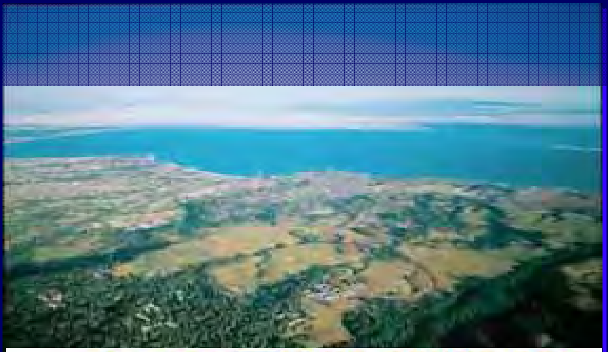
# Solid-State Thermionic Energy Conversion for Waste Heat Recovery




Ali Shakouri

Director, Thermionic Energy Conv. Center

Baskin School of Engineering

University of California Santa Cruz



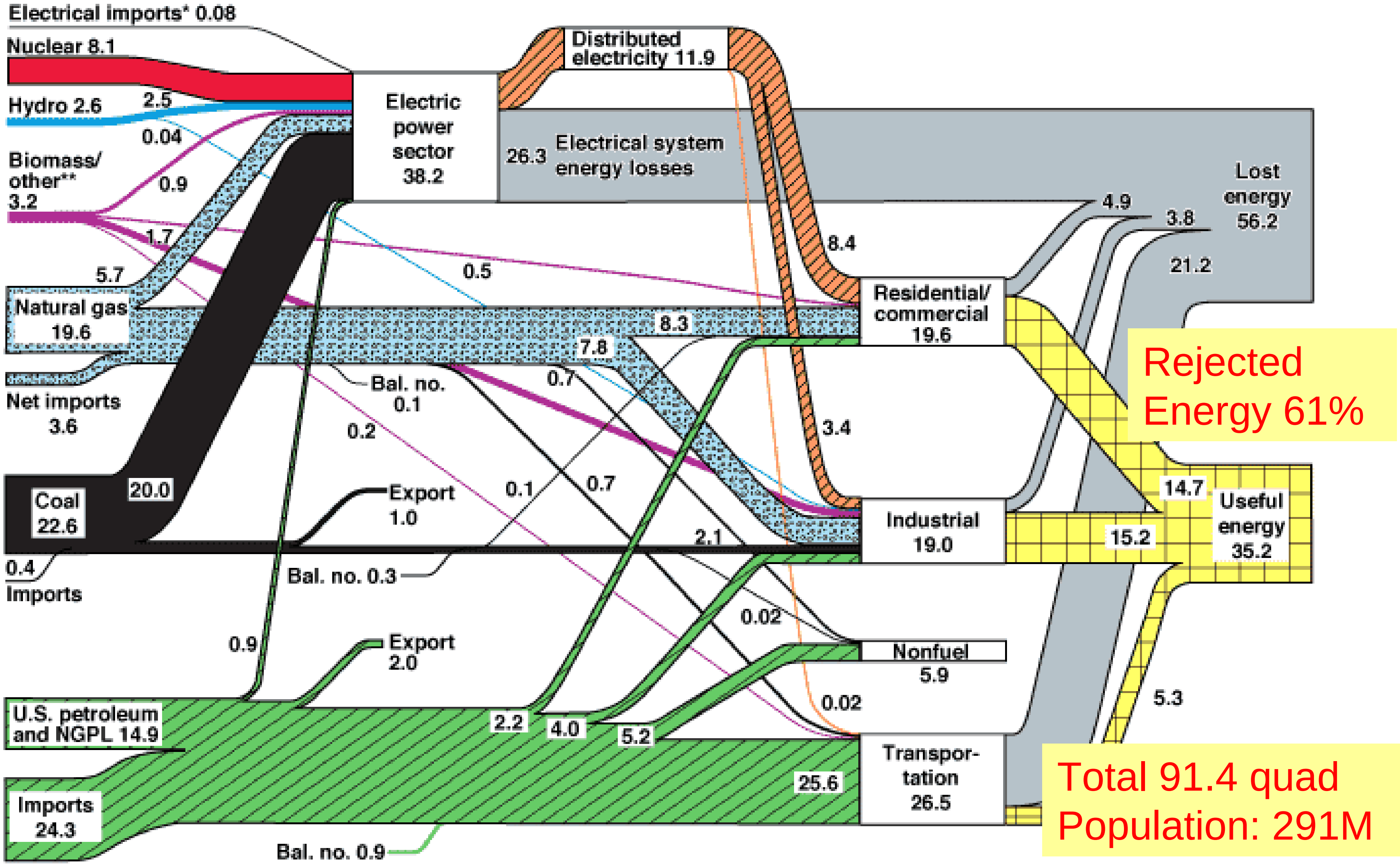
**Acknowledgement: ONR MURI**

**(Dr. Mihal Gross)**


**UCSC** (Schmidt), **Berkeley** (Majumdar), **Harvard** (Narayanamurti), **MIT** (Ram), **NCSU** (Nemanich, Sitar), **Purdue** (Sands), **UCSB** (Bowers, Gossard, Stemmer)

AVS Thin Film User Group, 8 Nov. 2007

# U.S. Energy Flow Trends – 2002
# Net Primary Resource Consumption ~97 Quads



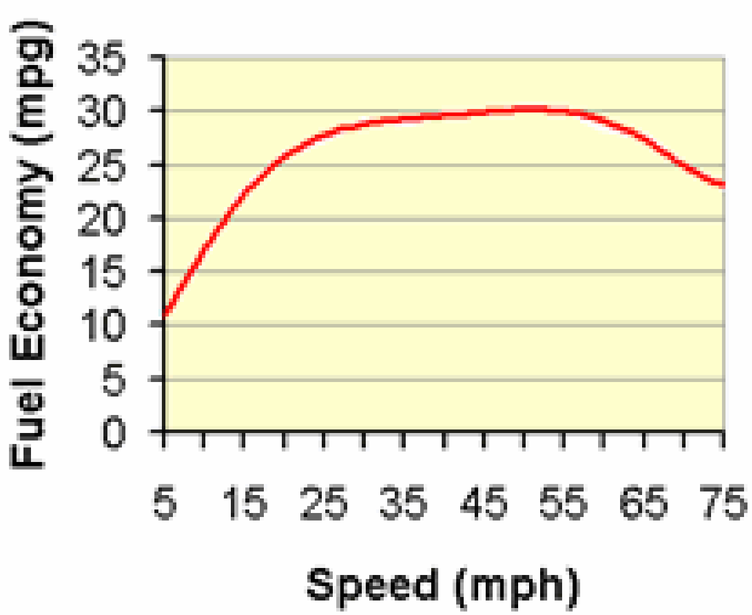

Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002*.
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

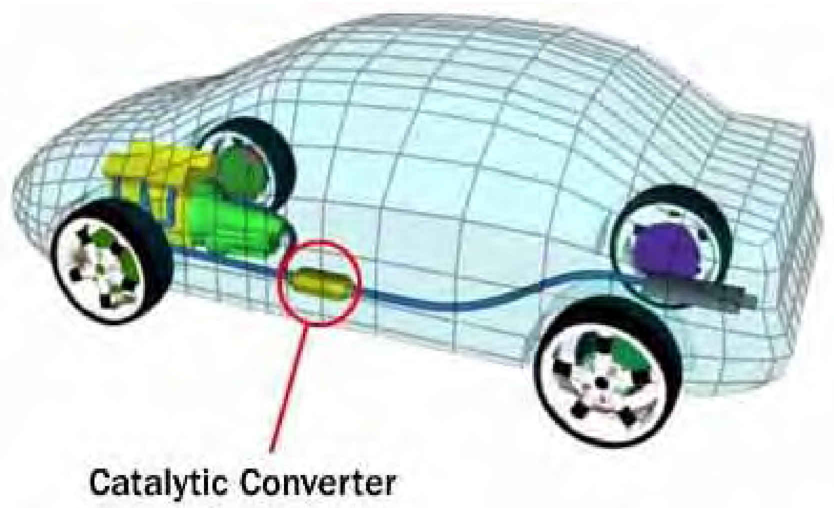
June 2004
Lawrence Livermore
National Laboratory
http://eed.llnl.gov/flow

# Energy Efficiency in Transportation



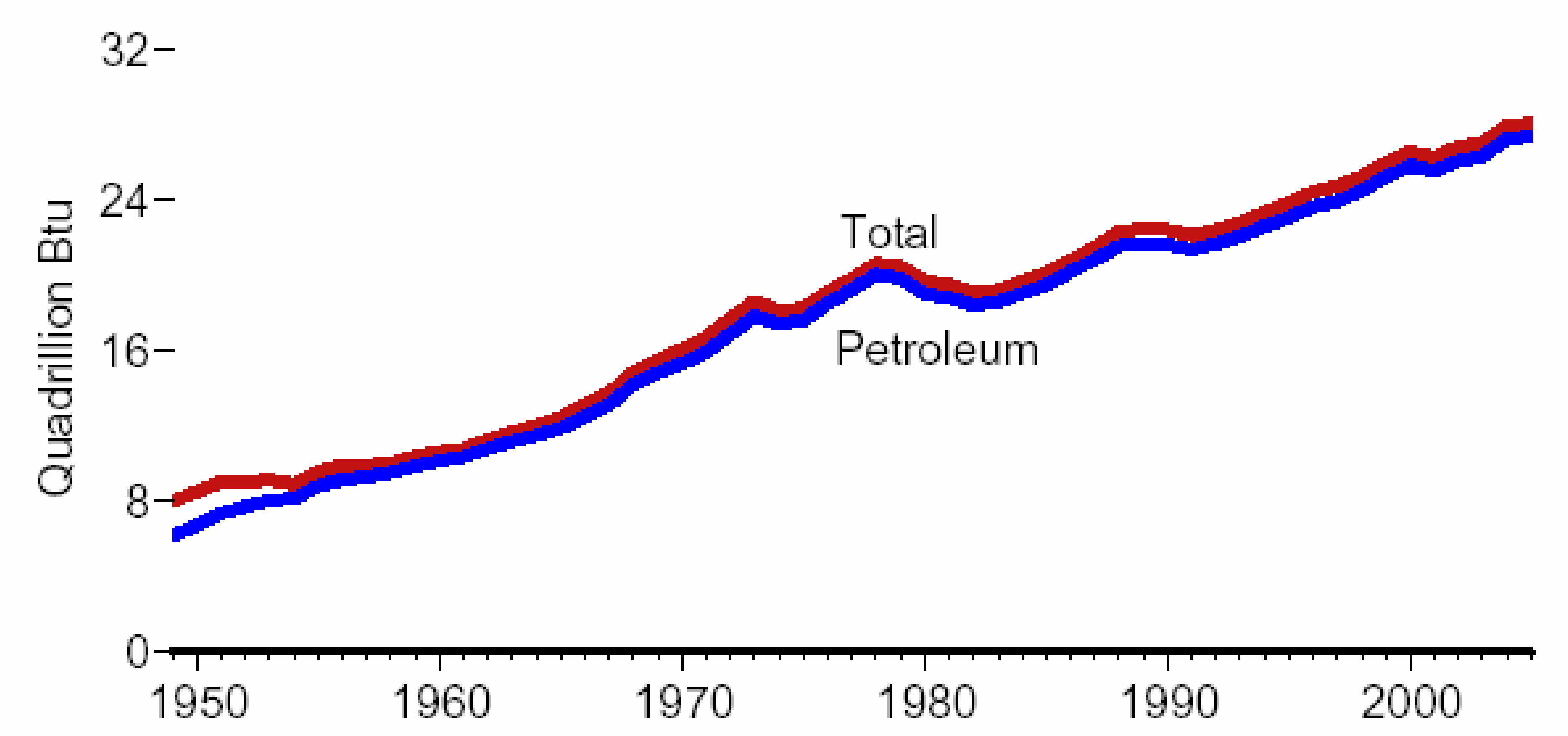
2/3 of the power in cars is dissipated (heat in the engine and in the catalytic converter)




Terry J. Hendricks, International Conf. on Thermoelectrics; Long Beach, 2002

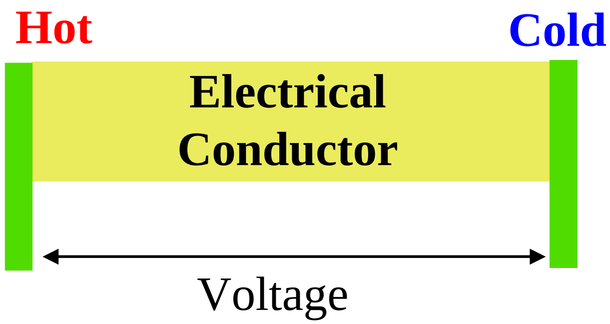
# Transportation Energy Consumption

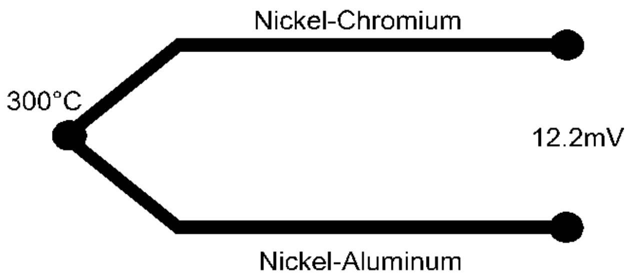



DOE, Energy Information Administration (EAI)

# Seebeck Effect (1821)

Seebeck: $S = \frac{\Delta V}{\Delta T}$

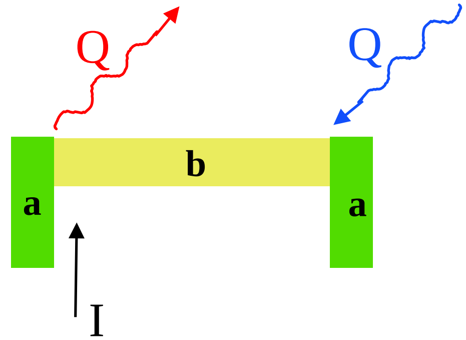


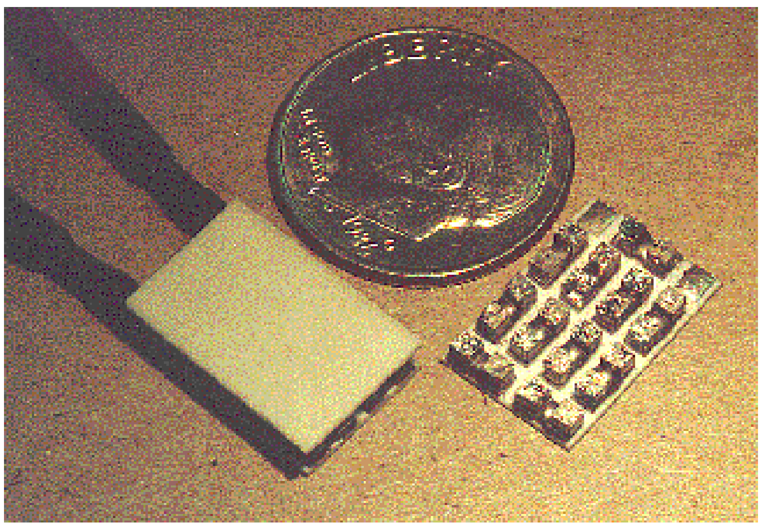




Temperature difference between two junctions can produce a voltage

# Peltier Effect (1834)

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



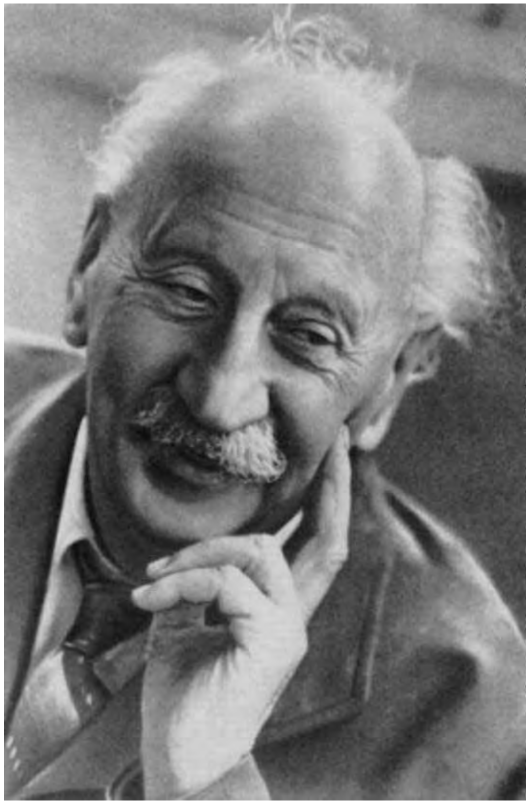
## Commercial TE Module

- $\Delta$T=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.

# Early Thermoelectricity

- First practical devices USSR during WWII
  - Tens of thousands built, to power radios from any available heat source.
- In the 1950s-60s many in the US & USSR felt semiconductor thermoelectrics could replace mechanical engines, much as semiconductor electronics were replacing vacuum tube technology.
  - Hint: it didn't happen!

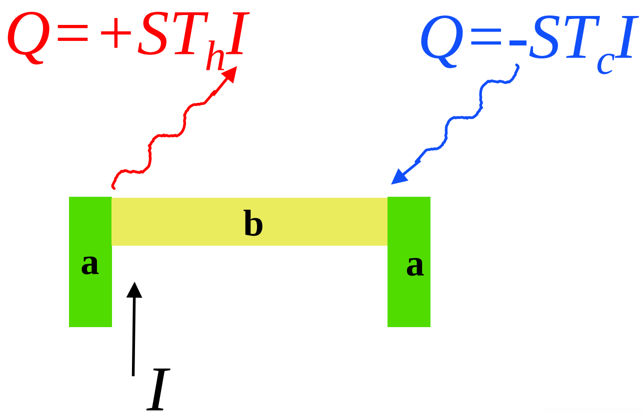


Abram F. Ioffe 1880-1960

Ioffe, A. F. (1957). Semiconductor Thermoelements and Thermoelectric Cooling. London, Infosearch Limited.

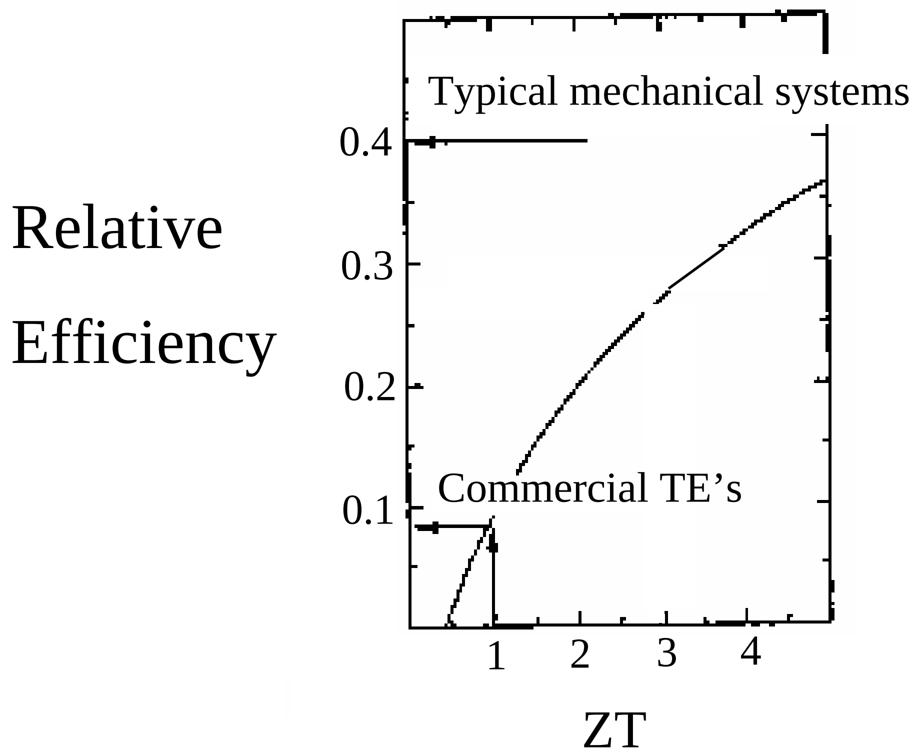
# Efficiency of Thermoelectric Devices






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

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



# TEs for Telecom Cooling



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

**Typical Distributed Feedback Laser:**

**$\Delta\lambda/\Delta T$= 0.1 nm/ºC**

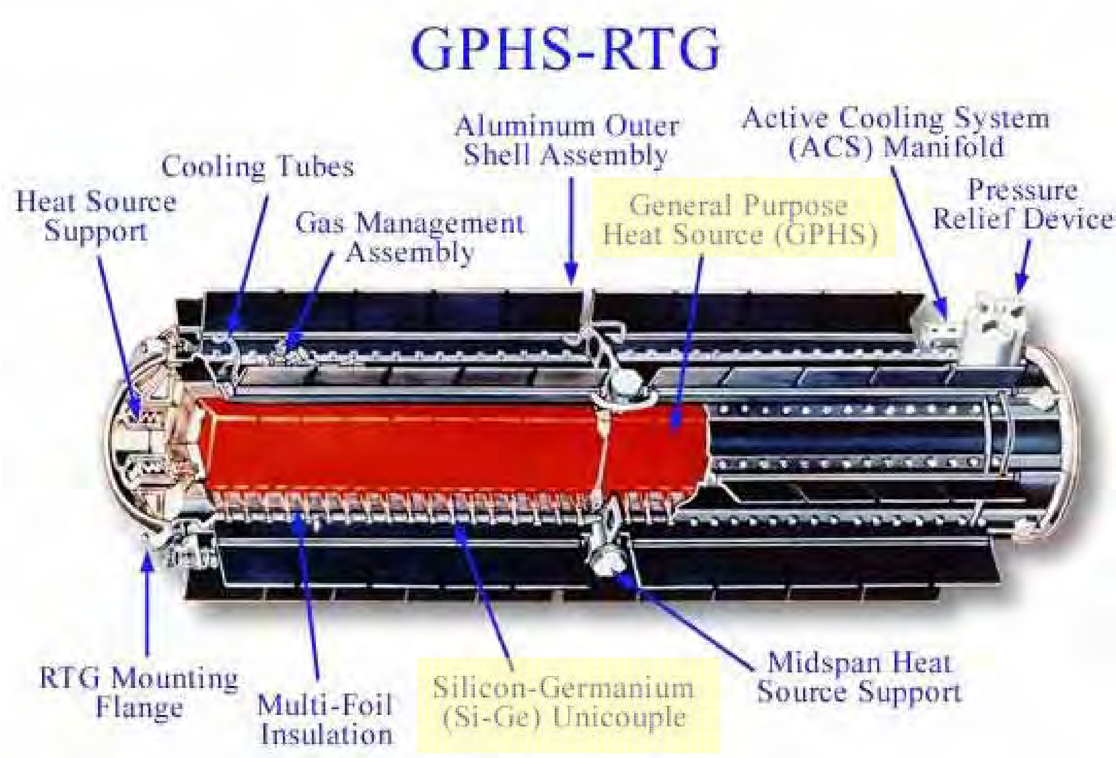
**Heat generation kW/cm²**

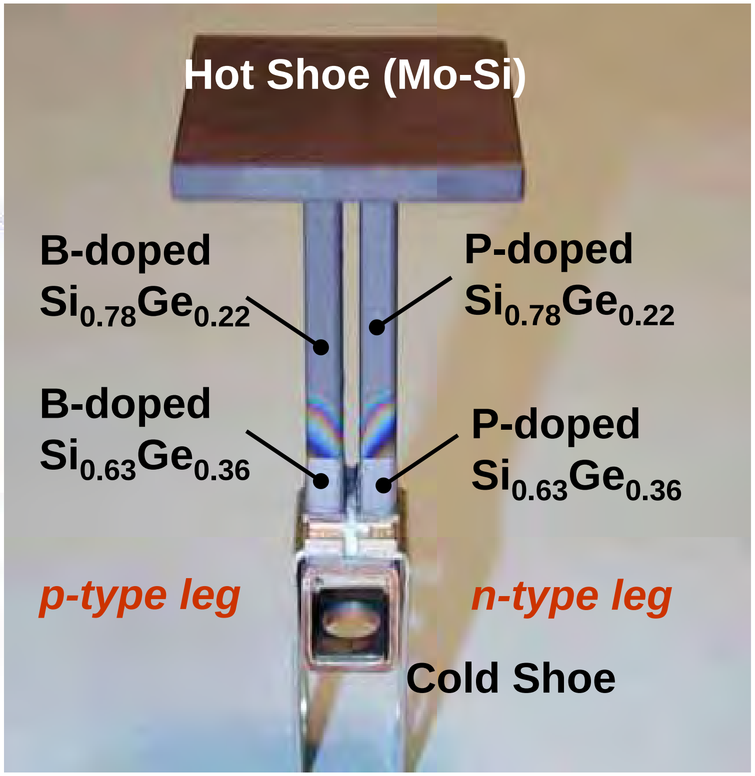
**Cronin Vining, ZT Services**

# 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



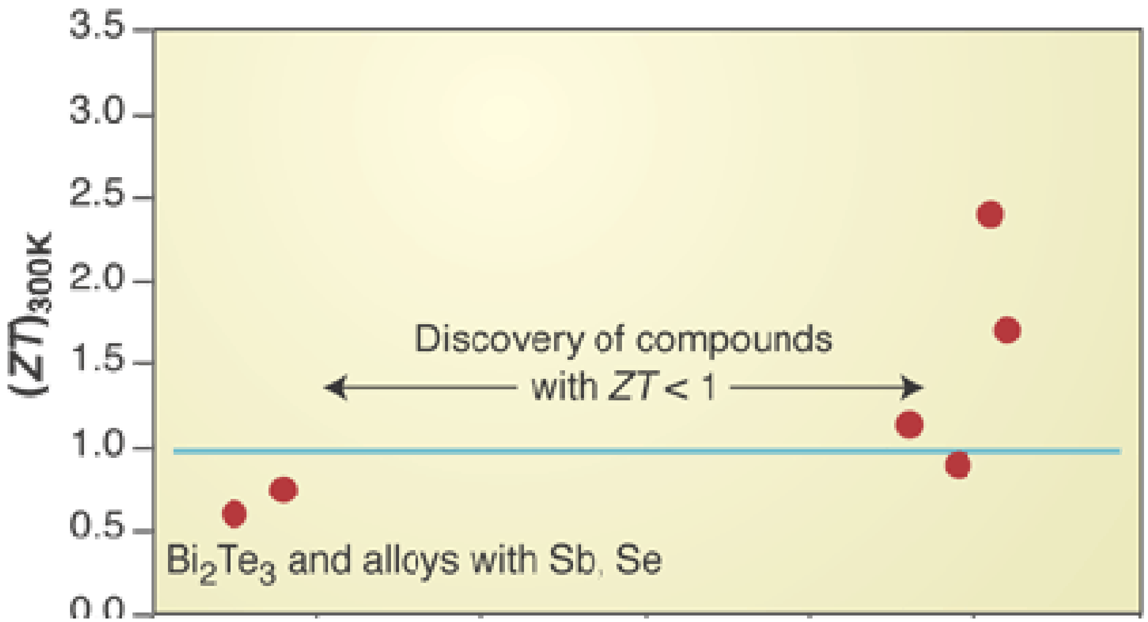




SiGe unicouple

**Cronin Vining, ZT Services**

# Recent Advances in Thermoelectrics

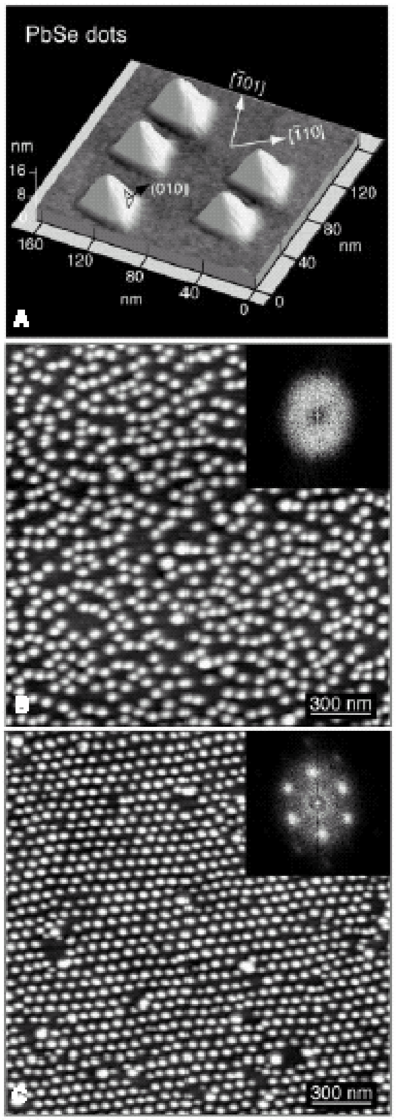





- Recent advances in nanostructured thermoelectric materials led to a sudden increase in $(ZT)_{300K} > 1$

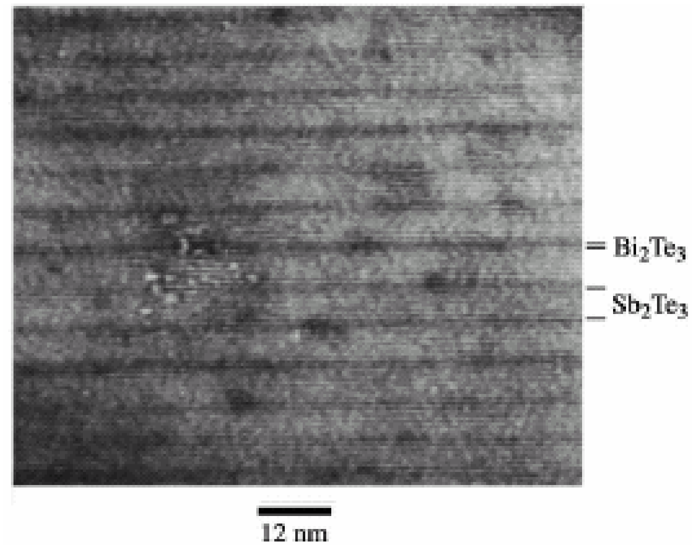
**A. Majumdar, *Science* 303, 777 (2004)**

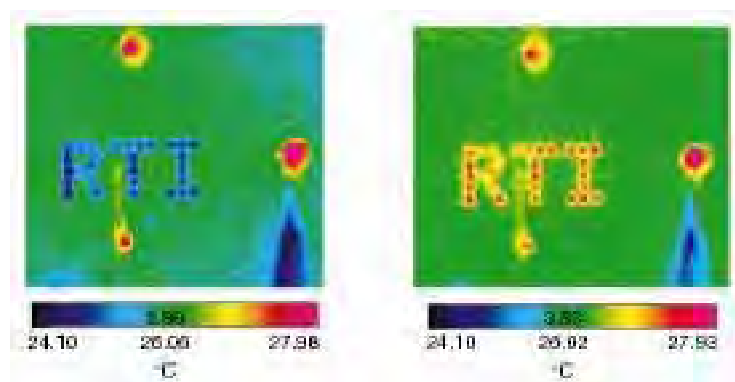
# Superlattices/ Quantum Dot Thermoelectrics
## *Harman (2002) and Venkatasubramanian (2001)*




**PbTe/PbTeSe Quantum Dot Superlattices**

**ZT=2**
**T.C. Harman, Science, 2002**



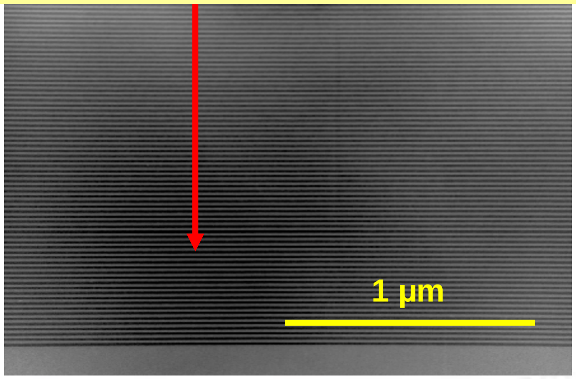

**ΔT=32.2 K, ZT ~2-2.4**
**R. Venkatasubramanian, Nature, 2001**

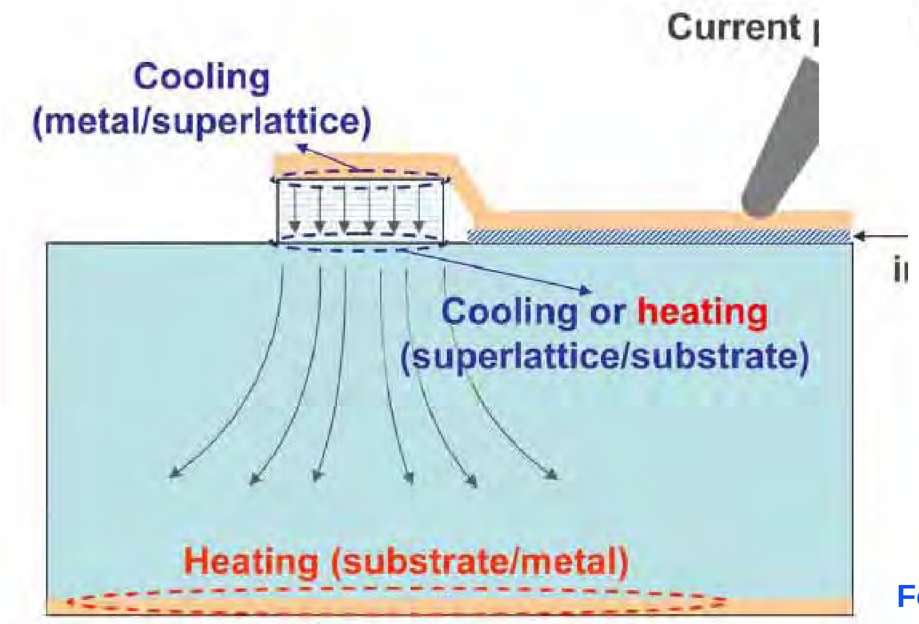
*(From M. S. Dresselhaus, Rohsenow Symposium, 2003)*

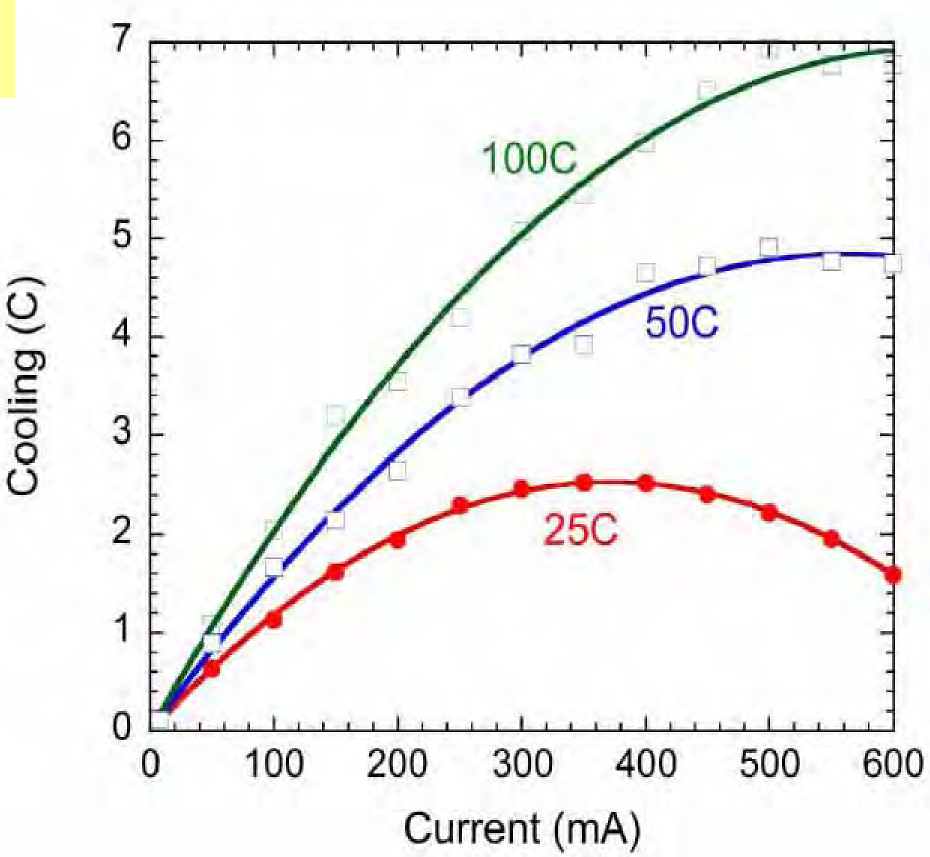
# Microrefrigerators on a chip



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



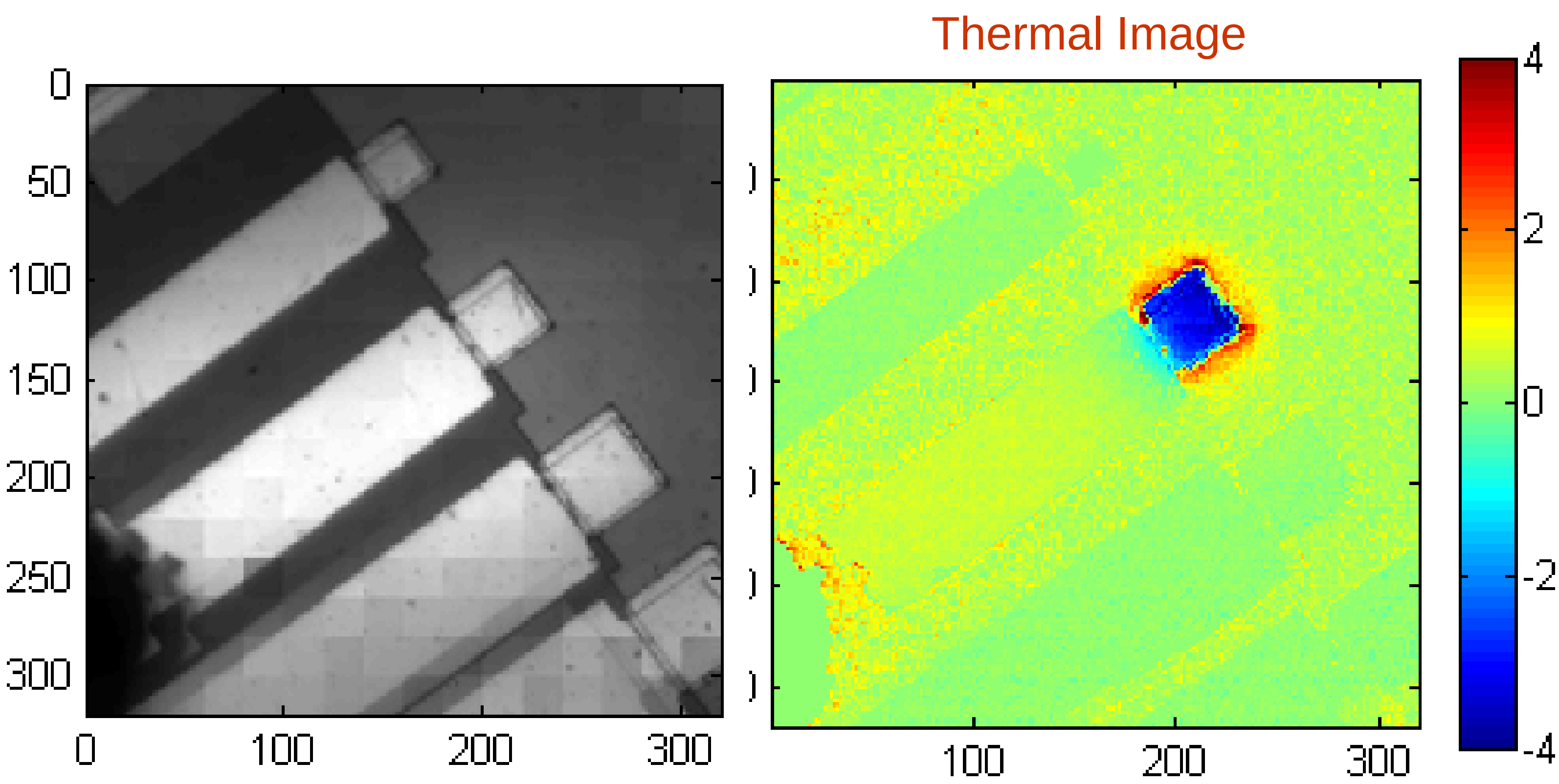

Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, **Proceedings of IEEE**, July 2006

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

# Ultra high resolution thermal imaging



- Temperature resolution: 0.006ºC
- Spatial resolution: submicron

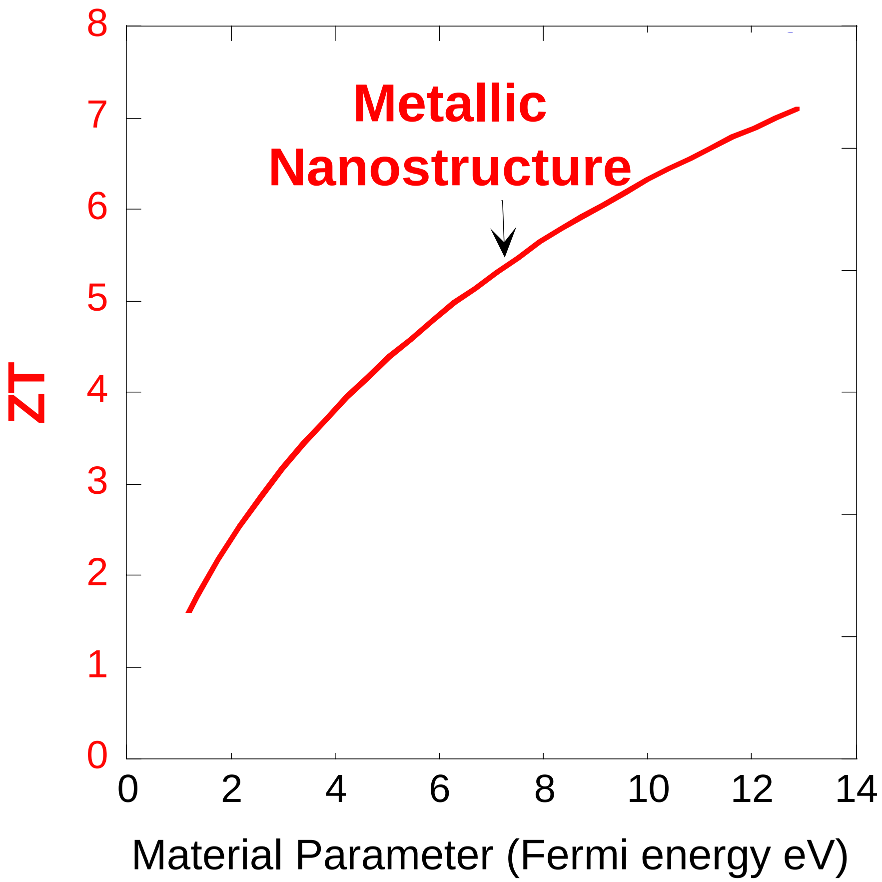


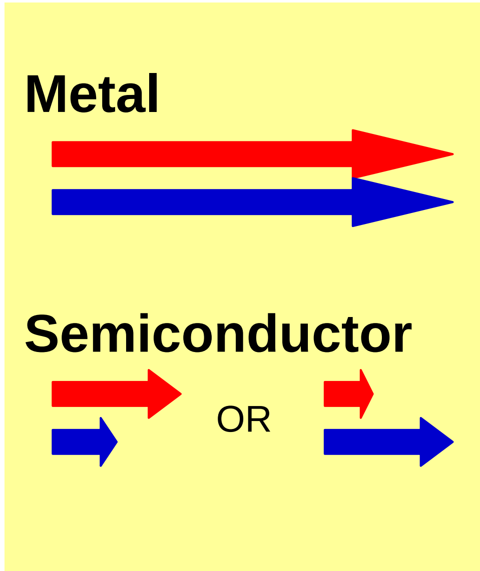
UCSC
Berkeley
Harvard
MIT
NCSU
Purdue
UCSB

Director:
A. Shakouri

Program Manager:
Mihal Gross

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




Electrons moving in the material

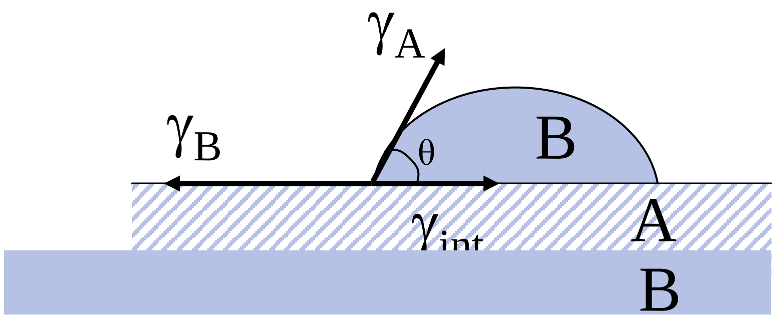
D. Vashaee., A. Shakouri, Physical Review Letters March 12, 2004

ZT>5 is possible with metallic structures with hot electron filters.

# Can metal/semiconductor multilayers be grown?



***Challenge:*** *No prior examples of metal/semiconductor multilayers or superlattices with nanoscale periods*



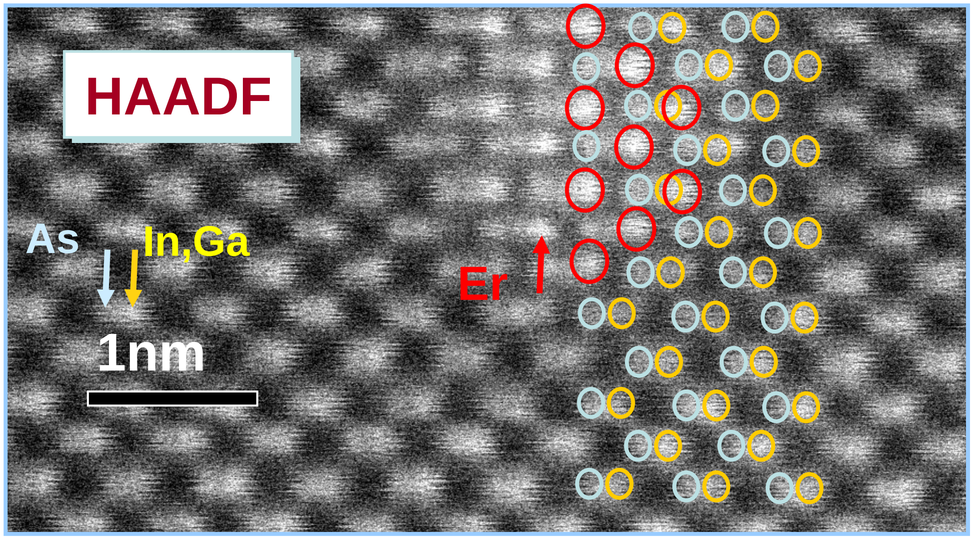

Late 80's: High speed metal base transistors $\rightarrow$ Not successful

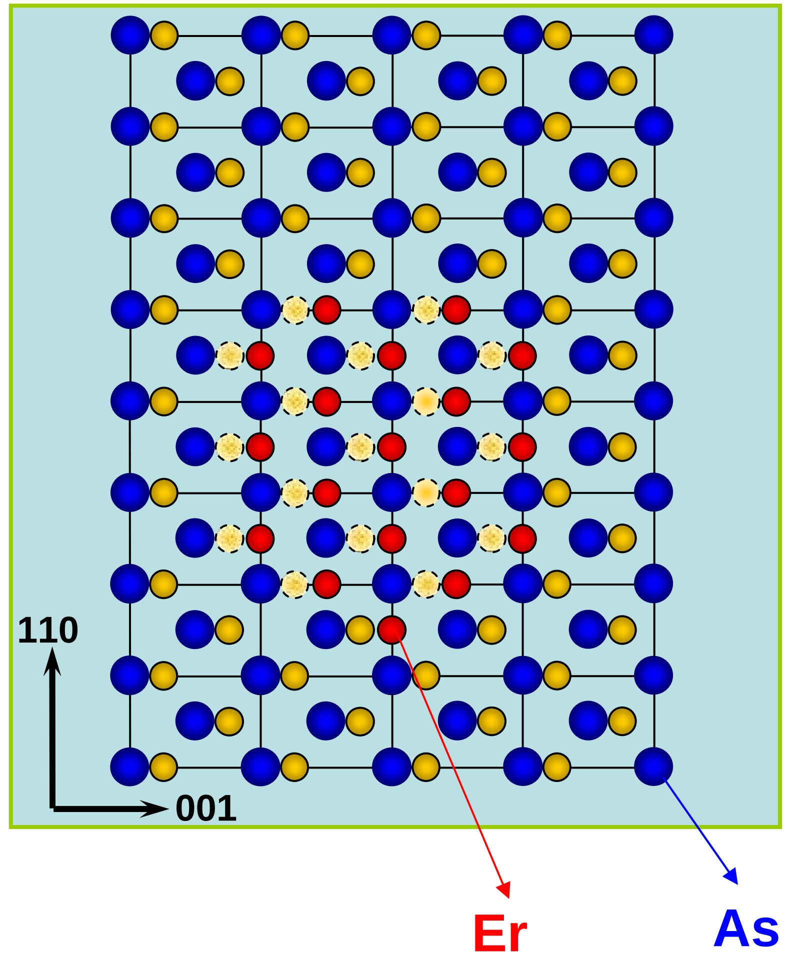
- Minimization of surface energy: If A wets B, B will not wet A.
- Different crystal structures: high defect density; multilayer will not be stable
- Lattice mismatch effect: strain may lead to island growth

**Tim Sands (Purdue)**

# High Resolution Microscopy of ErAs Nanoparticles





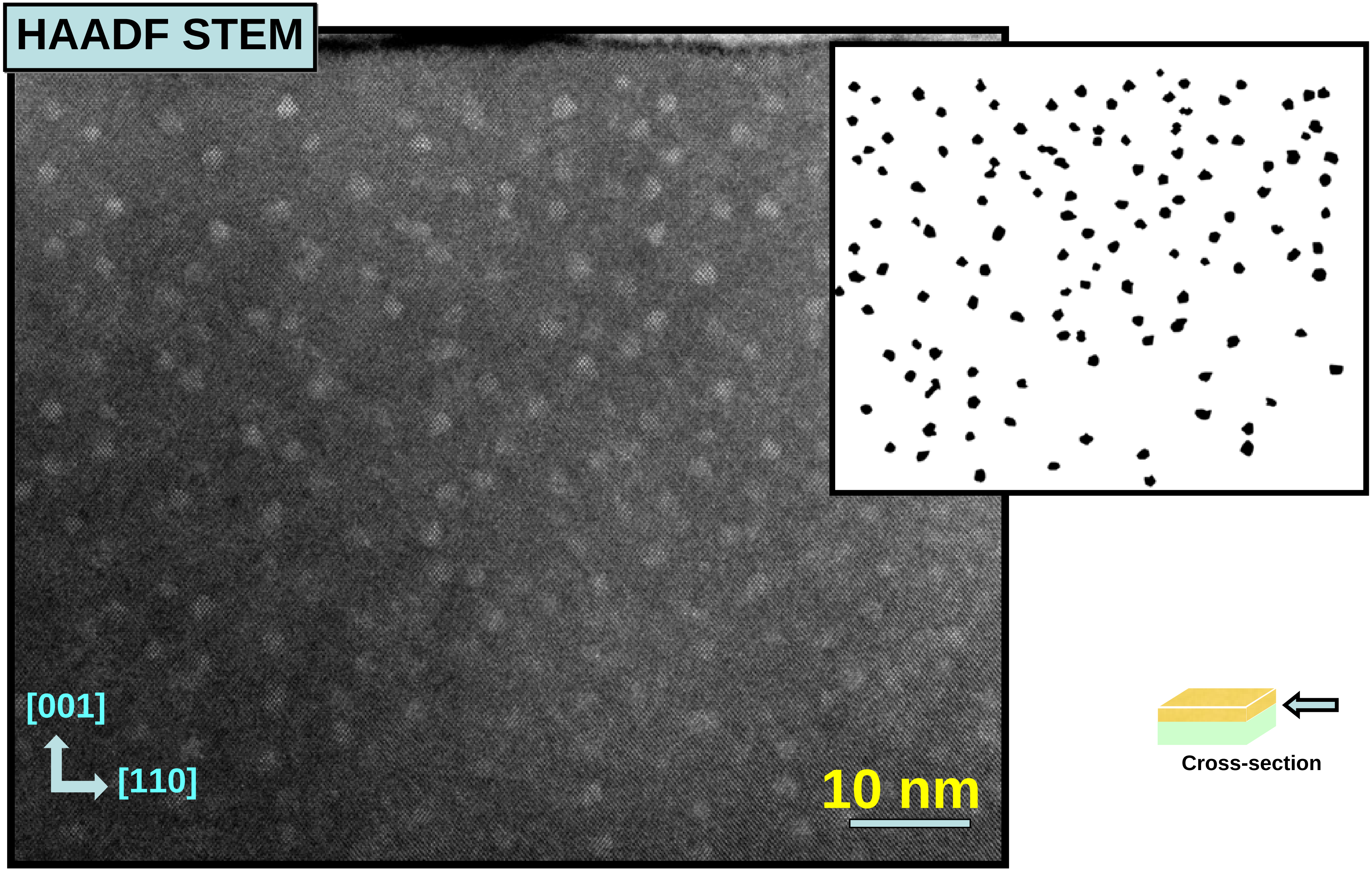




**ErAs particles have the rock salt structure and they are embedded inside InGaAs semiconductor.**

D. O. Klenov, D. C. Driscoll, A. C. Gossard, S. Stemmer, Appl. Phys. Lett. 86, 111912 (2005)

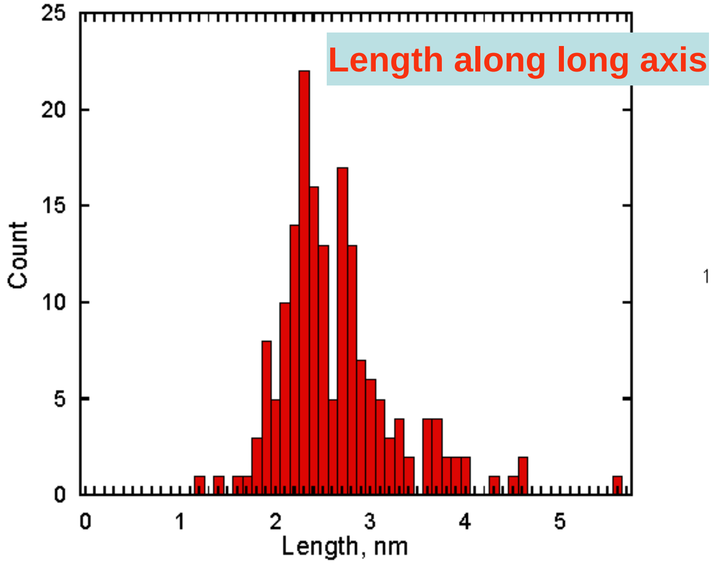
# Particle size distribution for 3% ErAs

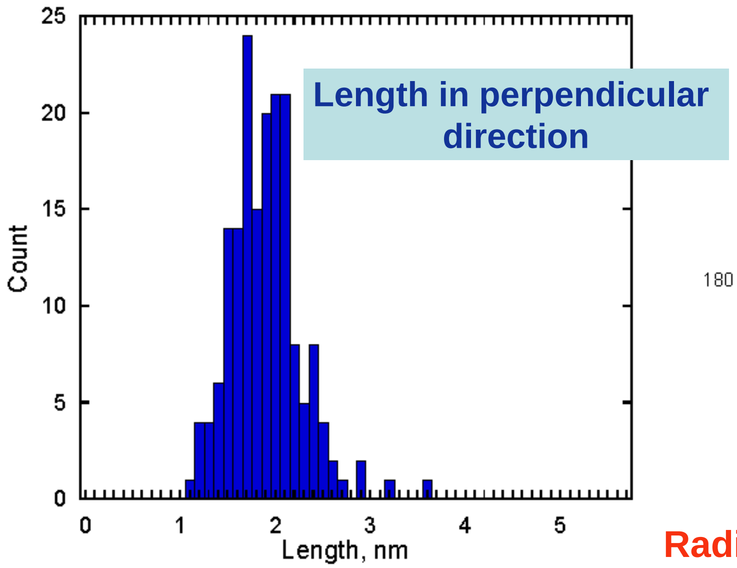




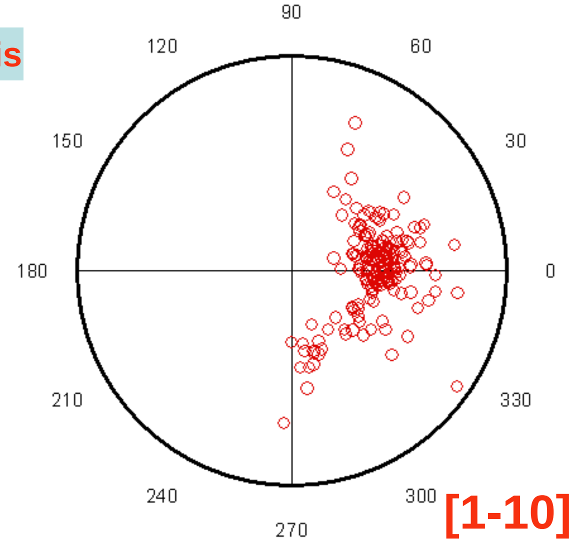
# Particle sizes and shapes for 3% ErAs

## Size

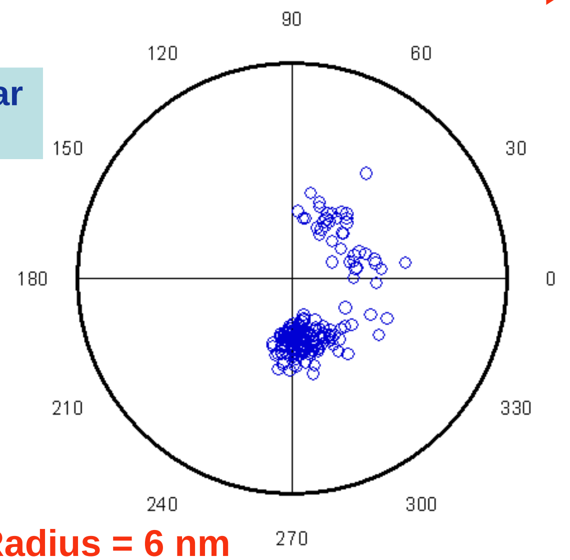



## Orientation



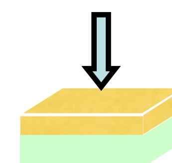

[1-10]




Radius = 6 nm

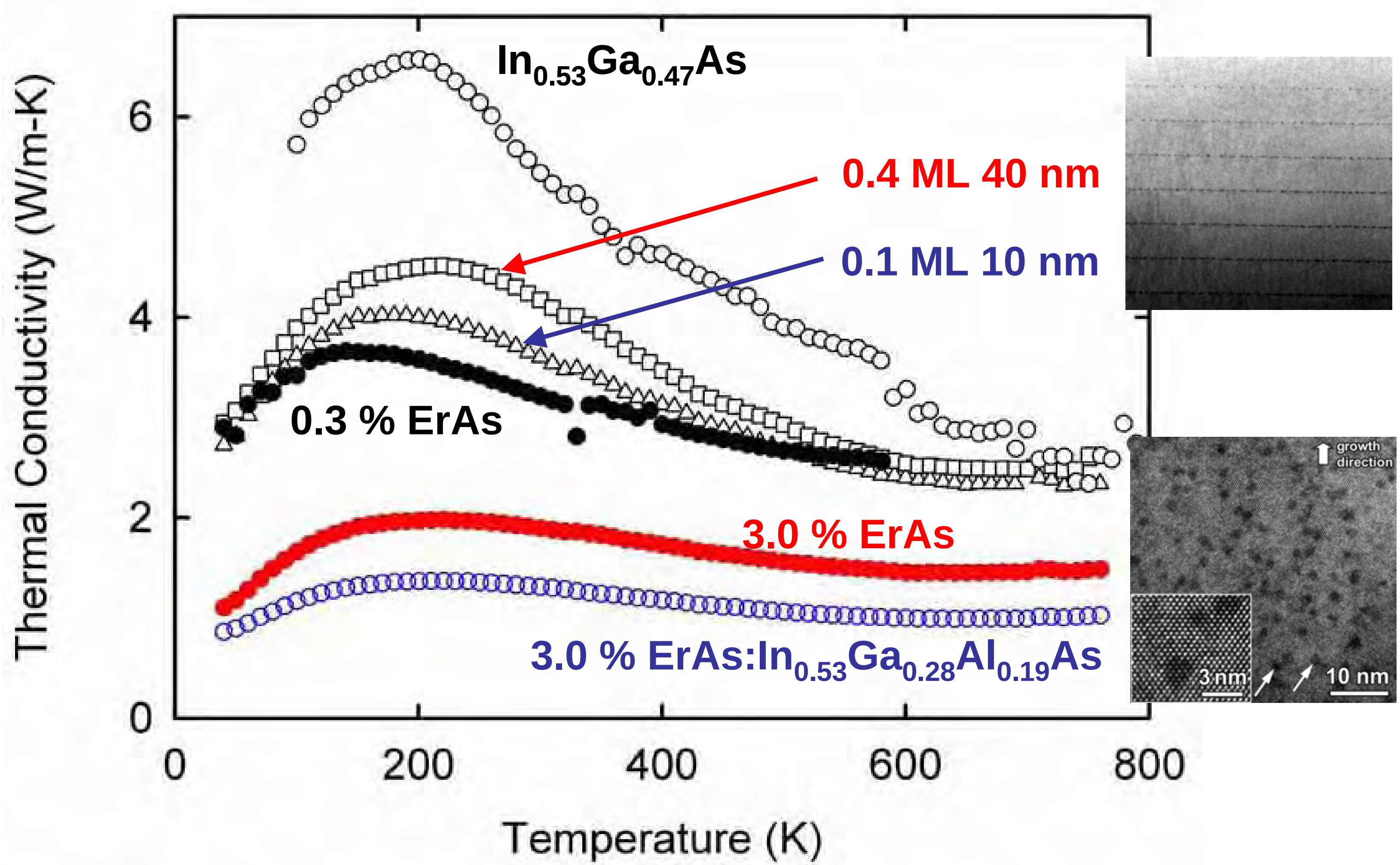
- **Particles are slightly elongated (~ 28%) along the fast [1-10] diffusion direction**

**Similar results as for superlattices.**



# Thermal Conductivity of ErAs:$In_{0.53}Ga_{0.47}As$

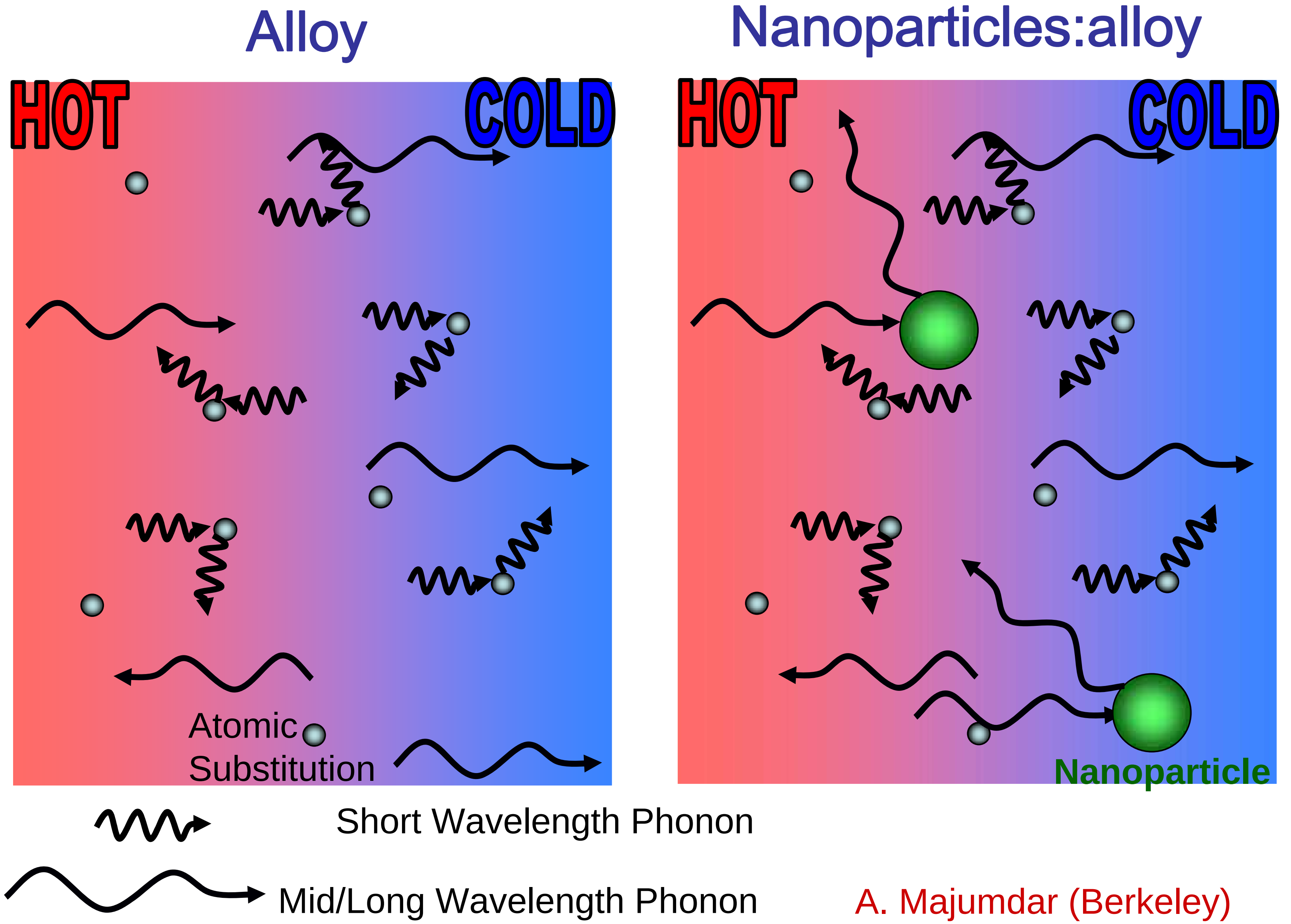





Kim et al., *Physical Review Letters*, **30,** 045901 (2006)

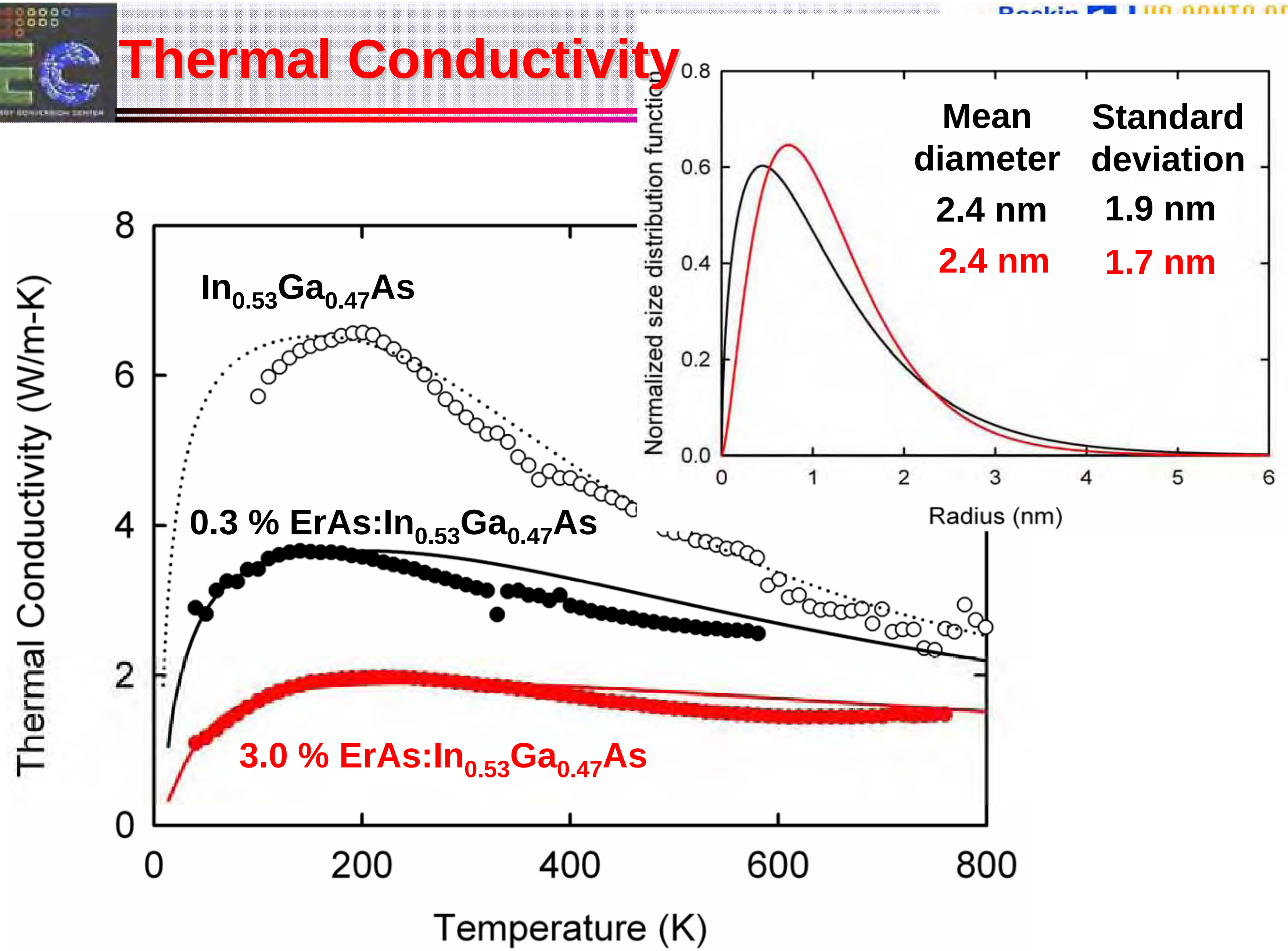
# Why Thermal Conductivity is Reduced?






A. Majumdar (Berkeley)

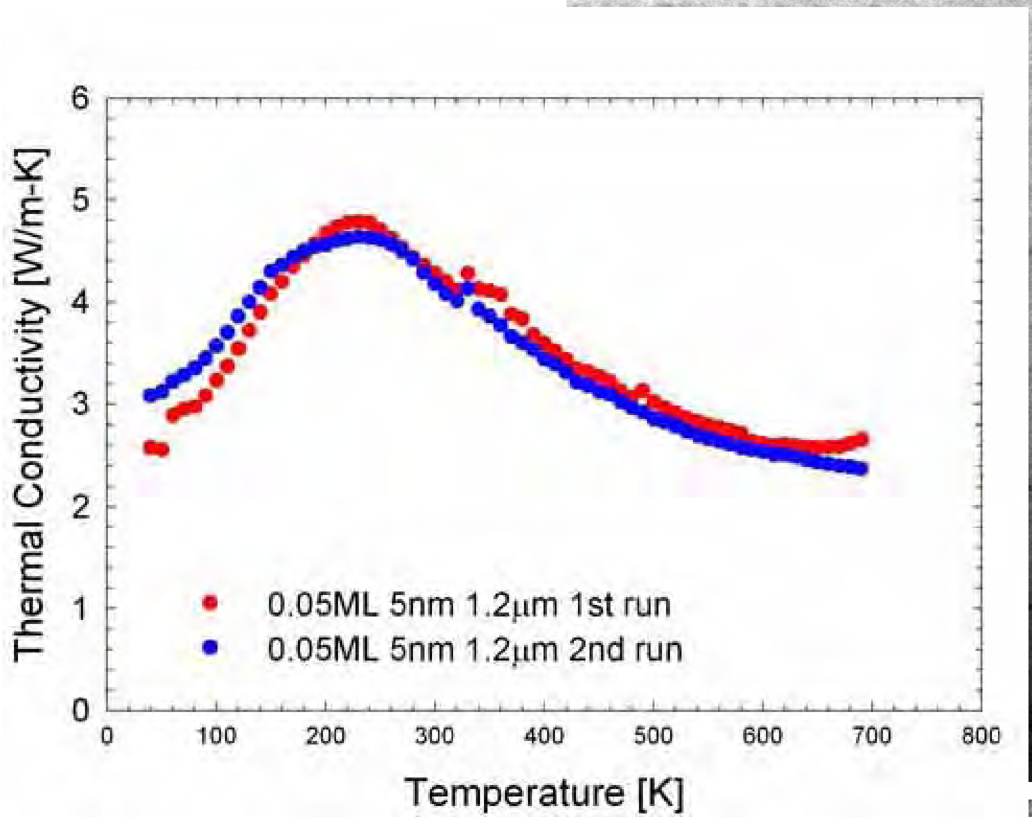
# Thermal Conductivity

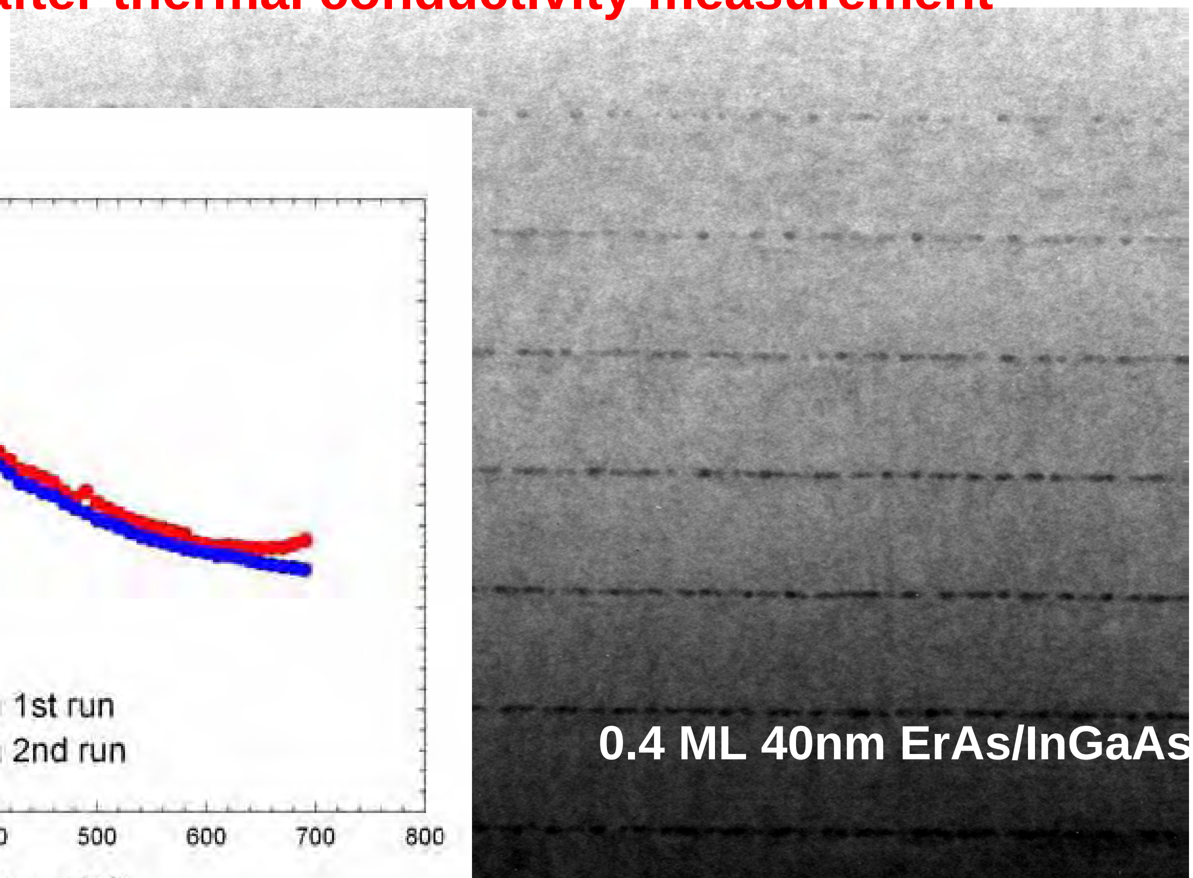


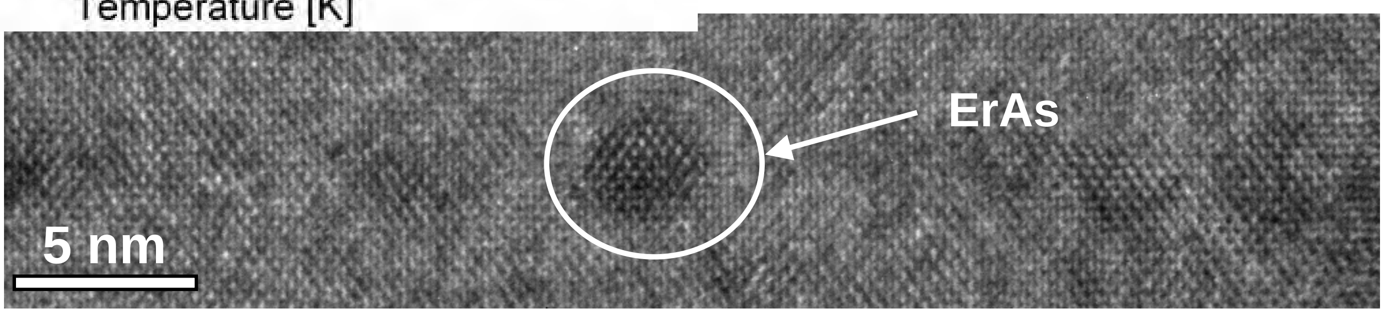

Kim et al., *Physical Review Letters*, **30,** 045901 (2006)

# Material stability

## ErAs/InGaAs TEM after thermal conductivity measurement



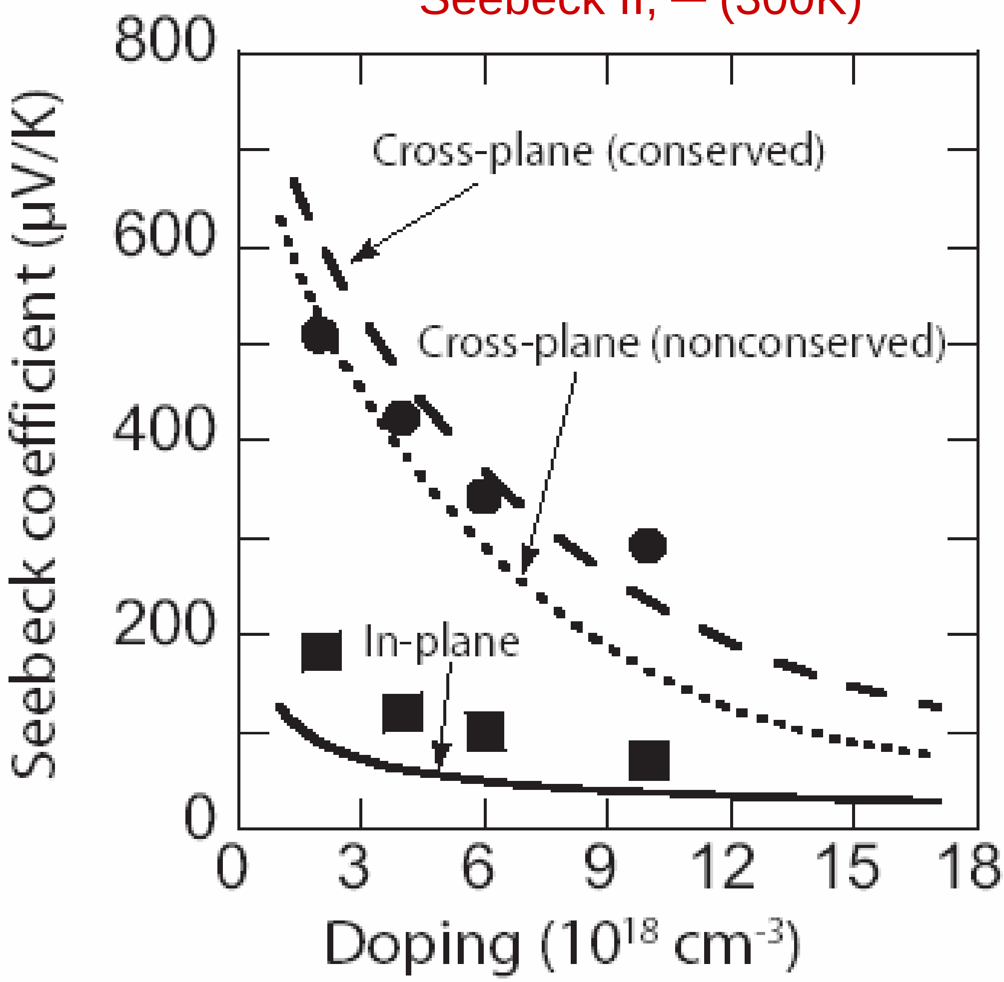




images from D. Klenov (UCSB)

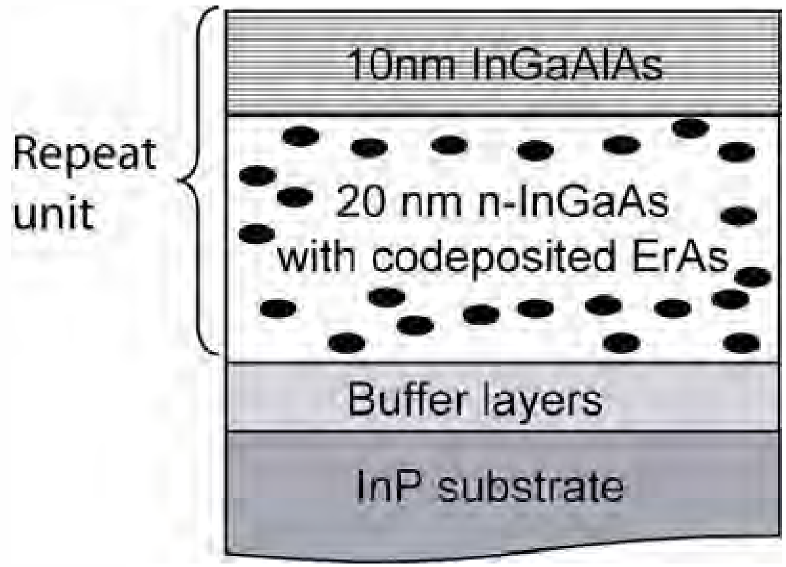
# Improve Seebeck using Energy Filters



Theory/Experiment
Seebeck II, ⊥ (300K)



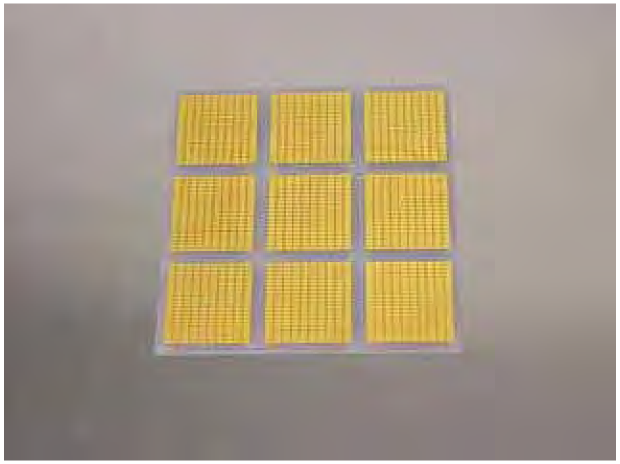

## ErAs:InGaAs /InGaAlAs Superlattices

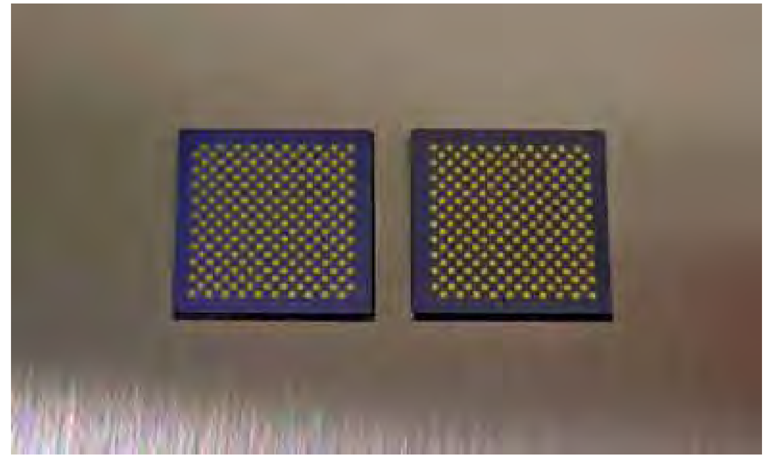


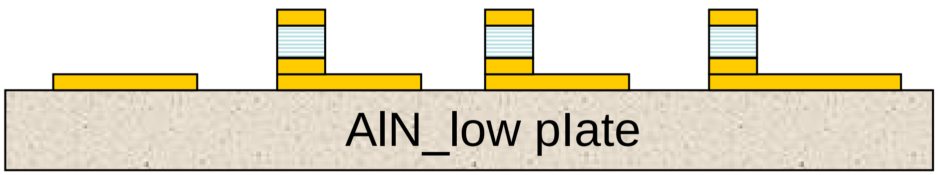

**J. Zide et al., (UCSB, UCSC) Physical Review B, 2006**

# Wafer scale module fabrication

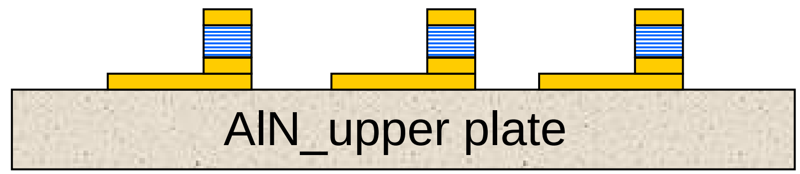






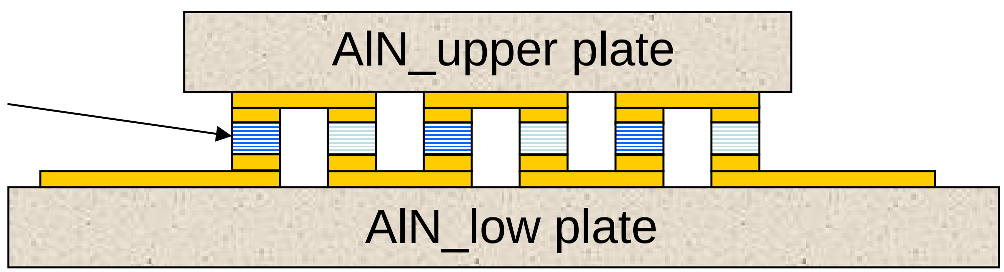



200 elements of p-ErAs array




200 elements of n-ErAs array

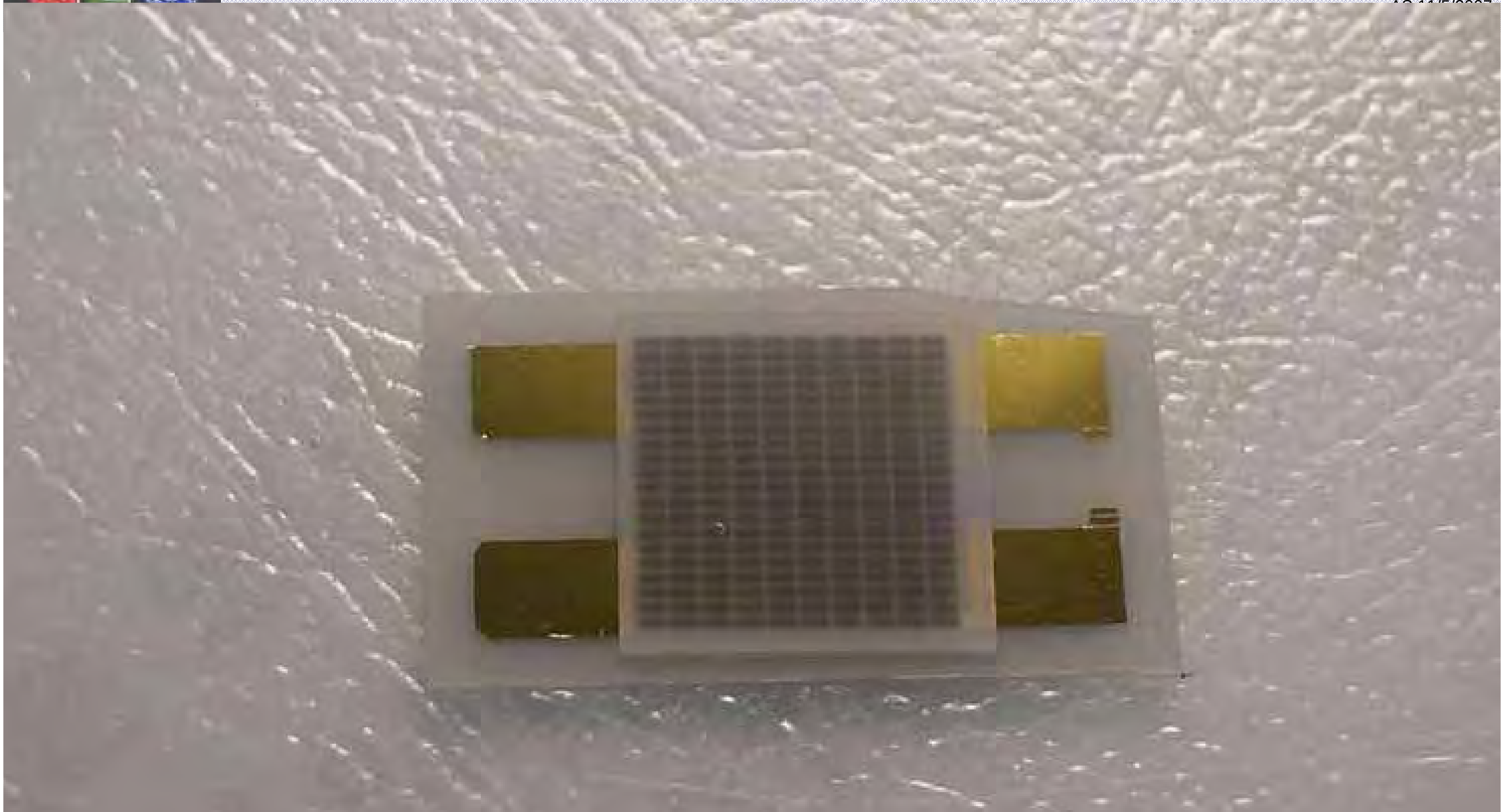
20 μm elements




400 element generator

**Gehong Zeng, John Bowers (UCSB)**

# Module Fabrication



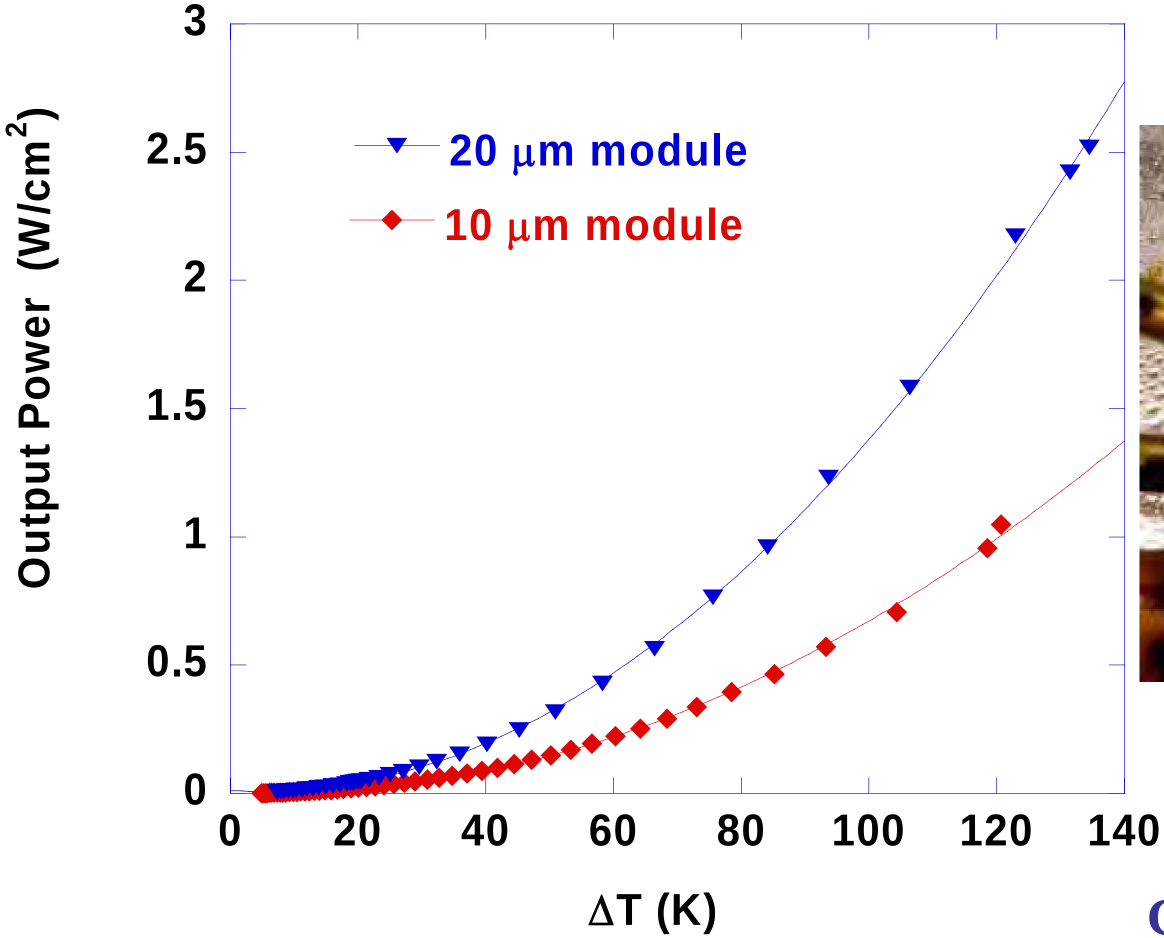
**400 element ErAs:InGaAlAs thin film generator**

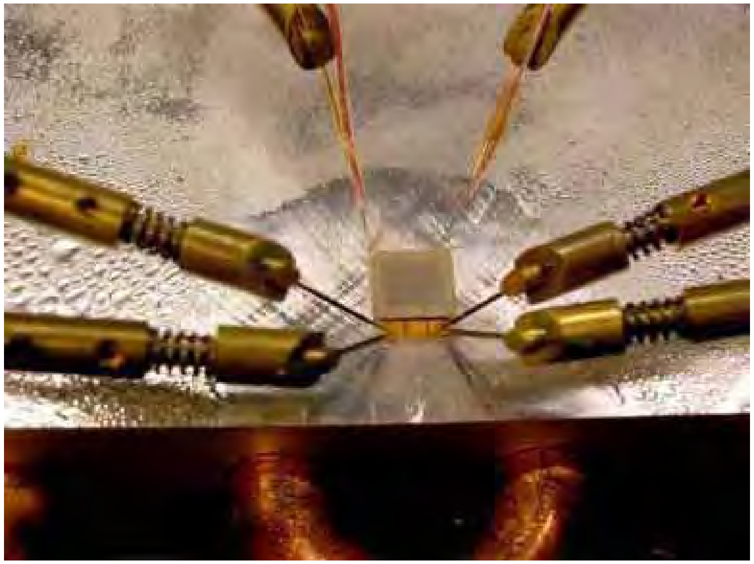
Gehong Zeng, John Bowers (UCSB)

# Module Power generation results



400 elements (10-20 microns ErAs:InGaAlAs thin films, 120x120$\mu m^2$)



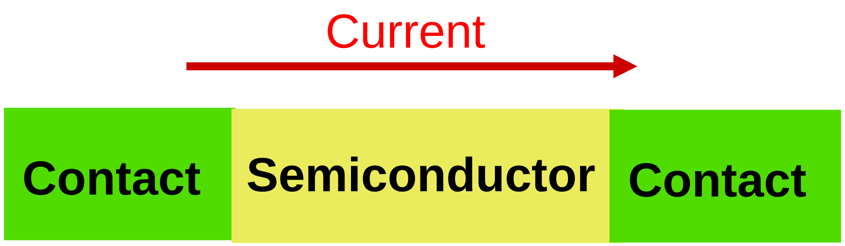



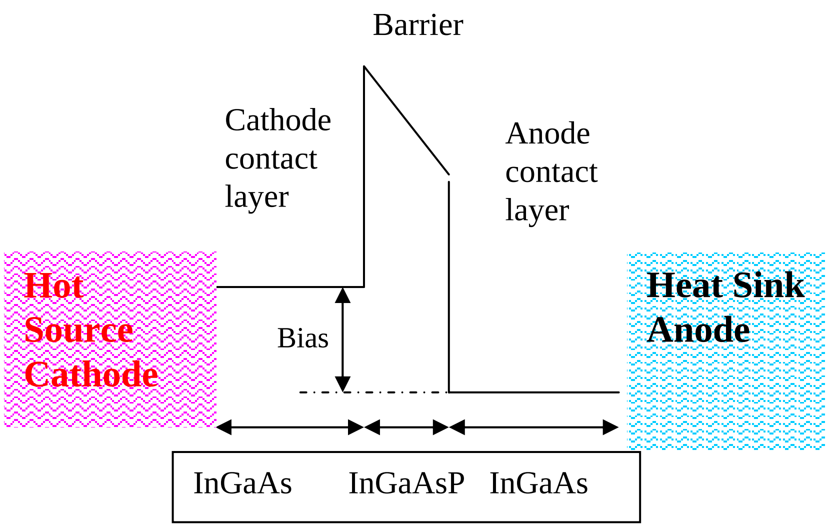
140 µm/140 µm AlN

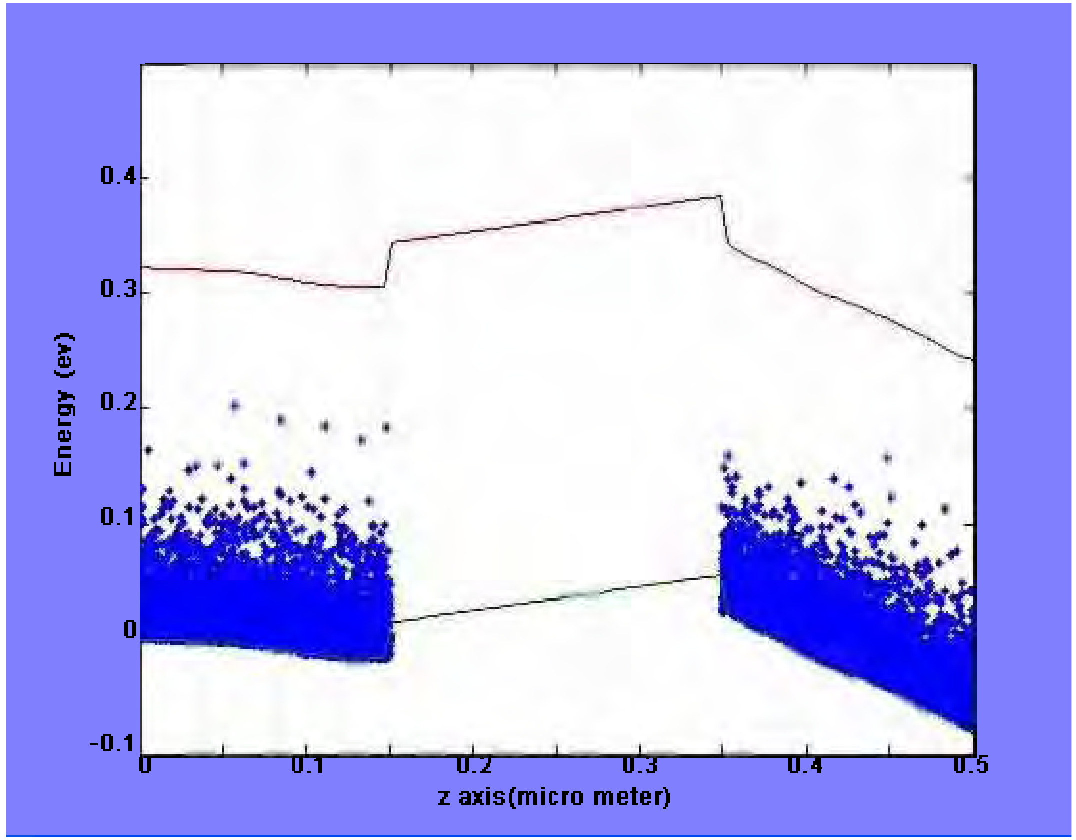
G. Zeng, J. Bowers, et al. (UCSB, UCSC) Appl. Physics Letters 2006

# Where does Peltier cooling happen?





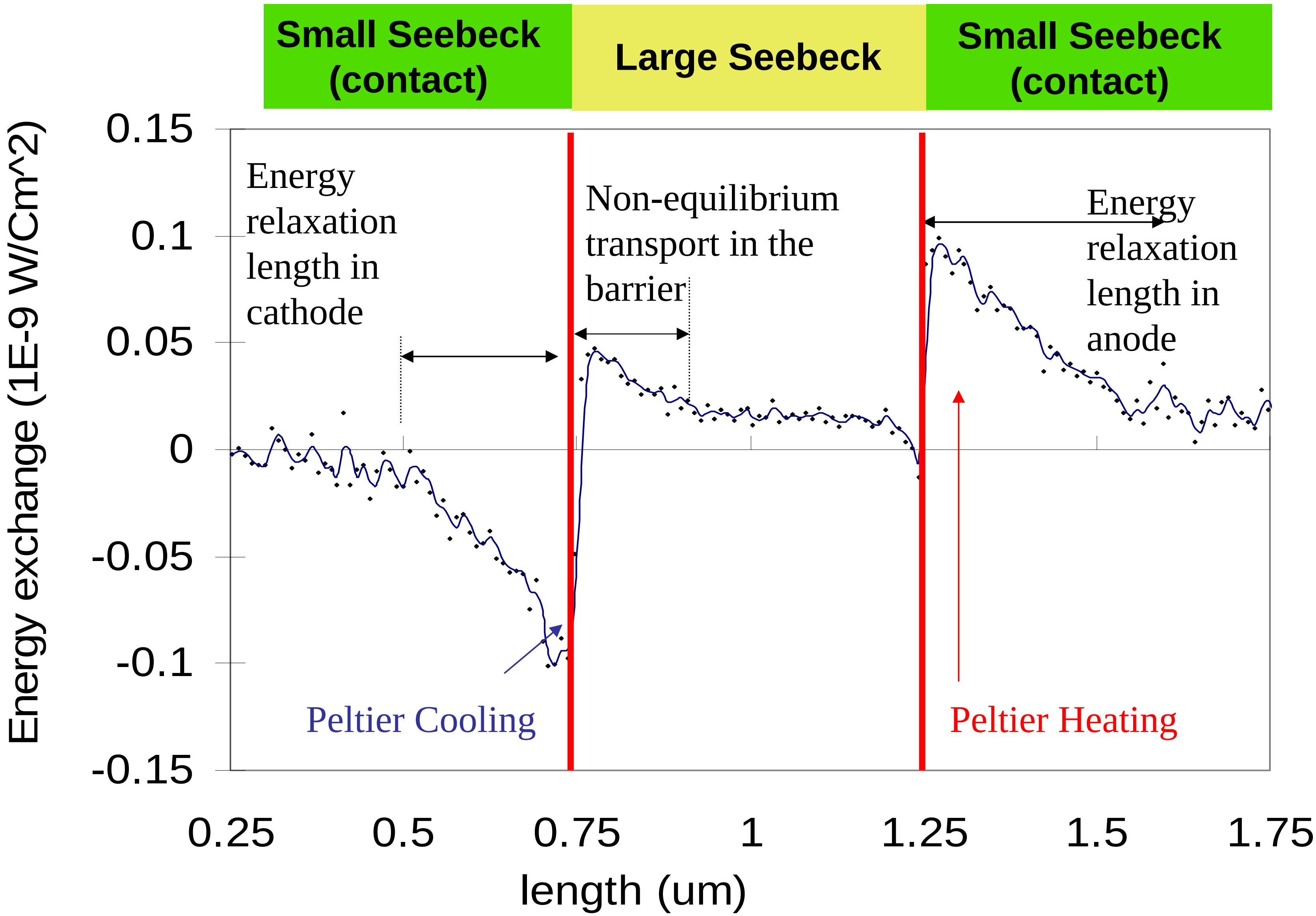




Distance

**Mona Zebarjadi, Keivan Esfarjani, Ali Shakouri Phys. Rev. B 74, 195331 (2006)**

# *Electron-crystal energy exchange*

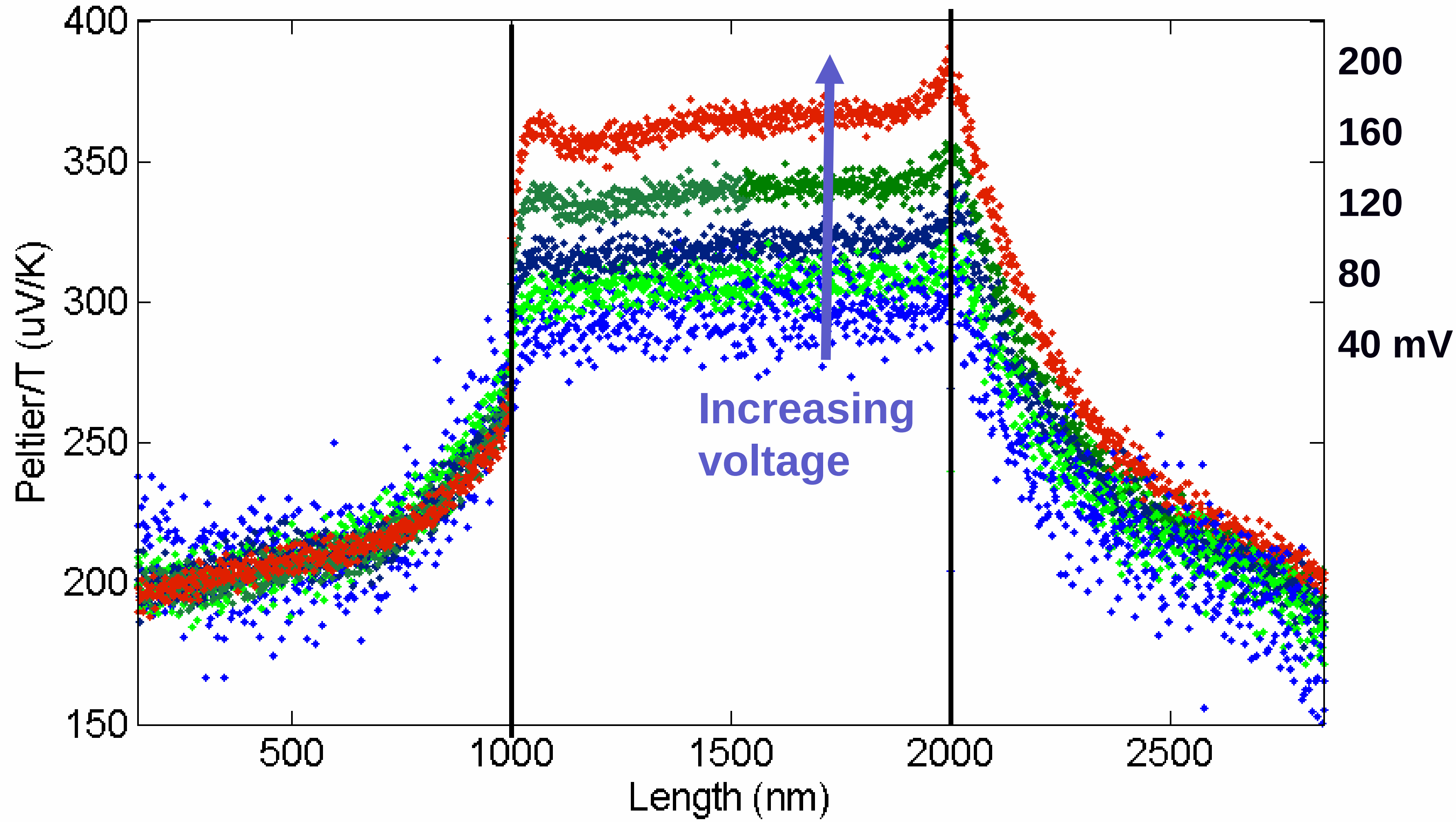





Mona Zebarjadi, K. Esfarjani, A. Shakouri, Phys. Rev. B, 74, 195331 (2006)

# Nonlinear Peltier Coefficient






**Mona Zebarjadi, Keivan Esfarjani, A. Shakouri –Applied Physics Letter 2007**

# SUMMARY (quantum.soe.ucsc.edu)

**Students/postdocs**

**UCSC**
**Zhixi Bian, Rajeev Singh, Mona Zebarjadi, Yan Zhang Daryoosh Vashaee, Tammy Humphrey**

**Berkeley**
**Woochul Kim**
**Susanne Singer**

**Harvard**
**Kasey Russel**

**MIT**
**Peter Mayer**

**Purdue**
**Vijay Rawat**

**UCSB**
**Josh Zide, Gehong Zeng, J-H Bahk**

- Significant amount of waste heat is generated in cars, power plants, etc.
- Thermoelectric generators can convert heat into electricity without any moving parts
- The efficiency of thermoelectric energy conversion can be improved with the use of nanostructures (increase Seebeck coefficient and electrical conductivity and reduce thermal conductivity)
  - Potential of semimetallic ErAs nanoparticles in InGaAlAs semiconductor matrix

**Acknowledgement: ONR MURI, Packard Foundation**