Challenges and Opportunities in Thermoelectric Energy Conversion

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University of California, Berkeley

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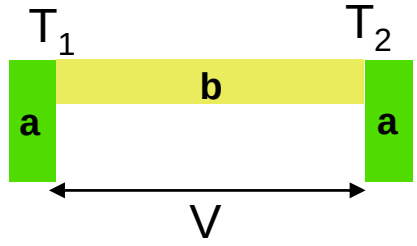
Lawrence Berkeley Lab

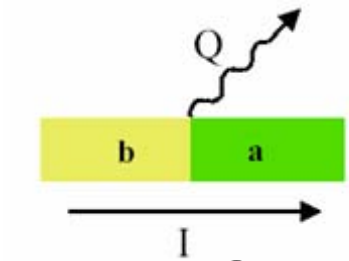
DOE, NSF, ONR, NASA

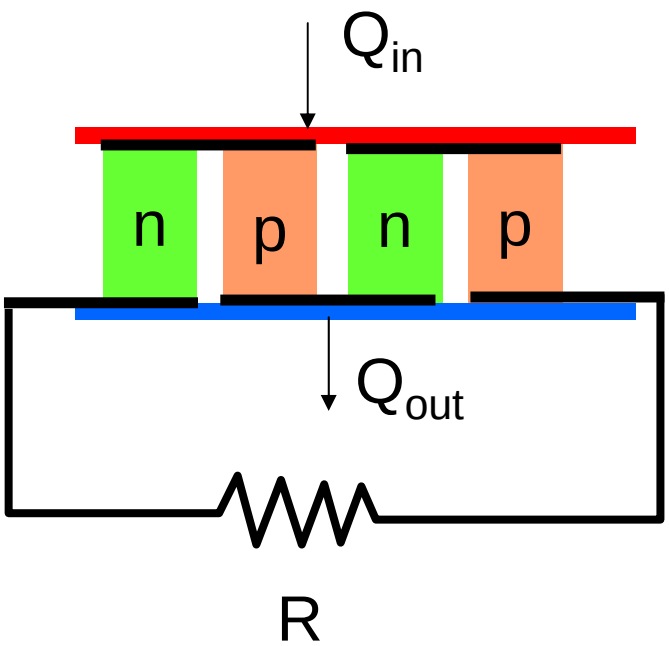
Thermoelectricity and Energy Conversion

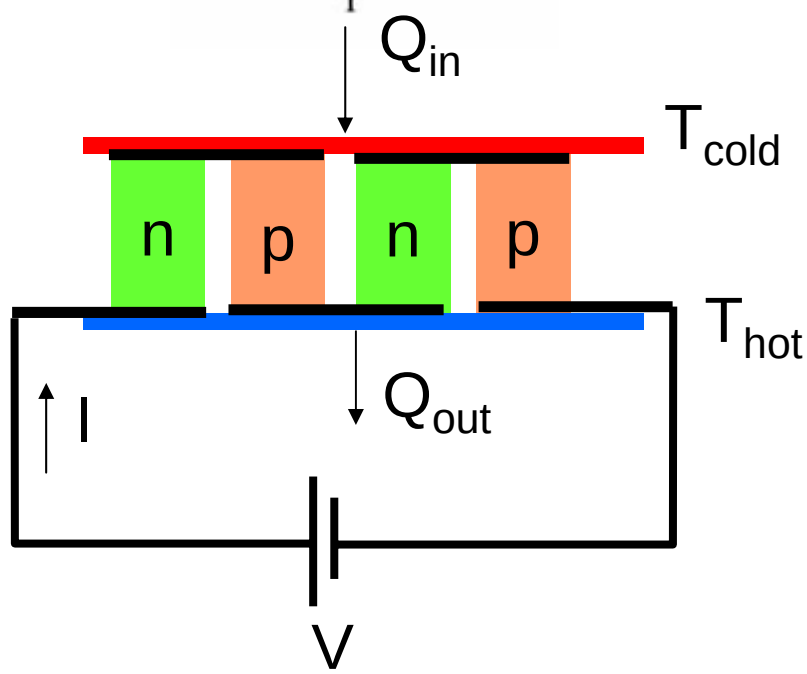
Seebeck Coefficient, $S = V/\Delta T$



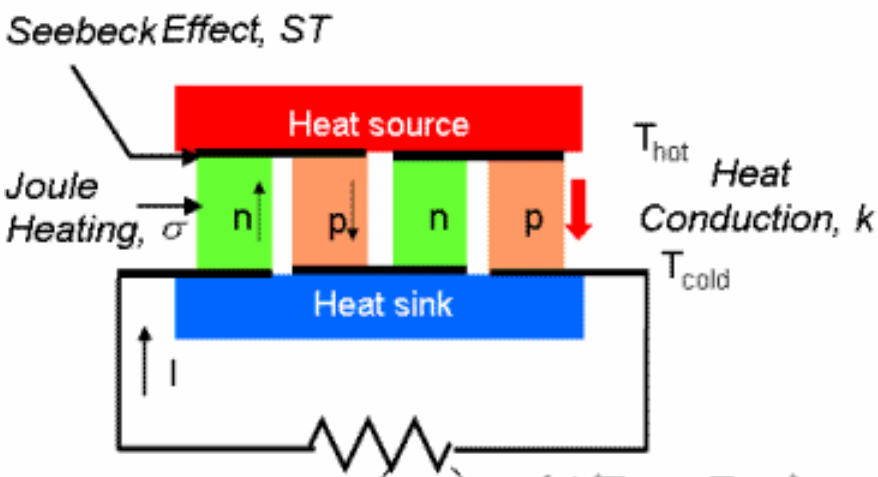
Peltier Coefficient, $\pi = Q/I = ST$





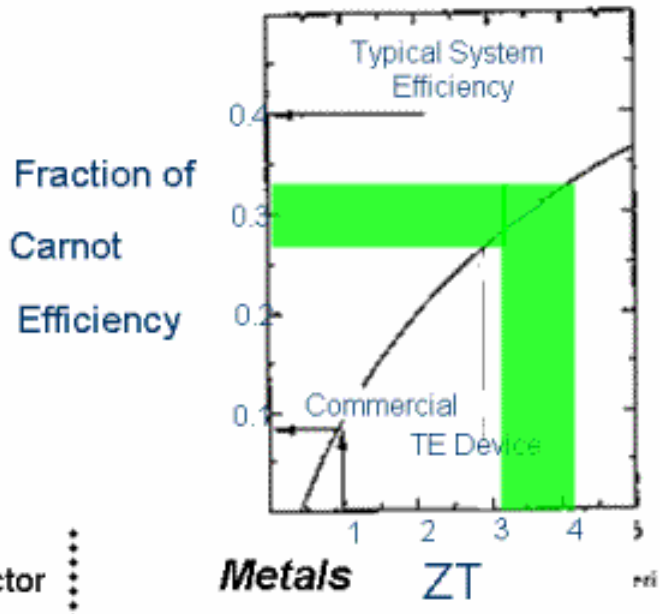


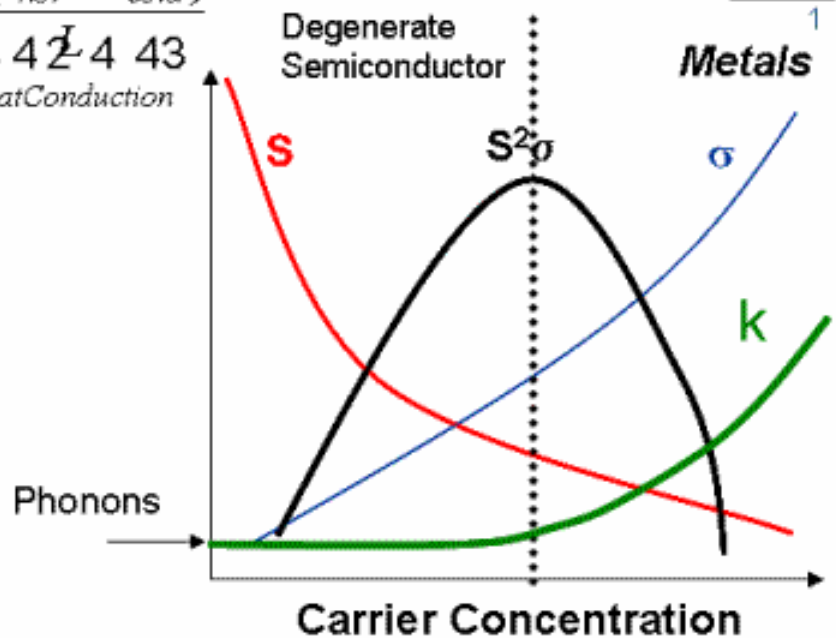
Thermoelectric Figure of Merit

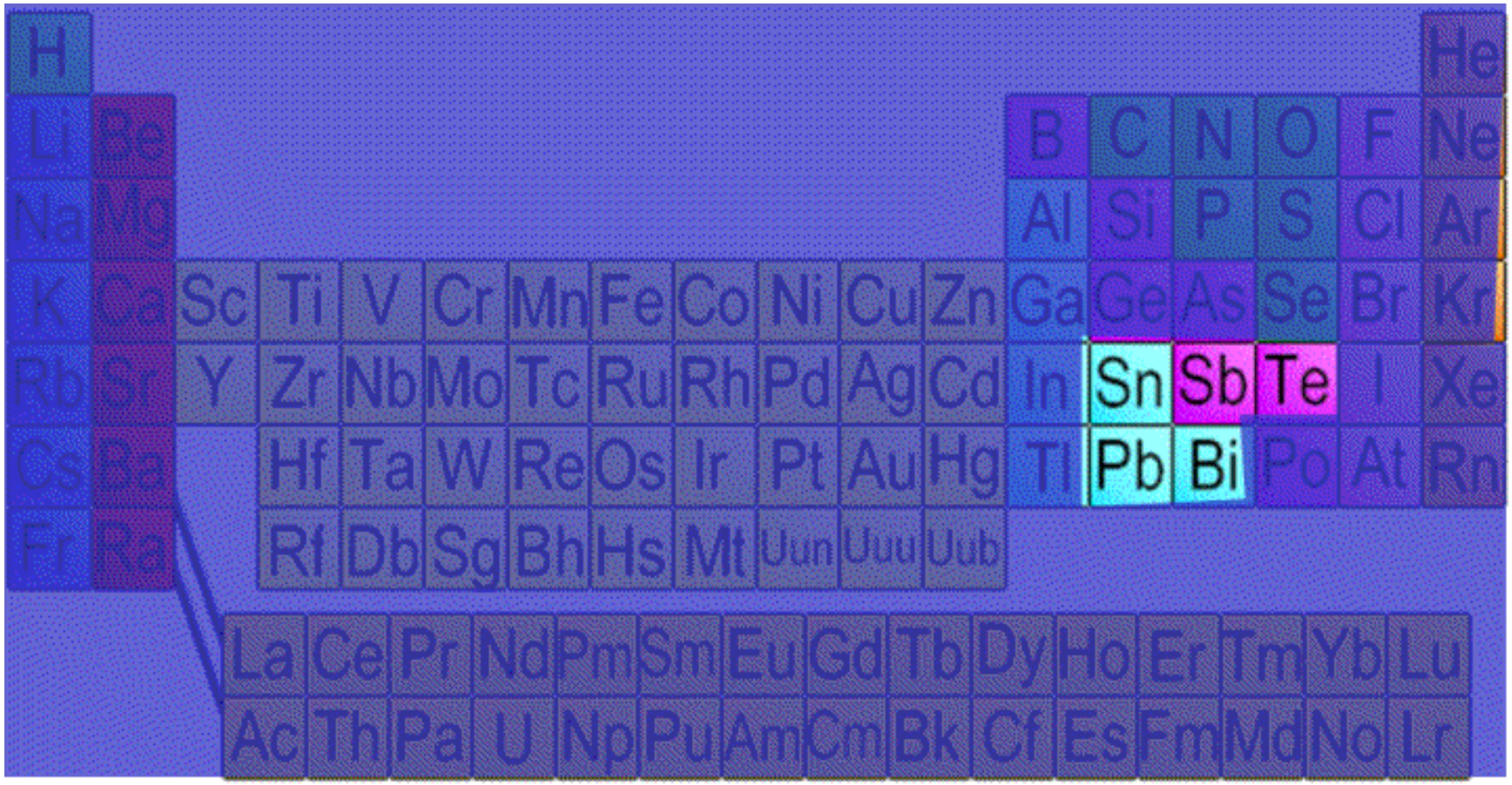


$$Q = \underbrace{STI}_{Peltier Cooling} - \underbrace{I^2\left(\frac{L}{\sigma A}\right)}_{Joule Heating} - \underbrace{\frac{kA(T_{hot}-T_{cold})}{L}}_{Heat Conduction}$$

$$ZT = \frac{S^2\sigma T}{k}$$






H
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Ni
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Br
Kr
Rb
Sr
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Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Po
At
Rn
Fr
Ra
Rf
Db
Sg
Bh
Hs
Mt
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Uuu
Uub
La
Ce
Pr
Nd
Pm
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Gd
Tb
Dy
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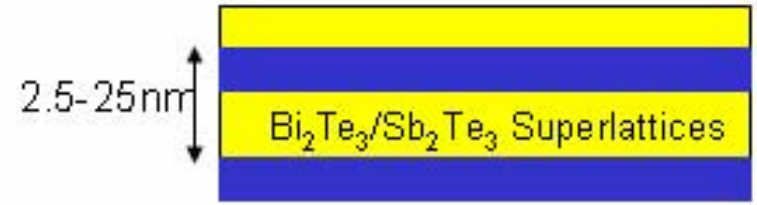
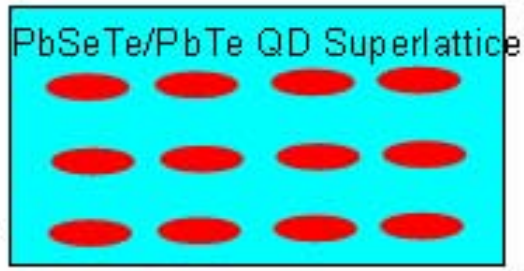
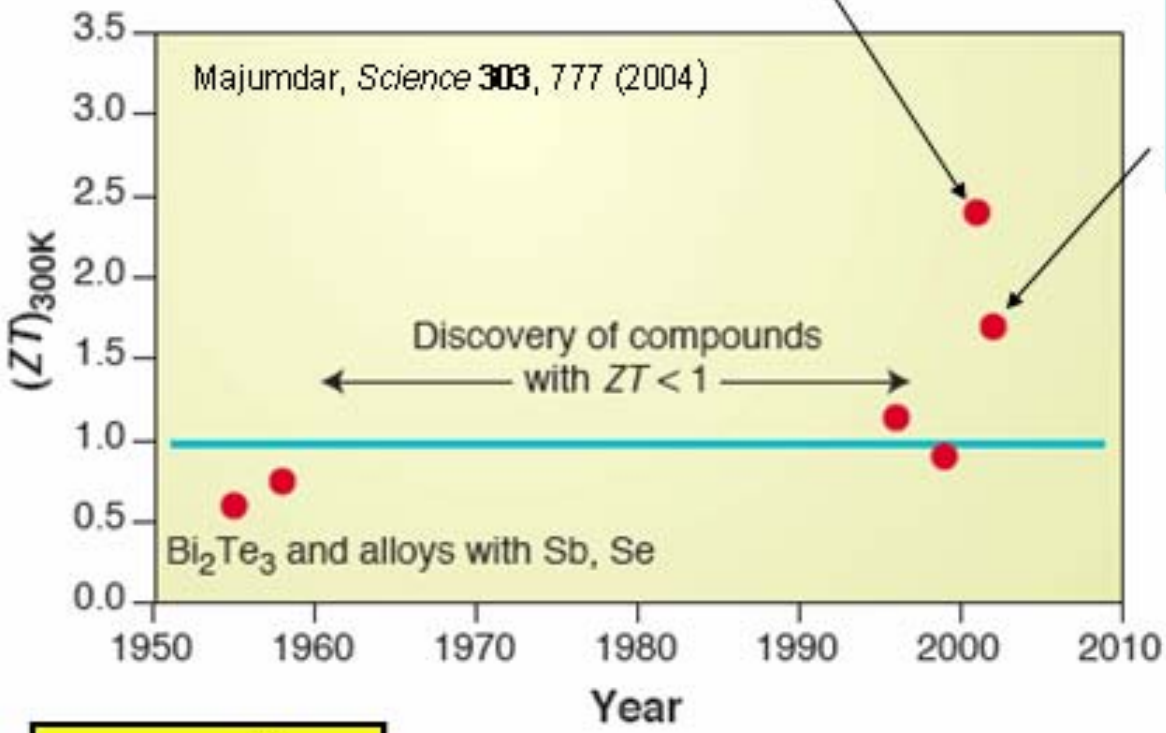
Lr

Venkatasubramanian et al. *Nature* **413**, 597 (2001)



Harman et al., *Science* **297**, 2229 (2002)

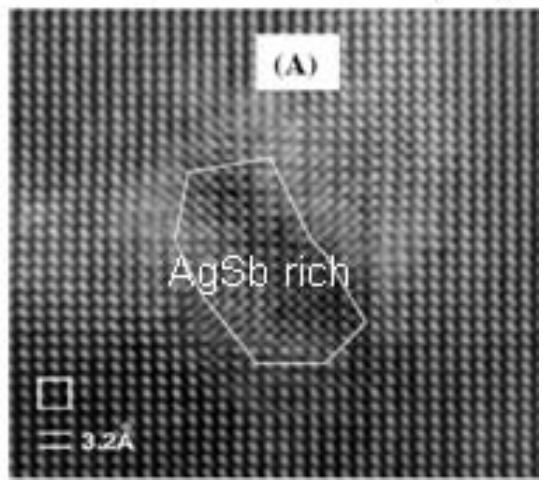


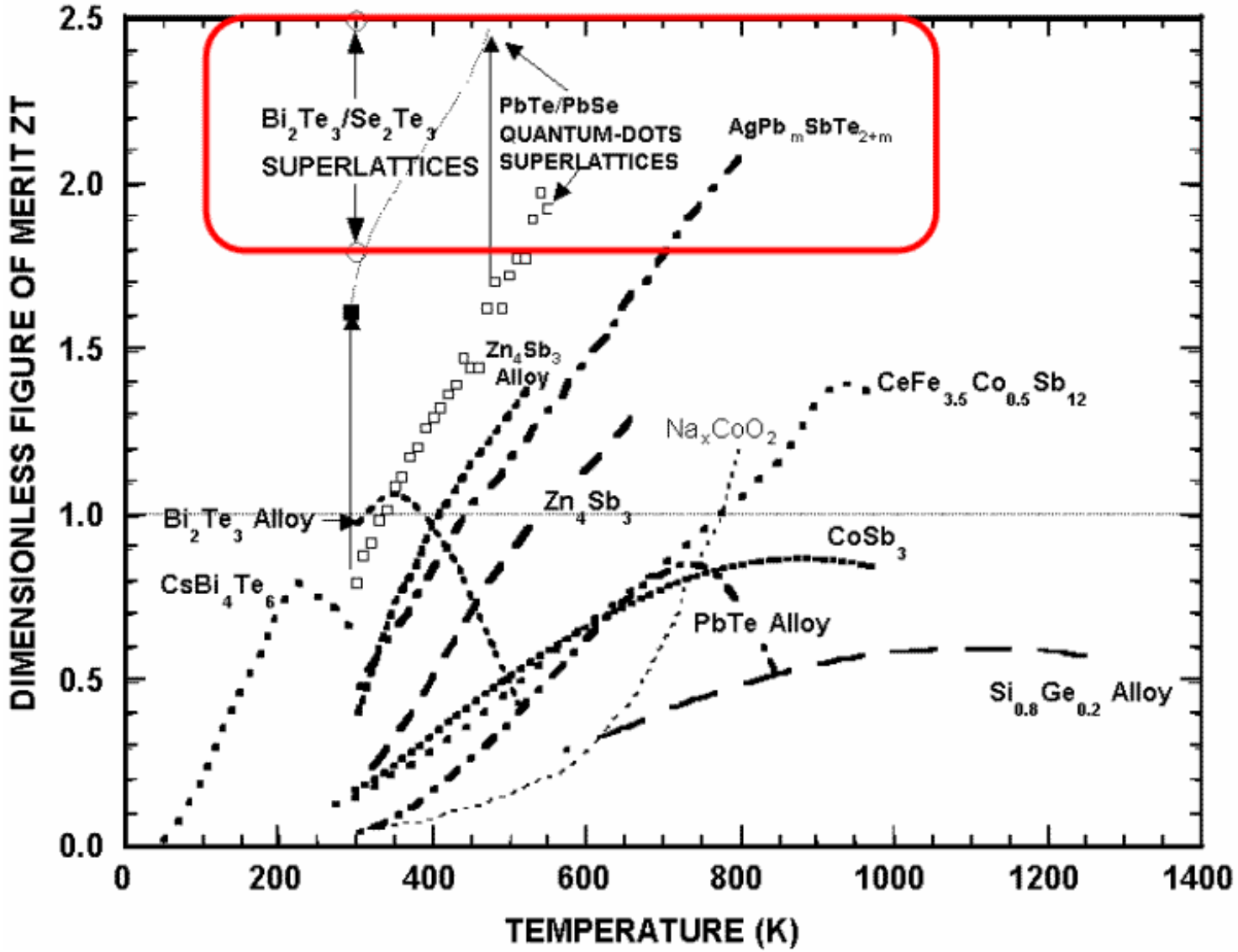


$$ZT = \frac{S^2 \sigma T}{k}$$

$AgPb_{18}SbTe_{20}$
ZT = 2 @ 800K

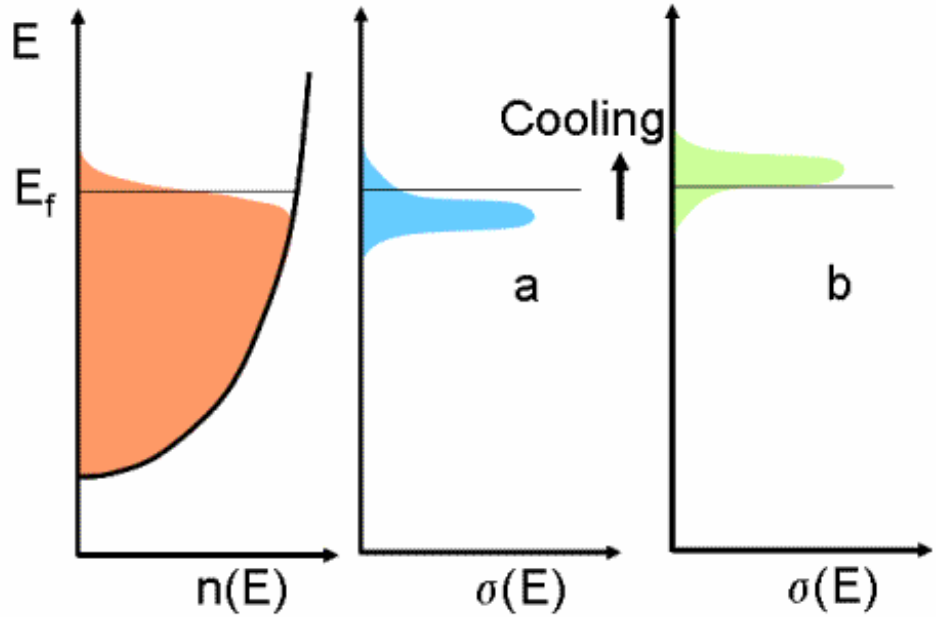
Hsu et al., *Science* **303**, 818 (2004)

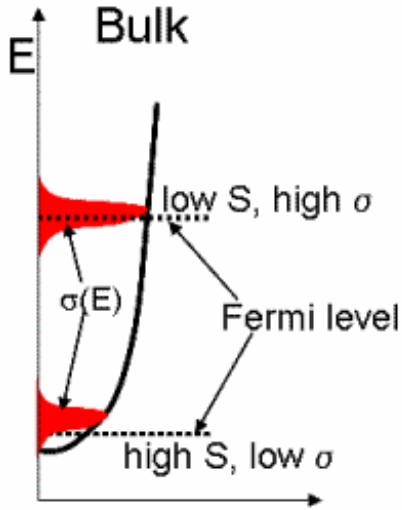


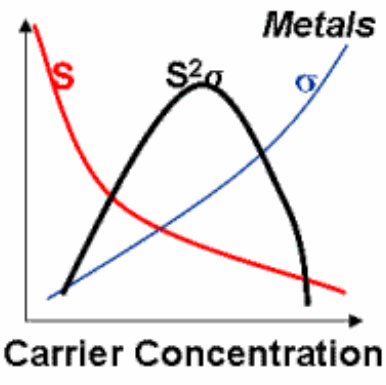


Courtesy: Gang Chen

Origins of Thermoelectricity



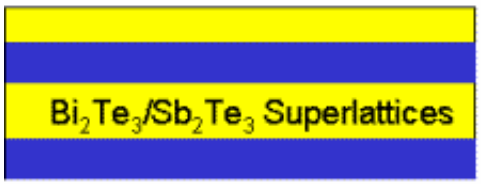


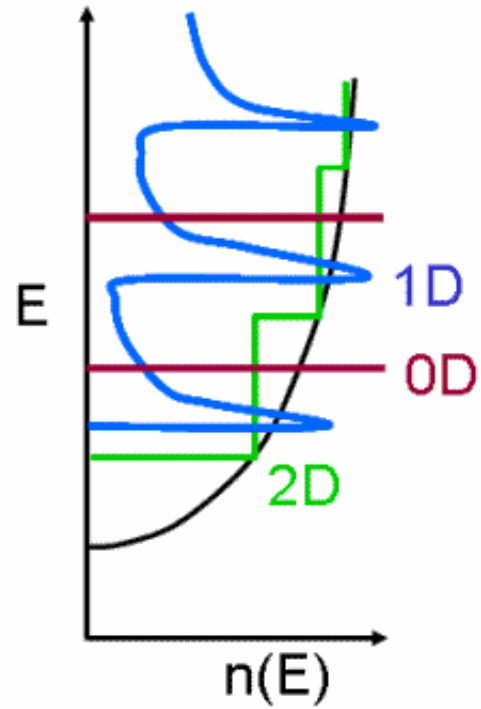


$$\sigma = \int \sigma(E)dE \qquad \sigma(E) = q^2\tau(E)v^2(E)n(E)\left(-\frac{\partial f_{eq}}{\partial E}\right)$$

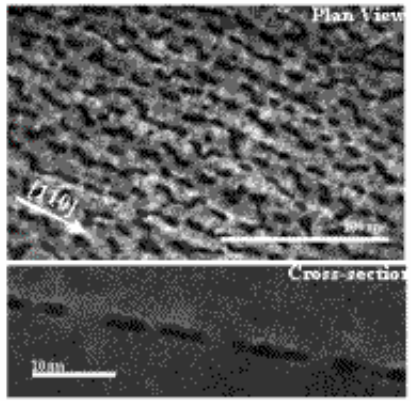
$$S = \frac{1}{eT}\frac{\int \sigma(E)(E - E_f)dE}{\int \sigma(E)dE}$$

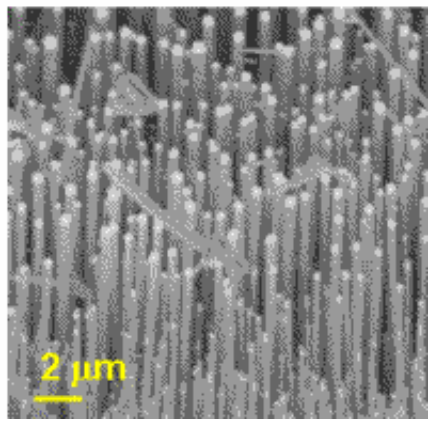
Effect of Nanostructuring on $S^2\sigma$





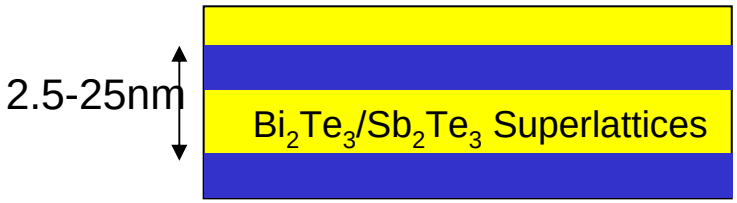
Quantum Confinement





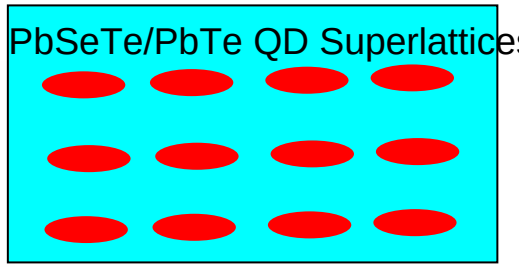
(Dresselhaus et al., 1993)

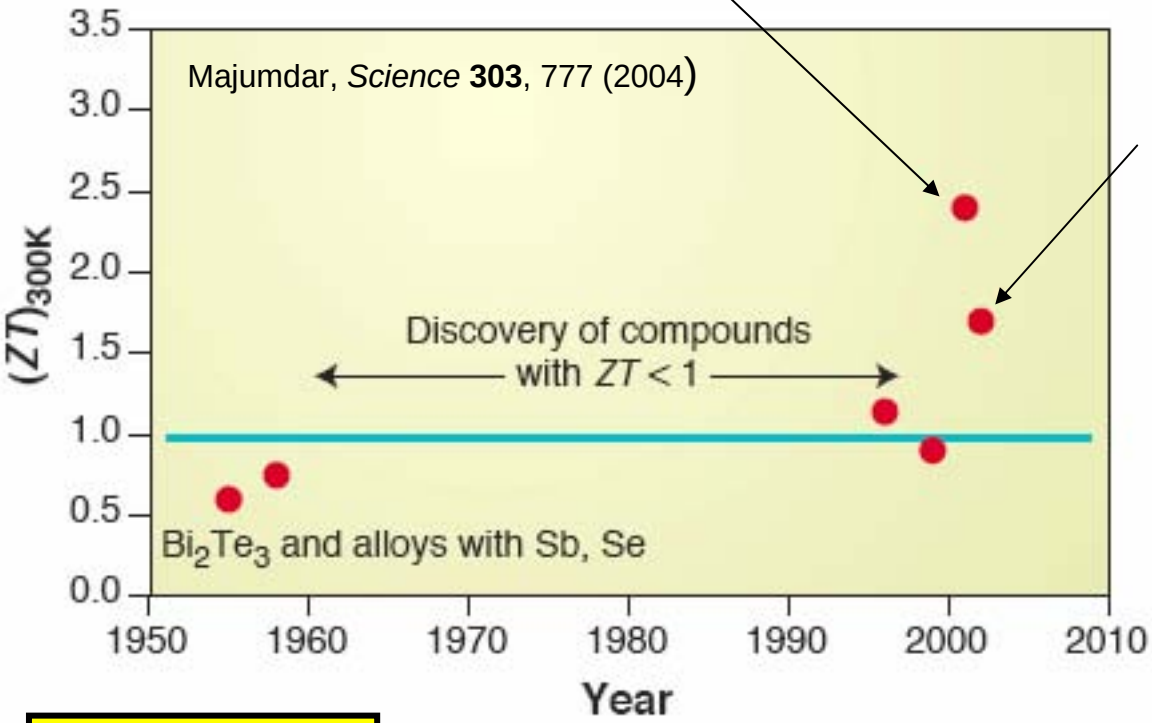
Venkatasubramanian et al. *Nature* **413**, 597 (2001)



k_{bulk} = 0.49 W/m-K
k_{ns} = 0.22 W/m-K

Harman et al., *Science* **297**, 2229 (2002)





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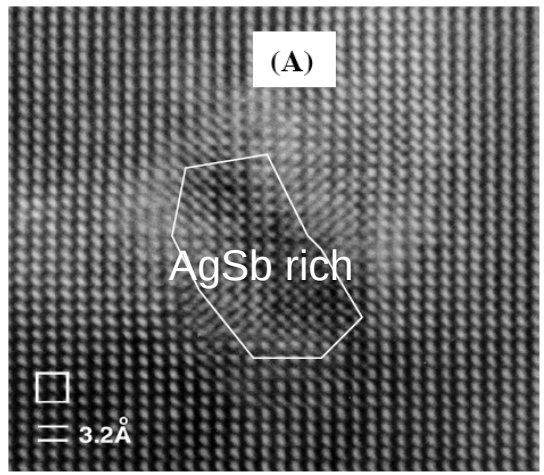
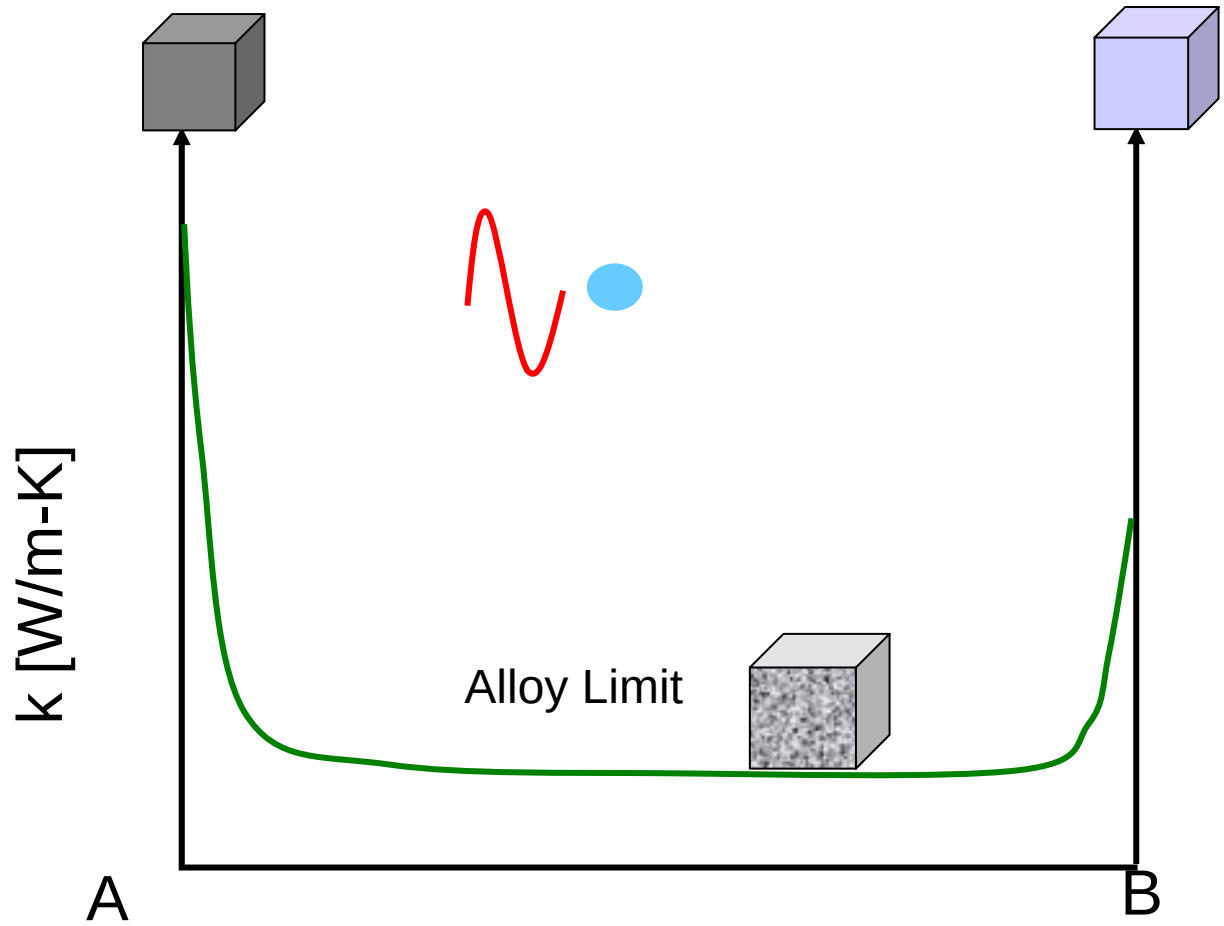
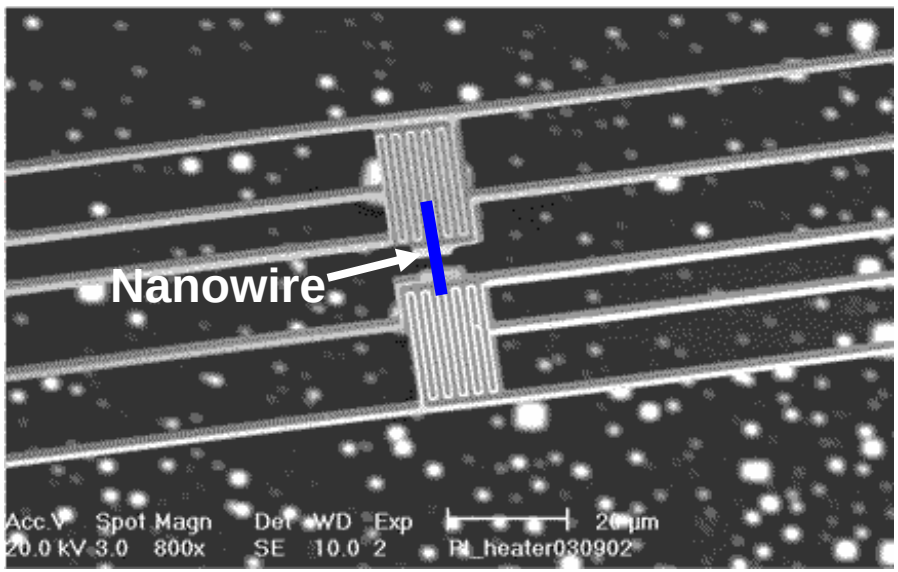


Alloy limit of thermal conductivity in crystalline materials!



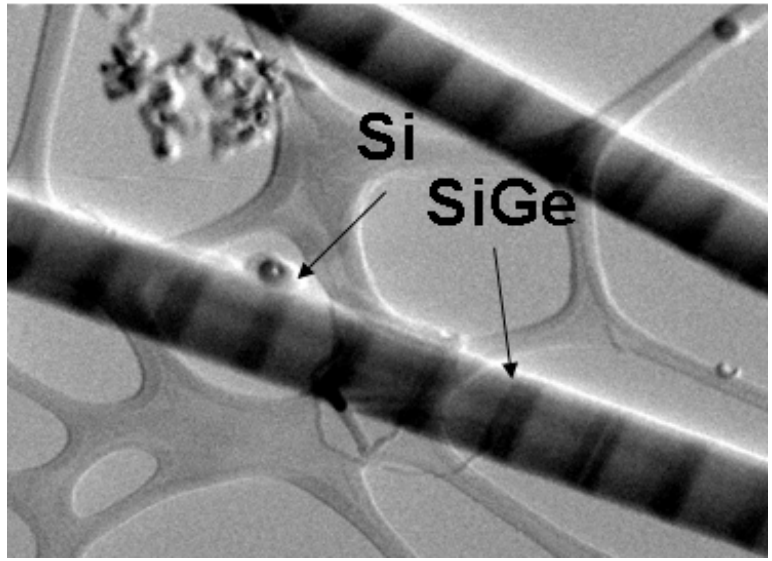
Si/SiGe superlattice nanowires

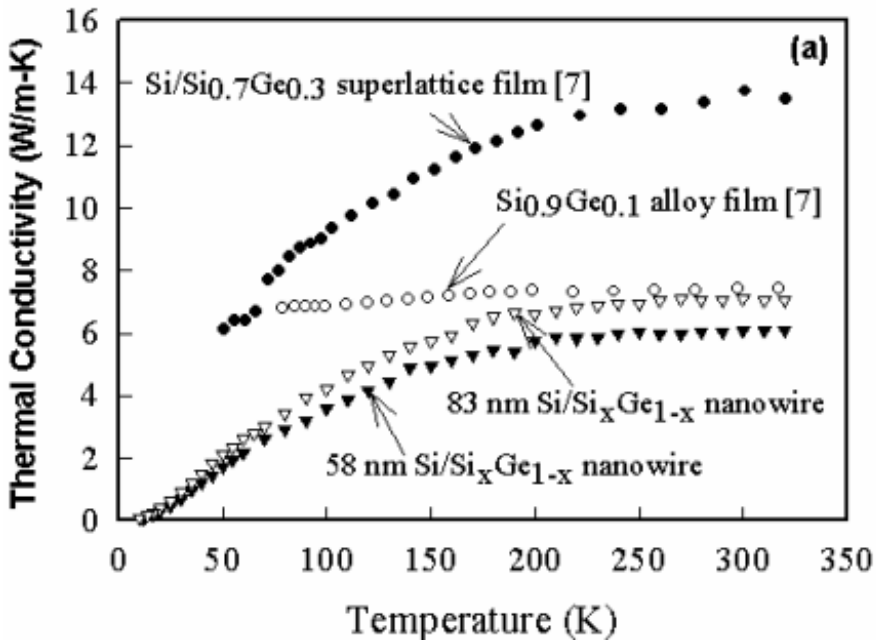


Li et al., *Appl Phys Lett* **83**, 3186 (2003)

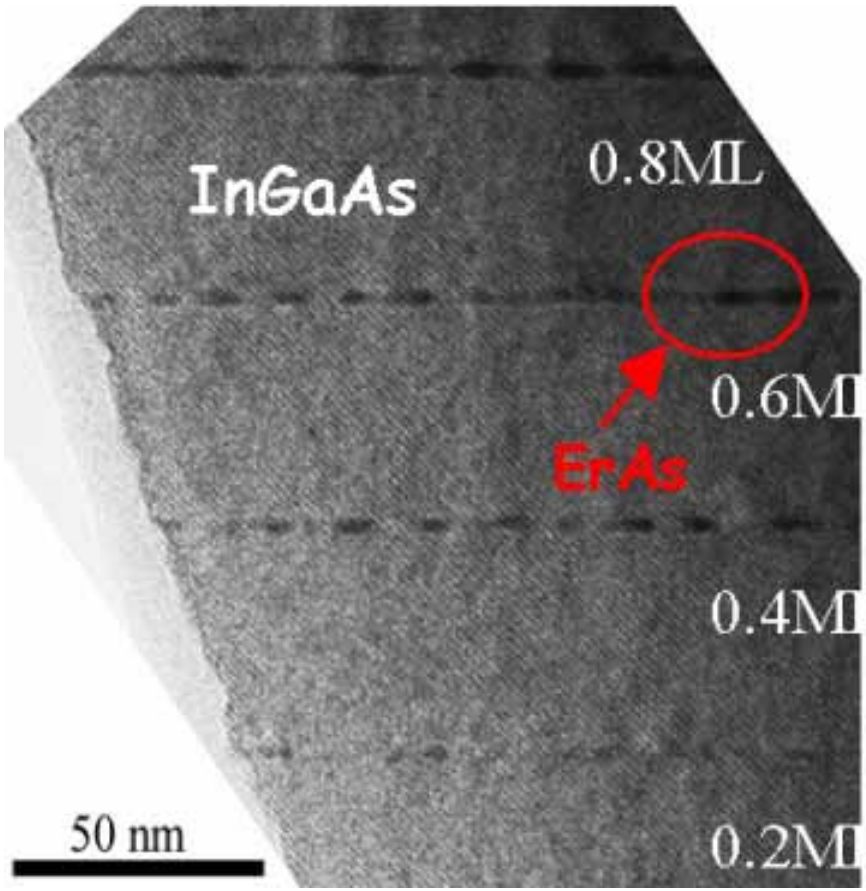
Deyu Li, Yiying Wu, Rong Fan, Peidong Yang

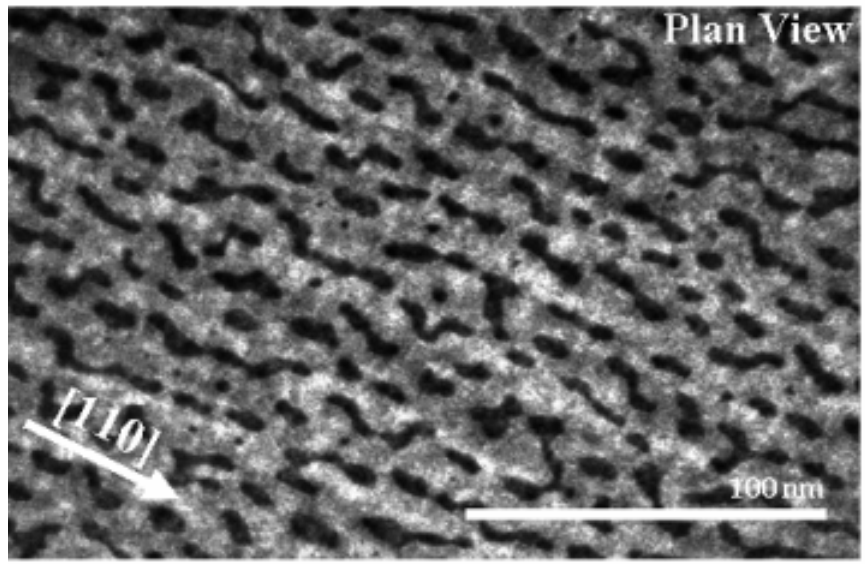
$Si/Si_{0.95}Ge_{0.05}$

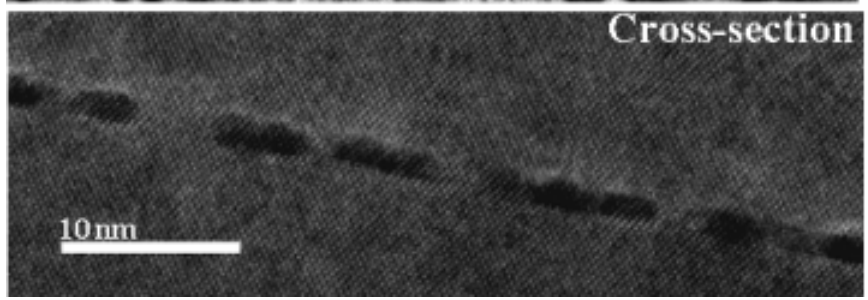




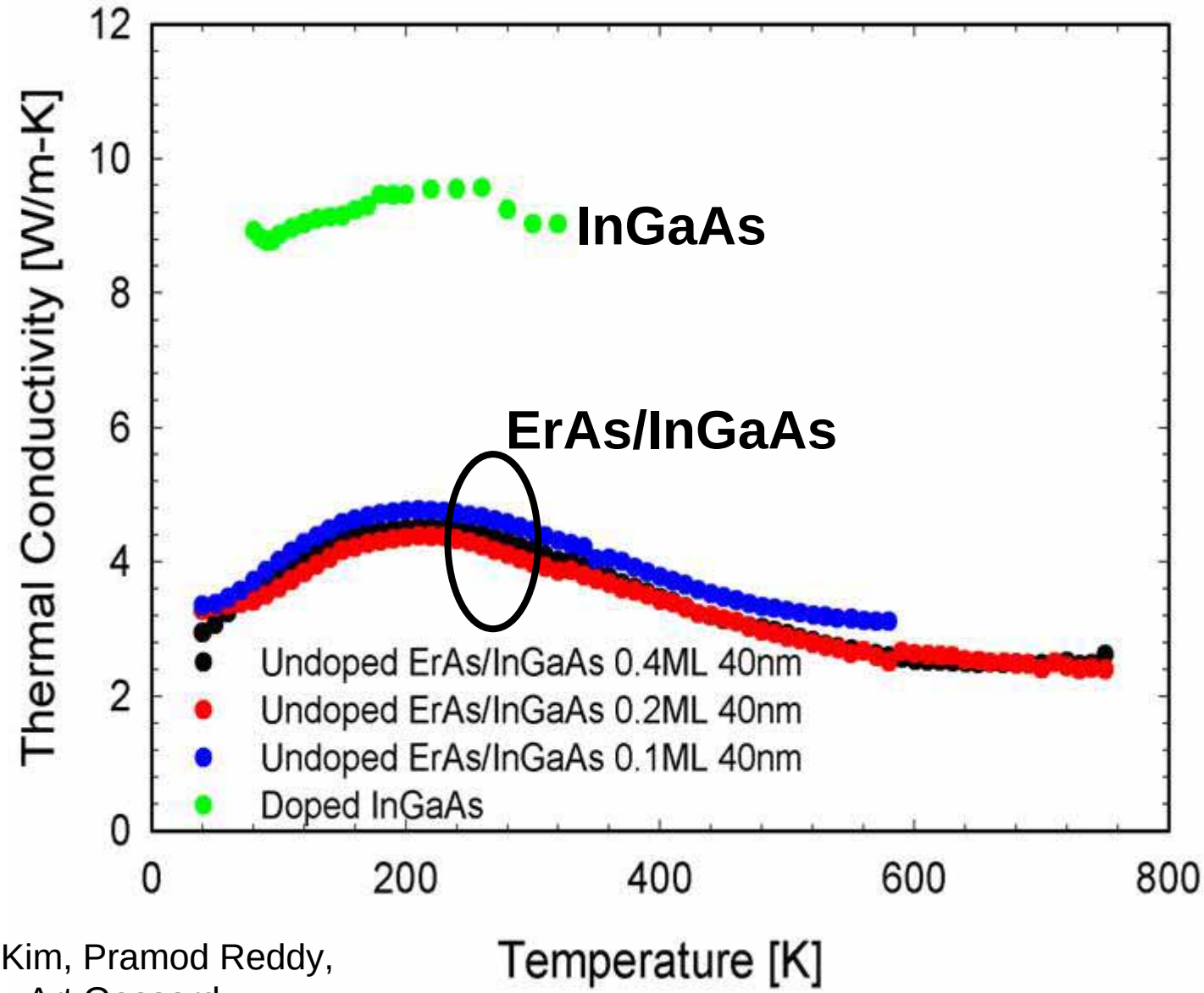
ErAs Nanostructures Embedded in InGaAs







Below Alloy Limit!



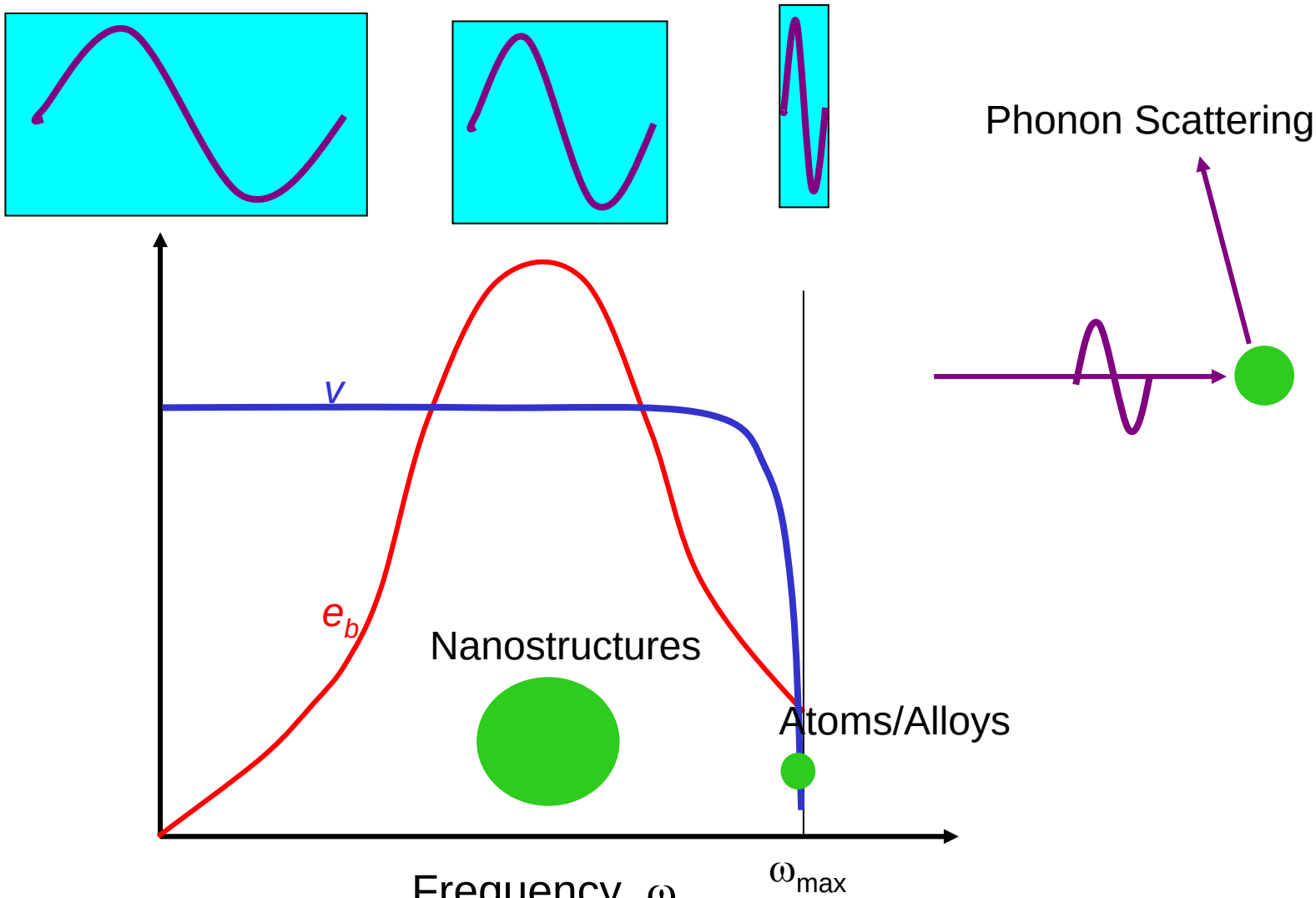
Woochul Kim, Pramod Reddy,
Josh Zide, Art Gossard

Hypothesis

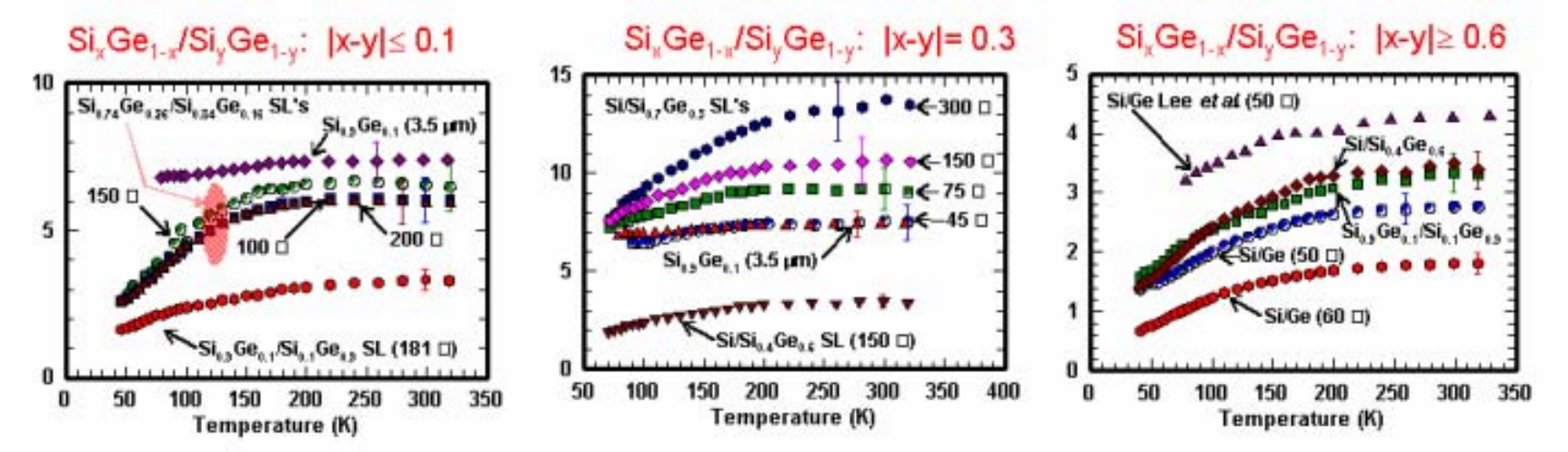
$$k = \frac{d}{dT}\left[\int_0^{\omega_{max}} e_b(\omega)\, v(\omega)\, l(\omega)\, d\omega\right]$$

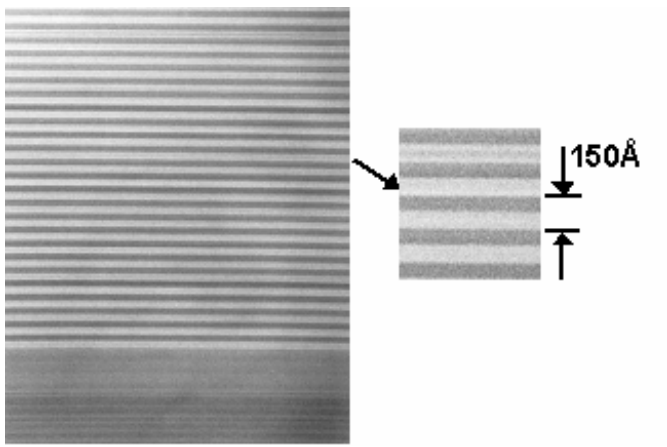
123

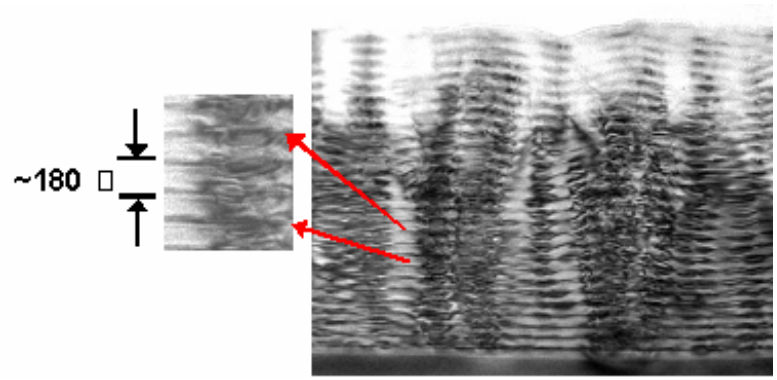
Planck BB Speed MeanFreePath



Si-Ge Superlattices

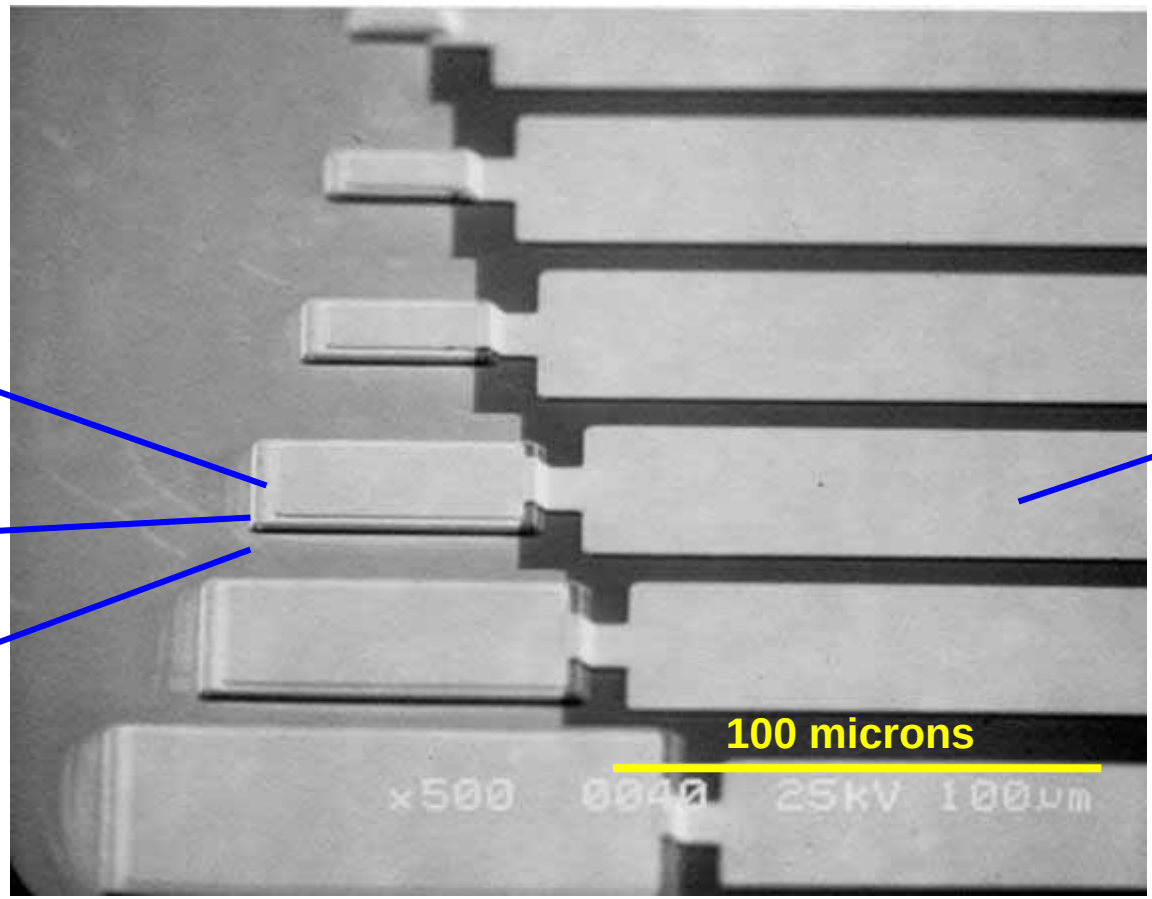






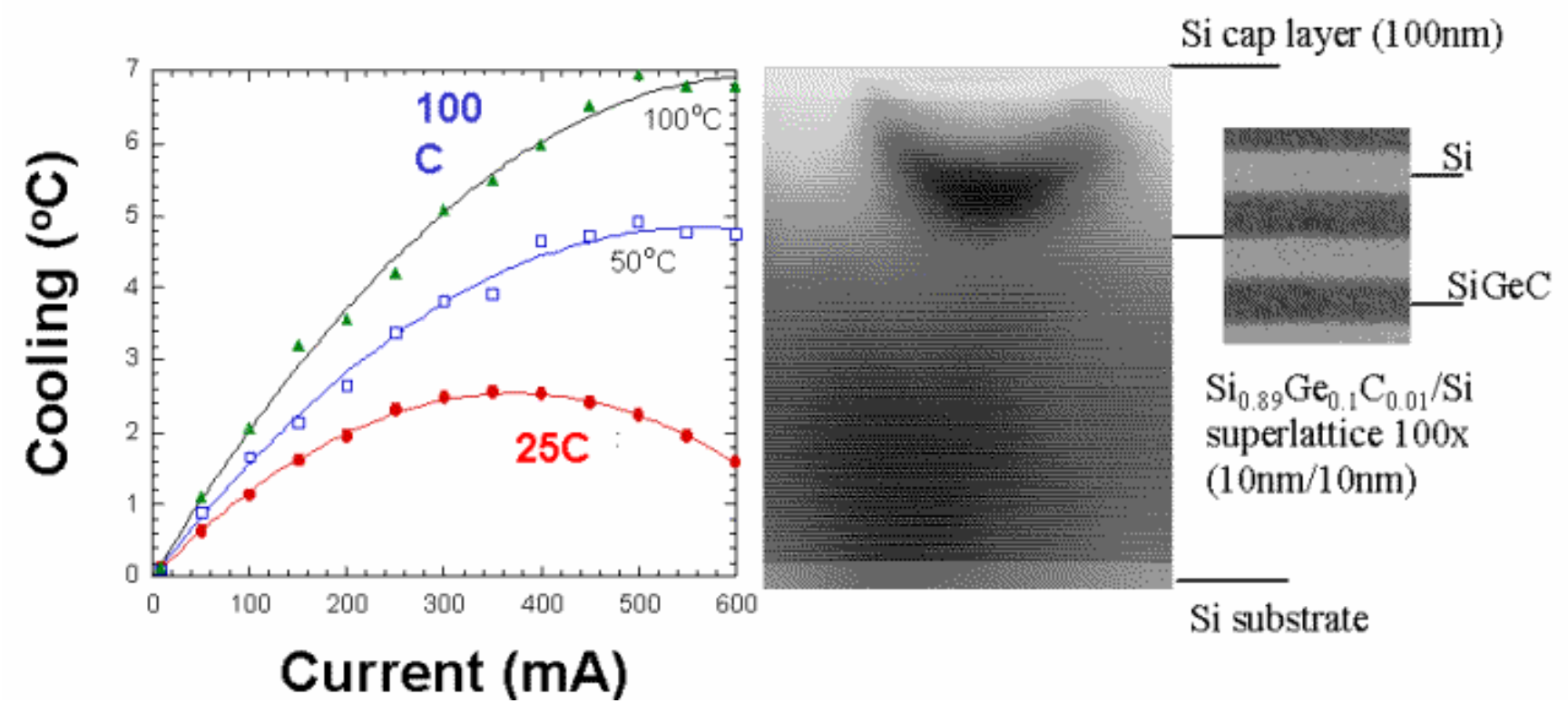
Courtesy: Ed Croke, Hughes Res. Lab. for materials

SEM Picture of Thin Film Coolers



Courtesy: John Bowers (UCSB); Ali Shakouri (UCSC)

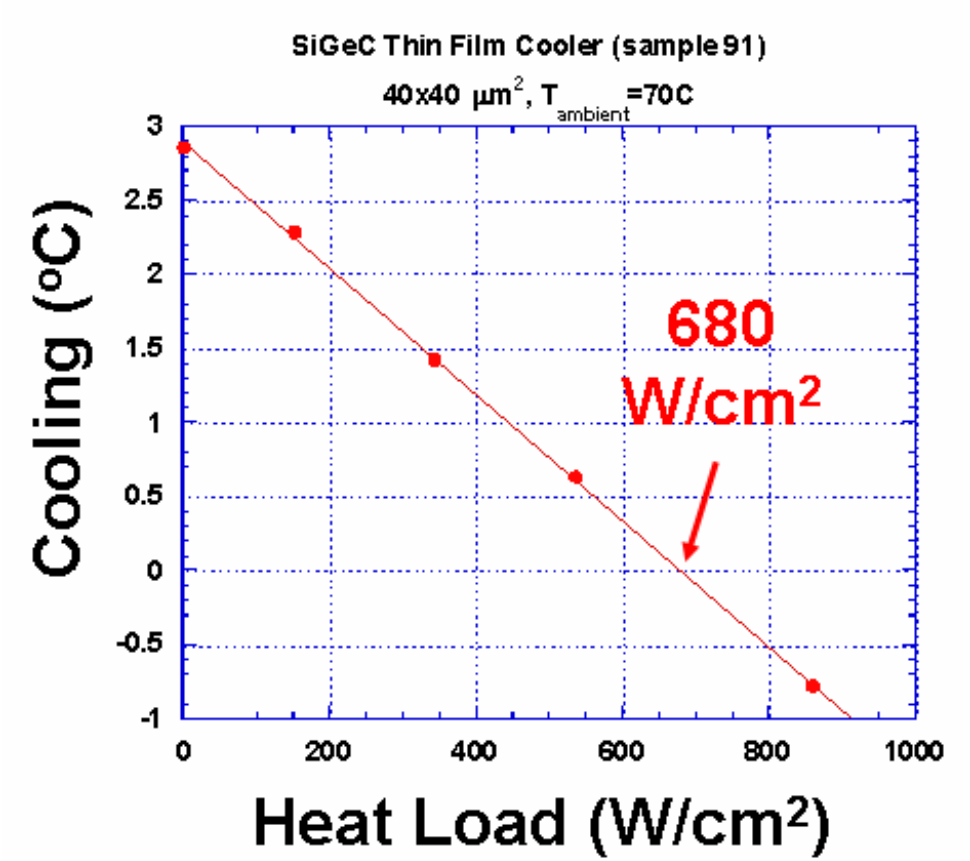
n-Si/SiGeC Superlattice Micro Cooler

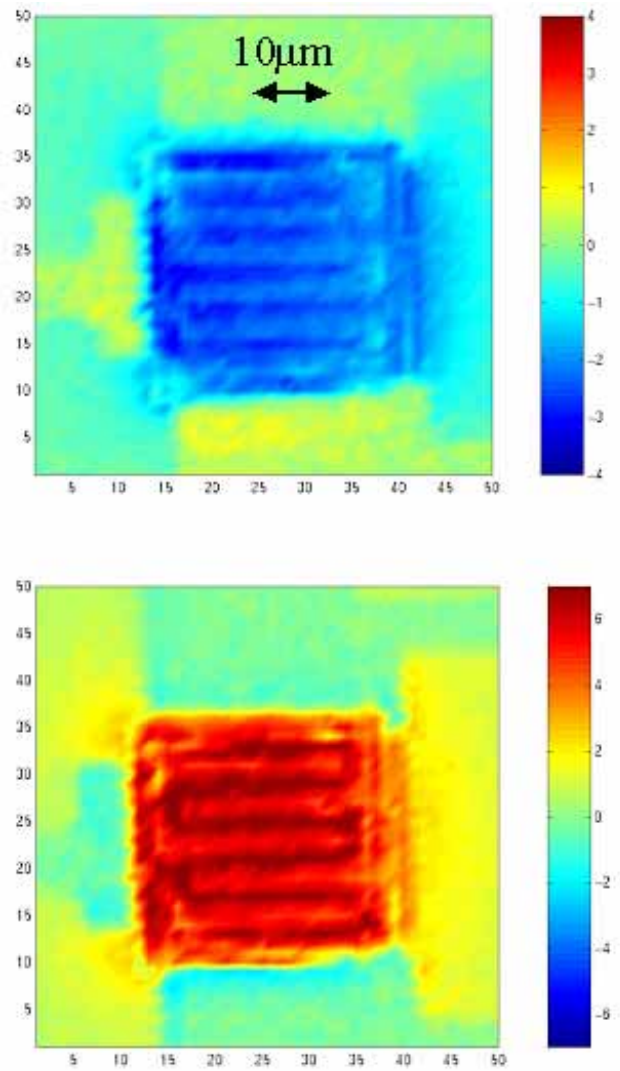


X. Fan, G. Zeng, C. LaBounty, E.Croke, C. Ahn, J.E. Bowers, A. Shakouri, "**SiGeC/Si superlattice micro cooler**," *Applied Physics Lett.*, Vol. 78, No.11, 12 March 2001.

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

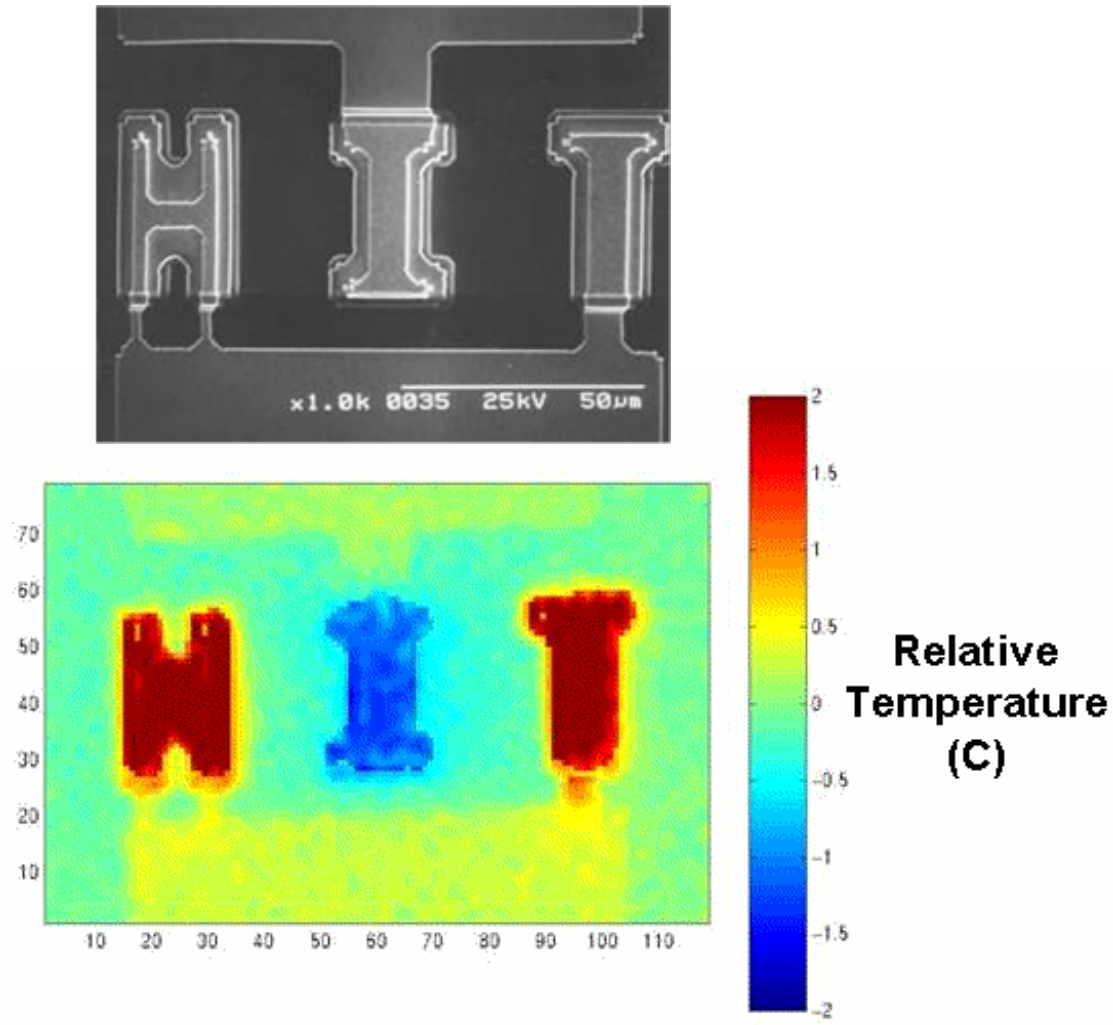
Micro Refrigerator Integrated with Thin-Film Heater





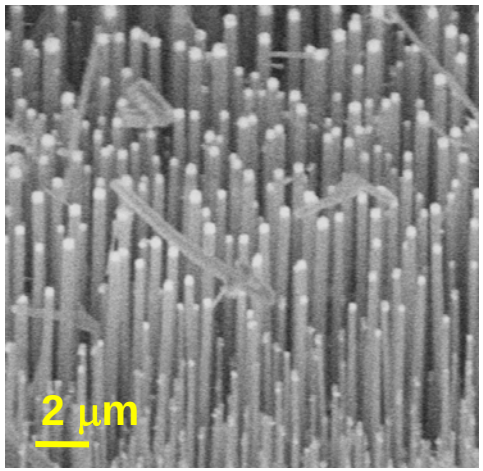
G. Zeng, X. Fan, C. LaBounty, J.E. Bowers, E.Croke, J. Christofferson, D. Vashaee, A. Shakouri, "**Direct Measurement of Cooling Power Density for Thin Film Suplerlattice Micro Coolers**," *submitted* to APL 2002.

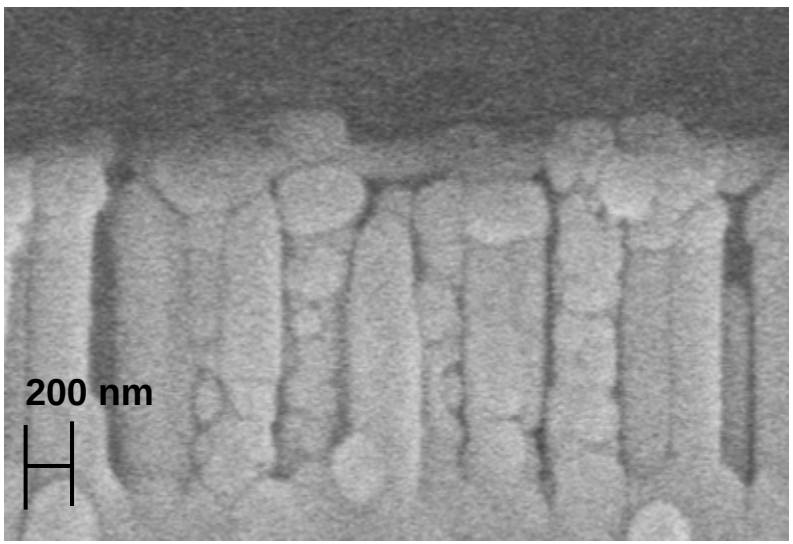
InP-based Micro Refrigerator & Micro Heater

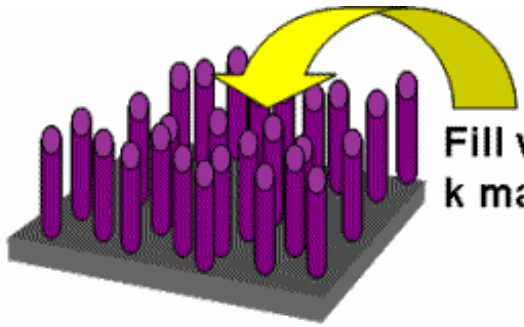


Localized control of temperature on the chip.

Nanowire Array Composites and Devices

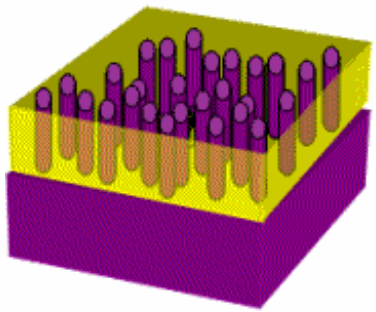




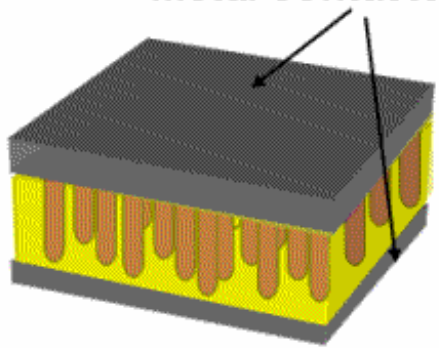


How to fill it, what to fill it with, and how to analyze it?

Etching down to expose tips and be ready for metal contacts

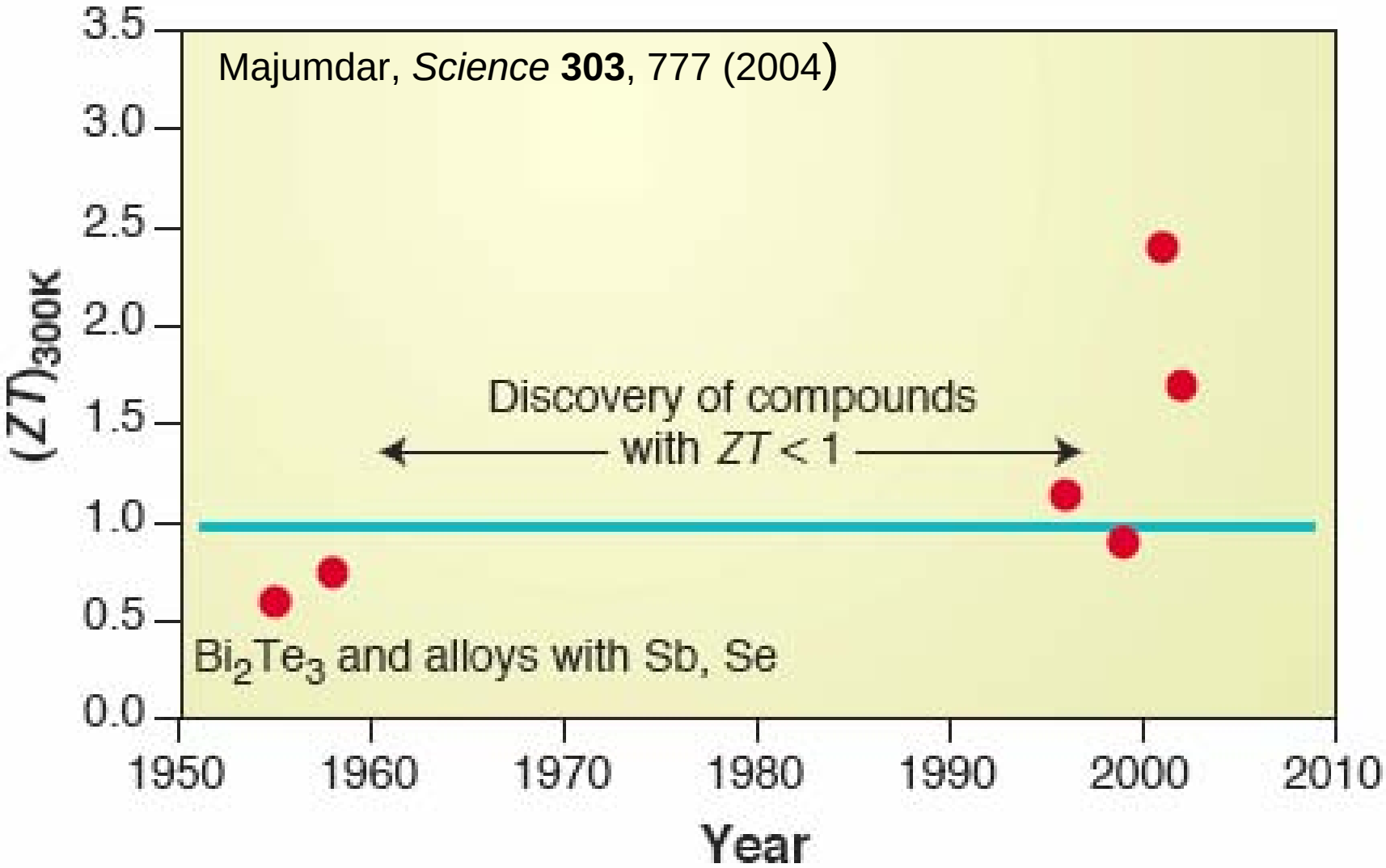


Metal contacts



Thermoelectric Device Component

Collaborators: Ali Shakouri, Peidong Yang, Ed Croke, Angy Stacy, Venky Narayanamurti, John Bowers, Tim Sands


Majumdar, *Science* **303**, 777 (2004)
$(ZT)_{300K}$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Discovery of compounds
with $ZT < 1$
Bi_2Te_3 and alloys with Sb, Se
1950
1960
1970
1980
1990
2000
2010
Year