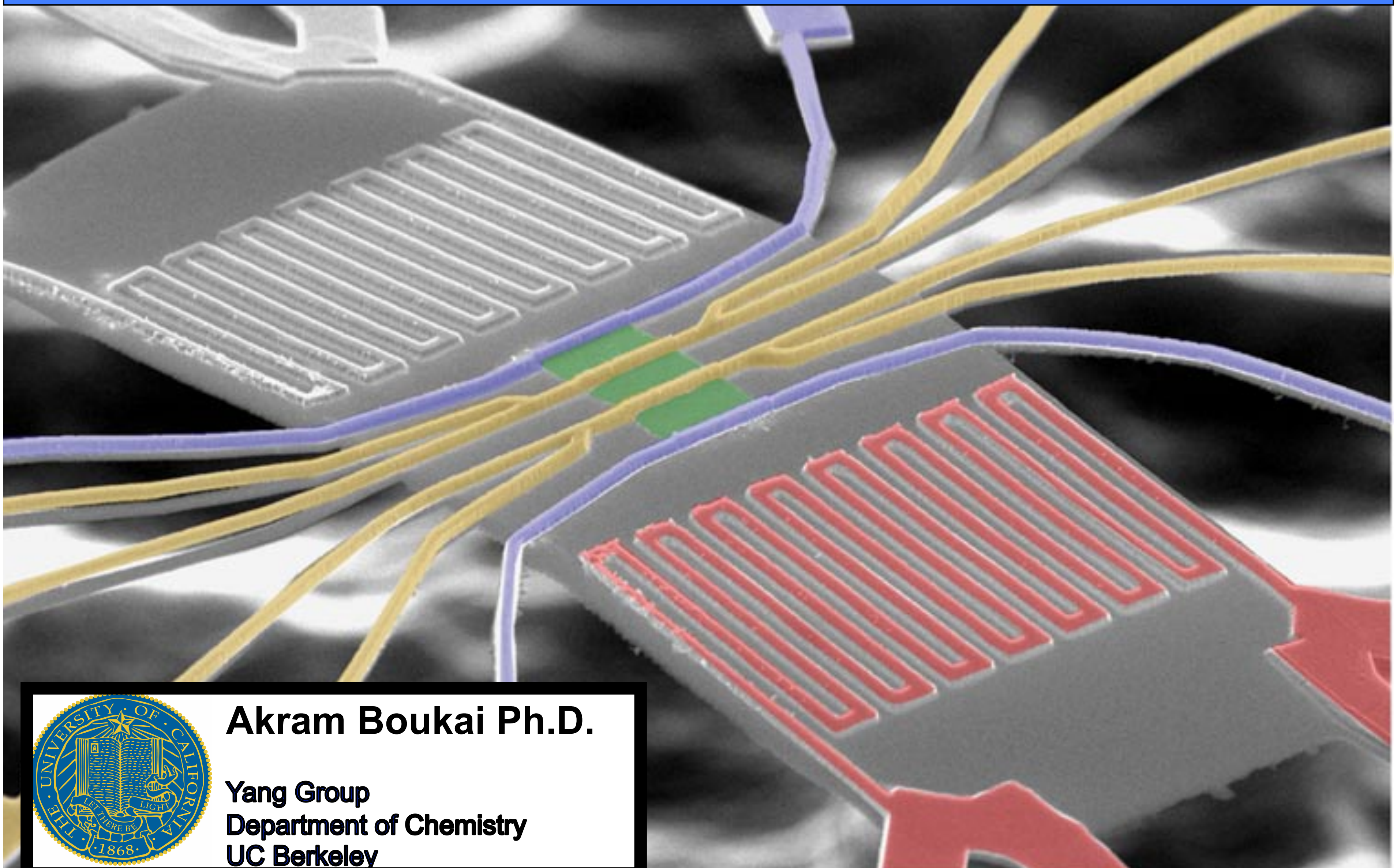
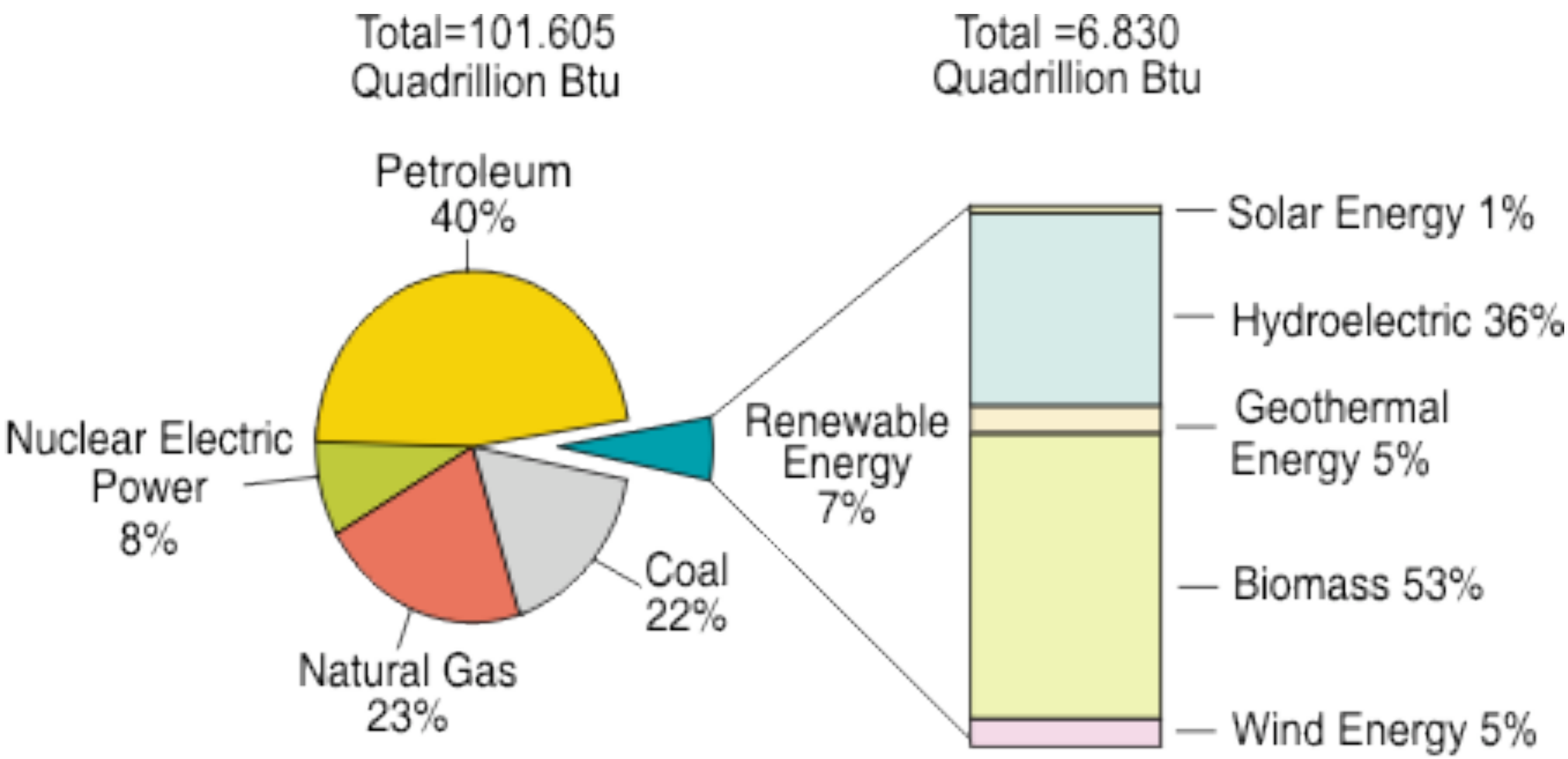
Clean Energy: Thermoelectrics and Photovoltaics



Akram Boukai Ph.D.

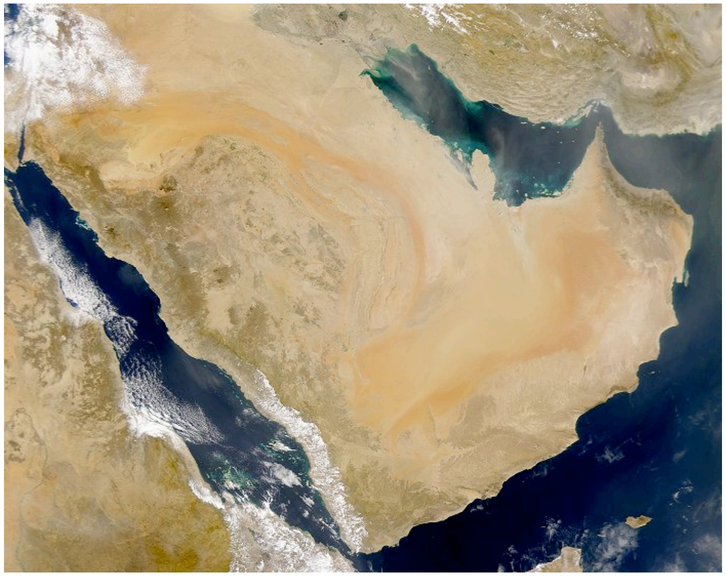
Yang Group
Department of Chemistry
UC Berkeley

Solar Energy Use

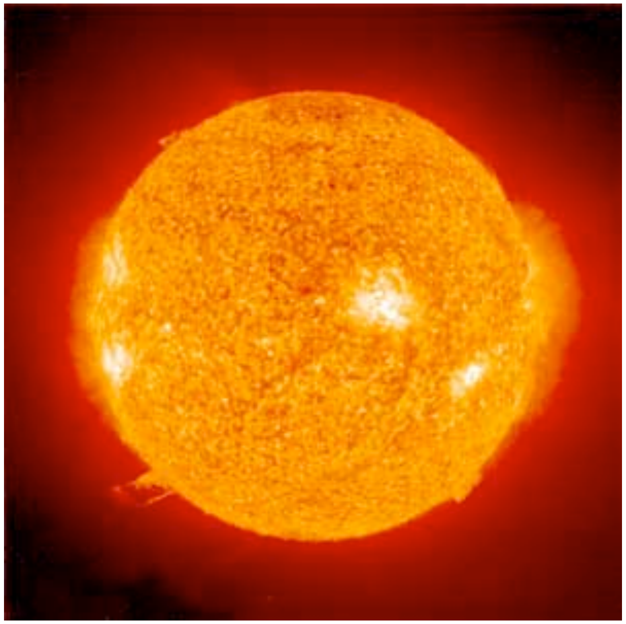


Note: Sum of components may not equal 100 percent due to independent rounding.
Source: EIA, *Renewable Energy Consumption and Electricity Preliminary 2007 Statistics*, Table 1: U.S. Energy Consumption by Energy Source, 2003-2007 (May 2008).

Hydrocarbons vs. Photons

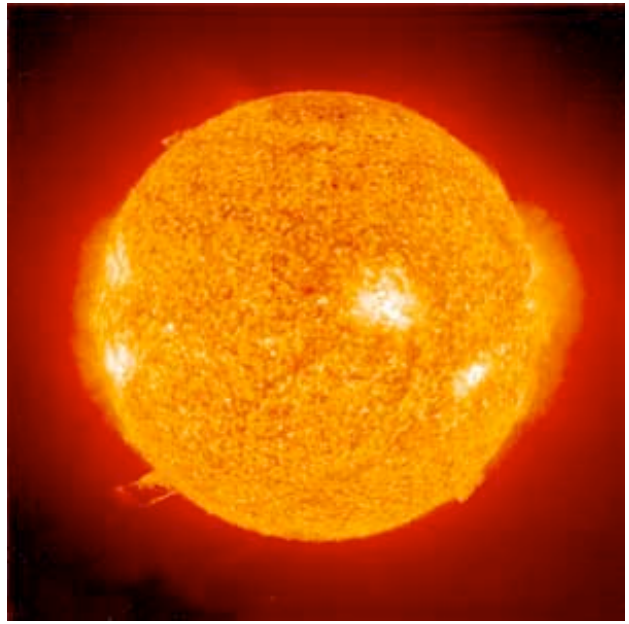


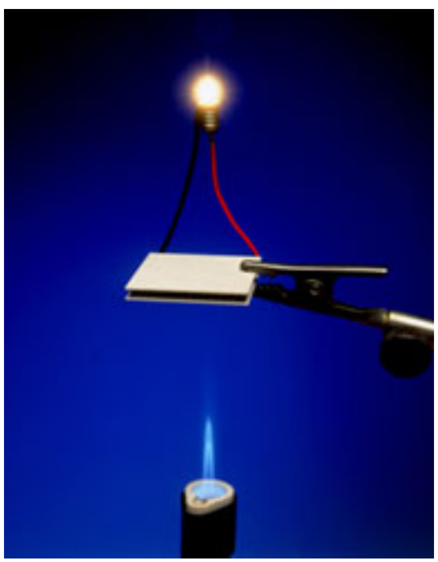
Arabian Oil: 600 years



Sun: 1.5 billion years

The Sun can Power both Solar Cells and Thermoelectrics

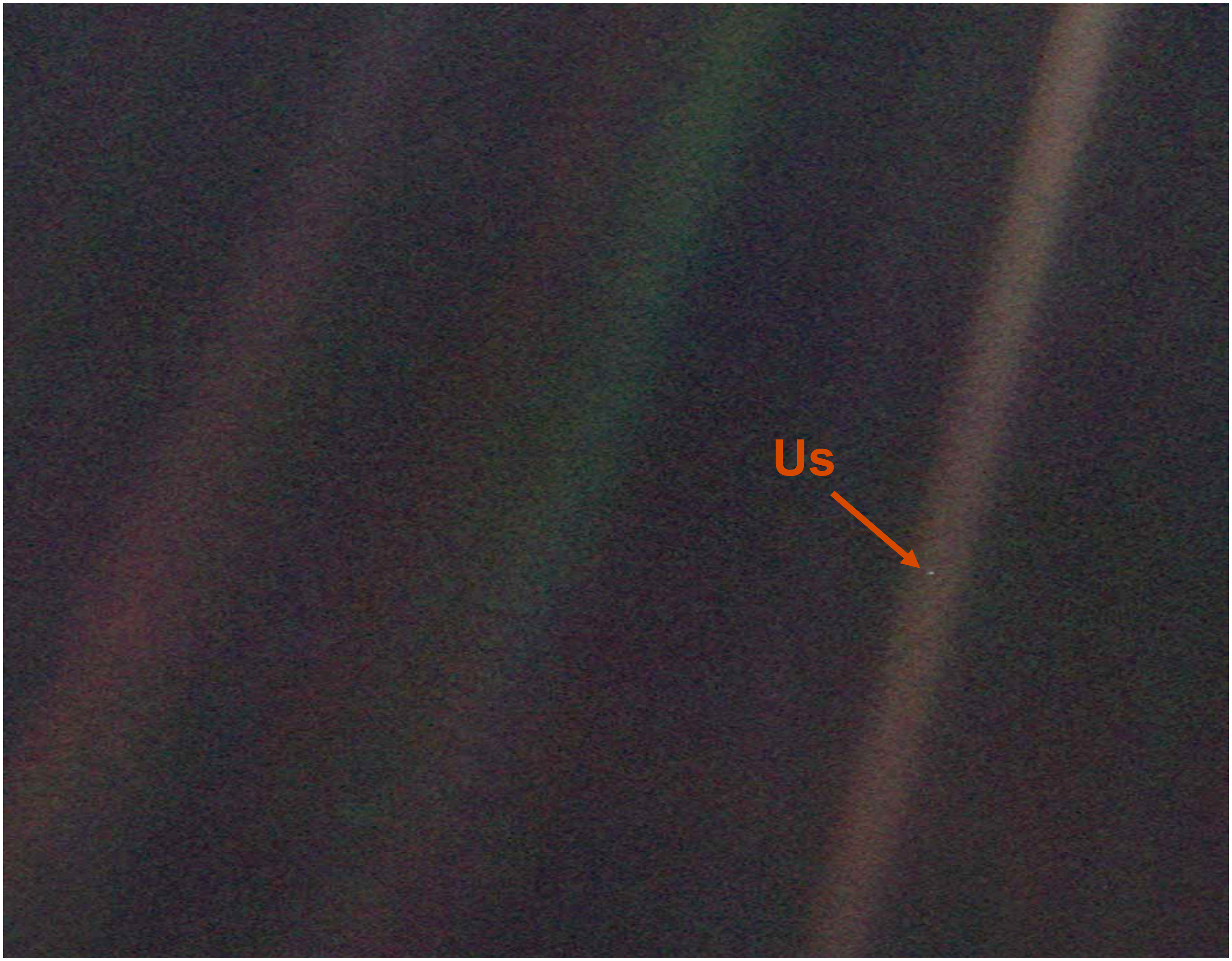




TE

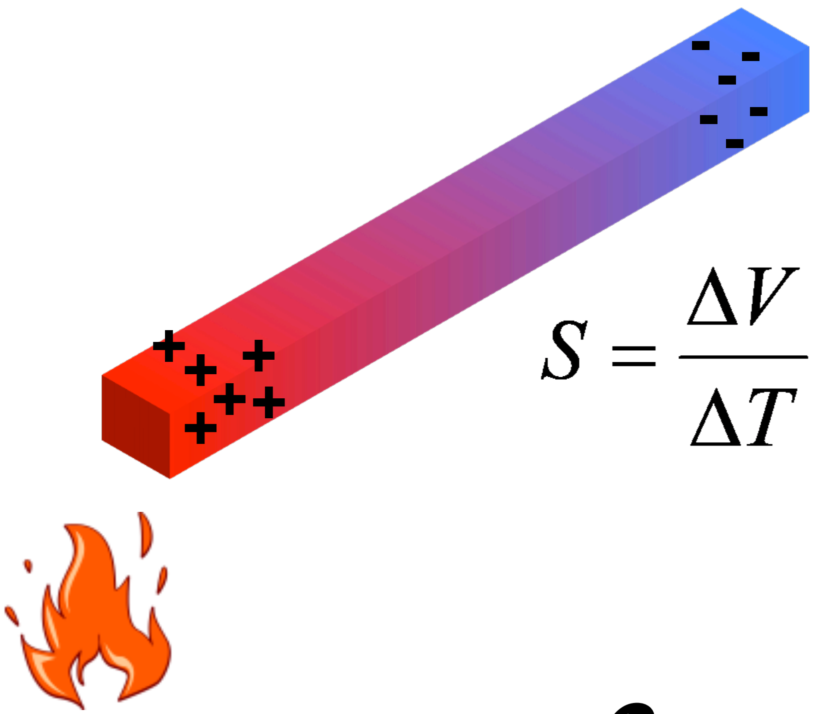
PV

Voyager Powered by Thermoelectrics



Thermoelectrics 101

Seebeck Effect

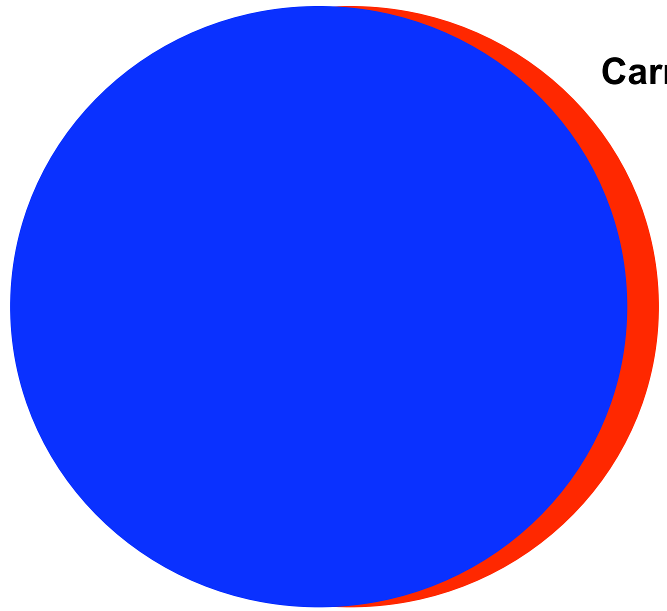


$$S = \frac{\Delta V}{\Delta T}$$

$$\oint E \cdot dx = 0$$

L. Onsager, Physical Review 37, 405 (1931)

Thermoelectrics 101



FOR A METAL

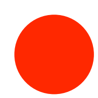
$$S = \frac{Q}{eT} = \frac{k}{e}\frac{kT}{E_F}$$

~ 1 μV/K

At 300K for
a typical metal

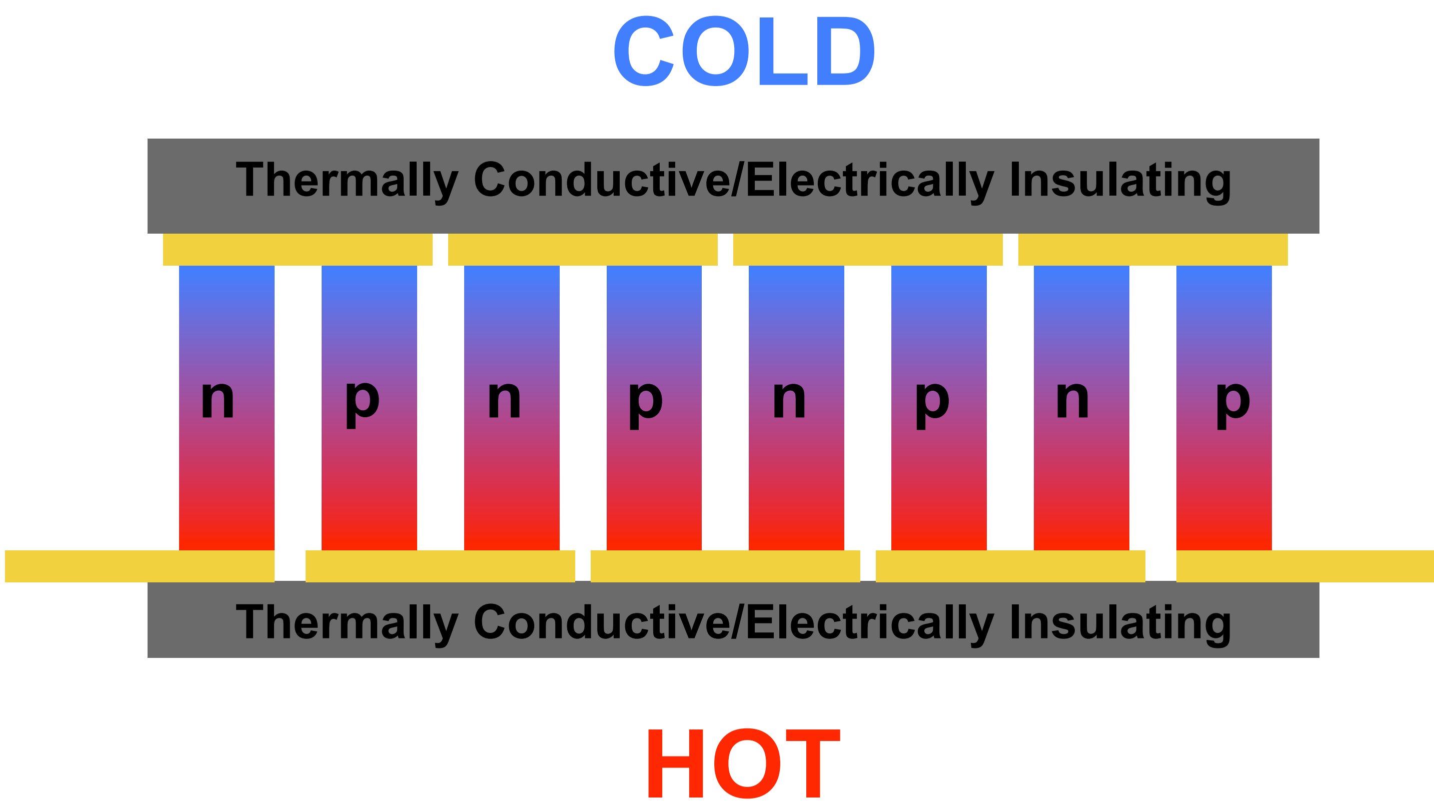
FOR A SEMICONDUCTOR

$$S = \frac{Q}{eT} = \frac{k}{e}$$



~ 100 μV/K

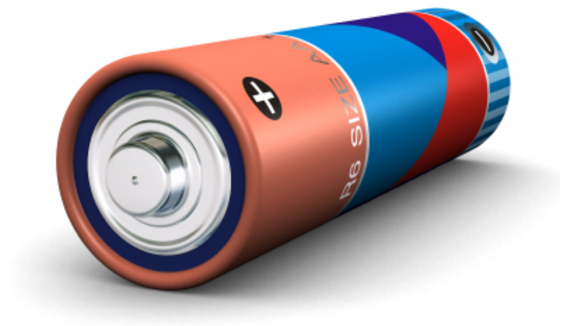
Off the Shelf Thermoelectrics

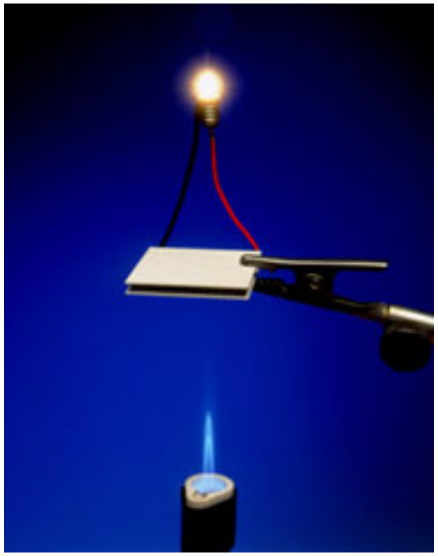


$$V_{OC} = N(S\Delta T)$$

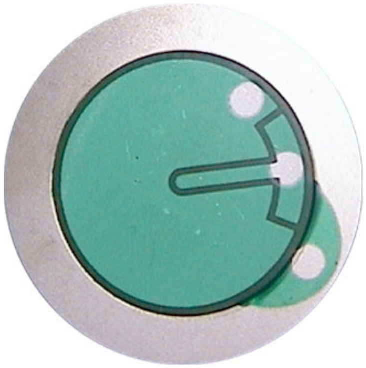
DC and AC Power-Generating Systems

DC Power





AC Power



What Governs Particle Flow?

$$\mathbf{dU = TdS + pdV + \mu dN + \phi de}$$

$$\eta = \mu + e\phi$$

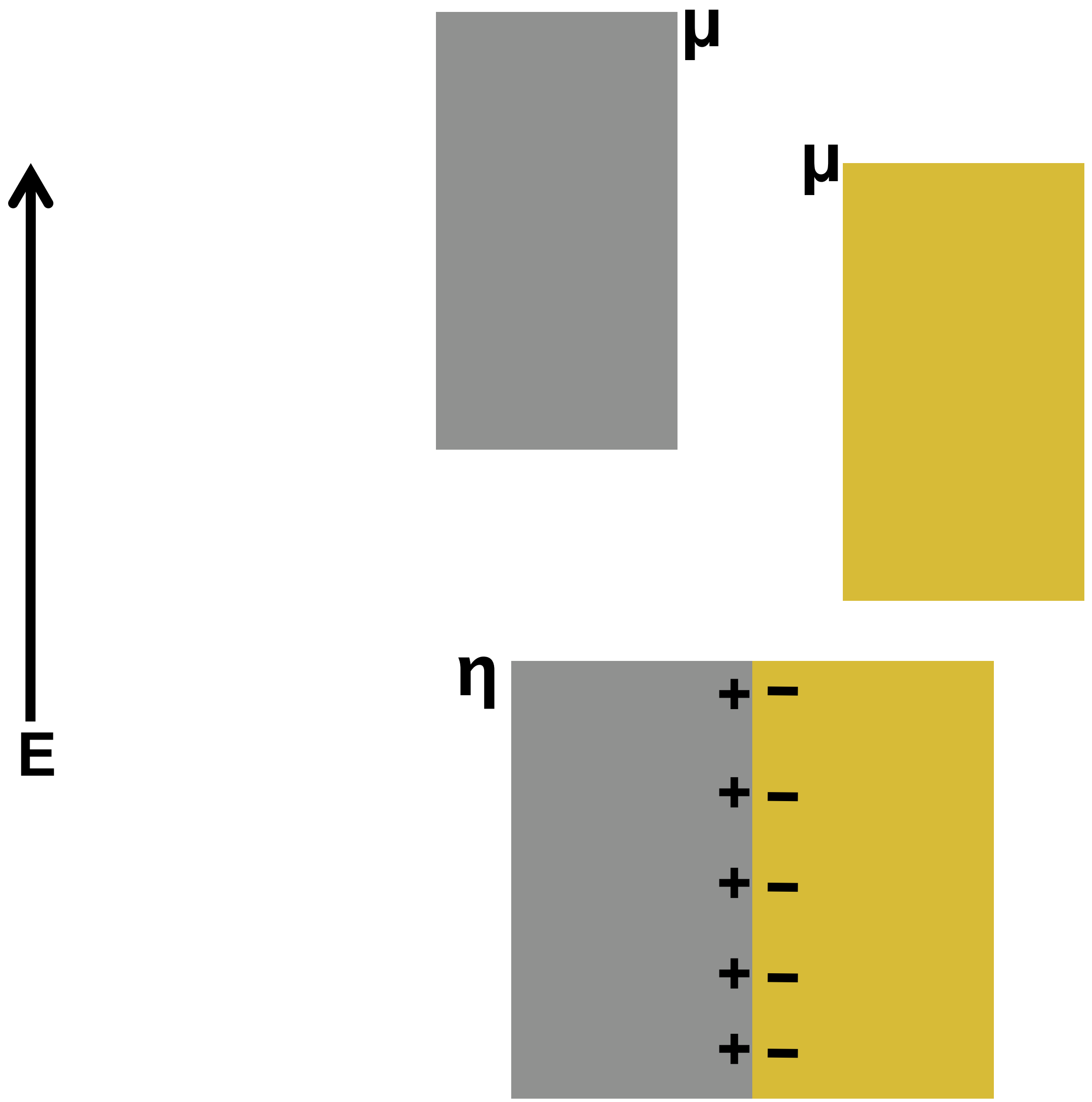
Particles move from high electrochemical potential to low electrochemical potential

Requirements for Electric Power

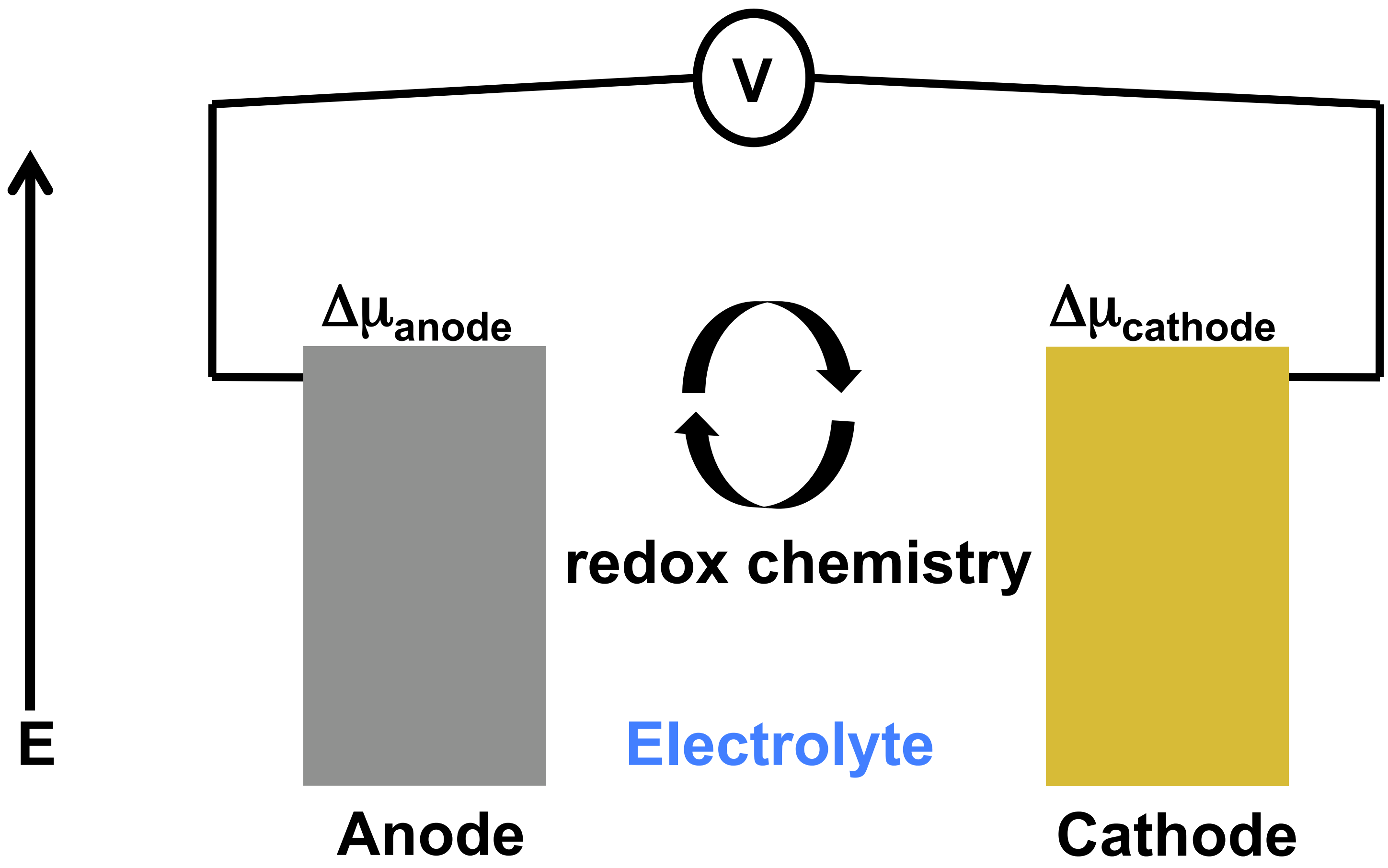
1. An Electrochemical Potential Difference Must be Present

2. A Selective Barrier Must be Present

The Contact Potential

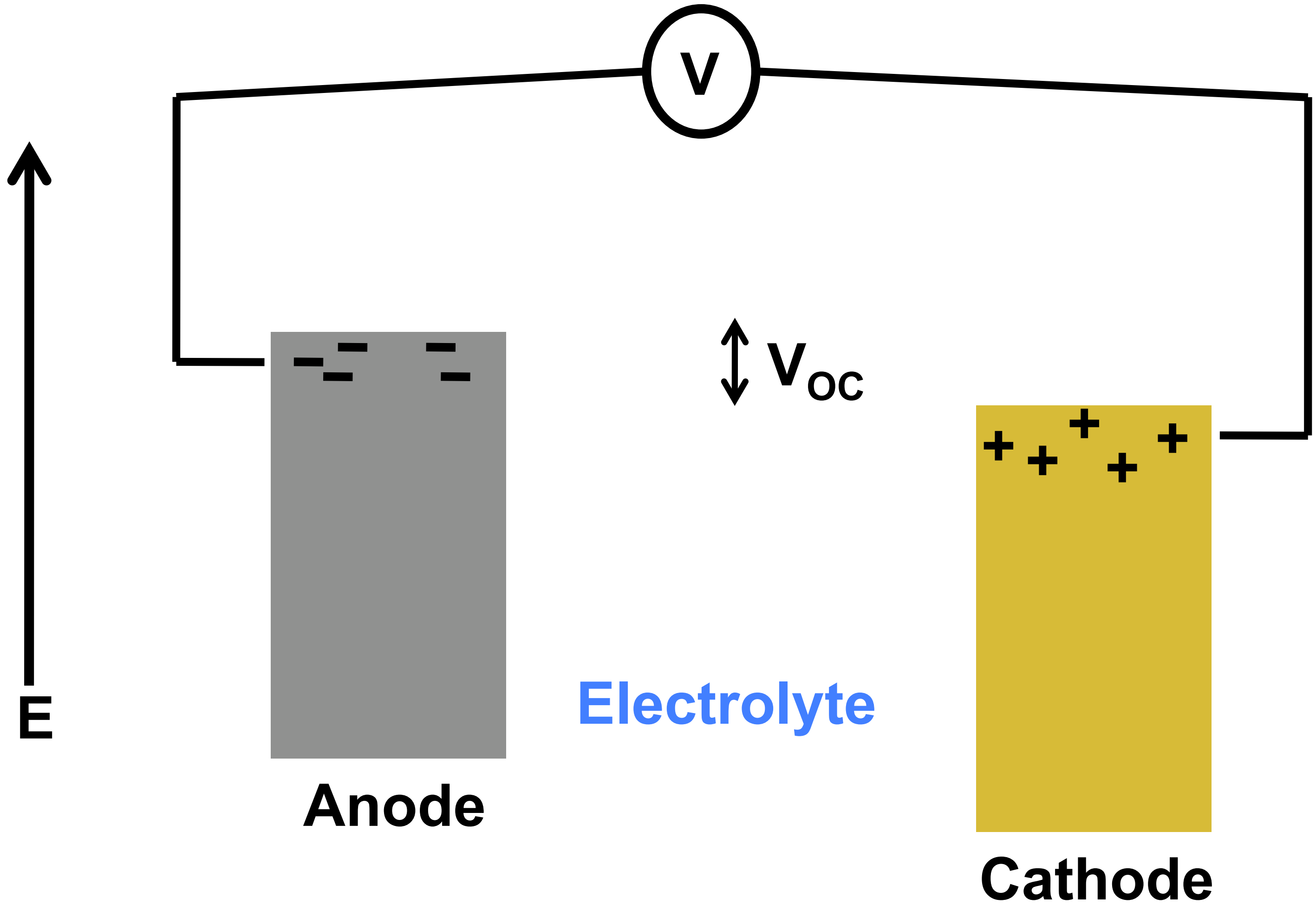


Batteries



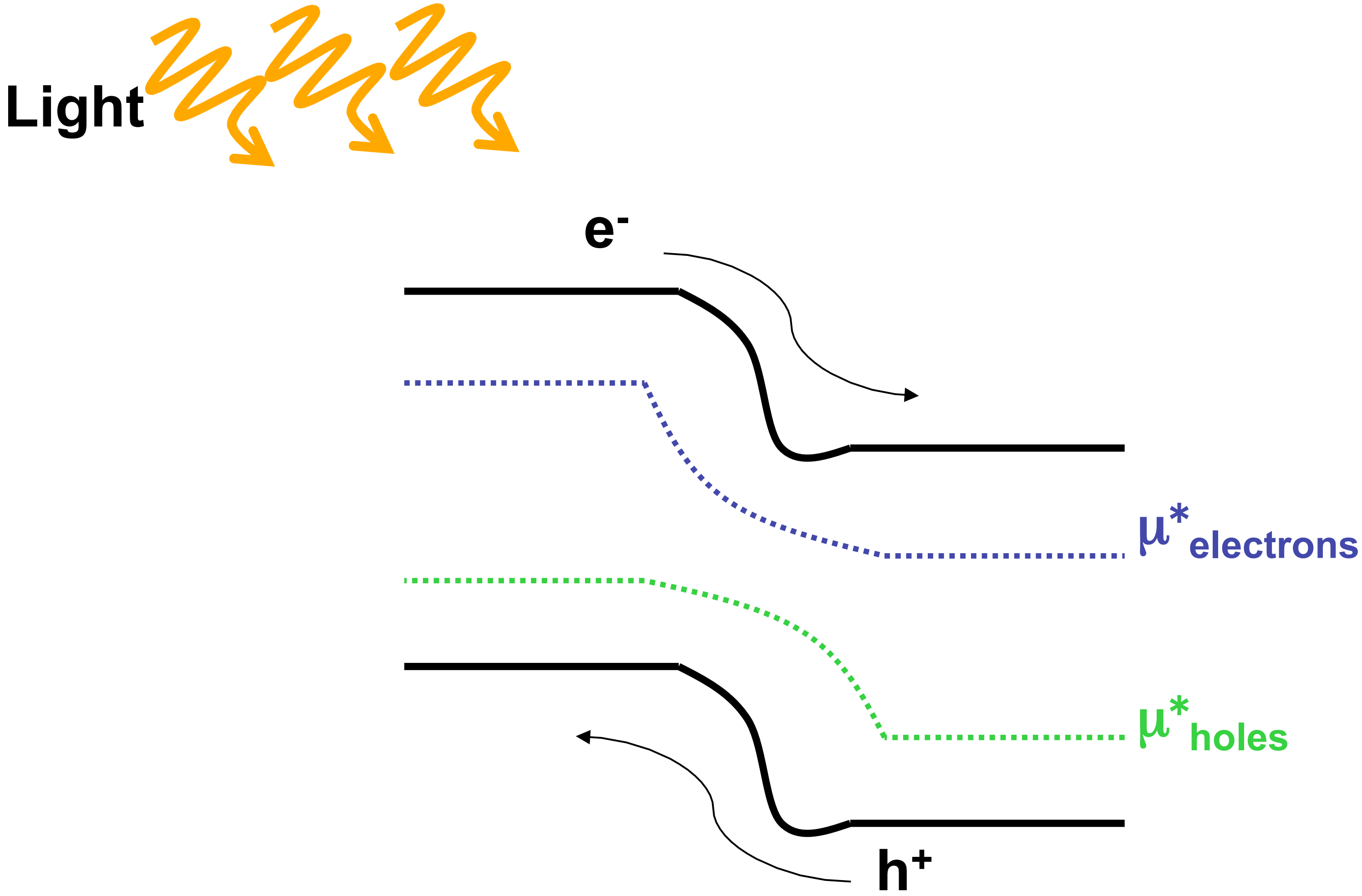
V
E
Δμanode
Δμcathode
redox chemistry
Electrolyte
Anode
Cathode

Batteries Continued

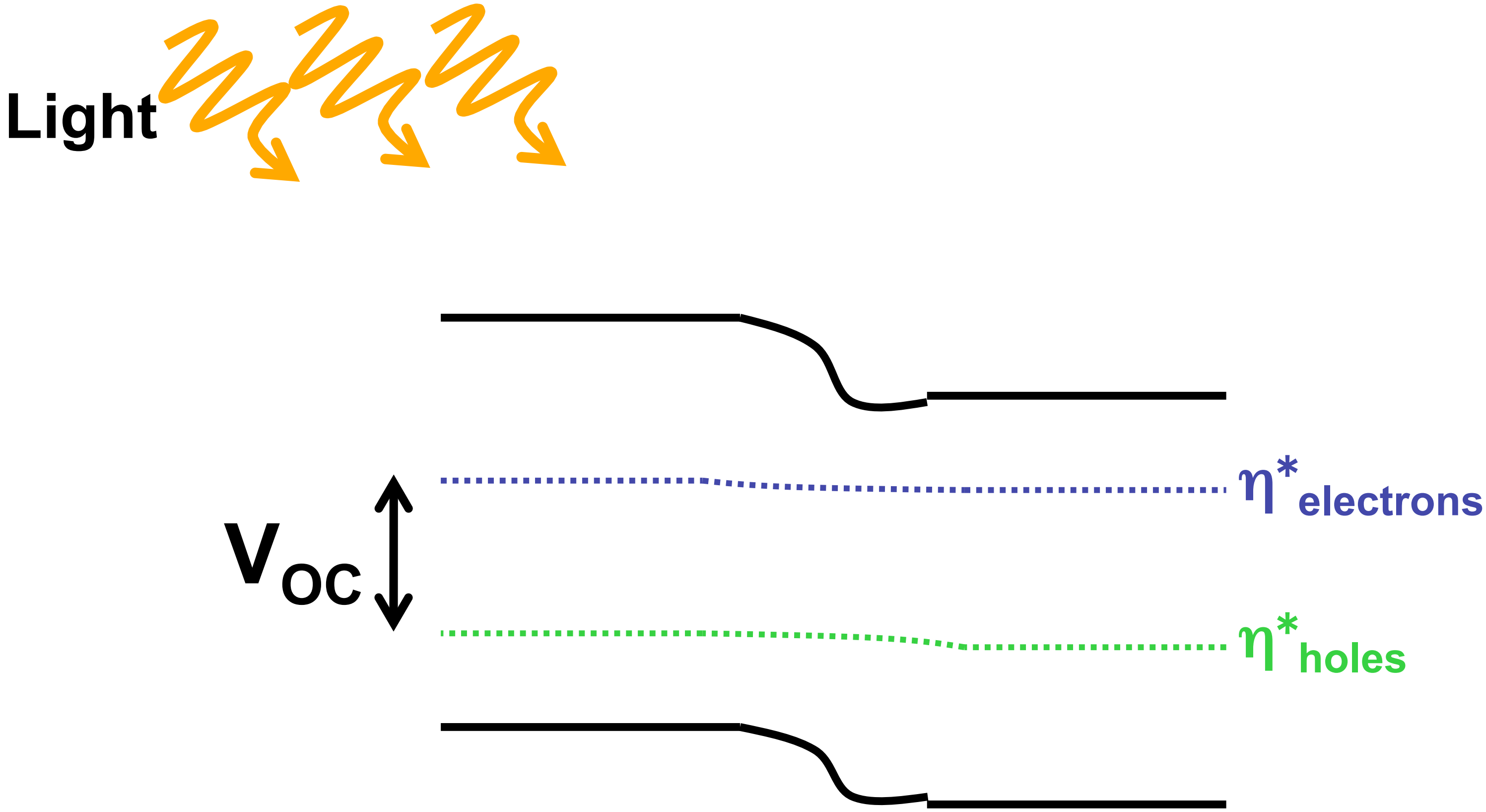


$$V_{OC} = \Delta\mu_{anode} + \Delta\mu_{cathode}$$

Solar Cells

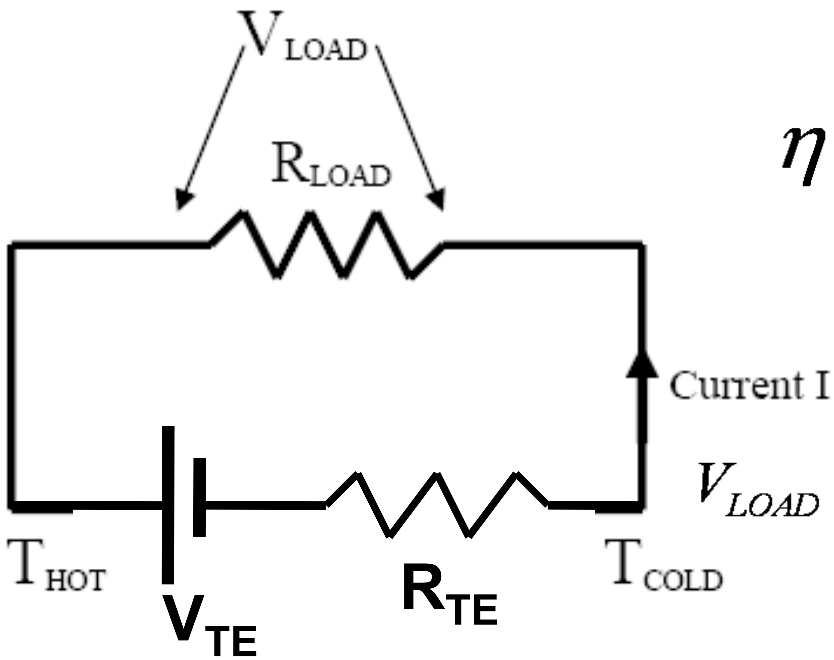


Solar Cells



$$V_{OC} = \Delta\mu_{electrons} + \Delta\mu_{holes}$$

Thermoelectrics as Heat Engines



$$\eta = \frac{W}{Q}$$ **W is the work output**
Q is the heat input

Work extracted is: $W = IV_{LOAD}$

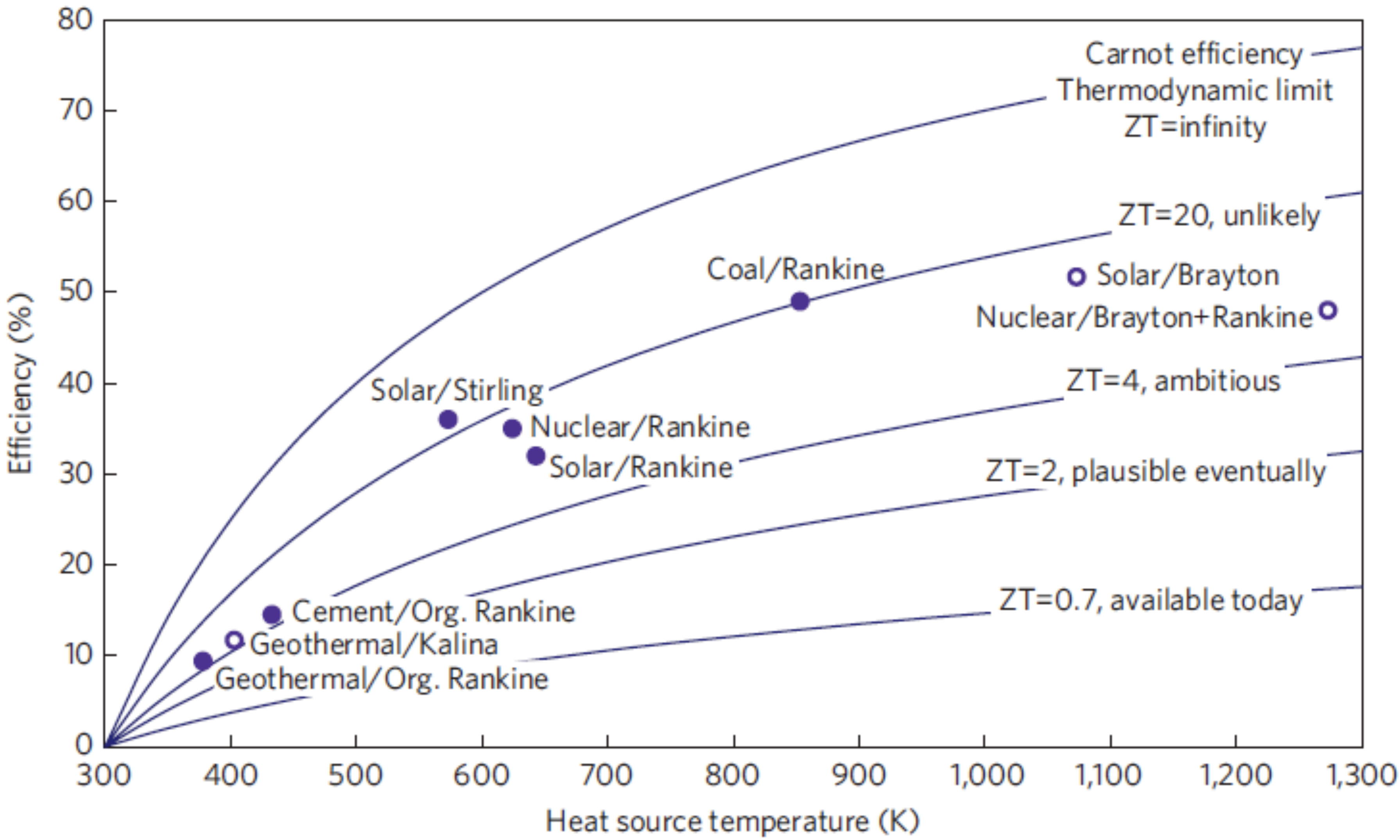
$$V_{LOAD} = V_{TE}\left(\frac{R_{LOAD}}{R_{TE} + R_{LOAD}}\right) = S\Delta T\left(\frac{R_{LOAD}}{R_{TE} + R_{LOAD}}\right)$$

$$W = S^2 \Delta T^2 \left[\frac{R_{LOAD}}{(R_{TE} + R_{LOAD})}\right]$$

Heat input consists of 3 terms: $Q_1 = \kappa \Delta T \quad Q_2 = IST_{HOT} \quad Q_3 = -\frac{1}{2} I^2 R_{TE}$

Plugging into η and maximizing: $$\eta = \frac{\Delta T}{T_{HOT}} \frac{\sqrt{1 + Z\overline{T}} - 1}{\sqrt{1 + Z\overline{T}} + \frac{T_{COLD}}{T_{HOT}}}$$

Heat Engines and Efficiency



Vining, C. *Nature Materials* 8, 83 (2009)

Figure of Merit for Thermoelectrics is ZT

Dimensionless number. Larger the better

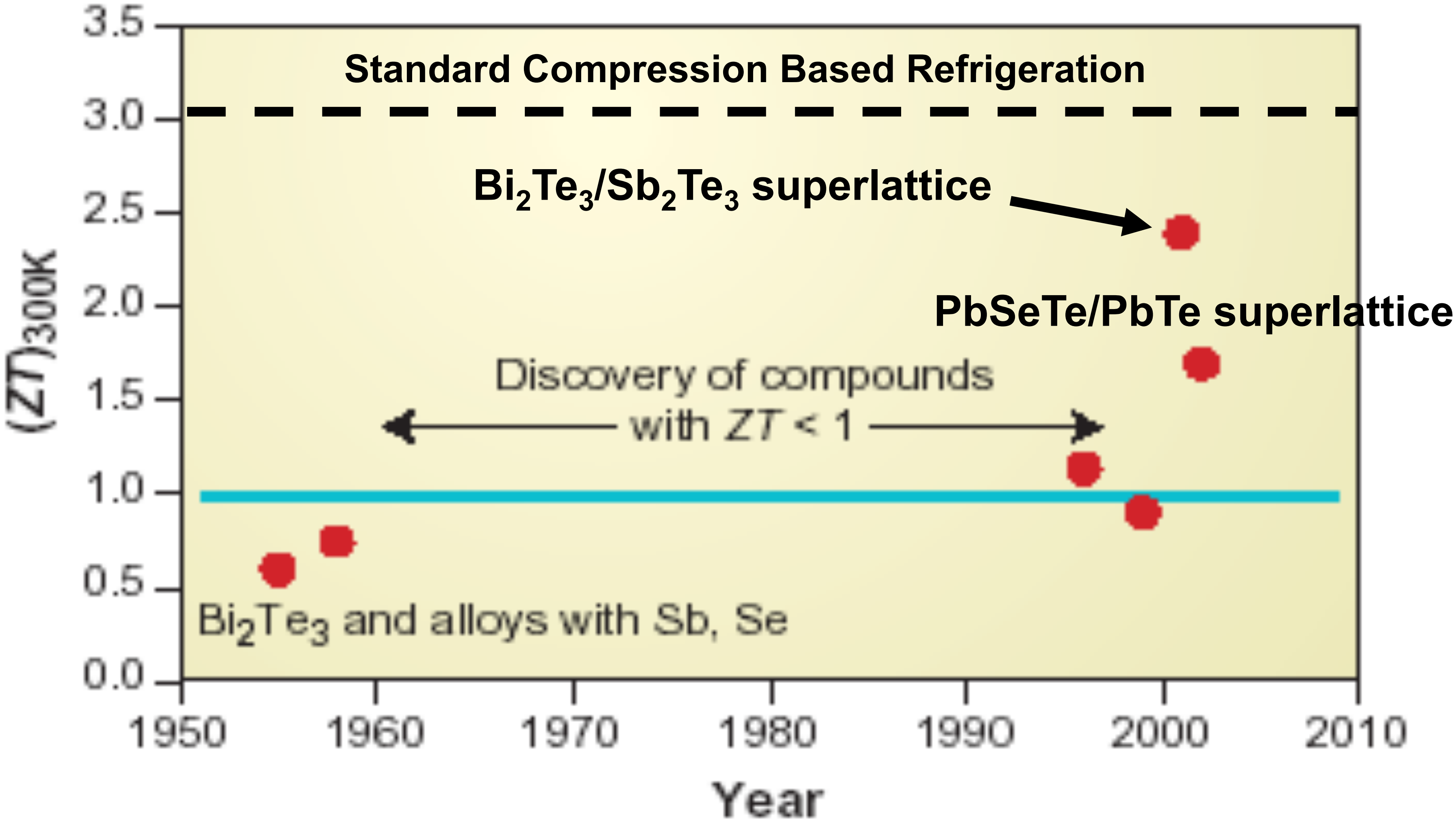
$$ZT = \frac{S^2 \sigma}{\kappa} T$$

S Thermopower

σ Electrical conductivity

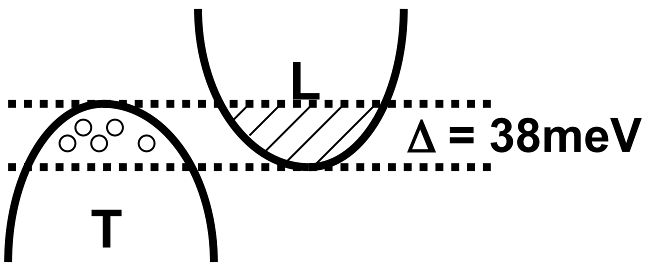
κ Thermal conductivity

Is There a Ceiling to ZT?

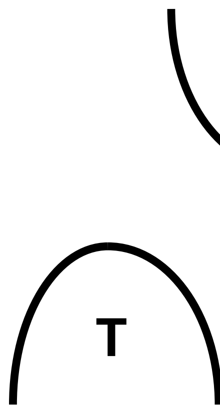


A. Majumdar, *Science* 303, 777 2004

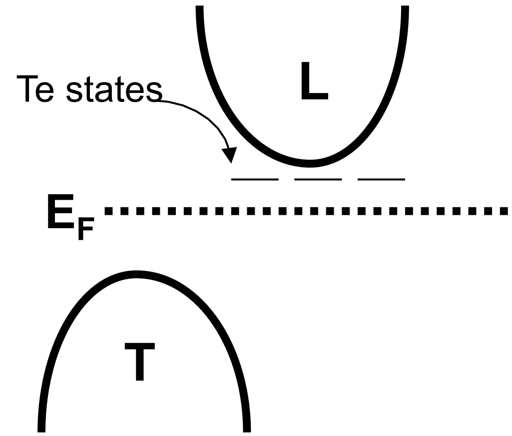
Is Bismuth a Good Thermoelectric?



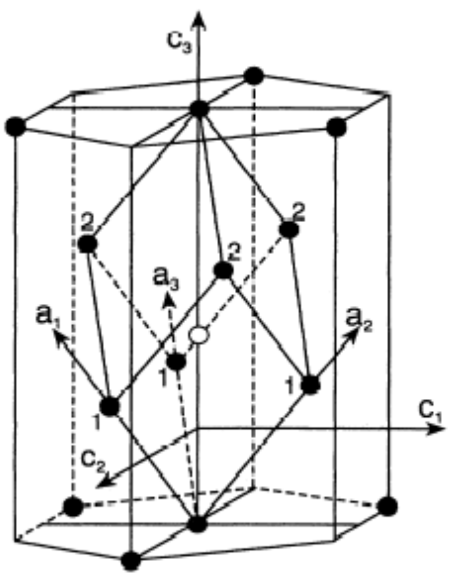
Bulk Bismuth



Bismuth wire with diameter < 50nm



Tellurium doped Bismuth nanowires



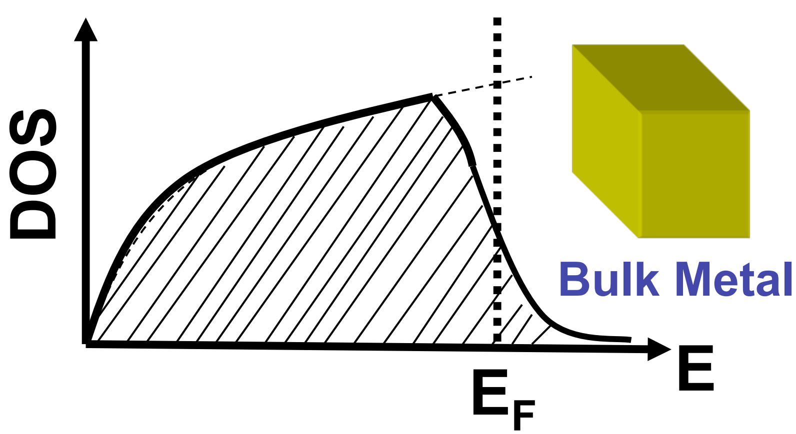
$m^* = .001m_e$ $\mu = 2.59\text{X}10^5\ cm^2\ V^{-1}\ s^{-1}$

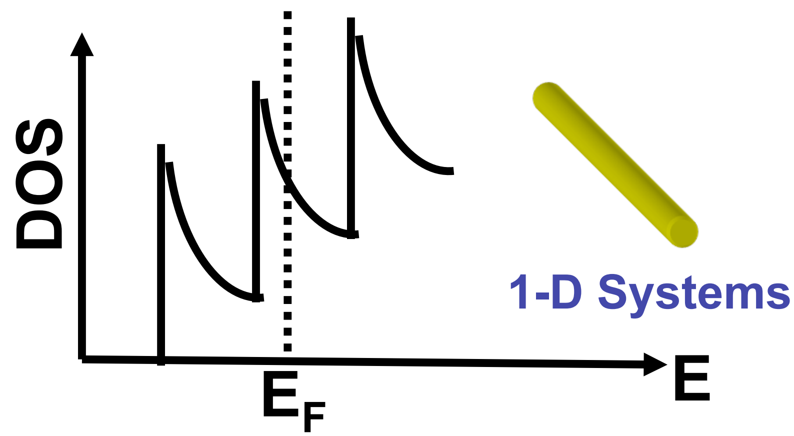
$S = 100\mu V/K$ $\kappa = 8\ W\ m^{-1}\ K^{-1}$

Electron mean free path is ~30 to 50nm at room temperature

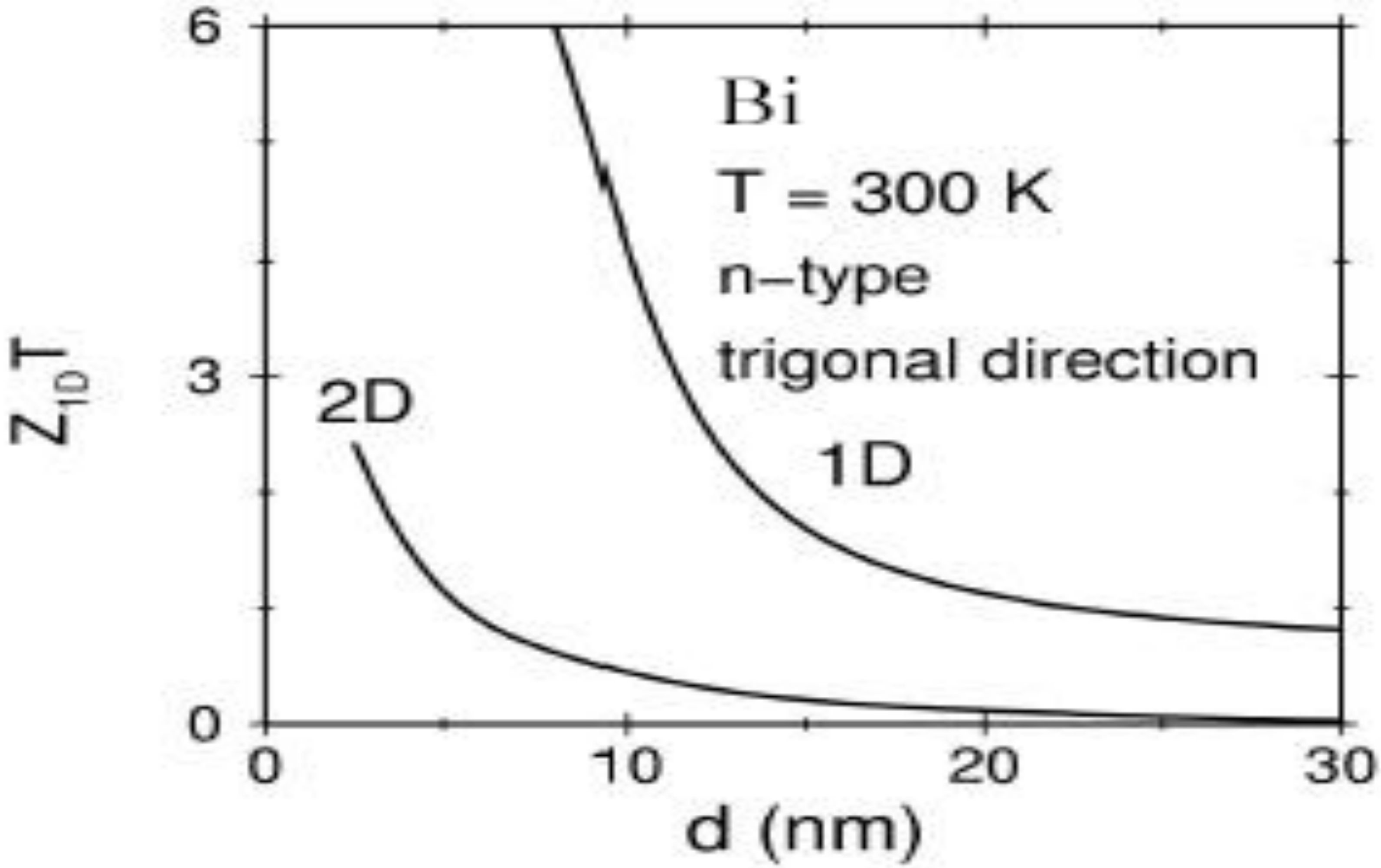
Density of States

$$S \propto T \left.\frac{\partial N(E)}{\partial E}\right|_{E_F}$$



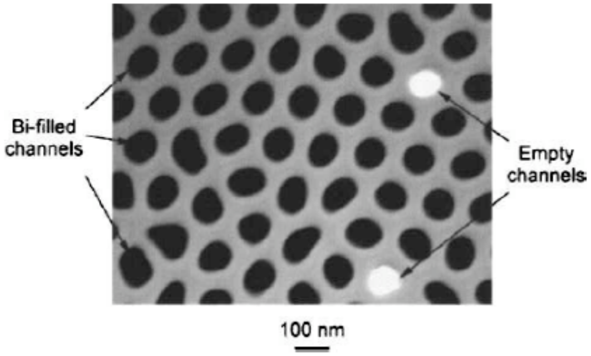


ZT for Bismuth Nanowires



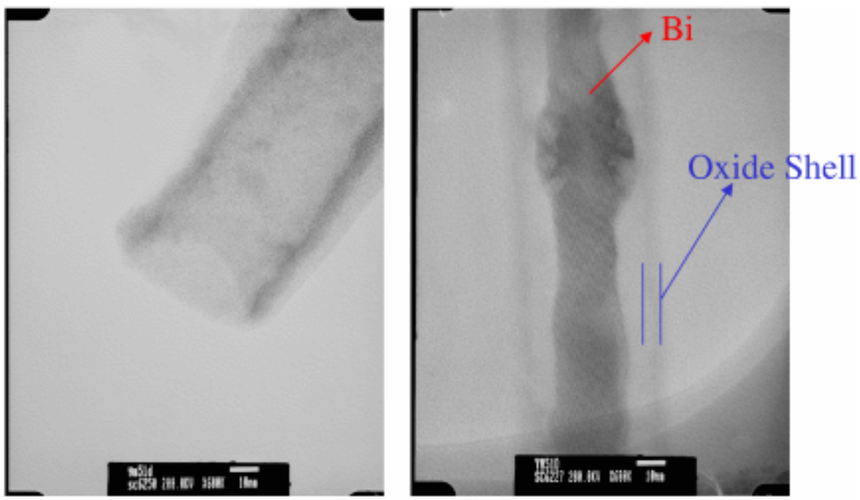
M.S. Dresselhaus, *Phys. Rev. B* 62, 4610 2000

Bismuth is Not an Easy Material to Work With



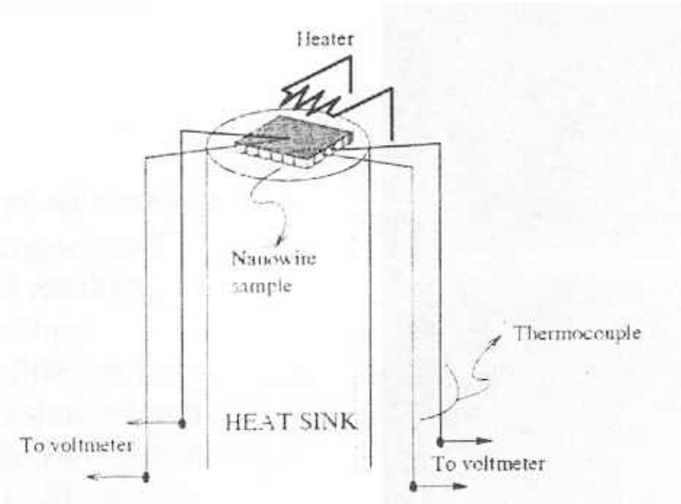
State of the art: Alumina assisted electrodeposition

M.S. Dresselhaus *et. al.*, *Int. Mater. Rev.* 48, 45-66 2003



Bismuth is sensitive to acids and bases and oxidizes readily

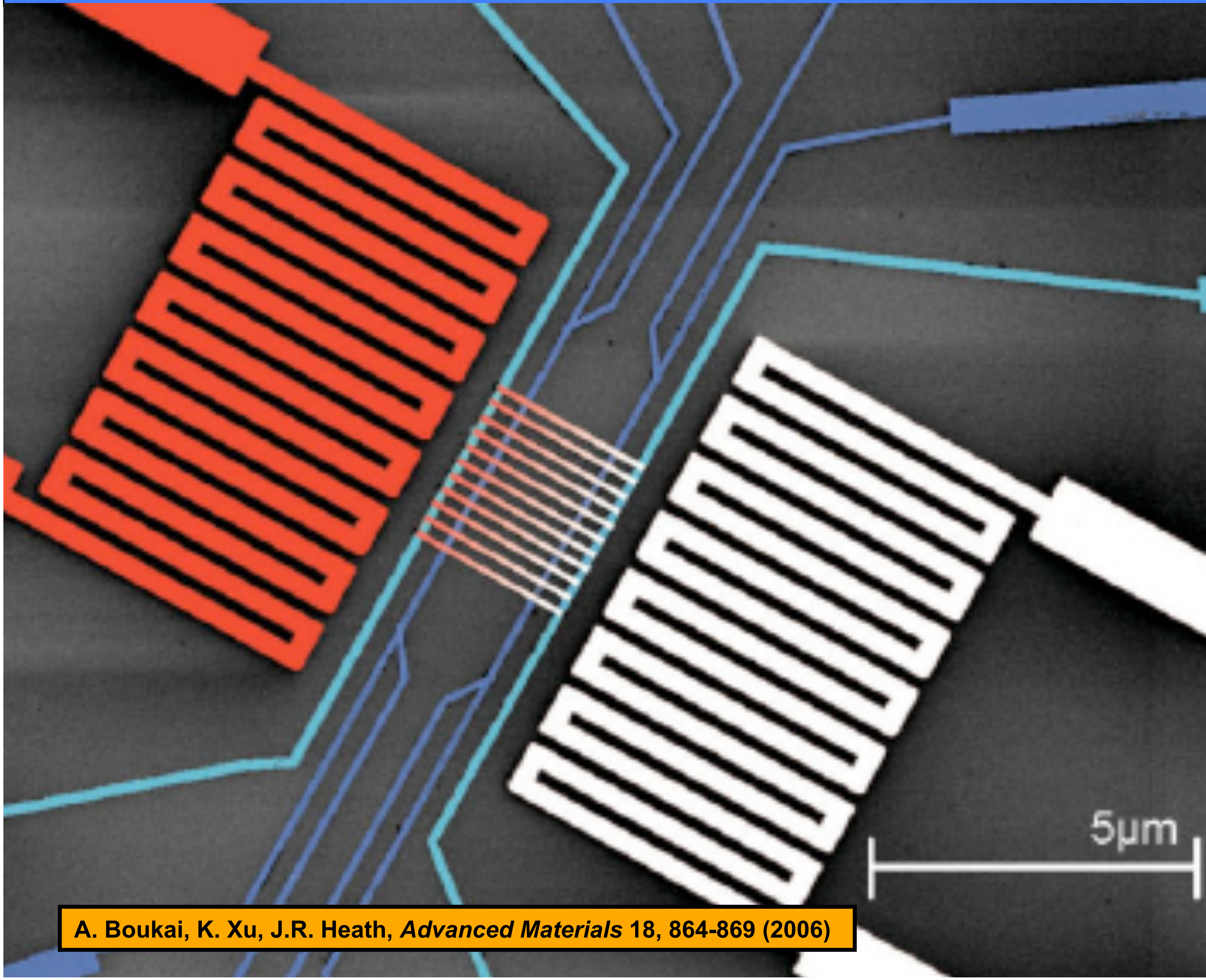
S.B. Cronin *et. al.*, *Nanotechnology* 13, 653-658 2002

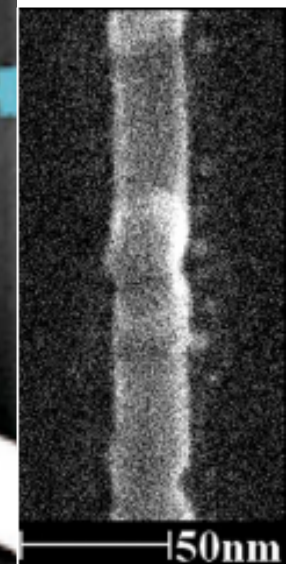


Measurement limited to 2-point and large thermocouples

Y.M. Lin *et. al.*, Mat. Res. Soc. Symp. Proc. 691, 377-382 2002

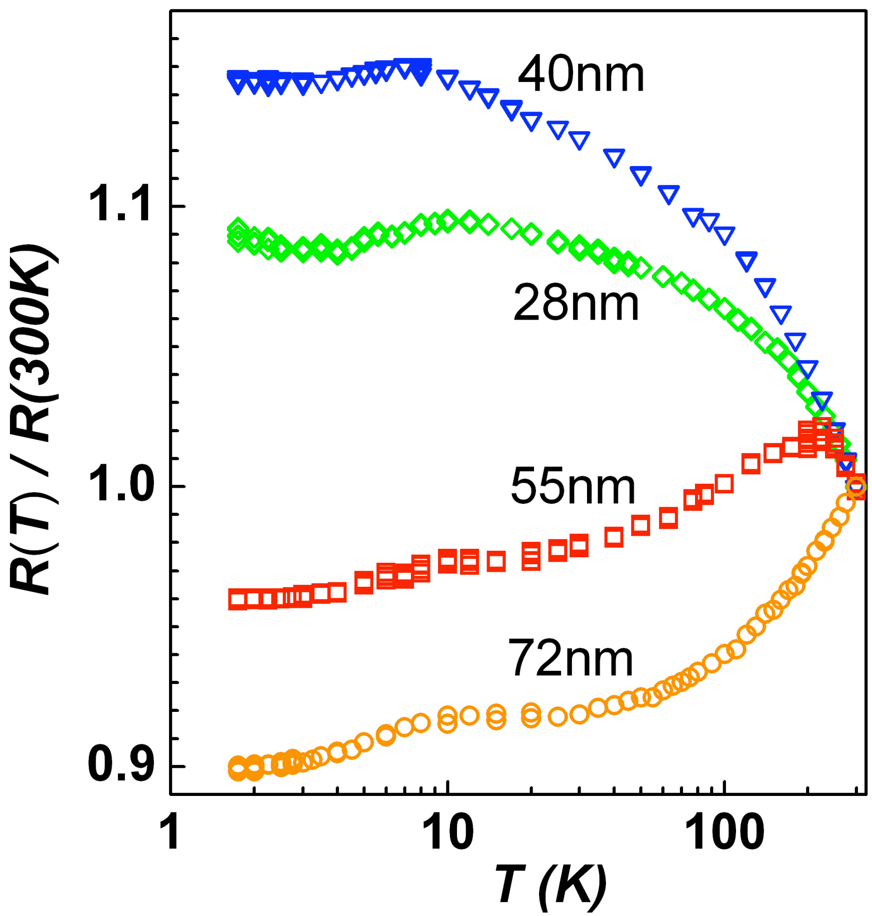
Bismuth Nanowire Thermoelectric Devices

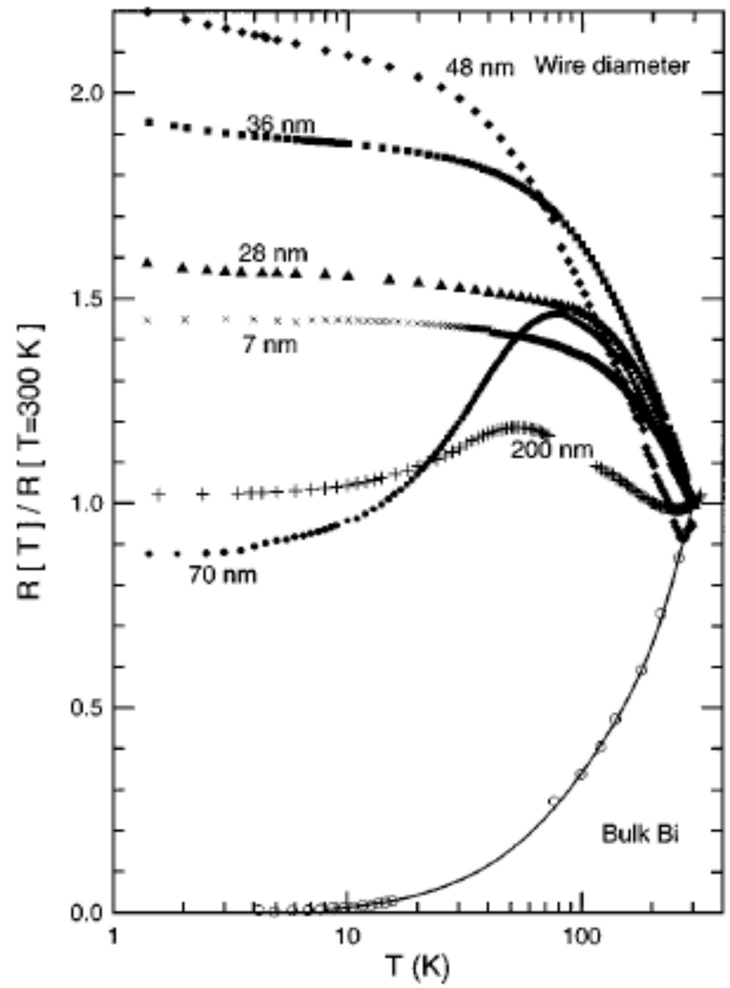




A. Boukai, K. Xu, J.R. Heath, *Advanced Materials* 18, 864-869 (2006)

Bi Nanowire Electrical Conductivity Results



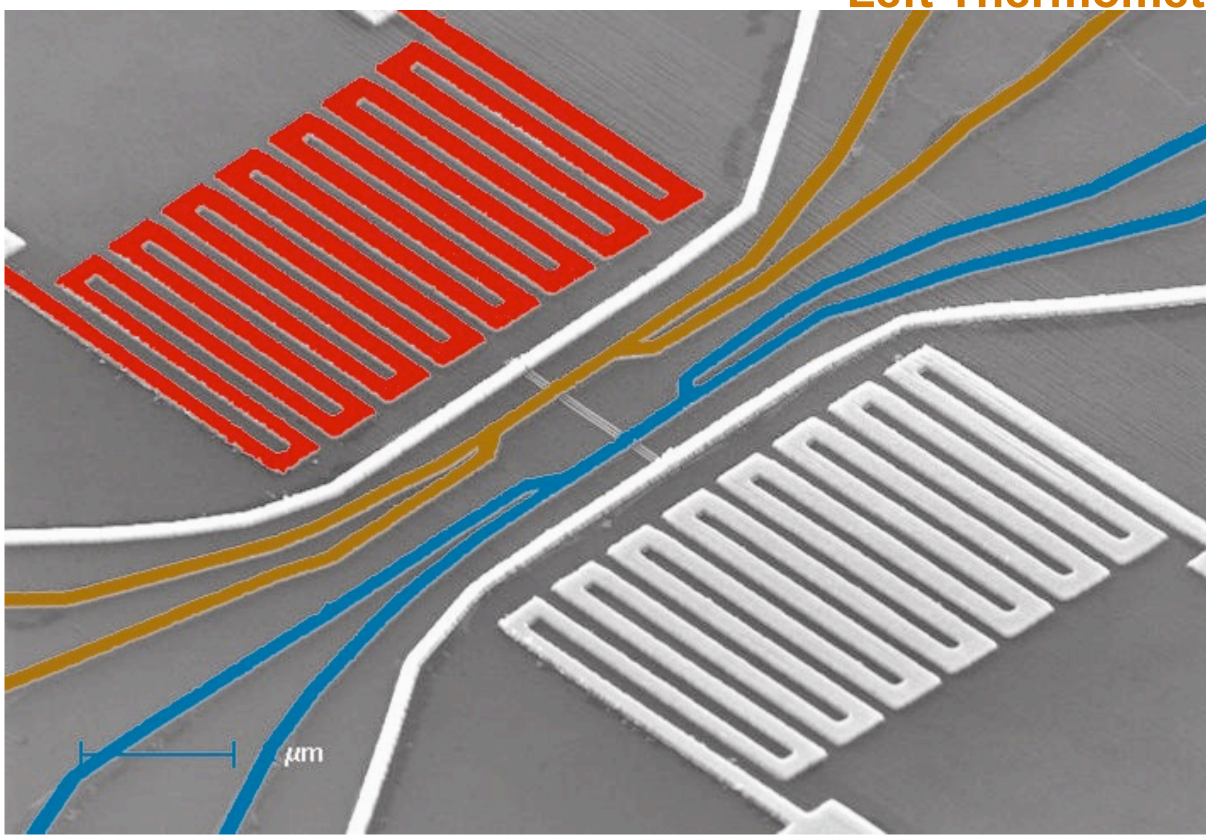


A. Boukai, K. Xu, J.R. Heath, *Advanced Materials* 18, 864-869 2006

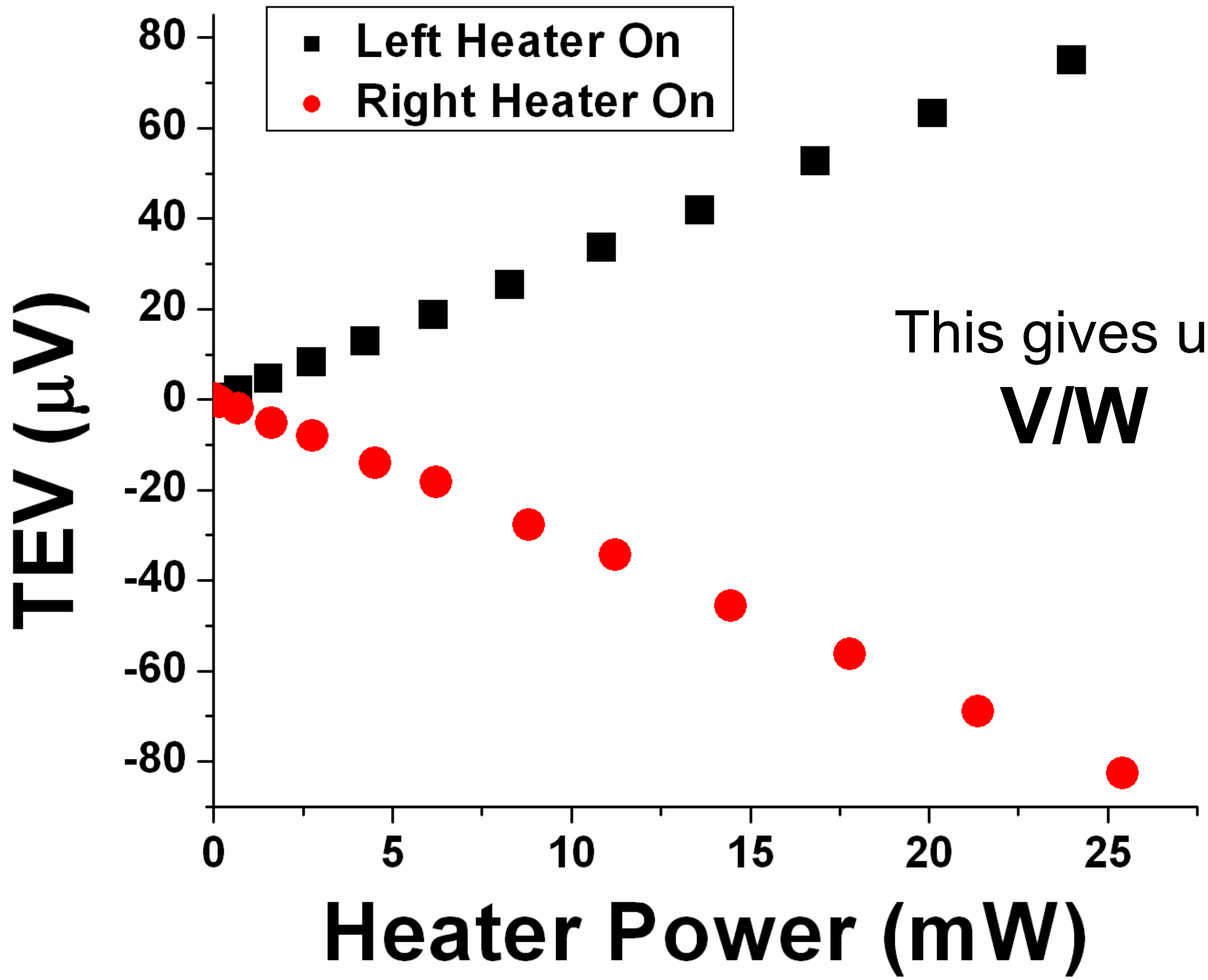
Heremans *et. al.*, *Phys. Rev. B* 61, 2921-2930 2000

Measuring the Thermopower

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



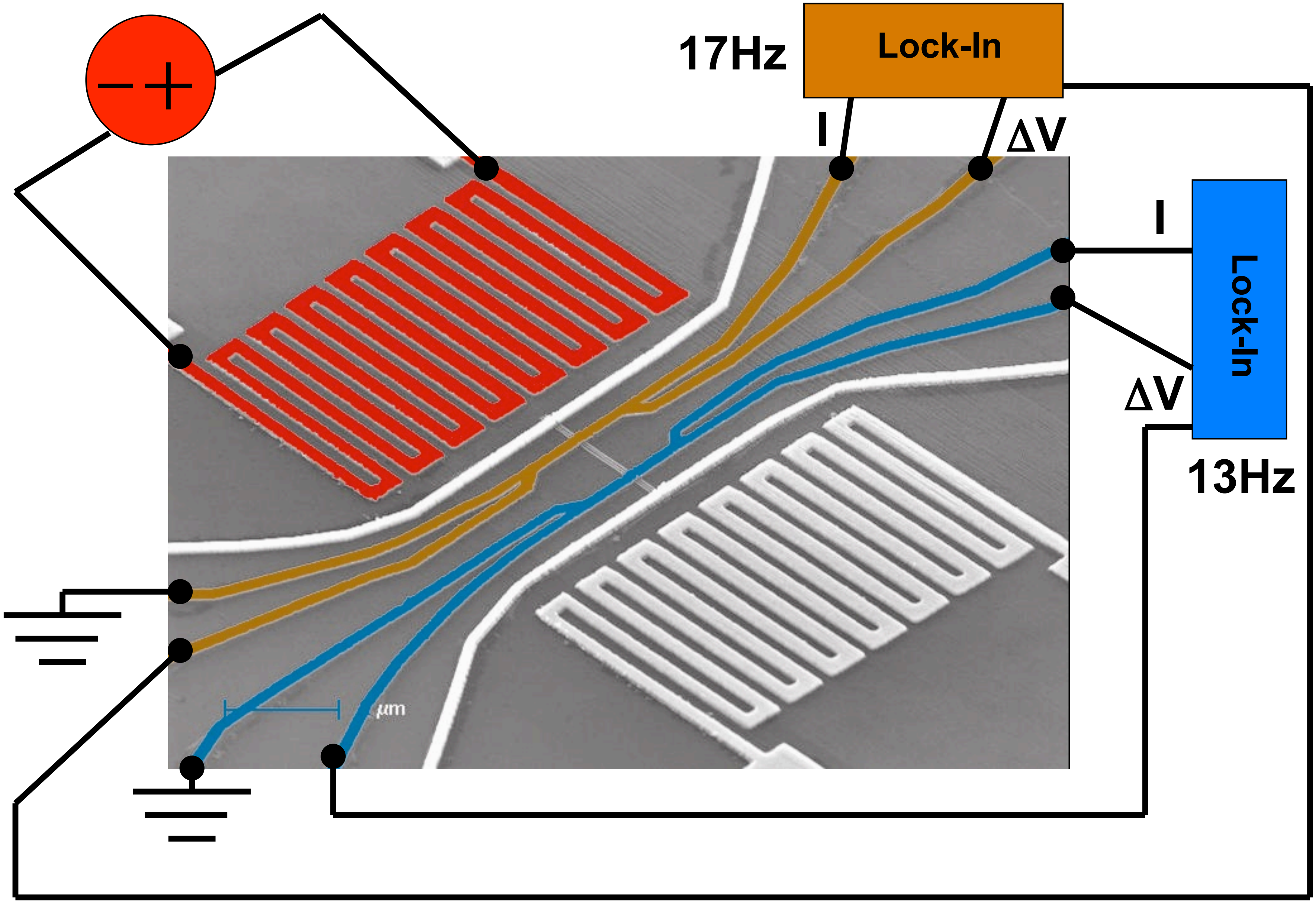
Measuring the Thermoelectric Voltage (TEV)



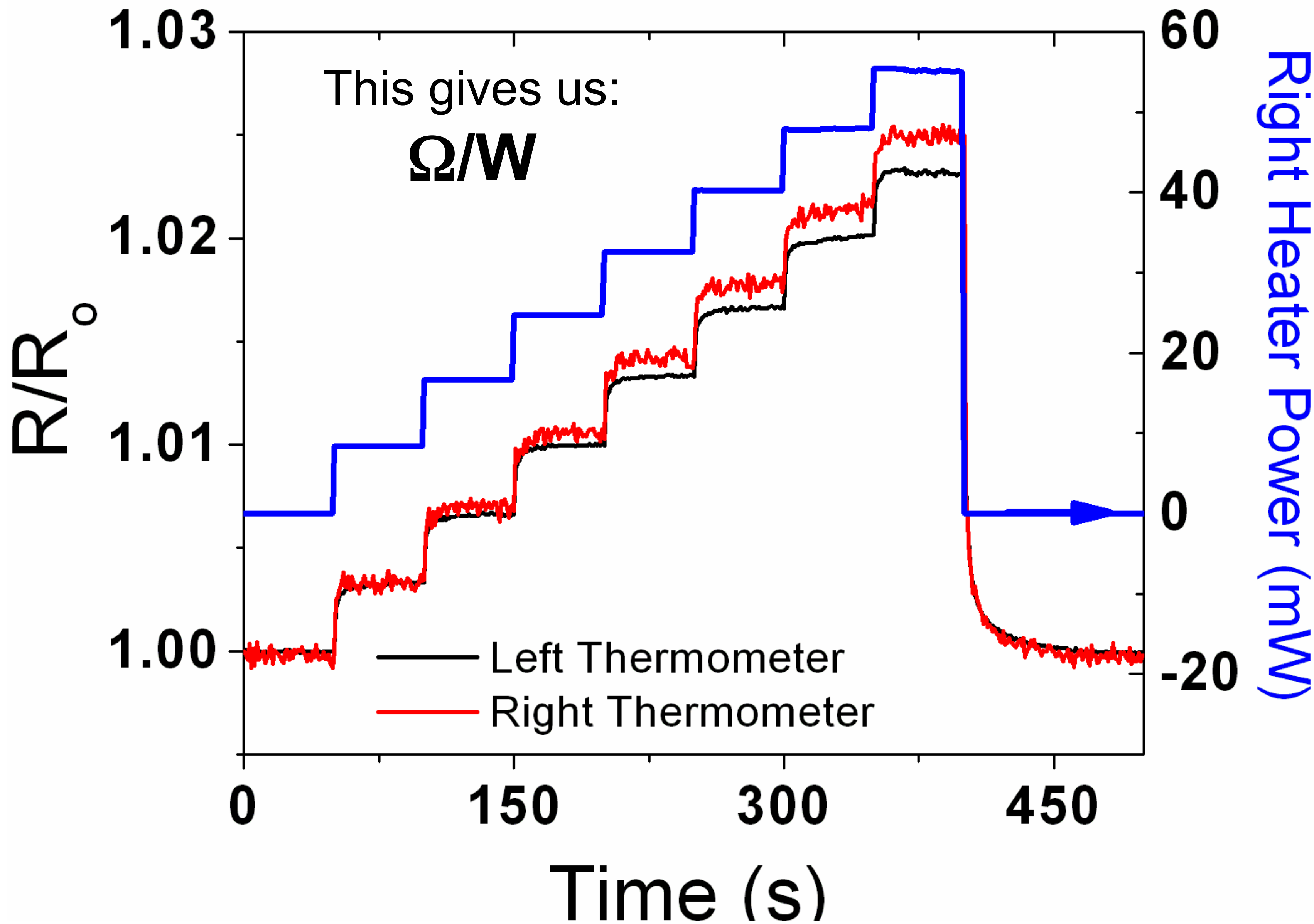
This gives us:

V/W

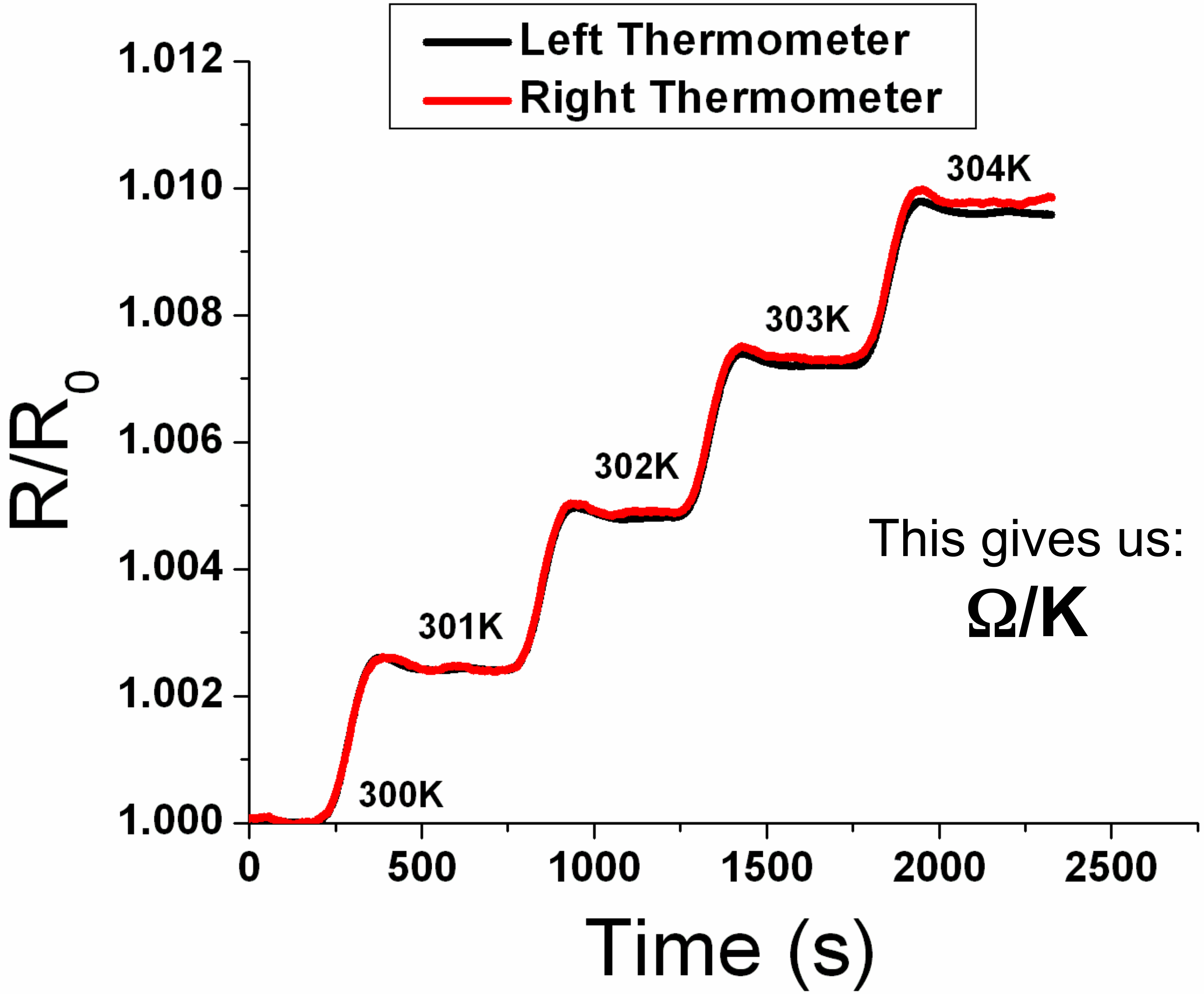
Measuring ΔT



Measuring ΔT



Measuring ΔT

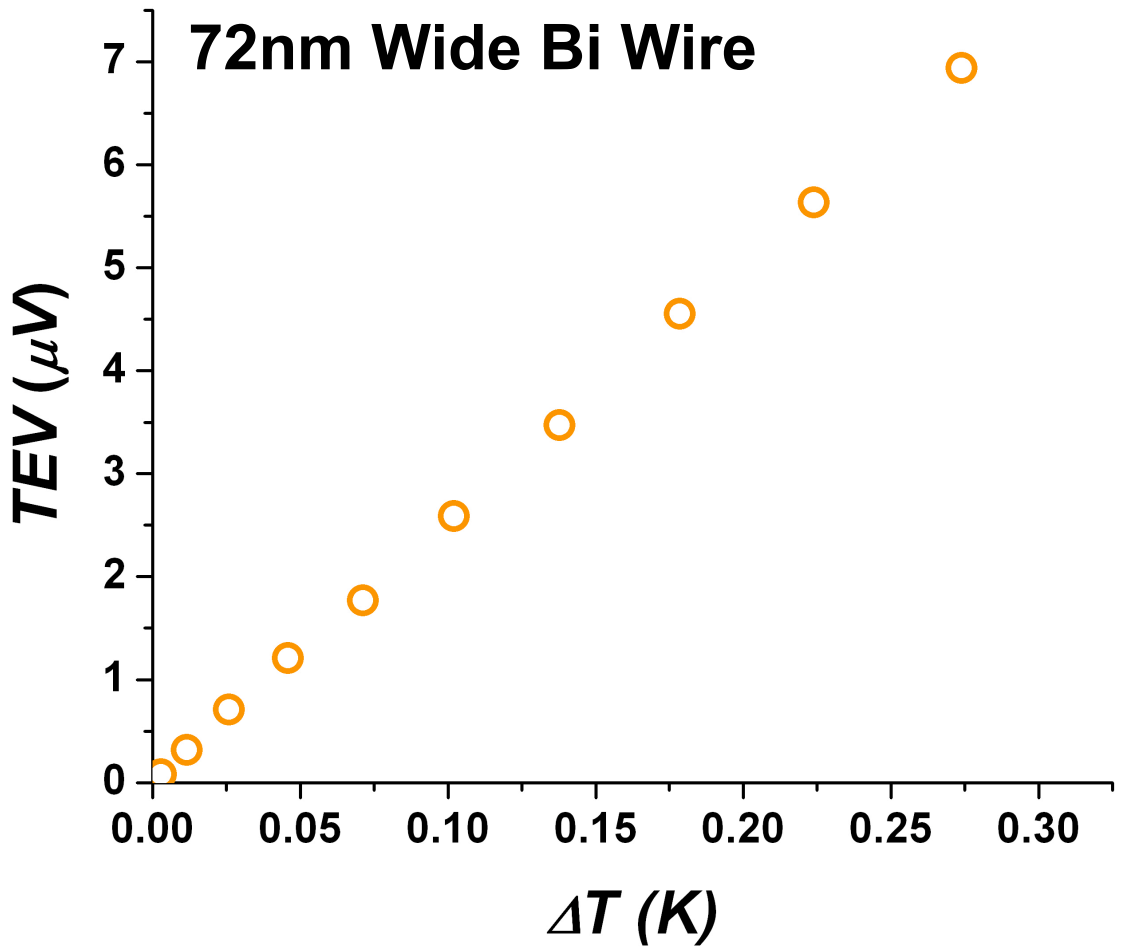


This gives us:

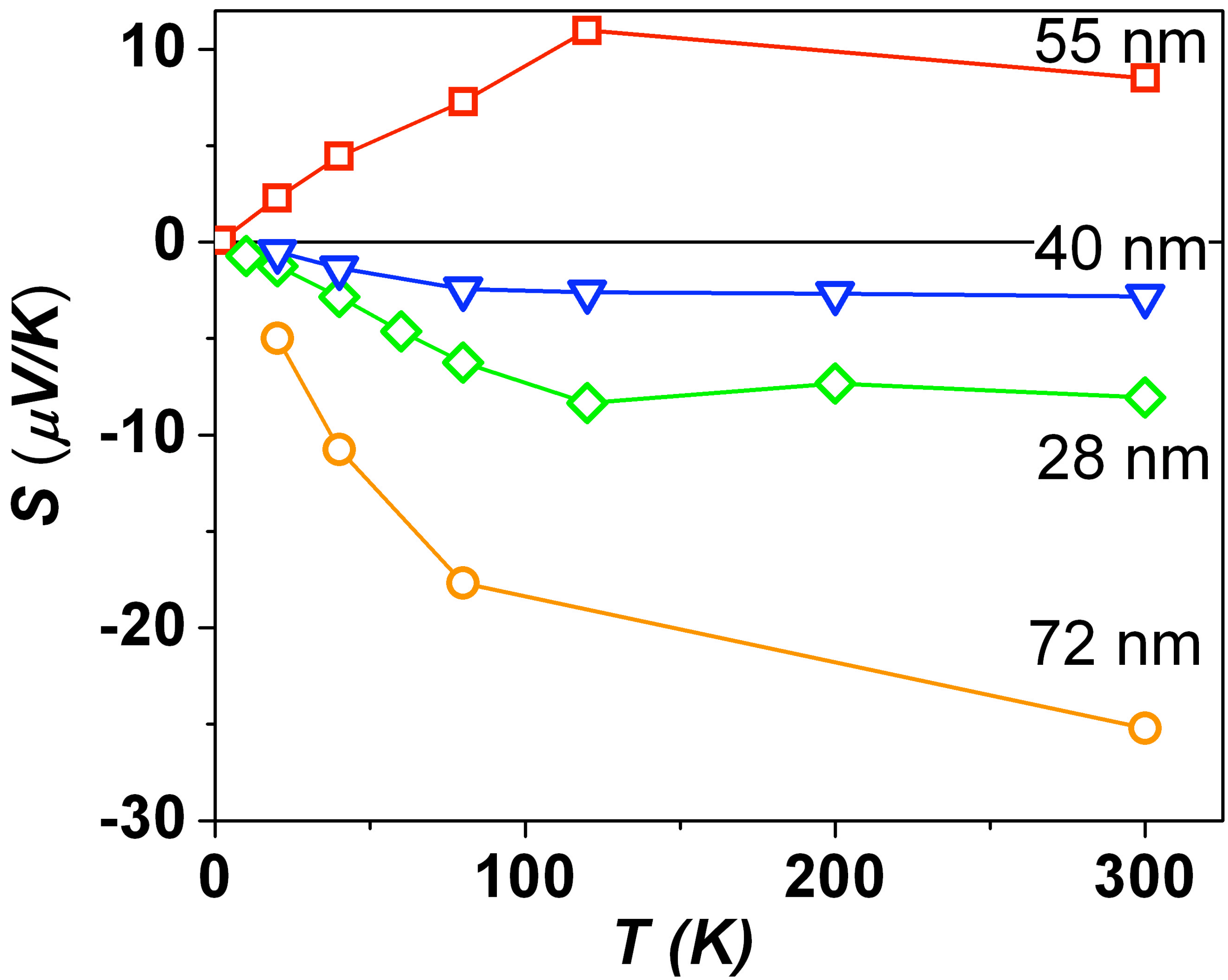
Ω/K

Measuring ΔT

Multiply: $$\frac{V}{W}\times\frac{W}{\Omega}\times\frac{\Omega}{K}$$



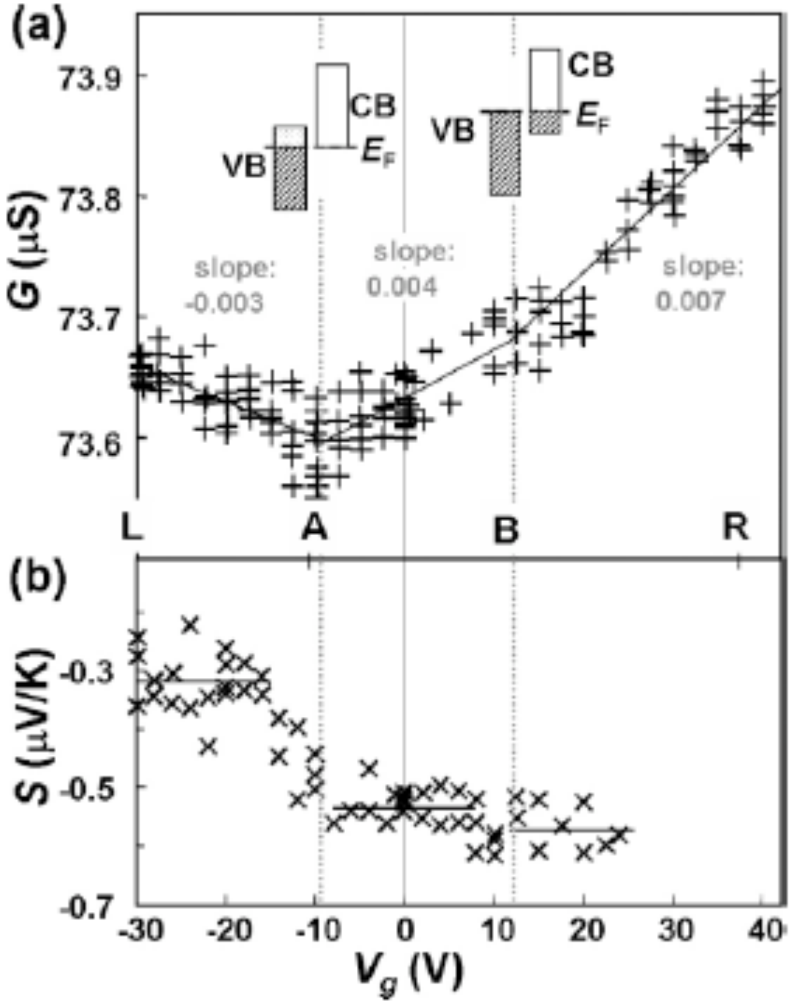
Bi Nanowire Thermopower Results



A. Boukai, K. Xu, J.R. Heath, *Advanced Materials* 18, 864-869 2006

Surface States Dominate Carrier Transport

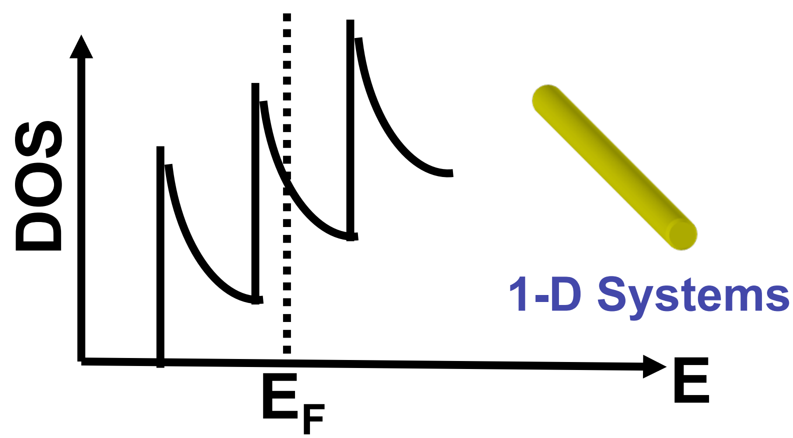
40nm wide Bi wire at 20K Results



Our results indicate that surface states dominate the carrier transport

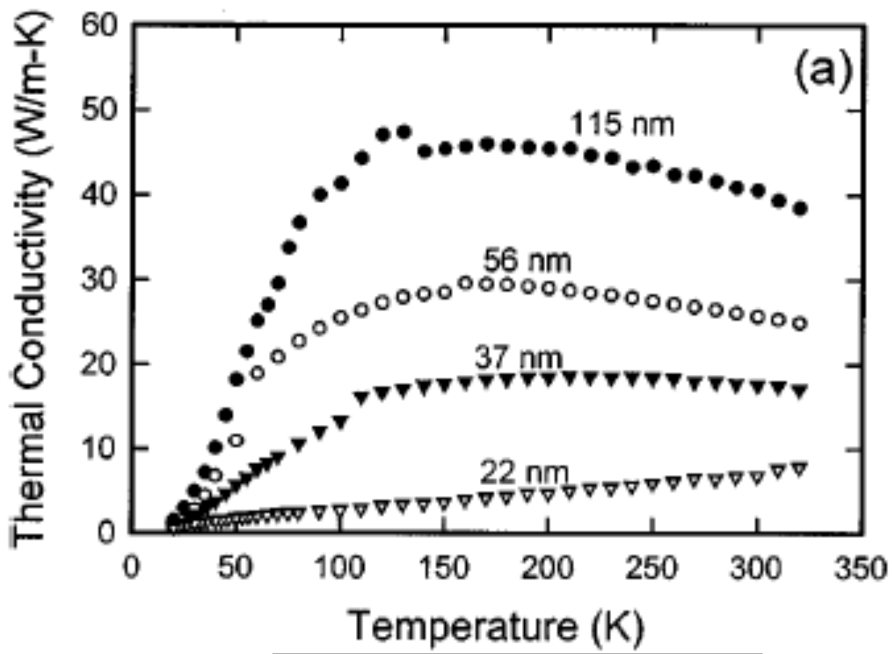
Thermopower is well correlated to Mott diffusion formula

$$S \propto \left.\frac{dN}{dE}\right|_{E_F}$$



And God Said, "Let there be Silicon and it was good."

Chemistry of Si is well understood
+50 years of Silicon R&D

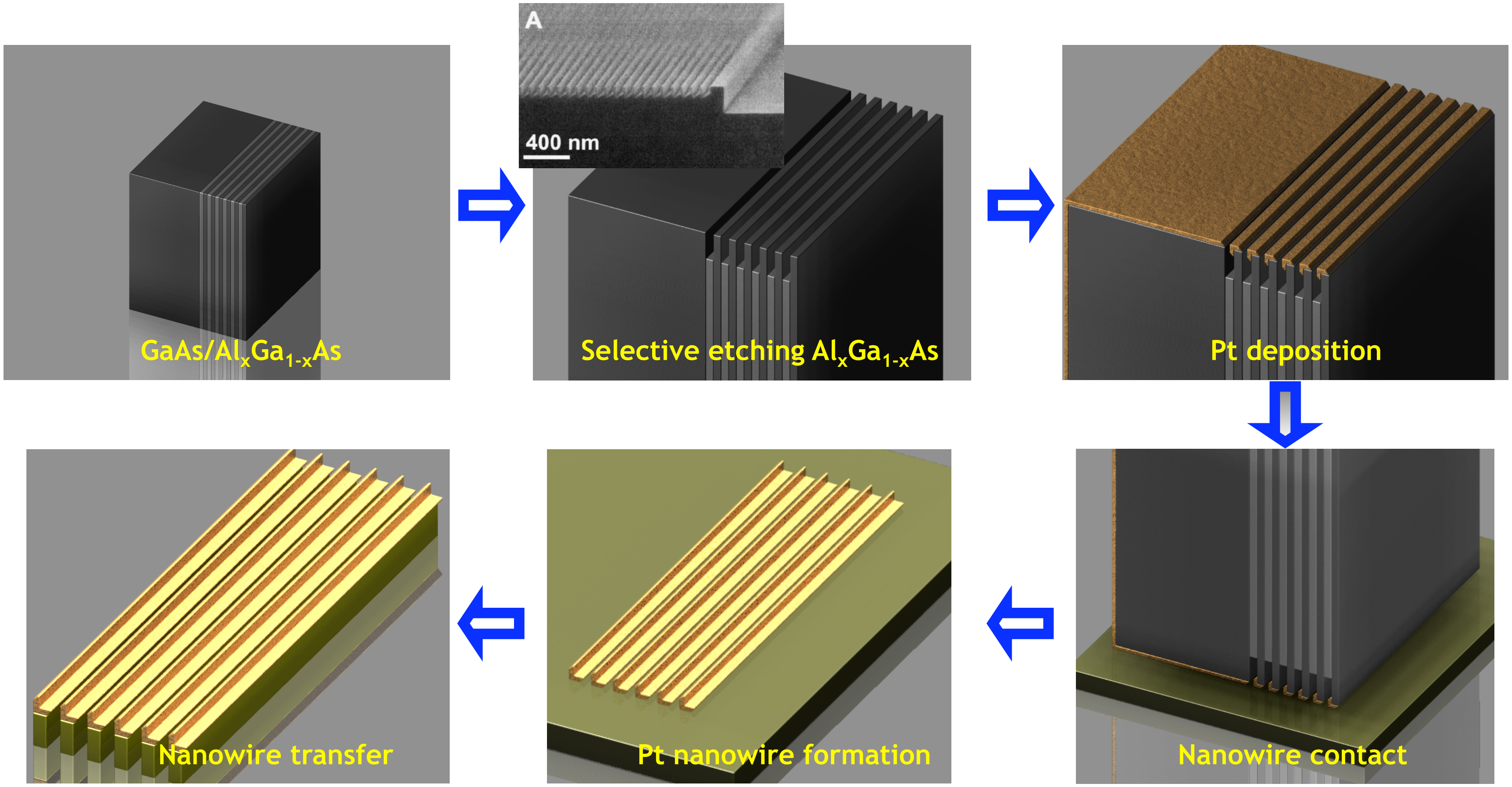


D. Li, et al. *APL* 83, 2935 2003

κ for bulk Si is ~150 W/(m-K) @300K

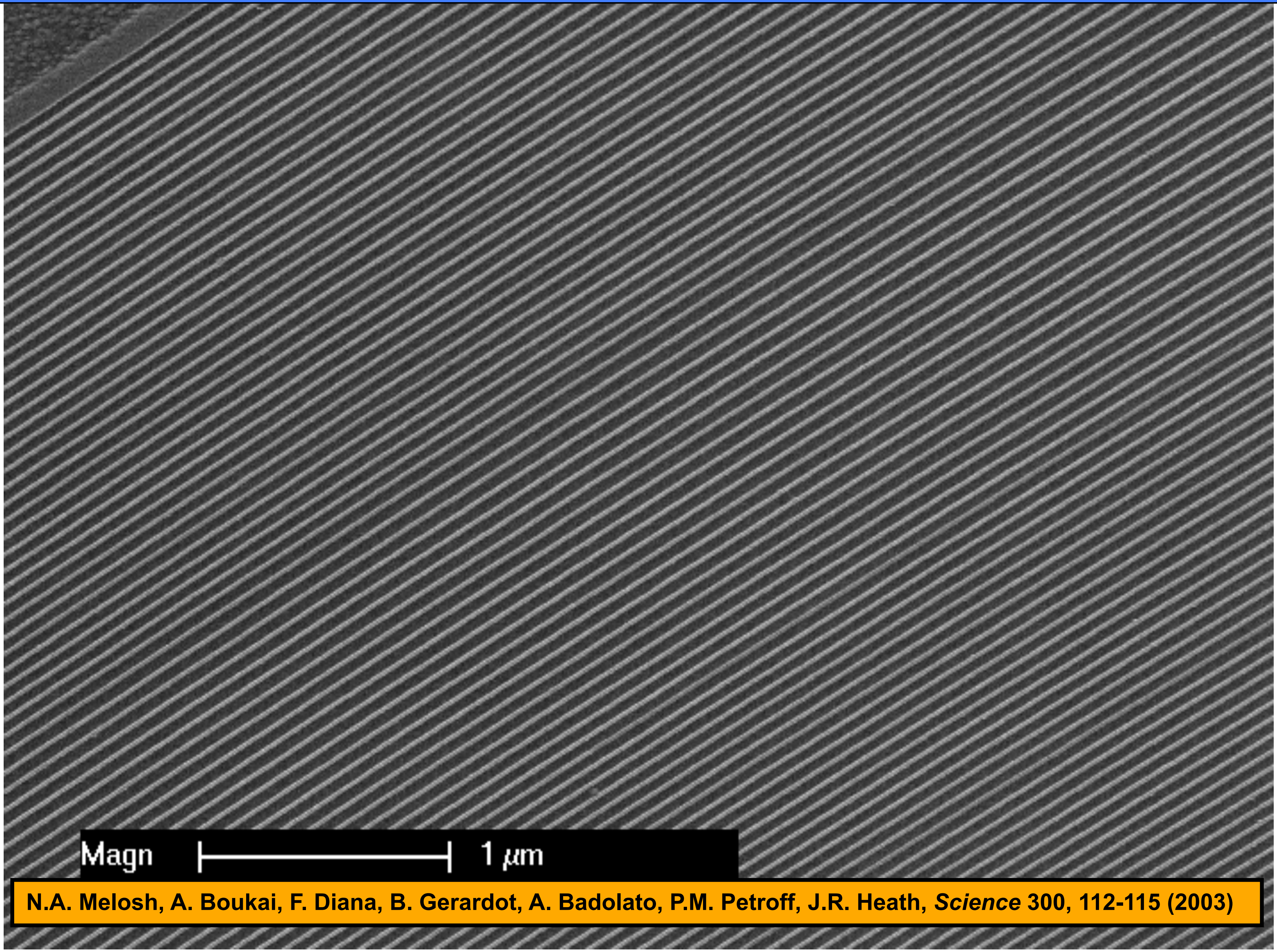
With SNAP, we have control over wire width, doping, crystal orientation, etc.

Superlattice Nanowire Pattern Transfer (SNAP)



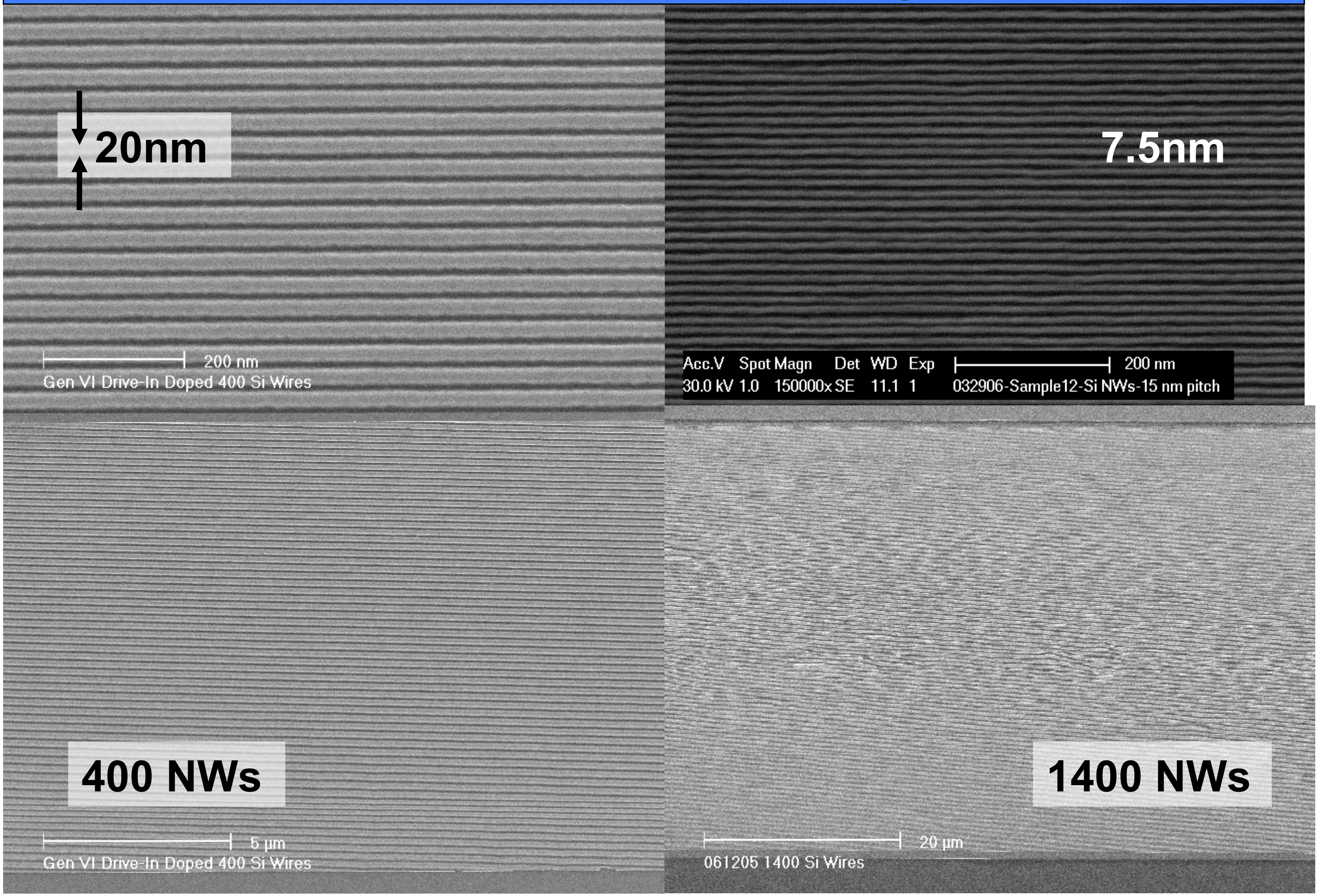
N.A. Melosh, A. Boukai, F. Diana, B. Gerardot, A. Badolato, P.M. Petroff, J.R. Heath, *Science* 300, 112-115 (2003)

Array of Si Nanowires Made With SNAP

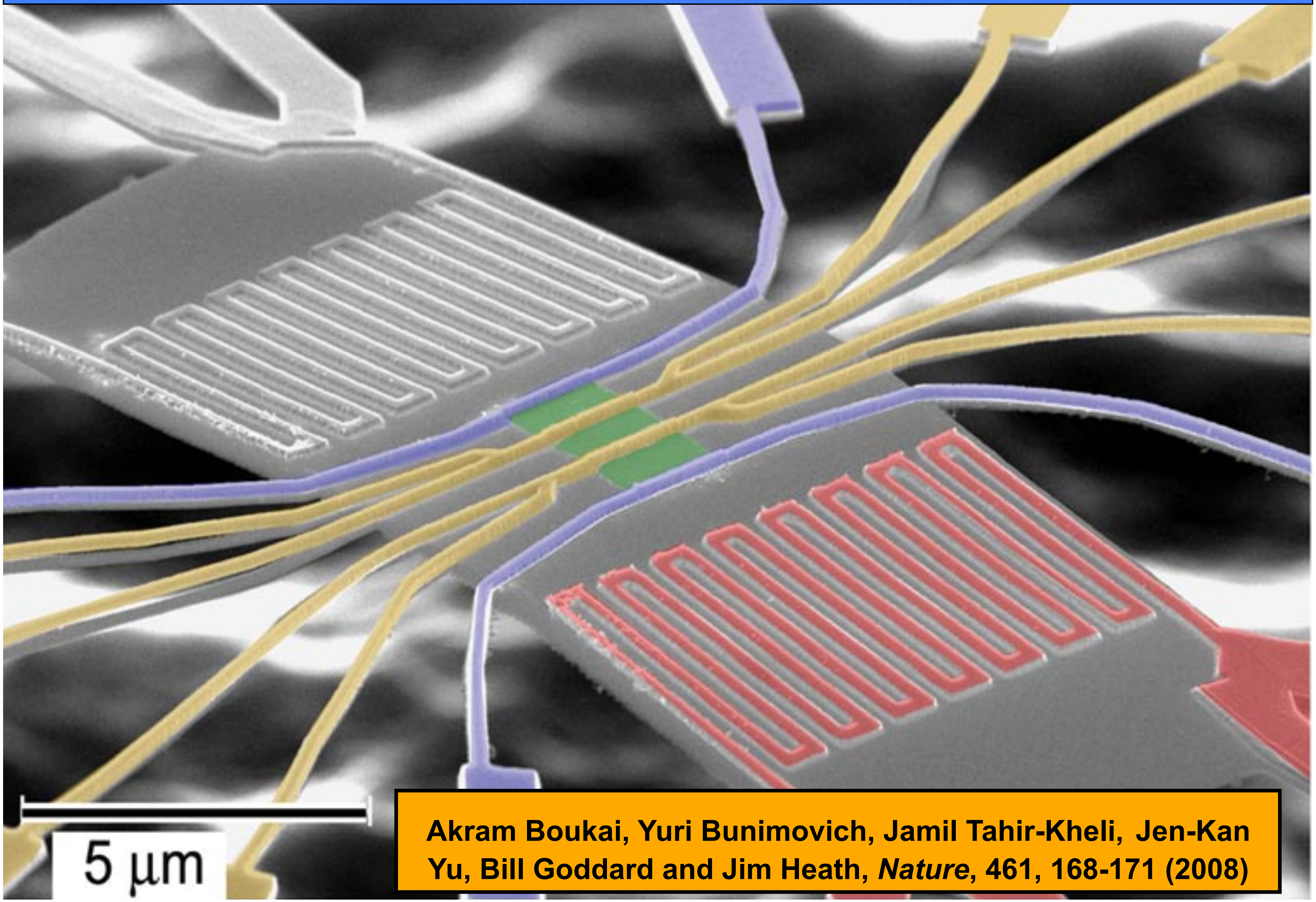


N.A. Melosh, A. Boukai, F. Diana, B. Gerardot, A. Badolato, P.M. Petroff, J.R. Heath, *Science* 300, 112-115 (2003)

SNAP's Versatility

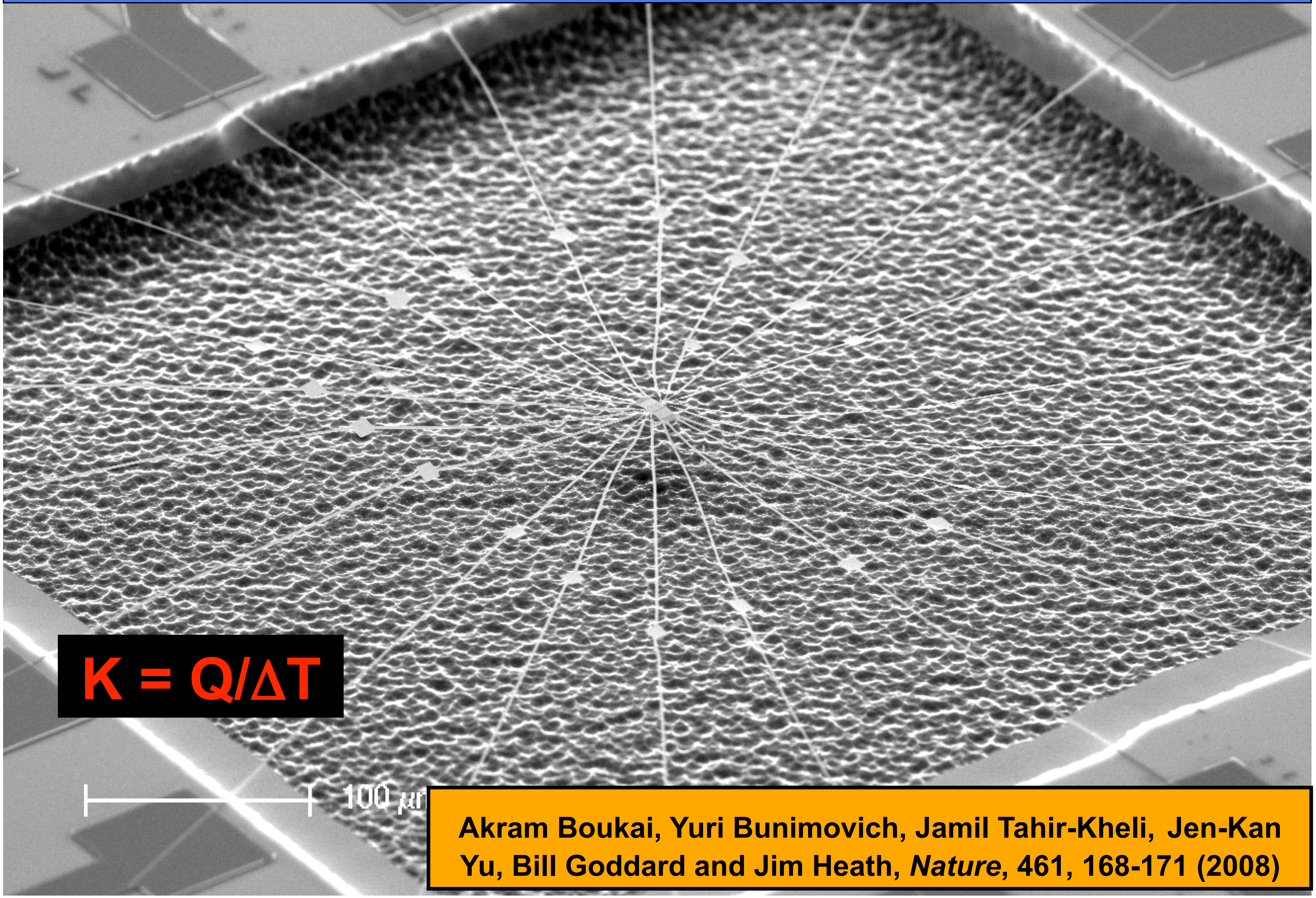


Si Nanowire Thermoelectrics



Akram Boukai, Yuri Bunimovich, Jamil Tahir-Kheli, Jen-Kan Yu, Bill Goddard and Jim Heath, *Nature*, 461, 168-171 (2008)

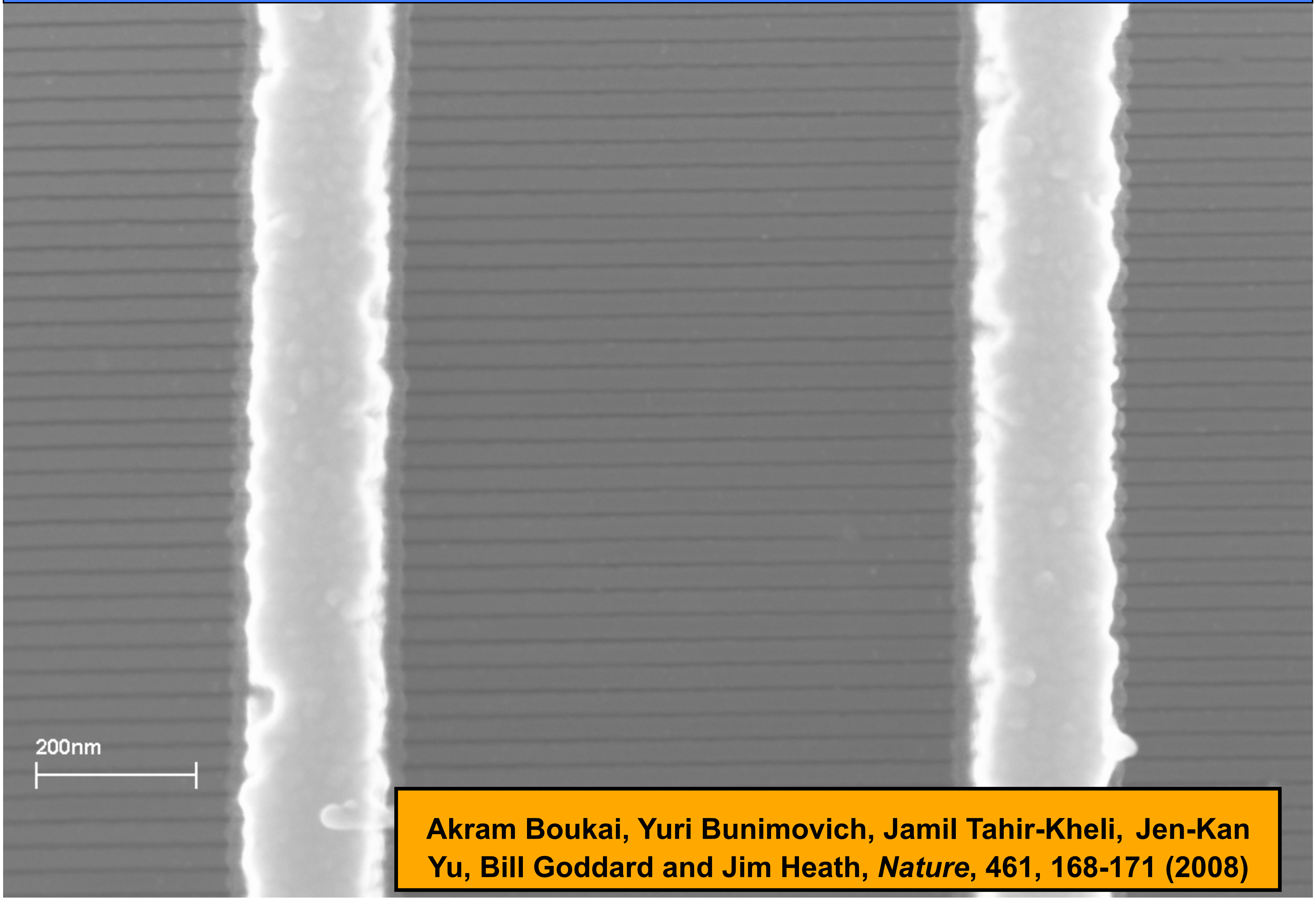
Suspended Platform Allows Measurement of ZT



$K = Q/\Delta T$

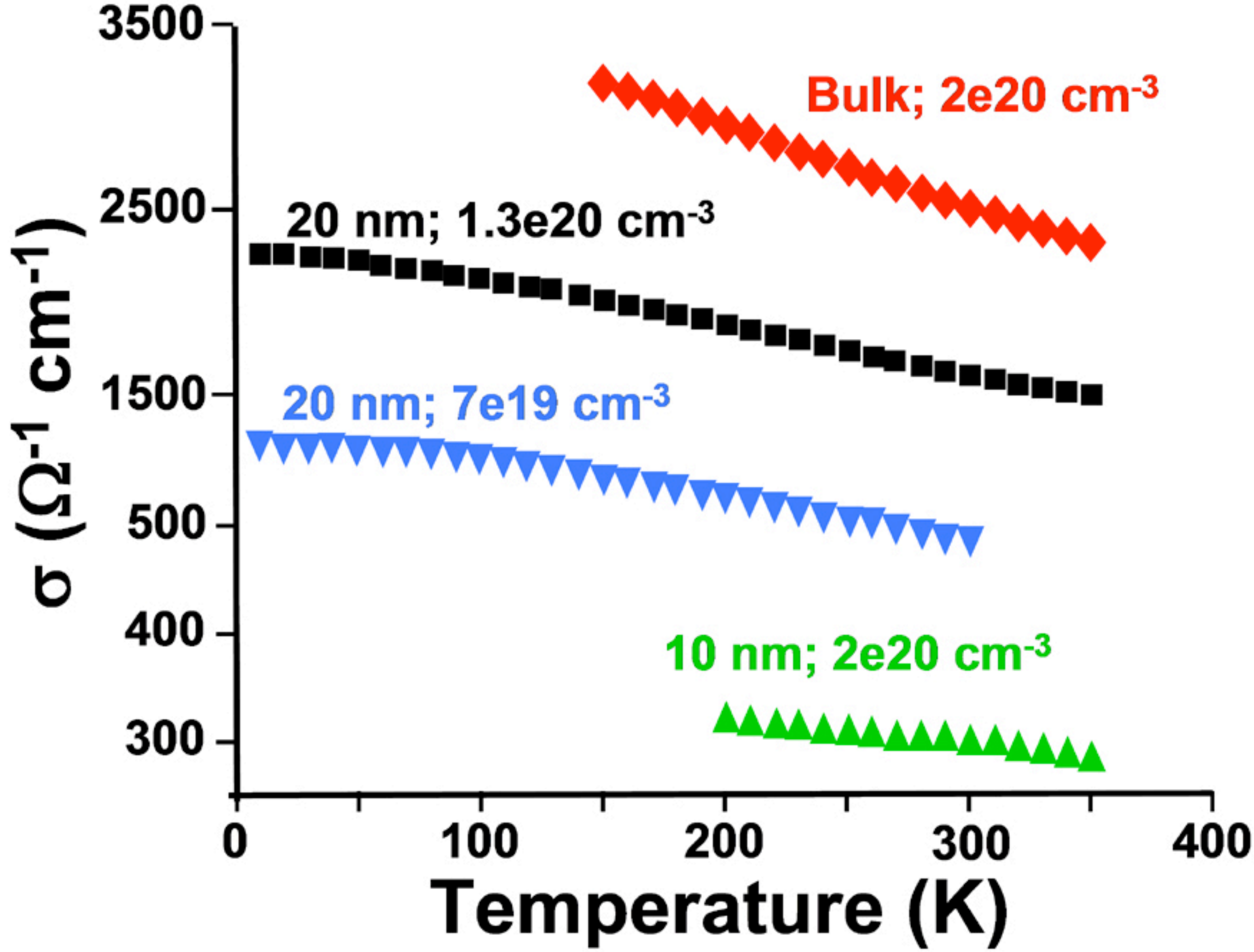
Akram Boukai, Yuri Bunimovich, Jamil Tahir-Kheli, Jen-Kan Yu, Bill Goddard and Jim Heath, *Nature*, 461, 168-171 (2008)

Measurements are Taken on an Array of Si NWs

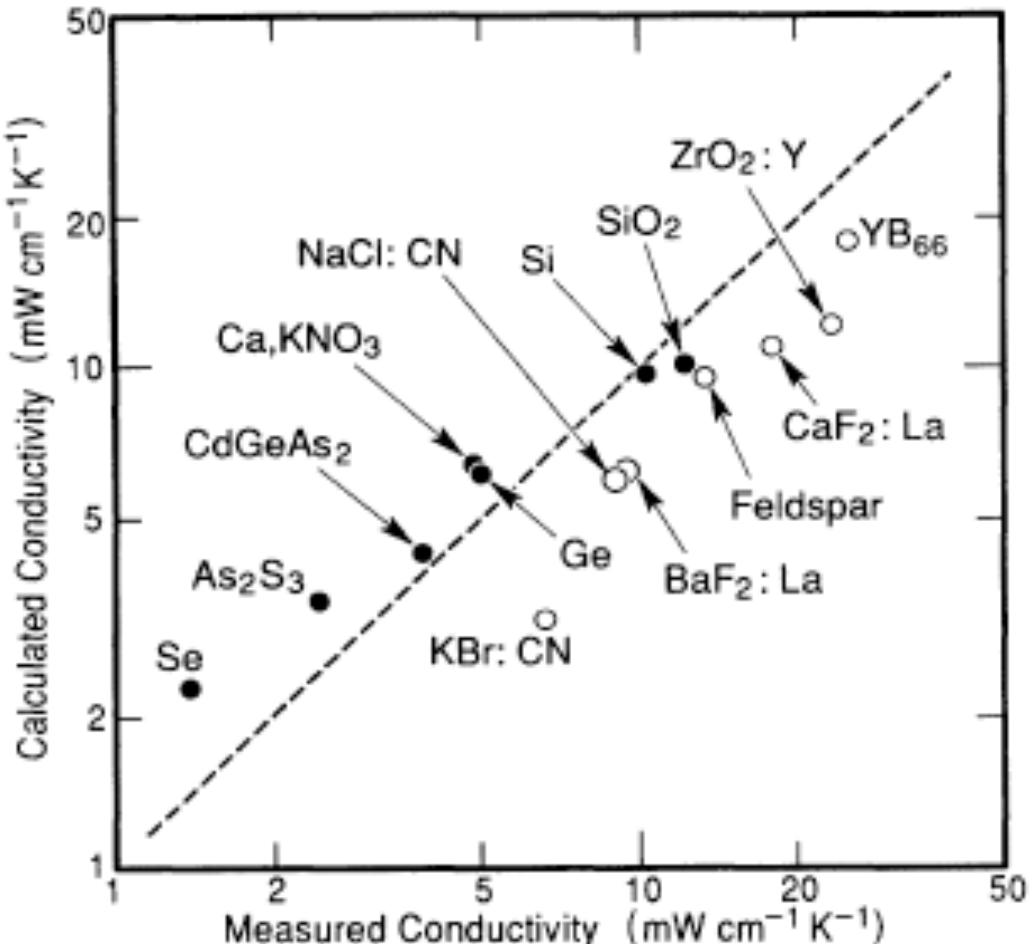


Akram Boukai, Yuri Bunimovich, Jamil Tahir-Kheli, Jen-Kan Yu, Bill Goddard and Jim Heath, *Nature*, 461, 168-171 (2008)

Si Nanowire Electrical Conductivity



Minimum Thermal Conductivity

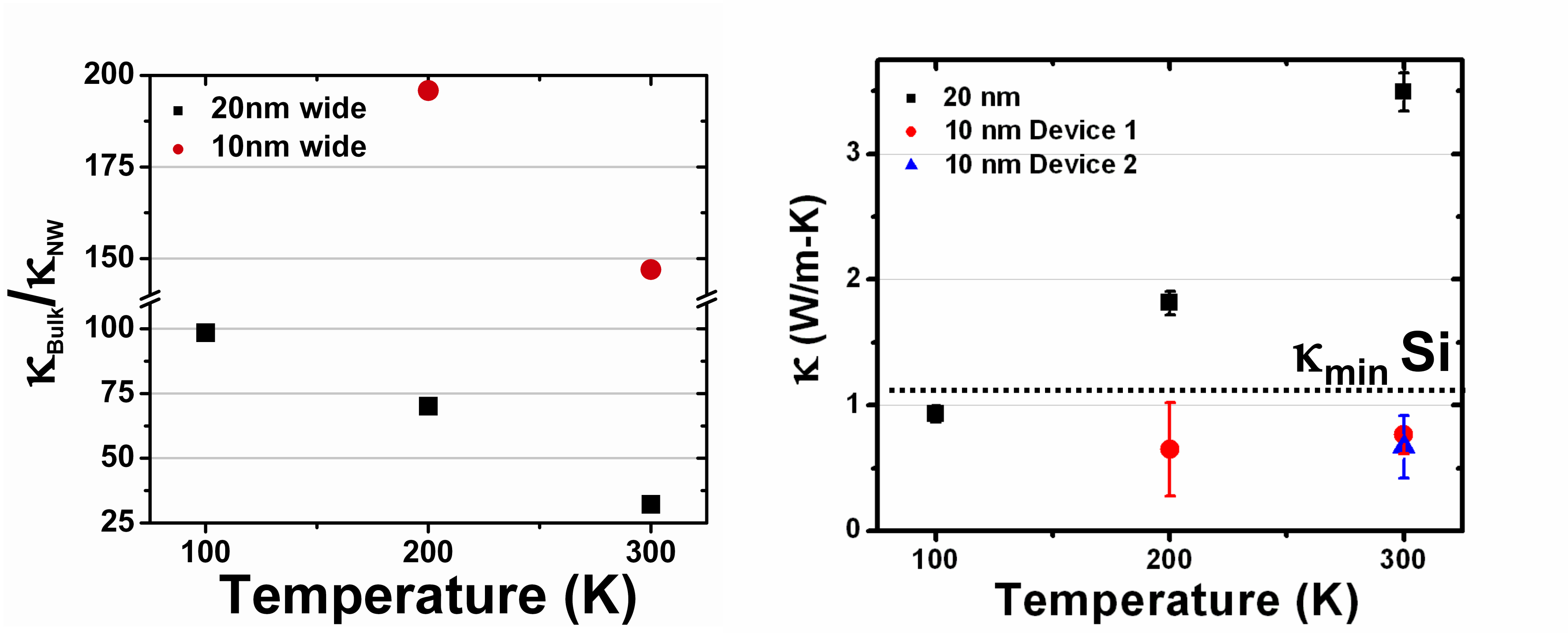


D.G. Cahill, et al. Phys. Rev. B 46, 6131 (1992)

κ_{min} for Si ~ 1 W/(m-K) @300K

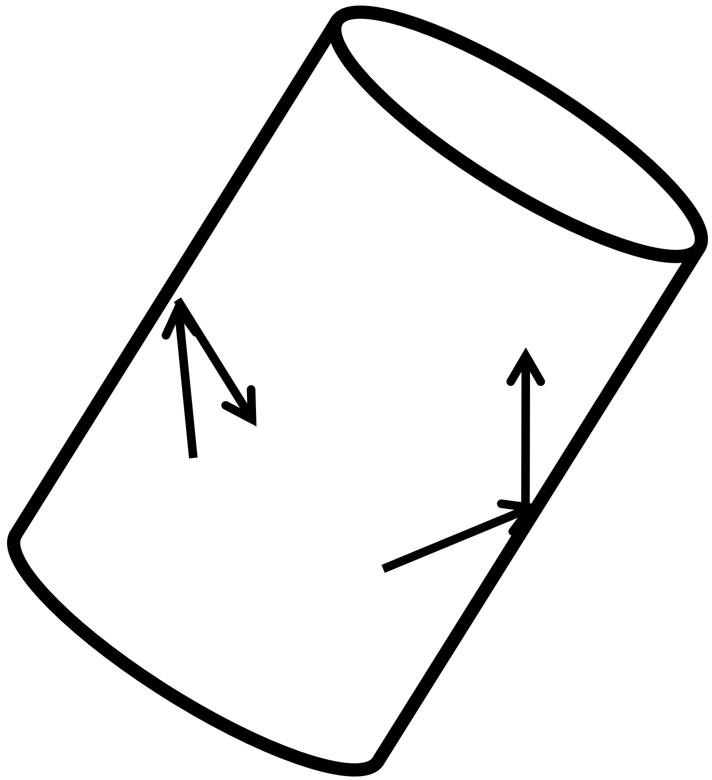
This occurs when Si is amorphous

Si Nanowire Thermal Conductivity

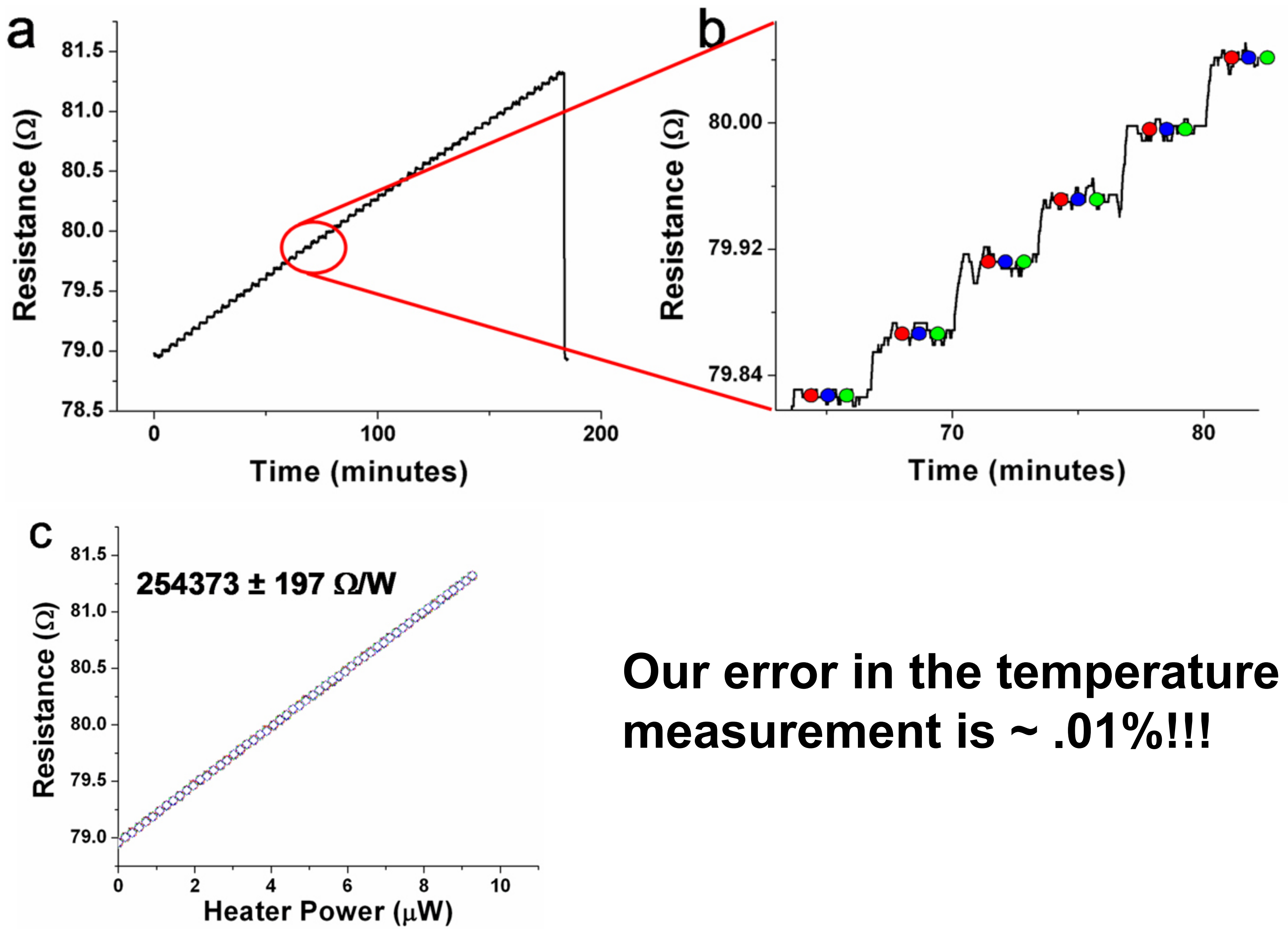


κ for bulk Si is ~150 W/(m-K) @300K

Diffuse vs Specular Scattering

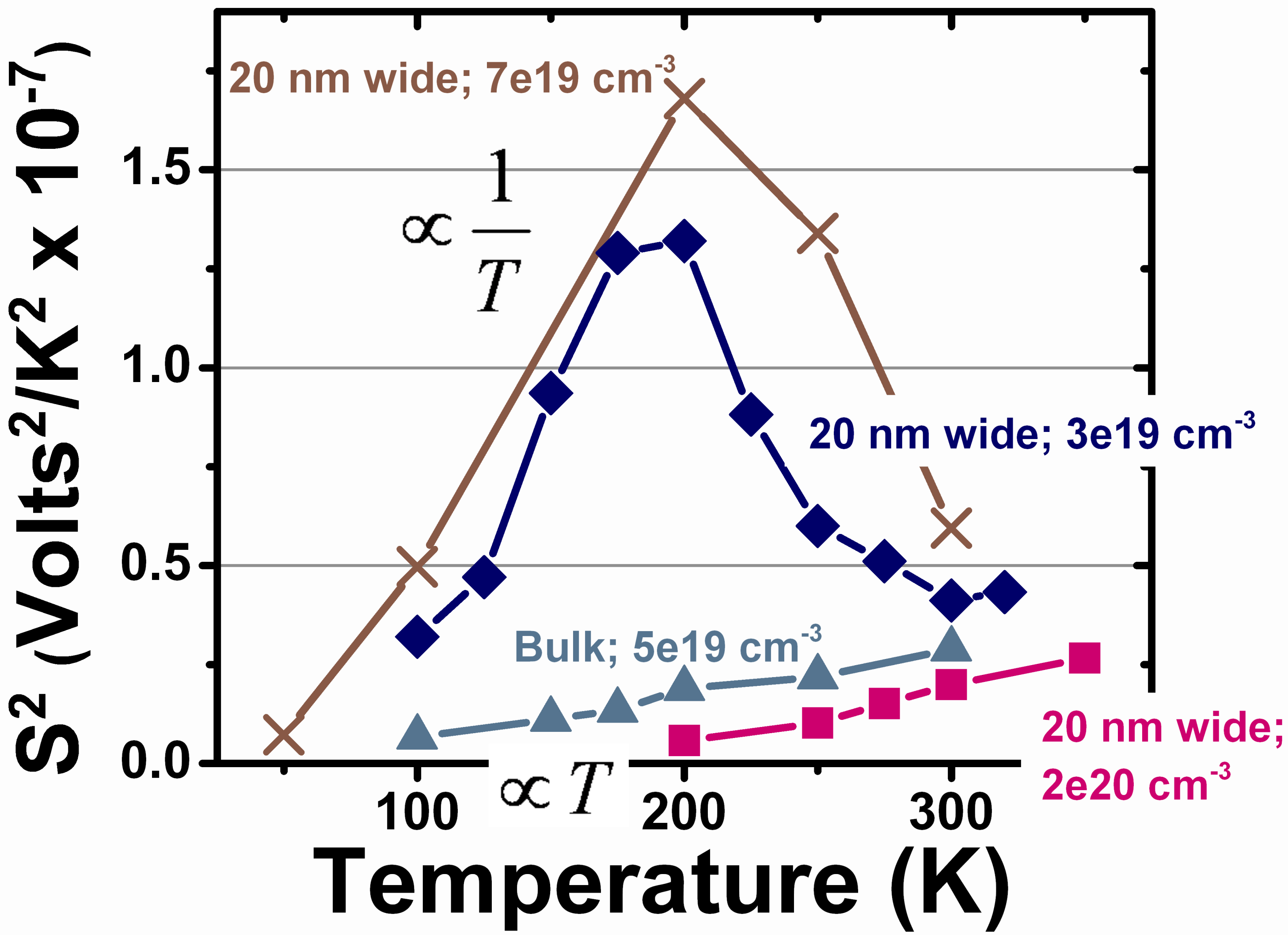


Lots of Data to Minimize Error Bars



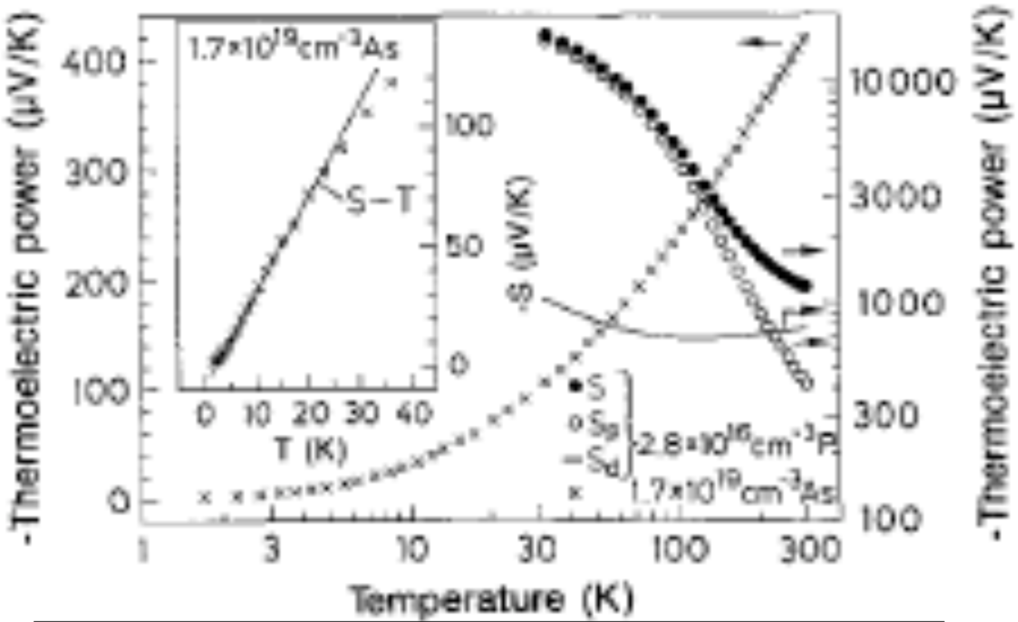
Our error in the temperature measurement is ~ .01%!!!

Si Nanowire Thermopower

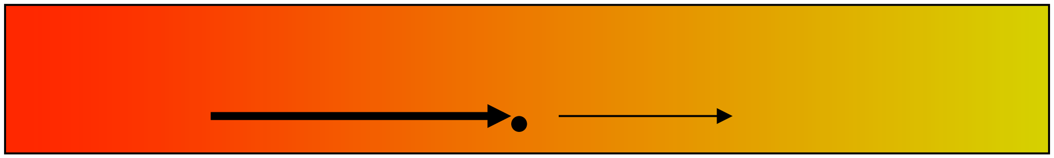


Phonon Drag

Bulk Silicon

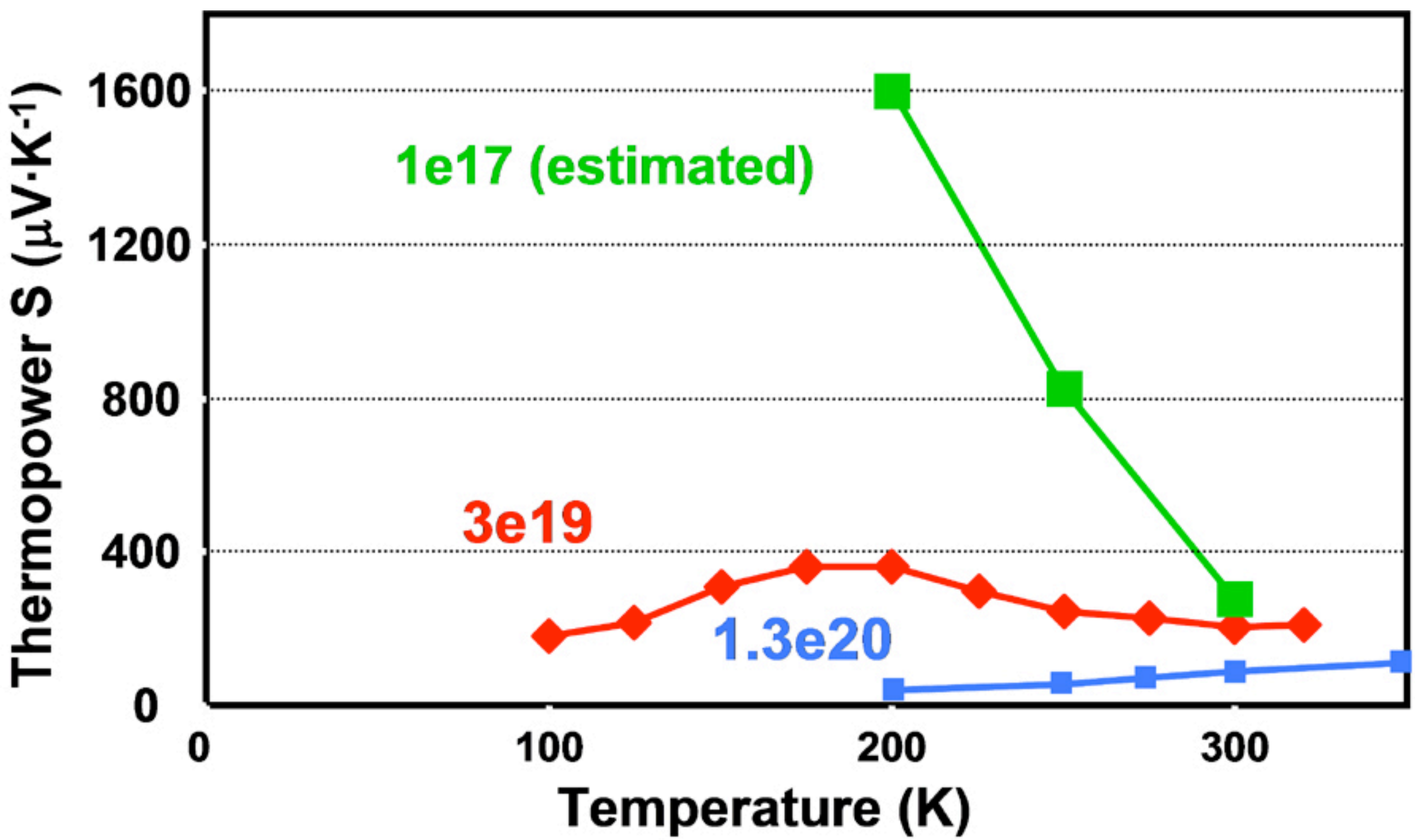


L. Weber, E. Gmelin, *Applied Physics A* 53, 136-140 (1991)

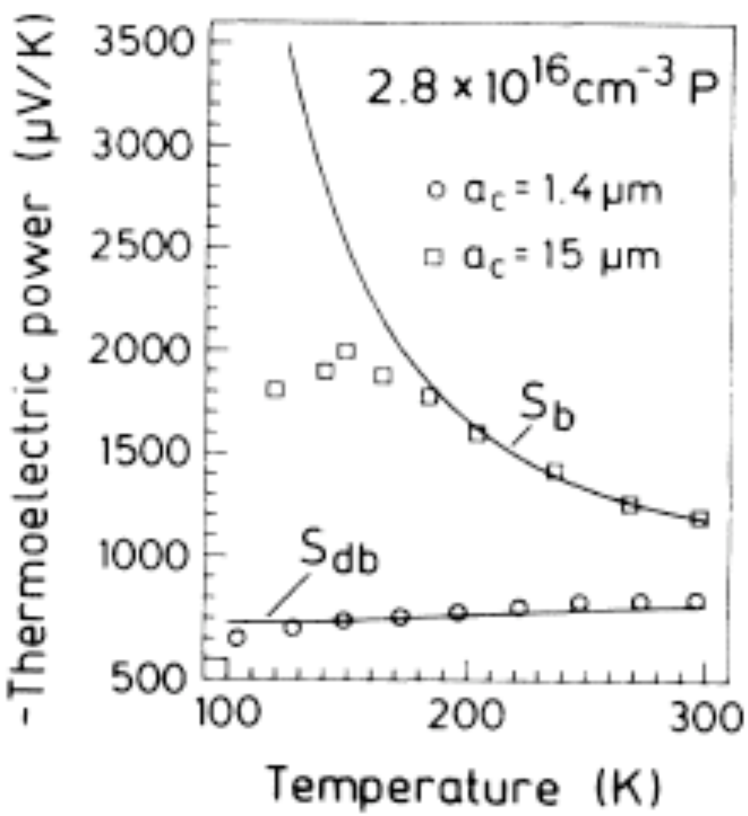


Phonons are not in equilibrium
Longitudinal modes push the electrons down the temperature gradient

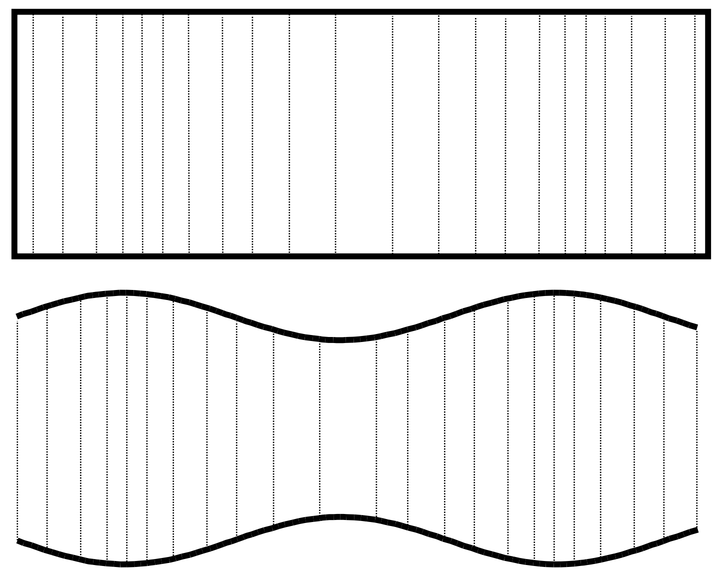
Phonon Drag in Our Si NWs



Phonon Drag is Supposed to Disappear at the Nanoscale

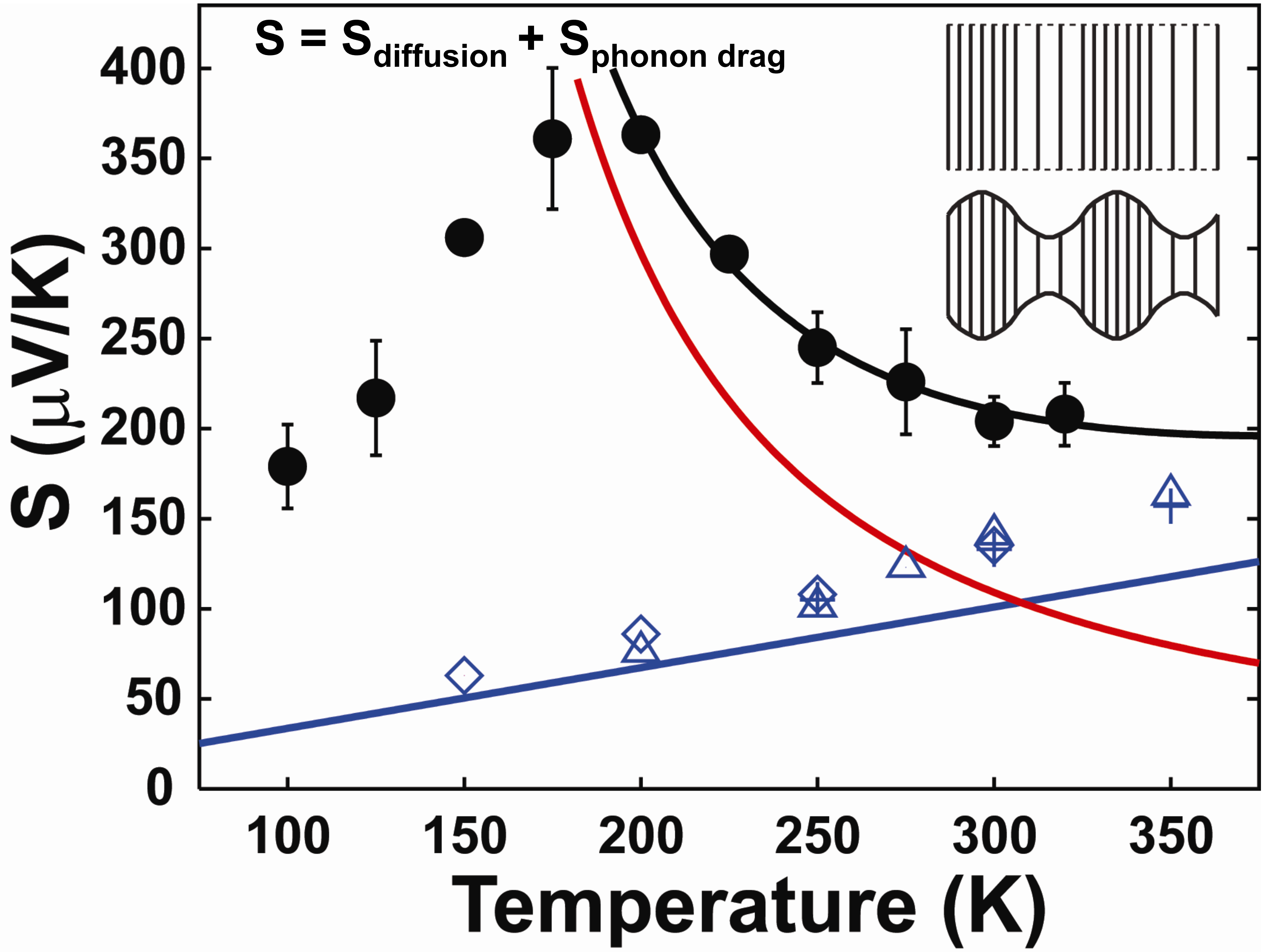


L. Weber, et al. Phys. Rev. B 46, 9511 (1992)



Thank you Jamil and Bill!

Phonon Drag in a 1-D System



Efficient Si Nanowires