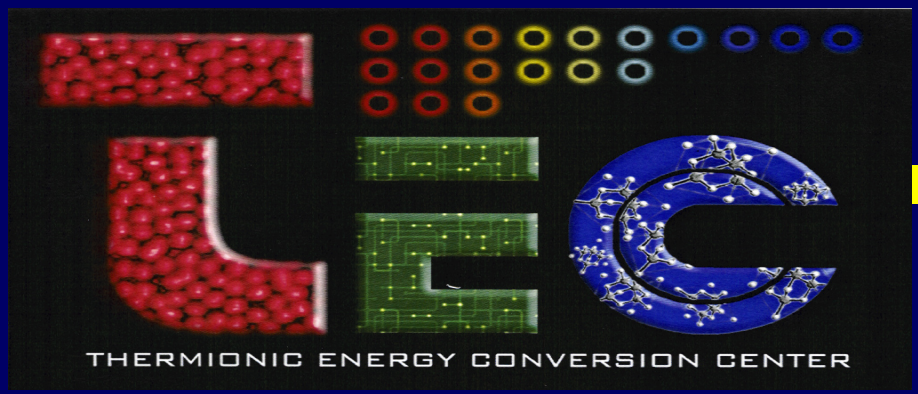
Hot Spot Management and Micro Refrigeration in Integrated Circuits

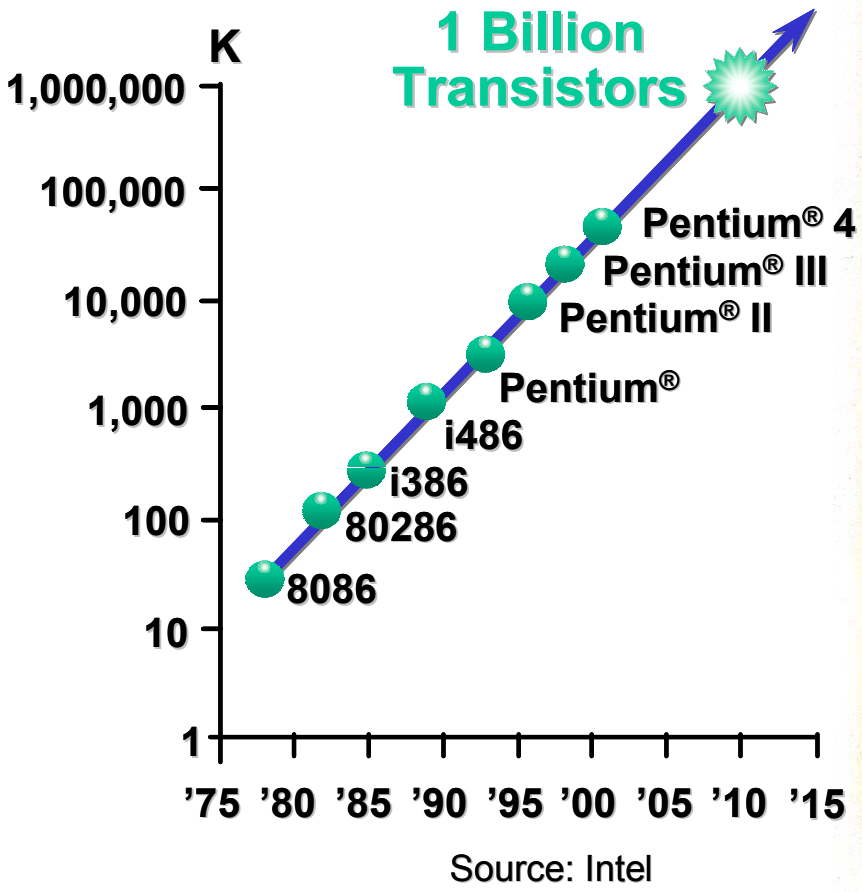
Ali Shakouri
Director, Thermionic Energy Conv. Center
Baskin School of Engineering
University of California Santa Cruz

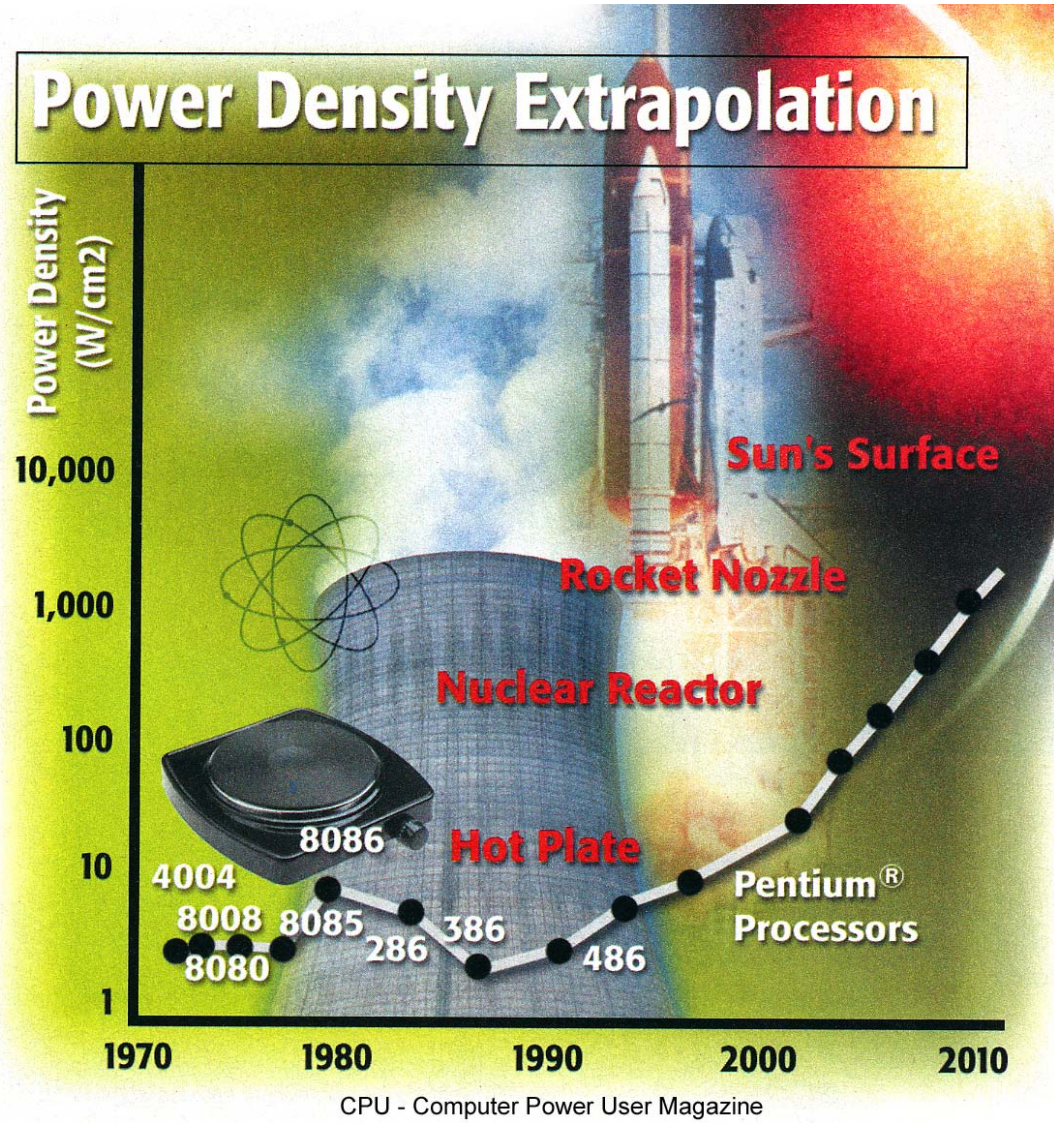


Acknowledgement:
National Semiconductor, Intel, Canon, Agility, SRC-Interconnect Focus Center, Packard, NSF, DARPA, ONR

IEEE CSS and CMPT Santa Clara Valley; San Jose, CA; 20 April 2009

Motivation: Microprocessor Evolution

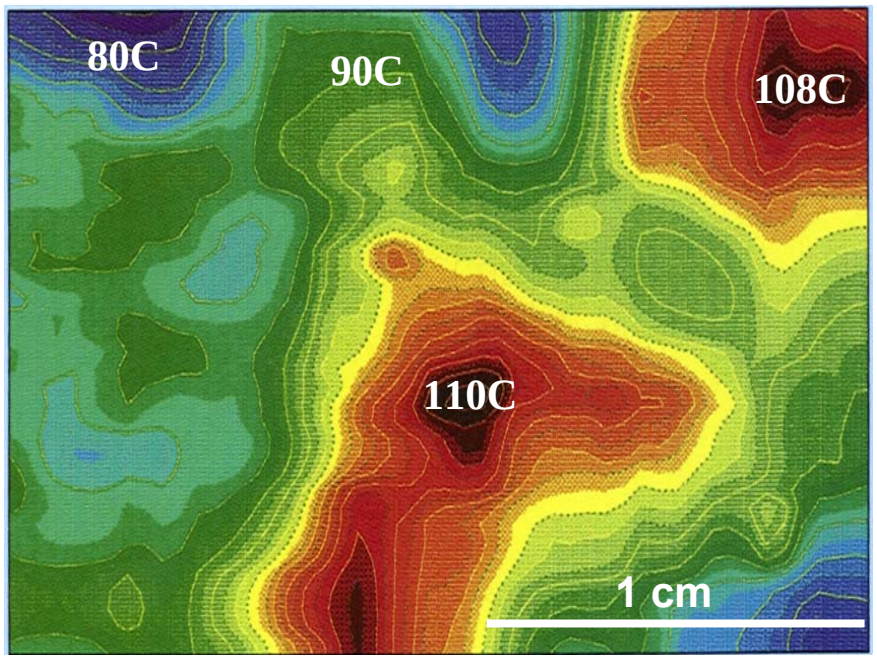




Problem:
Non Uniform Heat Generation in VLSI Chips

$\Delta T=20C$ ⇒

Mean-time-to-failure due to electromigration increase x5



On chip temperature contour

Steve Kang et al. **Electrothermal analysis of VLSI Systems**, Kluwer 2000

Impact of temperature on IC performance

15°C temperature increase:

- Cell and interconnect delay (10-15%)
- Crosstalk noise level increase (up to 25%)
- Leakage power exponential increase with temperature
  - 90nm →25-40% of total power
  - 60nm→50-70% of total power
  - Potential thermal runaway
- Lifetime exponential decrease with temperature (x ¼) – e.g. electromigration, oxide breakdown
- Clock gating and multithreshold CMOS increase on-chip thermal variation

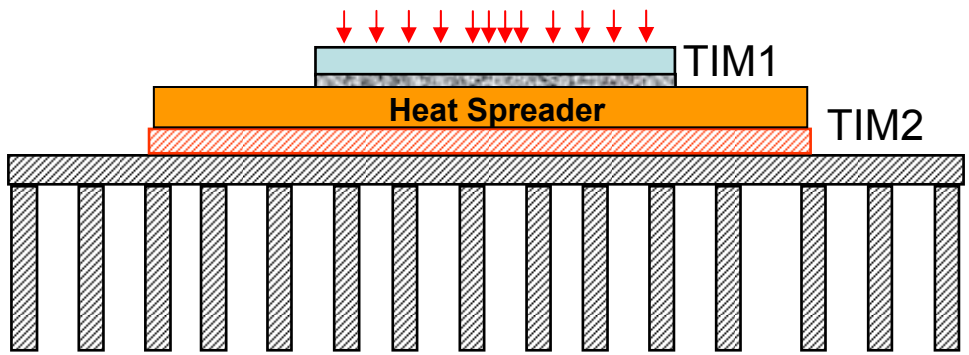
Thermal integrity: a must for low-power-IC digital design, EDN 15 Sept. 2005

Hot spot temperature rise

- Silicon Chip 10x10x0.5 mm^3, assume 100W
- 400μm diameter hot spot in the center, 1KW/cm^2 heat flux (1.25W) → $\Delta T_{hot\ spot}$ ~7C

$\Delta T_{hot\ spot}$ is approximately independent of the technique used to cool the whole chip.

Example: If the heat transfer coefficient changes from 5 to 20 KW/m^2K, this will change $T_{average}$ from 225 to 75C; when the average power dissipation is ~100W/cm^2 but this will not change $\Delta T_{hotspot}$



High Speed WDM Fiber Optics Systems

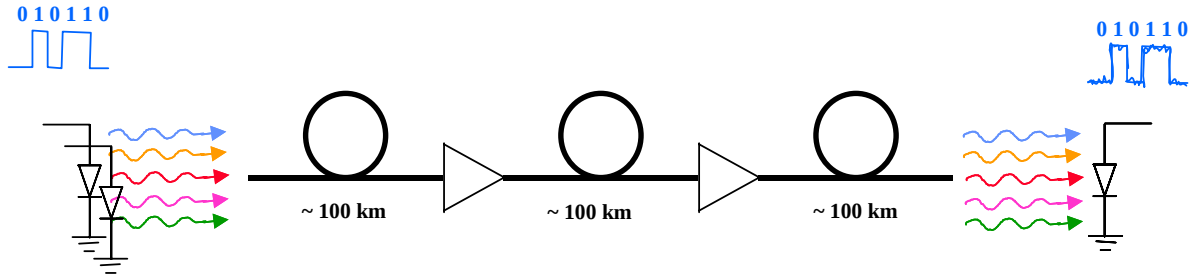
Wavelength Division Multiplexing

Fiber Optic Link: 3200 Gbit/s

80 Lasers, 40 Gb/s per laser

0.8nm channel spacing

Scheerer et al., Siemens AG,
Elec. Lett. 35, (20, Sept. 1999)



$\Delta\lambda \sim 0.8$ nm

- **Optoelectronic device used in high-speed, multi wavelength fiber optic communication systems generate kW/cm^2 and they need temperature stabilization.**

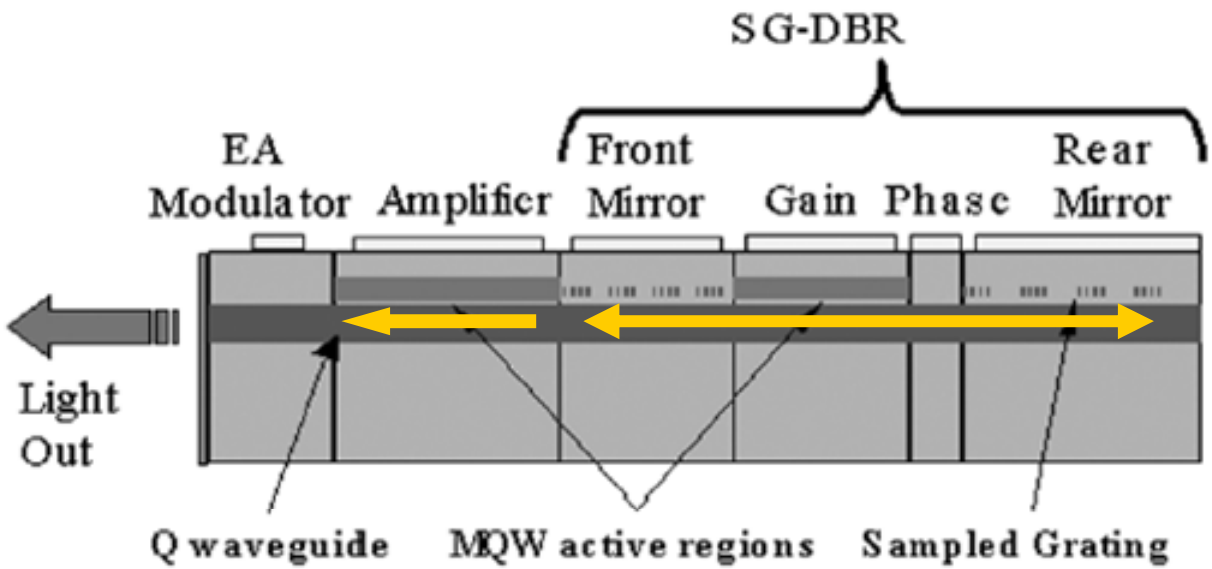
Typical DFB Laser:

$\Delta\lambda/\Delta T$= 0.1 nm/^{o}C

Heat generation kW/cm^2

Thermal Issues in Electroabsorption Modulator (EAM)

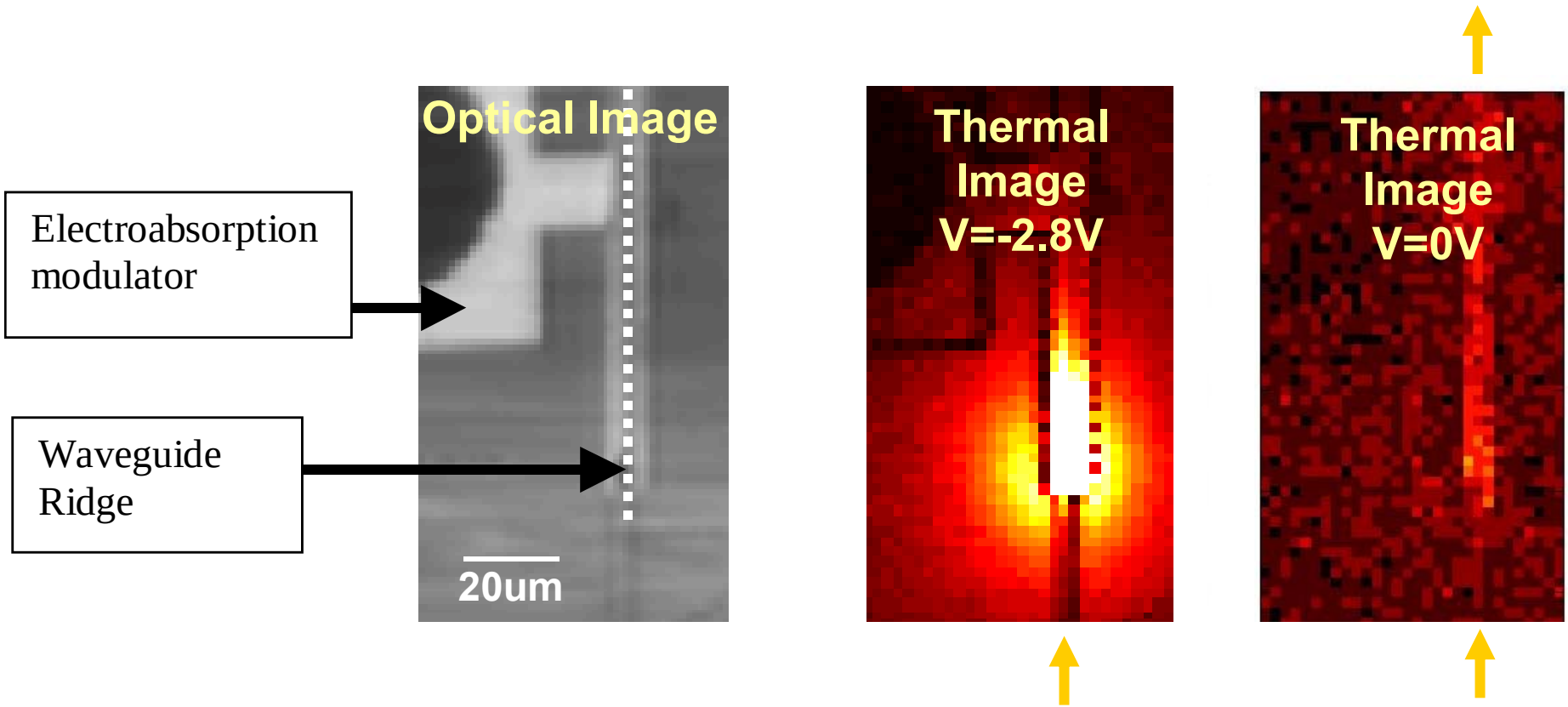
- EAM can be easily integrated into tunable lasers to offer high bandwidth (>10Gb/s), low chirp, low drive voltage and high extinction ratio



Akulova, et. al., IEEE Journal of Selected Topics in Quantum Electronics, 8 (6), Nov/Dec 2002

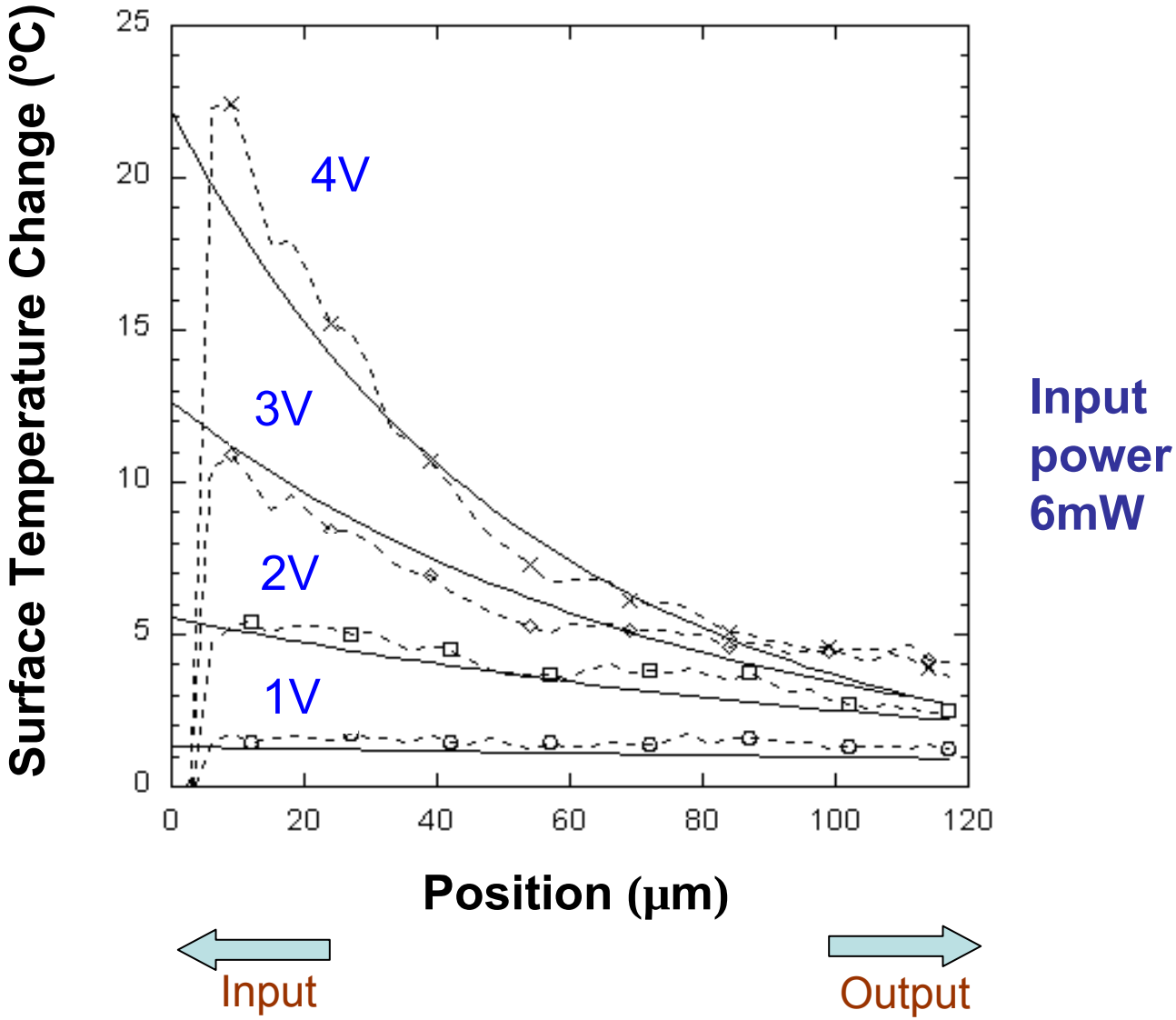
Collaborators: P. Kozodoy, P. Abraham (Agility Communications)

Thermal Imaging of Integrated Electroabsorption Modulator



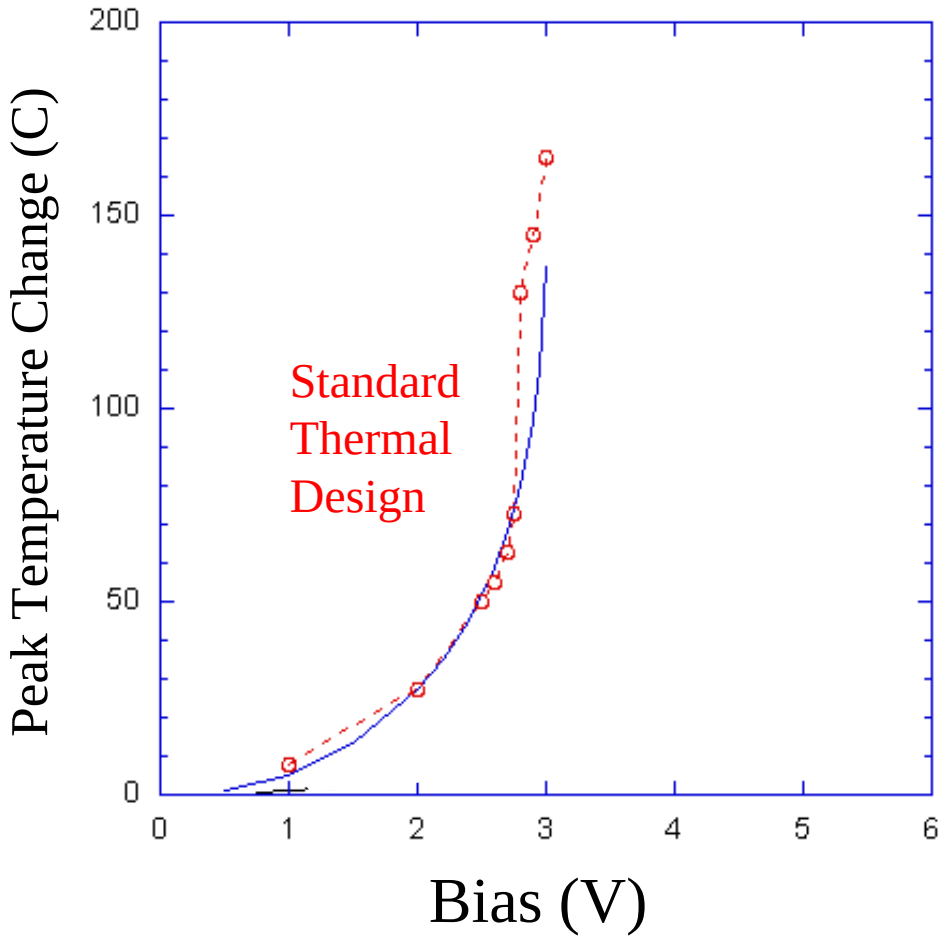
A. Shakouri, J. Christofferson, Z. Bian, and P. Kozodoy, Proceeding of Photonic Devices and System Packaging Symposium (PhoPack 2002), pp22-25, July 2002, Stanford CA.

Temperature Profile along Electroabsrorption Modulator



Input power 6mW

Peak Surface Temperature at High Input Power



measurement (points)

theory (line)

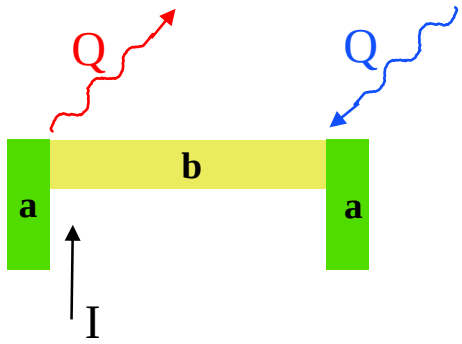
Input power ~ 35 mW
Wavelength ~1.55 μm.

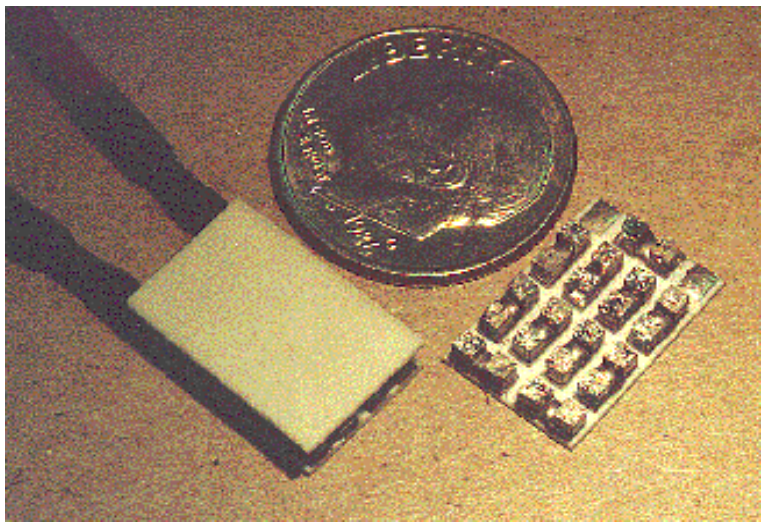
There is thermal runaway with standard device design

Z. Bian, J. Christofferson, P. Kozodoy, A. Shakouri, Applied Physics Letters 2003

Peltier Effect (1834)

Peltier: $$\pi_{ab} = \pi_a - \pi_b = \frac{Q}{I}$$





Commercial TE Module

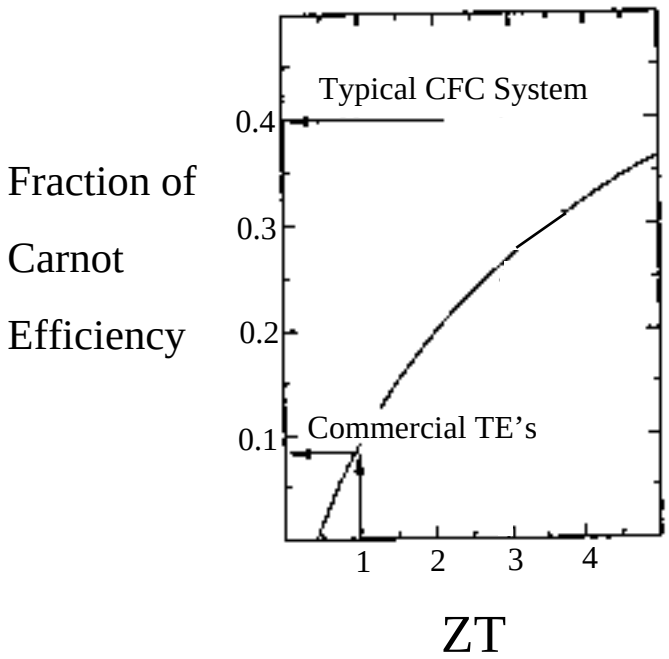
- ΔT=72C (no heat load)
- Cooling density <10W/cm^2
- Efficiency 6-8% of Carnot

When the current flows from material (a) into material (b) and then back to material (a), it heats the first junction and cools the second one (or vice versa). Thus, heat is transferred from one junction to the other one.

Efficiency of TE Coolers

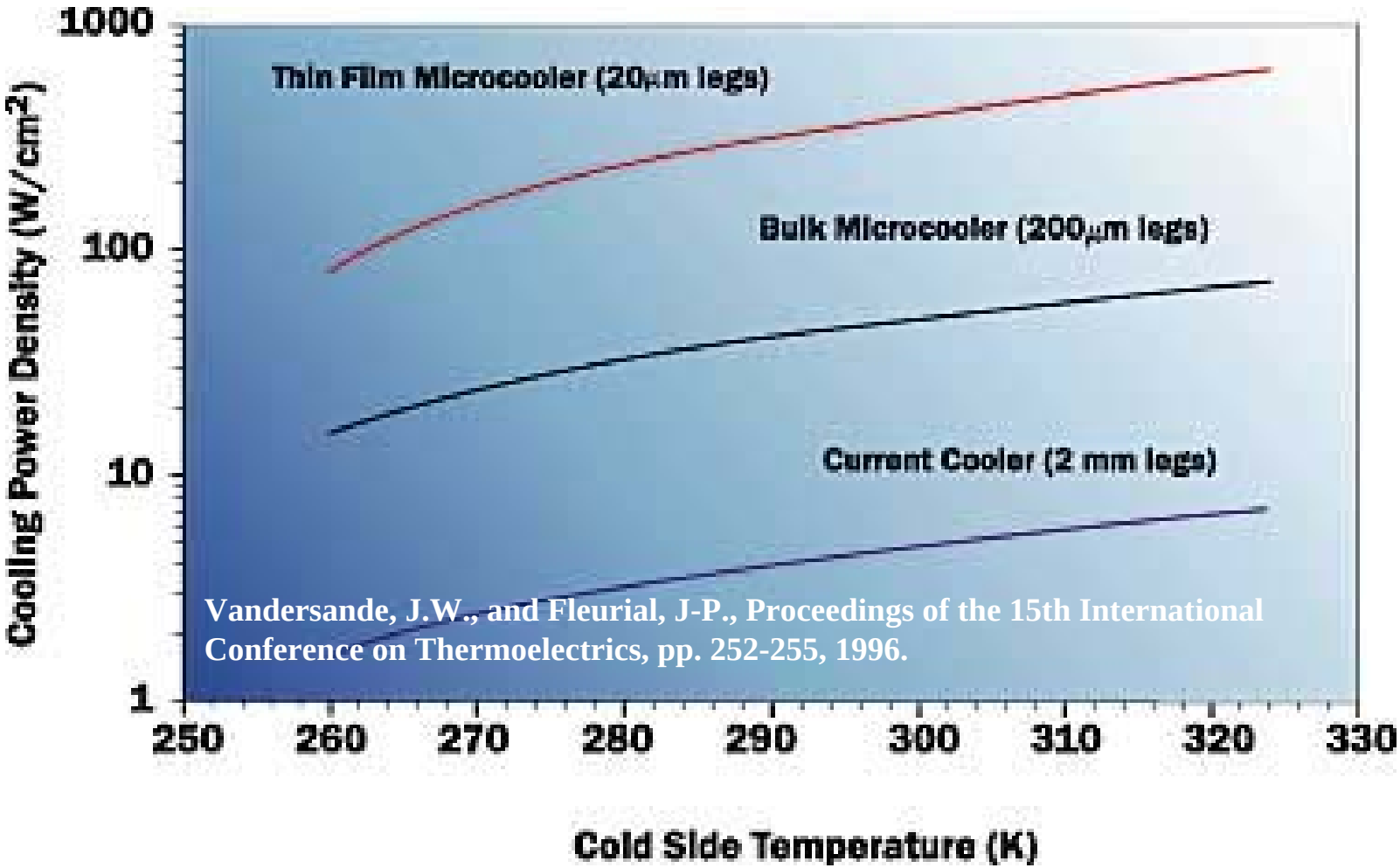
$$Z = \frac{S^2 \sigma}{\beta}$$

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



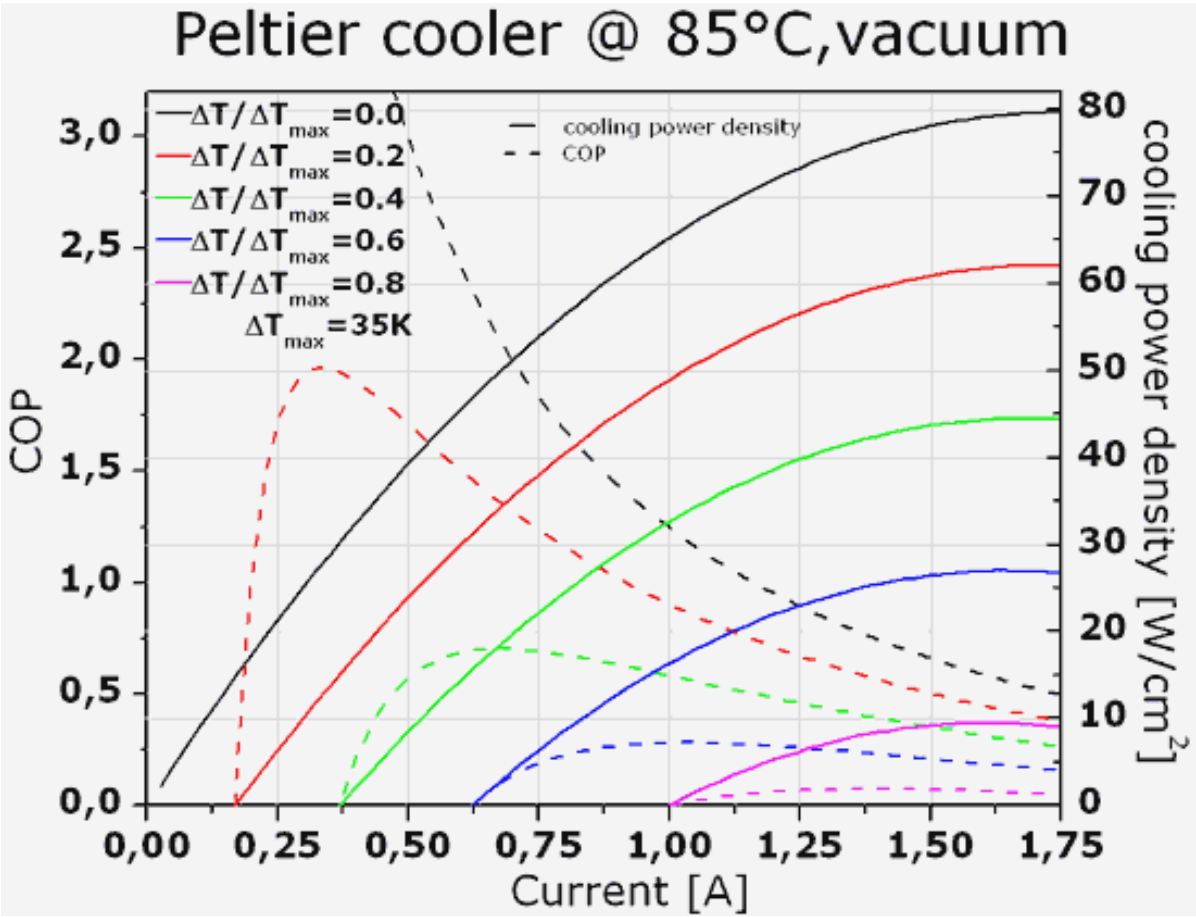
Single ratio Z determines efficiency (COP) and the maximum cooling of thermoelectric coolers .

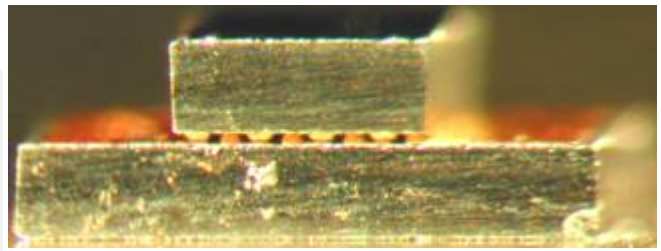
Cooling Power Density

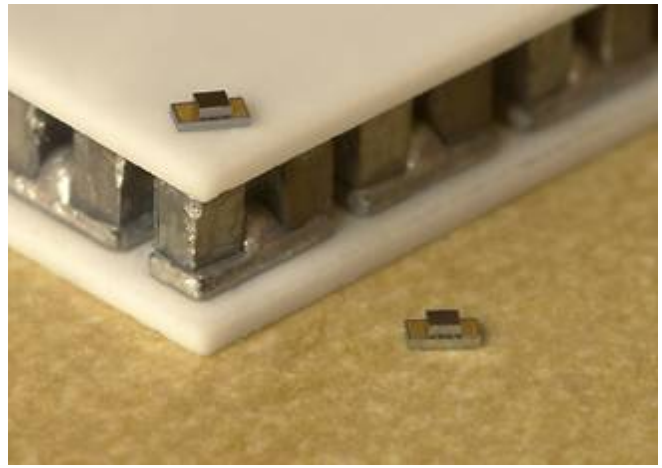


Vandersande, J.W., and Fleurial, J-P., Proceedings of the 15th International Conference on Thermoelectrics, pp. 252-255, 1996.

High Cooler Power Density Micro Peltier Coolers







H. Bottner

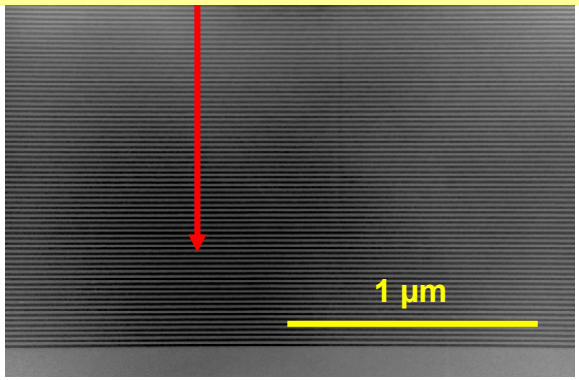
Fraunhofer IPM Institut Physikalische Messtechnik

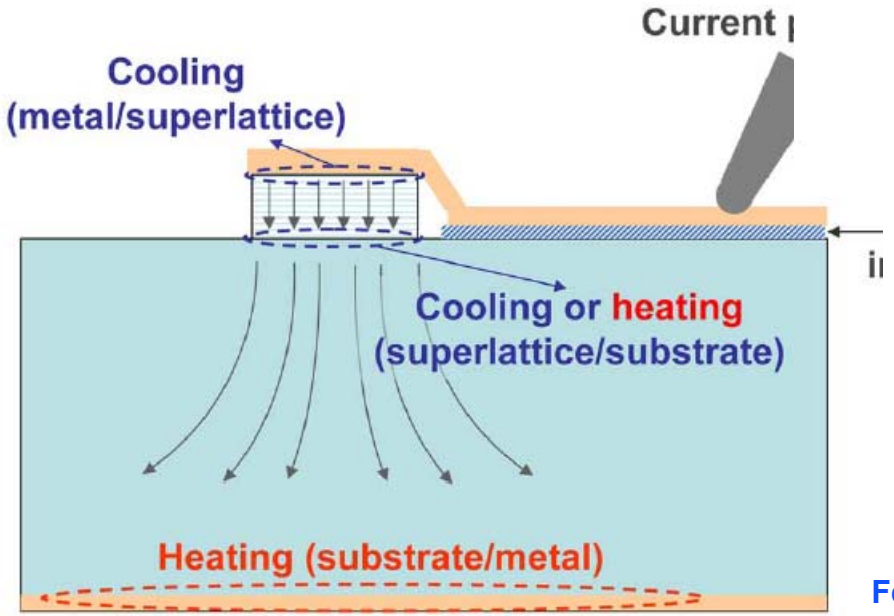
Infineon technologies

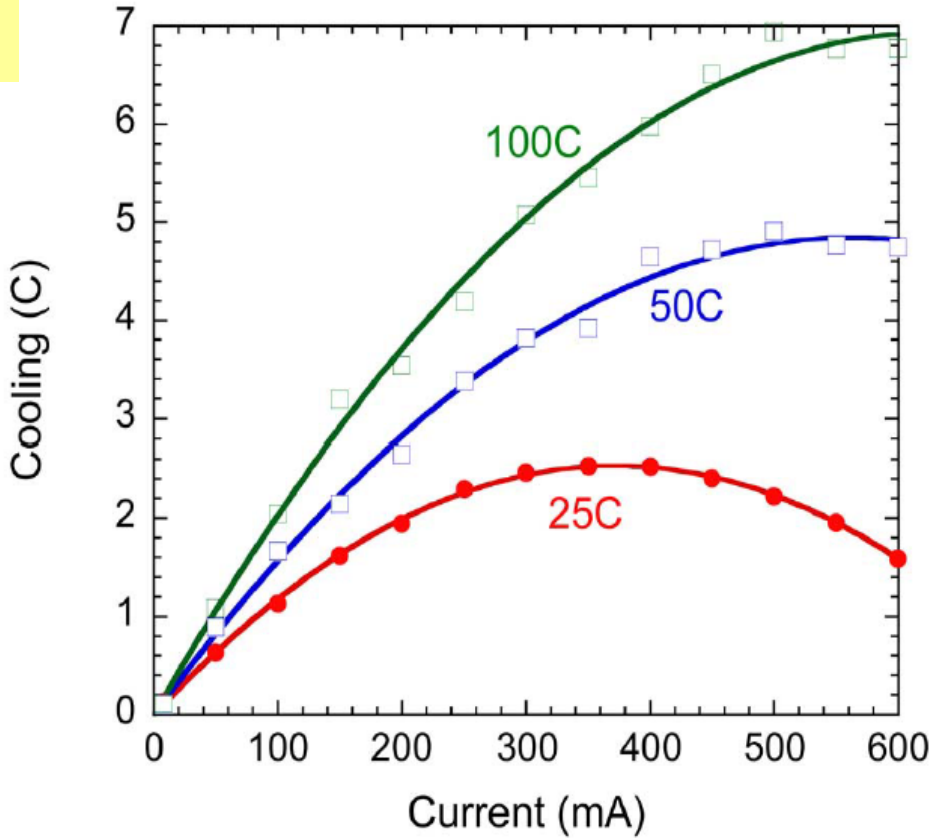
MicroPelt

Microrefrigerators on a chip

- Monolithic integration on silicon
- ΔT_{max}~4C at room temp. (7C at 100C)
- Cooling power density > 500W/cm^2





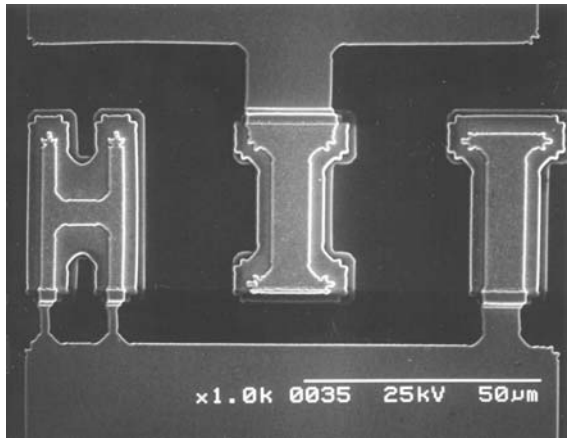


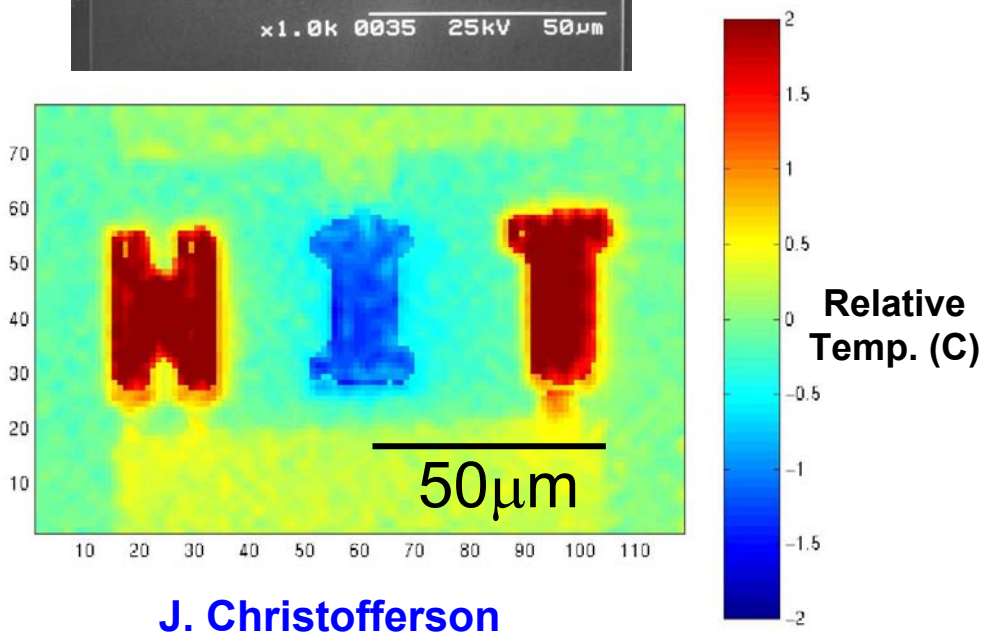
Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, **Proceedings of IEEE**, July 2006

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

Microrefrigerators on a chip

UCSC, UCSB, HRL Labs





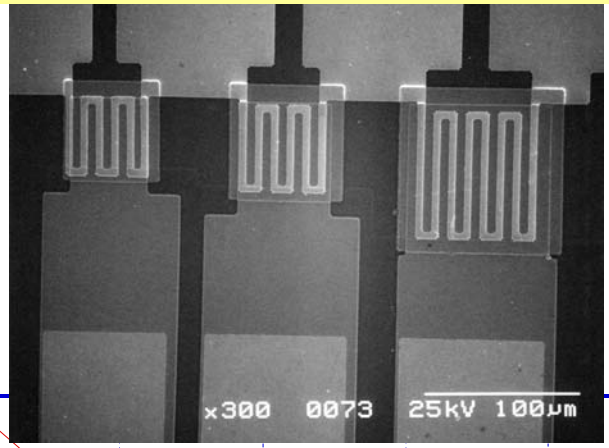
J. Christofferson

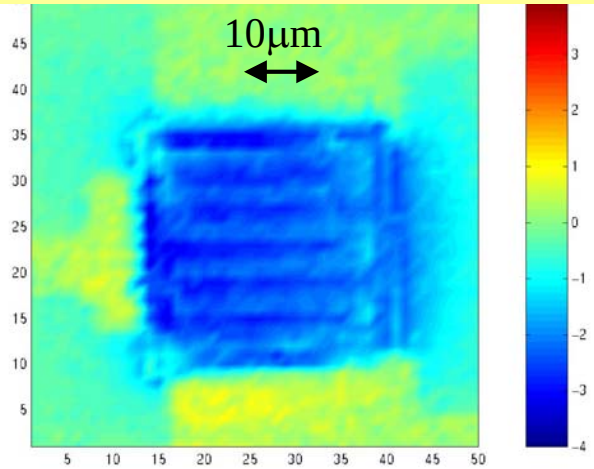
Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, **Proceedings of IEEE**, July 2006

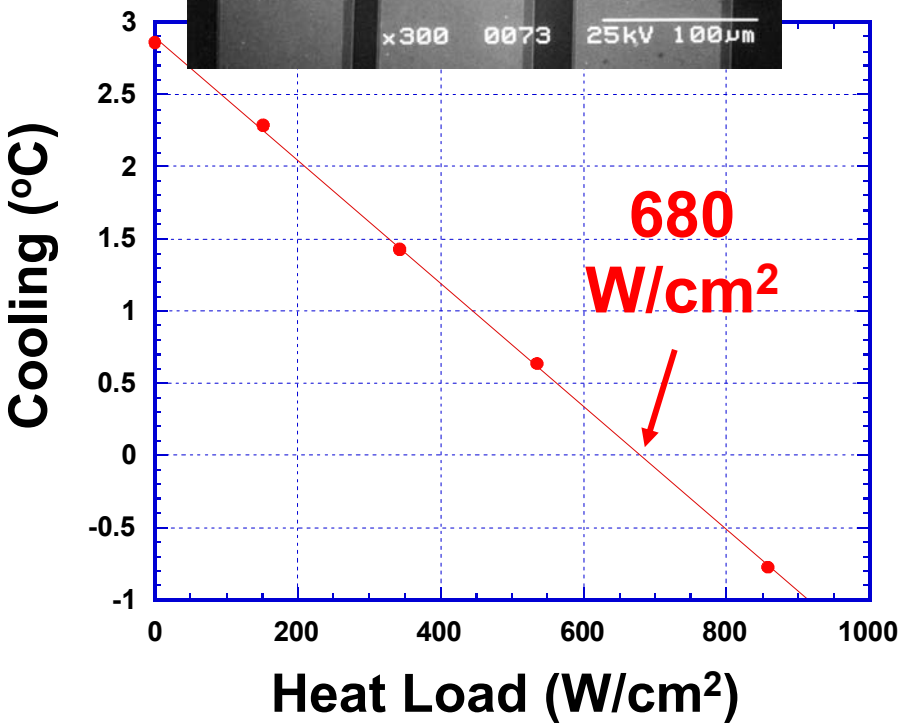
Featured in Nature Science Update, Physics Today, AIP April 2001

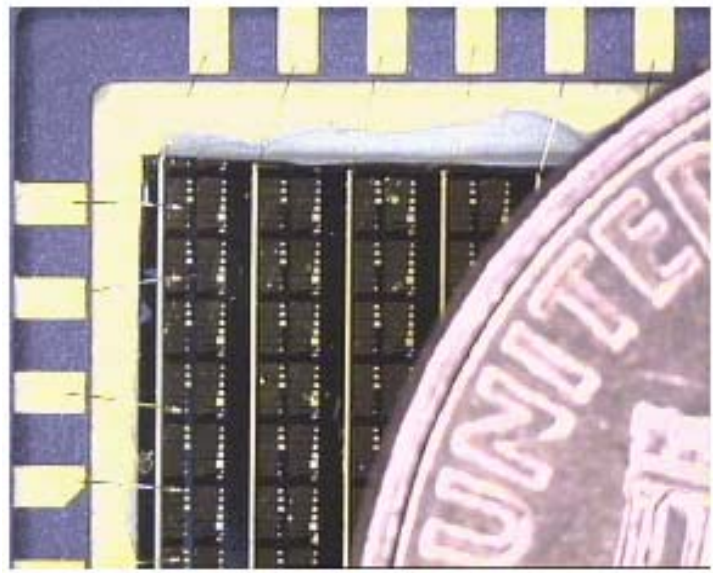
Micro Refrigerator Integrated with Thin Film Heater

Cooling power density >500W/cm^2 even though ZT~0.1. This is due to 3D device geometry





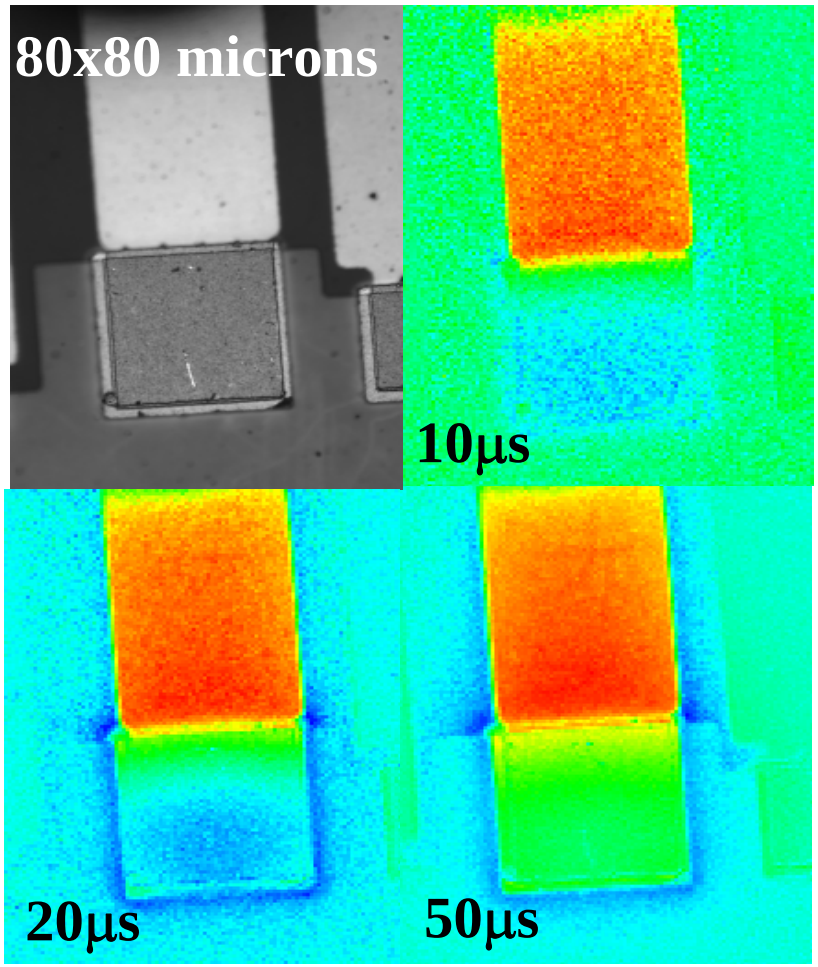


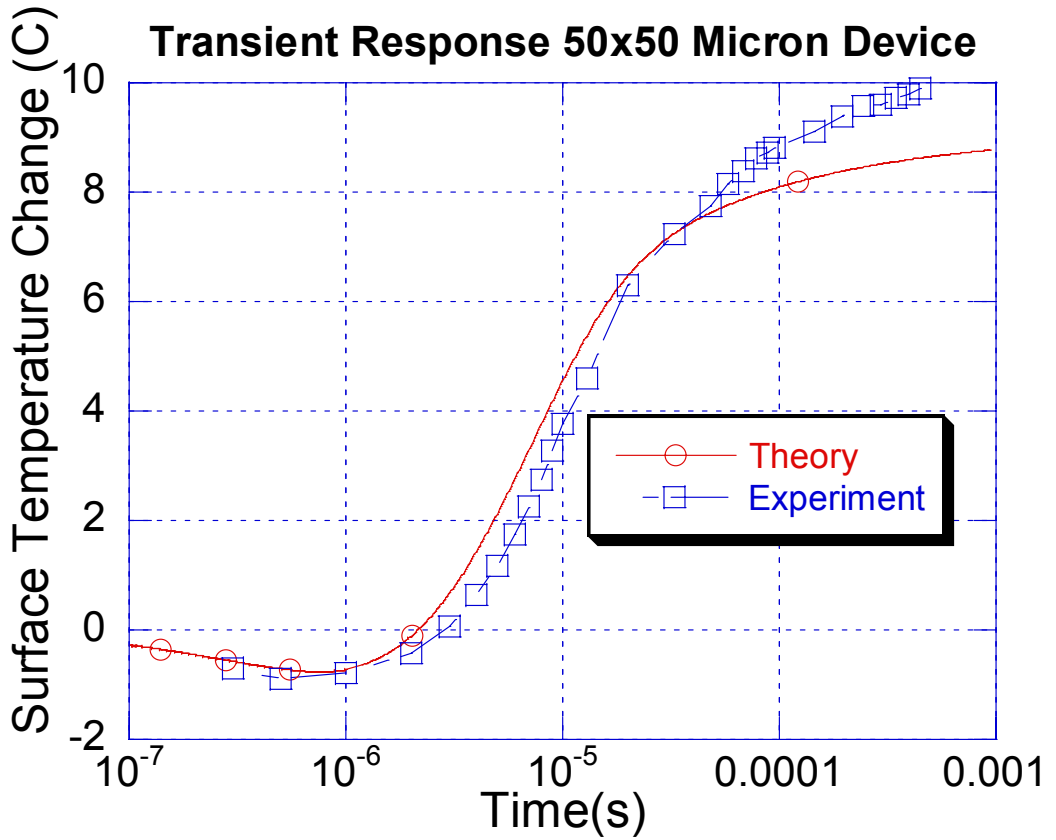


Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, **Proceedings of IEEE**, July 2006

Transient Thermal Imaging of a microcooler

- 100nsec, 300nm, 0.1C resolution





J. Christofferson et al. SemiTherm 2009

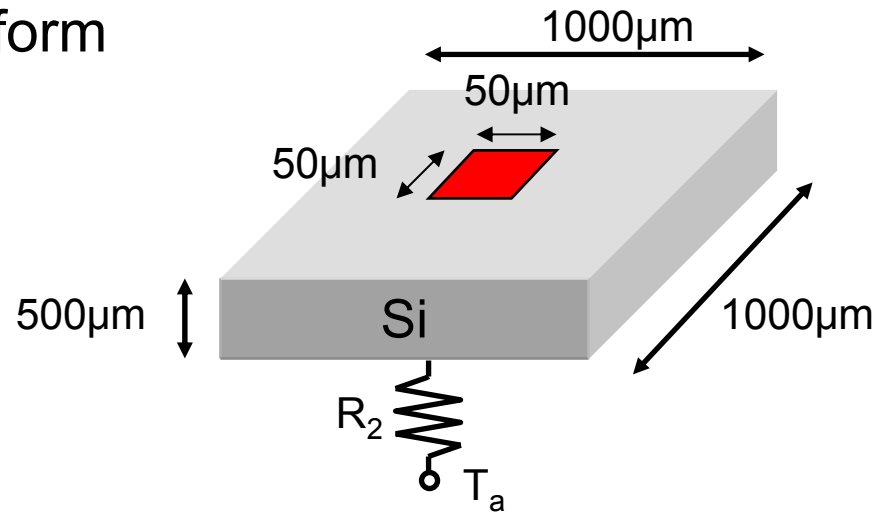
Spot Cooling with SiGe microrefrigerators in a packaged device

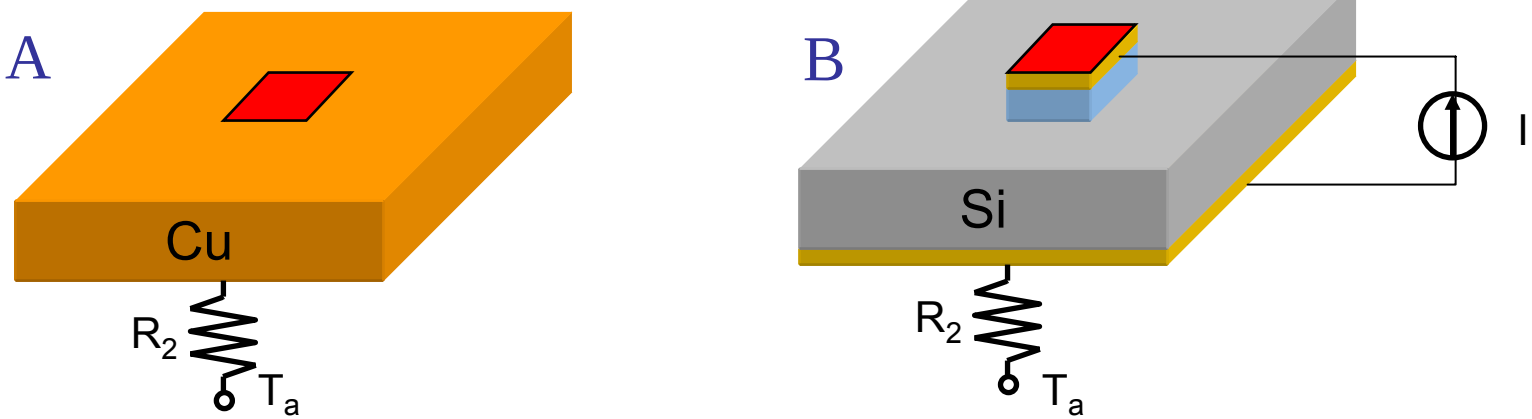
Si chip inside a package with non-uniform heating $Q_h=10xQ_b$ –reference-

Solutions:

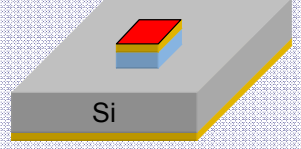
(A) Passive cooling: Cu substrate

(B) Active localized cooling: SiGe superlattice (no contact/parasitic resistances, optimized thickness)

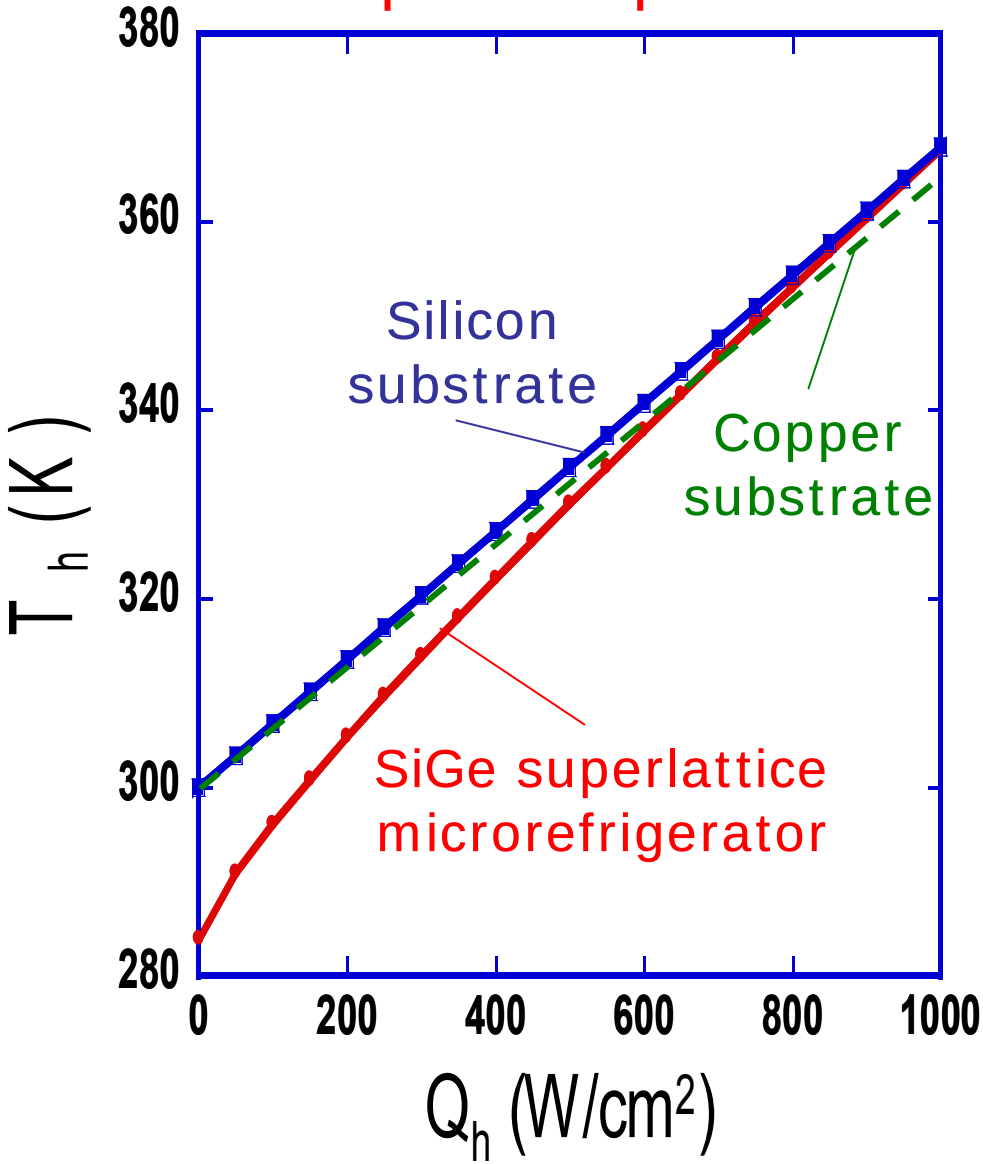


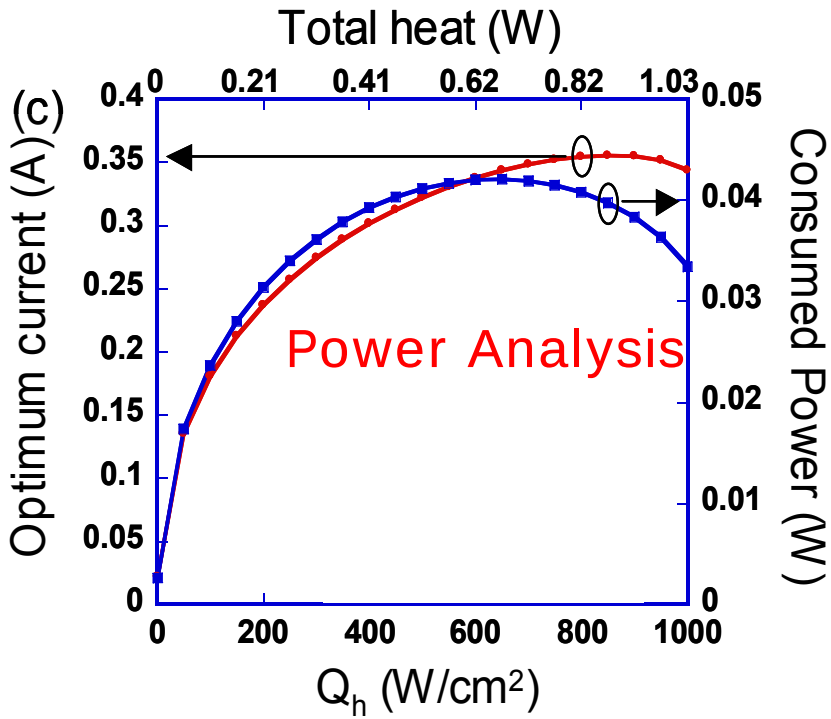


Package thermal resistance
R_2=61 K/W (per unit area: 6×10^{-5} m^2K/W)



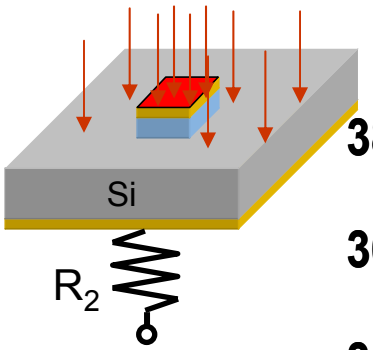
Hot spot temperature

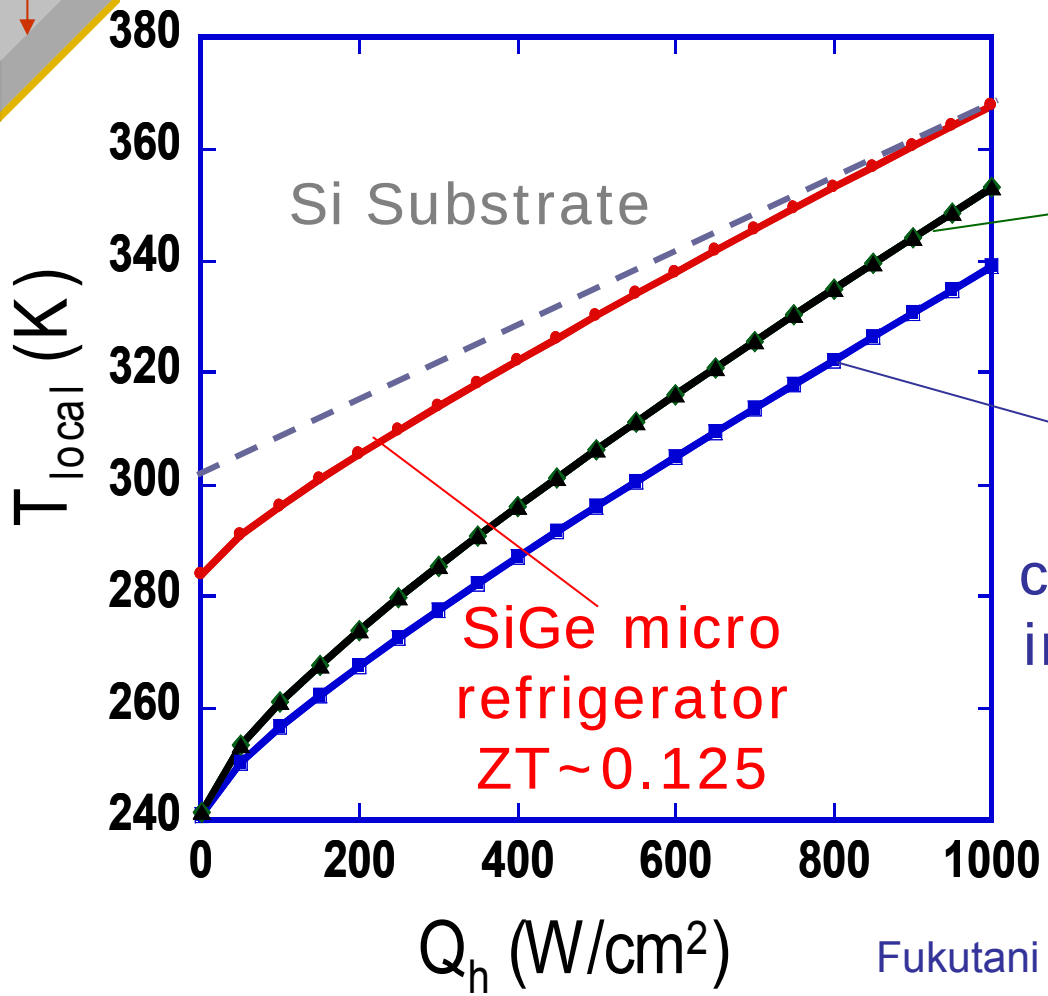




Fukutani and Shakouri (InterPACK06)

What could be achieved if SiGe material properties could be improved?





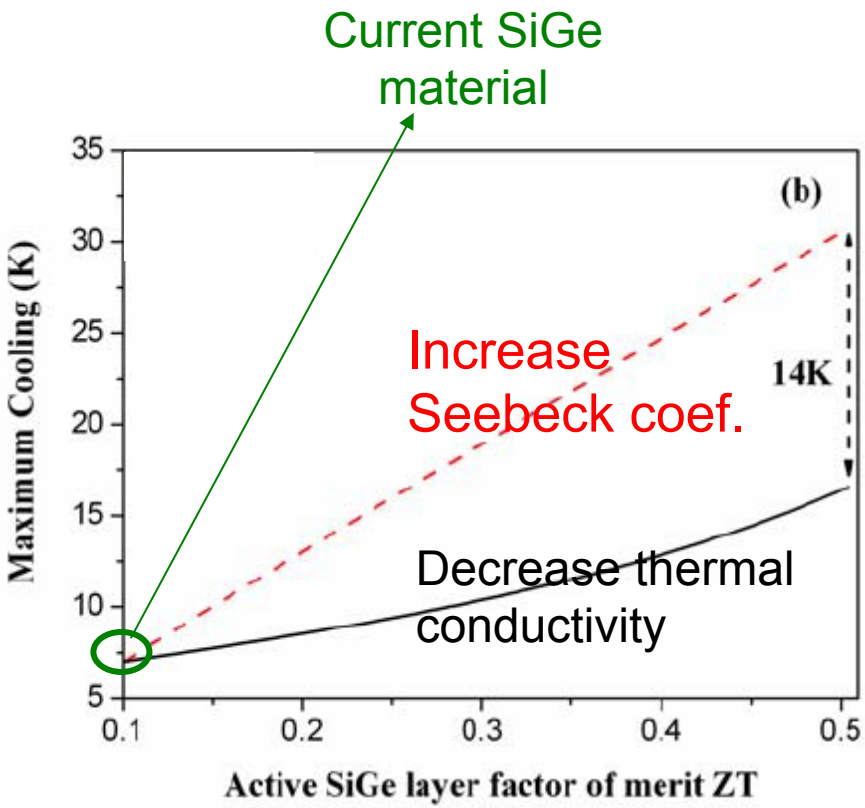
Thermal conductivity of SL reduced by 5

Seebeck coefficient of SL increased by $\sqrt{5}$

Fukutani and Shakouri (InterPACK 2006)

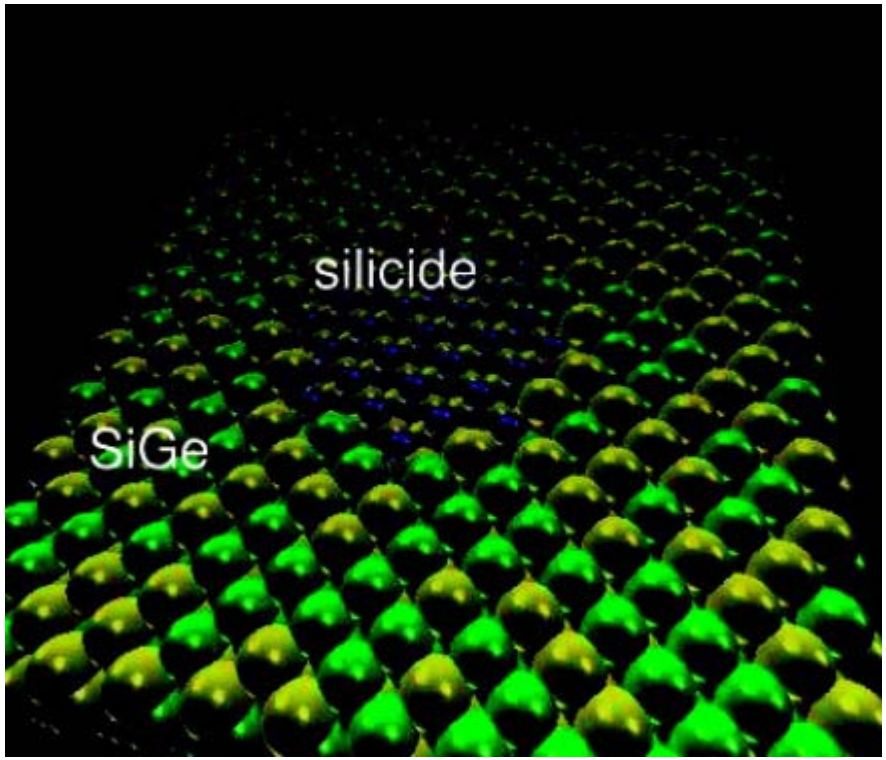
Thin Film Microrefrigerator Optimization

- 10 microns thick, 50x50μm^2 monolithic microrefrigerator with ZT~0.5 can cool a 1000W/cm^2 hot spot by >15C.

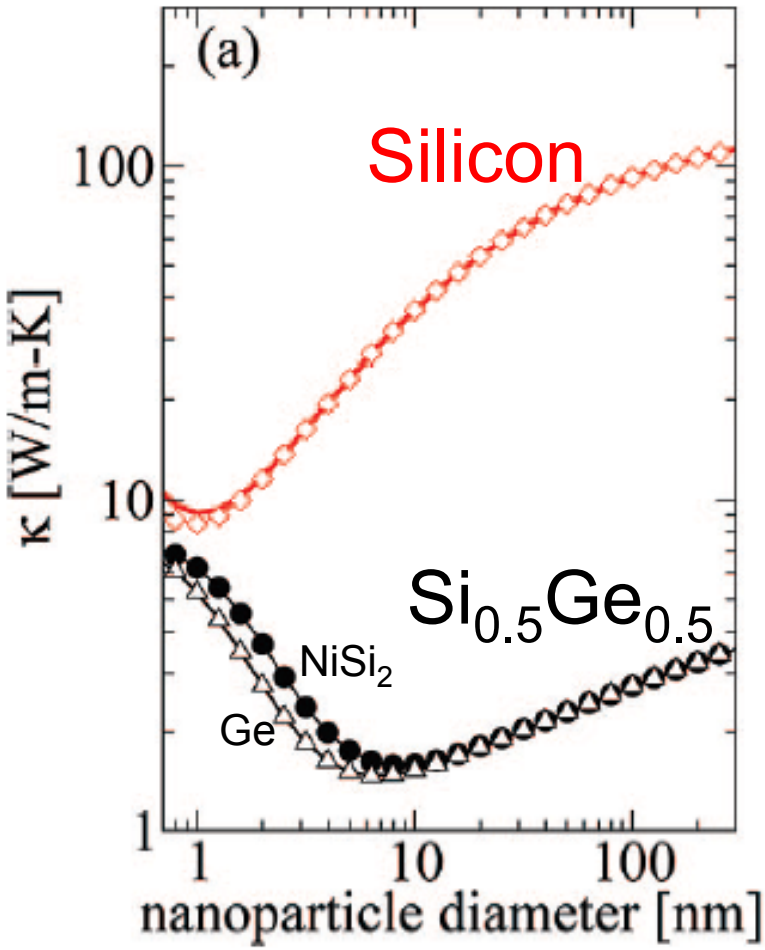


Younes Ezzahri et al. InterPACK07

Silicide nanoparticles in SiGe



300K
0.8% nanoparticles



Predictions:

ZT (300K) ~0.5

ZT (900K) ~1.8

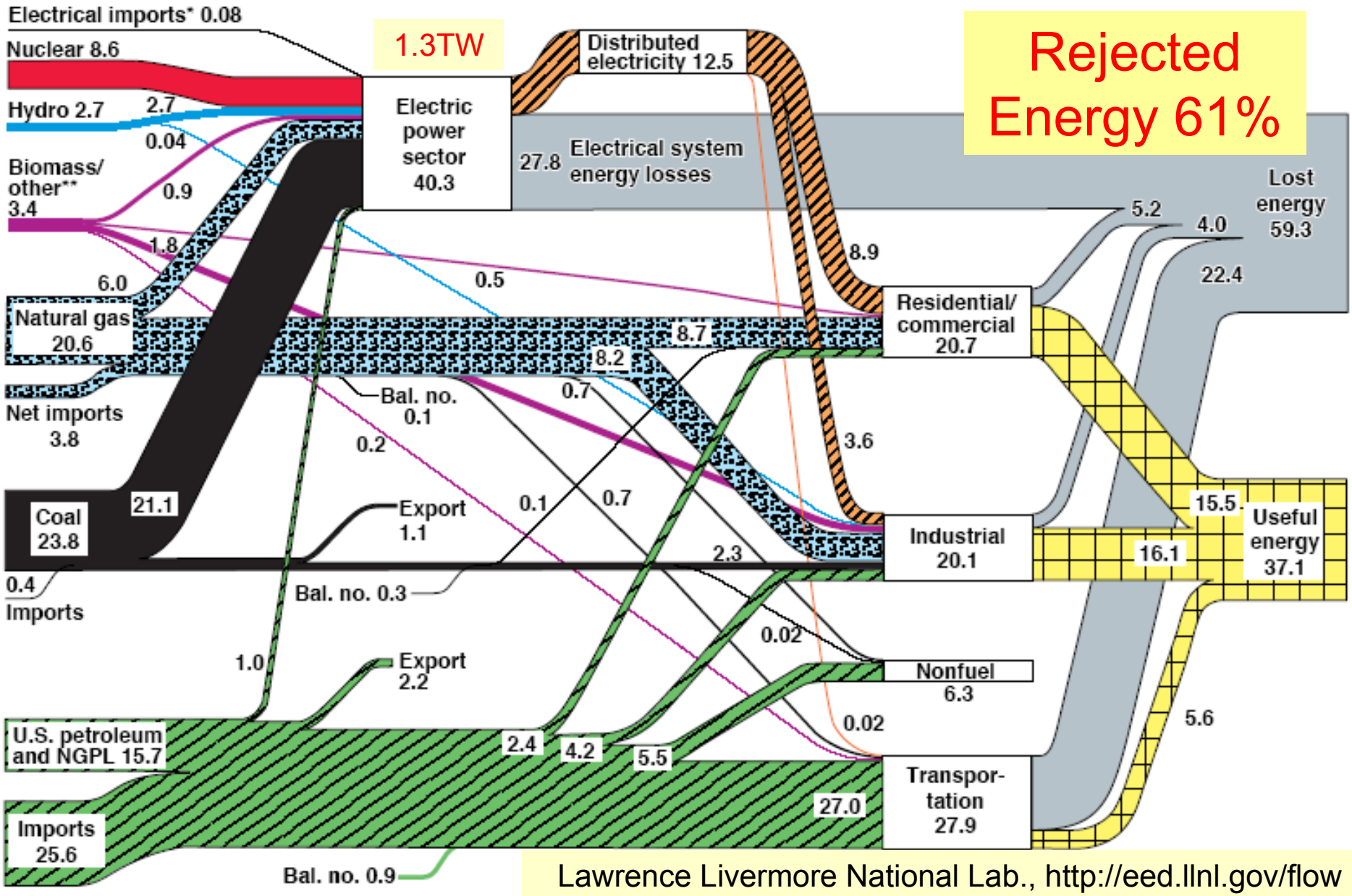
Natalio Mingo et al. Nano Letters 2009

U.S. Energy Flow Trends – 2002
Net Primary Resource Consumption ~103 Exajoules

Power ~3.3TW

UC SANTA CRUZ

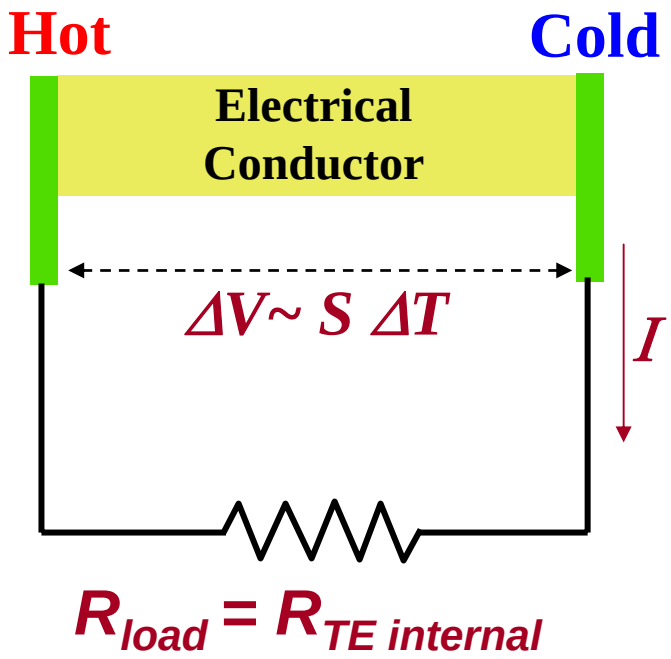
A. Shakouri 2/13/2009



Lawrence Livermore National Lab., http://eed.llnl.gov/flow

Direct Conversion of Heat into Electricity

Seebeck coefficient (1821) $S = \frac{\Delta V}{\Delta T}$

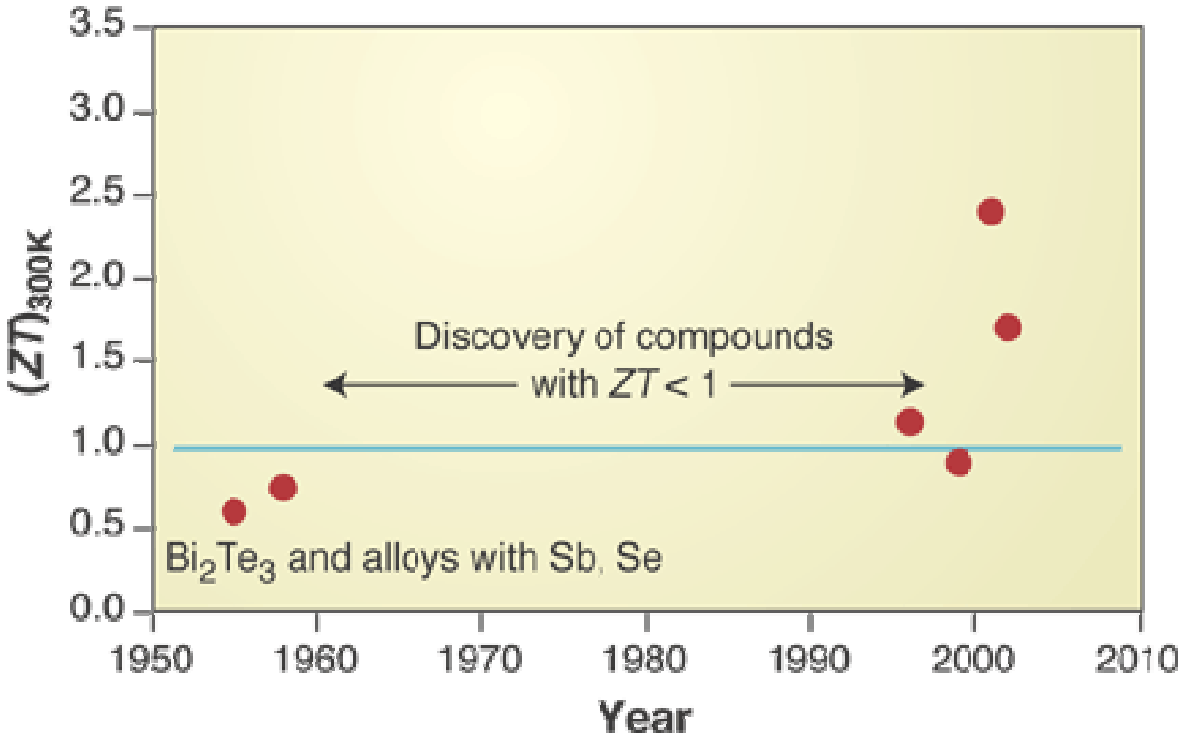


Efficiency function of thermoelectric figure-of-merit (Z)

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

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

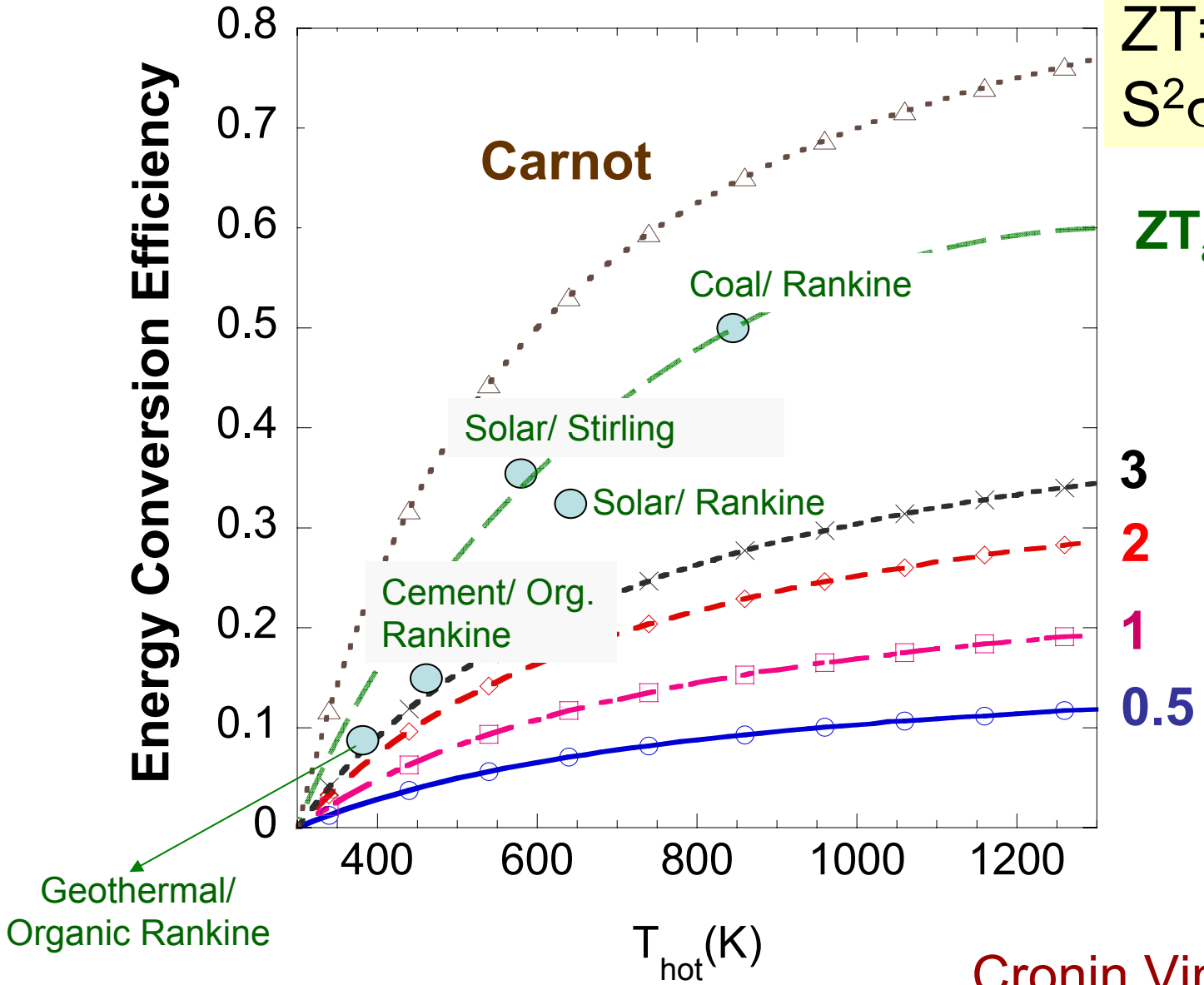
Recent Advances in Thermoelectrics



- Recent advances in <u>nanostructured</u> thermoelectric materials led to a sudden increase in $(ZT)_{300K} > 1$

A. Majumdar, *Science* 303, 777 (2004)

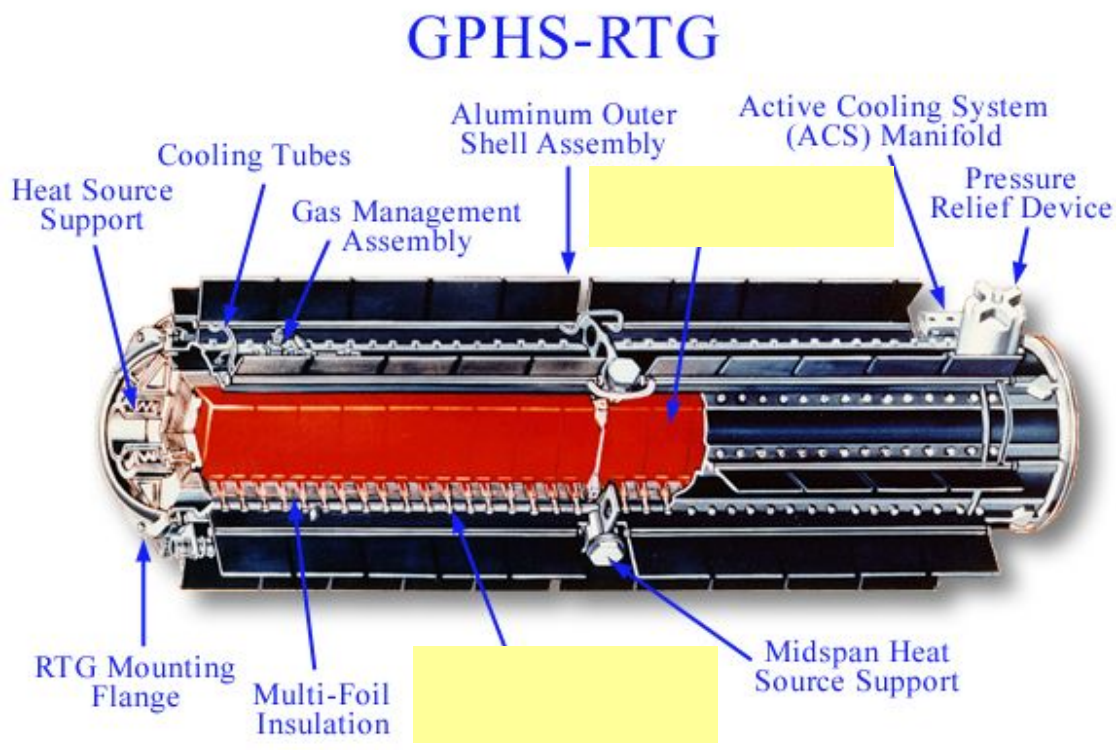
Power Generation Efficiencies of Different Technologies

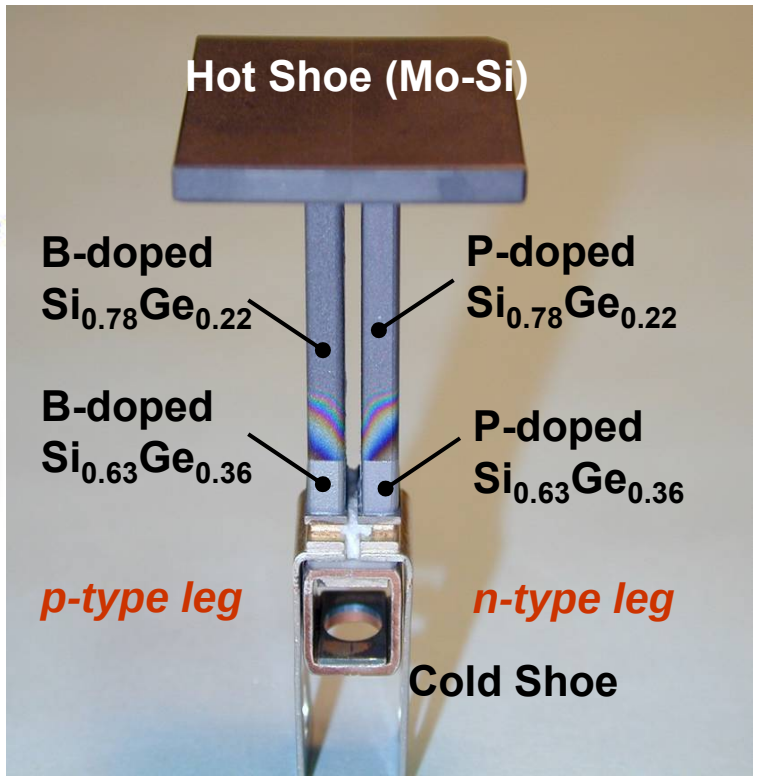


Cronin Vining

Radioisotope Thermoelectric Generators (Voyager, Galileo, Cassini, …)

- 55 kg, 300 W_e, 'only' 7 % conversion efficiency
- But > 1,000,000,000,000 device hours without a single failure



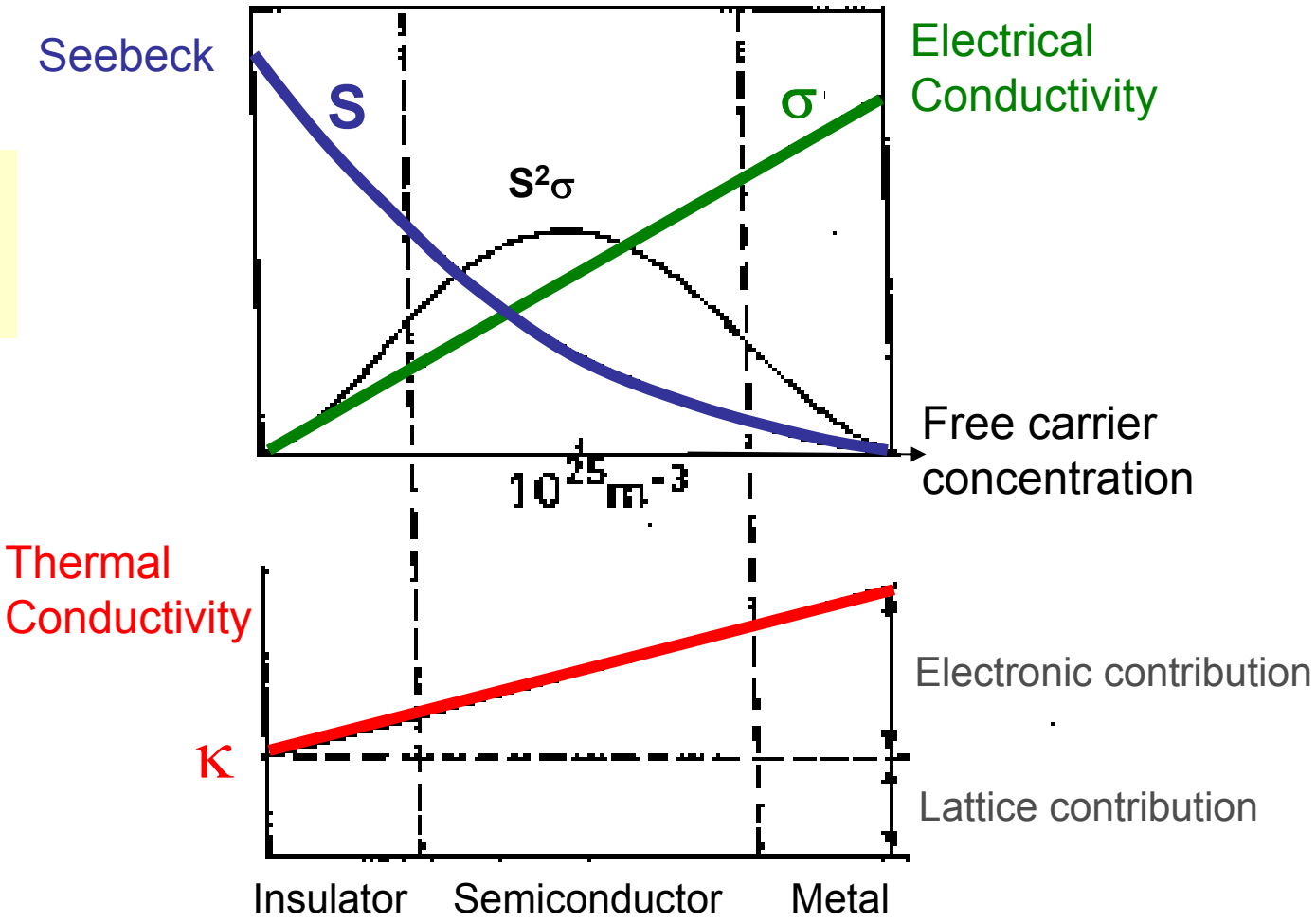


SiGe unicouple

Cronin Vining, ZT Services

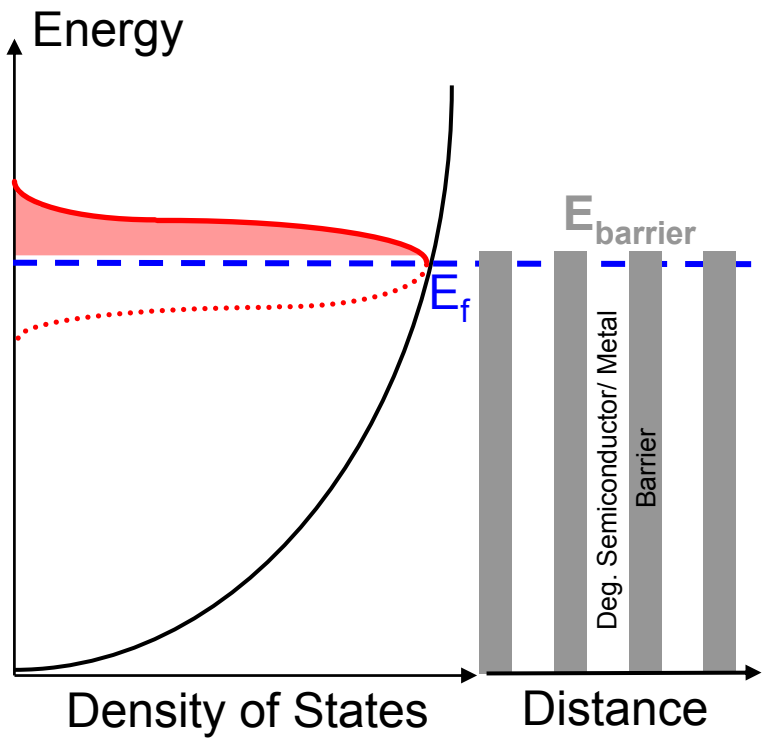
Best Thermoelectric Materials

$ZT = S^2\sigma T/\kappa$



For almost all materials, if doping is increased, electrical conductivity increases but Seebeck coefficient is reduced. Similarly $\sigma \leftrightarrow \kappa$

Solid-State Thermionics



Deg. Semiconductor/Metal
+ Energy Filter (barriers)

Go beyond the "energy band" trade offs in bulk semiconductors.

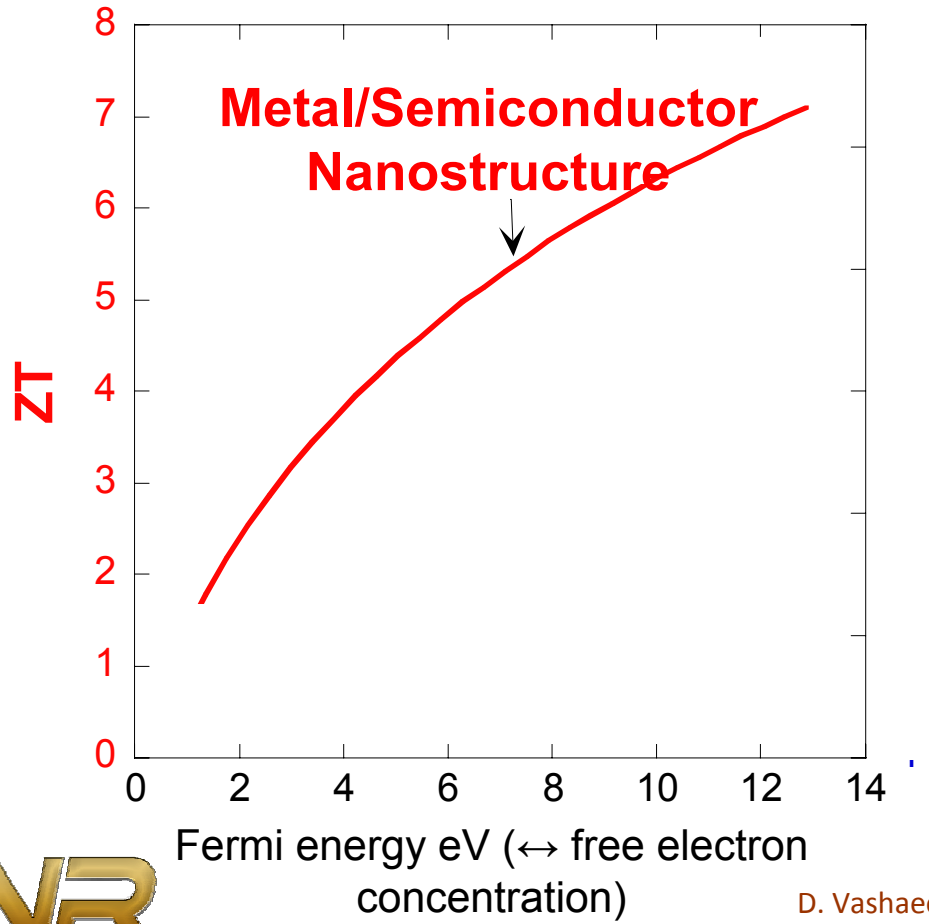
A. Shakouri, "Thermoelectric, thermionic and thermophotovoltaic energy conversion", ICT 2005

Optimize TE Efficiency: (Metal/Semiconductor Nanocomposites)

UC SANTA CRUZ
A. Shakouri 3/24/2009

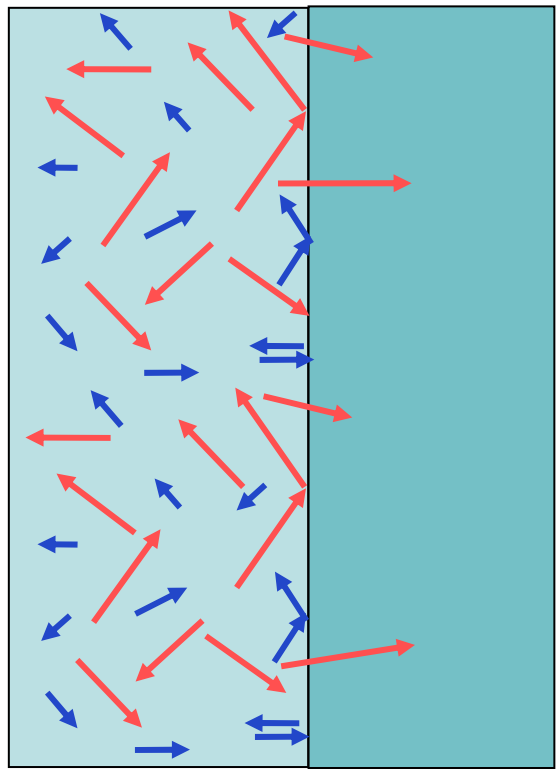
Even with only modestly low lattice thermal conductivity and electron mobility of typical metals, ZT > 5 is possible with hot electron filters

Assume: $\kappa_{lattice}$=1W/mK, mobility ~10 cm^2/Vs



Hot and cold electrons in equilibrium

Hot electron filter



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

Thermionic Energy Conversion Center

Ali Shakouri, Director

UC SANTA CRUZ

A. Shakouri 3/24/2009

MATERIALS

Sands/Ramdas	Zide	Gossard	Kobayashi
Purdue	Delaware	UC Santa Barbara	UC Santa Cruz
Sputtering /Bulk ZrN/HfN /Er_III-V	MBE Non-Er III-V	MBE p-Er_III-V	MOCVD Er_III-V

CHARACTERIZATION / MODELING

Majumdar	Ram	Shakouri (PI)	Bian
UC Berkeley	MIT	UC Santa Cruz	UC Santa Cruz
Thermal Charact./Modeling	Thermal Imaging, Z-meter	Overall organization TE measurements	Transport Theory ZT Characterization

DEVICES/ SYSTEMS

Bowers	Bell
UC Santa Barbara	BSST
TE elements and devices	Modules, Modeling Technology Transition

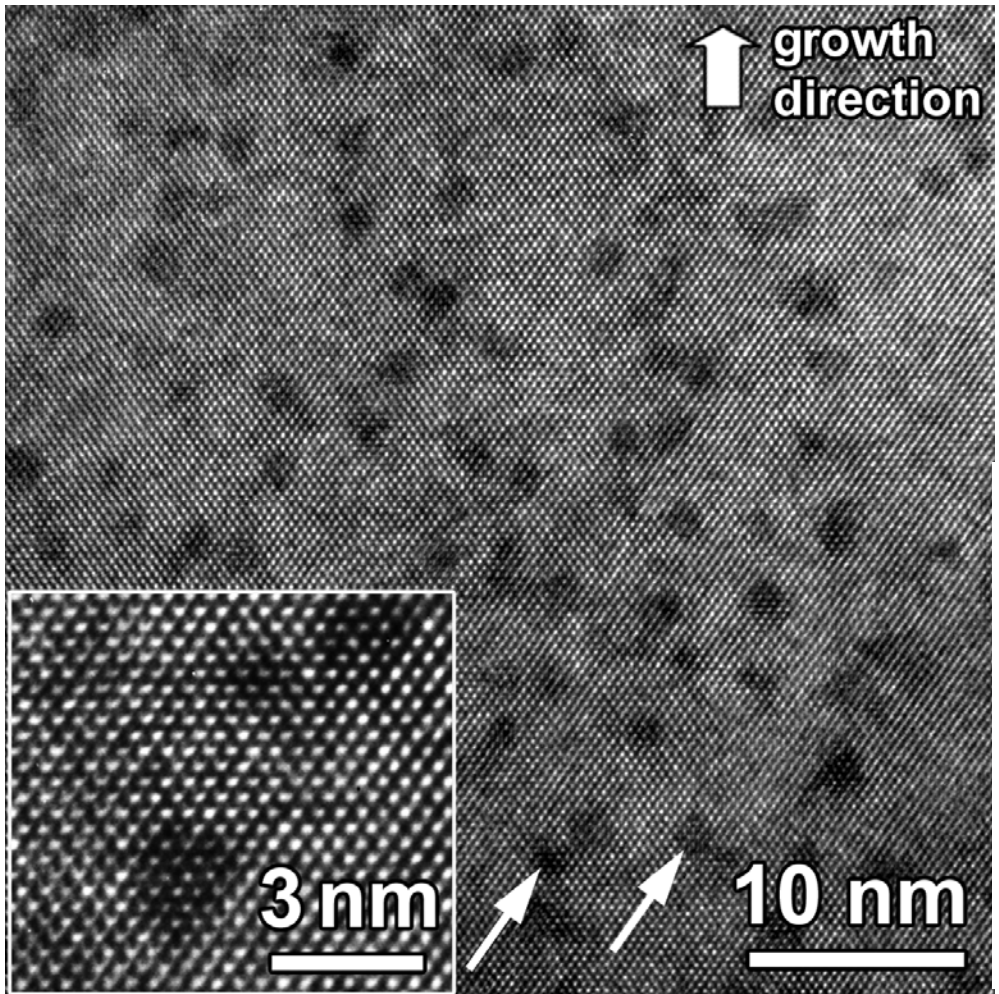
ONR Revolutionary Research . . . Relevant Results

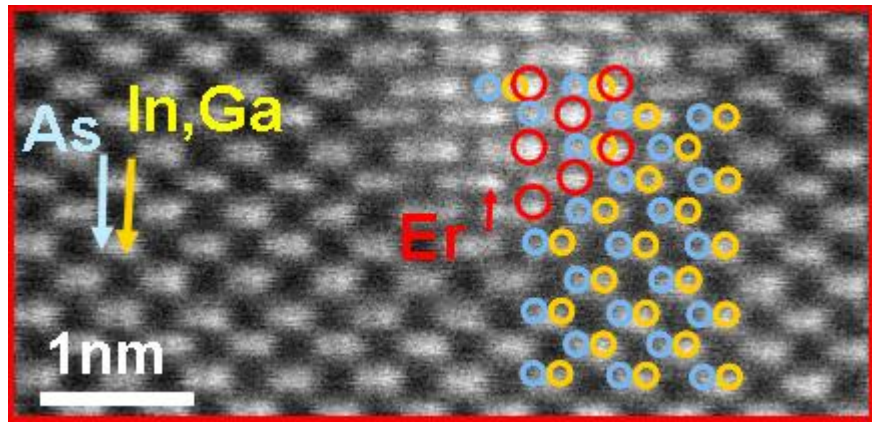
DARPA DSO DEFENSE SCIENCES OFFICE

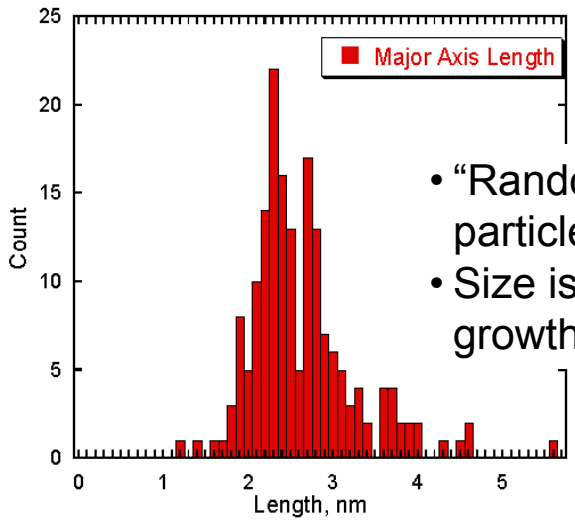
ErAs Semi-metal Nanoparticles imbedded in InGaAs Semiconductor Matrix

UC SANTA CRUZ
A. Shakouri 3/24/2009

- Molecular Beam Epitaxy (MBE) provides atomic layer control
- ErAs dots are lattice-matched and incorporate without any visible defects in InGaAs despite different crystal structures (Cubic vs. Zinc-blende)







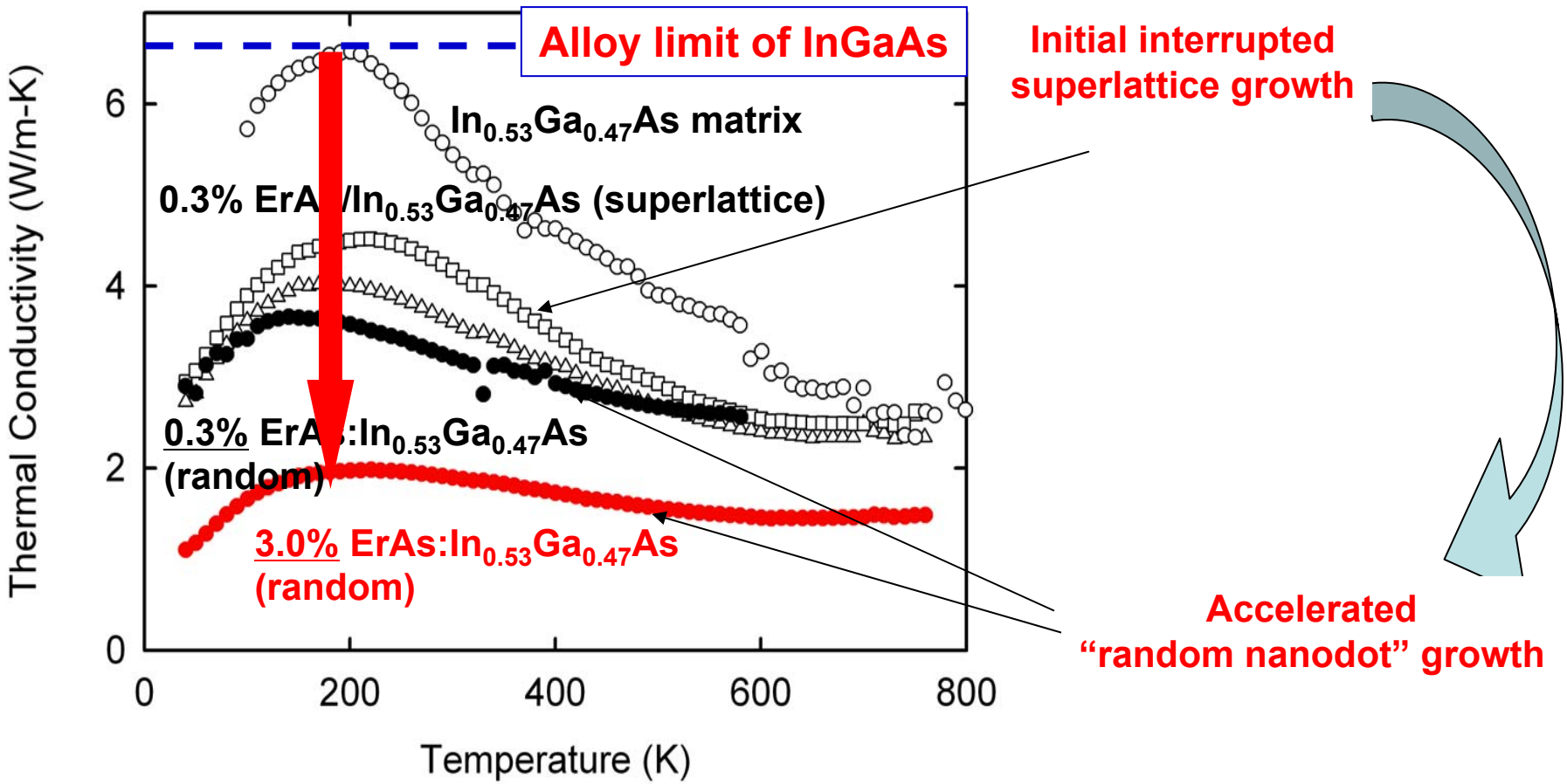
- "Random" ErAs particles ~ 2-3 nm
- Size is invariant to growth conditions

Beating the Alloy Limit in Thermal Conductivity
Ordered and Random ErAs:$In_{0.53}Ga_{0.47}As$

UC SANTA CRUZ
A. Shakouri 3/24/2009

Phonon scattering by ErAs nanoparticles

➡ **3-fold reduction in thermal conductivity *beyond* the alloy limit**



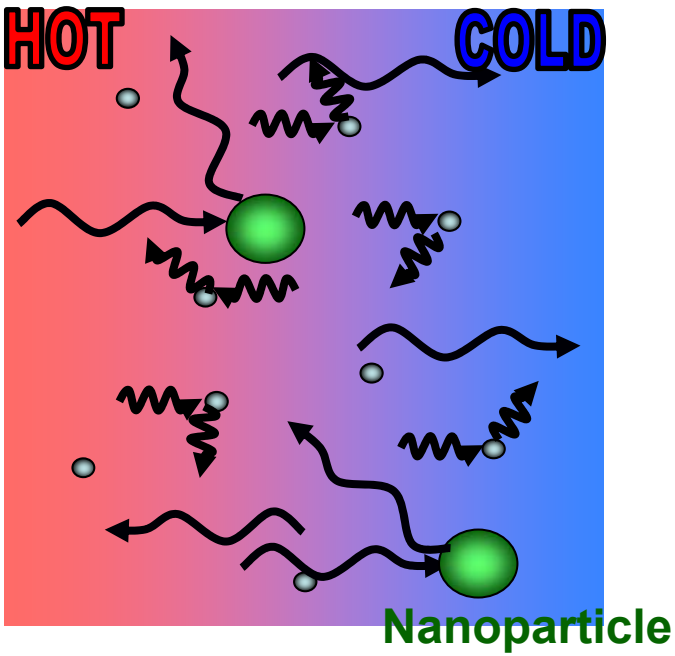
From superlattice to "random" nanoparticle distribution

➤Faster deposition rates enable record thick MBE grown films – up to **60μm**

Two Beneficial Effects of Metal Nanoparticles on Thermoelectric Performance

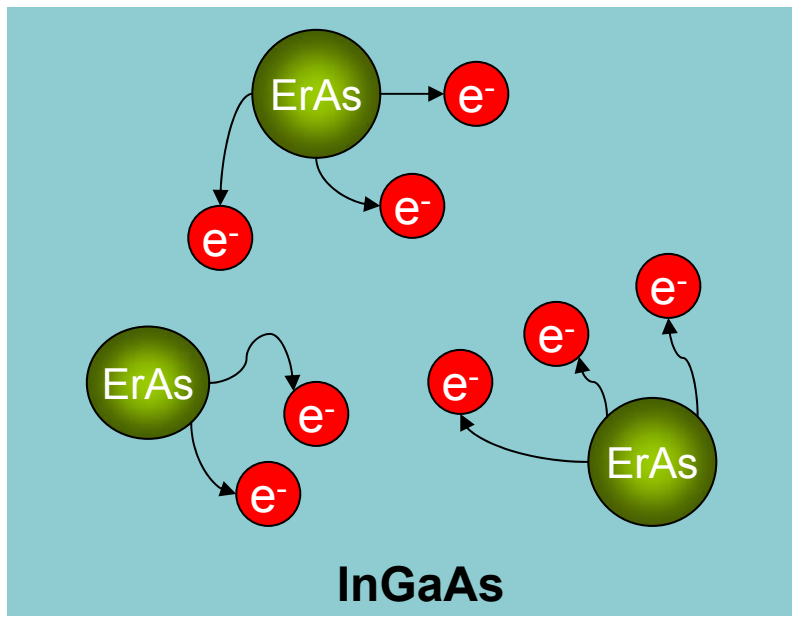
Metal nanoparticles ***scatter phonons***
➡ reduced thermal conductivity

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

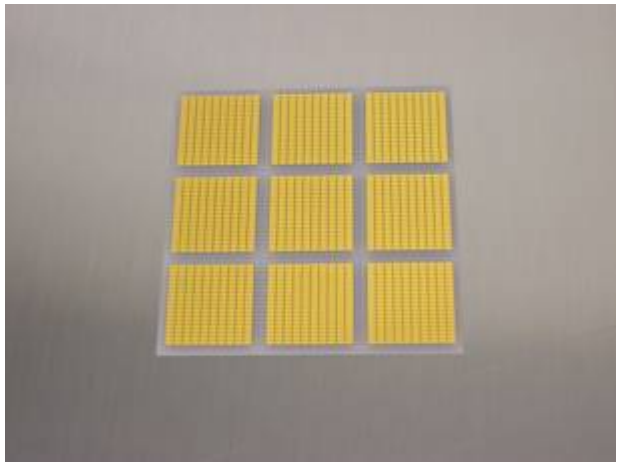


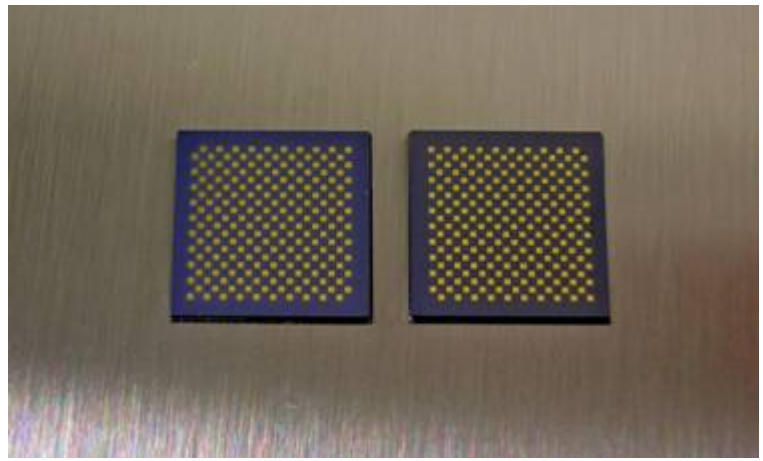
Metal nanoparticles ***donate electrons***
➡ enhanced electrical conductivity
➡ increased electron mobility in the matrix

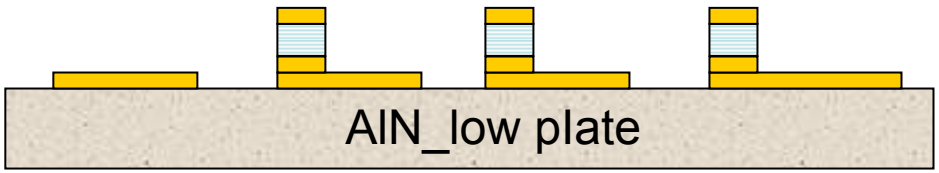
$$Z = \frac{(\text{Seebeck})^2(\textit{electrical conductivity})}{(\text{thermal conductivity})}$$



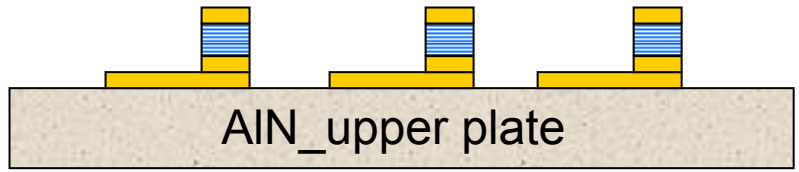
Wafer scale module fabrication





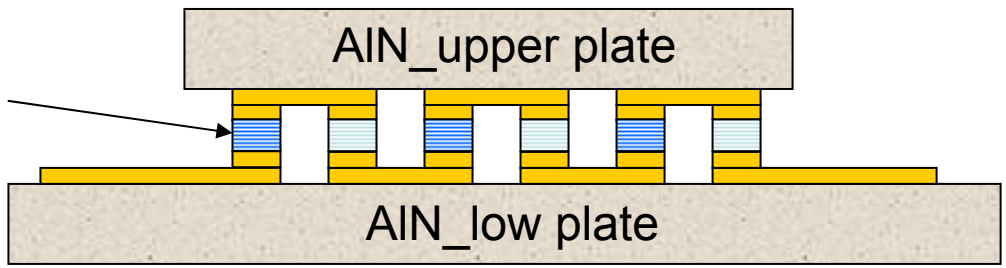


200 elements of p-ErAs array



200 elements of n-ErAs array

20 μm elements

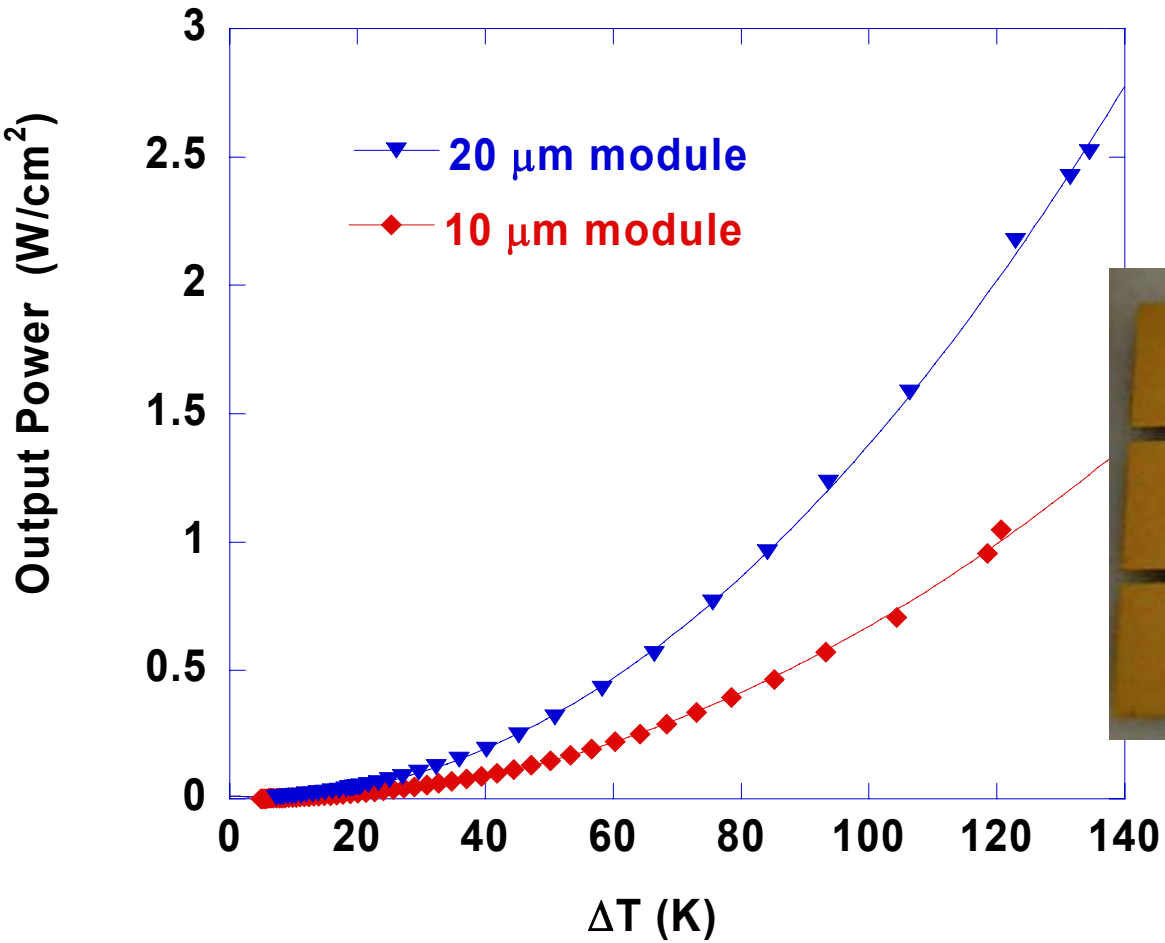


400 element generator

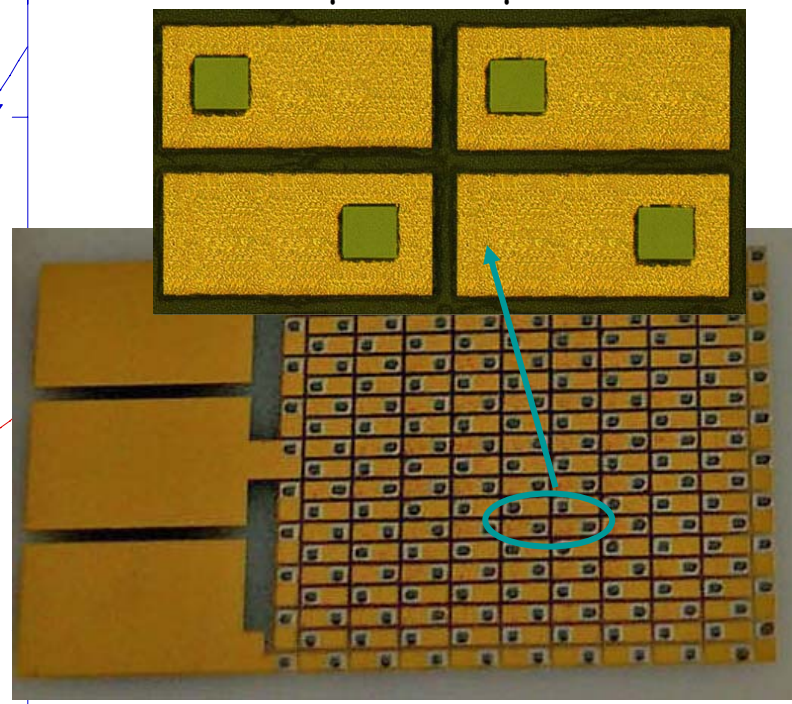
Gehong Zeng, John Bowers (UCSB)

Module Power generation results

400 elements (10-20 microns ErAs:InGaAlAs thin films, 120x120μm^2), array size 6x6 mm^2



140 μm/140 μm AlN

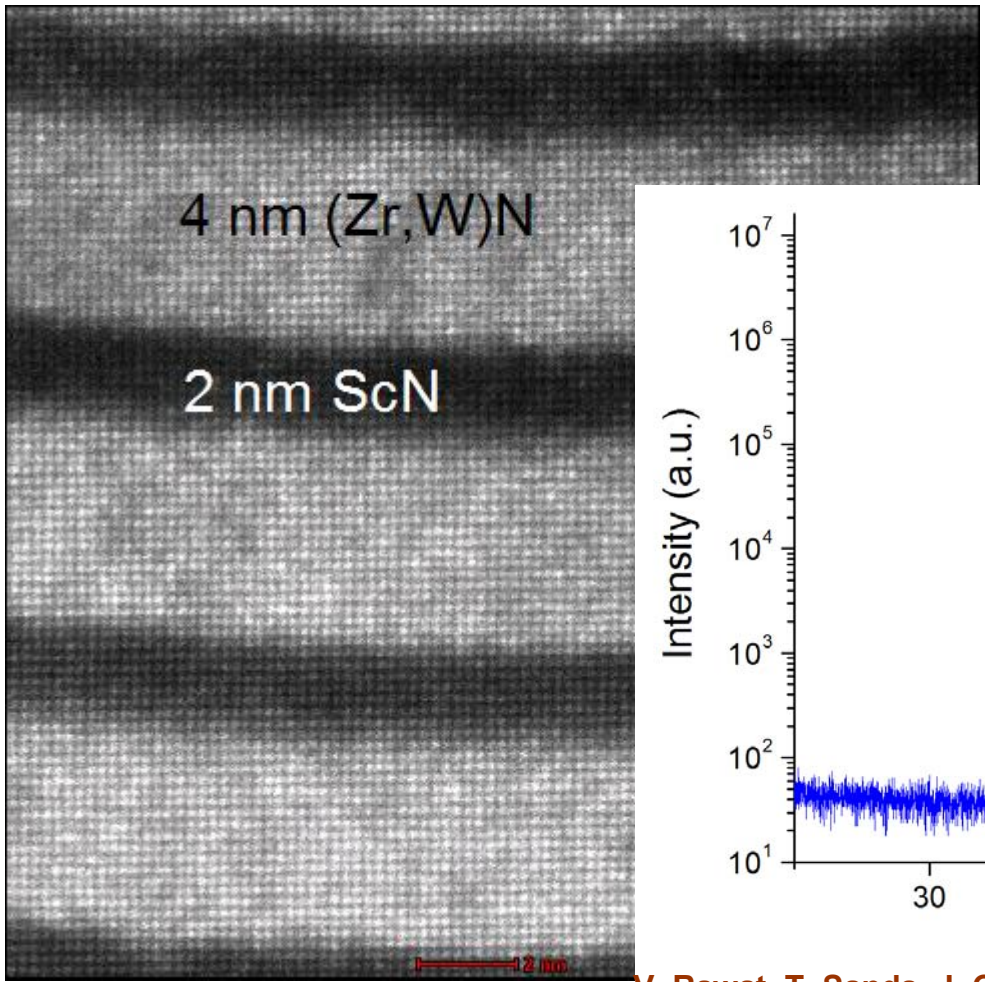


G. Zeng, J. Bowers, et al. (UCSB, UCSC) Appl. Physics Letters 2006

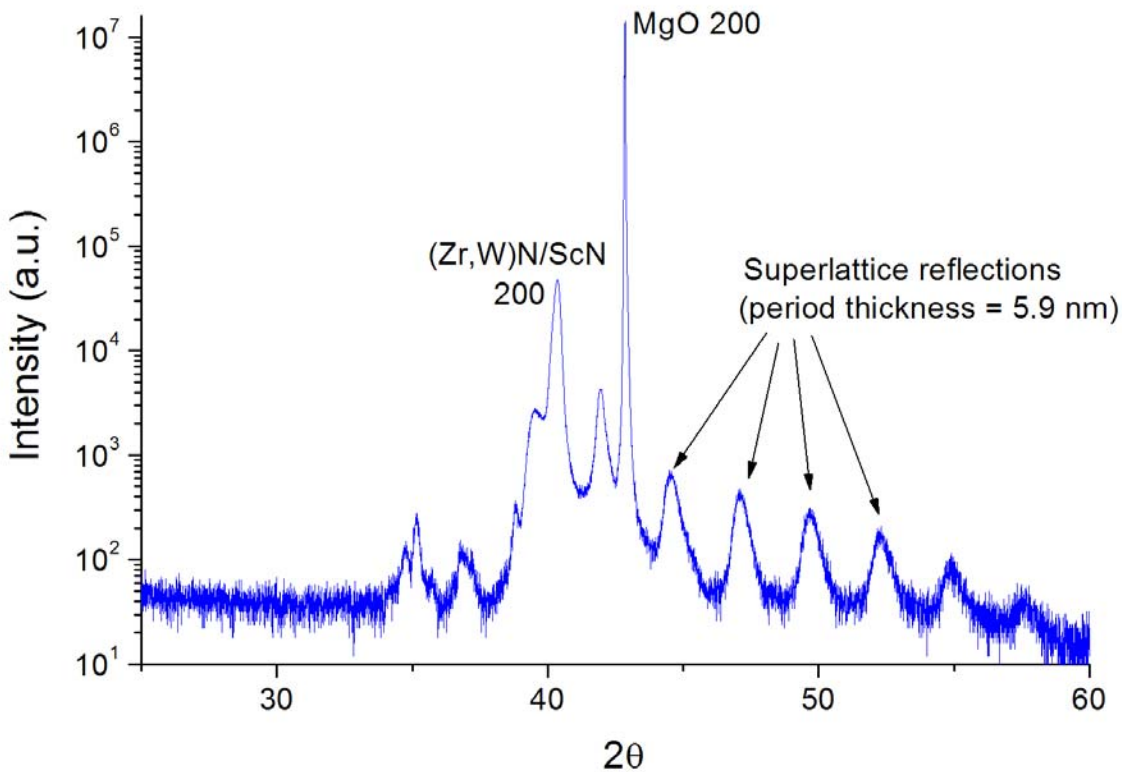
Working with BSST on high power density module demonstration

Refractory (Zr,W)N/ScN Metal/Semiconductor Superlattices for Higher Temperature Operation

- ZrN layers alloyed with W_2N
  - Reduction in thermal conductivity
  - Closer lattice match with ScN layer



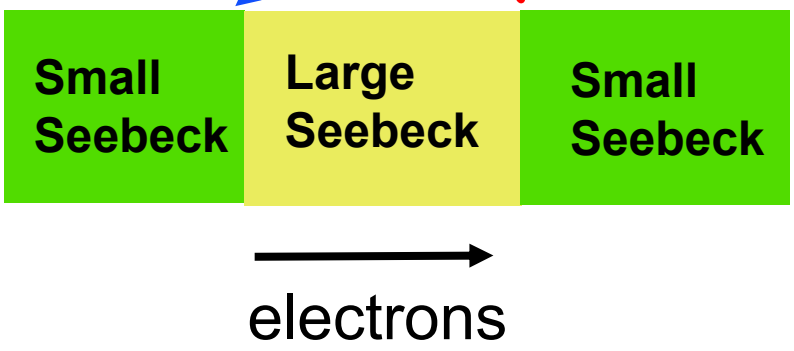
HAADF/STEM image of (Zr,W)N/ScN superlattice Courtesy: Joel Cagnon and Susanne Stemmer, UCSB

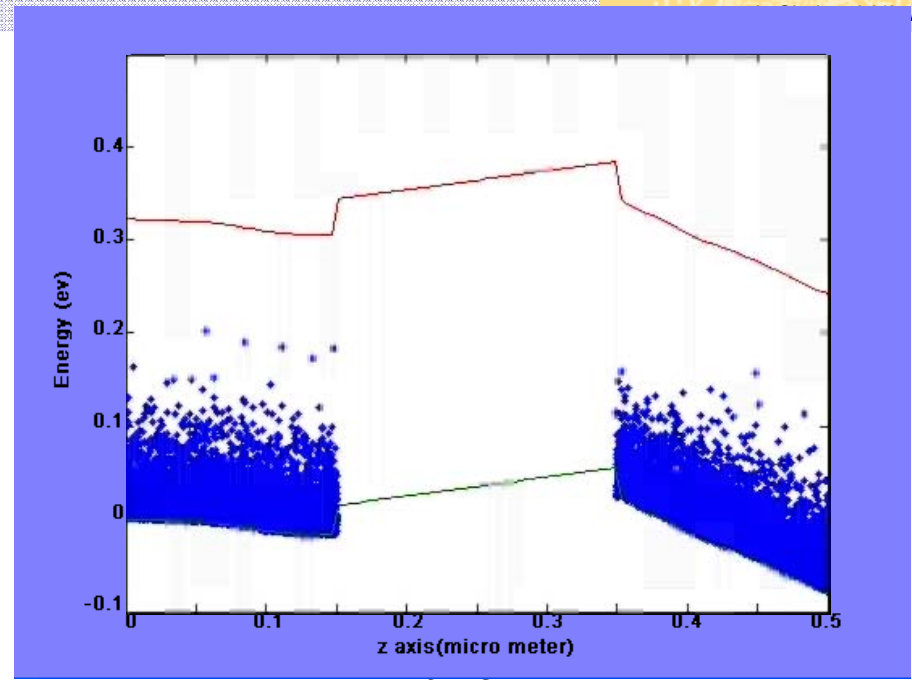


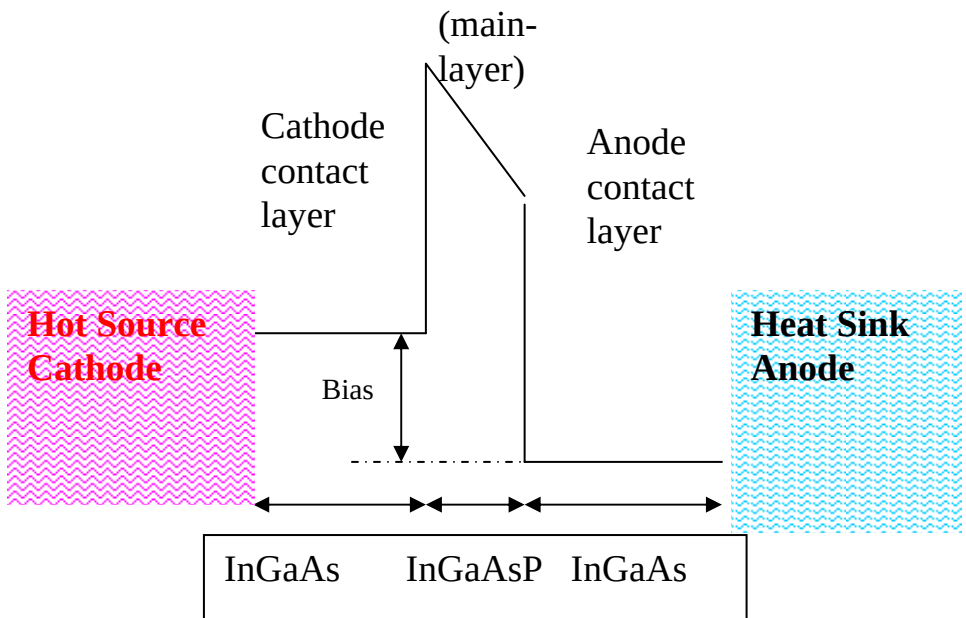
V. Rawat, T. Sands, J. Cagnon, S. Stemmer et al. 2008

Monte Carlo simulation of TE energy exchange

$Q = -\Delta S.T_c.I$ $Q = \Delta S.T_h.I$

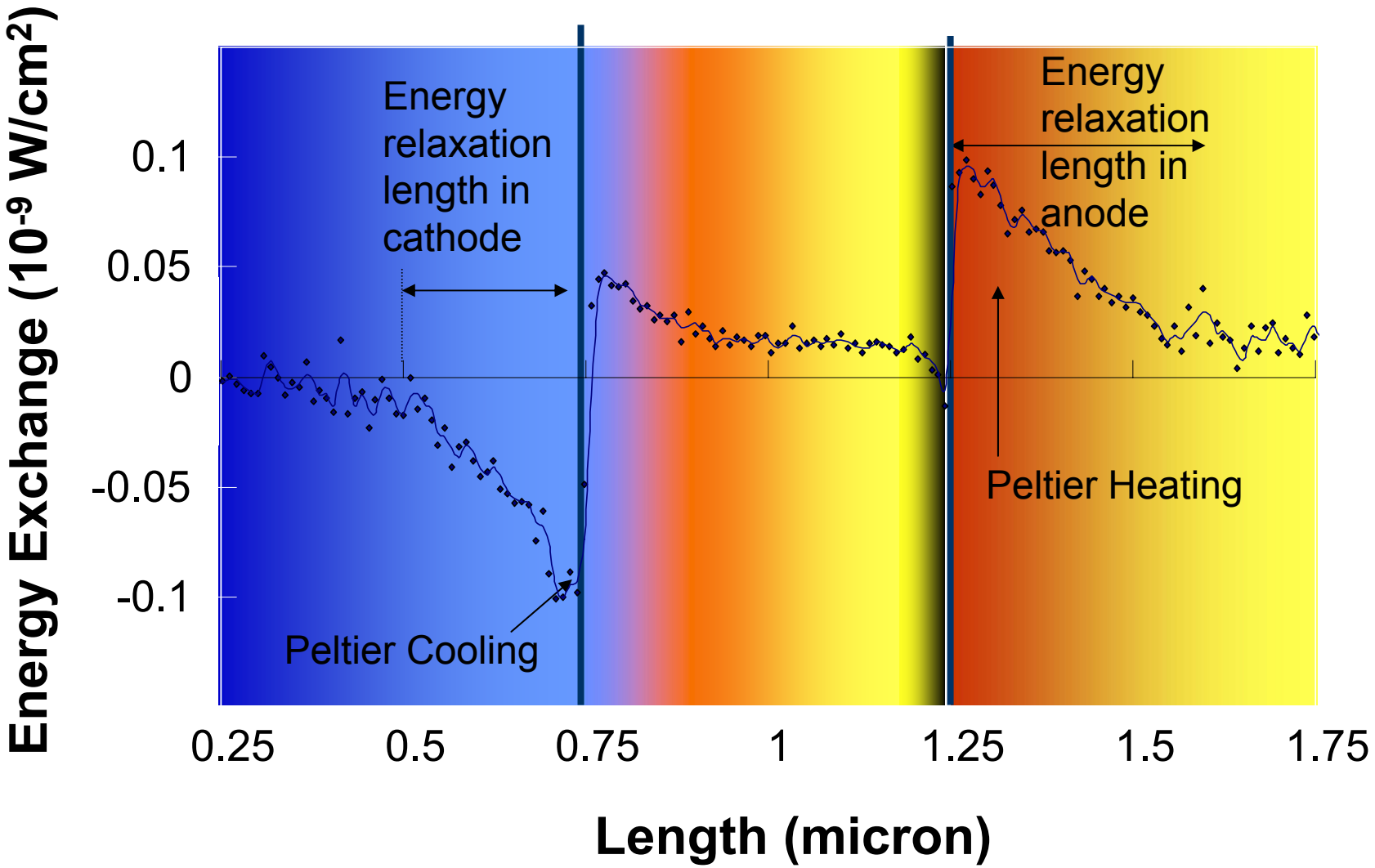






Mona Zebarjadi, Keivan Esfarjani, Ali Shakouri (Phys. Rev. B 2006)

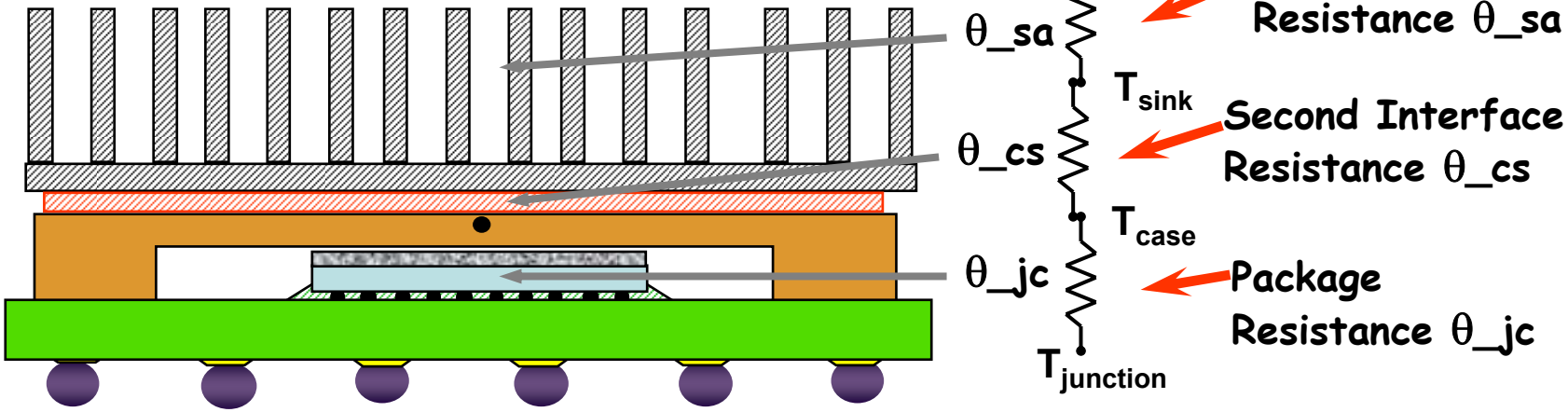
Electron-lattice energy exchange

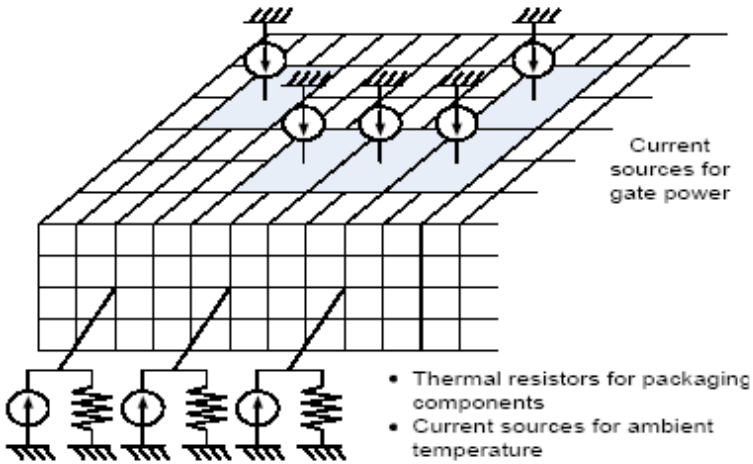


M. Zebarjadi, A. Shakouri and K. Esfarjani, Phys. Rev. B, Vol 74, 195331 (2006)

IC Chip thermal modeling

Real package

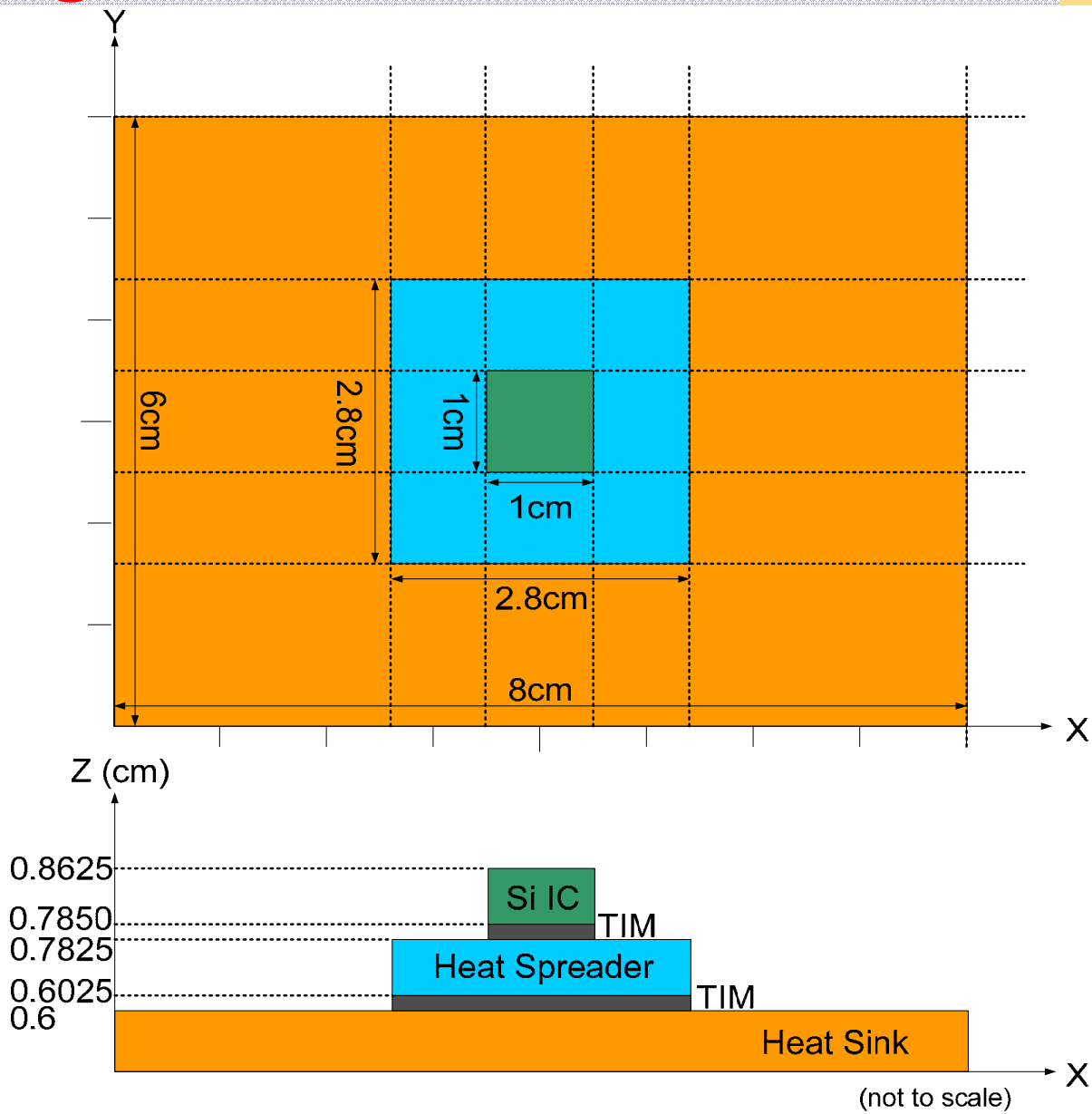




Thermal Resistor Network Model

Yi-Kan Cheng, et al., "Temperature-Driven Cell Placemnt." Electrothermal Analysis of VLSI Systems, 2000. 157-179.

Package Model



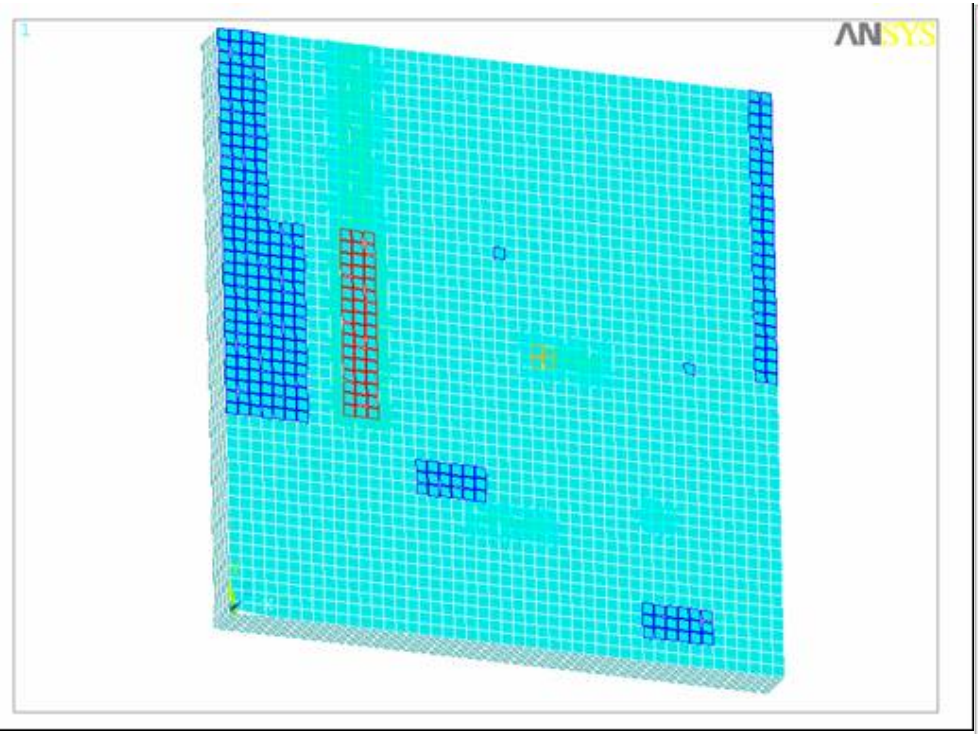
Finite Element Analysis (power map => temperature map)

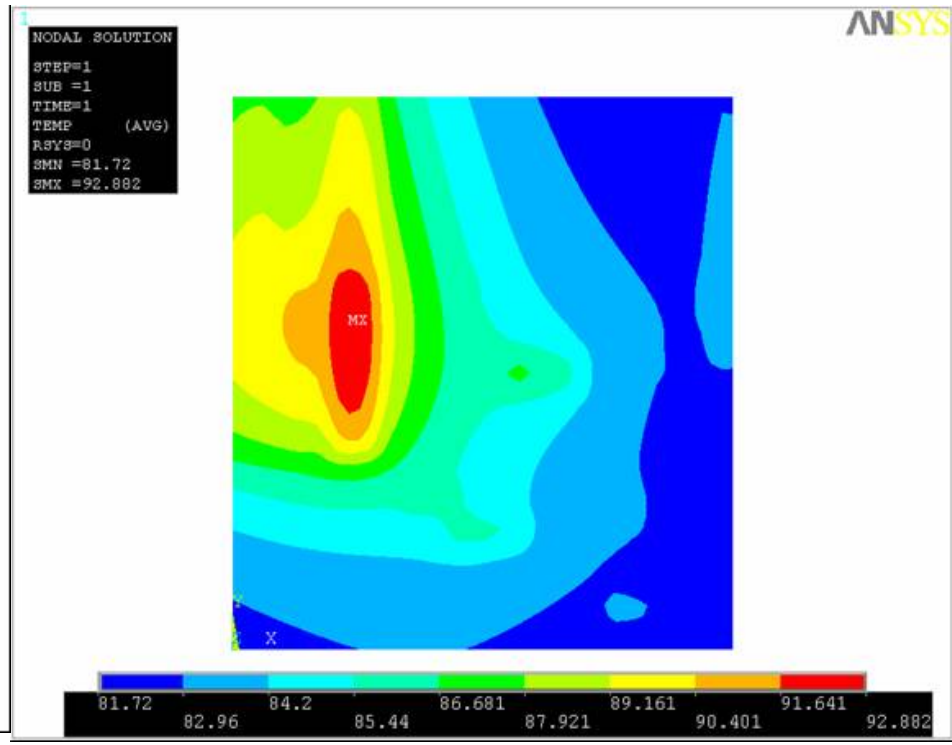
~16 sec

(Pentium 4, 65MB)

ANSYS

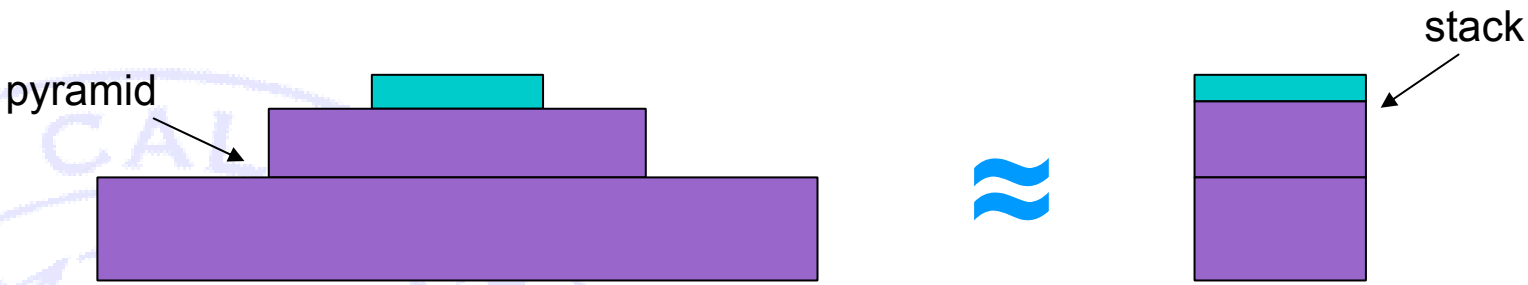
Power Map ⟶ Temperature Map





The road to a fast algorithm

–Analytic methods based on Green's Function



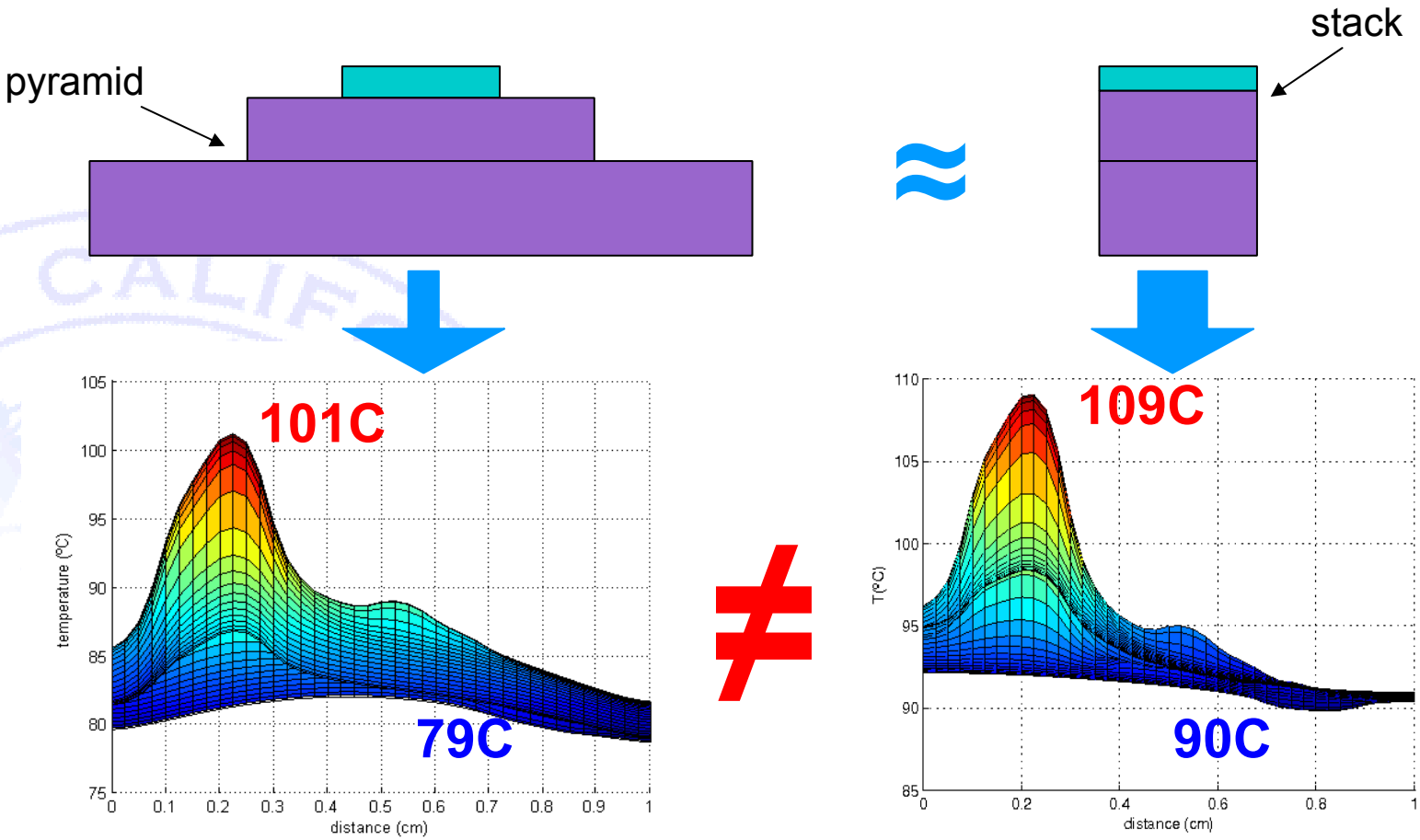
[1] York C. Gerstenmaier, Gerhard K.M. Wachutka, "Efficient Calculation of Transient Temperature Fields Responding to Fast Changing Heat Sources Over Long Duration in Power Electronic Systems" IEEE Trans on Components and Packaging Techn, 27 (1) March 2004

[2] YONG ZHAN and SACHIN S. SAPATNEKAR. A High Efficiency Full-Chip Thermal Simulation Algorithm. Proceedings of the 2005 IEEE/ACM International conference on Computer-aided design.

V. Martin et al. Semitherm 2007

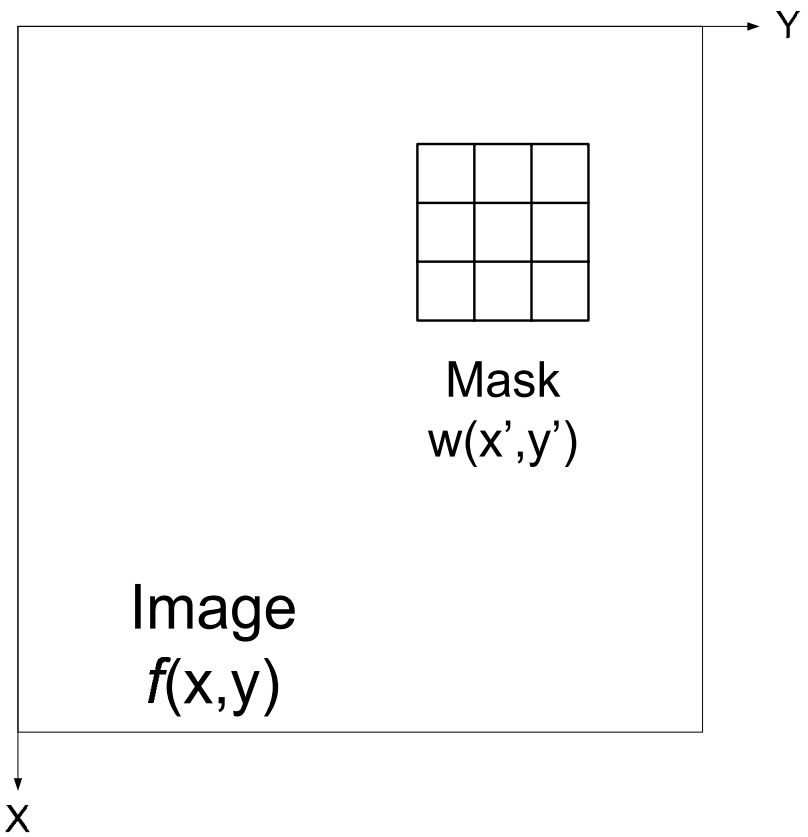
Limitation of simplified geometry

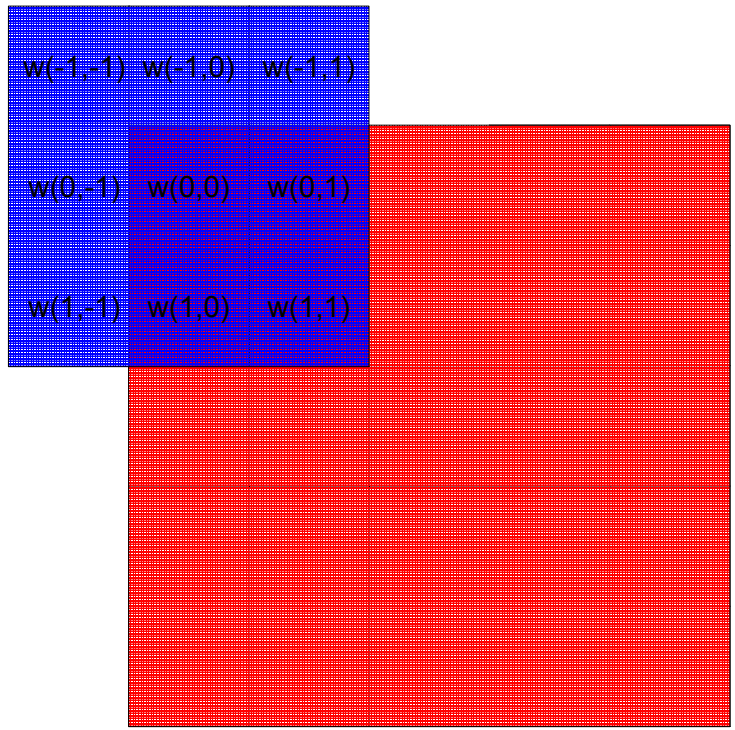
(analytical solution)



V. Martin et al. Semitherm 2007

Use of Image Blurring for full chip temperature calculation





$$\iiint_{V'} G(\vec{r},\vec{r}\,')\,q(x',y',z')\,dv' \qquad g(x,y)=\sum_s\sum_t w(s,t)\,f(x+s,y+t)$$

TRAVIS KEMPER, YAN ZHANG, ZHIXI BIAN and ALI SHAKOURI. Ultrafast Temperature Profile Calculation in IC chips. THERMINIC 2006

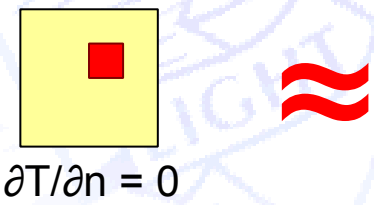
Convolution by Images

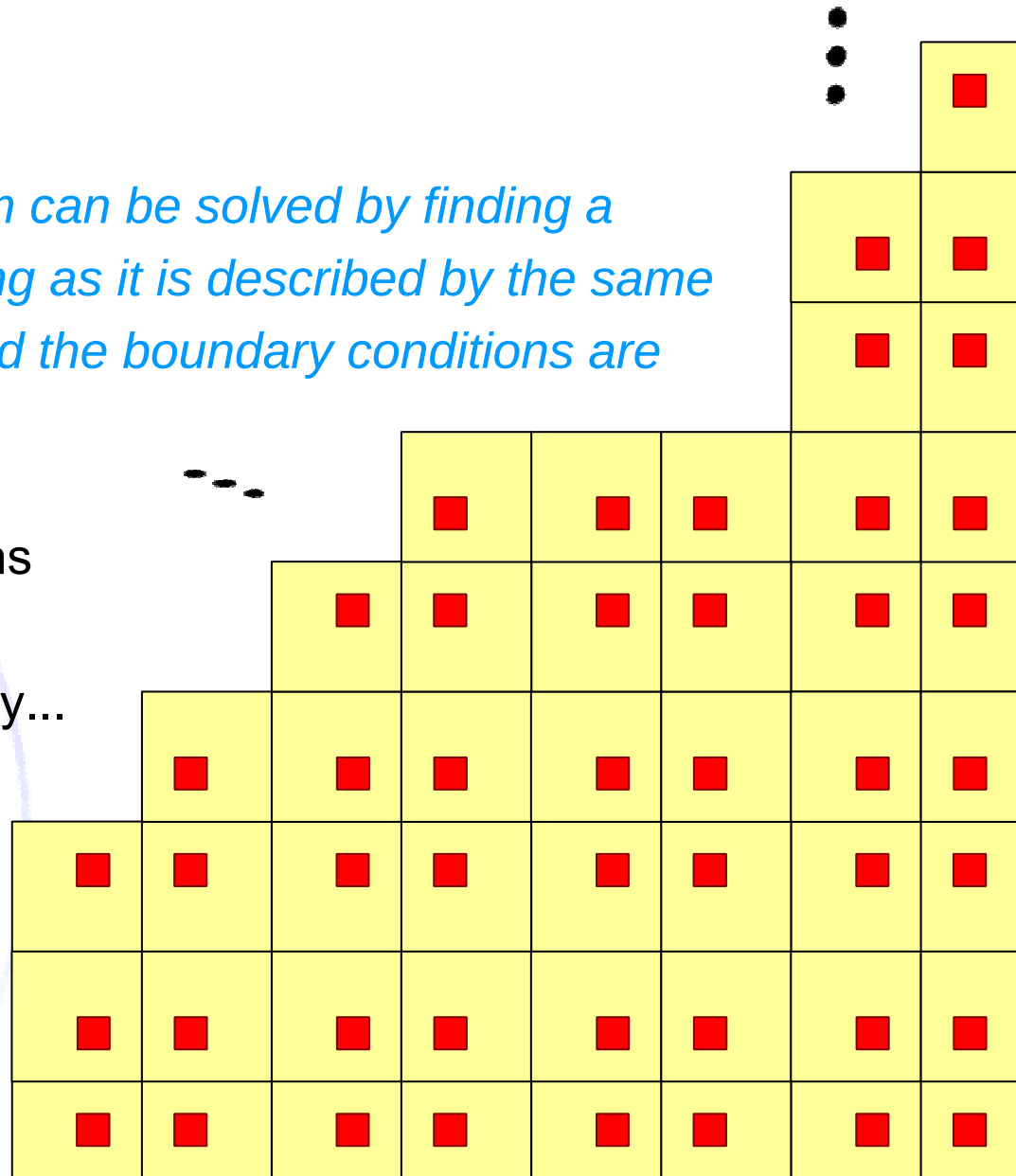
Images (electrostatics):

"A complicated problem can be solved by finding a simpler problem, as long as it is described by the same differential equation and the boundary conditions are equivalent"

Adiabatic Boundary Conditions

Go back to the stack geometry...

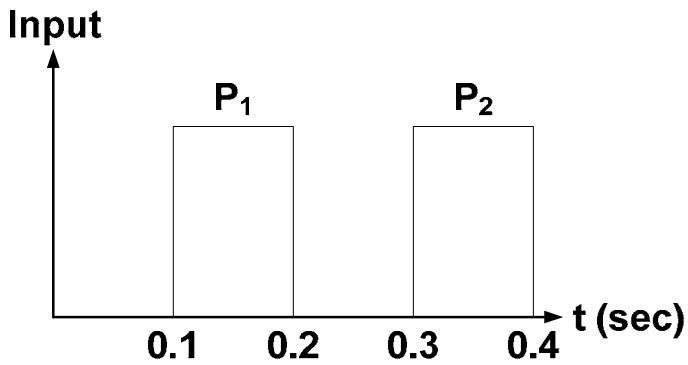


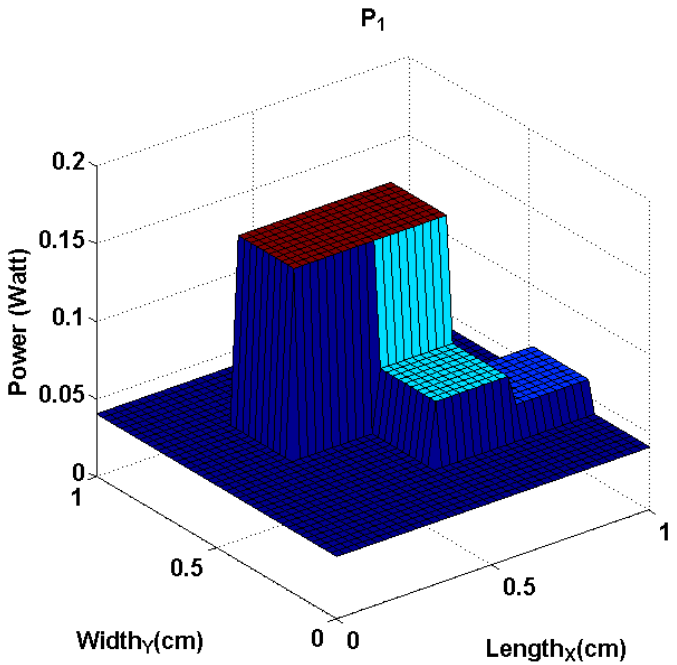


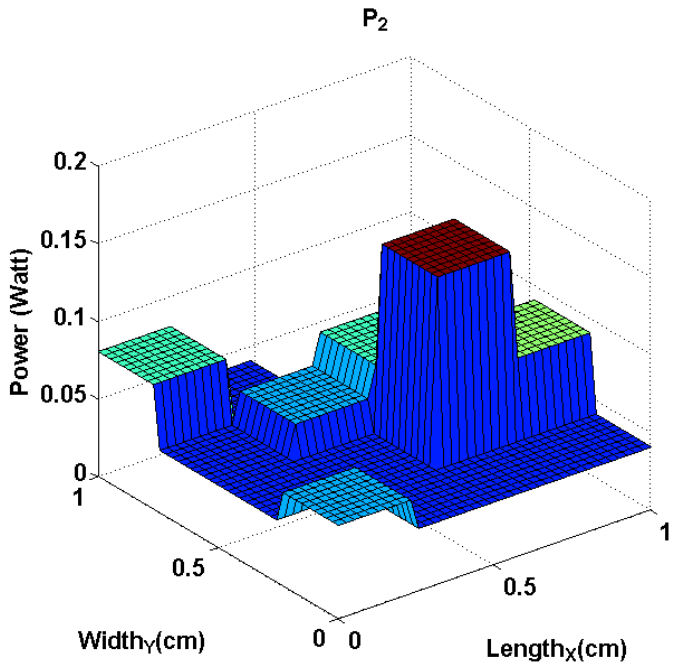
V. Martin et al. Semitherm 2007

Transient Temperature Change in IC

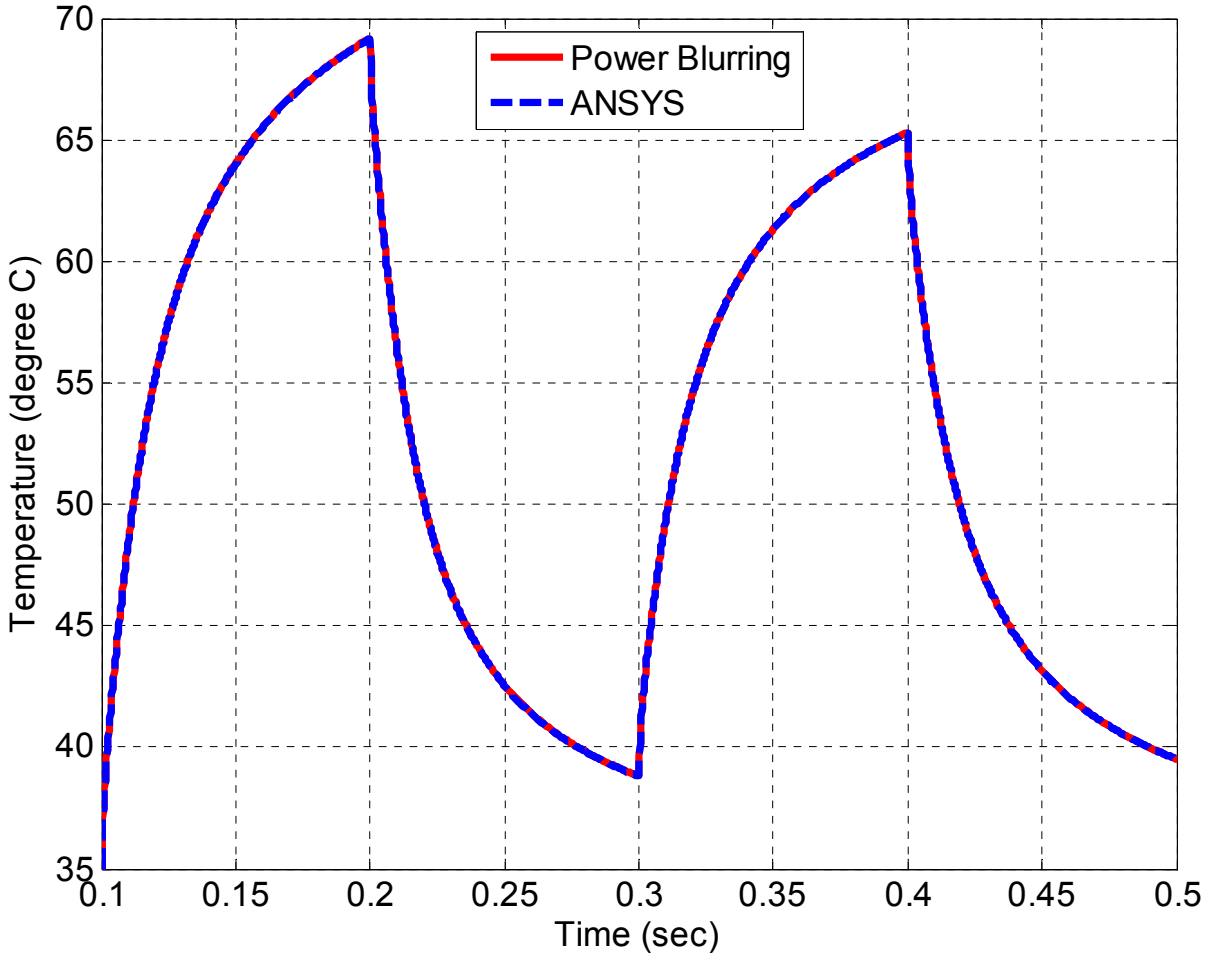
Input Pattern







Transient temperature at the chip center



Computation Time

ANSYS:10056 (sec)

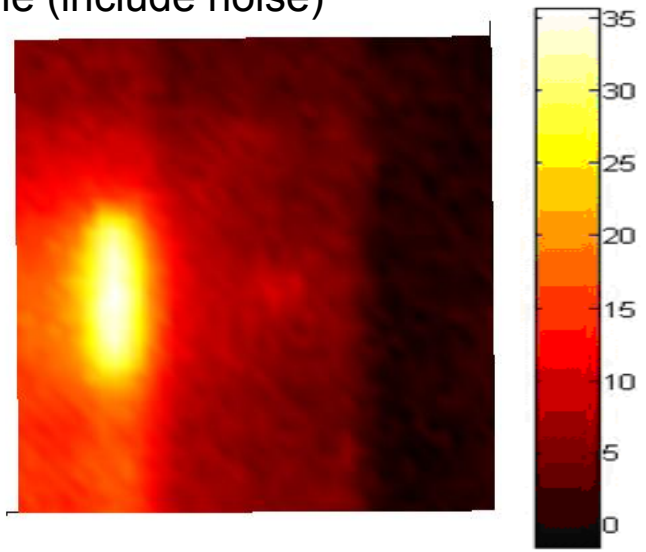
PB: 100 (sec)

Reduction Factor: 101

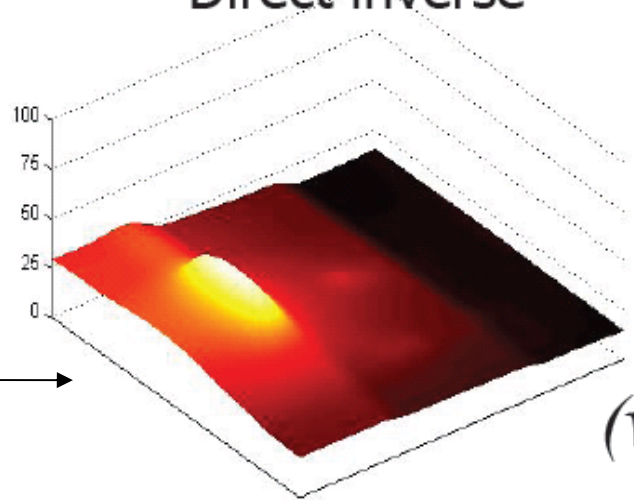
Virginia Martin Heriz, A. Shakouri et al. THERMINIC 2007

Inverse problem (temperature -> power)

Measured temperature profile (include noise)

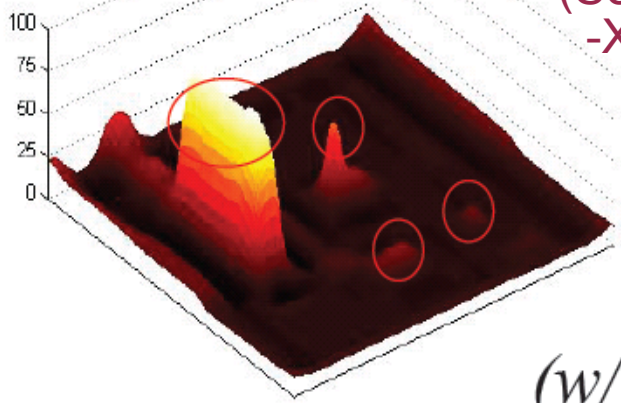


Direct inverse



(w/cm^2)

Power Trace



(w/cm^2)

(Semitherm 2007 -Xi Wang et al.)

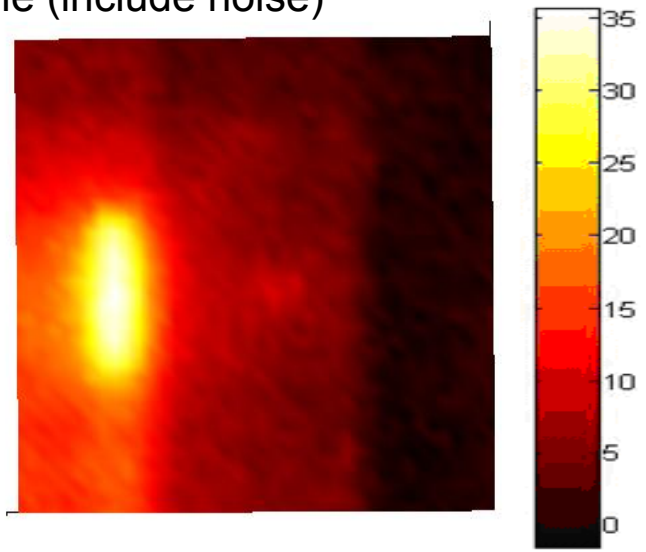
IMAGE DEBLURRING

REGULARIZATION:

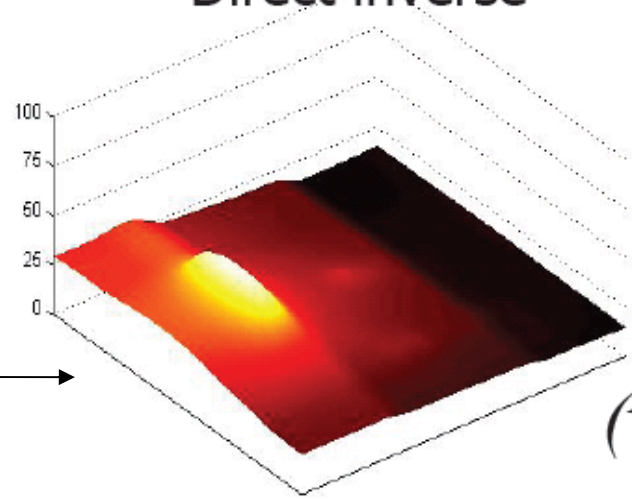
- Tikhonov Regularization (does not preserve edges)
- Bilateral Total Variation (Maximum a Postiori Cost function) Farsiu, et al. IEEE Trans on Image Processing, 13 (10), p. 1327 October, 2004.

Inverse problem (temperature -> power)

Measured temperature profile (include noise)

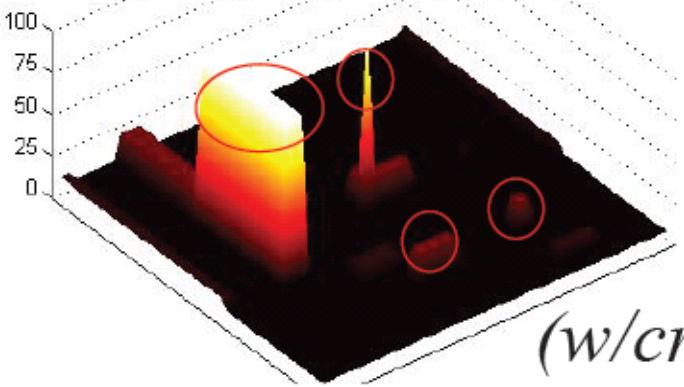


Direct inverse



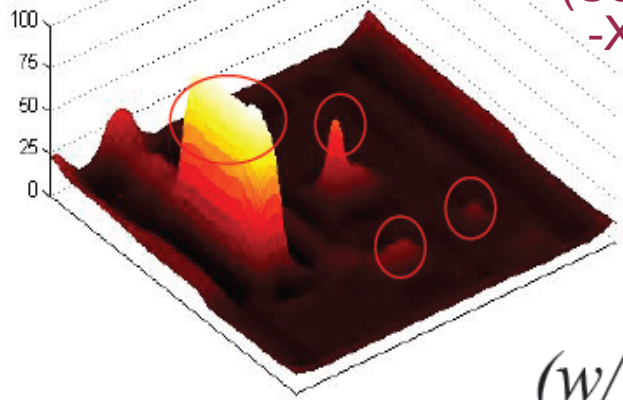
(w/cm^2)

True Power Map



(w/cm^2)

Power Trace



(w/cm^2)

(Semitherm 2007 -Xi Wang et al.)

Summary

- Metal / semiconductor nanocomposites can improve thermoelectric energy conversion
  - Mid/long wavelength phonon scattering
  - Hot electron energy filtering
- Micro Refrigerators on a Chip
  - Localized cooling (10 –150μm, 4-7C), based on SiGe, InP, > 500 W/cm^2
  - Potential to reach 20C cooling, 1kW/cm^2
- Fast transient thermal imaging using thermoreflectance
  - Resolution: ~250nm, 0.01C, 100ns
- Fast transient thermal calculation
  - Using image blurring/ de-blurring, ~100x faster than FEA
- Thermal issues in electro-absorption modulators

Acknowledgement

Alumni: Daryoosh Vashaee (Prof. Oklahoma State), Yan Zhang (Tessera) , Rajeev Singh (Sun Power), Zhixi Bian (Adj. Prof. UCSC), James Christofferson (Res. Scientist UCSC), Kazuhiko Fukutani (Canon), Javad Shabani (PhD student, Princeton), Tammy Humphrey, Virginia Martin, Travis Kemper

Postdocs/Graduate Students: Younes Ezzahri, Helene Michel, Mona Zebarjadi, Xi Wang, Kerry Maize, Hiro Onishi, Tela Favaloro, Paul Abumov, Phil Jackson, Je-Hyoung Park, Oxana Pantchenko

Mona Zebarjadi (UCSC) - **Material Research Society Gold Graduate Student Award**, Boston, MA 2007

Yan Zhang, James Christofferson, et al. (UCSC/UCSB) **– IEEE Transactions on Components and Packaging Best Paper Award 2006**

Je-Hyoung Park, Xi Wang, Yan Zhang (UCSC) - **Student Award, Advanced Thermal Workshop International Microelect. Packaging Society**, 2005-2009

Daryoosh Vashaee (UCSC), **Joshua Zide** (UCSB), **Xiaofeng Fan** (UCSB) - **Goldsmid Award (Best Graduate Student Research), International Conference on Thermoelectrics**, 2001, 2004, 2007