Challenges and Opportunities in Thermoelectric Energy Conversion

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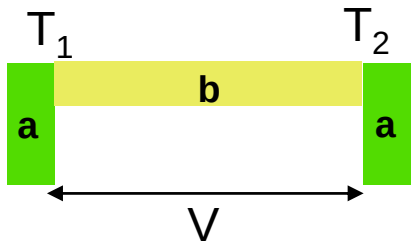
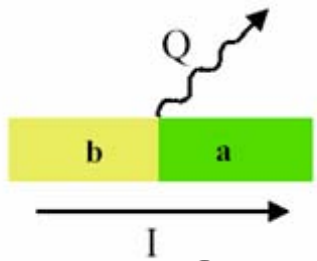
DOE, NSF, ONR, NASA

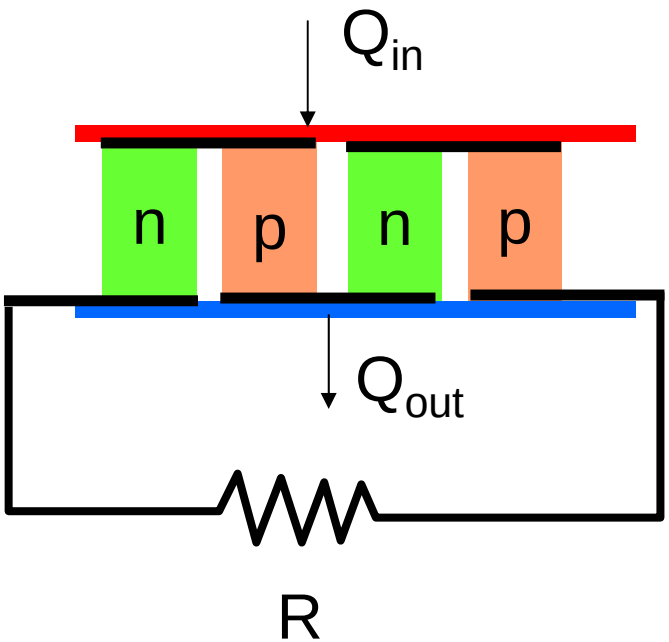
Thermoelectricity and Energy Conversion

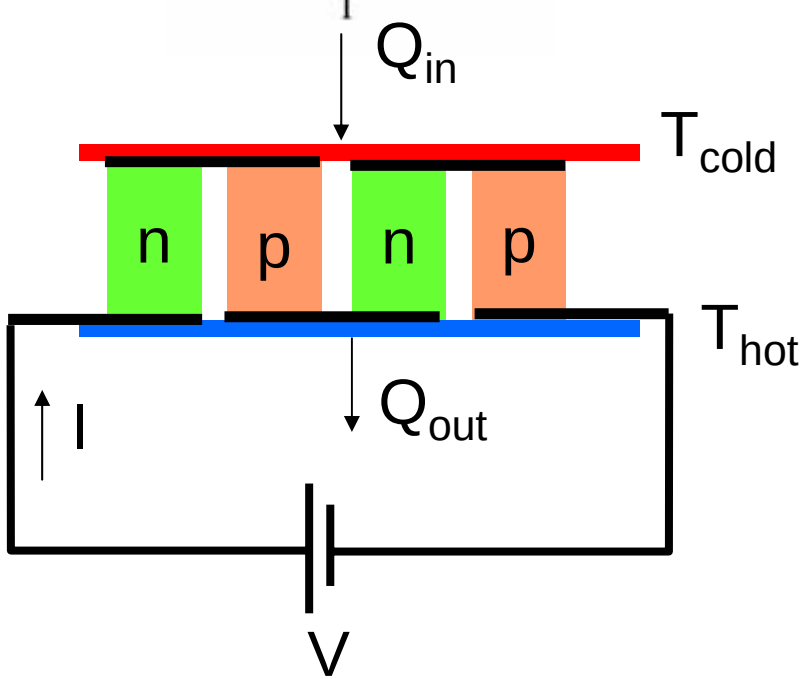
Seebeck Coefficient, $S = V/\Delta T$



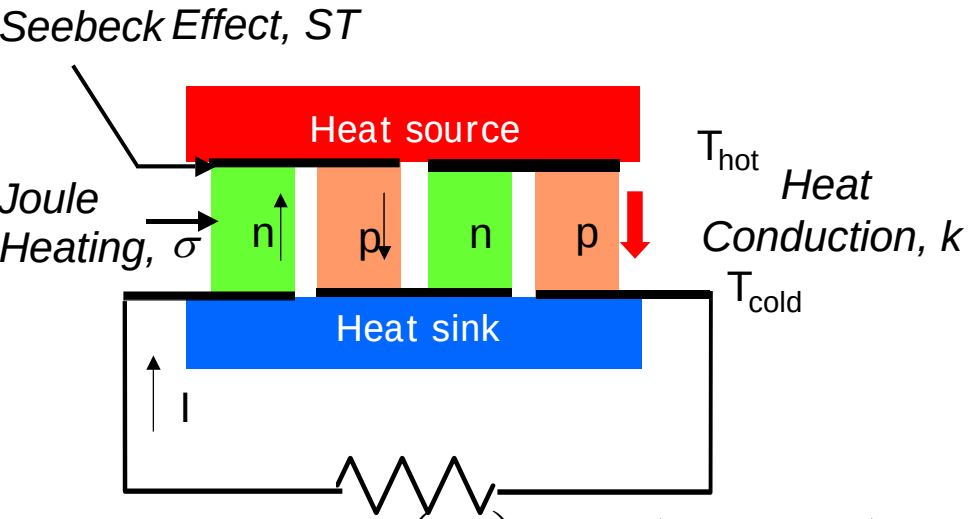
Peltier Coefficient, $\pi = Q/I = ST$

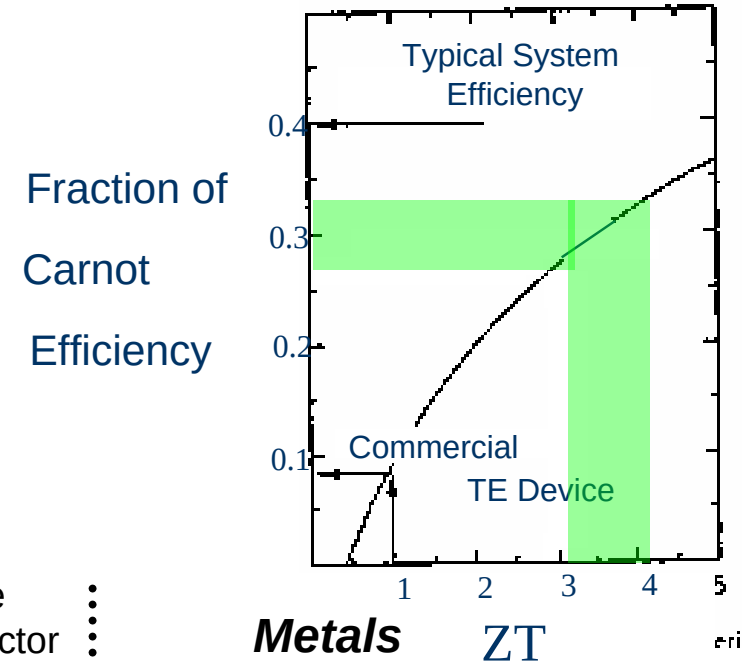






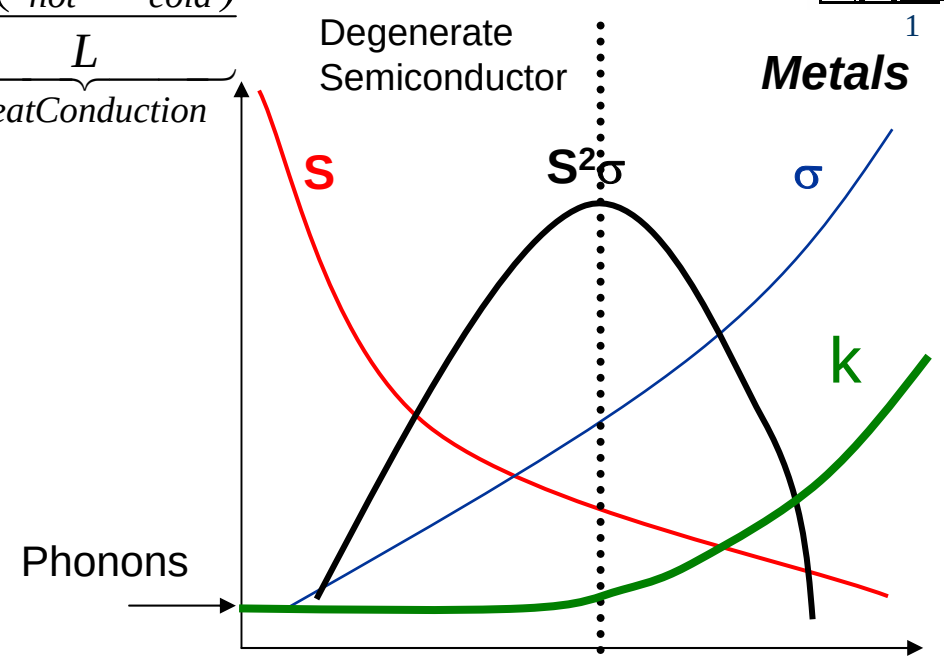
Thermoelectric Figure of Merit

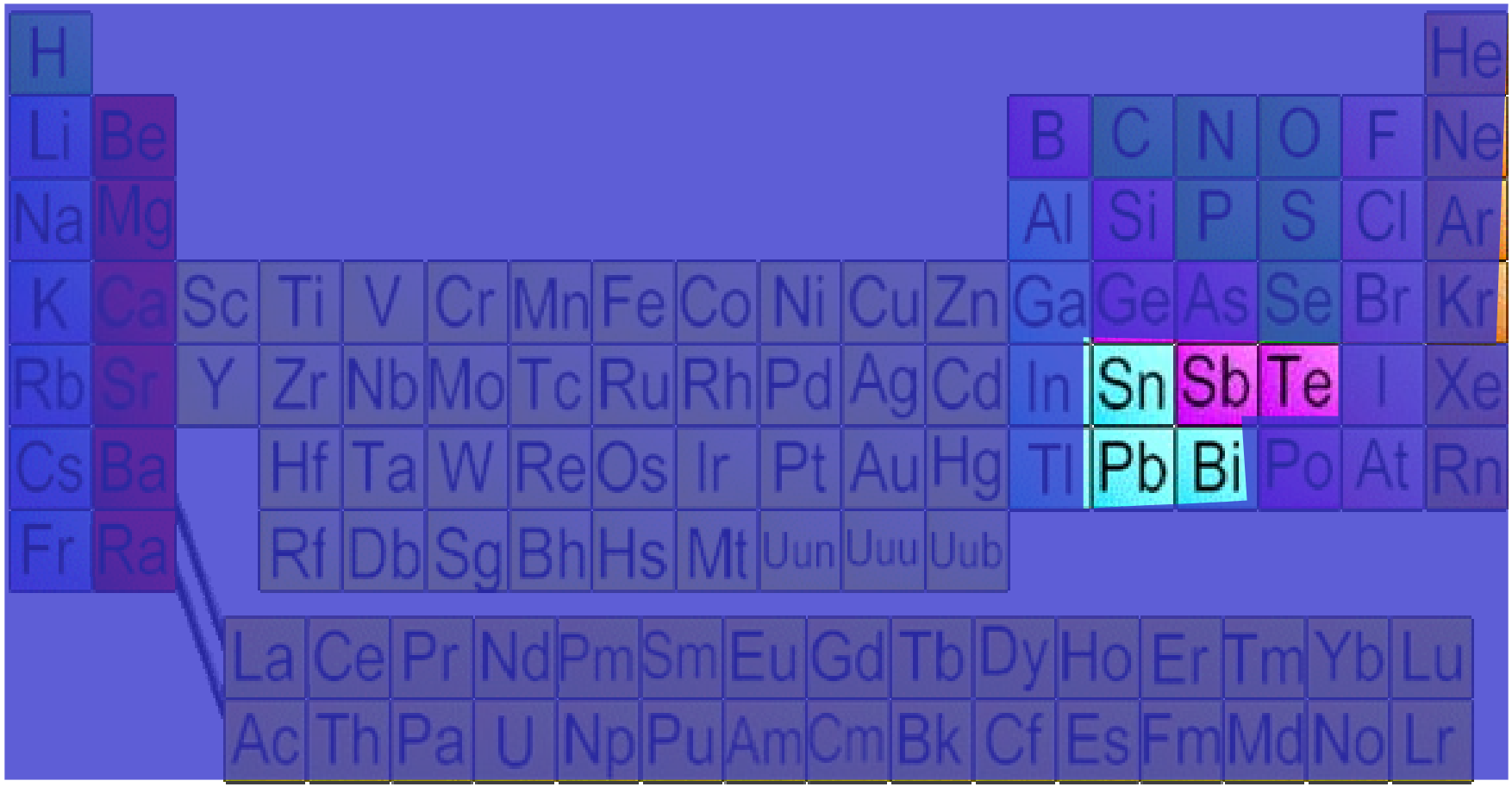




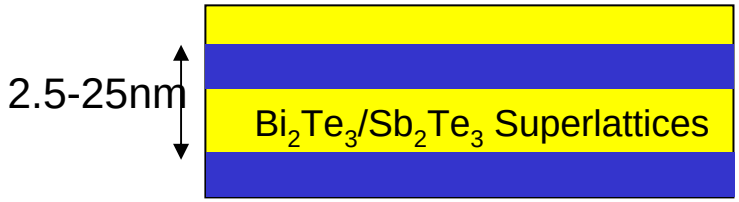
$$Q = \underbrace{ST \cdot I}_{PeltierCooling} - \underbrace{I^2\left(\frac{L}{\sigma A}\right)}_{JouleHeating} - \underbrace{\frac{kA(T_{hot} - T_{cold})}{L}}_{HeatConduction}$$

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

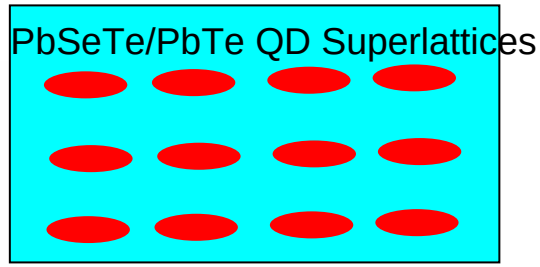


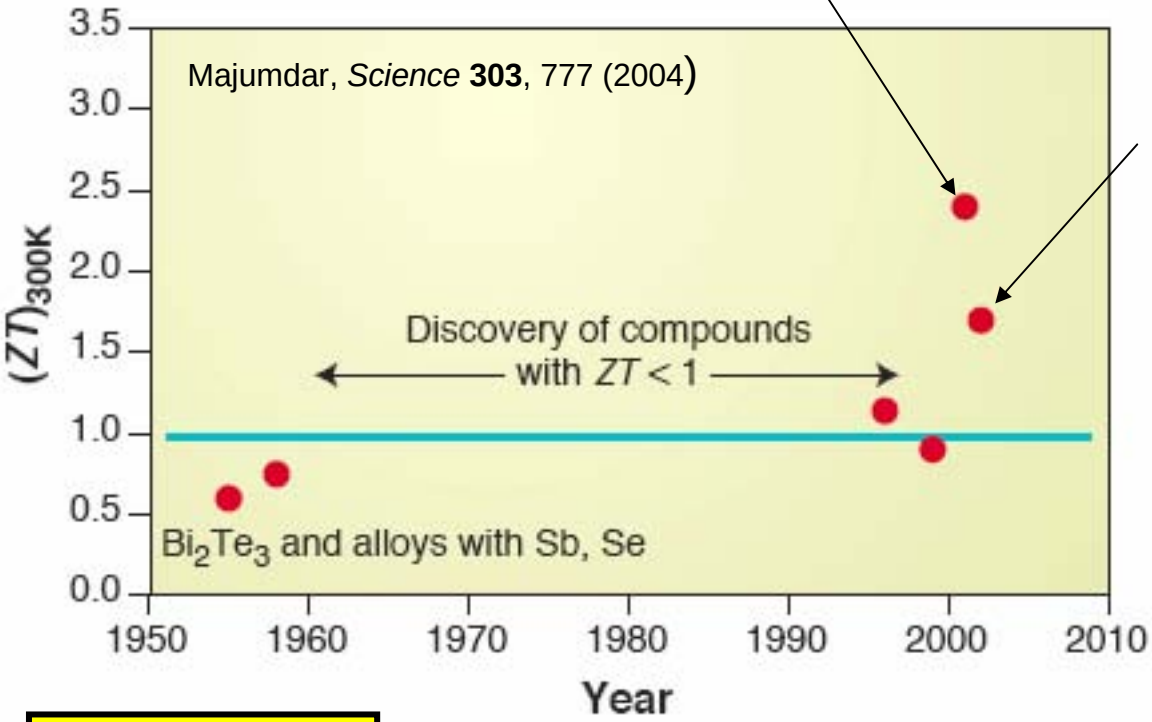

H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Uun Uuu Uub
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

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



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

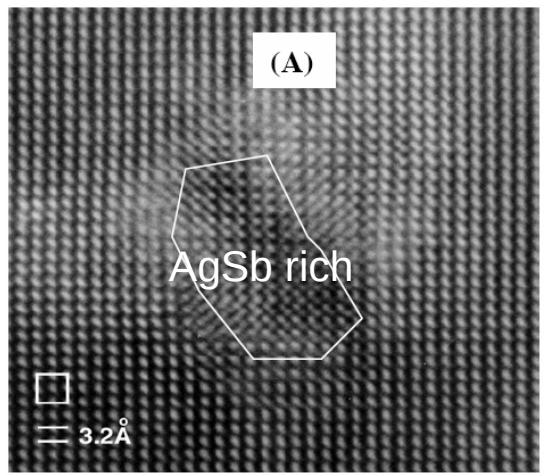




$$ZT = \frac{S^2 \sigma T}{k}$$

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

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



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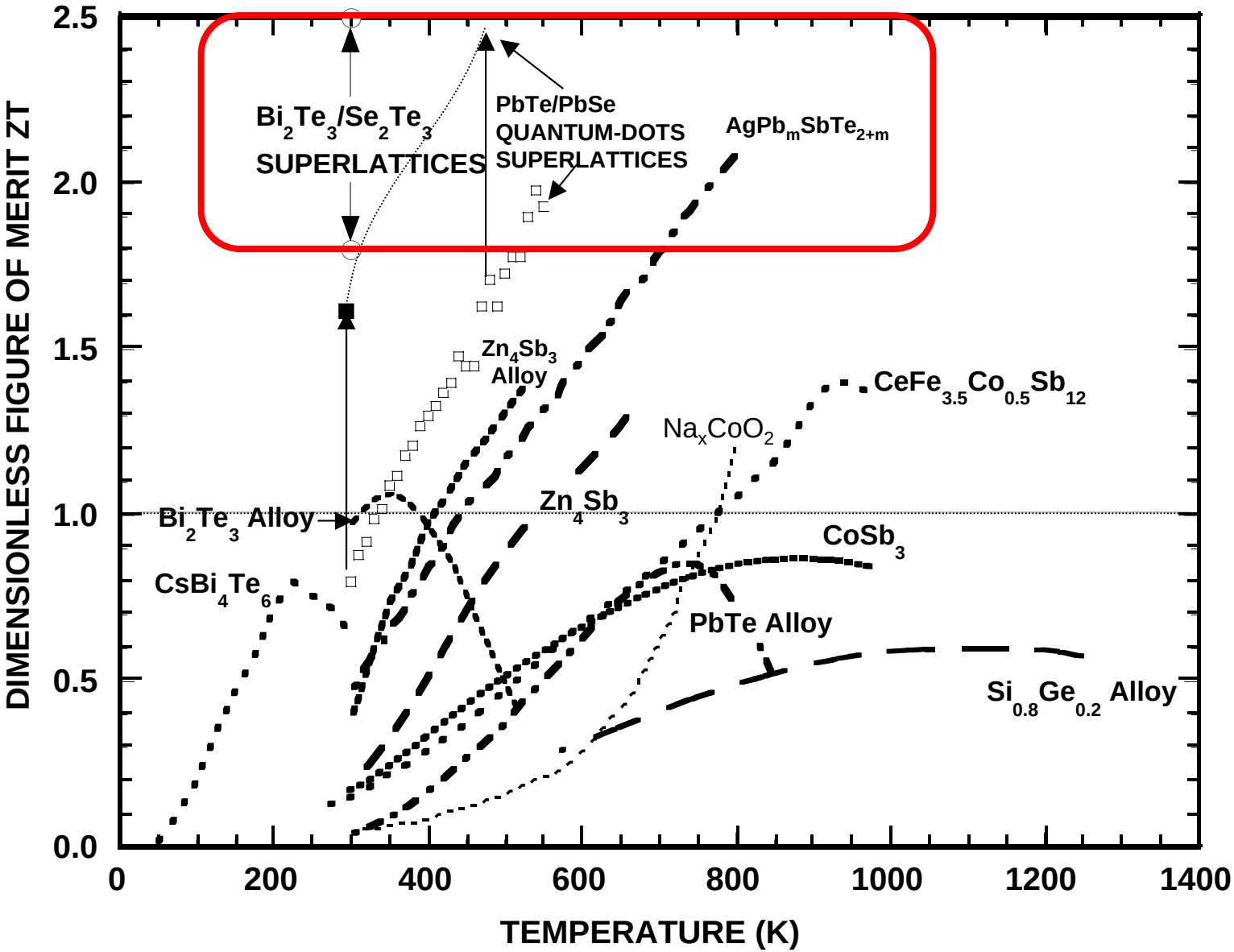
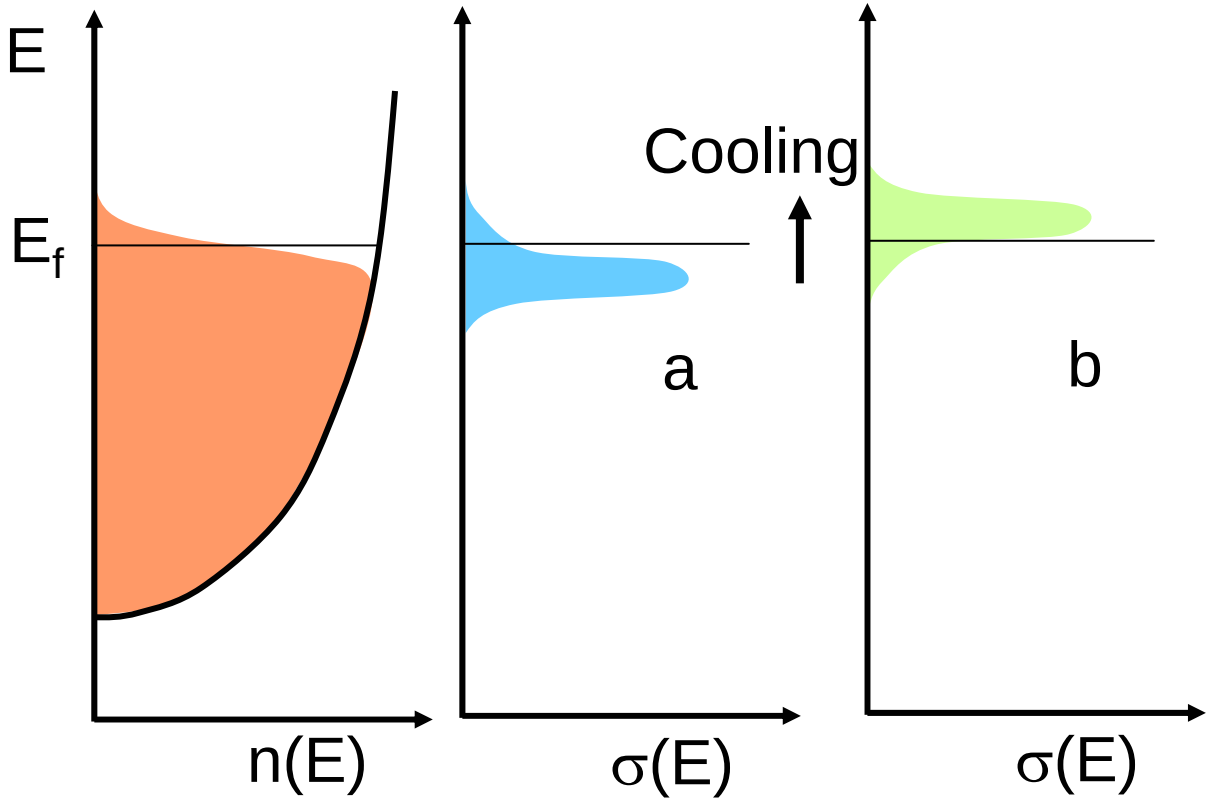
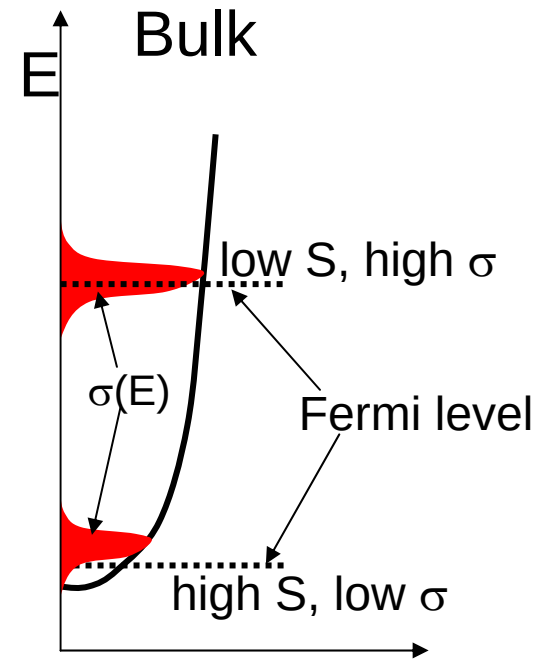


Courtesy: Gang Chen

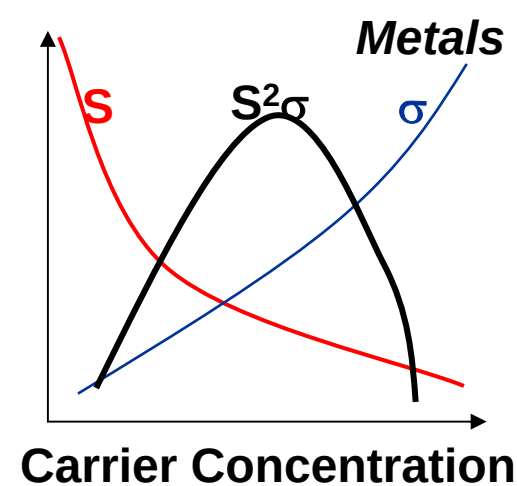
Origins of Thermoelectricity



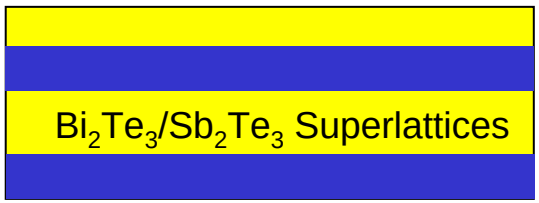


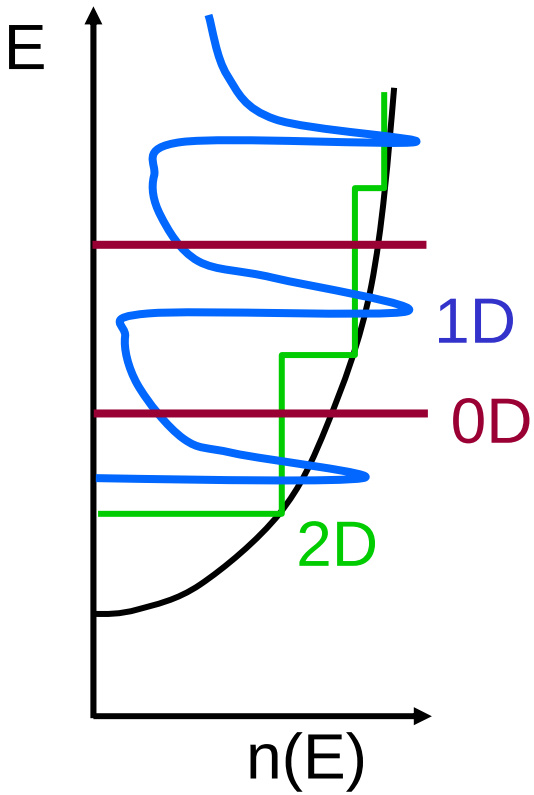
$$\sigma = \int \sigma(E)\,dE \qquad \sigma(E) = q^2 \tau(E) v^2(E) n(E) \left(-\frac{\partial f_{eq}}{\partial E} \right)$$

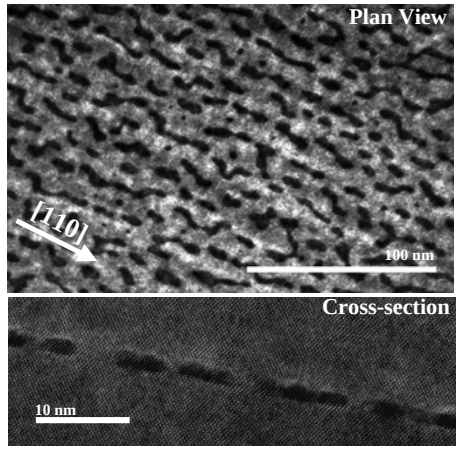
$$S = \frac{1}{eT} \frac{\int \sigma(E)(E - E_f)\,dE}{\int \sigma(E)\,dE}$$

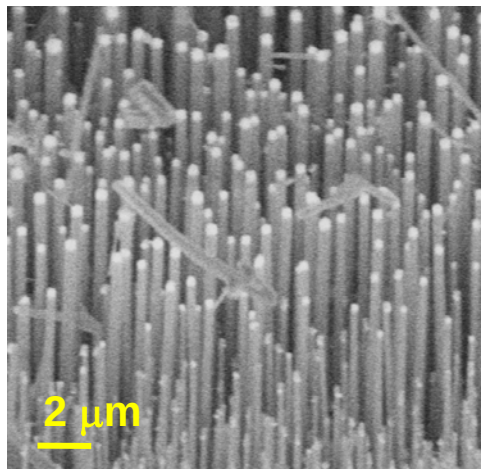


Effect of Nanostructuring on $S^2\sigma$





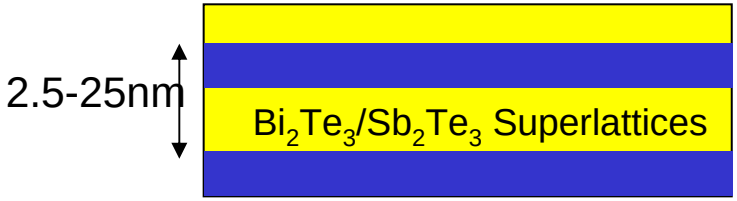




Quantum Confinement

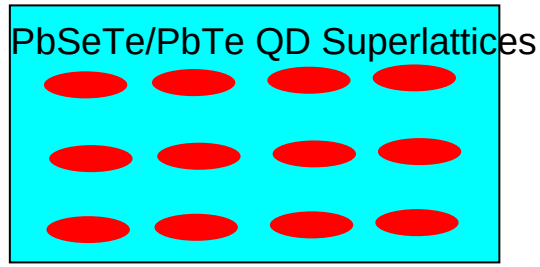
(Dresselhaus et al., 1993)

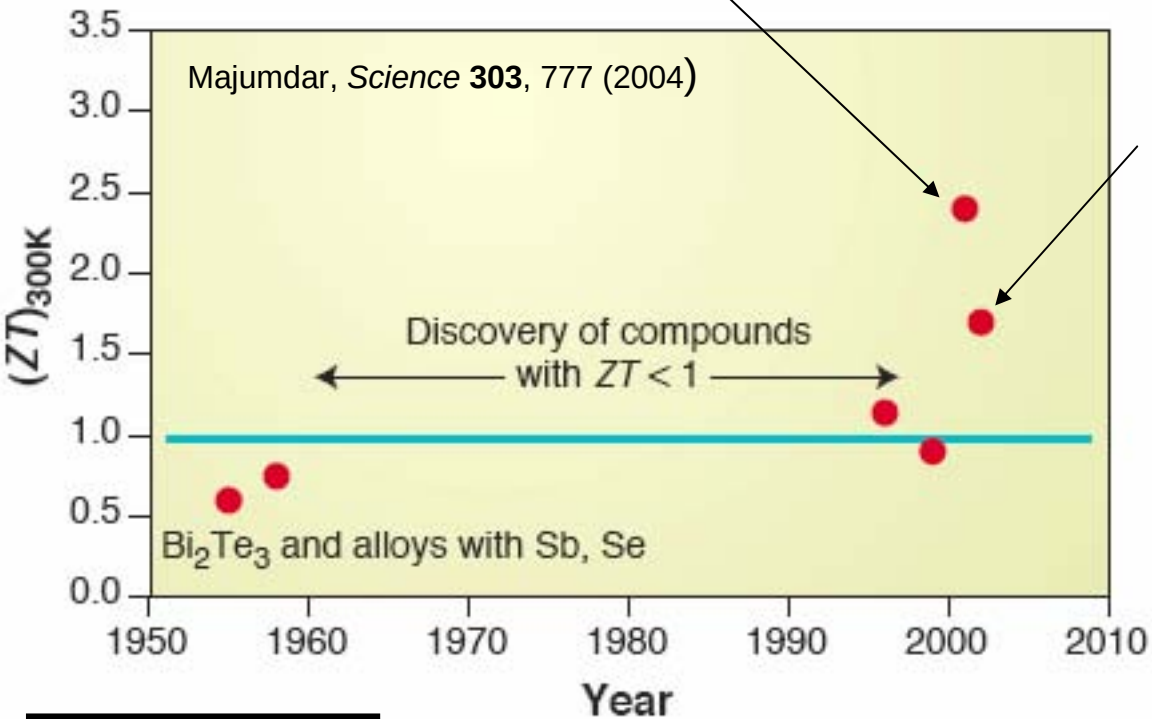
Venkatasubramanian et al. *Nature* **413**, 597 (2001)



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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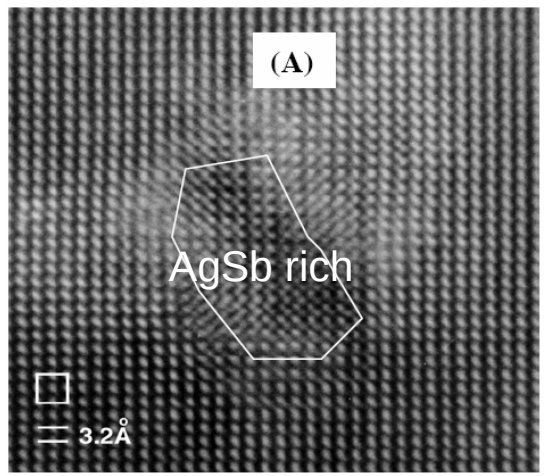

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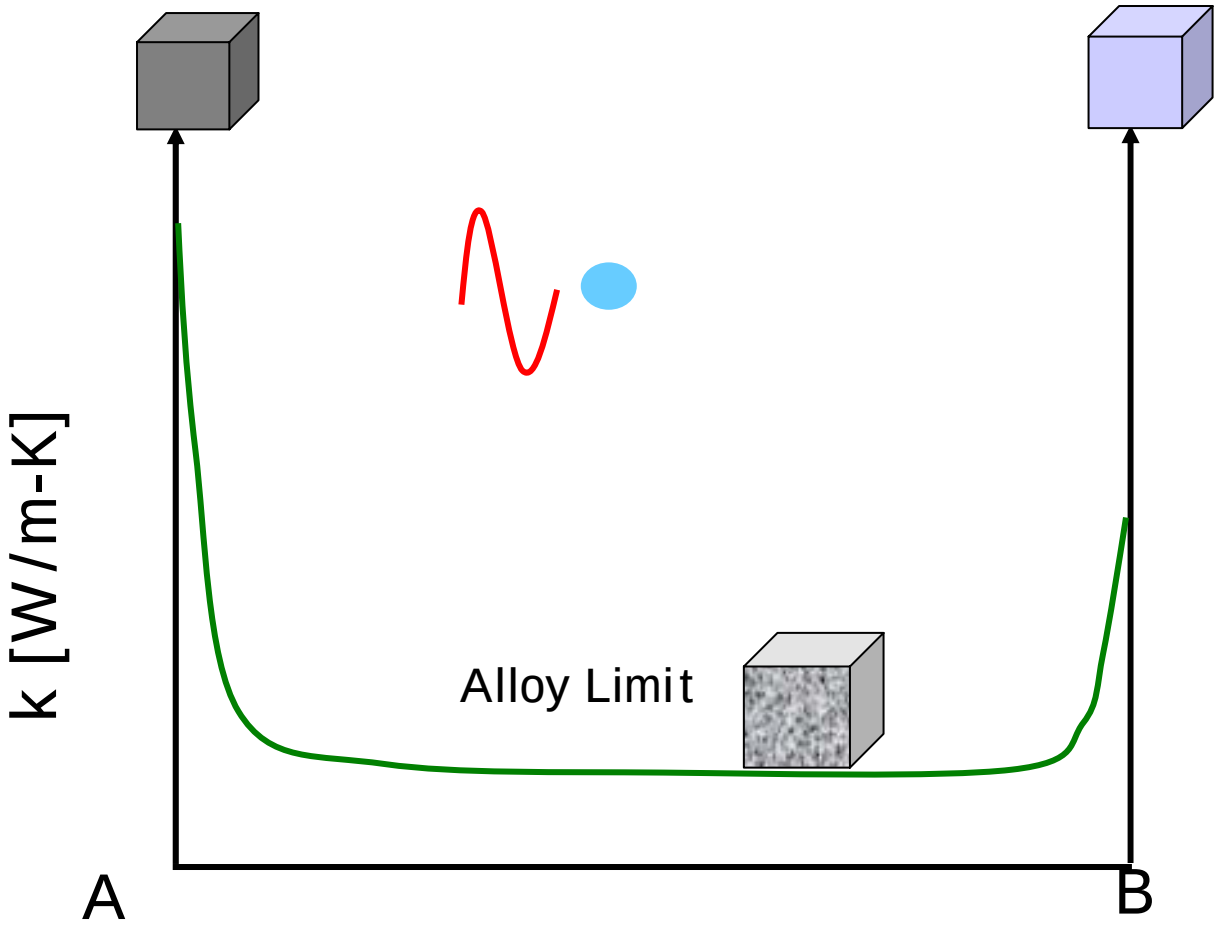
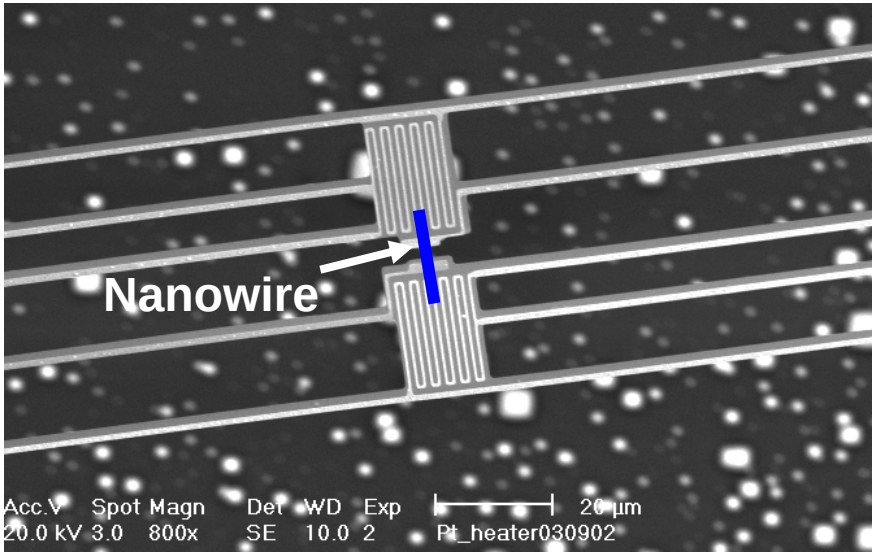
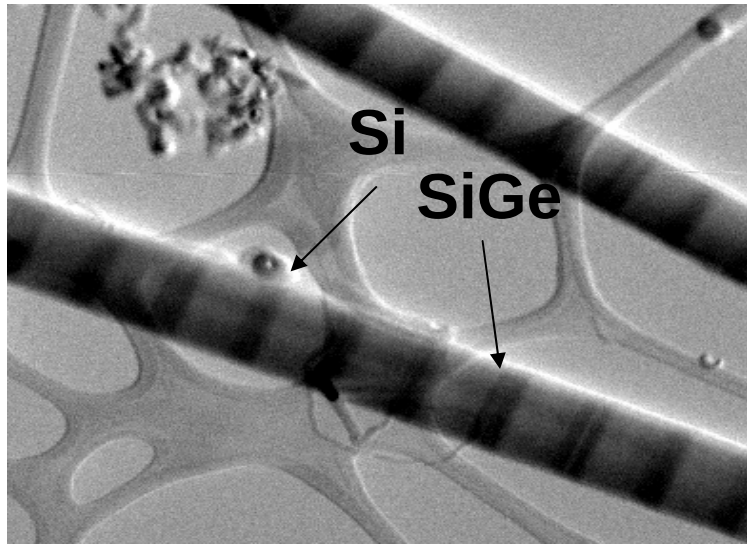
Alloy limit of thermal conductivity in crystalline materials!

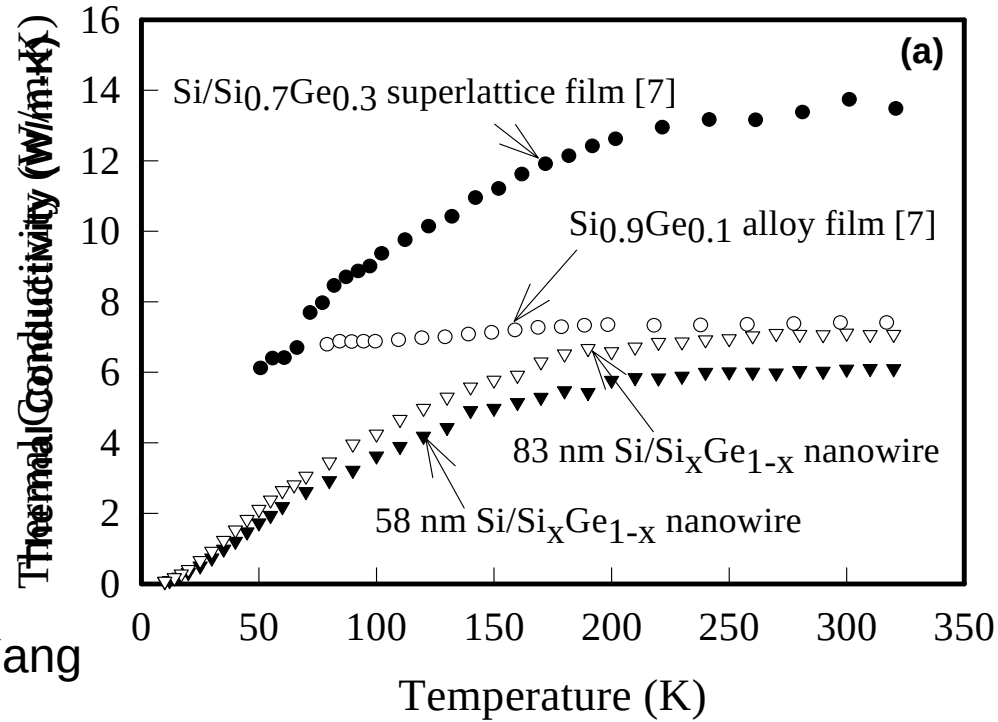


Si/SiGe superlattice nanowires



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

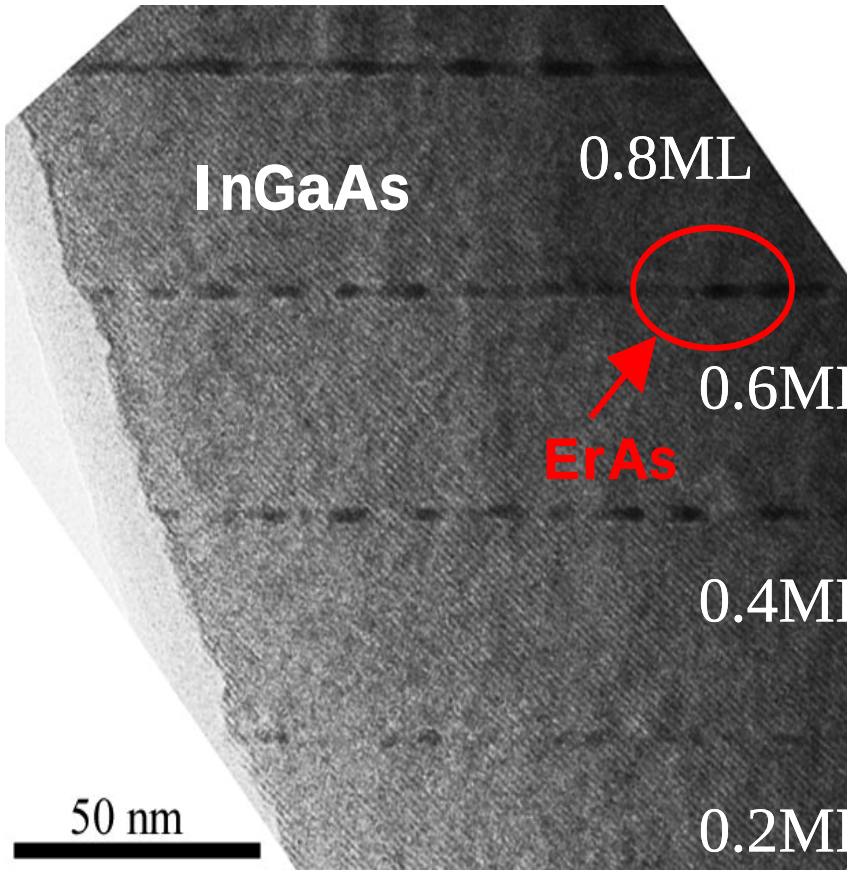


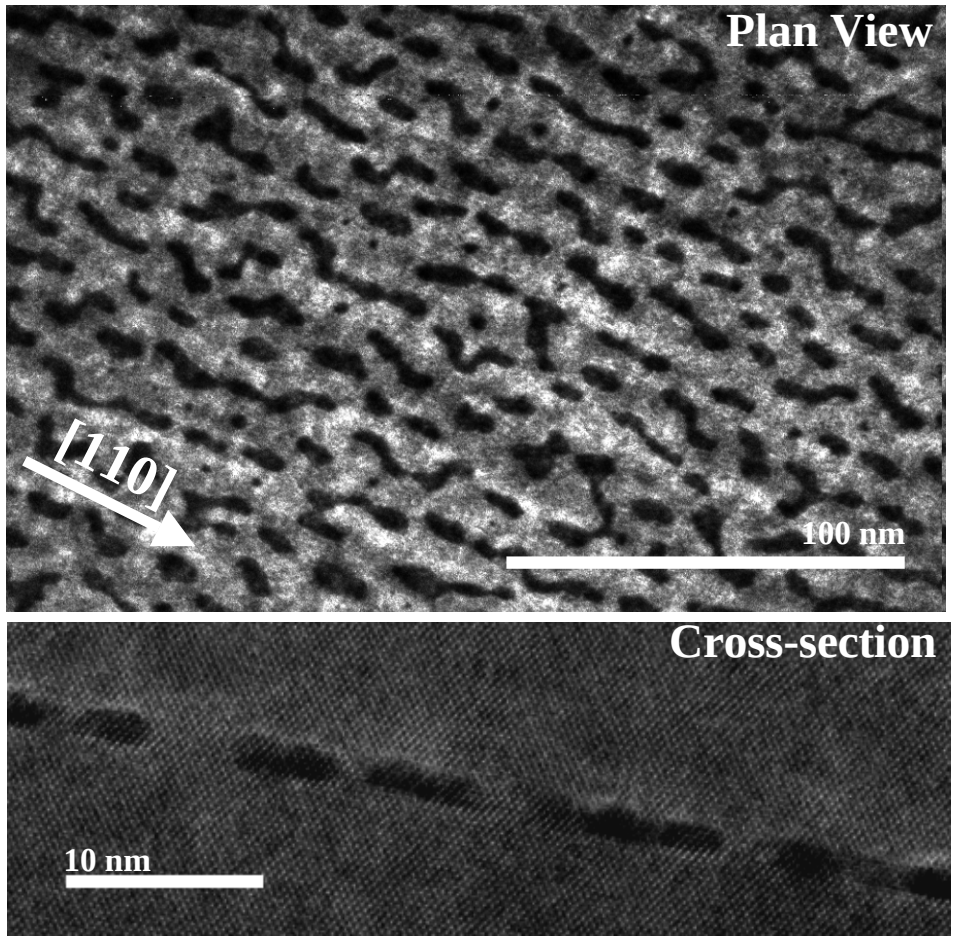


Li et al., *Appl Phys Lett* **83**, 3186 (2003)

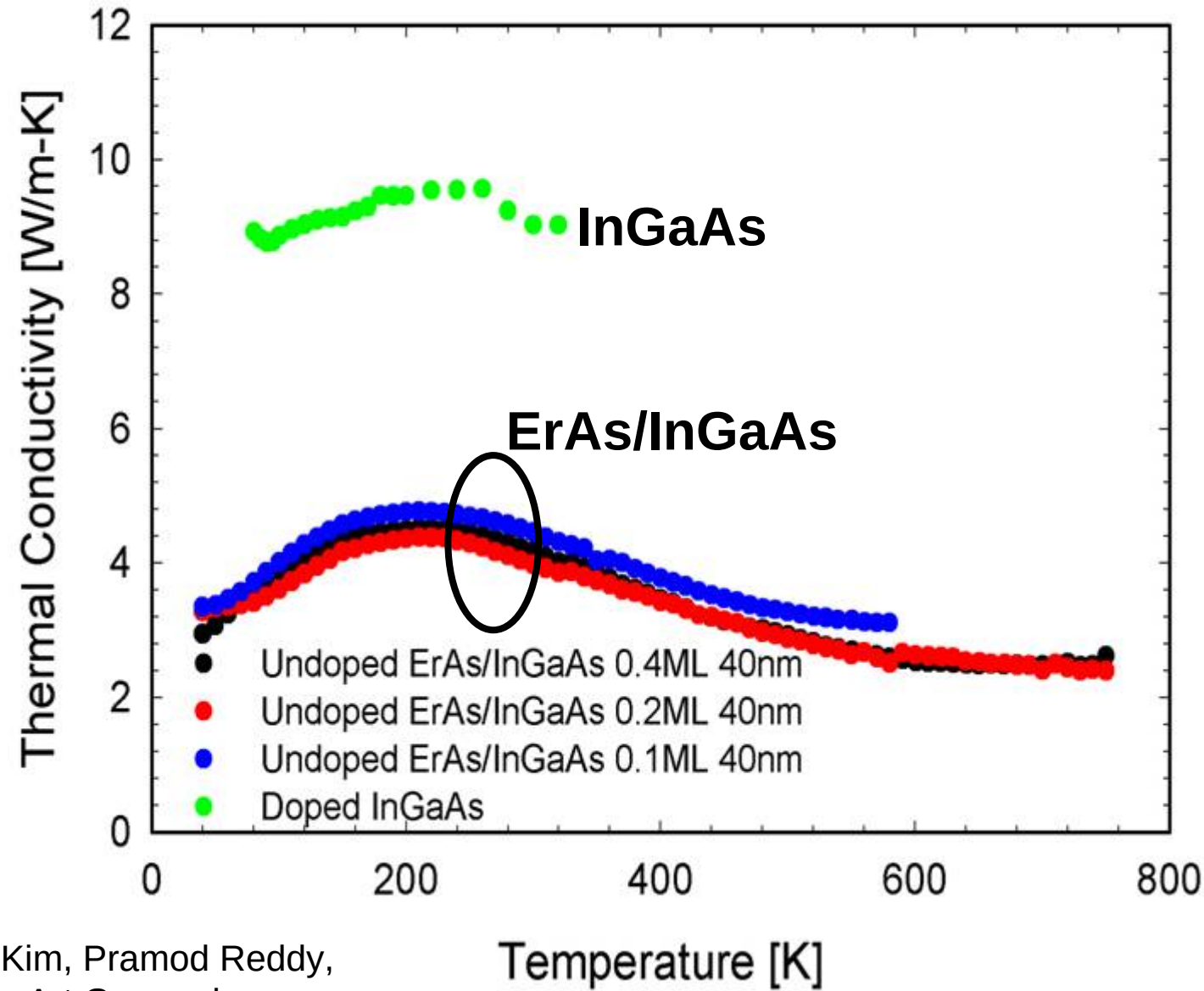
Deyu Li, Yiying Wu, Rong Fan, Peidong Yang

ErAs Nanostructures Embedded in InGaAs





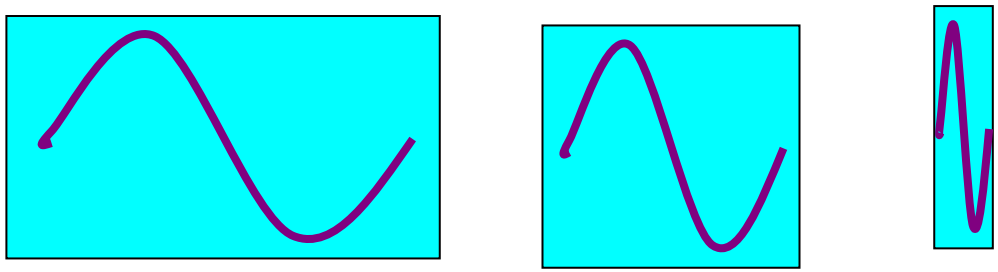
Below Alloy Limit!

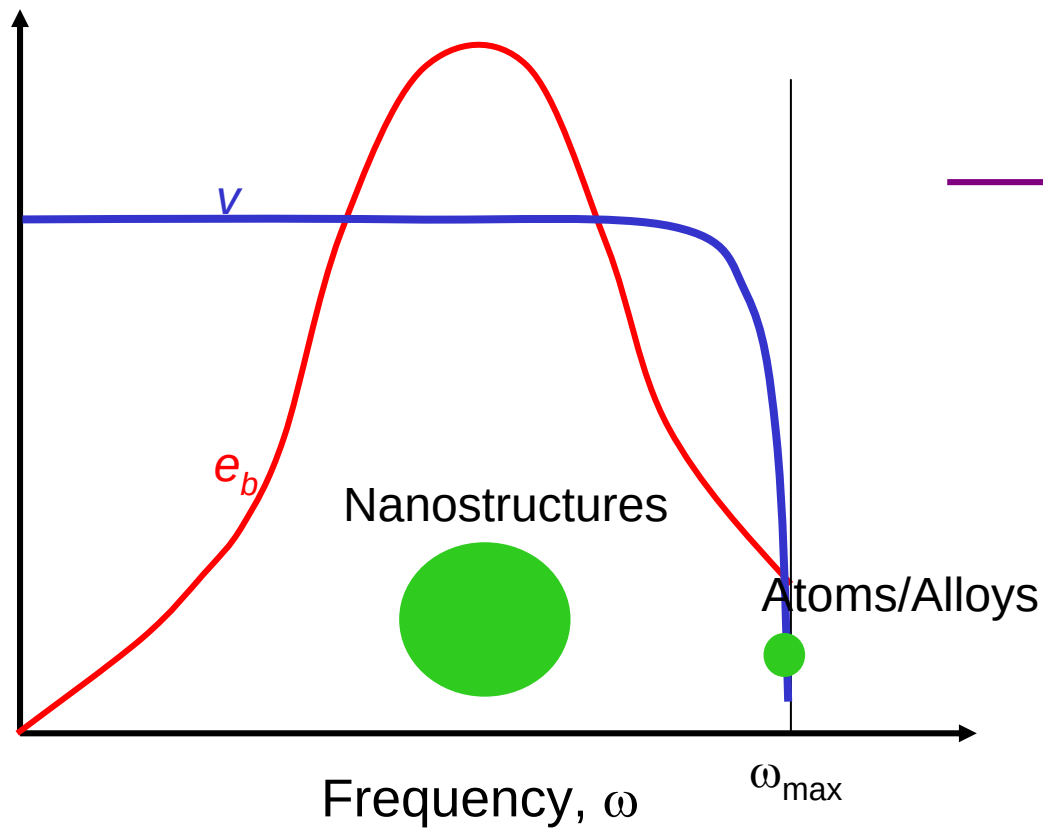


Woochul Kim, Pramod Reddy,
Josh Zide, Art Gossard

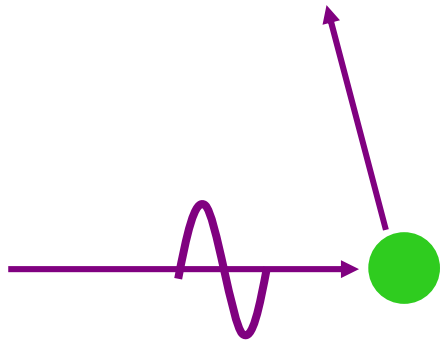
Hypothesis

$$k = \frac{d}{dT}\left[\int_0^{\omega_{max}} \underbrace{e_b(\omega)}_{Planck\ BB}\,\underbrace{v(\omega)}_{Speed}\,\underbrace{\ell(\omega)}_{MeanFreePath}\,d\omega\right]$$



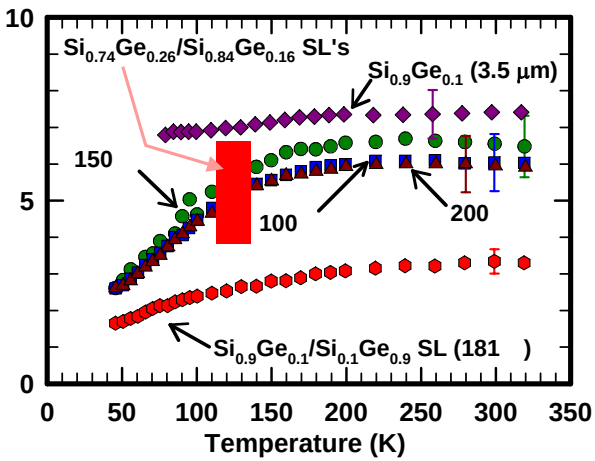


Phonon Scattering

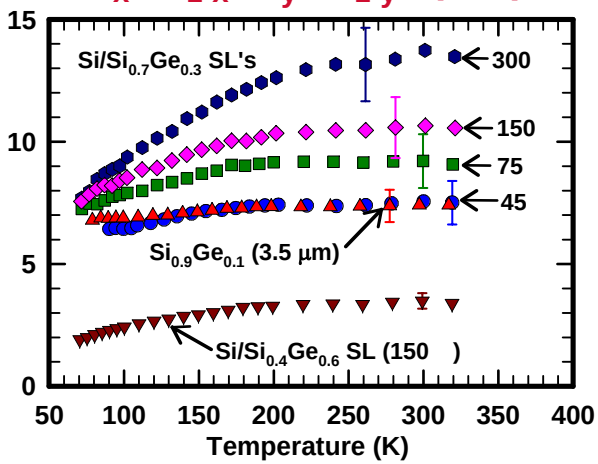


Si-Ge Superlattices

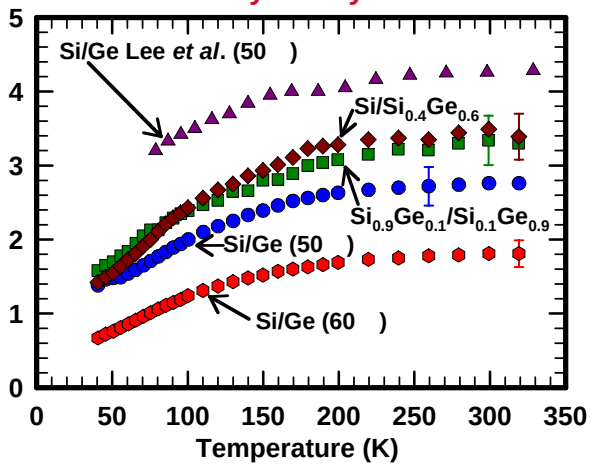
$Si_xGe_{1-x}/Si_yGe_{1-y}$: $|x-y| \leq 0.1$

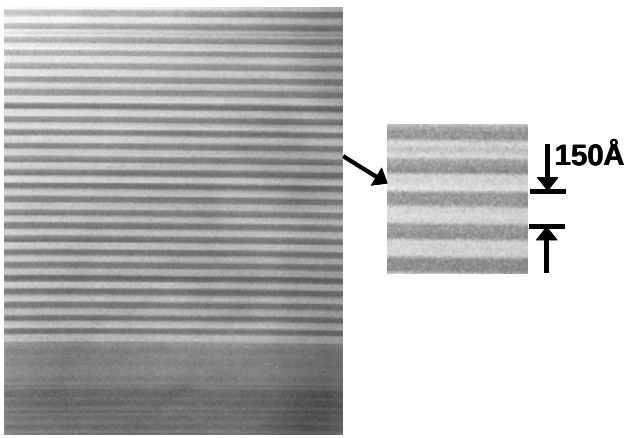


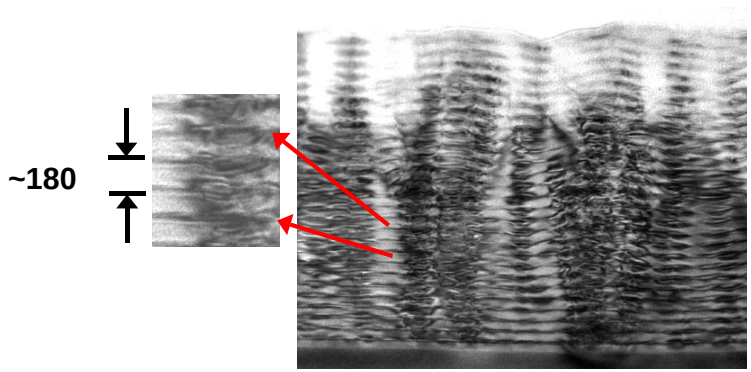
$Si_xGe_{1-x}/Si_yGe_{1-y}$: $|x-y| = 0.3$



$Si_xGe_{1-x}/Si_yGe_{1-y}$: $|x-y| \geq 0.6$

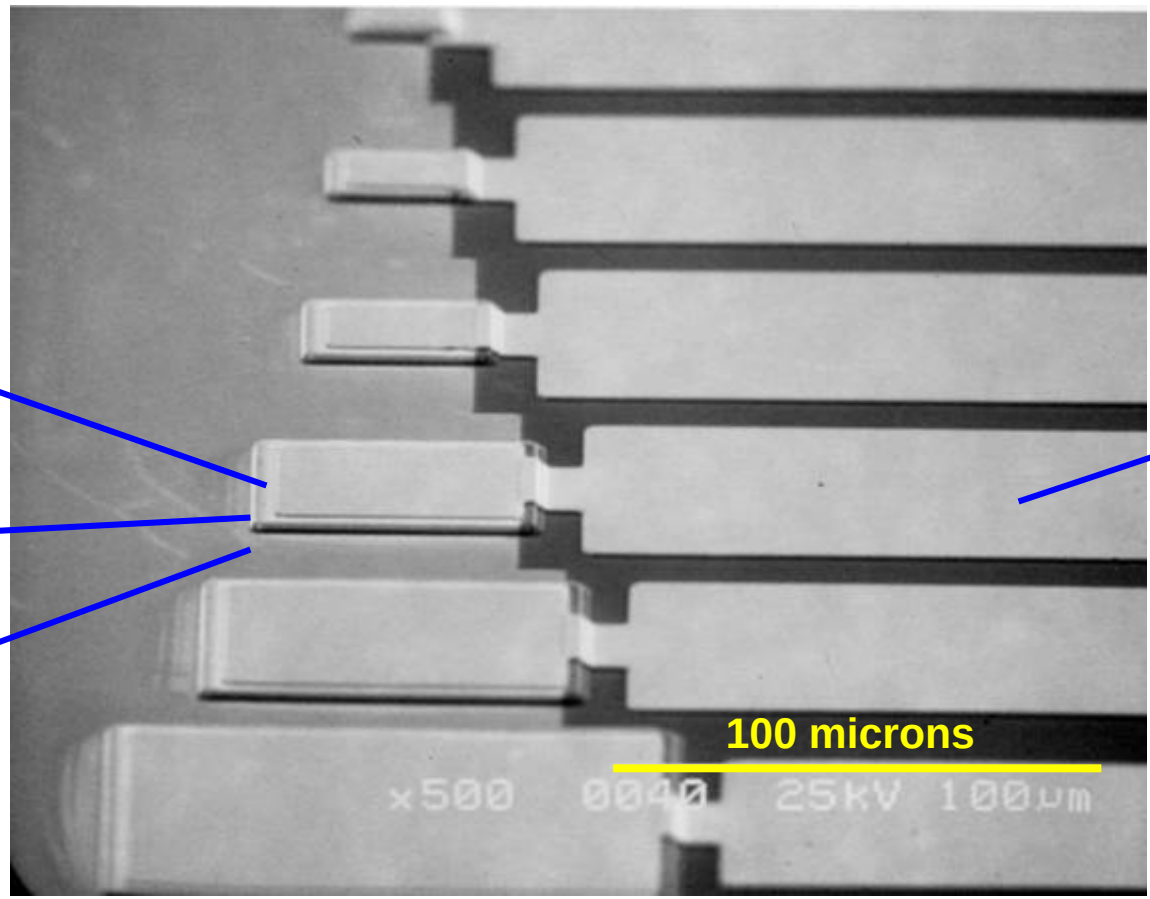






Courtesy: Ed Croke, Hughes Res. Lab. for materials

SEM Picture of Thin Film Coolers



Cathode

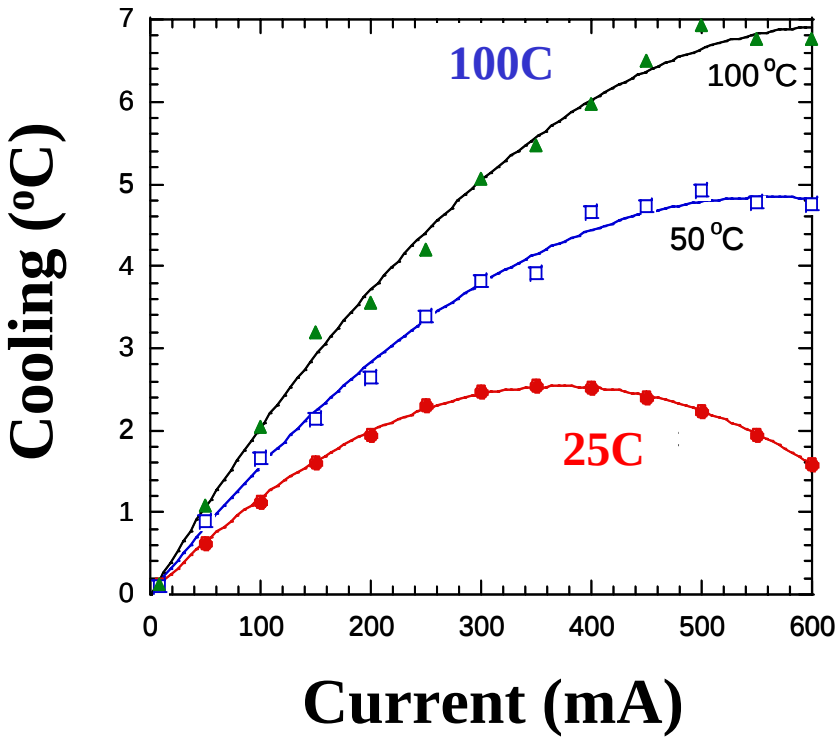
Barrier

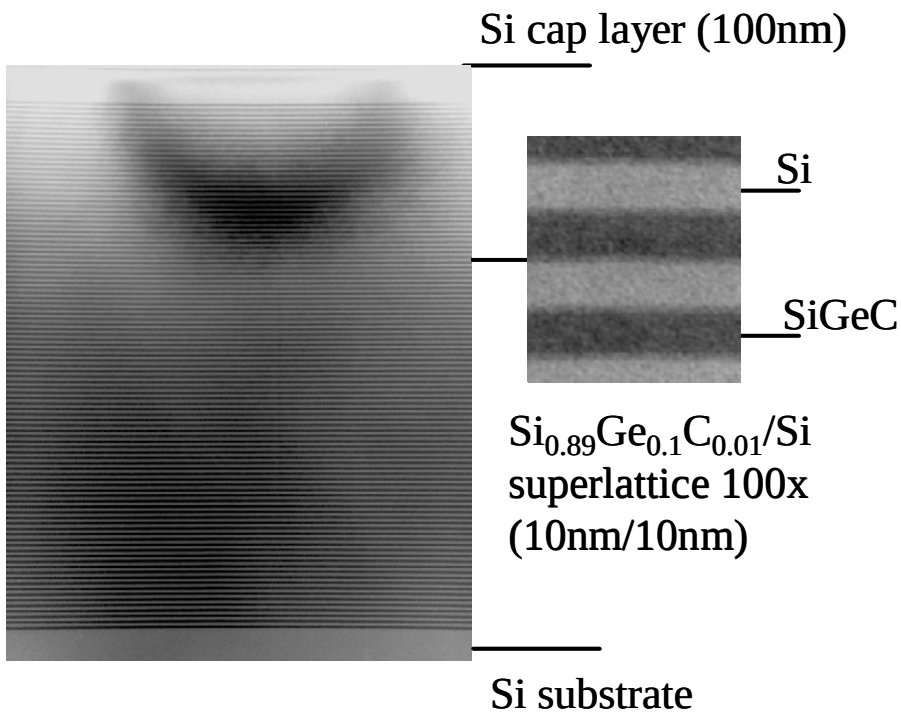
Anode

Metallic contact for top connection

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

n-Si/SiGeC Superlattice Micro Cooler

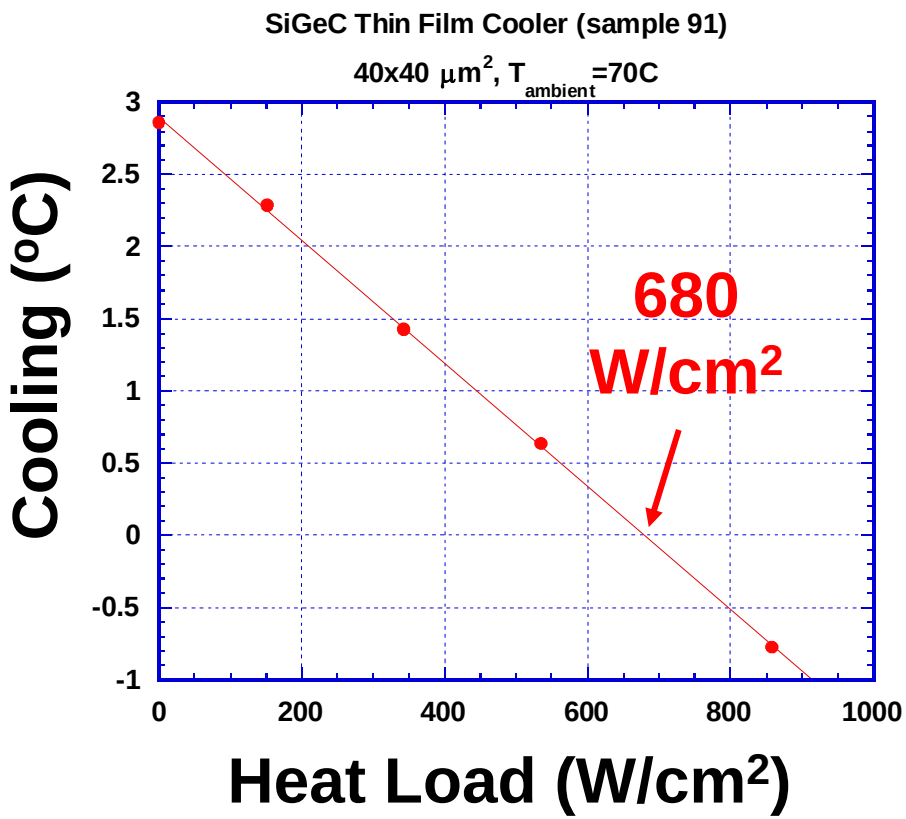


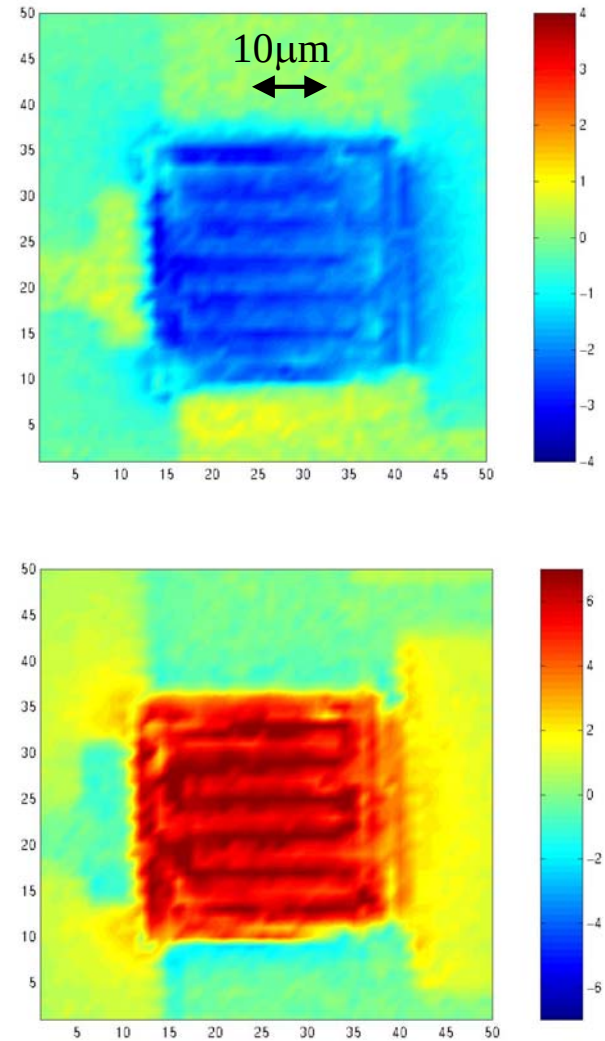


X. Fan, G. Zeng, C. LaBounty, E.Croke, C. Ahn, J.E. Bowers, A. Shakouri, "**SiGeC/Si superlattice micro cooler**," *Applied Physics Lett.*, Vol. 78, No.11, 12 March 2001.

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

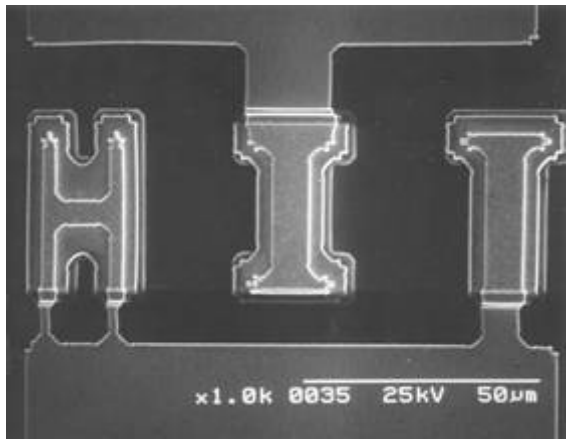
Micro Refrigerator Integrated with Thin Film Heater

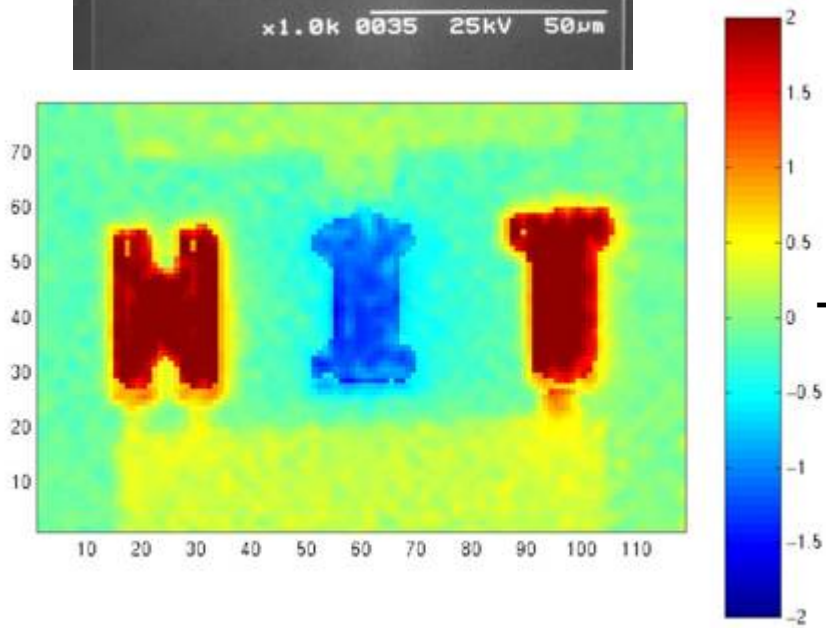




G. Zeng, X. Fan, C. LaBounty, J.E. Bowers, E.Croke, J. Christofferson, D. Vashaee, A. Shakouri, "**Direct Measurement of Cooling Power Density for Thin Film Suplerlattice Micro Coolers**," *submitted to APL 2002*

InP-based Micro Refrigerator & Micro Heater

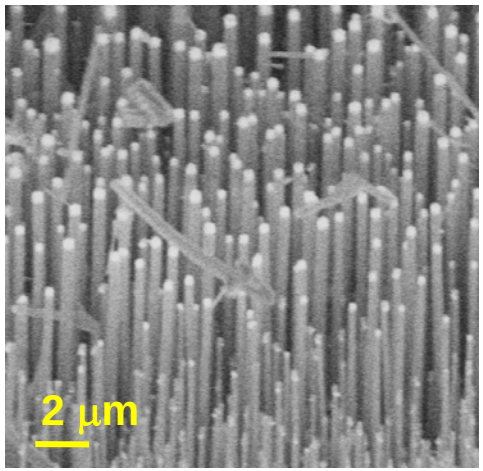


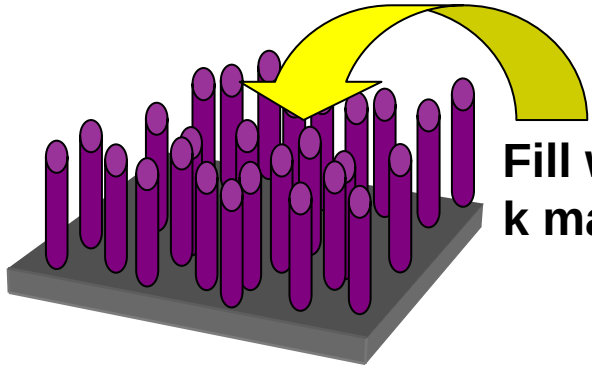


Relative Temperature (C)

Localized control of temperature on the chip.

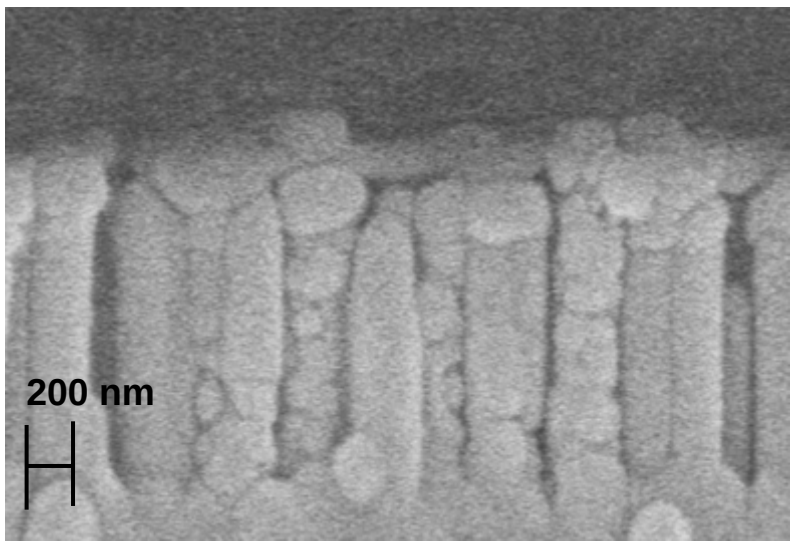
Nanowire Array Composites and Devices



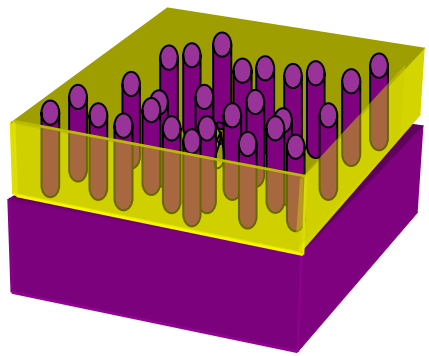


Fill with low k material

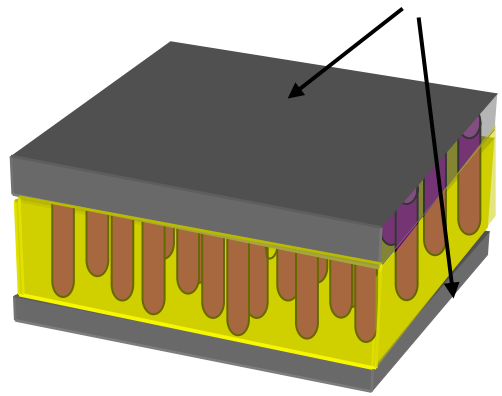
How to fill it, what to fill it with, and how to analyze it?



Etching down to expose tips and be ready for metal contacts

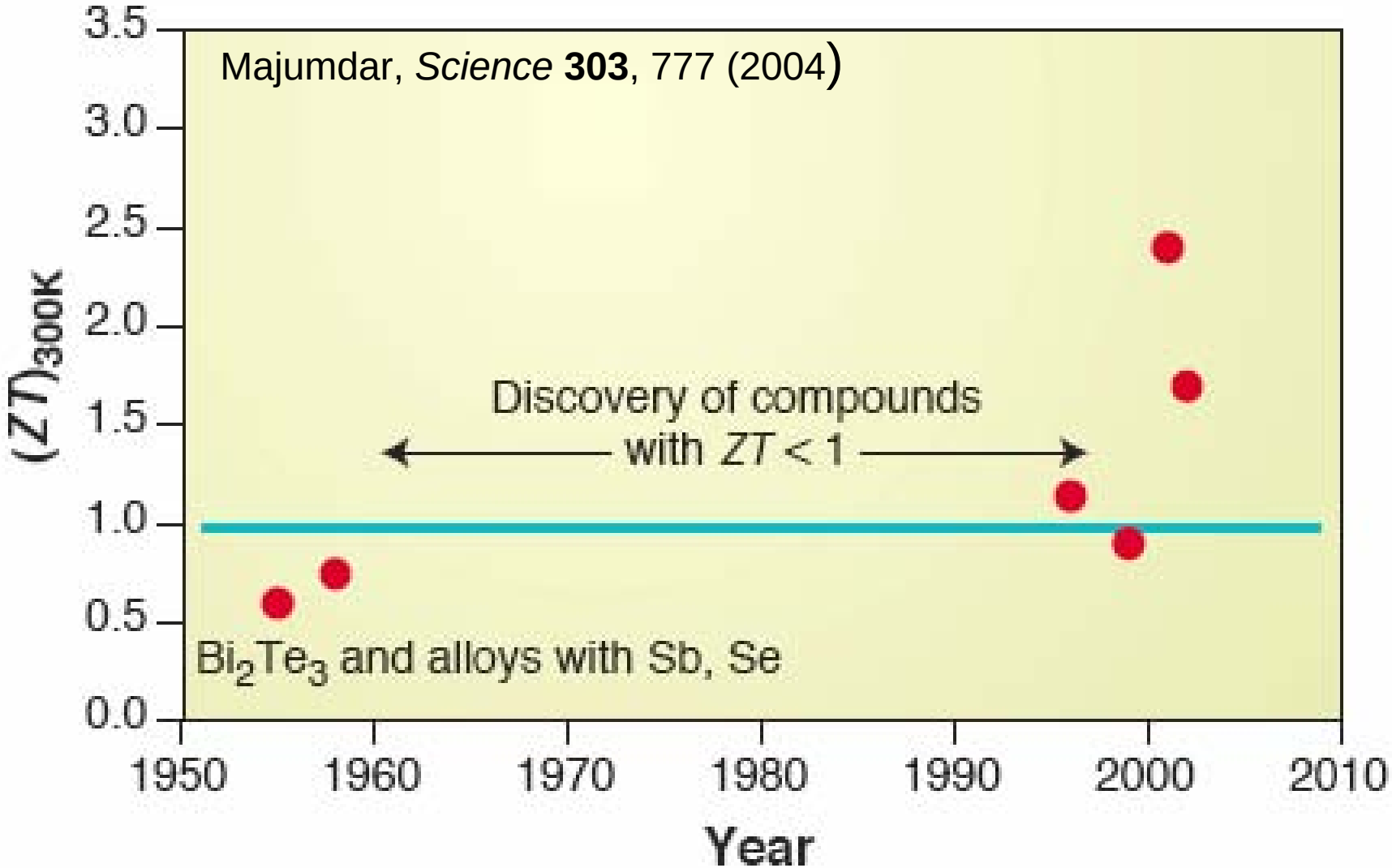


Metal contacts



Thermoelectric Device Component

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


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