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Challenges and Opportunities in Thermoelectric Materials Research for Automotive Applications

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CAML: Complex and Advanced Materials Laboratory

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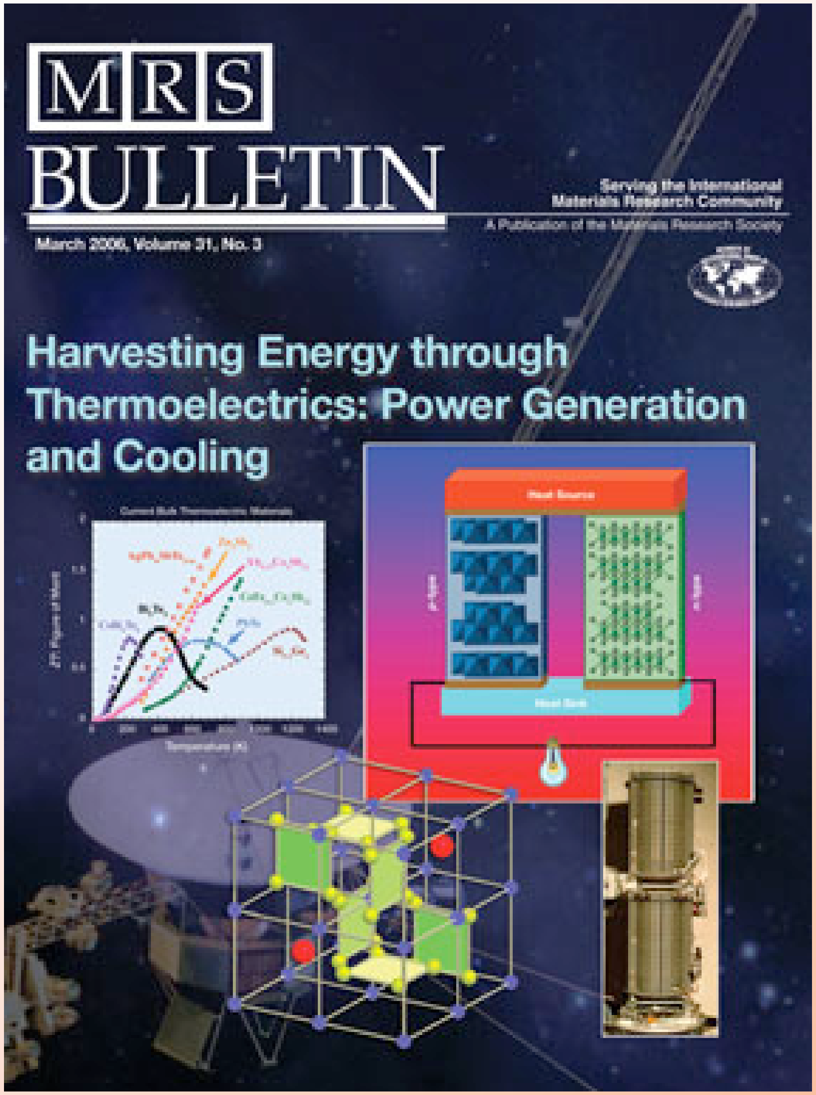
MRS Bulletin: Thermoelectrics, March 2006
Guest Editors: Terry M. Tritt and M. A. Subramanian



Introduction & Overview

Bulk TE Materials

Oxide TE's

Nano-structured TE Materials

Applications of TE Materials

Thin Film TE's

MRS Bulletin, Volume 31, No 3, March 2006

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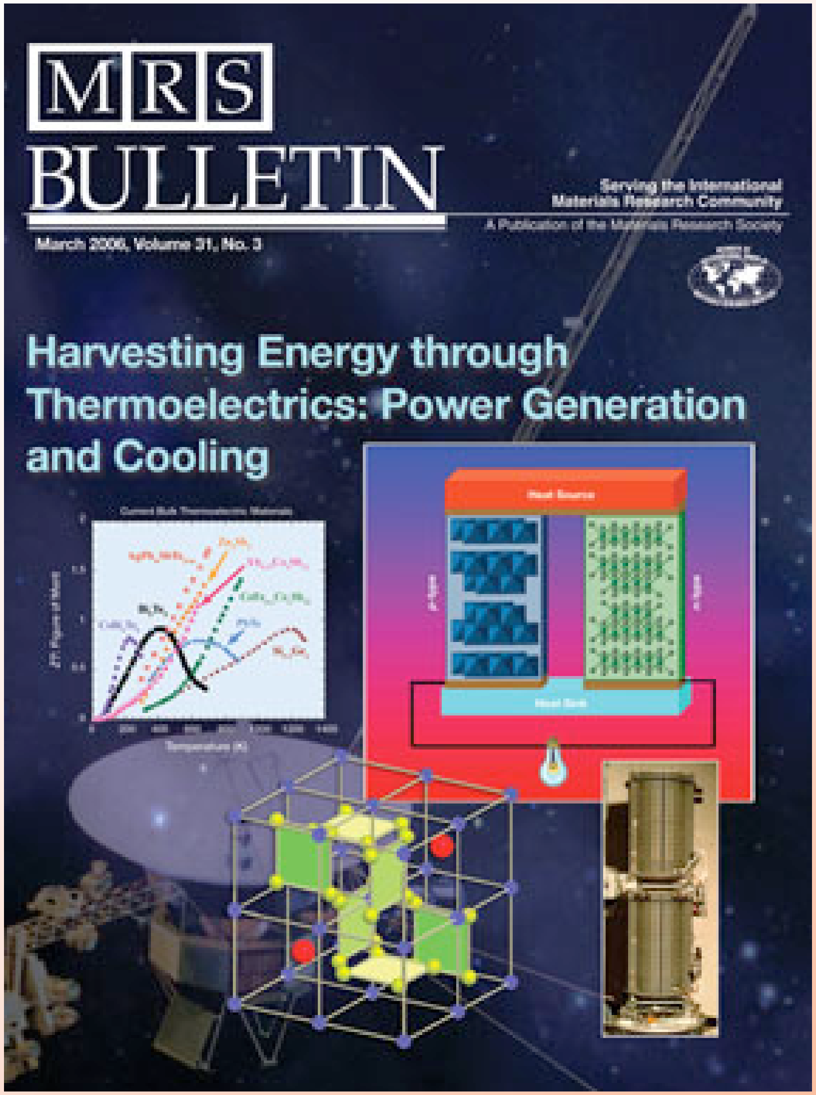


Introduction & Overview

Bulk TE Materials

Oxide TE's

Nano-structured TE Materials

Applications of TE Materials
(Automotive & Deep Space)

Thin Film TE's

MRS Bulletin, Volume 31, No 3, March 2006

Research Drivers

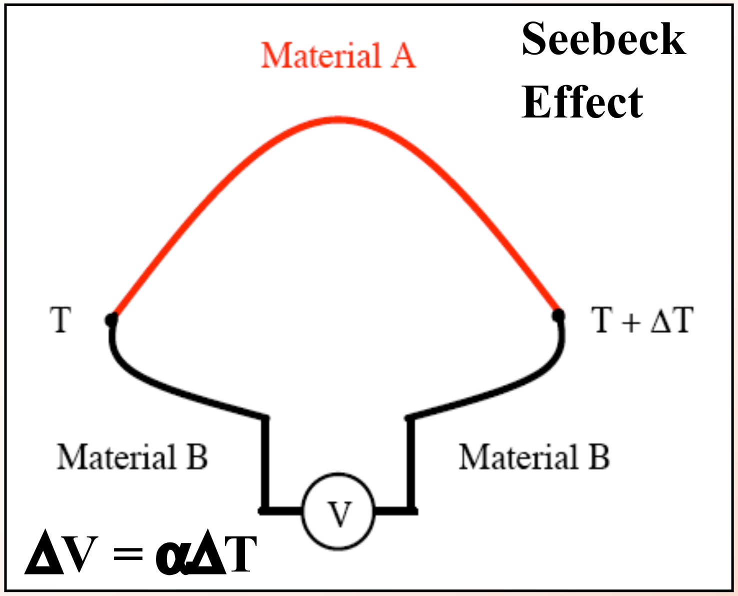
Desperately Need Alternative Energy Sources
over next 20 years

Automotive & Industrial
Waste Heat Recovery (eg. DOE-EERE, etc.)

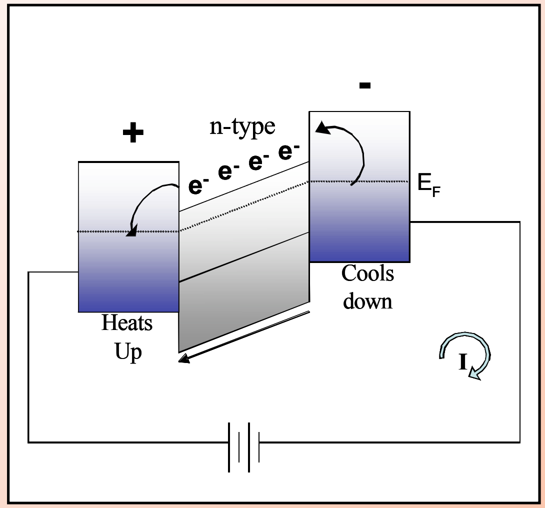
DOD Needs for
On Board Ship Power Systems & Cooling
Soldier 2020 Power Density Requirements

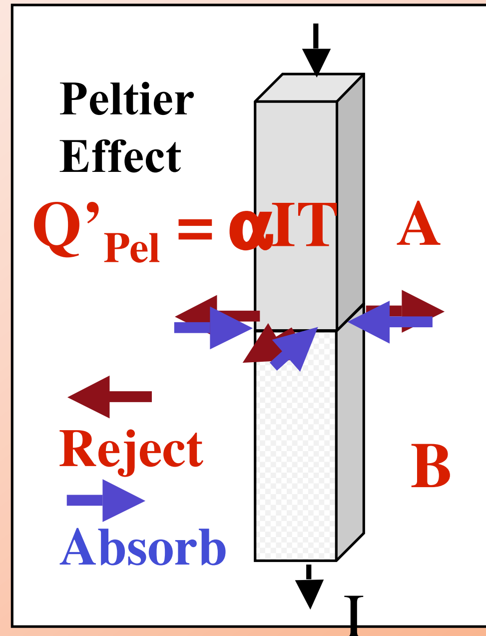
Solar Energy Conversion (DOE-BES)
Solar TE Thermal Storage & Conversion

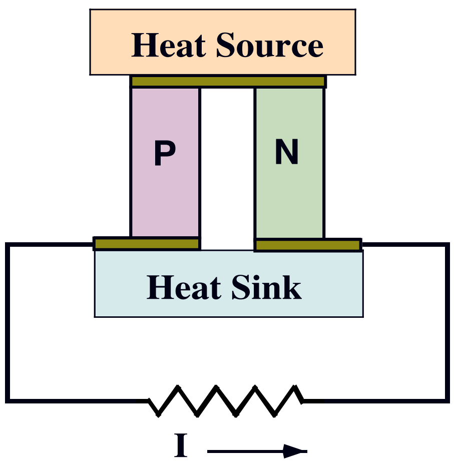
Overview of Thermoelectric Phenomena



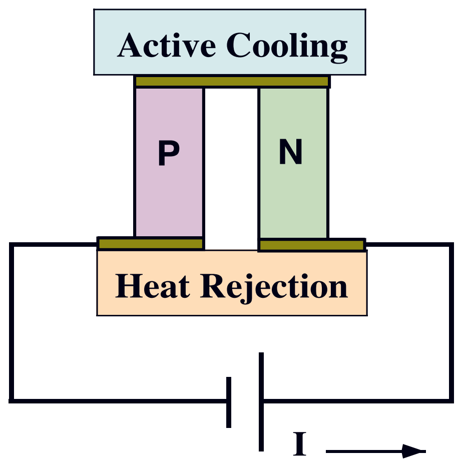
$Q'_{PEL} = \alpha I T$



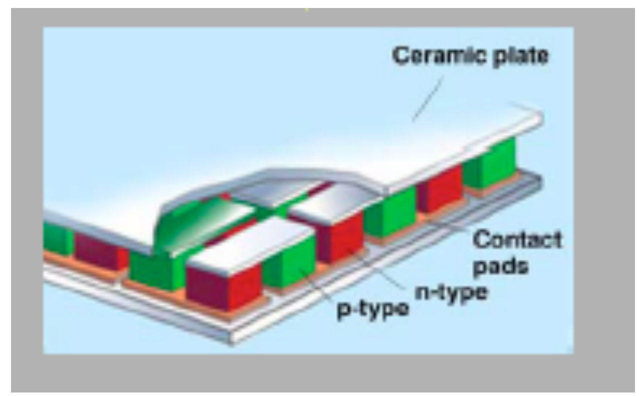




Power Generation Mode



Cooling Mode



Electrically in Series
Thermally in Parallel

The Thermoelectric Figure of Merit (ZT)

Efficiency ($\eta \approx ZT$)

$$ZT = \frac{\alpha^2 \sigma T}{(\kappa_E + \kappa_L)} = \frac{\alpha^2 T}{\rho}\left(\frac{1}{\kappa_E + \kappa_L}\right)$$

α = Thermopower
σ = Electrical Conductivity
ρ = Electrical Resistivity
κ_E = Electronic Thermal Conductivity
κ_L = Phonon Thermal Conductivity

To Evaluate the **Figure of Merit (ZT)**

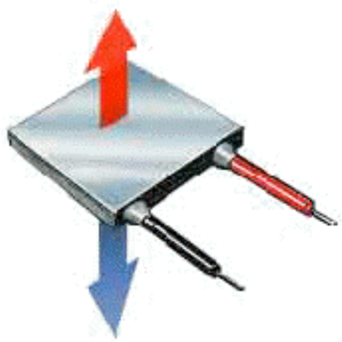
Requires the measurement of the properties over a broad range of temperature.

Low Temperatures (10K < T < 320K)
High Temperatures (300K < T < 1200K)

$$ZT = \frac{\alpha^2 \sigma T}{(\kappa_E + \kappa_L)} = \frac{\alpha^2 T}{\rho}\left(\frac{1}{\kappa_E + \kappa_L}\right)$$

α = Thermopower
σ = Electrical Conductivity
ρ = Electrical Resistivity
κ_E = Electronic Thermal Conductivity
κ_L = Phonon Thermal Conductivity

Thermal to Electricity Energy Conversion (TE)



TE Radio Lantern

TE Module Converter

Thermal Energy (Waste Heat)

Electrical Energy

Conceptually Simple Devices

TE Technology

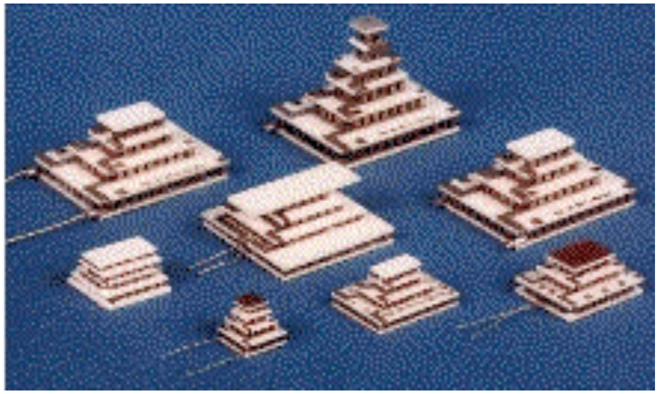
Converts Waste Heat to Electrical Energy

No Moving Parts

Solid State Technology

Several TE Commercial Applications

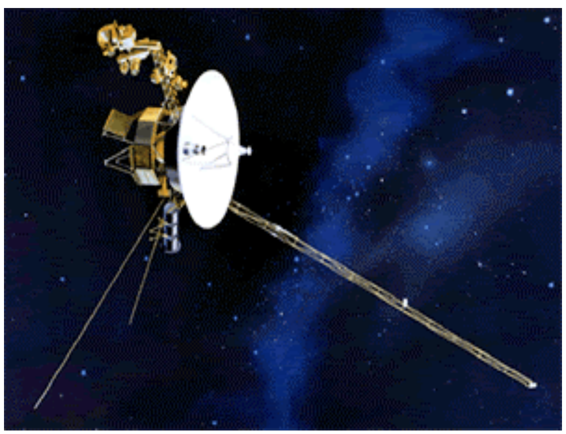
TE Modules (Marlow Indus.)



TE coolers/warmers
Coleman -Igloo

***Seiko* TE Watch**

RTG 's -- Deep Space - NASA



CCS - Climate Controlled Seat
Lexus & Lincoln etc.

TE Radio Lantern

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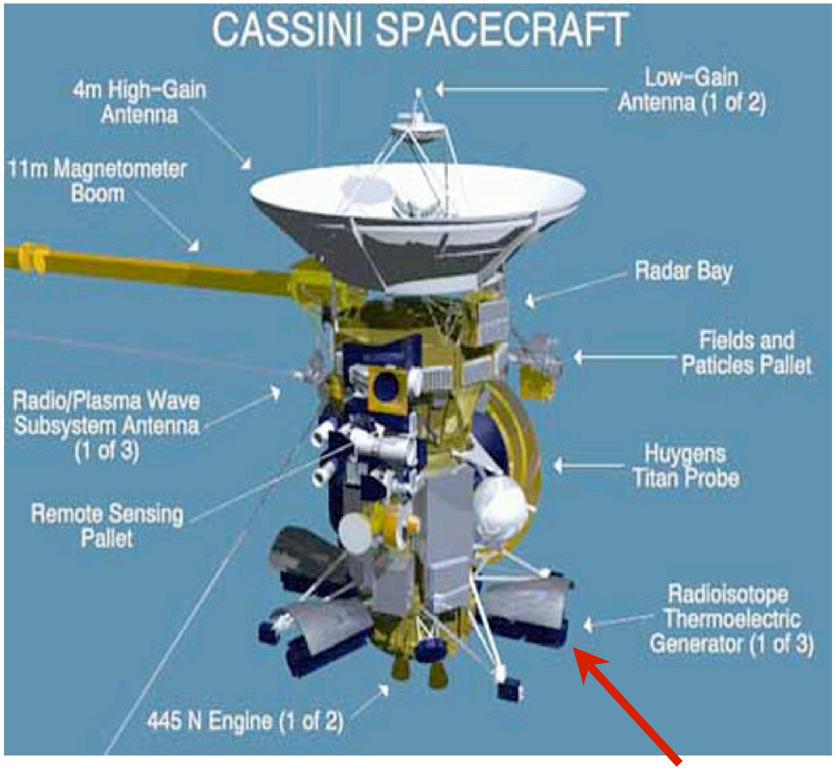
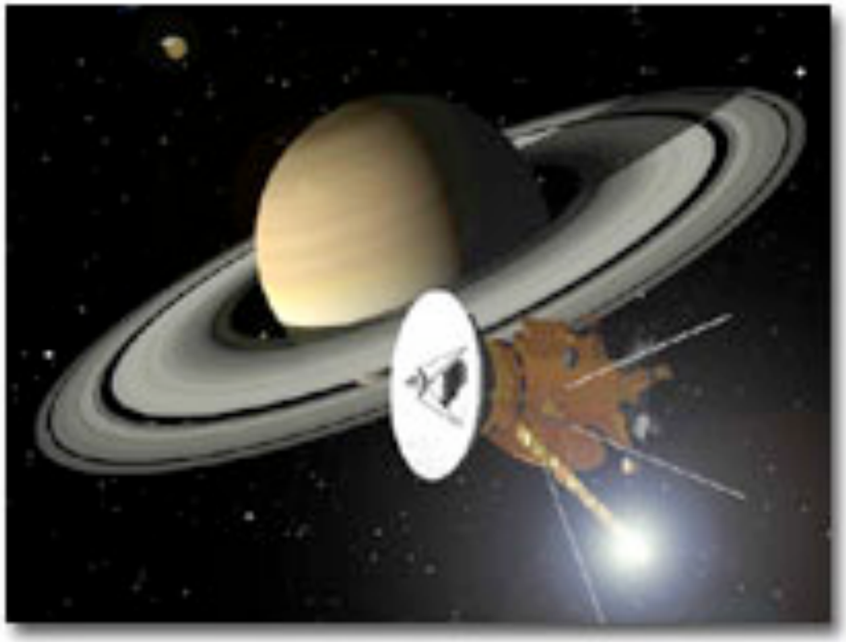
Radioisotope Thermoelectric Generator (RTG)



Cassini: Saturn's Rings

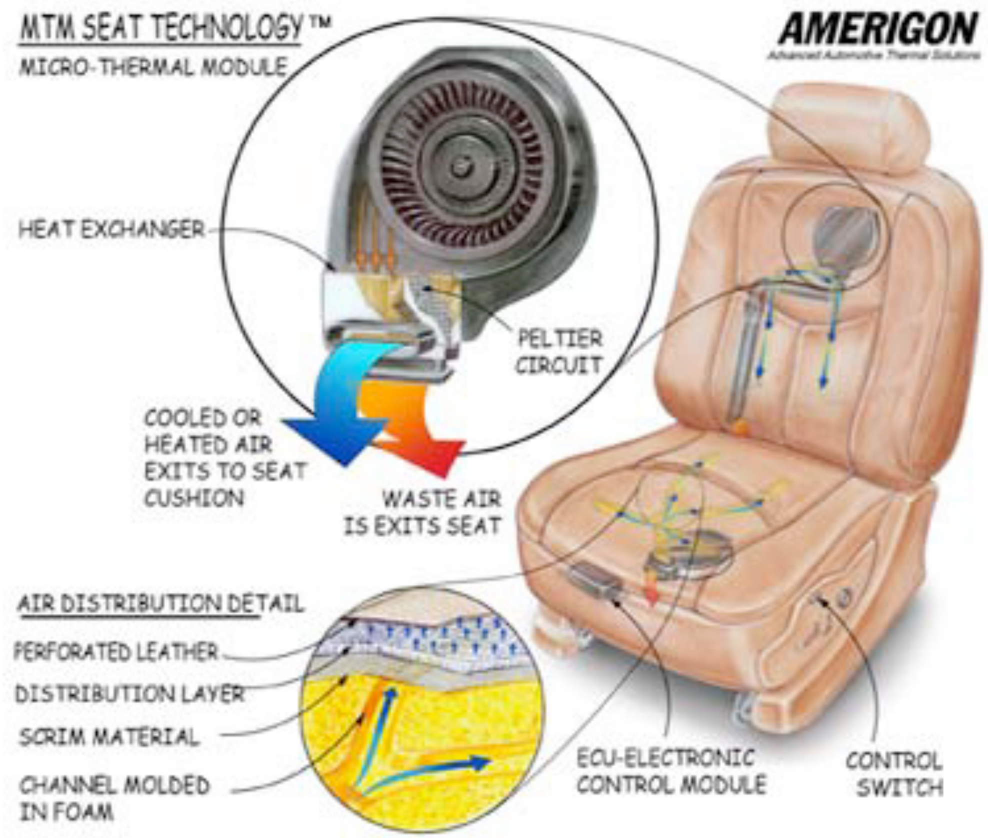


RTG's (1 of 3)
($T_H \approx 800^{\circ}$C)
≈ 300-400 Watts each

Deep Space Probes:
Cassini (≈ 1997)
See NASA Website
Pictures of Saturn's Rings
http://saturn.jpl.nasa.gov/multimedia/

Also Voyager I & II
(mid 1970's)
Can't use Solar
or Battery Power!

Automotive: The "Amerigon Climate Controlled Seat"



Climate Controlled Seat:
(cooled or warmed)

Uses new packaging
to improve efficiency.

The BSST cycle

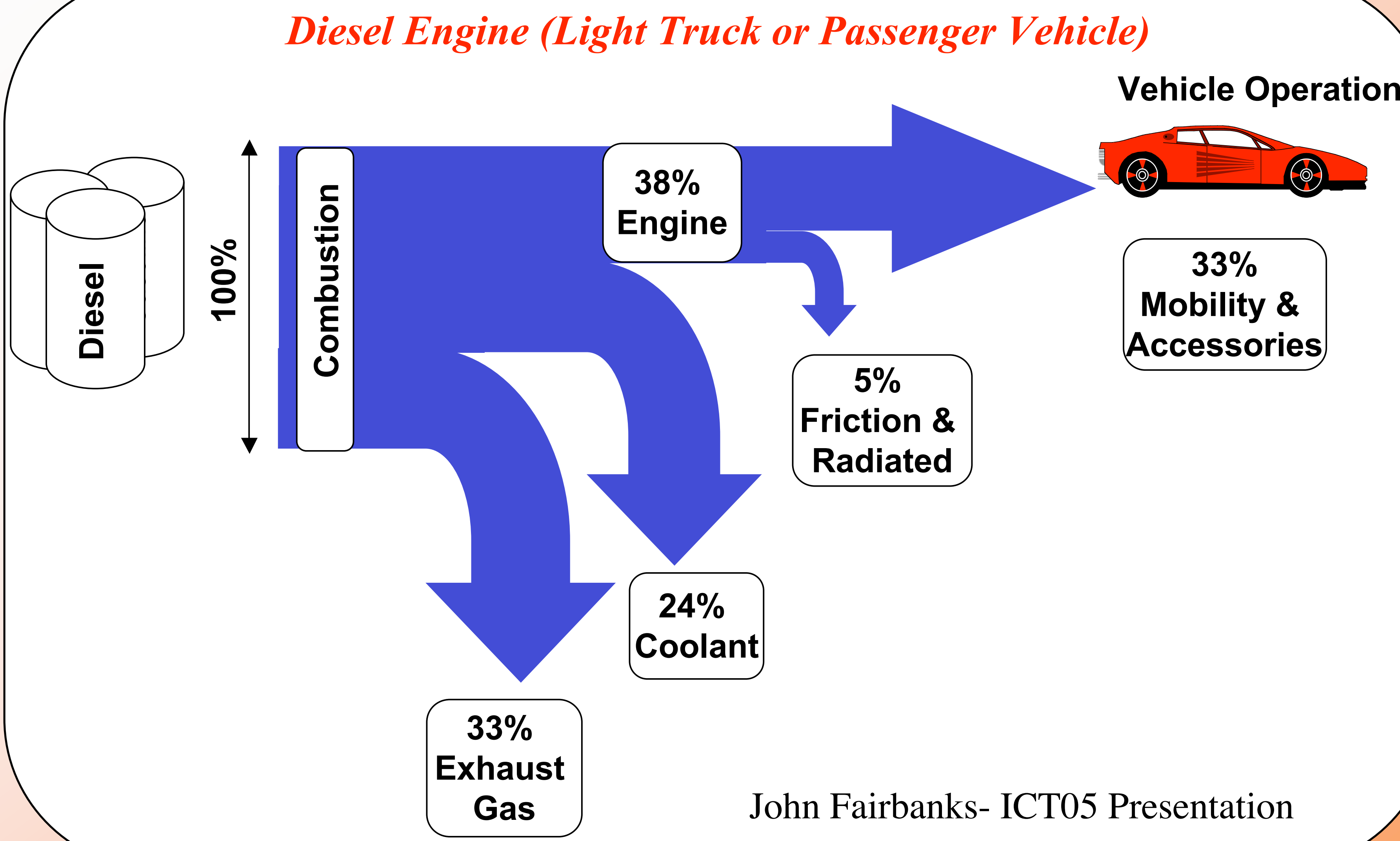
In many luxury cars:
(≈ 1 million units
sold in 2005)

Huge New market!

Climate Controlled Seat (CCS)

www.Amerigon.com

Large Waste Heat in Automotive Propulsion System

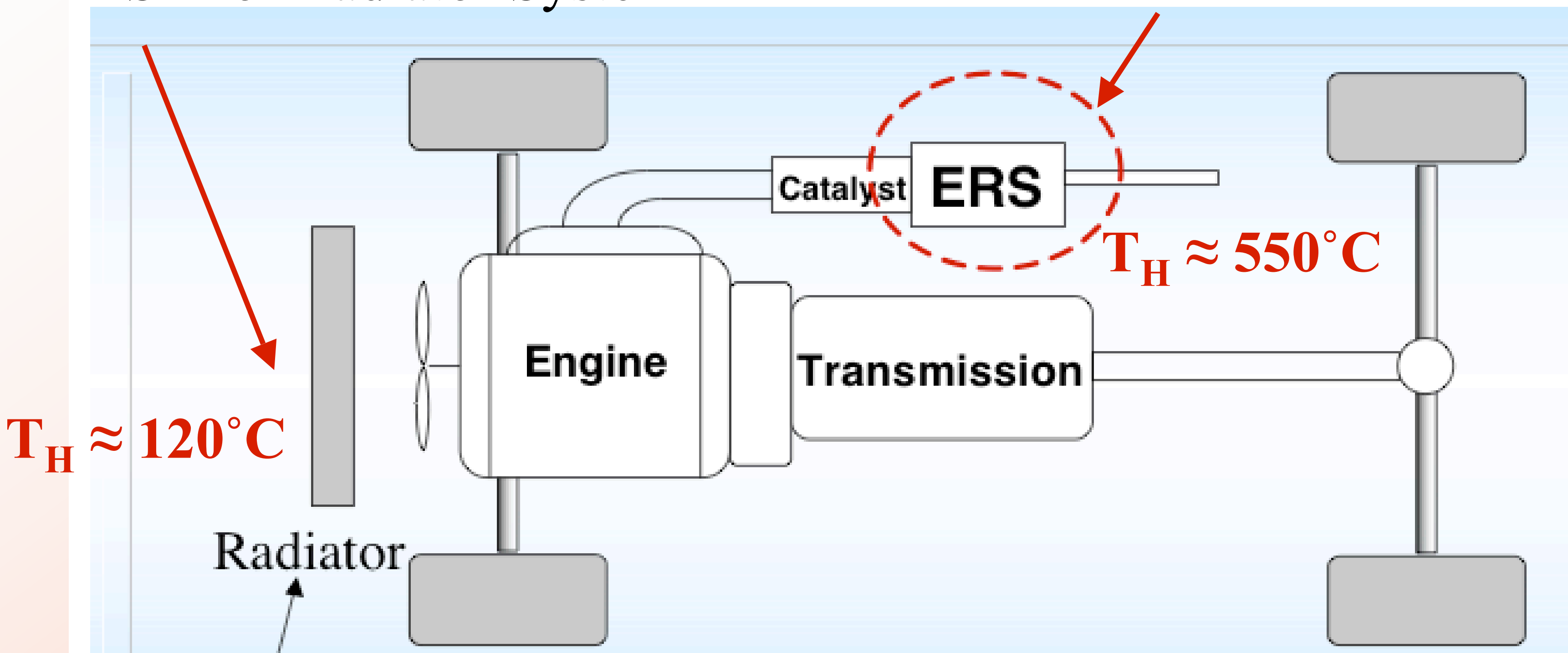


John Fairbanks- ICT05 Presentation

Proposed Energy Recovery System (ESR):

ESR for Radiator System

ESR for Exhaust System

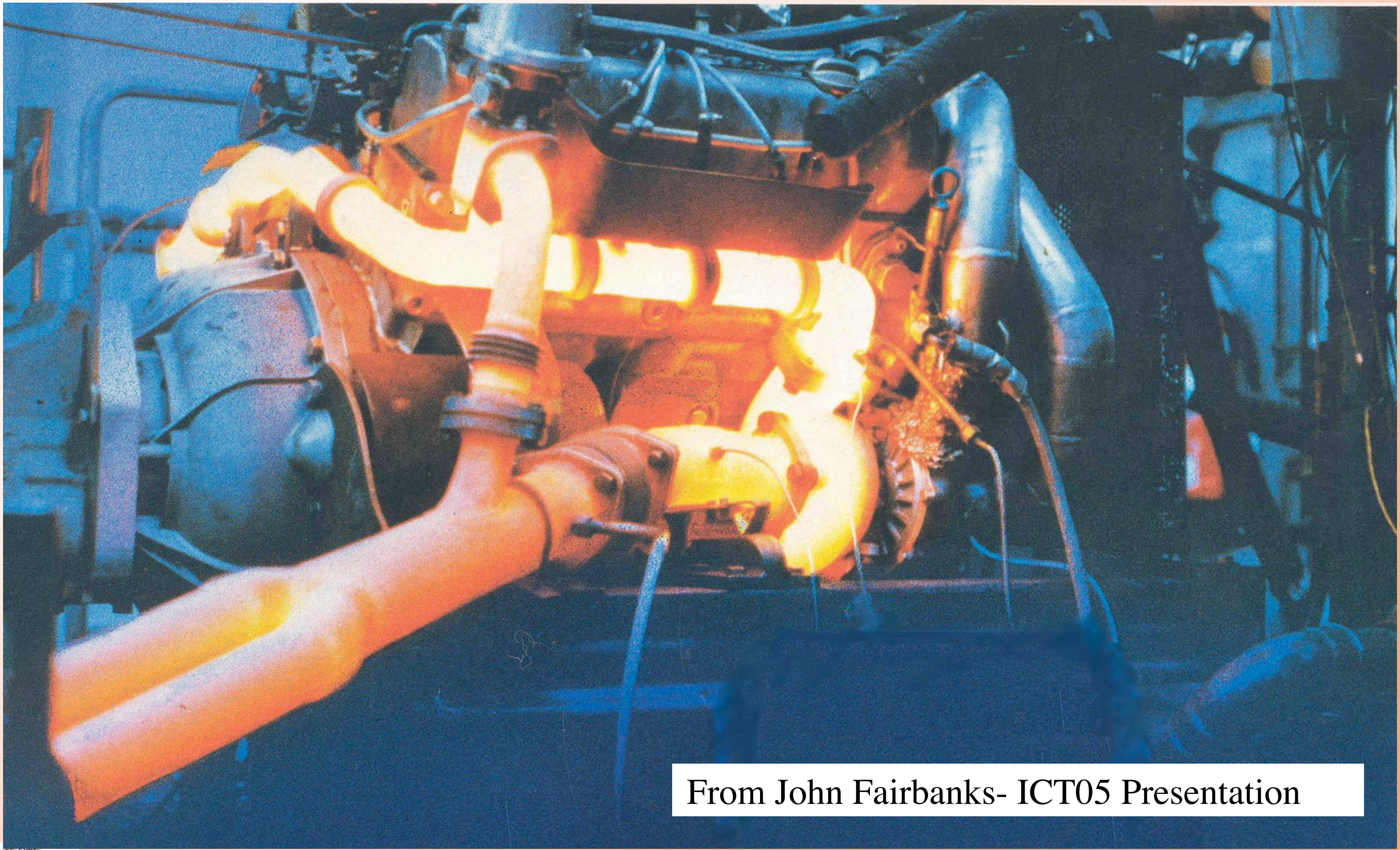


Alternate: make the radiator into an energy recovery device. (Small delta T)

Utilize or Convert Waste Heat into Recovered Energy

Courtesy Dr. Jihui Yang
General Motors R&D

Available Energy in Diesel Engine Exhaust System



From John Fairbanks- ICT05 Presentation

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Waste Heat Recovery: TE Power Generation

Heat Rejection

Waste Heat > 50%

$T_H \approx 500^\circ C$

$T_C \approx 30^\circ C$

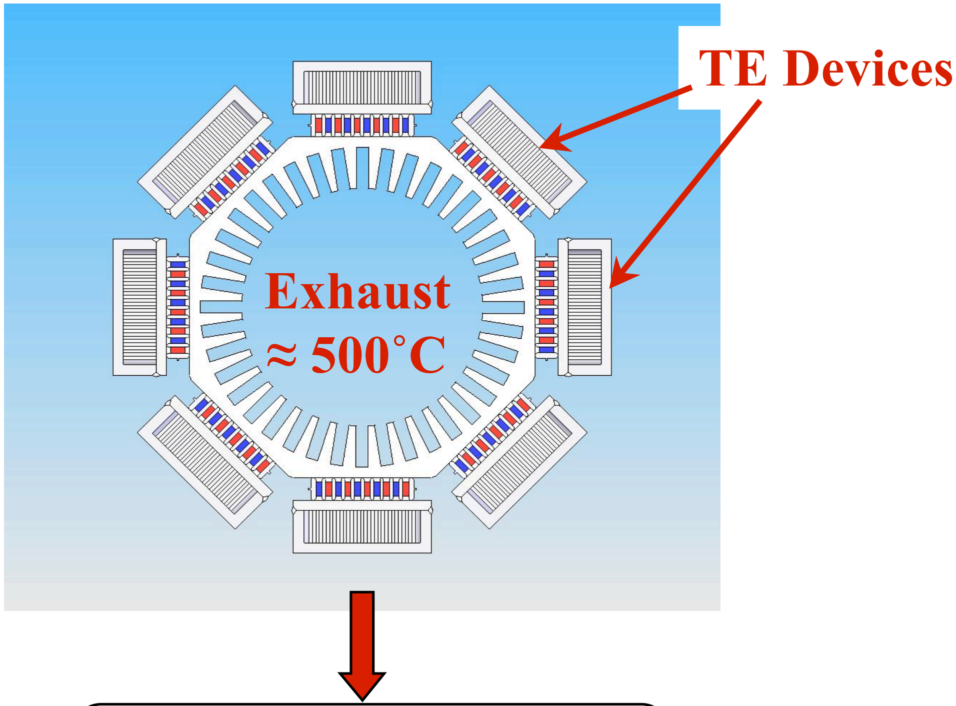
Waste Heat Recovery: TE Power Generation

Heat Rejection

Waste Heat > 50%

$T_H \approx 500^\circ C$

$T_C \approx 30^\circ C$



Waste Heat Recovery

Goal > 10%

Waste Heat Recovery: TE Power Generation

Heat Rejection
Waste Heat > 50%

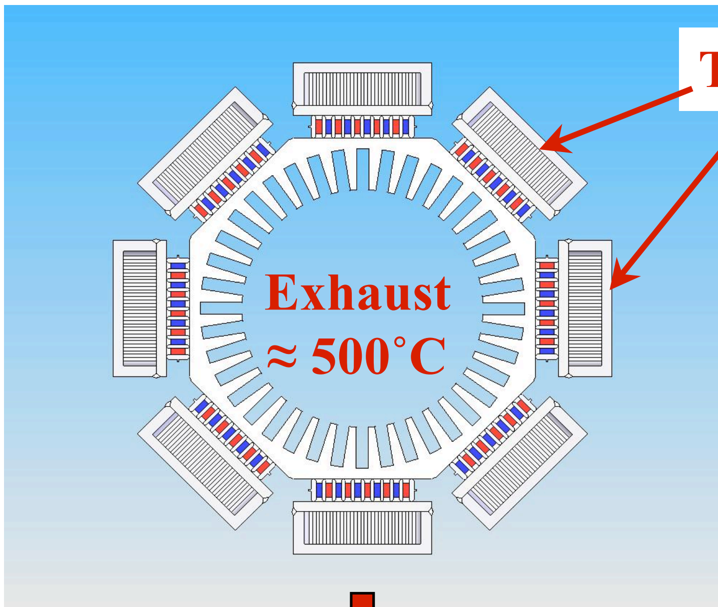
$T_H \approx 500^\circ C$

$T_C \approx 30^\circ C$

Carnot Efficiency

$$\eta_C = \frac{T_H - T_C}{T_H}$$

TE Devices



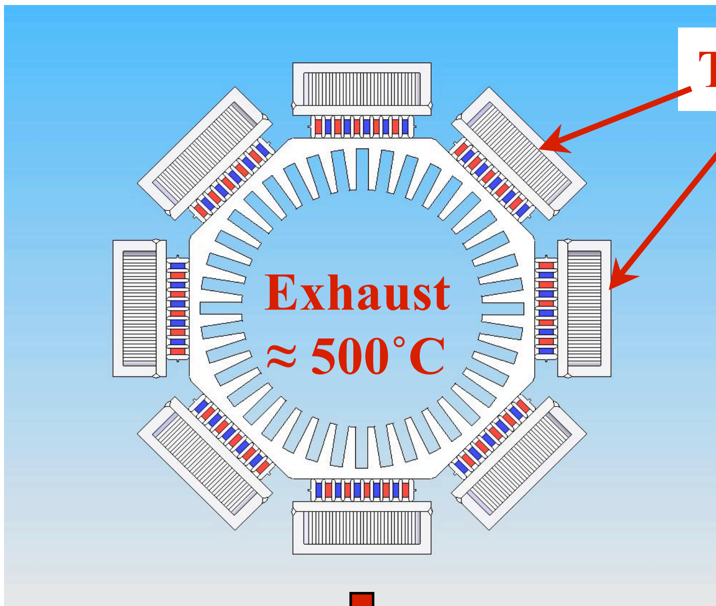
Waste Heat Recovery
Goal > 10%

Waste Heat Recovery: TE Power Generation

Heat Rejection
Waste Heat > 50%

$T_H \approx 500^\circ C$

$T_C \approx 30^\circ C$



Waste Heat Recovery
Goal > 10%

Carnot Efficiency

$$\eta_C = \frac{T_H - T_C}{T_H}$$

TE Efficiency

$$\eta = \left(\frac{T_H - T_C}{T_H}\right)\left(\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_C/T_H}\right)$$

$$ZT = \frac{\alpha^2 \sigma T}{(\kappa_E + \kappa_L)}$$

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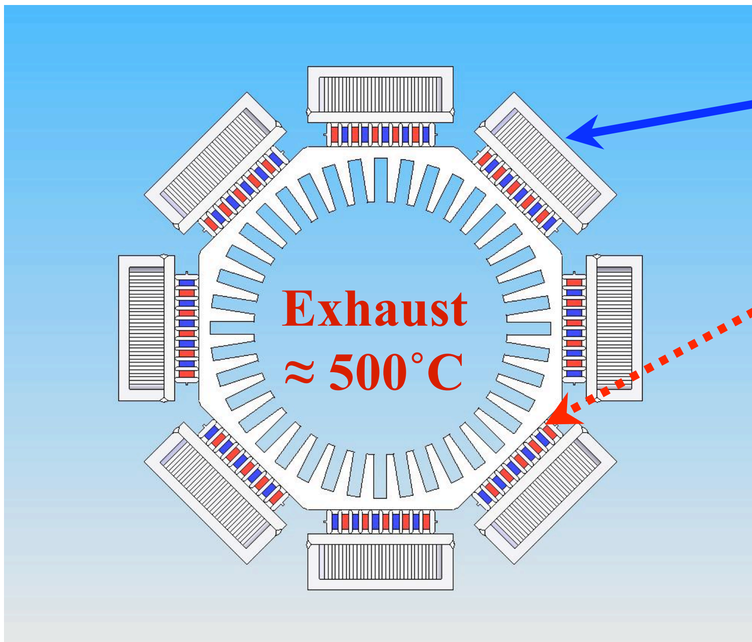
Automotive Waste Heat Conversion System

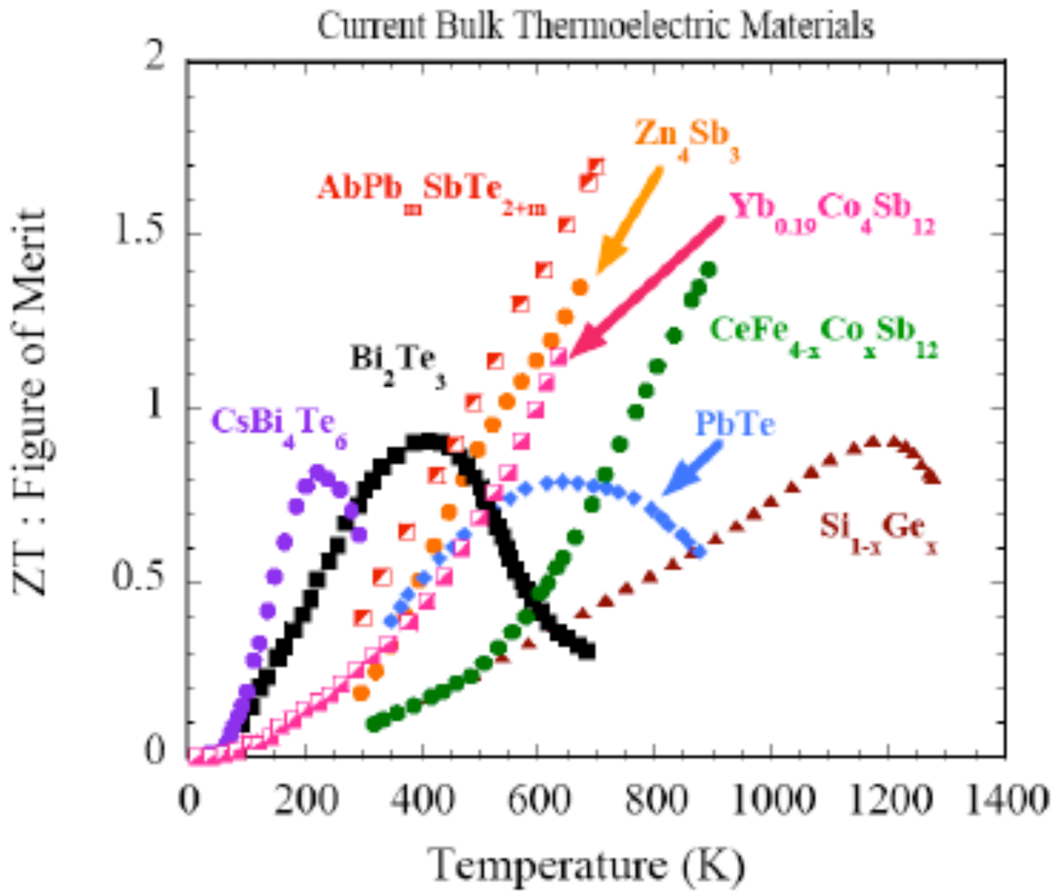


Cold Side
Heat Exchangers
Thermal Contact

High Efficiency
Thermoelectric Modules
$ZT \approx 2$

<u>Some Issues</u>
Thermal Stability
Mechanical Stability
Thermal Cycling
Parasitic Losses
Added Weight & Cost

ZT of Best TE Materials (ZT ≈ 1):



Terry M. Tritt & Mas Subramanian
MRS Bulletin TE Theme, March 2006

State of the Art
Device TE Materials
(ZT ≈ 1)

$$ZT = \frac{\alpha^2 T}{\rho \kappa}$$

Bi_2Te_3 ➠ Cooling

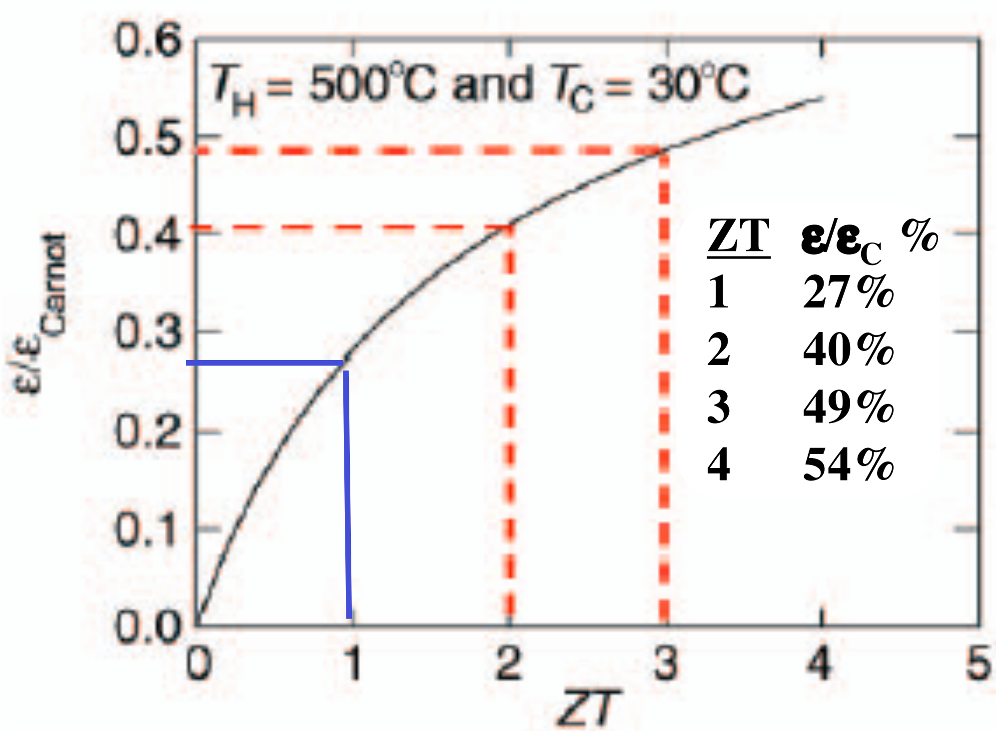
$Si_{1-X}Ge_X$ & PbTe ➠ Power Generation

Future Material Needs
ZT ≈ 2-3!
➡ η ≈ 20%

Why a Goal of ZT ≈ 2-3?

Yang & Caillat (MRS Bulletin, Vol. **31**, 2006)

$$ZT = \frac{\alpha^2 T}{\rho \kappa}$$



ZT	$\varepsilon/\varepsilon_C$ %
1	27%
2	40%
3	49%
4	54%

Future Material Needs

ZT ≈ 2-3!

➔ $\eta = \varepsilon \approx 20\%$

ZT	Xtra Eff %
1	-
2	48%
3	22%
4	10%

As ZT >> 1 then $\varepsilon \approx \varepsilon_C$ (Carnot efficiency)

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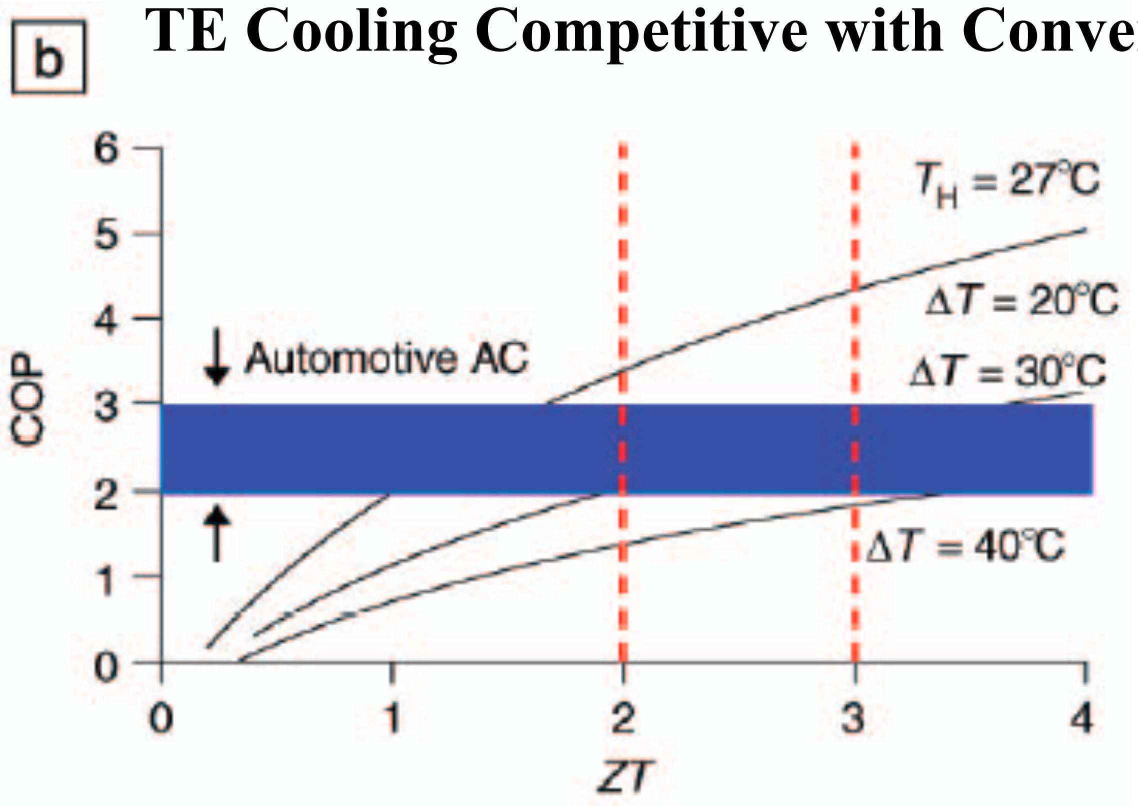
Why a Goal of ZT ≈ 2-3?

For ZT ≈ 2-3

TE Cooling Competitive with Conventional COP



Yang & Caillat (MRS Bulletin, Vol. **31**, 2006)

Potential Impact of DOE Freedom Car TE Program !!

DOE's Freedom Car Program in TE's:
Incorporate TE Conversion Devices on Exhaust of Heavy Trucks:
Convert Waste Heat into Electrical Energy

Transport
Truck/Trailer A

Rough Program Goals:

10% Increase in Fuel Efficiency
(No added emissions)

≈ 1 KW TE System (min 350 Watts)

≈ $ per Watt (Cost effective)

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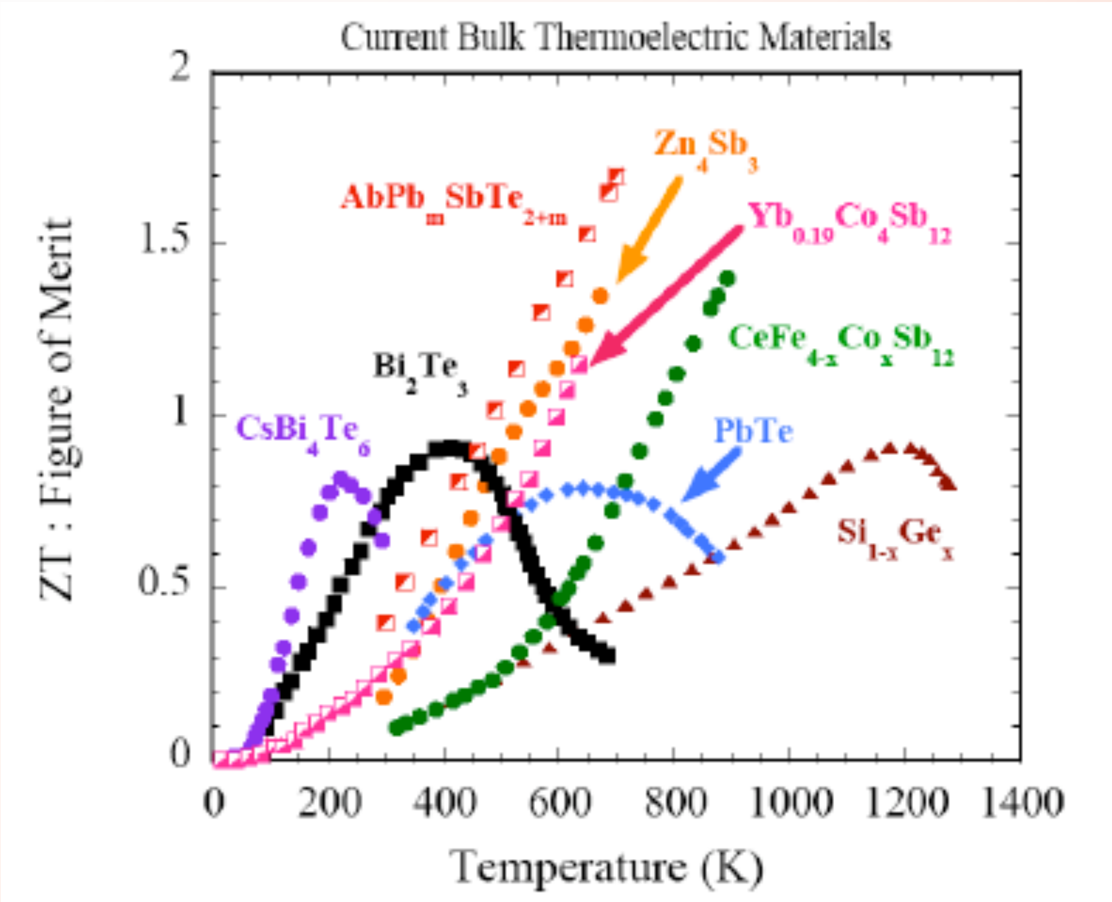
Diesel Engine (Potential Fuel Savings w/ 10% gain)

	ISB Dodge Pickup	ISX Class 8 Truck
Emissions Useful Life	185,000 miles	435,000 miles
Typical Fuel Consumption	16 mpg	5 mpg
Fuel Consumed During the Useful Life	11,500 Gallons	87,000 Gallons
Fuel Consumed with Improved Efficiency	10,500 Gallons	79,100 Gallons
Fuel Saved	1000 Gallons	7900 Gallons
Money Saved ($2.00 gallon)	$2000	$15,800

We have discussed the applications & needs

→ Focus on the <u>Materials Research</u>.

Figure of Merit for Bulk TE Materials



Terry M. Tritt & Mas Subramanian
MRS Bulletin, Vol. **31**, March 2006

$$ZT = \frac{\alpha^2 \sigma T}{(\kappa_E + \kappa_L)}$$

Future Material Needs
ZT ≈ 2-3!
➔ η ≈ 20%

Broad Range of Temperatures!

TE Measurements!

PGEC Research Strategy: High ZT!

What Knobs to Turn? ➠ Design Material Properties!

Bulk Nanocomposites
Interface - Phonons
Quantum - Seebeck

Lower κ_L ➠ Scatter Phonons
"Rattlers" in the Cage Structure
Mass Fluctuation
Defect & Grain Boundary Scattering
Heavy Atoms, Complex Structure

$$ZT = \frac{\alpha^2 \sigma T}{(\kappa_E + \kappa_L)}$$

High ZT??

High Seebeck (α)
Tune Bandgap ($\alpha \approx E_{GAP}$)
Limit Minority Carriers
Large dn/dE at $E = E_F$
Low Dimensional Systems
Large Effective Mass (m*)

High Electrical Conductivity (σ)
Doping ($n \approx 10^{19}$ carriers)
High Mobility Carriers
Narrow Gap Semiconductors
Minimize Electron Scattering

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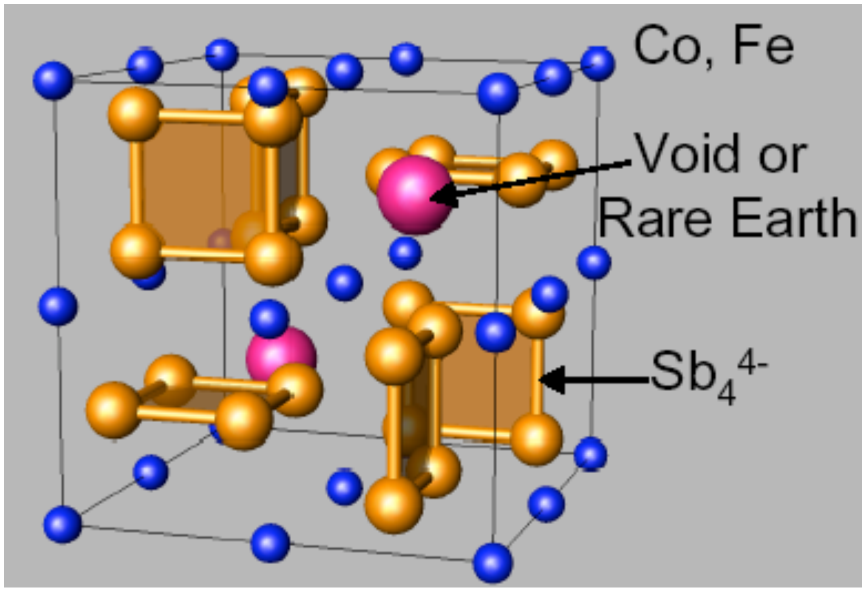
Skutterudites

eg. $Re_2Co_4Sb_{12}$



Cage Structures ➟ Rattling Modes

Lower κ_L !

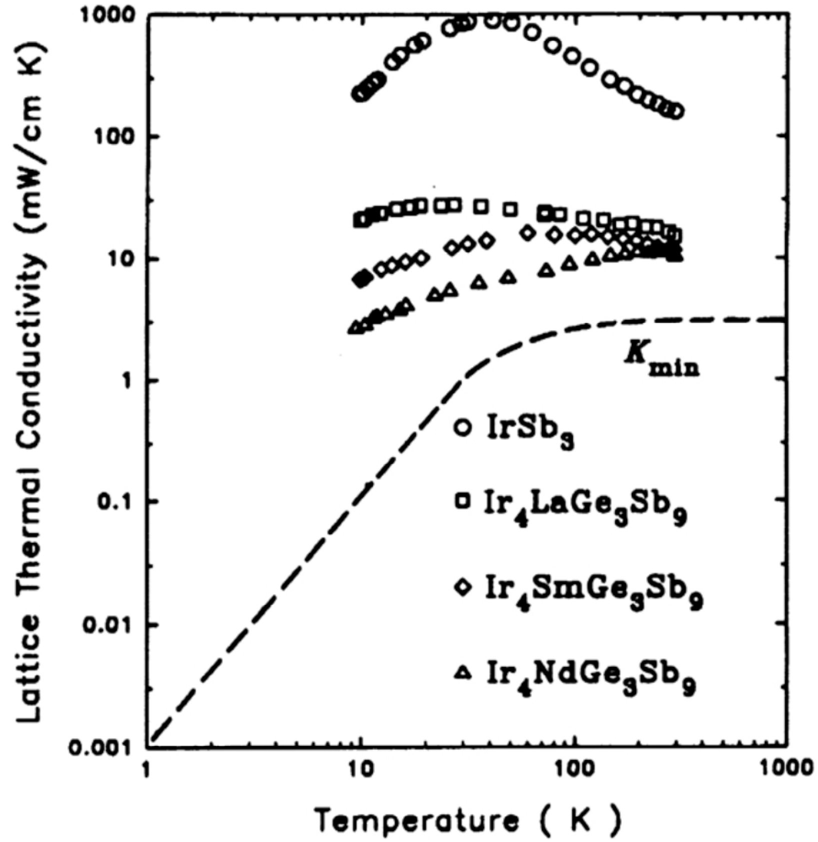


FIG. 2. Lattice thermal conductivity vs temperature for the La-, Nd-, and Sm-filled-skutterudite samples as well as the unfilled-skutterudite sample. The calculated minimum thermal conductivity κ_{min} for $IrSb_3$ is also included in the figure. In effect, the lattice thermal conductivity cannot be made smaller than κ_{min}.

G. S. Nolas, G. A. Slack, D. T. Morelli, T. M. Tritt, and A. C. Ehrlich, J. Appl. Phys. **79**, 4002 (1996).

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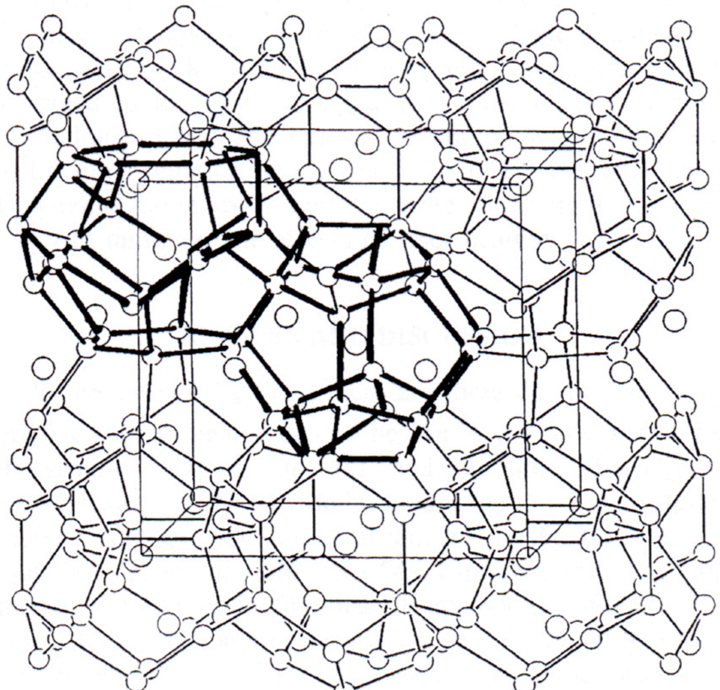
Cage Structure Clathrates
eg: $Eu_8Ga_{16}Ge_{30}$
or $Sr_8Ga_{16}Ge_{30}$



Nolas & Slack, Am. Scientist, **89**, 136, 2001

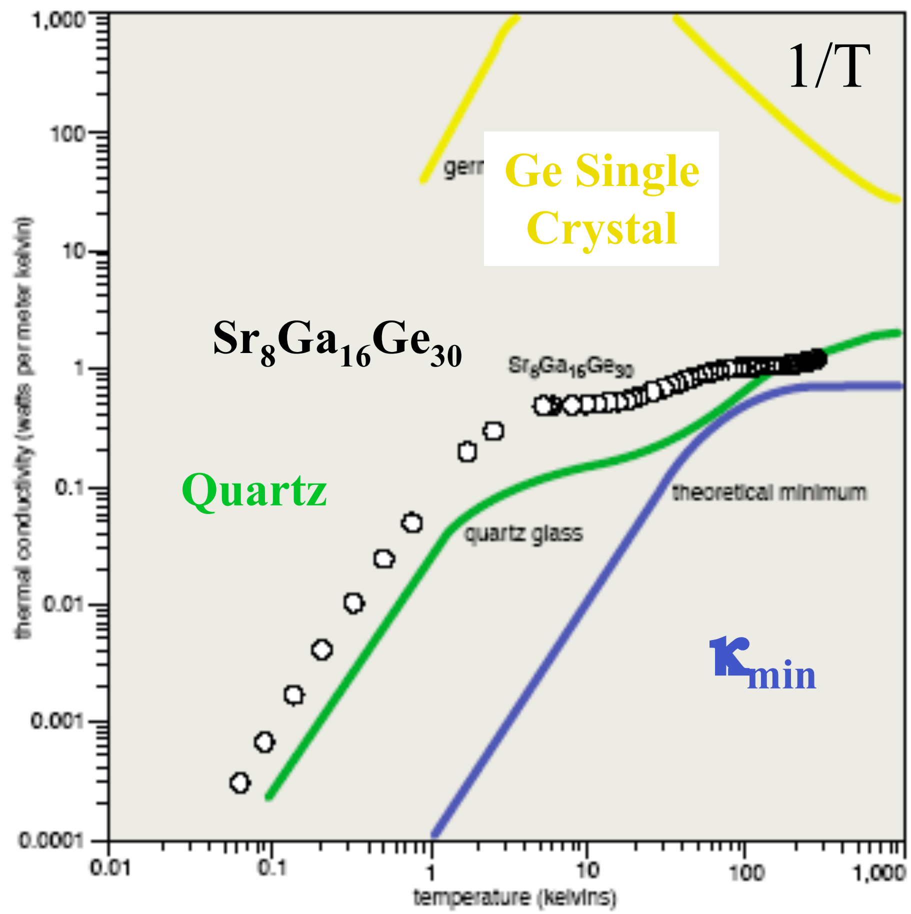


Figure 7. Thermal conductivity of a candidate clathrate material, $Sr_8Ga_{16}Ge_{30}$ *(open circles)*, is considerably lower than that of a pure germanium crystal *(yellow)*. Above a temperature of about 200 kelvins (–73 degrees Celsius) the value dips even below the thermal conductivity of quartz glass *(green)* and approaches the theoretical minimum *(blue)*. Such low thermal conductivity is a requirement for a high-efficiency thermoelectrics, which would waste energy if thermal conduction allowed heat to flow from the hot to the cold side of a device.

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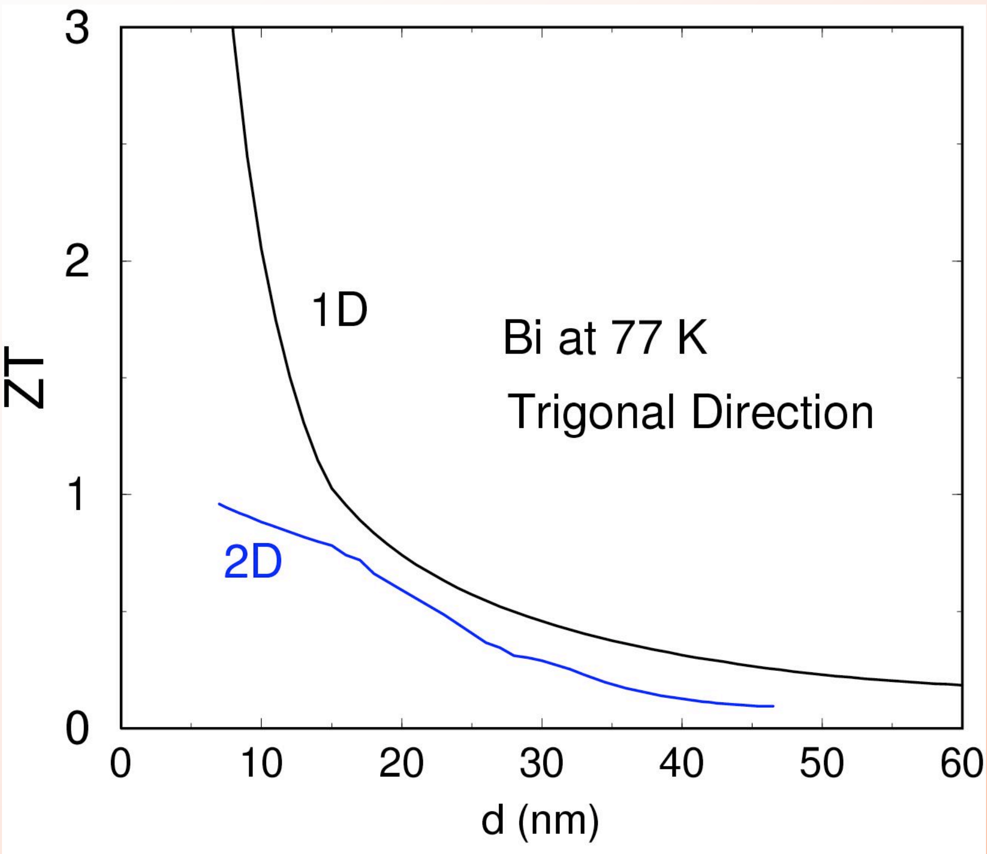
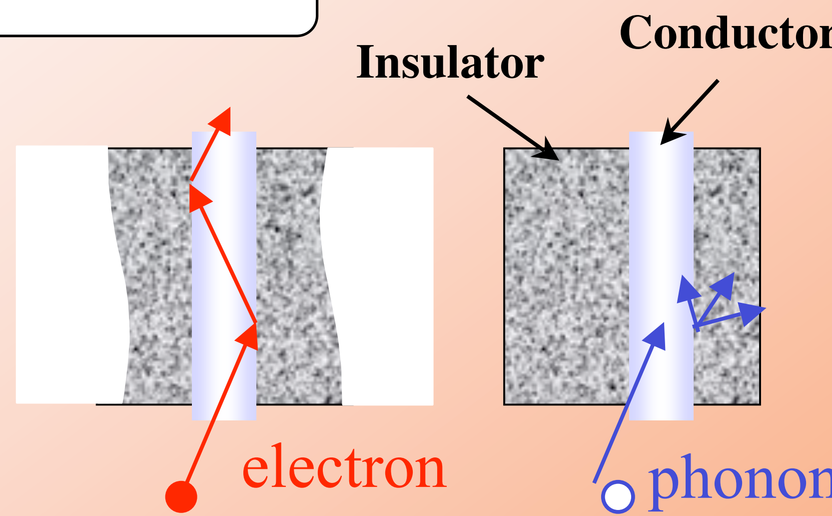
Motivation for Low Dimensional TE Materials:



Hicks & Dresselhaus, PRB 1993
Dresselhaus, Plenary Talk - ICT 05



Quantum Enhancement
Increase Seebeck

Interface Scattering
Large Kapitza Resistance
Reduce κ_L

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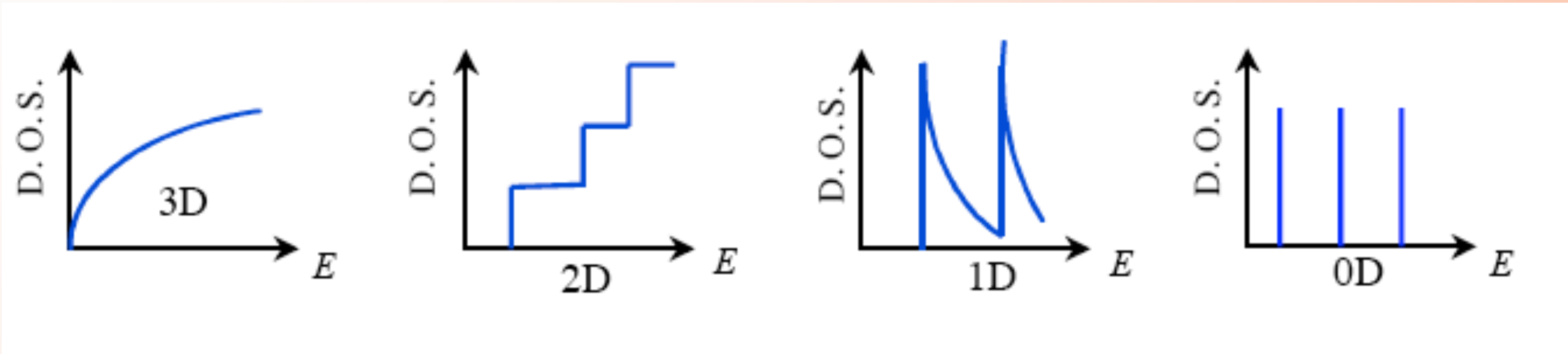
Role of Lower Dimensions in Thermoelectrics:

Density of States (DOS) for Low D

Hicks & Dresselhaus, PRB, 47, 12727 (1993)



$$ZT = \frac{\alpha^2 \sigma T}{(\kappa_E + \kappa_L)}$$

Large variation of DOS yields large Seebeck Coef.

$$\alpha \propto \left.\frac{\partial DOS}{\partial E}\right|_{E_F}$$

← Low D yields large dn(E)/dE

$$ZT \approx \alpha^2\sigma \approx \alpha^2 n$$

$$ZT_{2D} \geq ZT_{3D}$$

$$\alpha = \frac{\pi^2 k_B^2 T}{3e}\left[\frac{\partial \ln \sigma}{\partial E}\right]_{E_F}$$

M. Dresselhaus et al, *APL* **63** 3230 (1993)

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Recent Results: Bi_2Te_3/Sb_2Te_3 Superlattices

ZT > 2.4 @ 300K

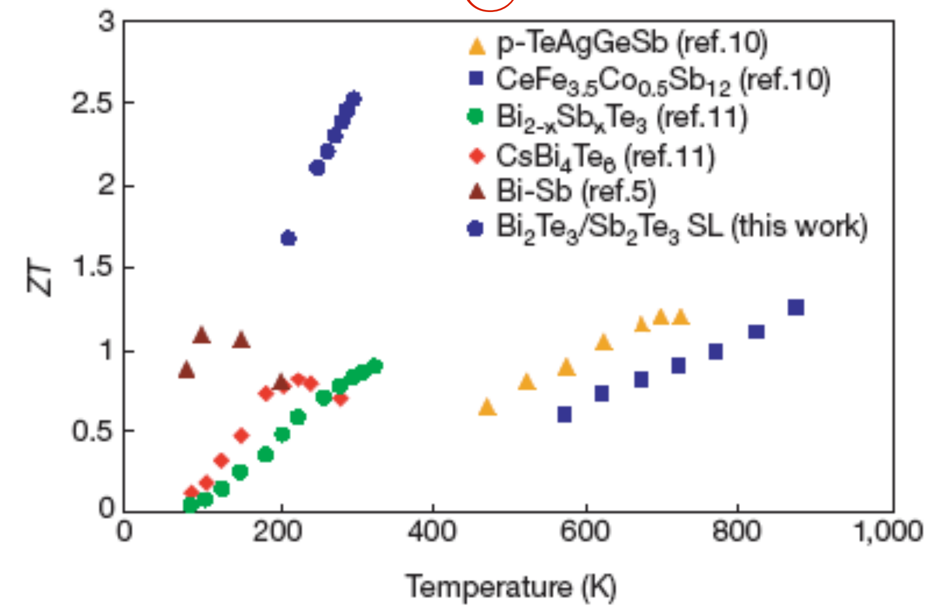
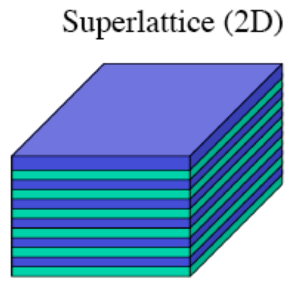
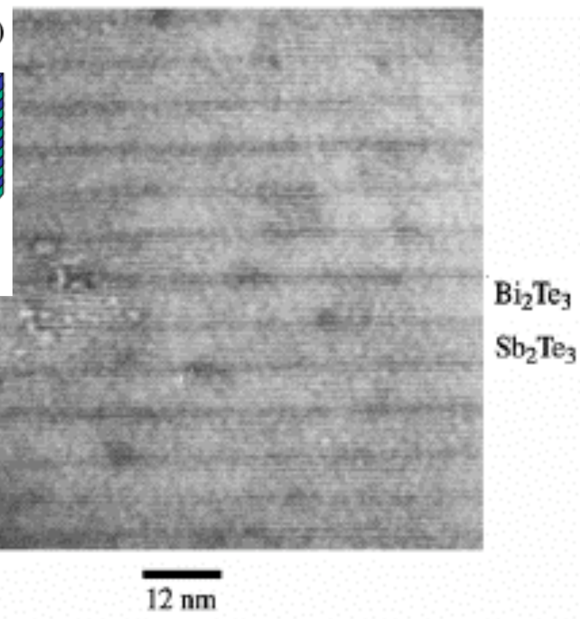


Figure 3 Temperature dependence of *ZT* of 10Å/50Å p-type Bi_2Te_3/Sb_2Te_3 superlattice compared to those of several recently reported materials.





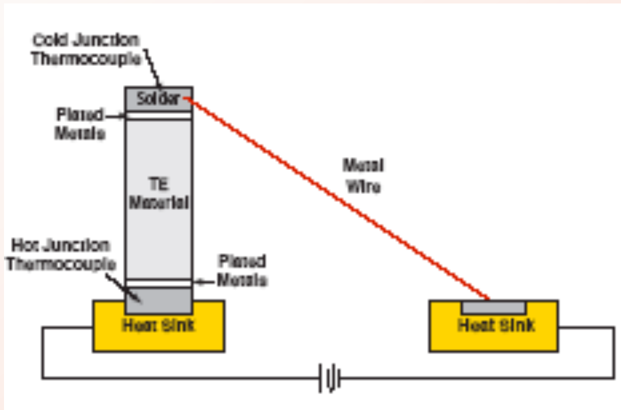
Applied Physics Letters, 75, 1104 (1999).

Bi_2Te_3/Sb_2Te_3 Superlattice
R. Venkatasubramanian, et. al., Nature, **413**, 597, 2001

Bi_2Te_3/Sb_2Te_3	Superlattice	Bulk
Power Factor($\mu W/cmK^2$)	40	50.9
Thermal Conductivity(W/mK)	0.5	1.26

Recent Results: PbTe Quantum Dots

PbTe Quantum Dot Superlattice
T. Harman et.al, Science, **297**, 2229 (2002)



Device $ZT_D \approx 1.4$ @ 300K
Materials ZT > 2 @ 300K

Fig. 1. Schematic cross section of the quantum-dot superlattice structure investigated.

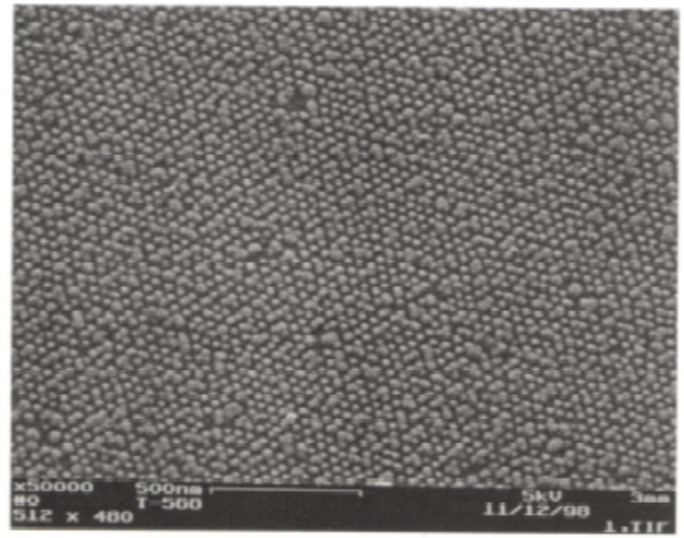
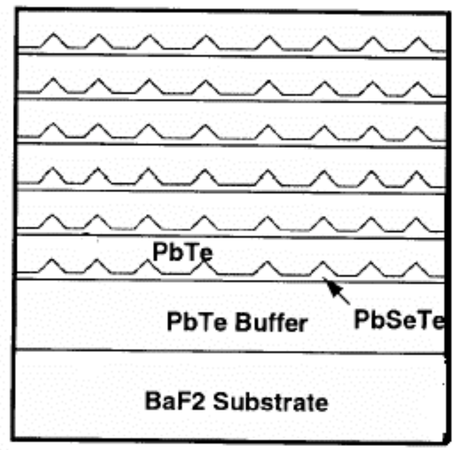


Fig. 2. Field-emission SEM image of quantum-dot superlattice structure.

Table 1. 300 K thermoelectric properties of Bi-doped (n-type) QDSL $PbSe_{0.98}Te_{0.02}$/PbTe samples grown by MBE and an n-type BiSbSeTe alloy sample.

Sample	S(μV/K)	ZT	Carrier conc. (cm^{-3})	Carrier mobility (cm^2/V-s)
n-QDSL A	−219	1.6*	1.2×10^{19}	370
n-QDSL B	−208	1.3*	1.1×10^{19}	300
n-BiSbSeTe A	−228	0.9**	4.6×10^{19}	110

*Values based on thermal conductivity values of 5.8 mW/cm-K calculated from the QDSL device test data. **Value based on a measured thermal conductivity value of 13.6 mW/cm-K.



$PbSe_xTe_{1-x}$ quantum dots in PbTe layers

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Relative Importance of α^2/ρ and κ

Bi_2Te_3 / Sb_2Te_3	Nano	Bulk
α^2/ρ (μW/cm-K^2)	40	51
κ (W-$m^{-1}K^{-1}$)	0.6	1.45
ZT (T =300K)	2.4	1.0

Venkatasubramanian et.al., Nature 413, 597, 2001

PbTe/PbSeTe	Nano	Bulk
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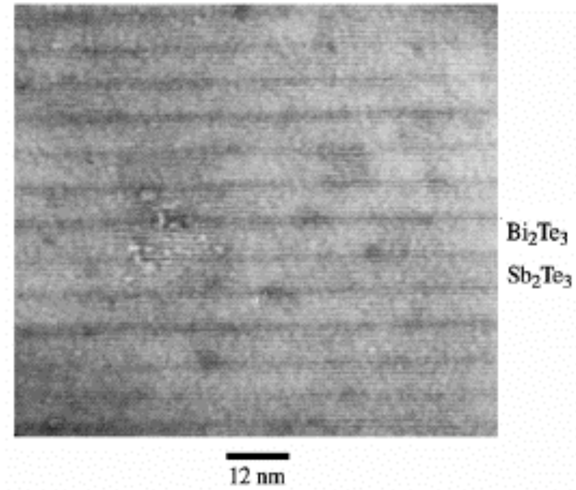
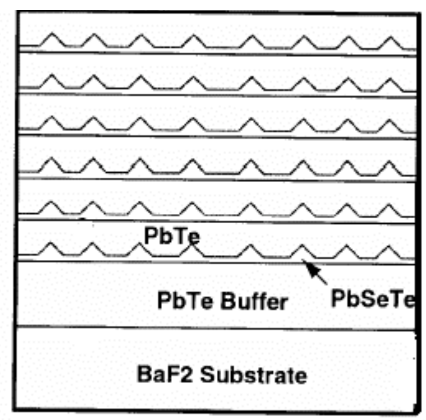
T. Harman et.al, Science, 297, 2229 (2002)

Bi_2Te_3/Sb_2Te_3 Superlattice



PbTe/PbSeTe Quantum Dots



$PbSe_xTe_{1-x}$ quantum dots in PbTe layers

Relative Importance of α^2/ρ and κ

Thermal Conductivity Reduction

Bi_2Te_3 / Sb_2Te_3	Nano	Bulk
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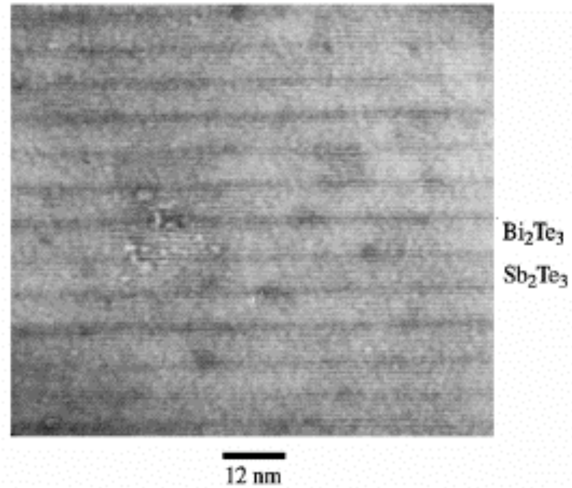
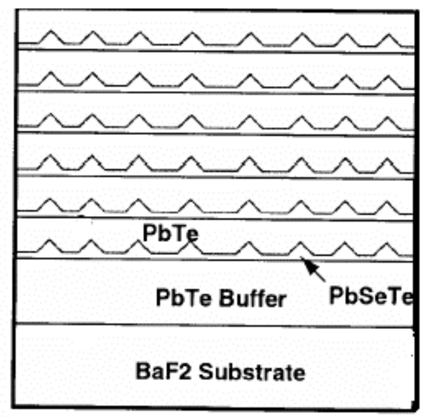


PbTe/PbSeTe Quantum Dots



$PbSe_xTe_{1-x}$ quantum dots in PbTe layers

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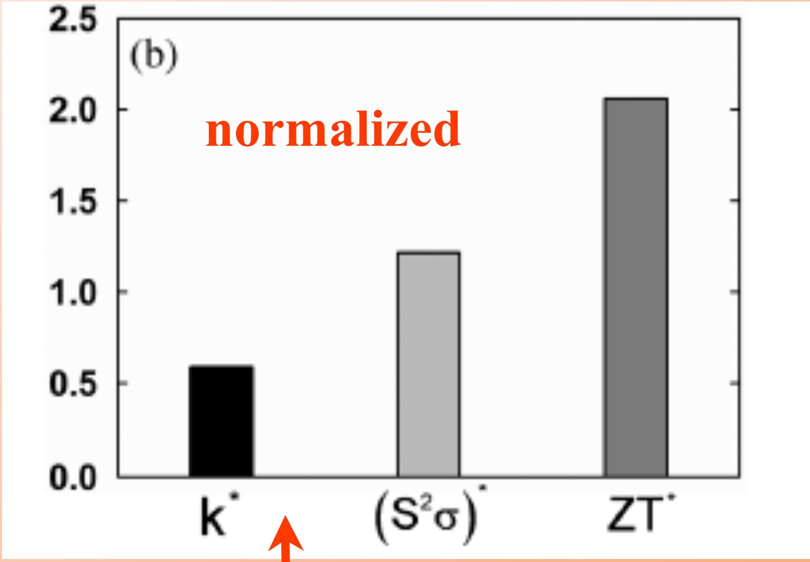
Embedding Nanoparticles in Crystalline Semiconductors

ErAs nanoparticles in $In_{0.53}Ga_{0.47}As$ matrix
Epitaxial growth
Goal to "Beat the Alloy Limit"
Uncorrelated Phonon Scattering

W. Kim et.al., PRL, 96-045901 (2006)
Santa Cruz & Berkeley Groups

- Reduction in κ_L ("nano- phonon effect")
  Depends on ML thickness (ErAs nano)*
- Power Factor about same
  but ErAs can act as a dopant
- ZT significantly enhanced
- Theoretical analysis showed that
  - ErAs nanoparticles scatter
    mid to long λ phonons*
  - While atomic scale defects scatter
    short λ phonons.



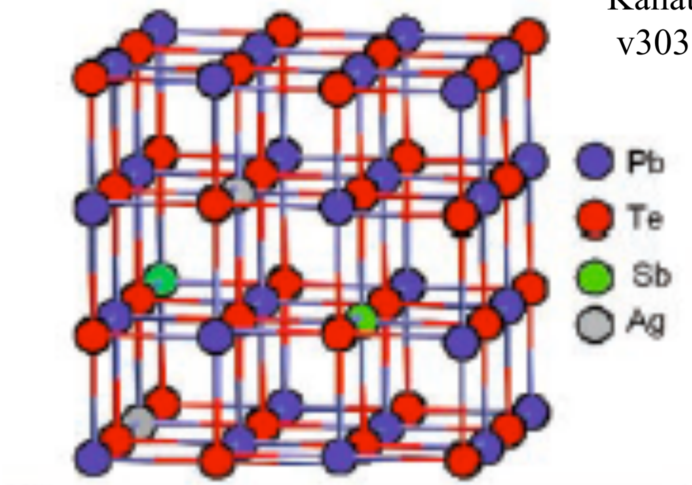
κ_L reduced a factor of 2 below the alloy limit!

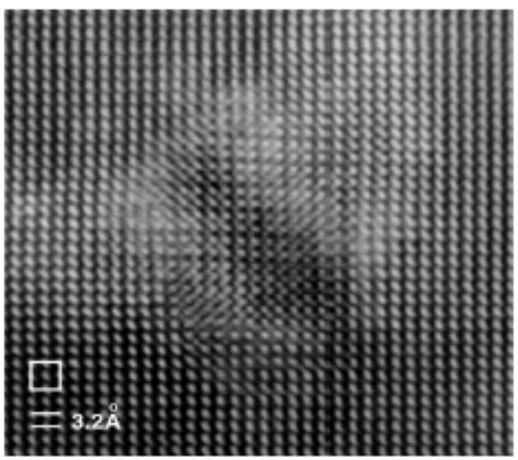
ZT enhanced a factor of 2 !

Complex Chalcogenides -$AgPb_{18}SbTe_{20}$

$AgPb_{18}SbTe_{20}$ (LAST)

Kanatzidis Group, Science, v303, p818 2004





AgSb-rich Nanodot in $AgPb_{18}SbTe_{20}$

Mich. St. Results:

Results Show ➠ ZT >2

Cubic material
Nanoscale microstructure !!

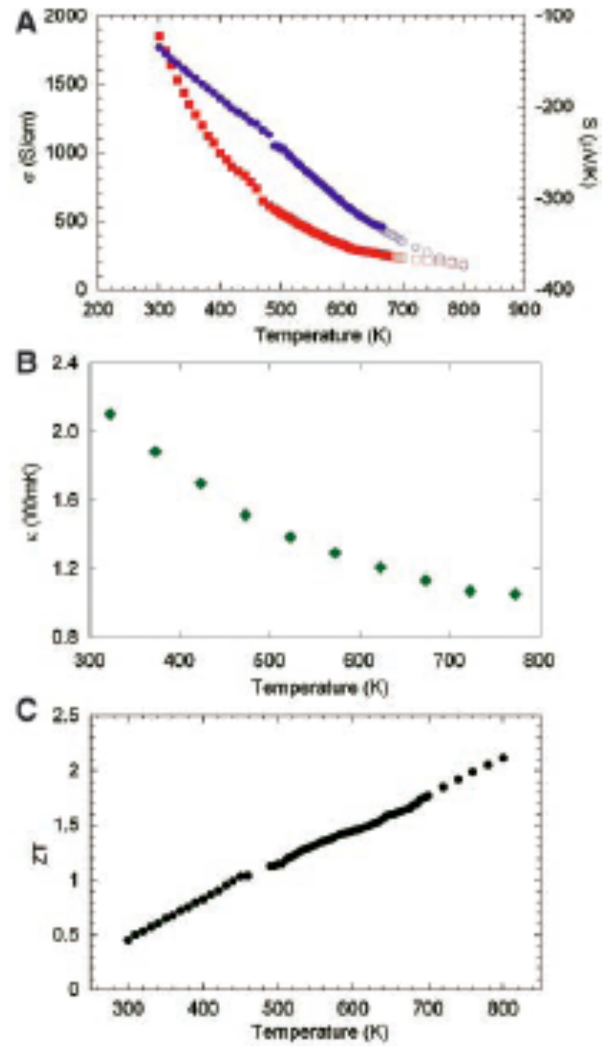


Fig. 3. Variable-temperature charge transport and thermal transport data for $AgPb_{18}SbTe_{20}$:

Bulk Materials Need **"Tuning Knobs"** for Improvement!

The Low Dim. approaches give us potential new directions in TE's, however, there are some disadvantages of these materials.

1. The superlattices and quantum dots are expensive.
2. The superlattices and quantum dots are too small to be used in routine industry applications.
3. For the $AgPb_mSbTe_{2m}$, it is hard to control the nano-sized dots (inhomogeneity) in the materials.

So the need is to grow a bulk material with controlled nano-scale inclusions?

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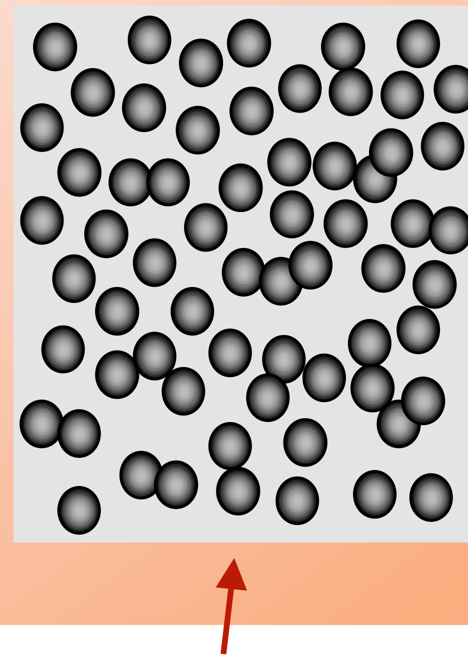
Combine the **"Nano and Bulk"** - TE Composite Material

Potential route to enhance ZT
Incorporate nanoparticles into bulk matrix phase
Or directly press nanoparticles into pellets,
Yield **"Bulk Nano-Composites"**

Goals:
Phonon scattering at interface could significantly **Reduce the lattice thermal conductivity.**
Or Quantum Enhancement Effects due to Low Dim. **Enhance Seebeck Coefficient**



Bulk TE Material w /Nanoparticles!

How to grow large amount of size-controllable TE nanoparticles?

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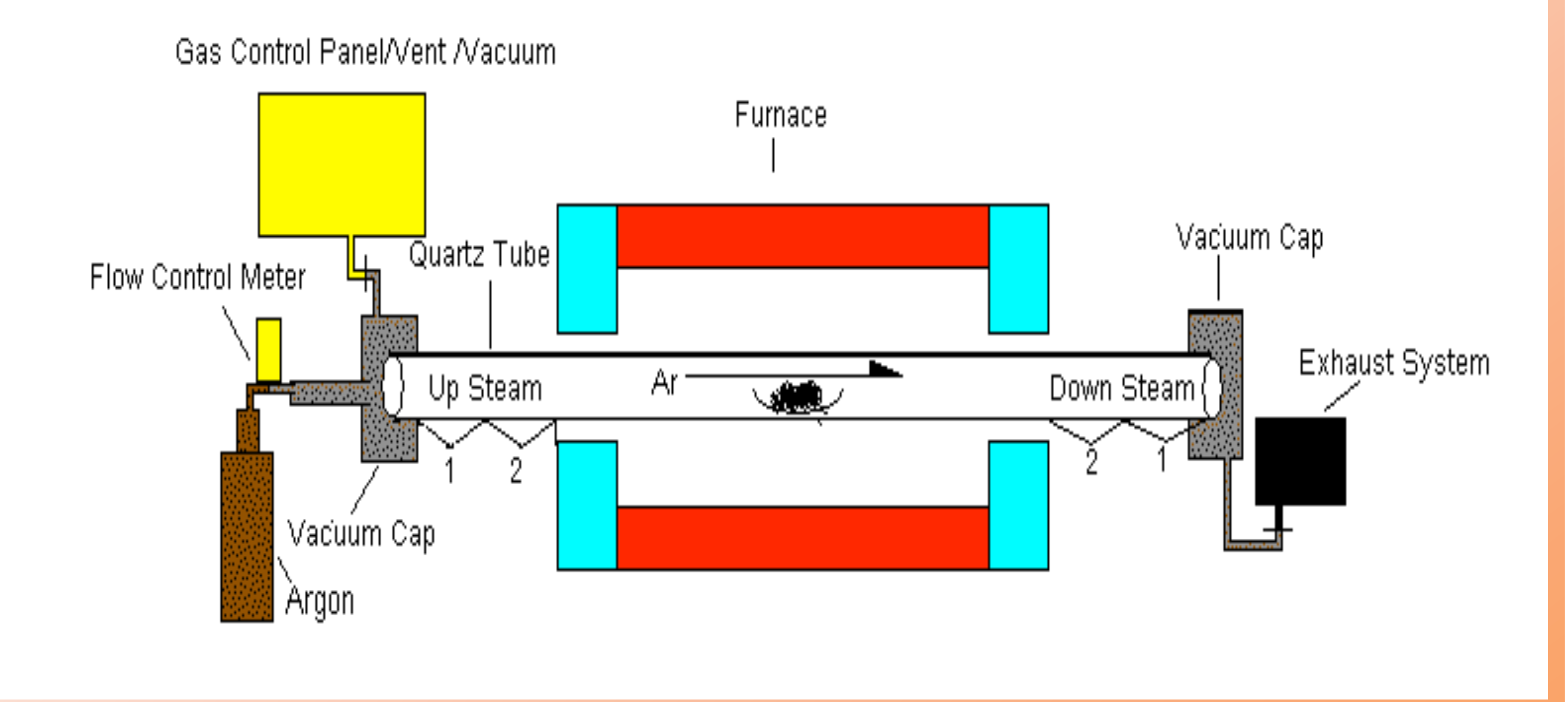
Chemical Vapor Deposition: Synthesis of Nanoscale TE Materials

Diagram of CVD:

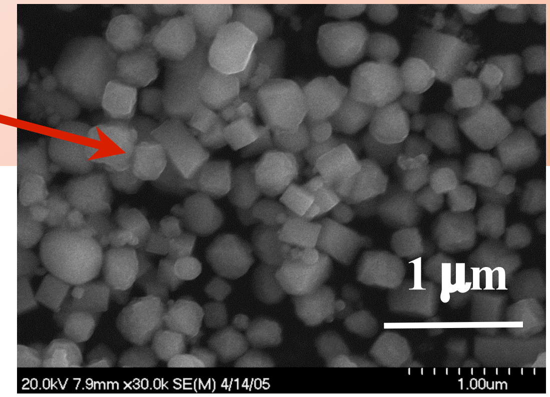
Requires 1200 ˚C Furnace, Ar Gas, Au Seed Particles and Flow Meters



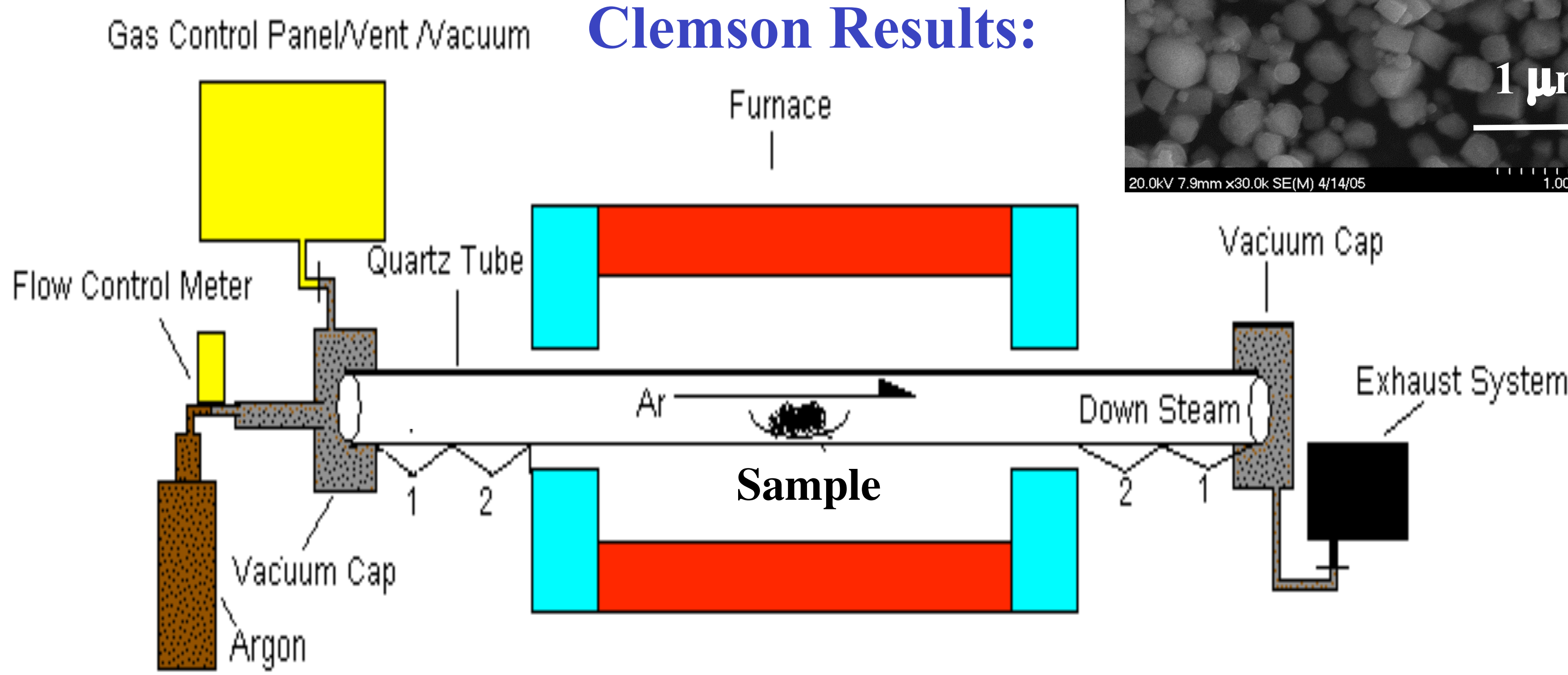
Chemical Vapor Deposition: Synthesis of Nanoscale TE Materials

Diagram of CVD: For Growth of Nano-particles of TE Materials!

PbTe Cubic Nano Particle (≈ 200 nm)
Size Selective & Mono Dispersed



Clemson Results:



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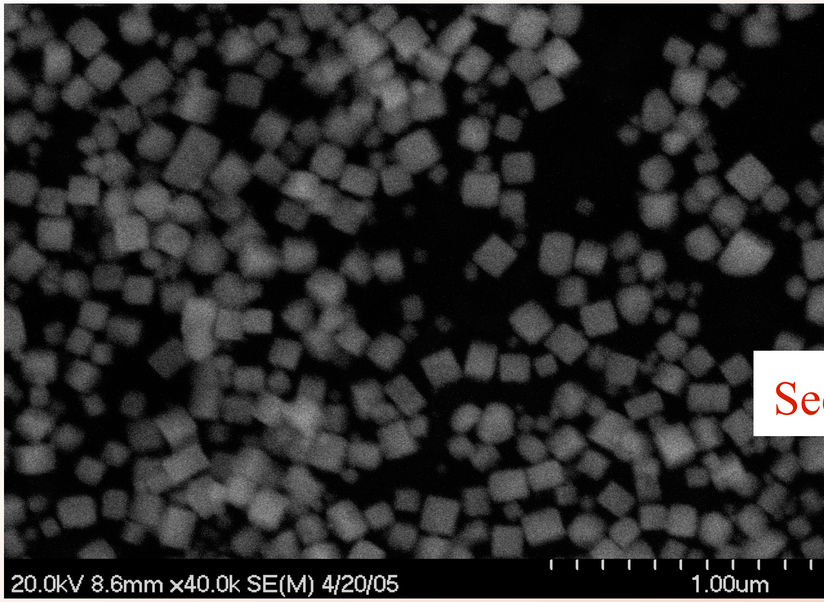
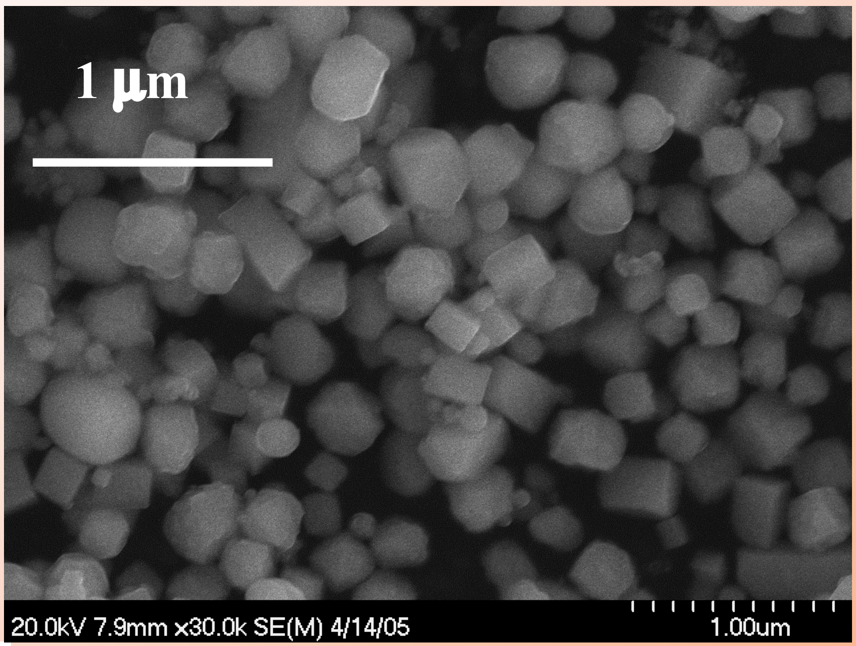


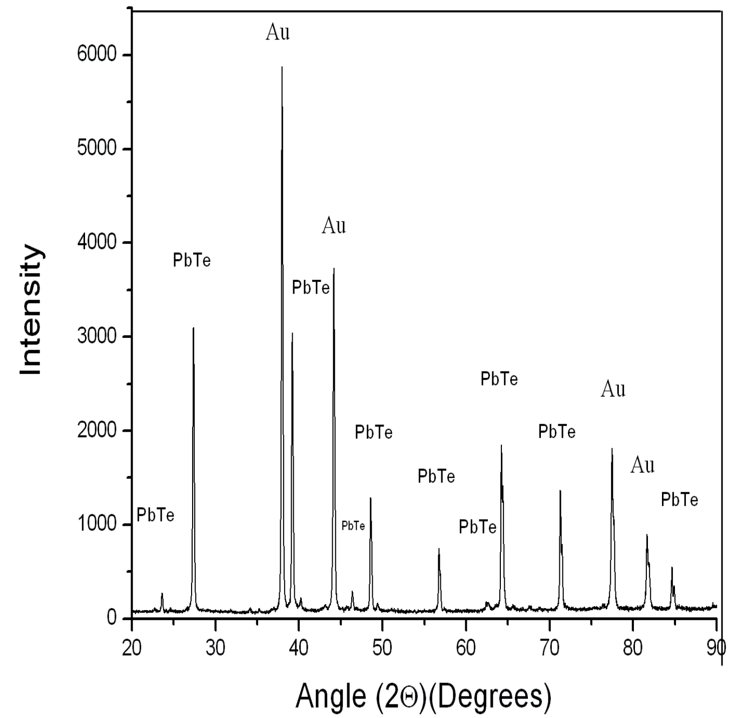
PbTe Nanocrystals

≈ 200 nm cubic structures

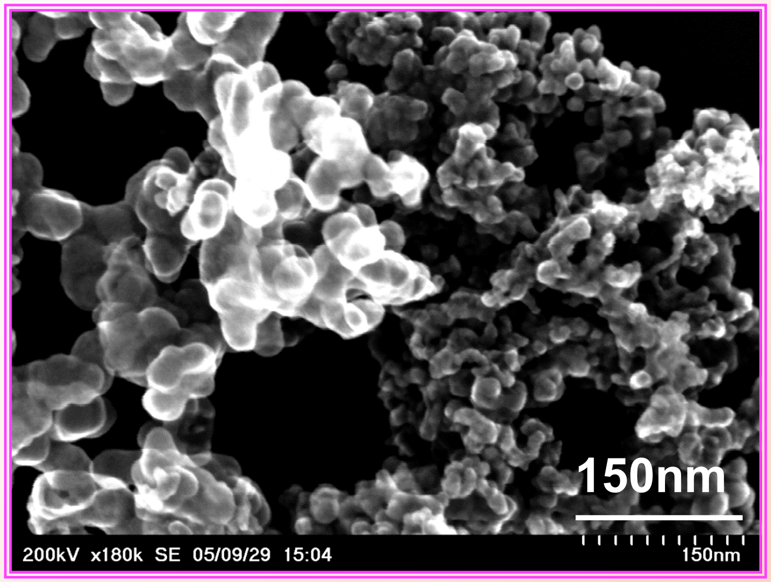
Sharp X-Ray Diffraction peaks

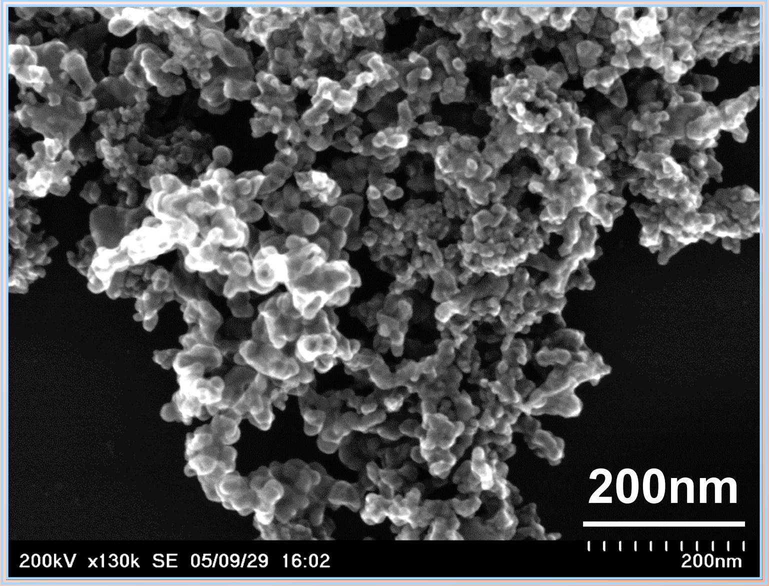
See B. Zhang , Appl. Phys. Lett., **88**, 043119 2006



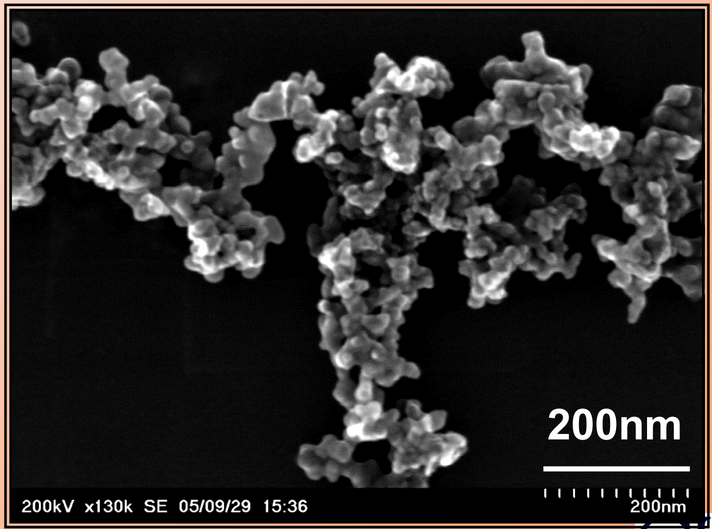


Hydrothermal Synthesis of Nanomaterials: Bi_2Te_3 & $CoSb_3$





Skutterudite (**$CoSb_3$**)
Nano Structures
20-40 nm



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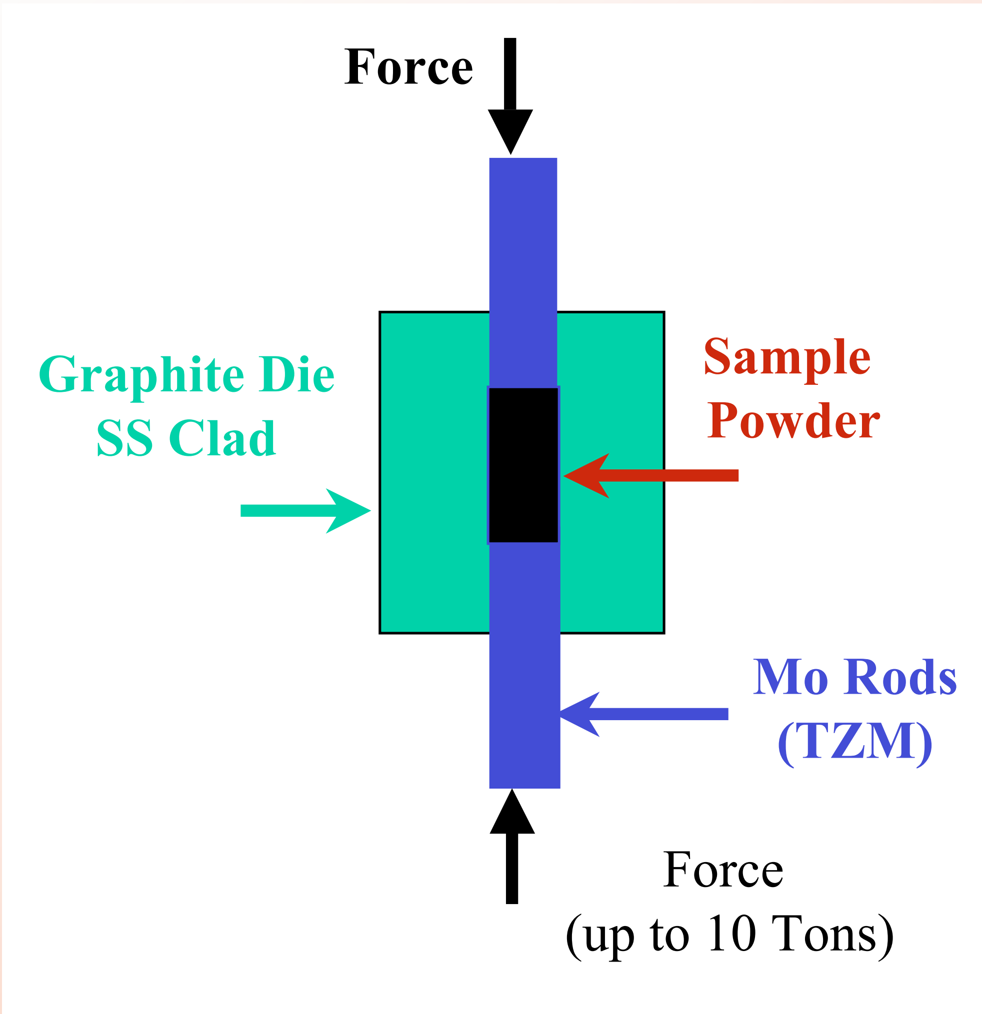
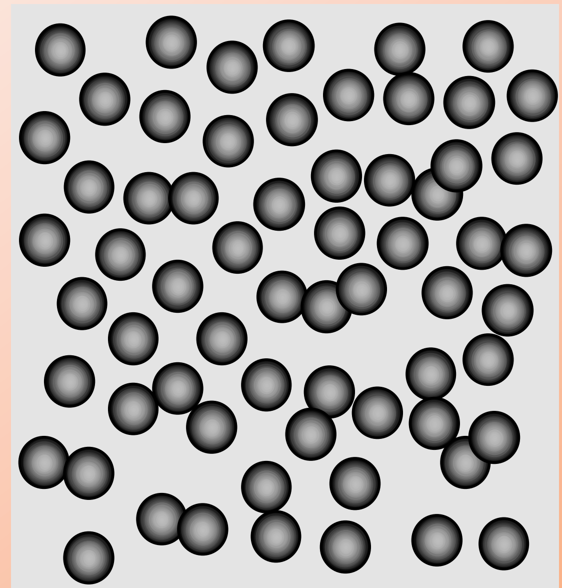
We made the Nano-materials!
So How to Make the Nano-Composite?
Needs to be Densified!

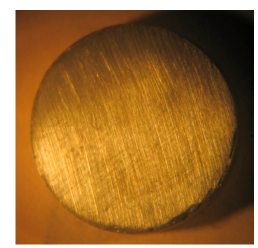
Hot Isostatic Press
10 Ton, 2000°C



Composite
Bulk & Nano



1/2” diameter
≈ 3/8” Long Sample



Success: Able to grow nanostructures!
Thermal conductivity is reduced!

Issue: When mixing PbTe or $CoSb_3$ nanoparticles

Homogeneous mixing and control of the bulk powders & the nanostructures?

Typically High Resistivity.

Success: Able to grow nanostructures!
Thermal conductivity is reduced!

Issue: When mixing PbTe or $CoSb_3$ nanoparticles

Homogeneous mixing and control of the bulk powders & the nanostructures?

Typically High Resistivity.

Developed a **Nano-Coating Process**

Start with ball milled seed particles (several microns)

Coat Hydrothermally (tens of nm) -- Then Hot press:

Stability of the nanostructure within the composite?

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Hydrothermal Nano-Coating Process for $CoSb_3$

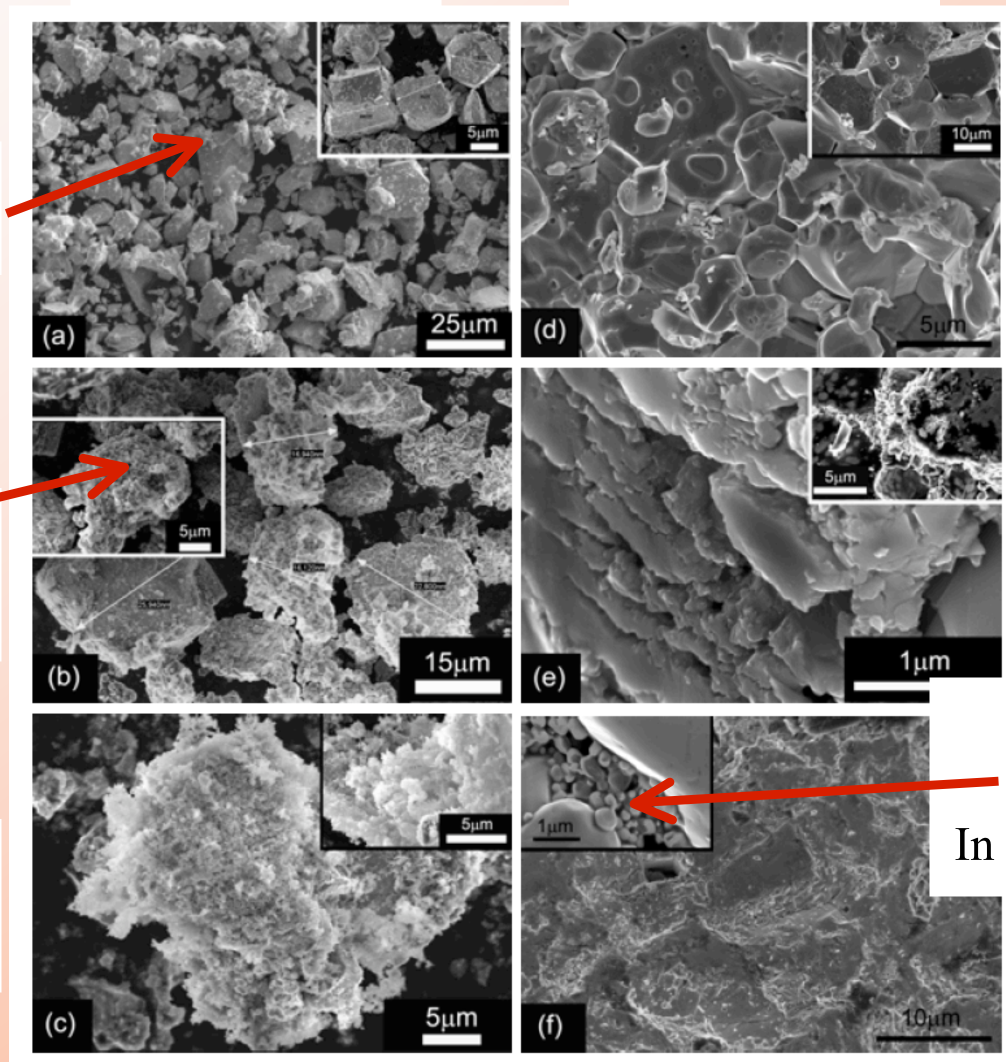
Before Hot Press

After Hot Press

$CoSb_3$ Seed Particles
Several μm's

$CoSb_3$ Hydrothermal Coating

$CoSb_3$ Hydrothermal Coating

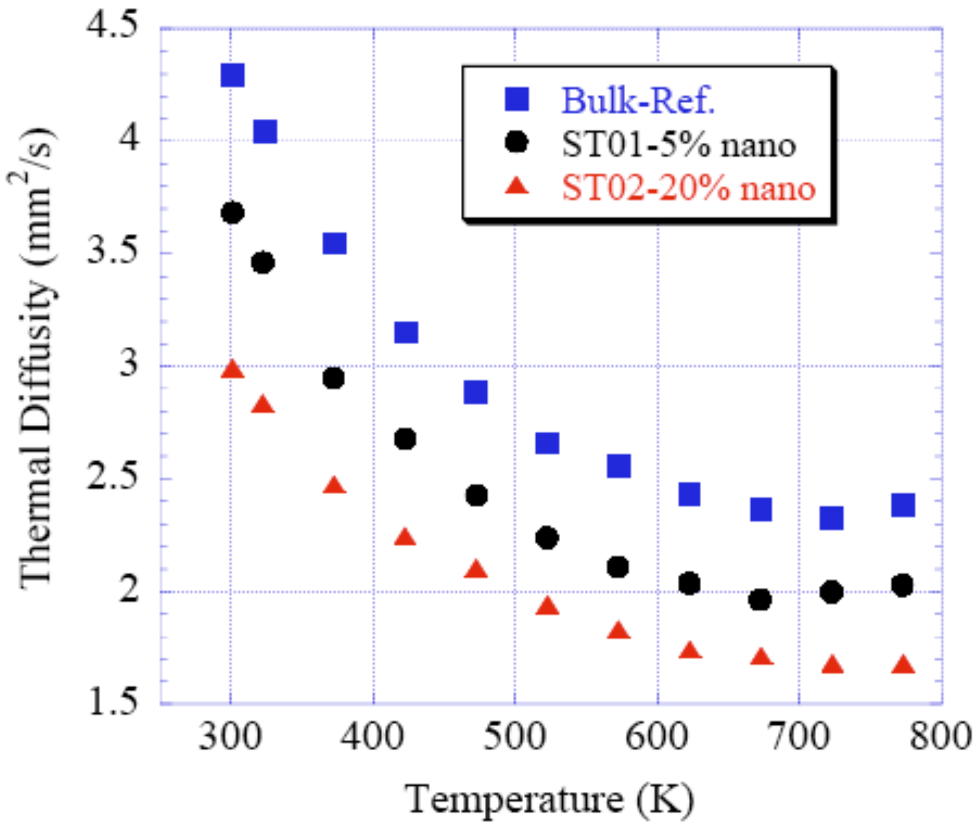


$CoSb_3$ Nano-Coating
In Grain Boundaries

Hydrothermal Nano-Coating Process for $CoSb_3$

Effect on Thermal Properties

High Temperature Thermal Diffusivity



NETZSCH LFA 457

Thermal Diffusivity (*d*)

$$\kappa = d\rho_D C_V$$

Three Samples

All three from same starting powders

1.) Bulk Ball Milled Powder

2.) Bulk with 5 wt% nano

3.) Bulk with 20 wt% nano

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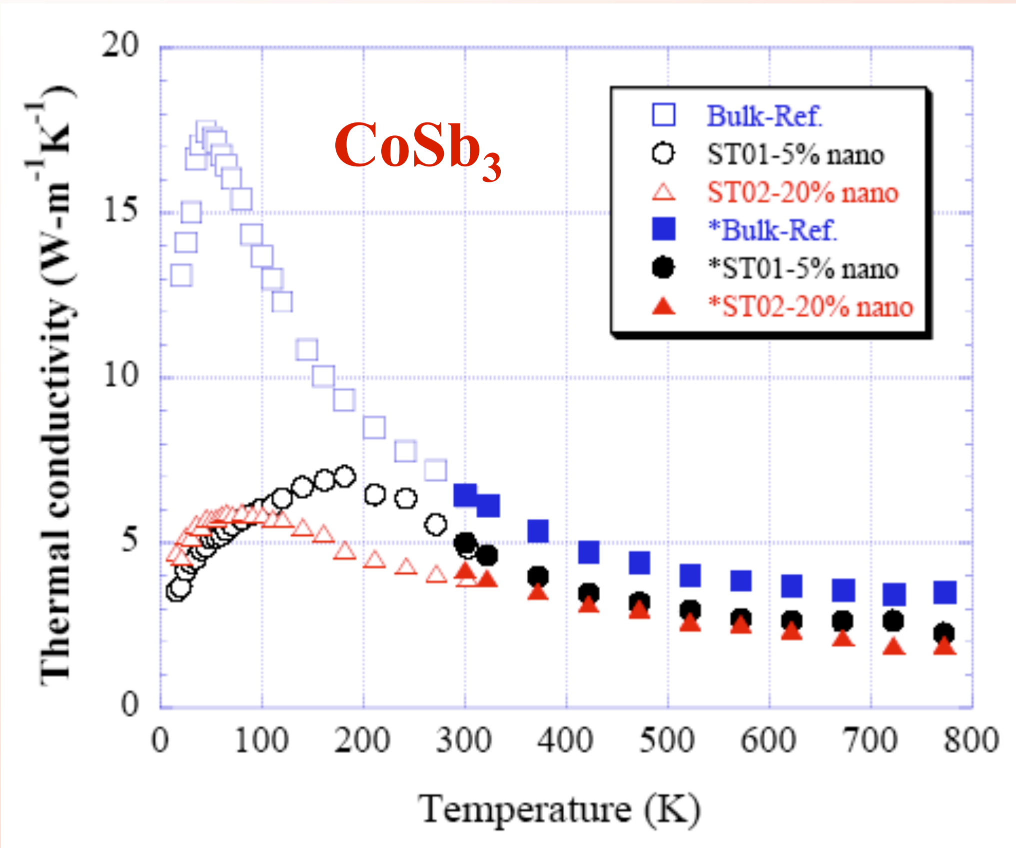
Hydrothermal Nano-Coating Process for $CoSb_3$

Effect on Thermal Properties

High & Low Temperature Thermal Conductivity

See X. Ji. *et.al* , Rap. Res.. Lett., **in press** 2007



Major Points:

1.) Very good match high & low temp

2.) Thermal conductivity reduces with addition of nano-coating

3.) More amorphous-like behavior evident at low T

4.) Future Work: <u>Filled Skutterudites</u>

$CoSb_3$ Work Summary

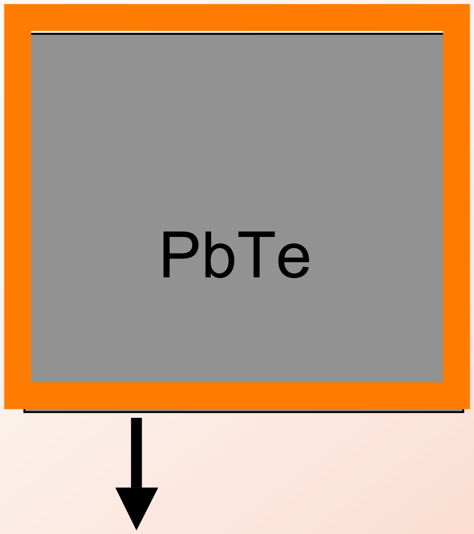
Used rather low purity starting materials
Even bulk $CoSb_3$ --- high resistivity

Wanted to see effect of thermal conductivity
Proof of Concept

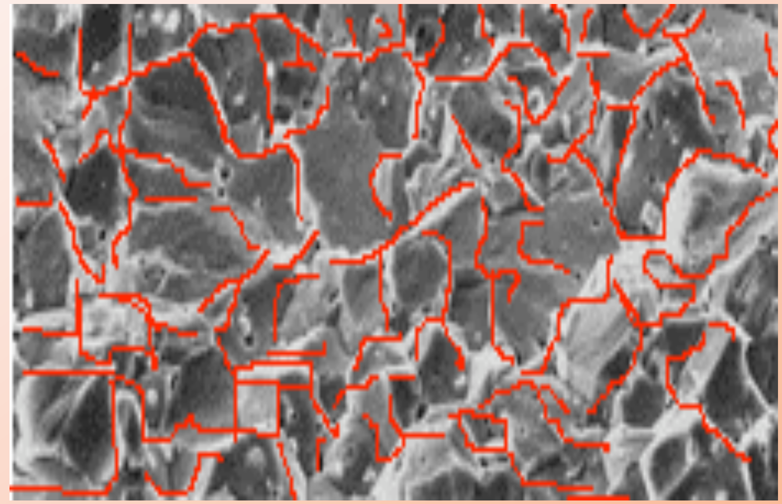
Nano-coating lowered resistivity by 20%
Probably due to self doping

Move to PbTe Coating Project
More control over the starting seed particles

Nanocomposites made by Surface Modification of PbTe Micron Particles.



Nanolayer of PbSe



Approximately 500 layers/mm along one direction

1. Homogenous distribution of Nanostructures
2. Naturally prevent Nanostructures and Grain Growth.

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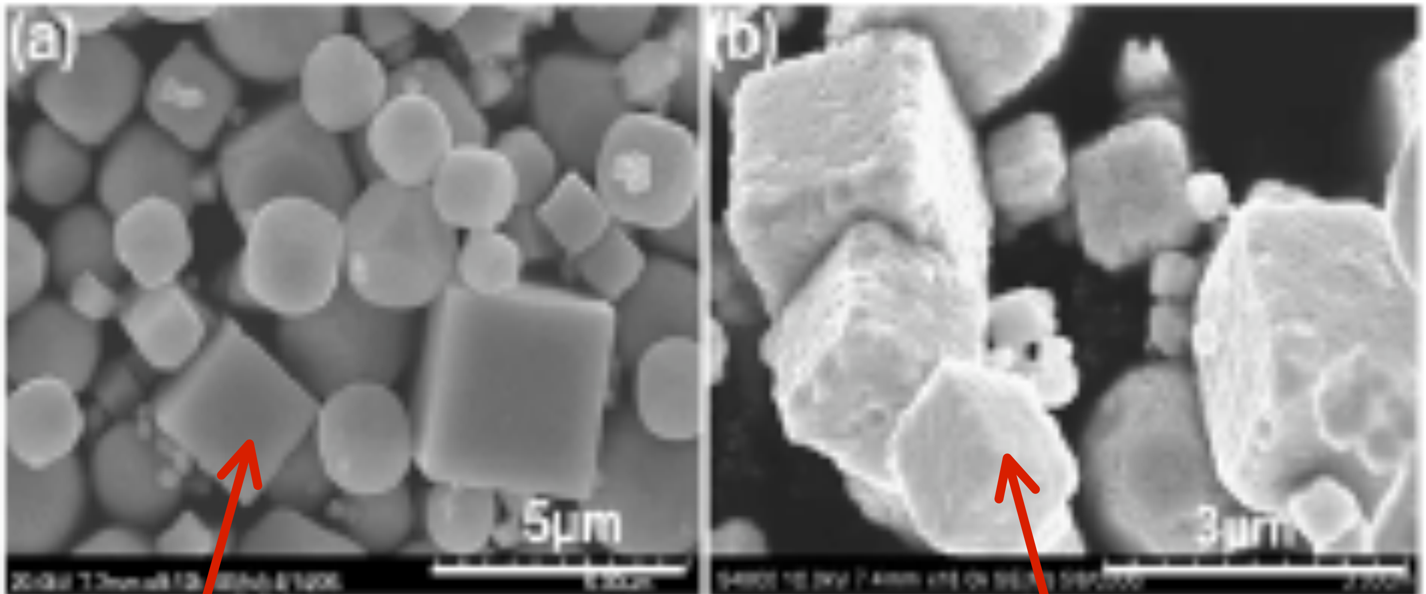
Hydrothermal Nano-Coating Process on PbTe



PbTe: As grown via CVD

PbTe: after hydrothermal Treatment with PbSnSe -- Notice thin coating

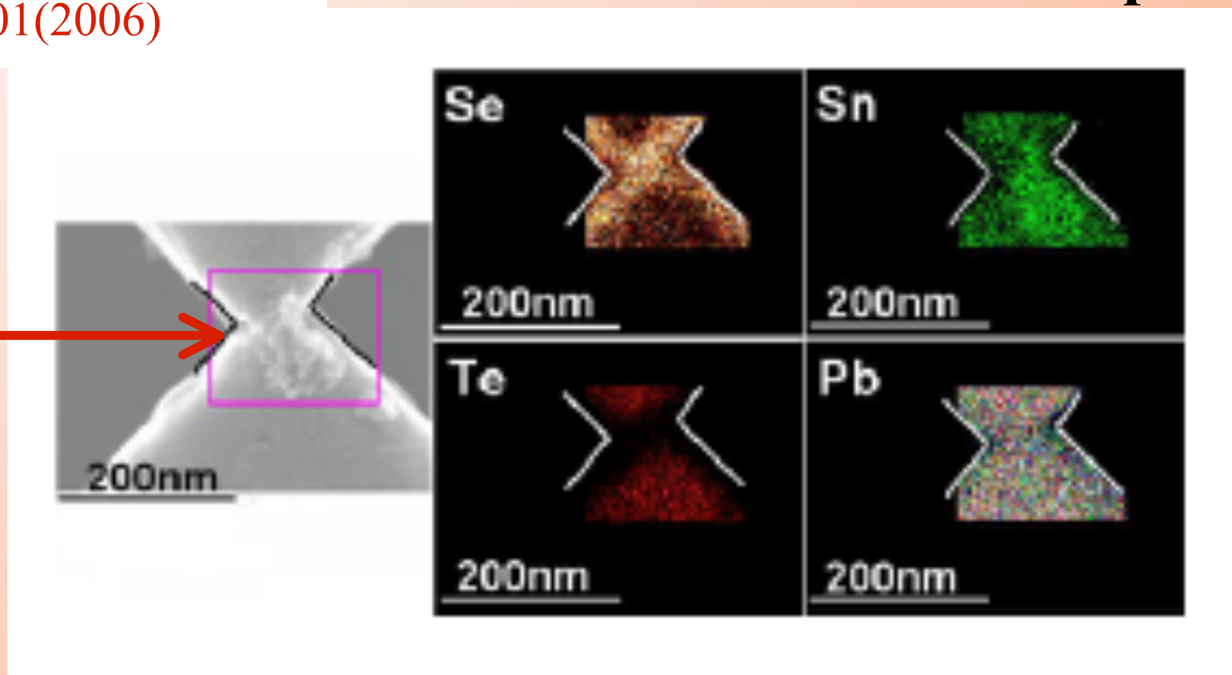
Hydrothermal Nano-Coating Process on PbSnTe

Start with PbSnTe Seed particle (several µm)
Hydrothermal Nano-Coating (PbSnSe)

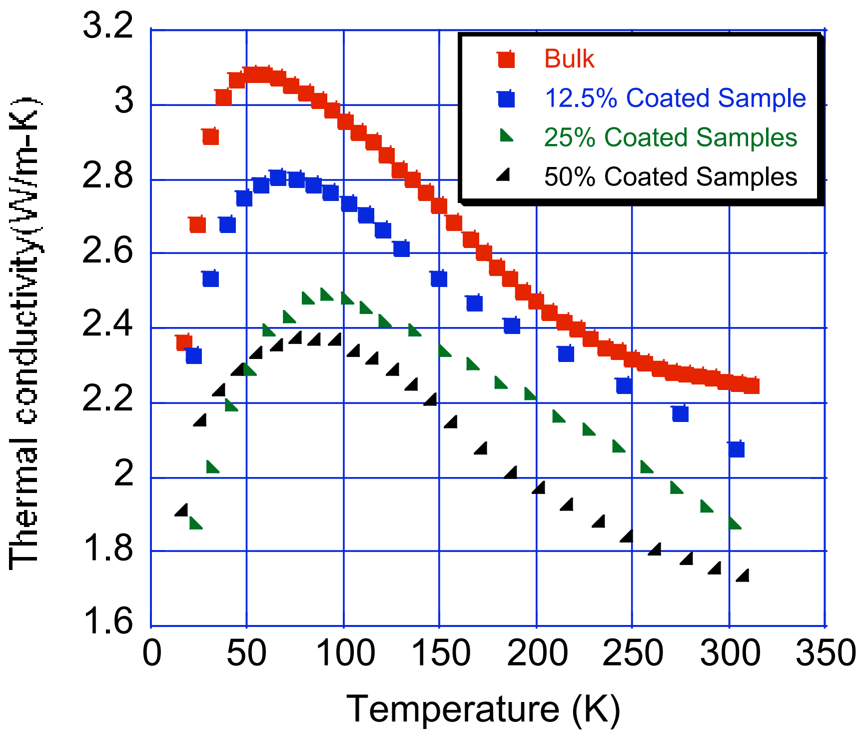
B. Zhang, *et.al*., Appl. Phys. Lett., **88**, 022101(2006)

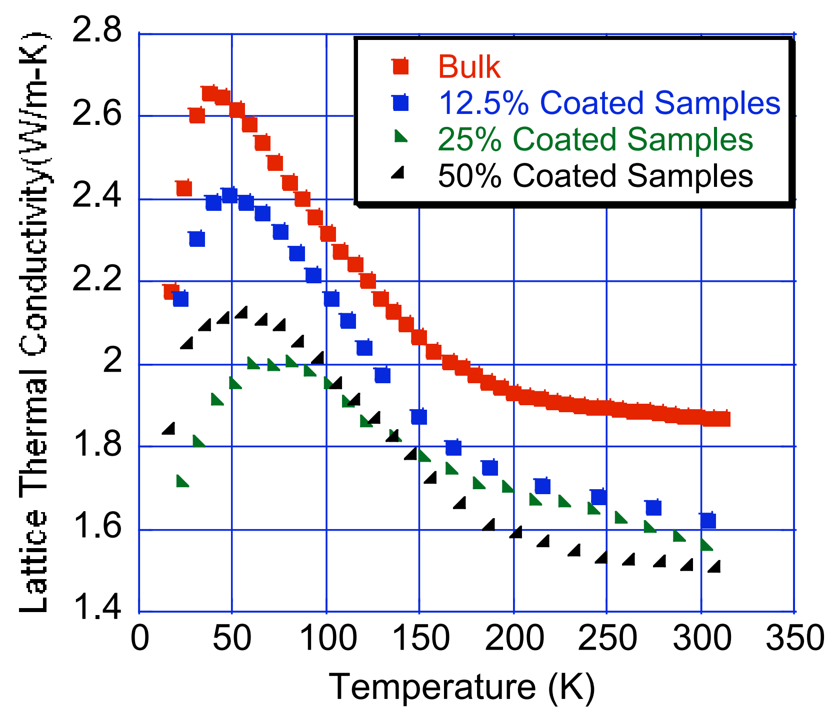
Elemental "Smart Map"

Focus On this area



Hydrothermal Coated PbSnTe: Thermal Conductivity





κ_L systematically lowered in coated samples

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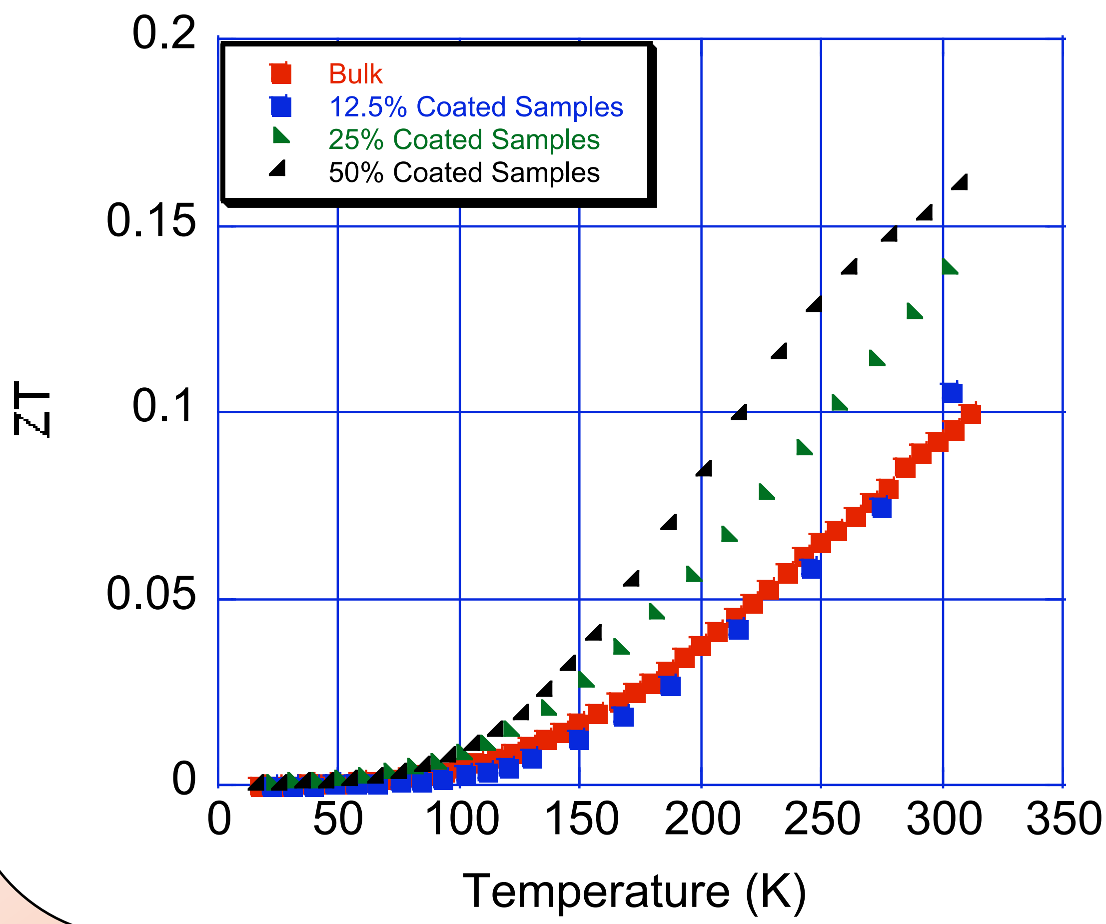
Hydrothermal Coated PbSnTe: Figure of Merit



ZT is enhanced in the coated samples By about 50%

Note: Bulk means uncoated seed particles.

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Concluding Remarks

- Increased Demands for Alternative Energy Systems
- Significant Progress in TE's in Last 10 Years
- Thermoelectrics: (Shift to Waste Heat Recovery)
  - Efficiency & Stability is a Materials Issue.
- Thermoelectric Materials Research:
  - "Designer Materials" Approach
  - Complex Structures & Transport
  - Challenges in Theory, Synthesis & Characterization
- Many Opportunities in Nanocomposites or
  Nanoscaled Bulk TE Materials (Several Active Groups)
- More Theoretical Modeling & Insight Needed
- Materials Research is the KEY to Significant Advances.

Thermoelectric Power Generation for Automotives

- Current TE Materials are Viable ($\eta \approx$ 7-8% efficiency)
- Need a High ΔT ($\approx$ 500˚C)
- $\approx$ 300 watt systems are being produced
- Likely Market (Heavy Duty Trucks - Tractors etc.)
- Desired 1 KW System

- Will Need Better Thermal Management Design
  (eg. BSST - see later talks)
- Need Higher Efficiency Bulk TE Materials
  (ZT $\approx$ 2-3, $\eta \approx$ 15-20% and $/Watt in right range)
- "Nano-Engineered" Bulk TE Materials
  Likely Candidates.

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Dept. of Energy: DOE EPSCoR Implementation Grant (DOE #: DE: FG02-04ER-46139)

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SC EPSCoR & Clemson University

Thank You !!

Basic Energy Sciences DOE EPSCoR

South Carolina EPSCoR / IDeA Program

Office of Naval Research

MRS Fall Meeting

Boston, MA

Thermoelectric Power Generation

Symposium U

November 25th - 30th, 2007

Over 100 Oral & Poster Presentations

Tim Hogan, Michigan St.

Jihui Yang, GM R&D

Terry M. Tritt, Clemson University

Ryoji Funahashi, AIST, Japan

Tritt Research Group: Summer 2006

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