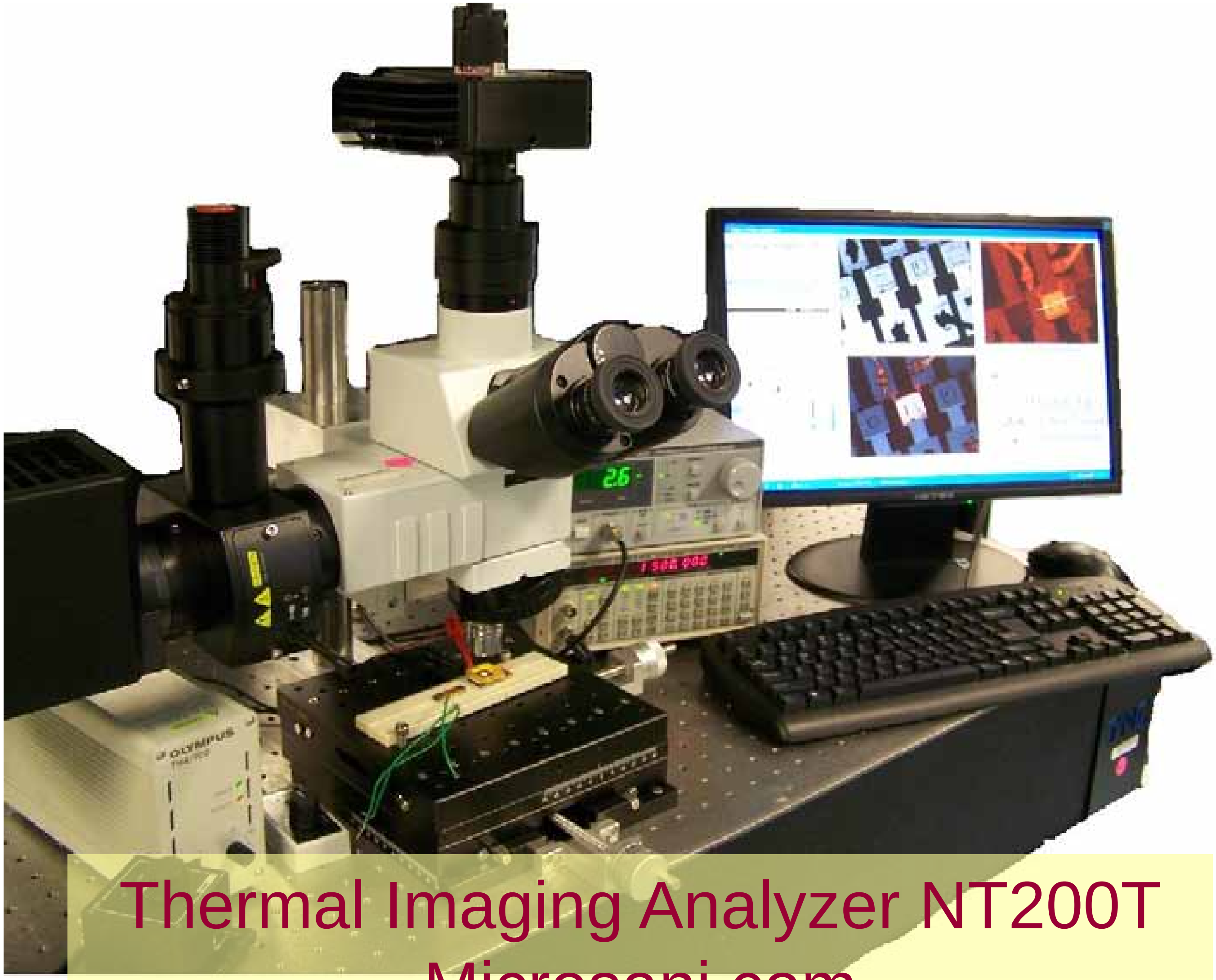
Technology Transition:

Stand alone thermoreflectance imaging system

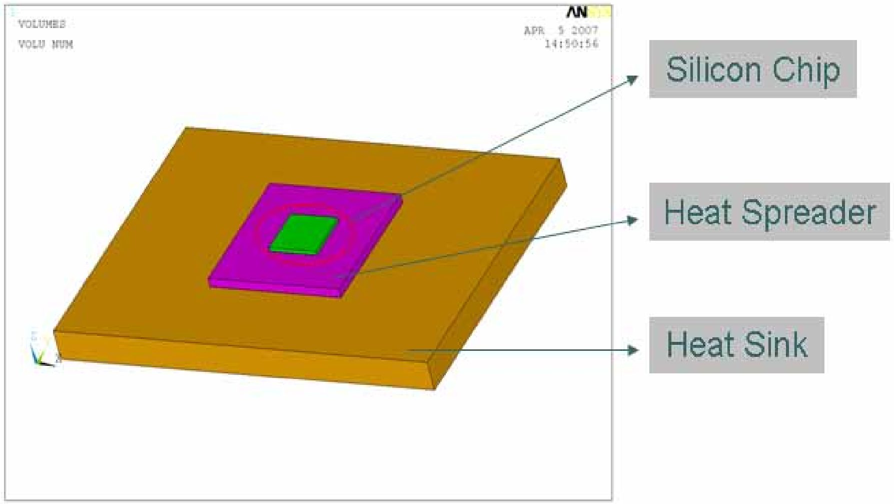
(resolution: 200nm, 100ns, 0.2C, pixels: 1024x1022)



Thermal Imaging Analyzer NT200T
Microsanj.com

Ultrafast Thermal Simulation Techniques

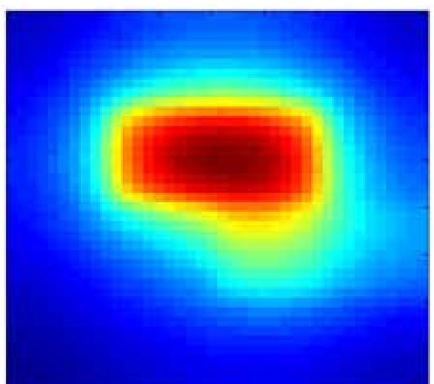
THERMAL SIMULATION APPROACHES



Power Map

4W	4W	4W	4W
4W	16W	16W	4W
4W	4W	8W	6W
4W	4W	4W	4W

Temperature Profile



- Heat Equation

$$\rho c_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} + k\frac{\partial^2 T}{\partial z^2} + q^*$$

T = temperature
t = time
k = thermal conductivity
ρ = density
c_p = heat capacity
q^* = heat generation rate per unit volume

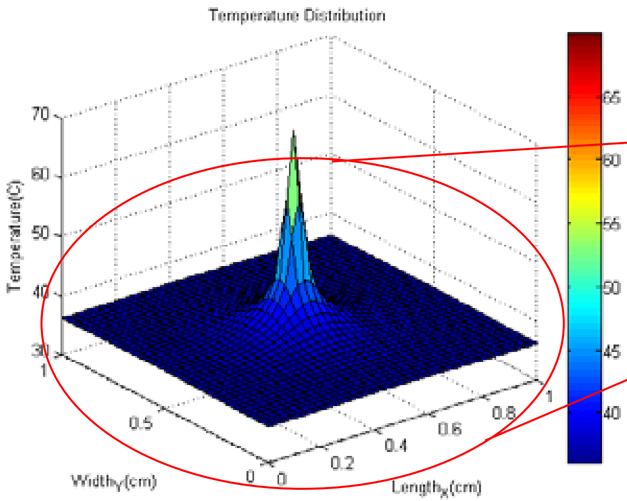
- Approaches
  - Finite Difference Method
  - Finite Element Method
  - *Green's Function Method*

=> Analogy with image blurring (power blurring)

T. Kemper, Y. Zhang, Z. Bian, A. Shakouri, 12th International Workshop on THERMAL INVESTIGATIONS of ICs and SYSTEMS (THERMINIC), Nice, France, 27-29 September 2006

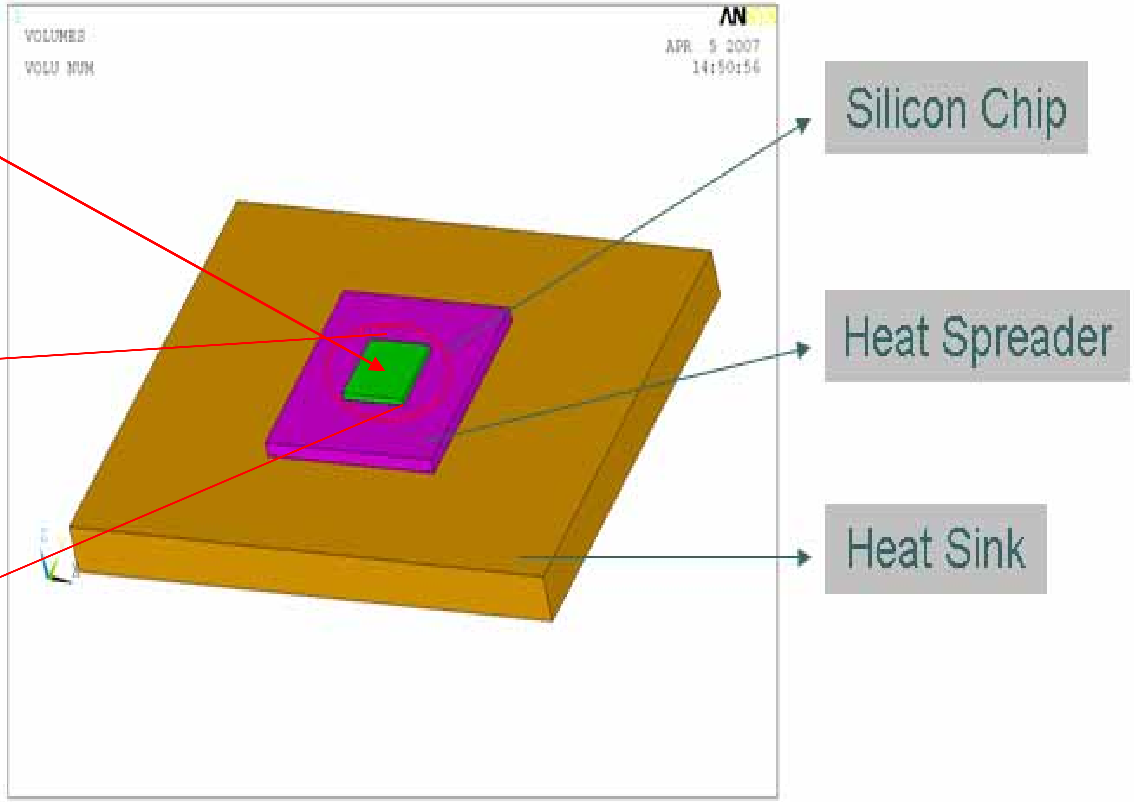
Finite Element Analysis

Apply Point Heat Source



normalization

Thermal Mask

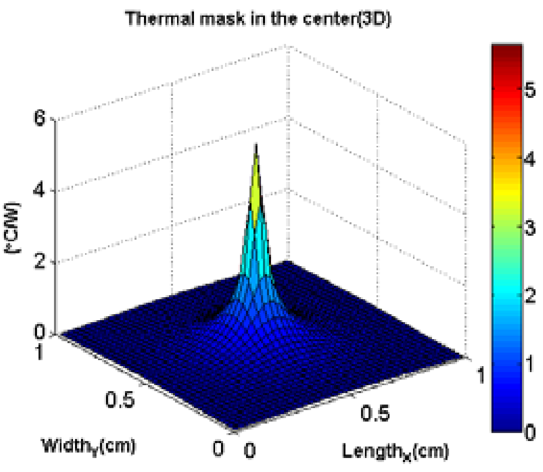


Package Model

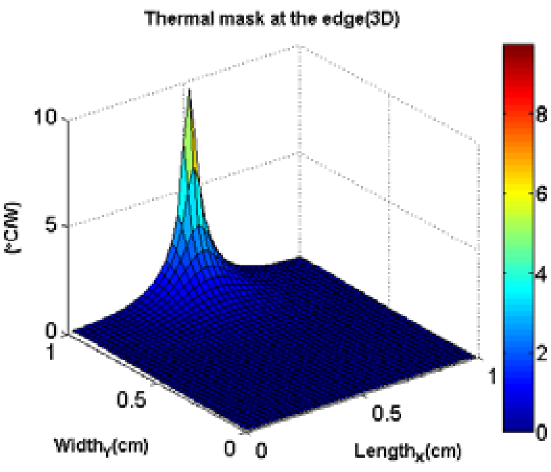
QUANTUM ELECTRONICS

BOUNDARY EFFECTS

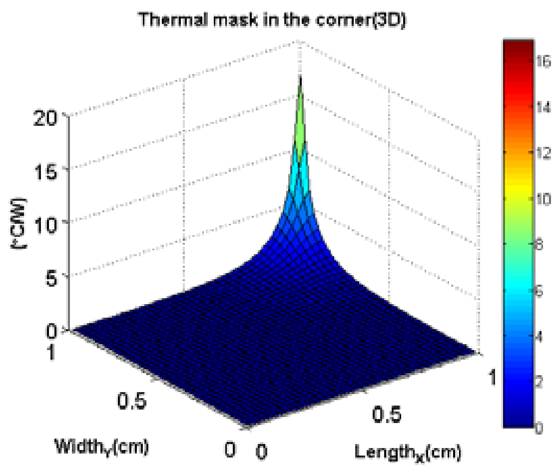
Due to the finite dimension of the Si-Chip, boundary effect is important.
=> simplification: Use Method of Images and uniform heat compensation



Center



Side Edge

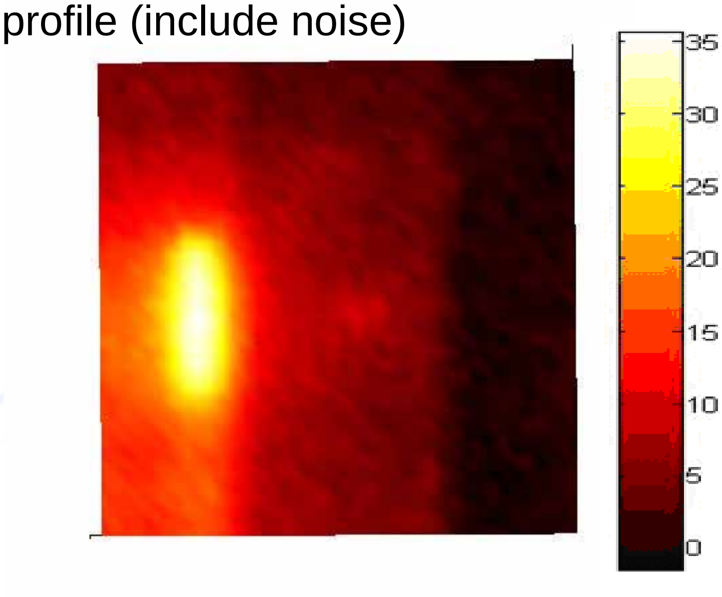


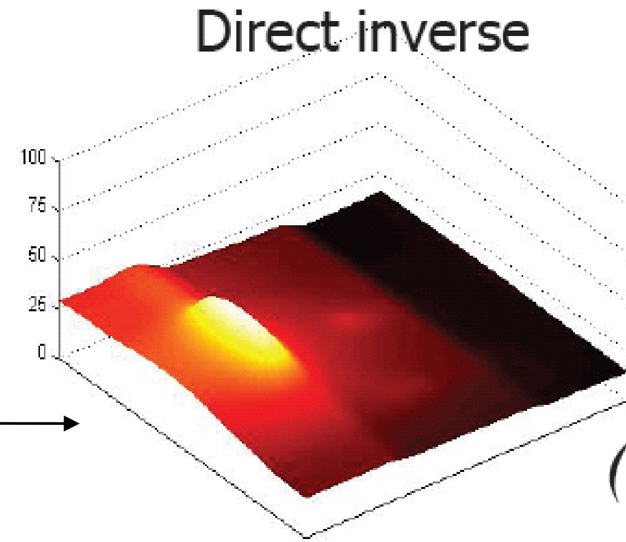
Corner

V. Heriz, J.-H. Park, T. Kemper, S.-M. Kang, A. Shakouri, International Workshop on Thermal Investigation of ICs and Systems (Therminic), pp.18-25 Sept. 2007
A. Shakouri et al. US Patent 7,627,841

Inverse problem (temperature -> power)

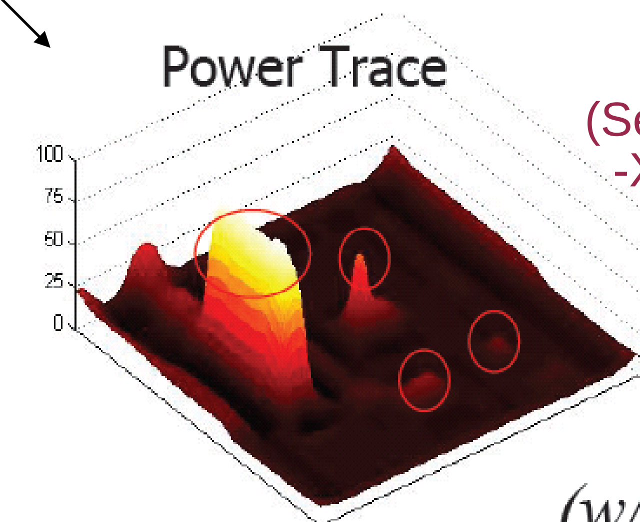
Measured temperature profile (include noise)





(w/cm^2)

IMAGE DEBLURRING



(Semitherm 2007 -Xi Wang et al.)

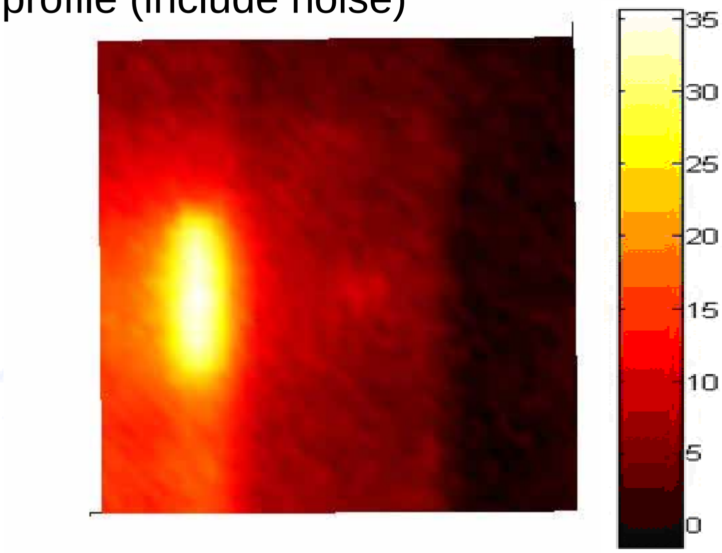
(w/cm^2)

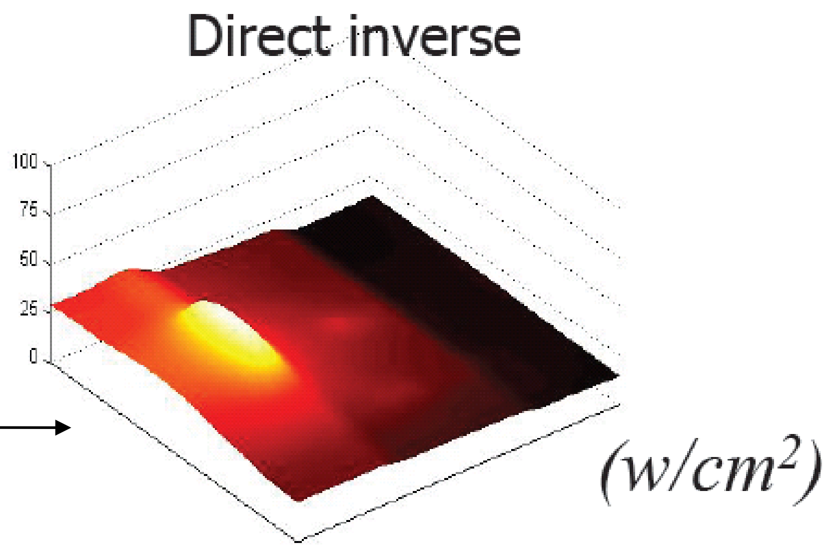
REGULARIZATION:

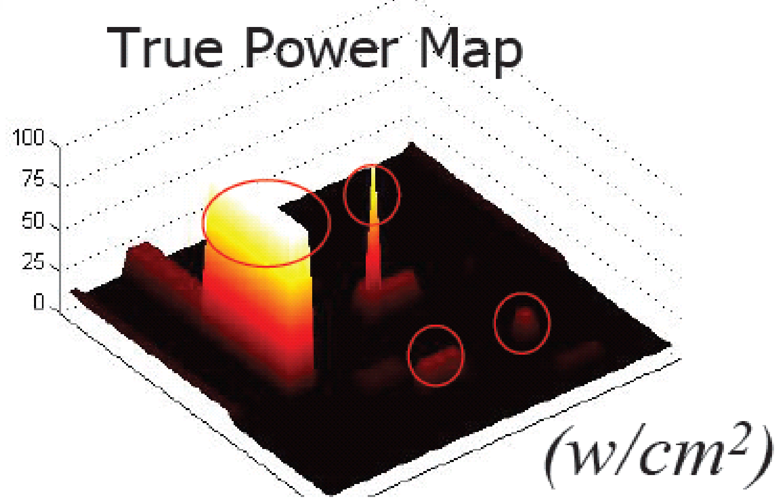
- Tikhonov Regularization (does not preserve edges)
- Bilateral Total Variation (Maximum a Postiori Cost function) Farsiu, et al. IEEE Trans on Image Processing, 13 (10), p. 1327 October, 2004.

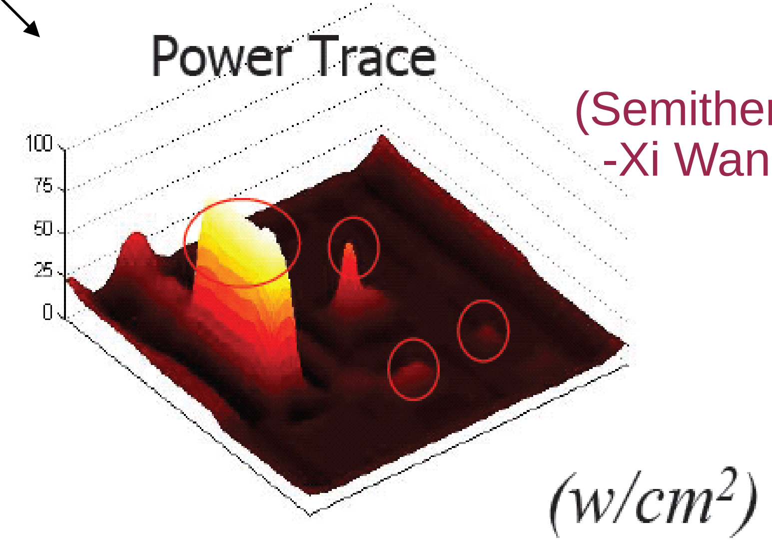
Inverse problem (temperature -> power)

Measured temperature profile (include noise)





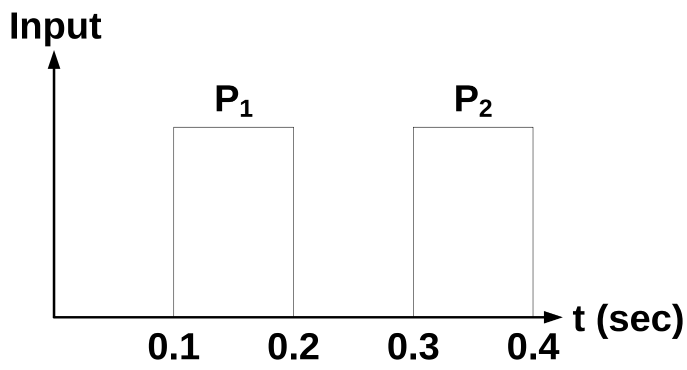


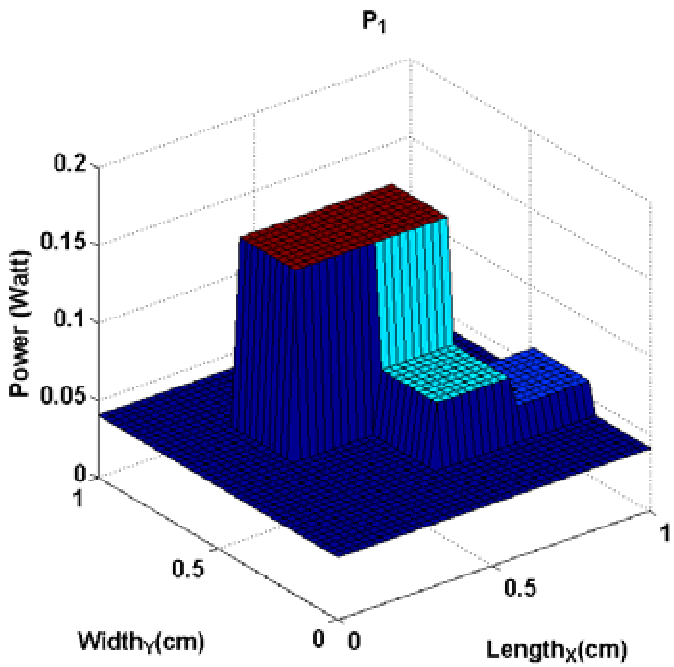


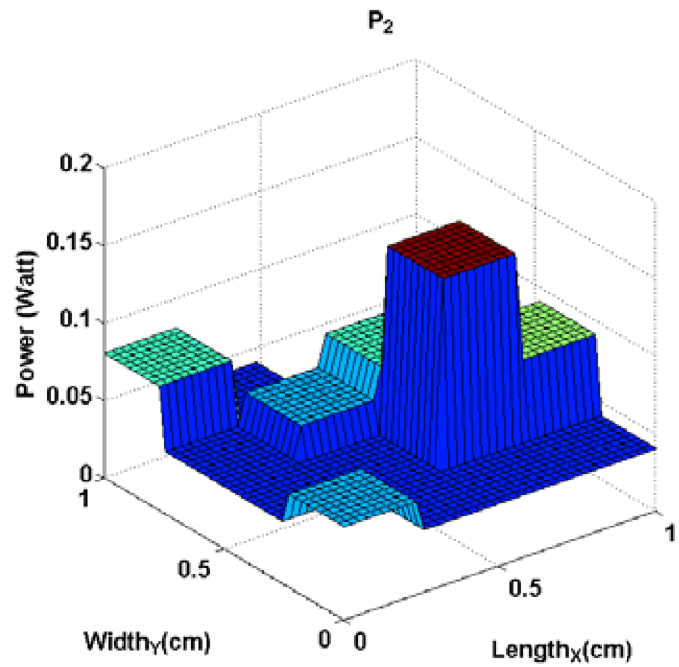
(Semitherm 2007 -Xi Wang et al.)

Transient Temperature Change in IC

Input Pattern

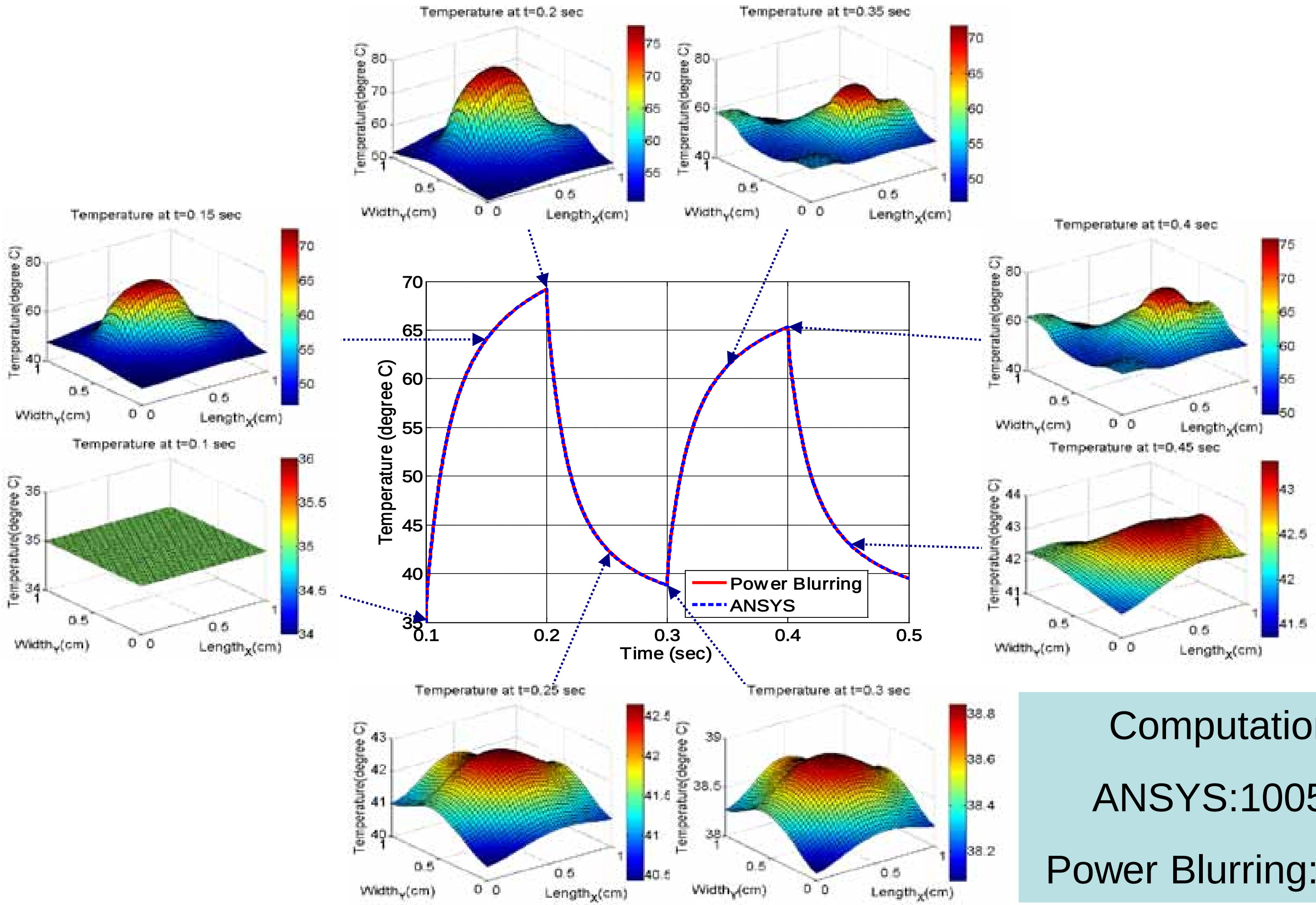






QUANTUM ELECTRONICS

Transient temperature at the chip center



Computation Time

ANSYS:10056 (sec)

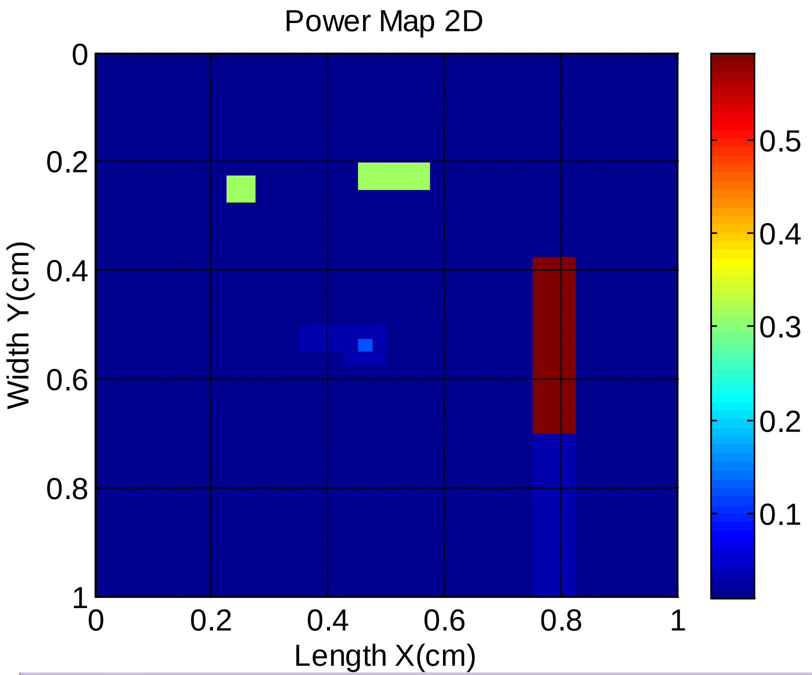
Power Blurring: 100 (sec)

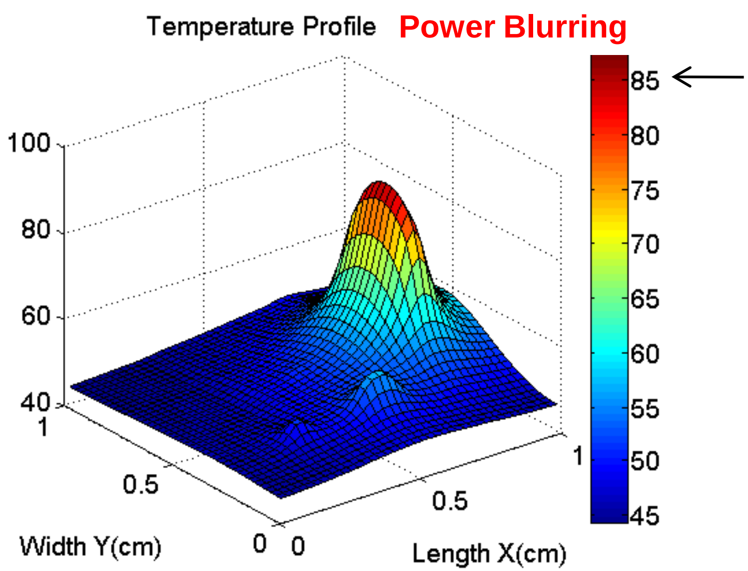
QUANTUM ELECTRONICS

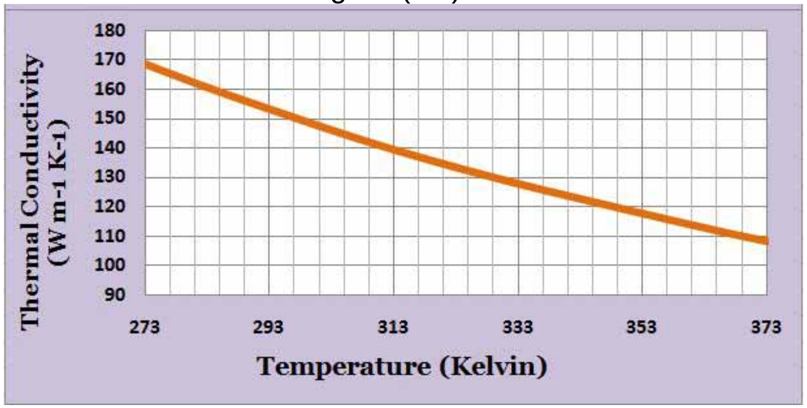
Virginia Martin Heriz, A. Shakouri et al. THERMINIC 2007

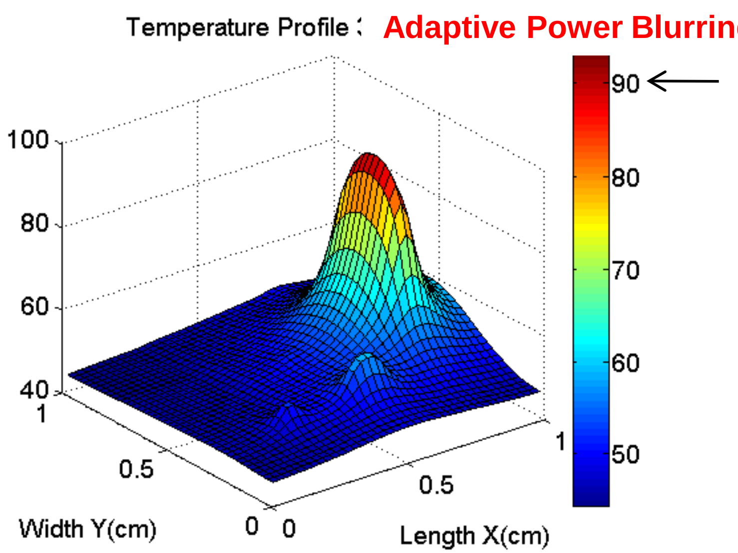
ADAPTIVE POWER BLURRING

A. Shakouri 2/16/2011





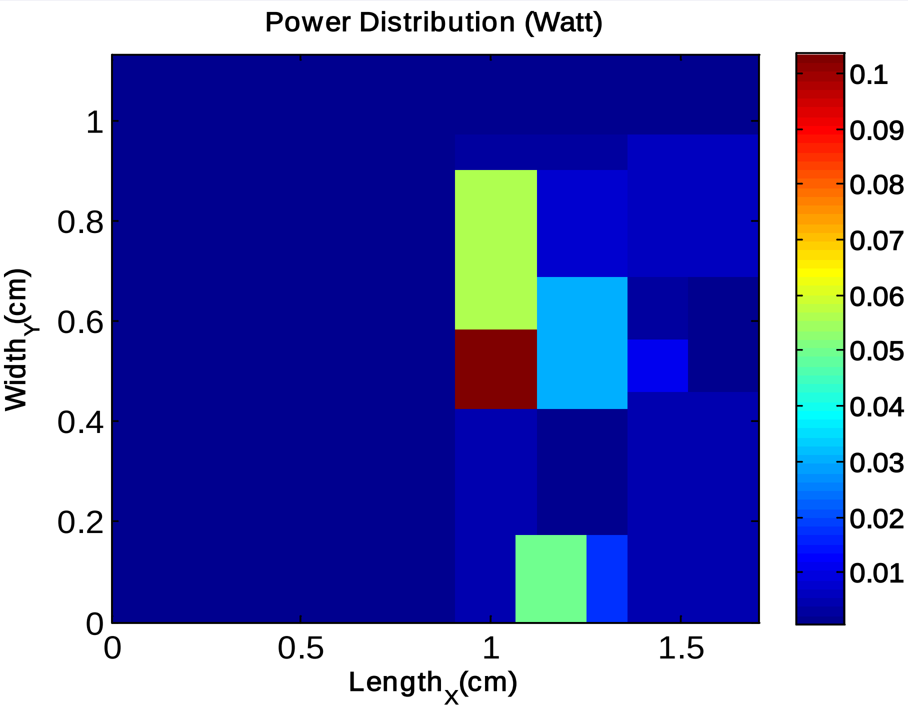


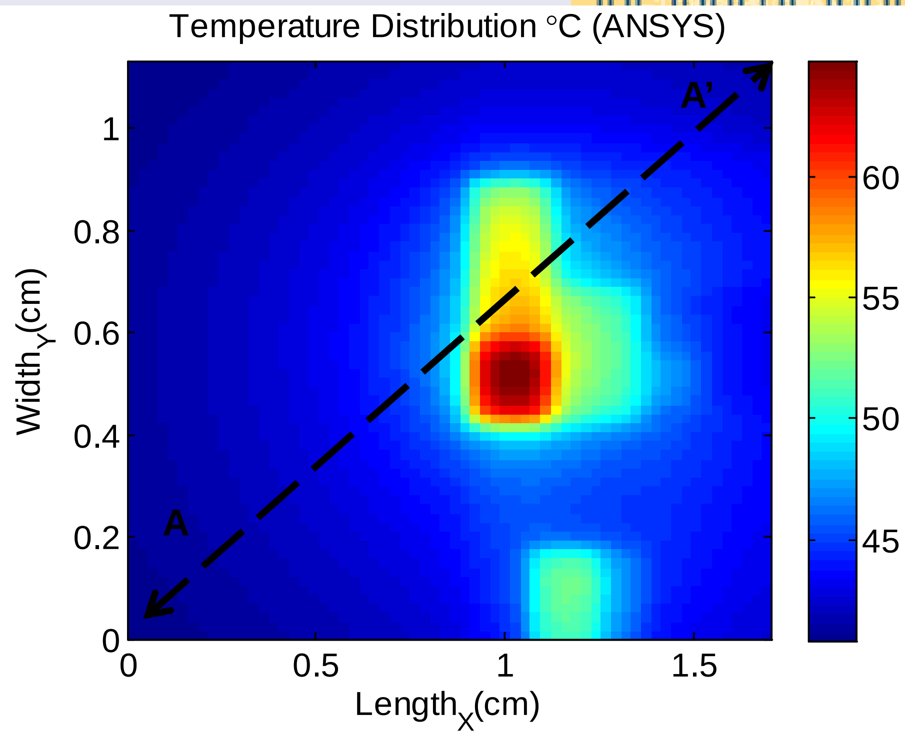


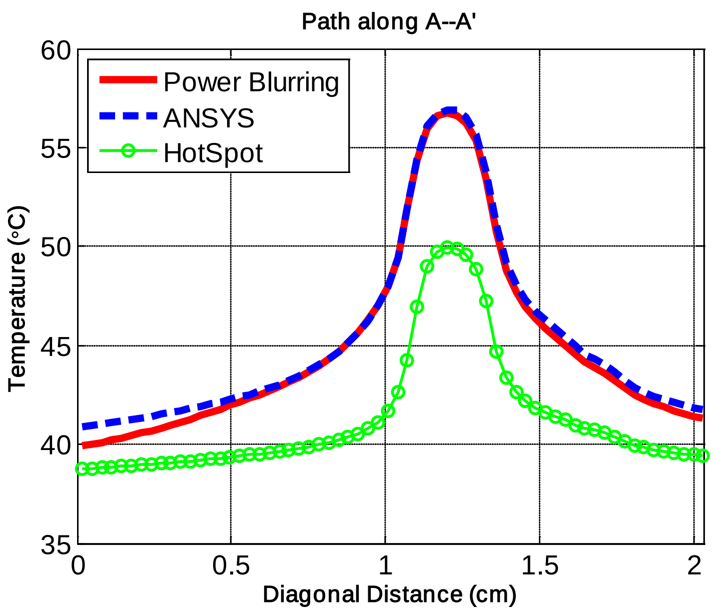
A. Ziabari et al, *IMAPS*, 2010.

Average execution time for PB, APB_I, APB_II, ANSYS: 0.04s, 0.16s, 0.83s, 16s

Architecture level thermal simulations





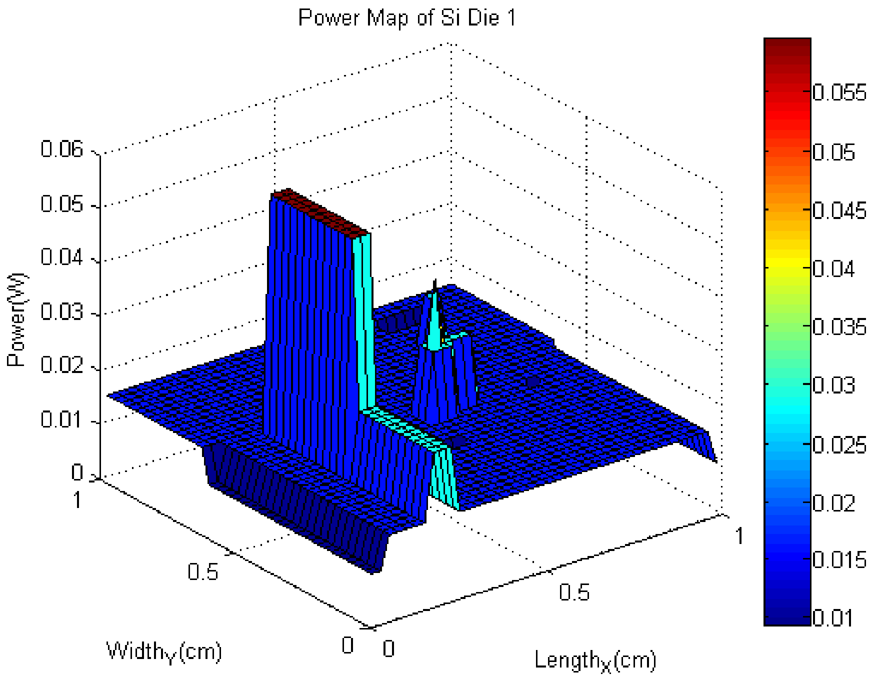


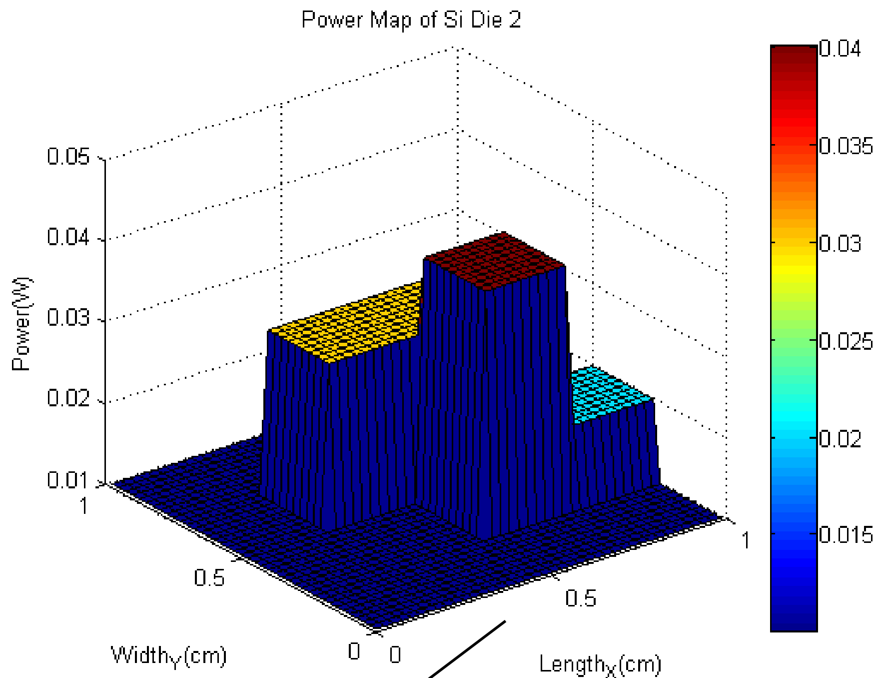
	ANSYS	HotSpot	PB
Computation Time	56 s	0.11 s	0.041 s
Relative error at hottest spot	-	29%	0.3%
Absolute temperature error	-	2-9°C	<1°C

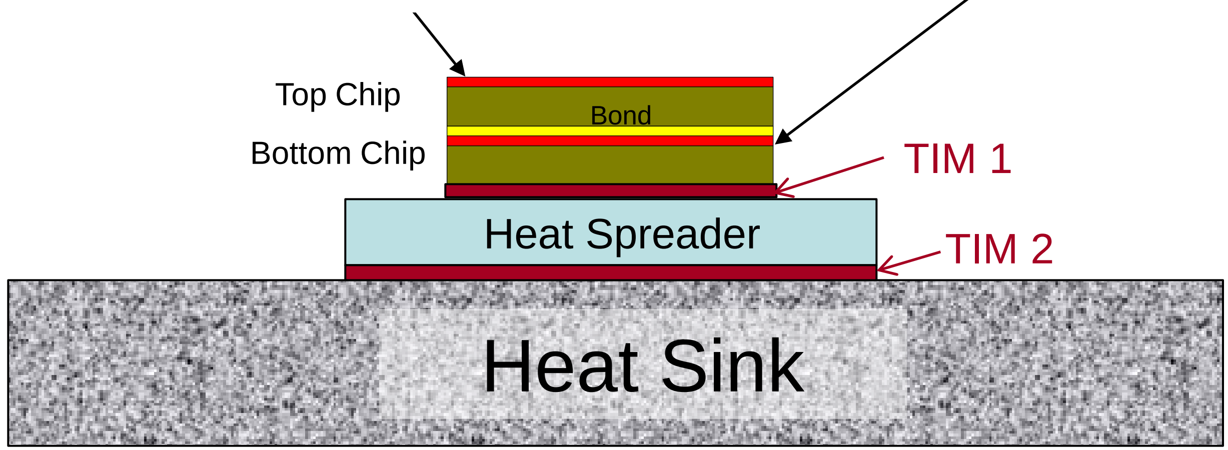
A. Ziabari et al, *submitted to SemiTHERM 2011*

3D Chip Thermal Simulation

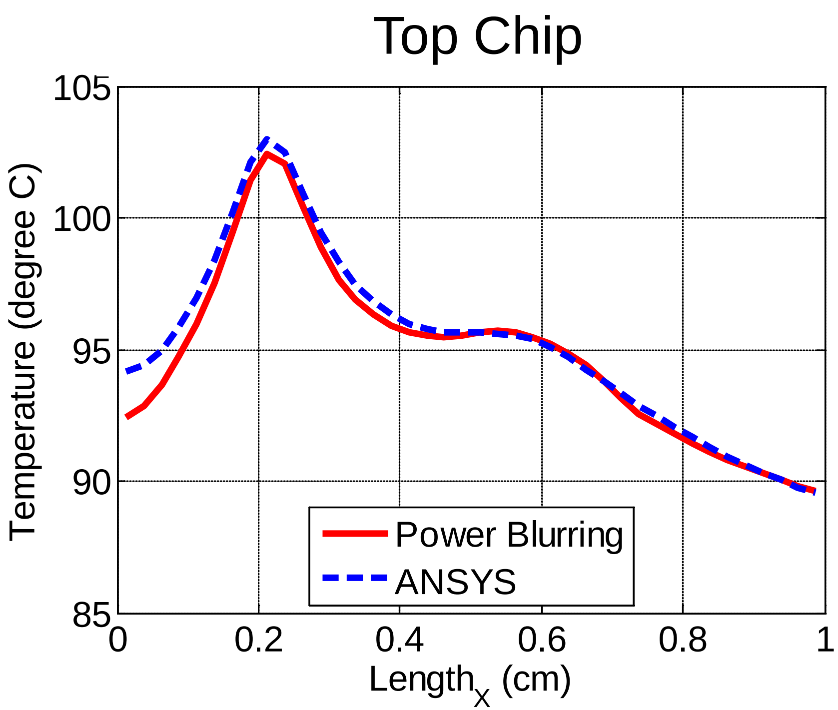
A. Shakouri 2/16/2011

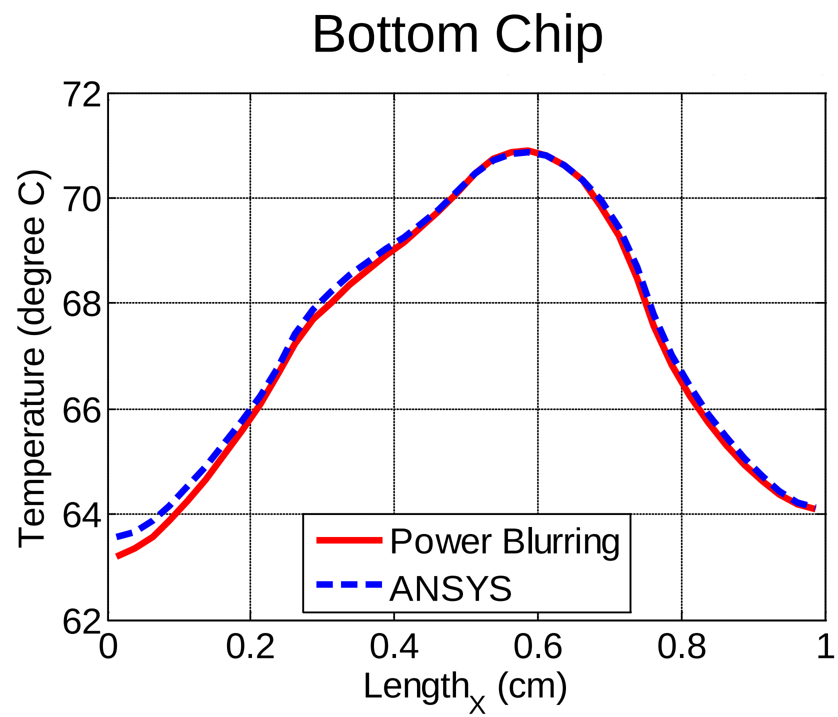






Cross-section temperature profiles





Je-Hyoung Park, Ali Shakouri, and Sung-Mo Kang, "**Fast Thermal Analysis of Vertically Integrated Circuits (3-D ICs) Using Power Blurring Method**," *Proceedings of the InterPACK Conference,* San Francisco, July 19-23, 2009.

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http://quantum.soe.ucsc.edu/

Thermal Characterization Lab at NASA Ames Research Center

300 sq feet space for optical/thermal characterization system
Resolution: 6mK temperature, 500 nm spatial, DC/Transient - 100ns

Santa Cruz Campus

Exclusive research collaboration
Sharing and transferring our techniques and tools via industrial affiliate program

Major Equipment

High Temperature Cryostat System (4-1000K)
Raman and Luminescence Spectroscopy System
Thermal Imaging Camera
Femto/Picosecond Laser
Atomic Force Microscope
Mid/Near-infrared Thermal Imaging (InSb, InGaAs cameras)
OLYMPUS FluoView FV1000-Confocal Microscope

QUANTUM ELECTRONICS

Summary

- Metal / semiconductor nanocomposites can improve thermoelectric energy conversion
  - Mid/long wavelength phonon scattering, Hot electron energy filtering
- Micro Refrigerators on a Chip (need ZT~0.5 on chip to cool 1kW/cm^2 hot spots by 10-15C)
- Fast transient thermal imaging (~200nm, 0.2C, 800ps)
- Thermal characterization of high power transistors, ESD devices, solar cells, LEDs and copper vias
- Fast thermal simulation of packaged IC chips (adaptive power blurring) –T-dependent material properties

A. Shakouri and M. Zeberjadi, "Chapter 9: **Nanoengineered Materials for Thermoelectric Energy Conversion**," in: *Thermal Nanosystems and Nanomaterials*, ed. by S. Volz, Springer, pp. 225-299 (2009)

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