Thermoelectricity:
From Atoms to Systems

Week 4: Thermoelectric Systems

Lecture 4.6: Overview of Week 4

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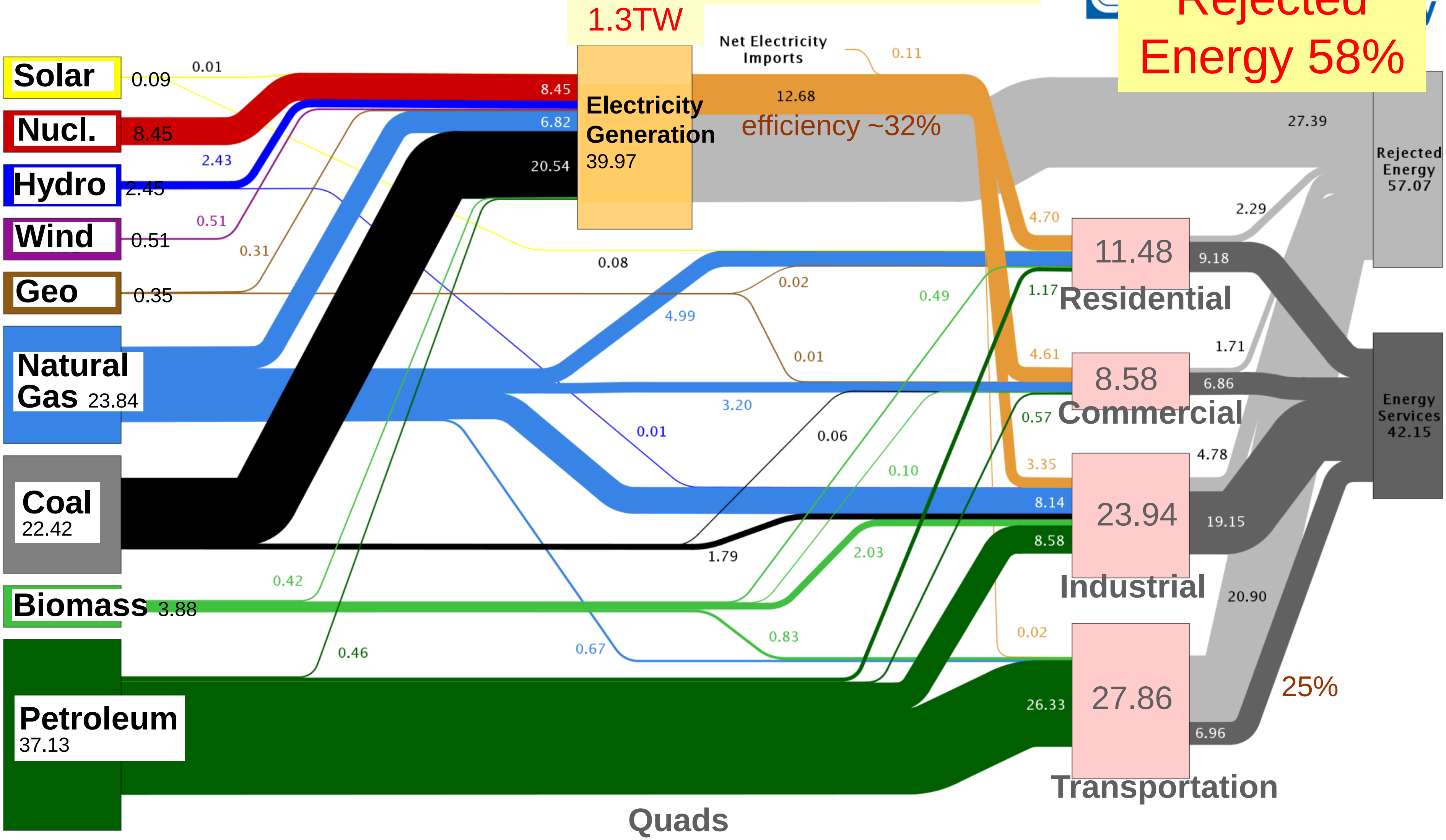
US Energy Flow 2008

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



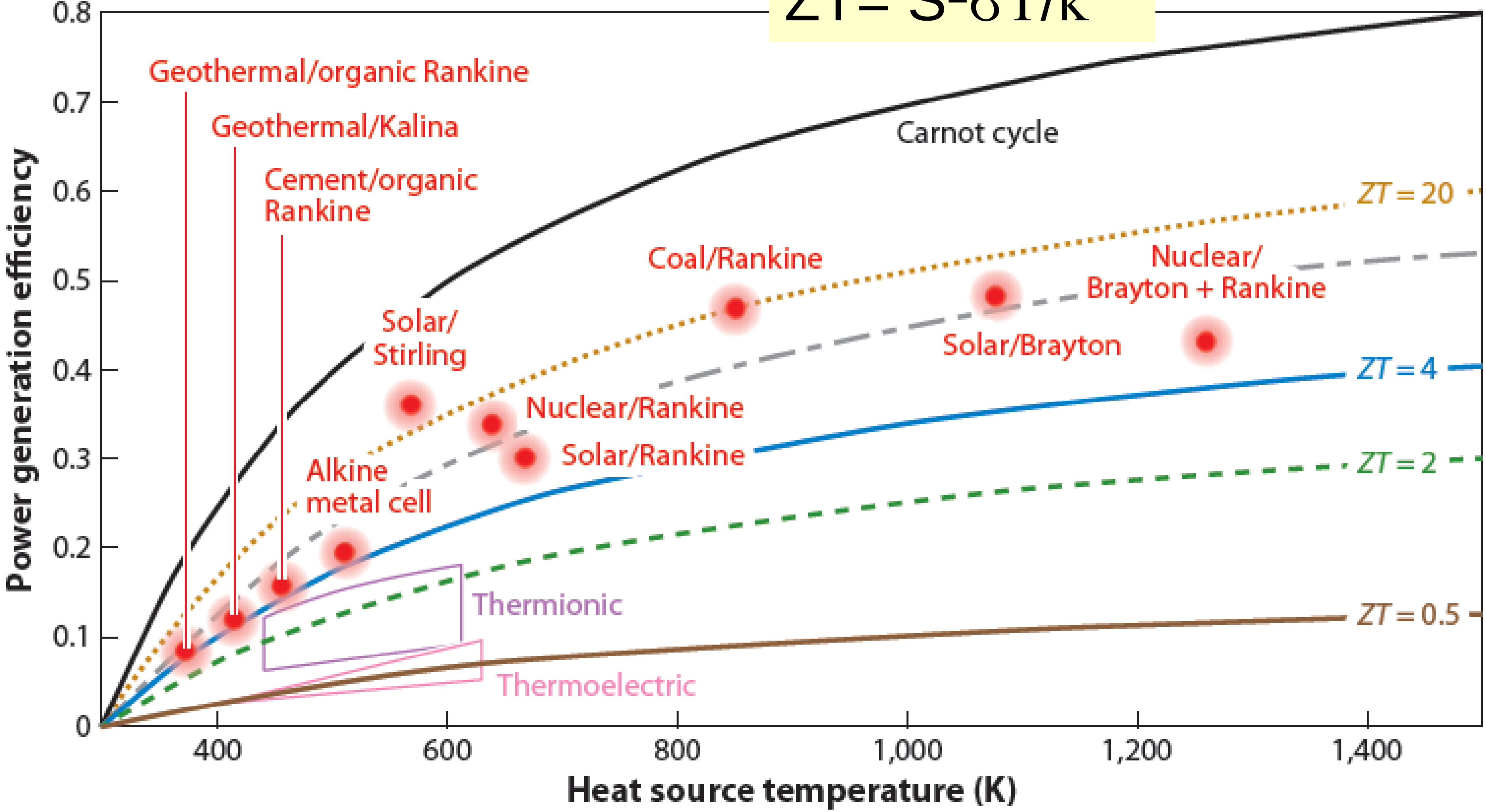
TEs for Telecom Cooling

- TE manufacturers provide coolers specifically designed for Telecom laser-cooling and low noise detector/sensor applications

Cronin Vining, ZT Services

Power Generation Efficiencies

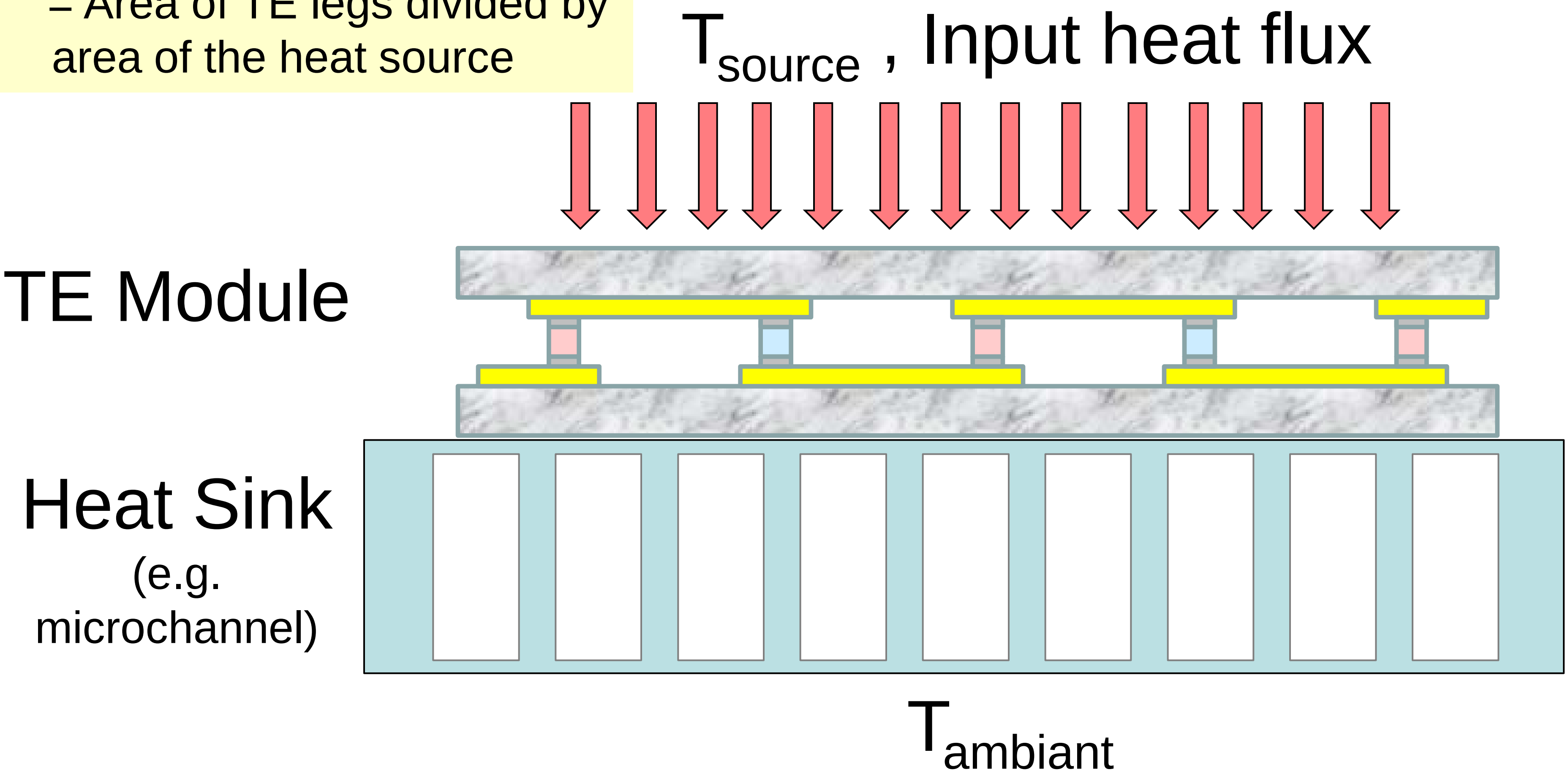
$ZT = S^2\sigma T/\kappa$



Adapted from Cronin Vining, Nature Materials 2009

Use of heat spreading inside TE module (thermal concentration)

F= Fractional area coverage
= Area of TE legs divided by area of the heat source

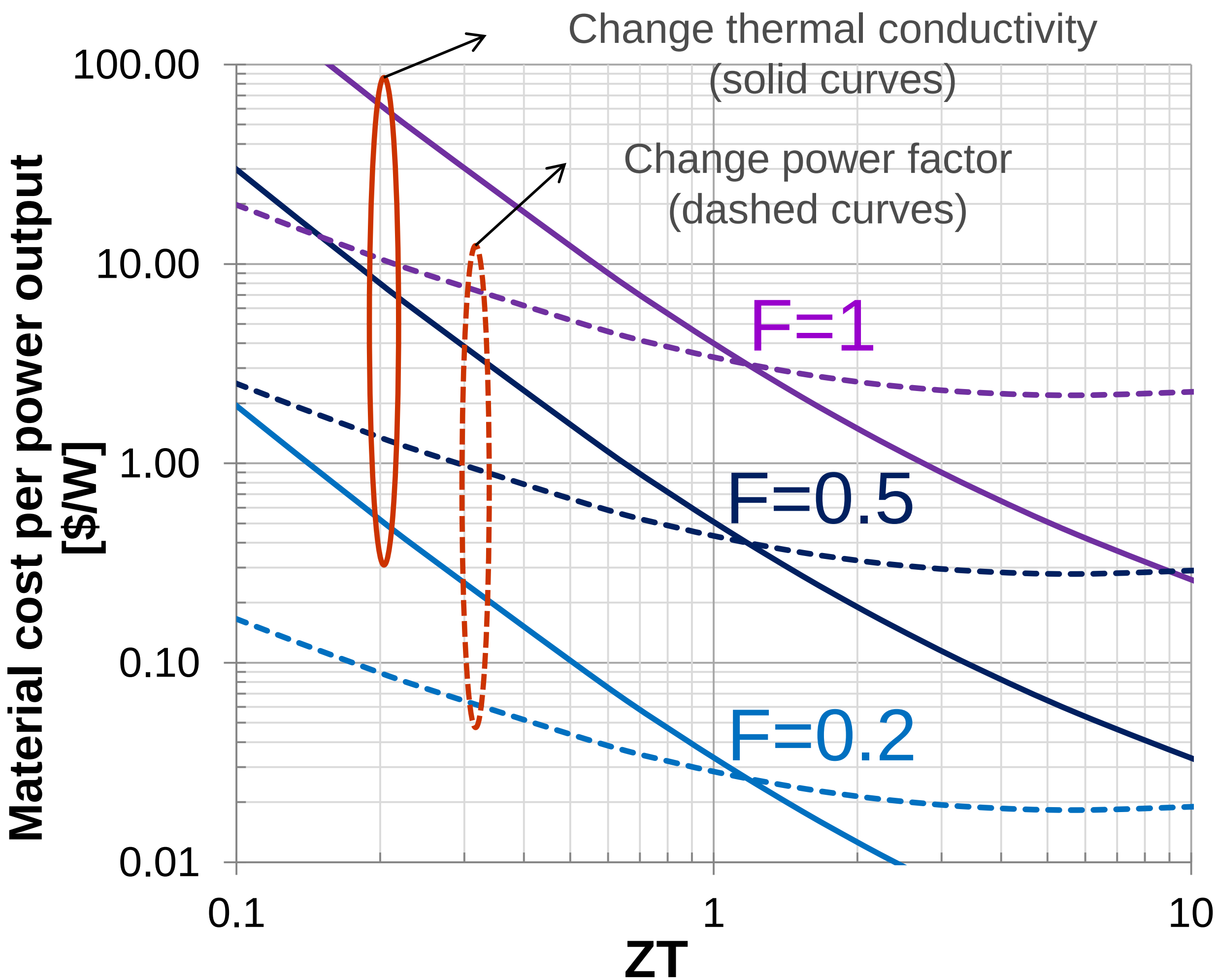


Yazawa and Shakouri, Env. Science and Technology (July 2011)

TE Module/Heat Sink Material Cost per Watt (car exhaust application)

Yazawa & Shakouri; Journal of Material Research 2012

DOE/EFRC CEEM Center



ZT=1, β=1.5 W/mK,
β_{sub} =23 W/mK,
t_{sub} =0.2mm,

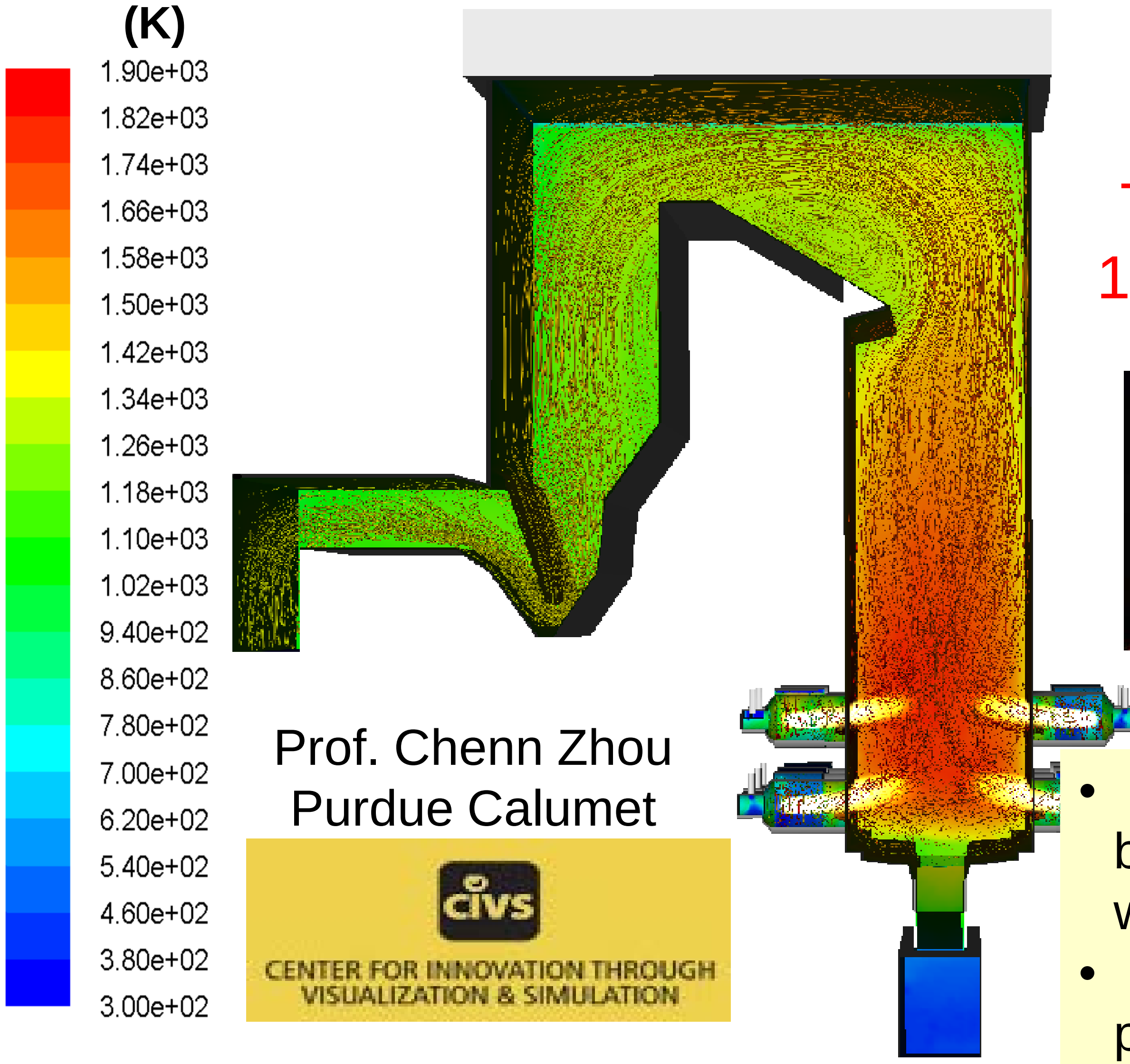
Ts=900K, Ta=330K,
Pump efficiency 30%

TE: $500/kg,
Alumina substrate: $ 5/kg,
Copper heat sink: $ 20/kg

U_h=4.6x10^{2}W/m^{2}K
U_c=1.5x10^{3}W/m^{2}K (U_c/U_h=0.3)

- TE material with ZT=0.5-1 can have a big impact in high heat flux waste heat recovery applications if the source of heat is free (neglect impact on the topping cycle).

TE for topping cycle applications



Prof. Chenn Zhou
Purdue Calumet

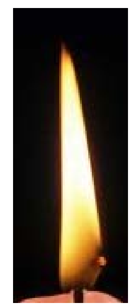
CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

Coal Power Plant

T_{hot}= 1900K

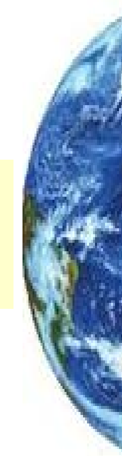
$T_{interface}$

$T_{ambient}$



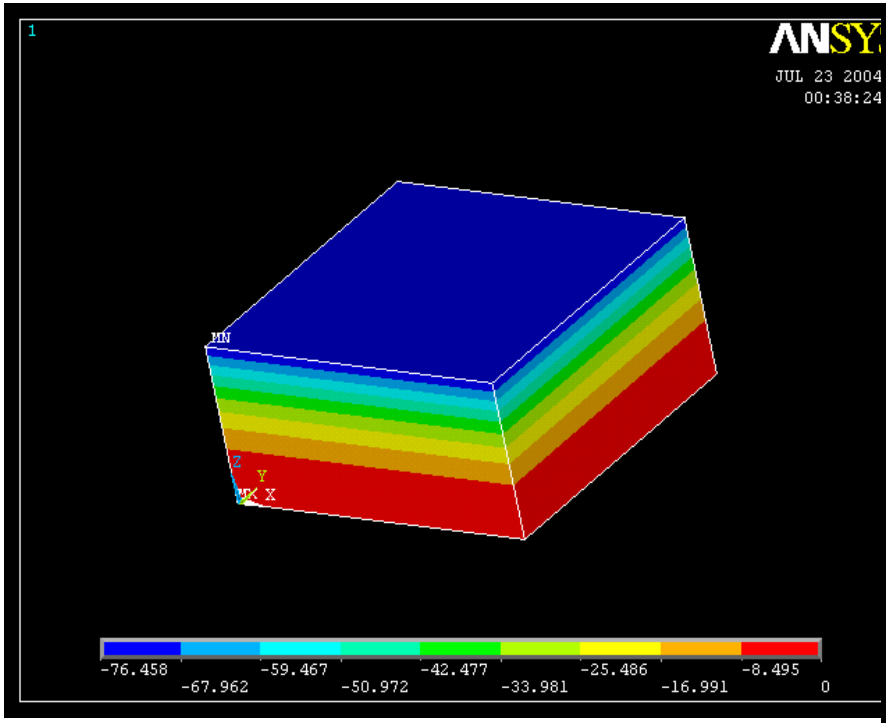
TE System

Rankine cycle

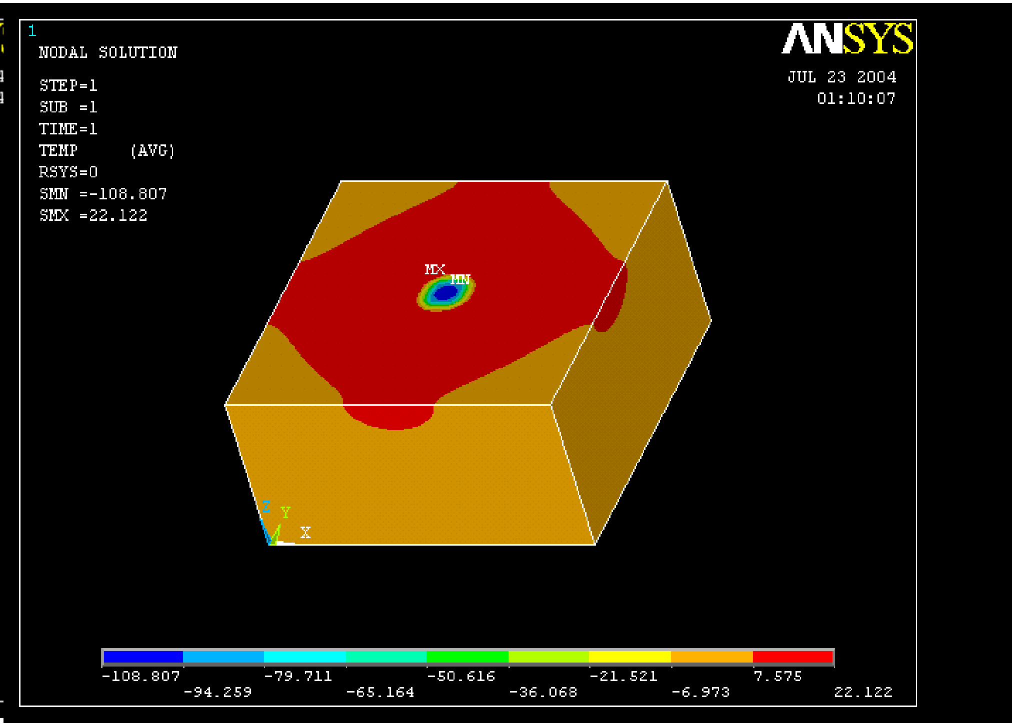


- Highest exergy lost is between the flame and the working fluid (steam).
- Highest steam temperatures/ pressures are limited by the turbine materials.

1D vs. 3D thermoelectric legs

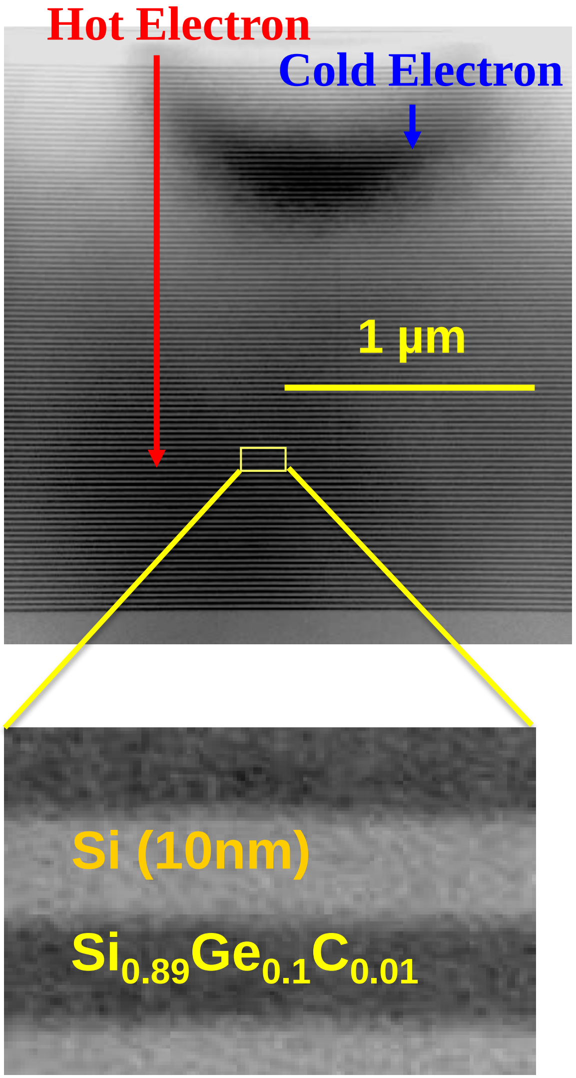


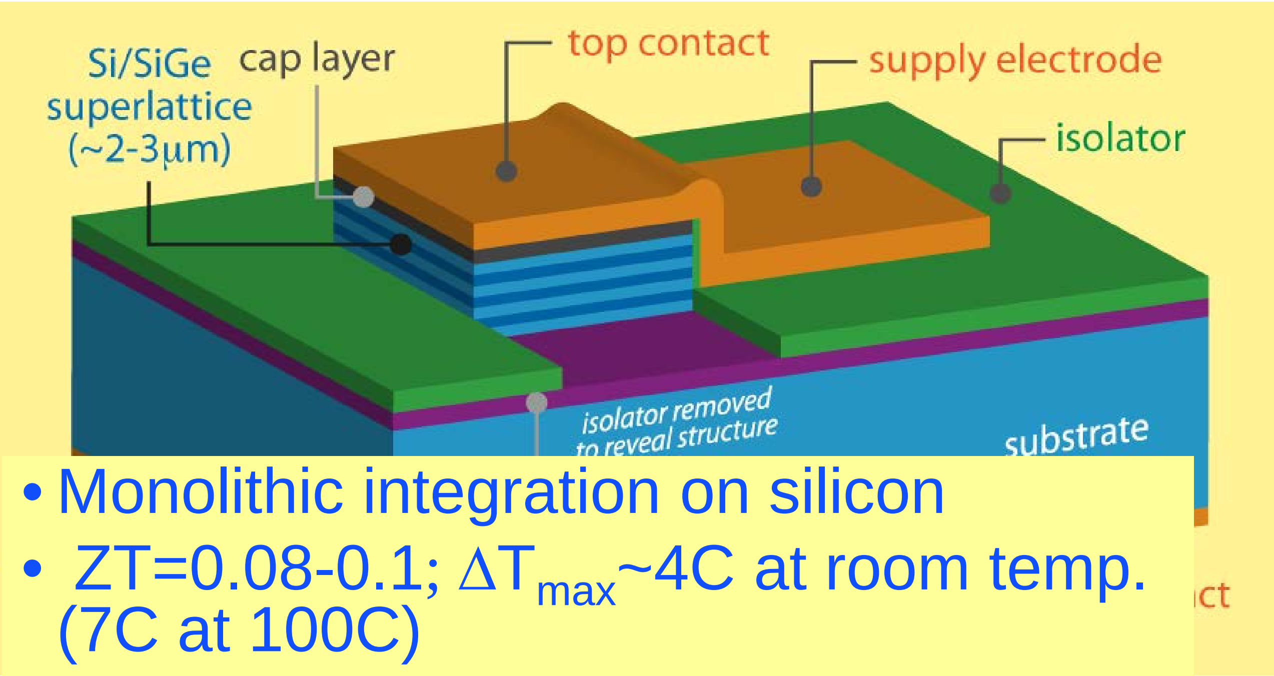
1D device, contact area 410x410μm^2
Max. Cooling, 76.5^{0}C, (I=4A)
Cooling power density ~100W/cm^2



3D device, contact area 50x50μm^2
Max. Cooling, 108.8^{0}C (I=0.8A)
Cooling power density ~655W/cm^2 at center 20x20 μm^2

Microrefrigerators on a chip



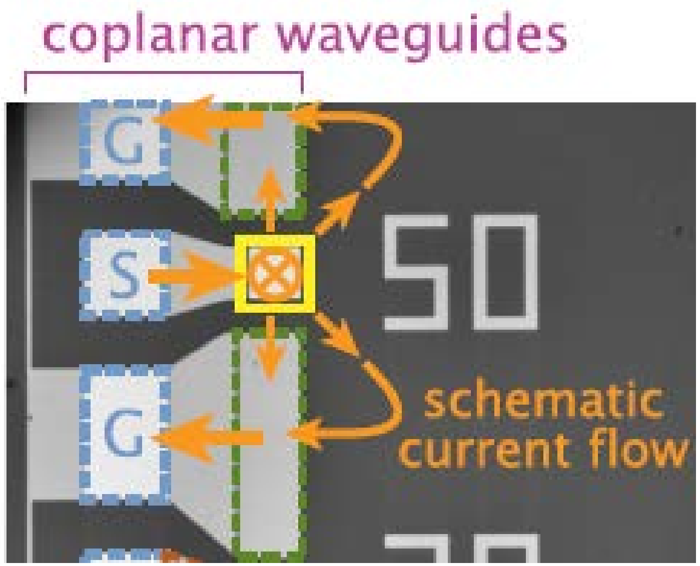


- Monolithic integration on silicon
- ZT=0.08-0.1; ΔT_{max}~4C at room temp. (7C at 100C)
- Cooling power density > 500 W/cm^2

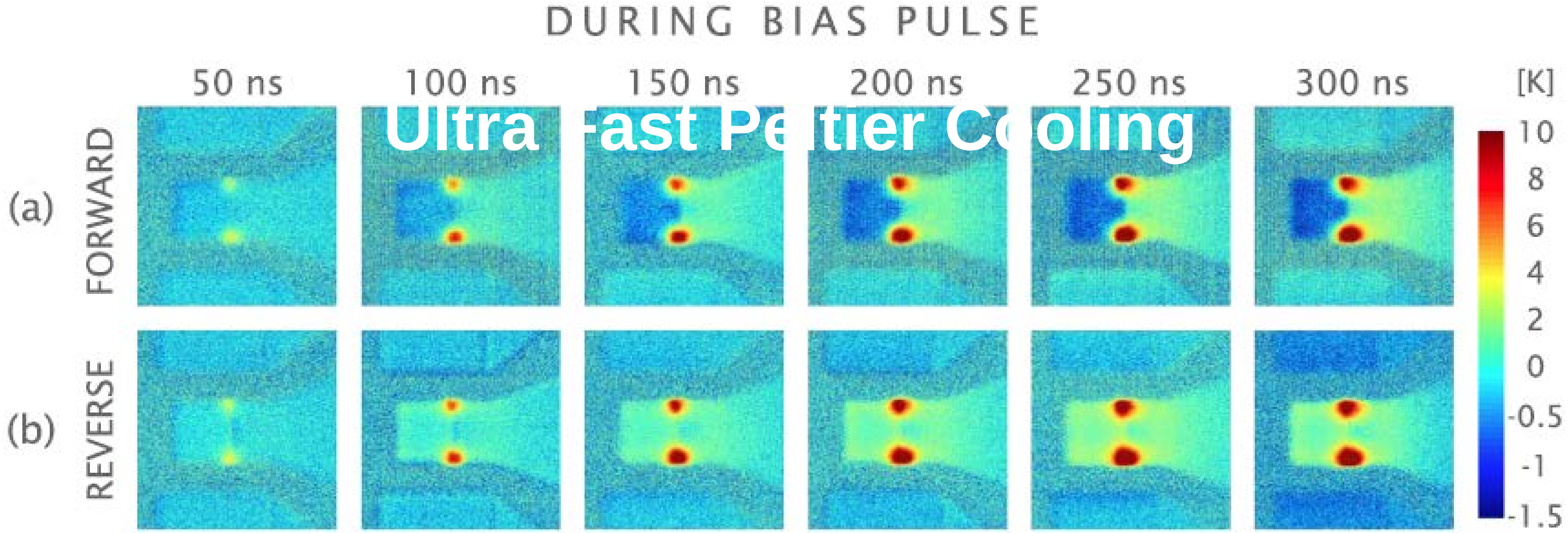
Heterostructure Integrated Thermionic Coolers; A. Shakouri and John Bowers, **Appl. Phys. Lett.** 1997

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

Ultra Fast Peltier Cooling



B. Vermeersch et al. JAP 2013



Superlattice vs. Alloy Thin Film SiGe Cooler

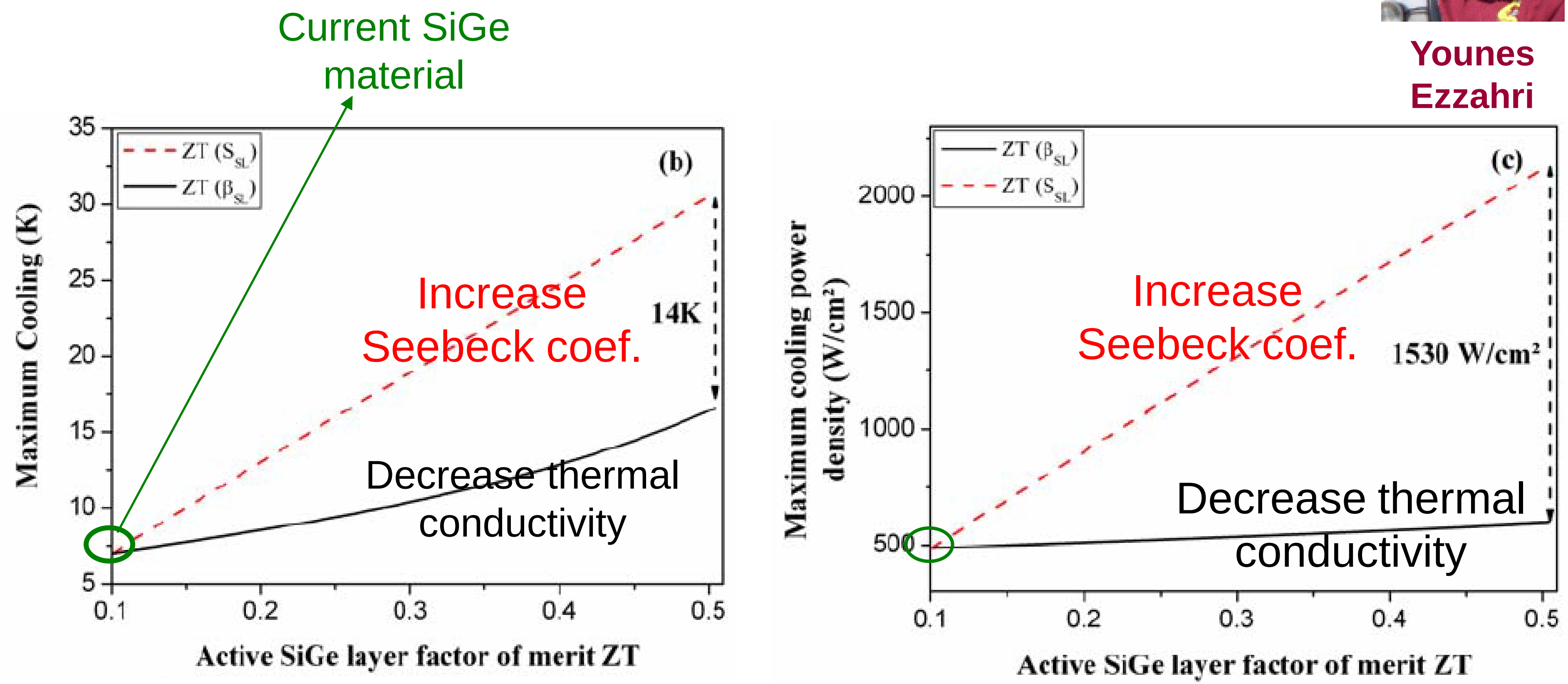
Material	Seebeck Coefficient, S (μV/K)	Electrical Conductivity, σ (Ωcm)$^{-1}$	Thermal Conductivity, β (W/mK)	Power Factor, $S^2\sigma$ (10^{-3} W/K^{2}m)	Figure-of-Merit, $ZT = S^2\sigma T/\beta$
$Si_{0.8}Ge_{0.2}$ alloy (Micro refrigerator ΔT_{max}=4.0K)	210	367	5.9	1.6	0.08
Superlattice $Si/Si_{0.7}Ge_{0.3}$ (10nm/5nm) (Micro refrigerator ΔT_{max}=3.5K)	200 (∥)	300 (∥)	10.7-12.9 (⊥)	1.8 (⊥, estimated) 1.2 (∥)	0.07 (⊥, estimated)
Superlattice $Si/Si_{0.75}Ge_{0.25}$ (3nm/12nm) (Micro refrigerator ΔT_{max}=4.2K)	200-220 (⊥) 180 (∥)	384 (∥)	6.8-8.7 (⊥)	2.2 (⊥, estimated) 1.2 (∥)	0.085 (⊥, estimated)

A. Shakouri, **Proceedings of IEEE**, July 2006

Thin Film Microrefrigerator Optimization

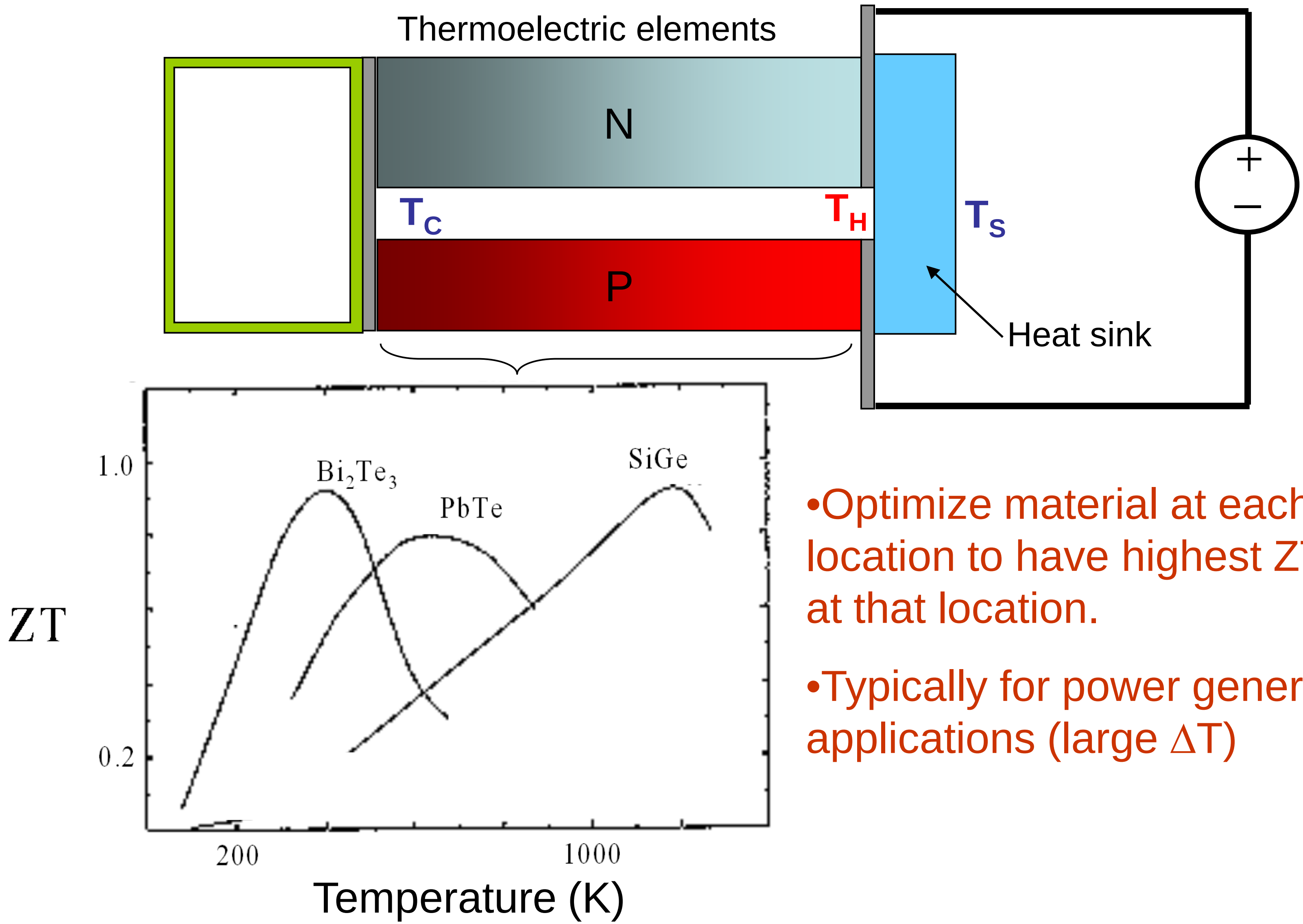
10 microns thick, 50x50μm^2 monolithic microrefrigerator with ZT~0.5 can cool a 1000W/cm^2 hot spot by >15C.

Younes Ezzahri



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

Conventional Functionally Graded or Segmented Thermoelectric Materials



- Optimize material at each location to have highest ZT_{local} at that location.
- Typically for power generation applications (large ΔT)

ZT of Composite Thermoelectrics

Thermoelectric properties of a composite medium

David J. Bergman and Ohad Levy

We study the thermoelectric properties of a composite medium. … We prove that $Z_{effective}$ of the composite can never exceed the largest value of Z in any component.

(rigorous proof for two-component system)

$$Q_{e11}=\frac{1}{V}\int dV(Q_{11}E_1^{(1)^2}+2Q_{12}\mathbf{E}_1^{(1)}\cdot\mathbf{E}_2^{(1)}+Q_{22}E_2^{(1)^2})$$

Journal of Applied Physics -- December 1, 1991 – V.70 (11), pp. 6821-6833

An intuition to improve maximum cooling in graded thermoelectric materials (Zhixi Bian)

Assumption: power factor and thermal conductivity are constant through the materials, small ZT

$$S^2\sigma = \text{constant}$$

L	L/4	L/9
S	2S	3S
σ	σ/4	σ/9
R	R	R

- If I=ST/R, Joule heating and Peltier cooling are cancelled inside material

$$\Delta T_{\max} = \frac{1}{2} Z T_C{}^2 \sum_{n=1} \frac{1}{n^2}$$

n= number of sections

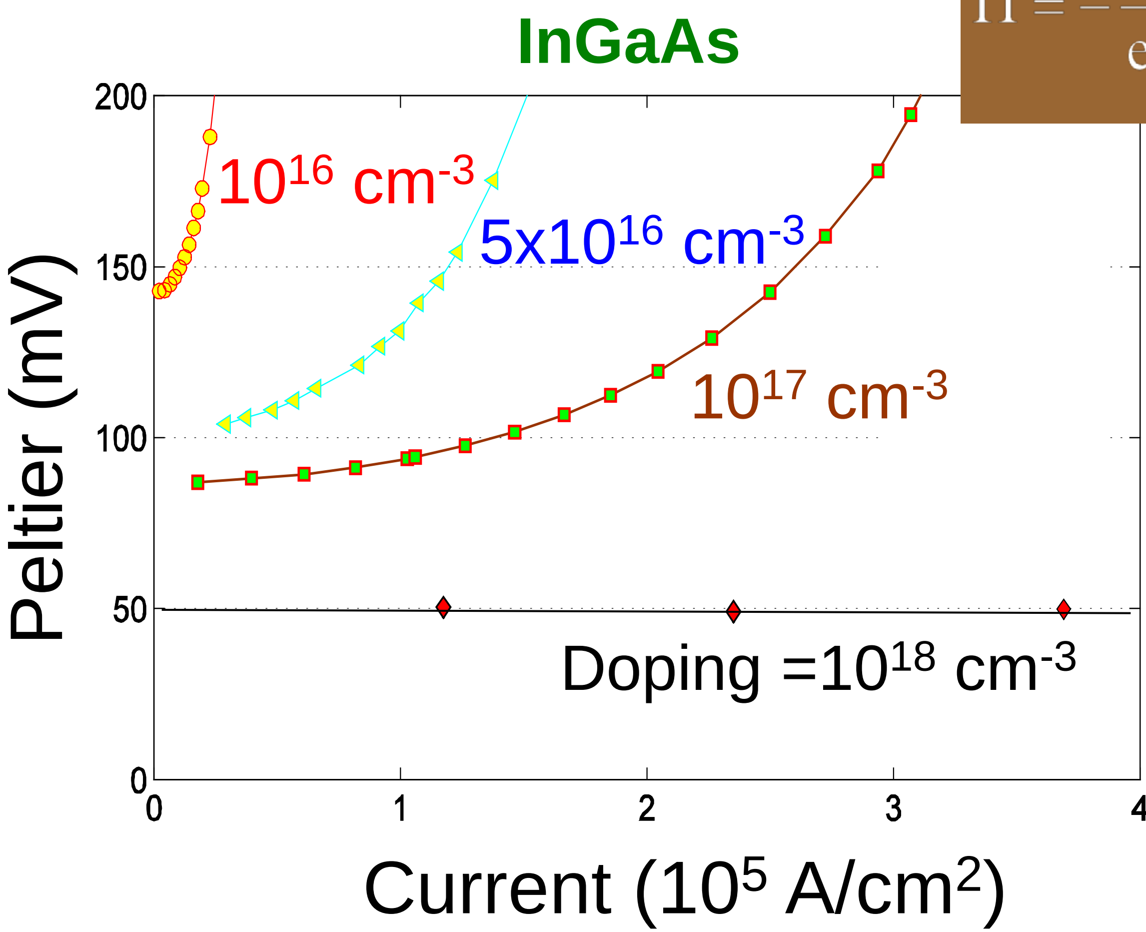
Maximum cooling can be 33-78% times larger for 2-5 sections (S_{max}/S_{min}~10).

Zhixi Bian et al. Applied Physics Letters 2006

Zhixi Bian

Nonlinear Peltier Coefficient

$$\Pi = -\frac{\mu}{e} + \frac{5k_B T}{2e} + \frac{m}{e^3 n^2 \tau}\left(\frac{\tau}{2} + \frac{5\tau_E}{3}\right) J^2$$

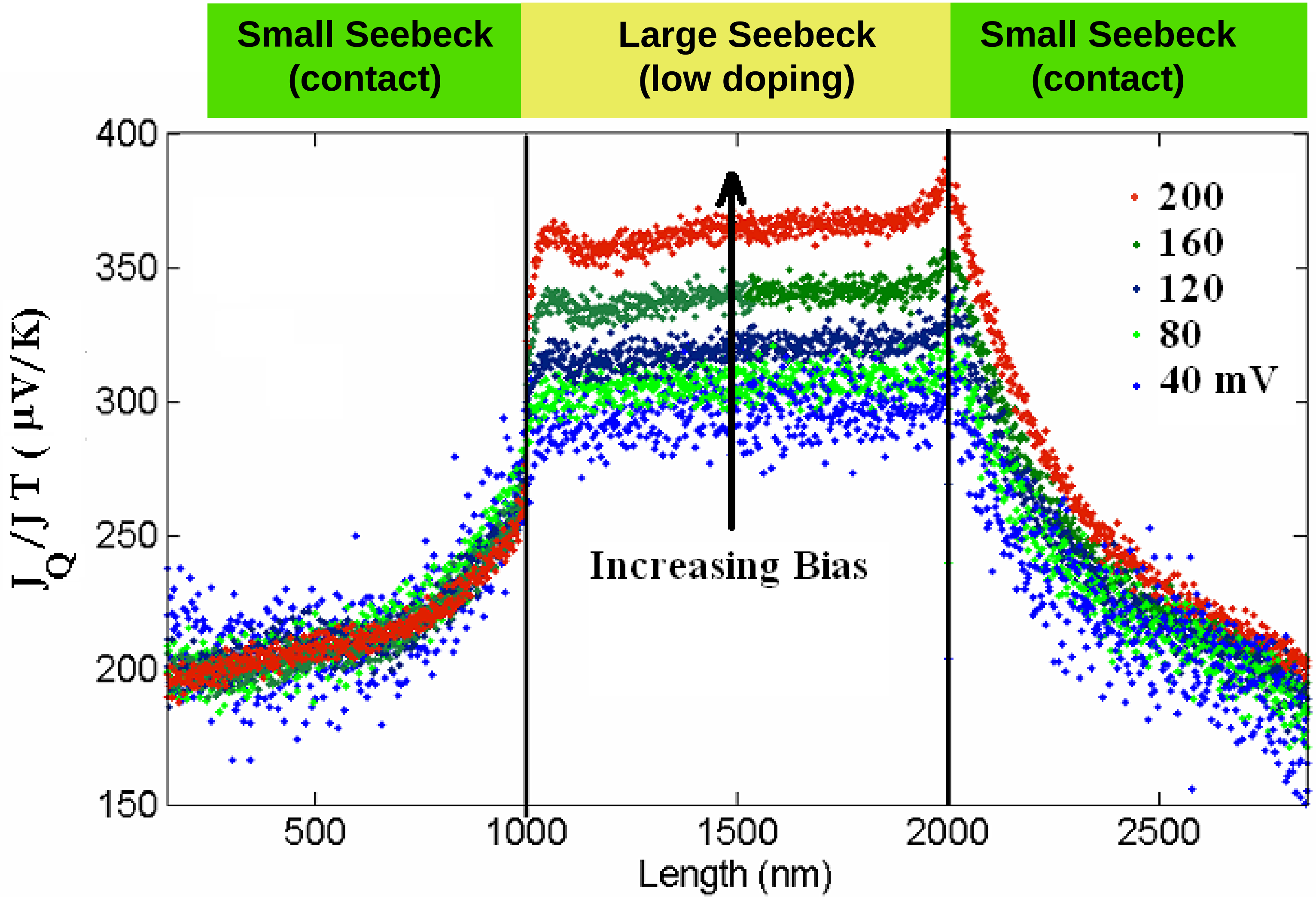


Peltier coefficient can increase significantly with bias, especially at low temperatures.

Mona Zebarjadi

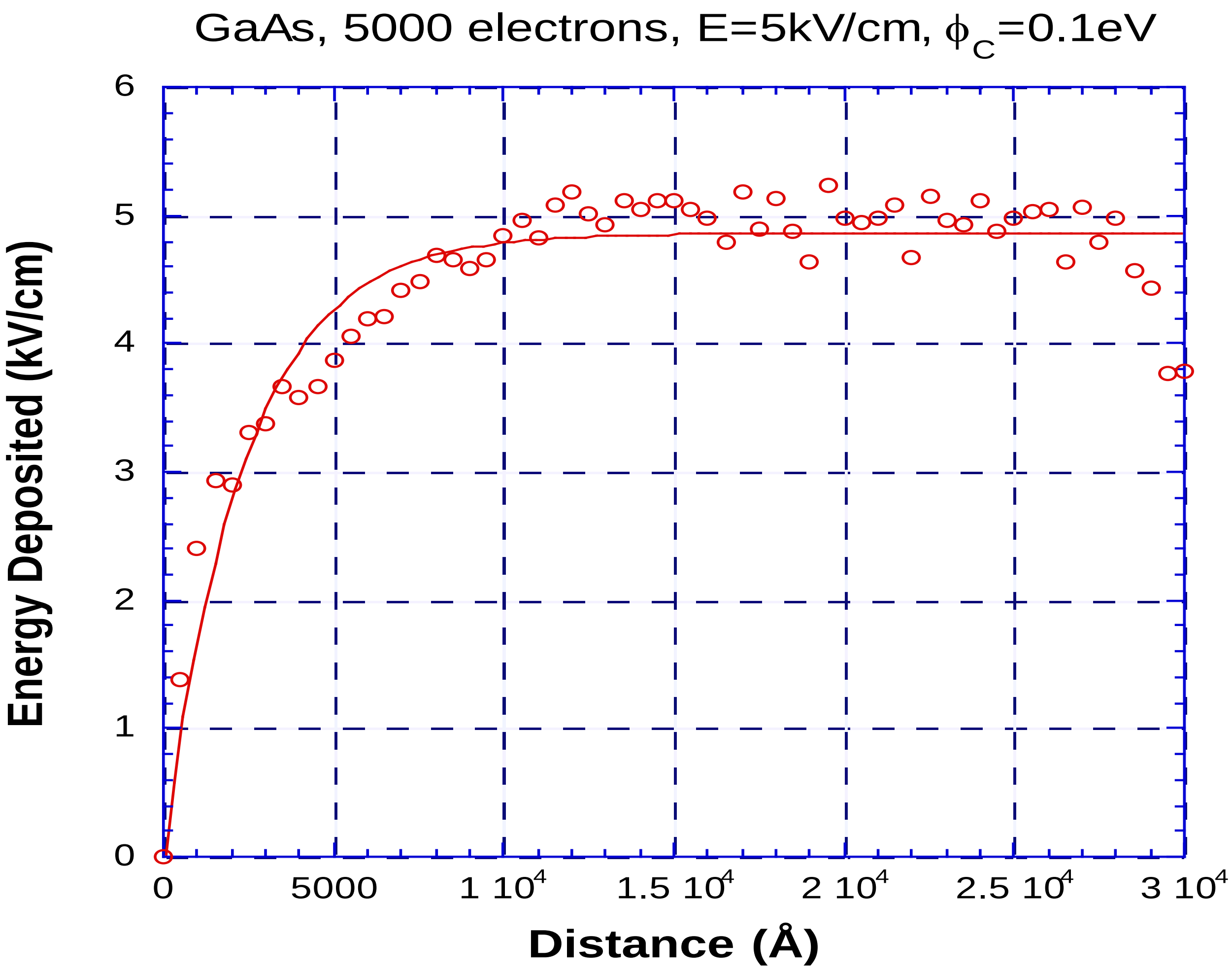
M. Zebarjadi, K. Esfarjani & A. Shakouri , Appl. Phys. Lett., 91, 122104 (2007)

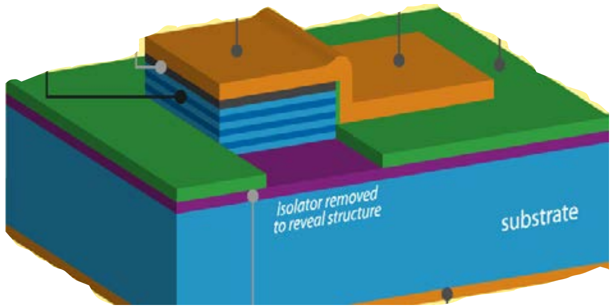
Thermal Current → Local Seebeck coefficient

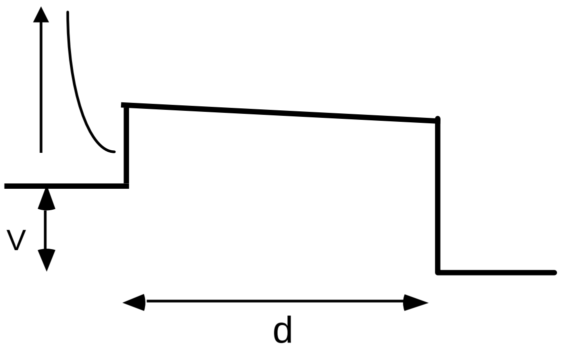


M. Zebarjadi, K. Esfarjani & A. Shakouri , PRB (2007)

Joule Heating in the Barrier

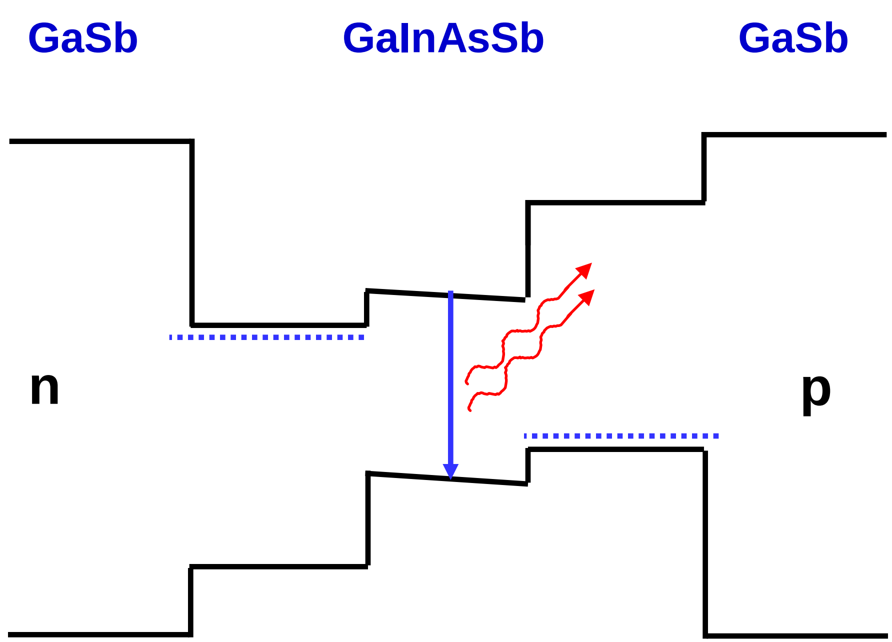


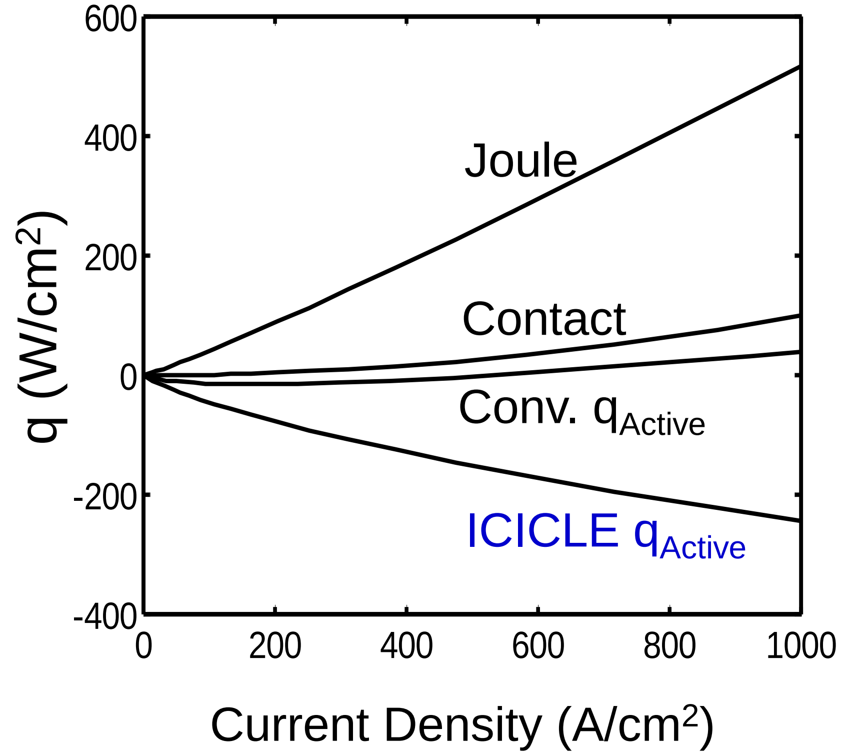




A. Shakouri, et al.; Microscale Thermophysical Engineering, 2(1), January-March 1998, pp. 37-47.

Injection Current Internally Cooled Light Emitter





Electrically pumped "optical refrigeration"

Kevin Pipe, Rajeev Ram and Ali Shakouri, Photonic Techn. Lett., Apr. 2002

Week 4: TE System Summary

4.1 • TE's for waste heat recovery and for localized cooling

4.2 • New TE module designs with fractional area coverage can reduce the cost significantly ($1-2/W -> $0.10-0.20/W)

• Topping cycle thermoelectrics with ZT~0.3-1 can improve power plant efficiency by 2-8%

4.3 • SiGe Microrefrigerator on a chip (7C cooling)

• Fully integrated cooler with ZT~0.5 can achieve ΔT~15C, cooling power density >1kW/cm^2

4.4 • Maximum cooling of Peltier devices can be increased using graded material (uniform efficiency criterion)

• 3D Peltier devices has high cooling power density

4.5 • Nonlinear and bipolar Peltier effects

• Internal cooling in electronic and optoelectronic devices