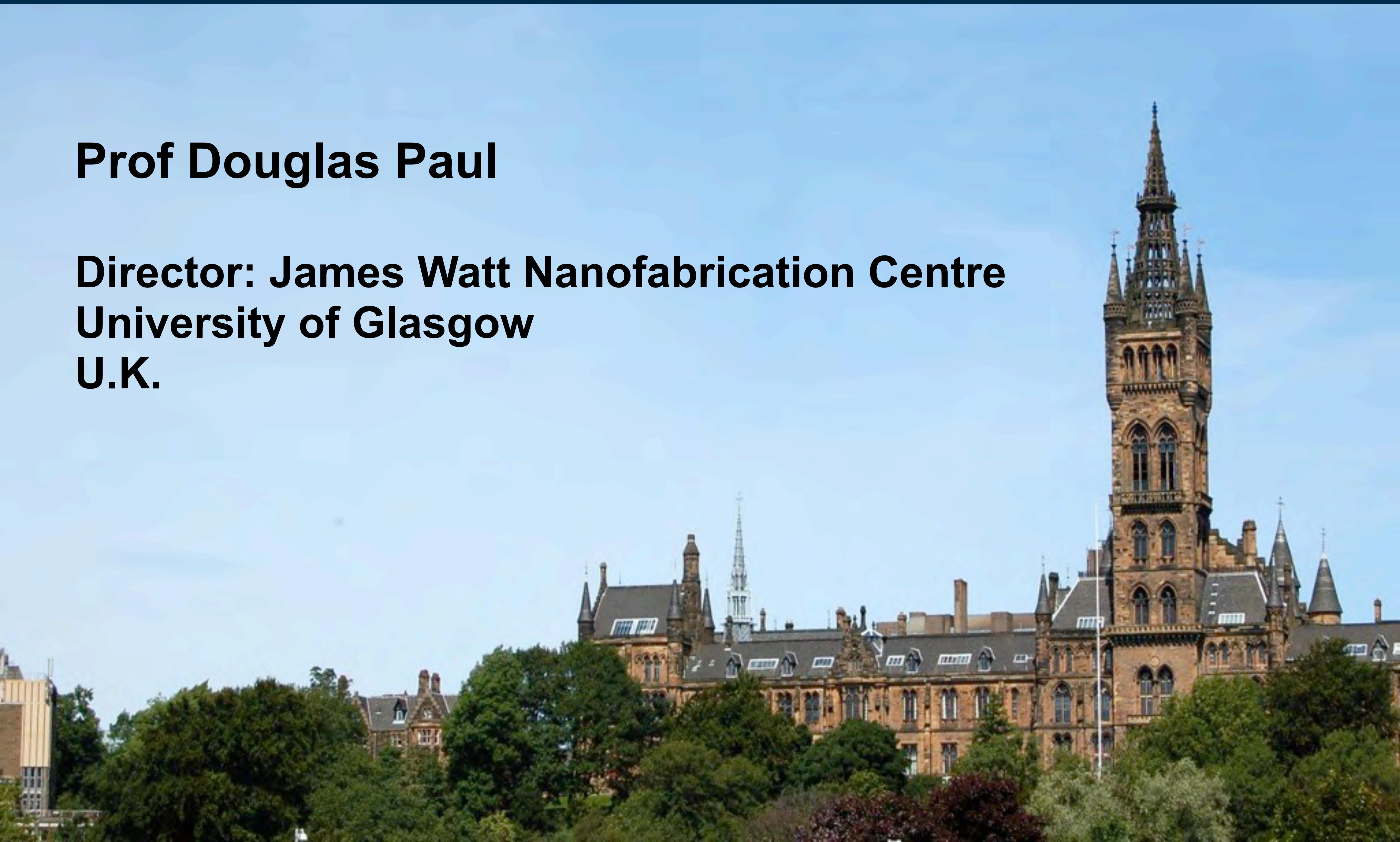
Thermoelectric Energy Harvesting



Prof Douglas Paul

Director: James Watt Nanofabrication Centre
University of Glasgow
U.K.

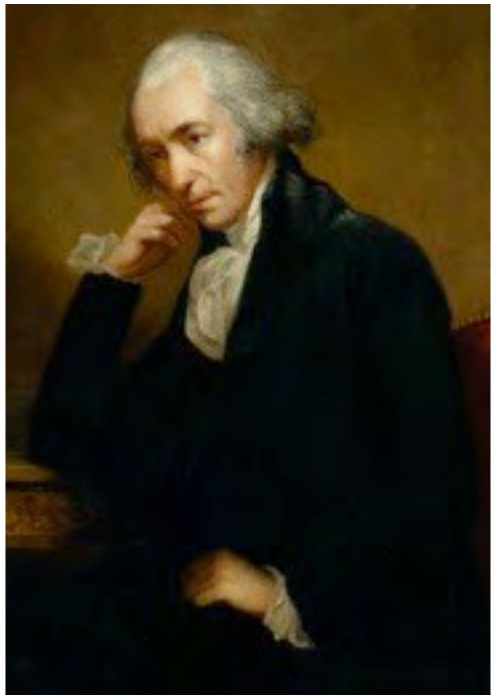
The University of Glasgow

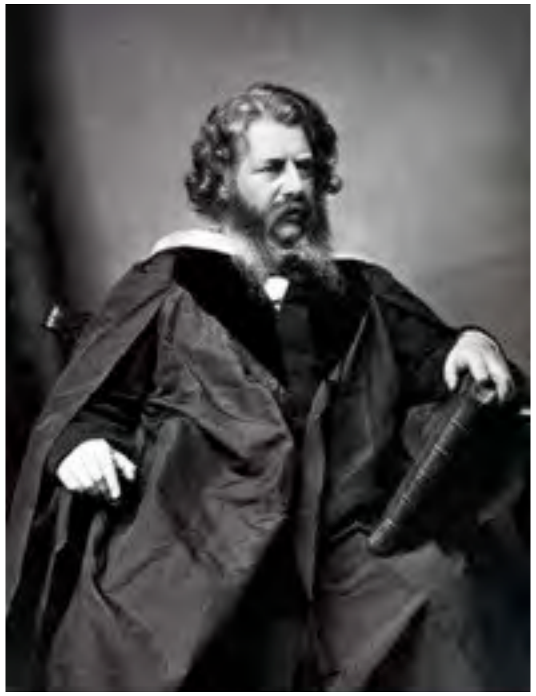
- Established in 1451
- 7 Nobel Laureates, 2 SI units, ultrasound, television, etc......
- 16,500 undergraduates, 5,000 graduates and 5,000 adult students
- £186M research income pa

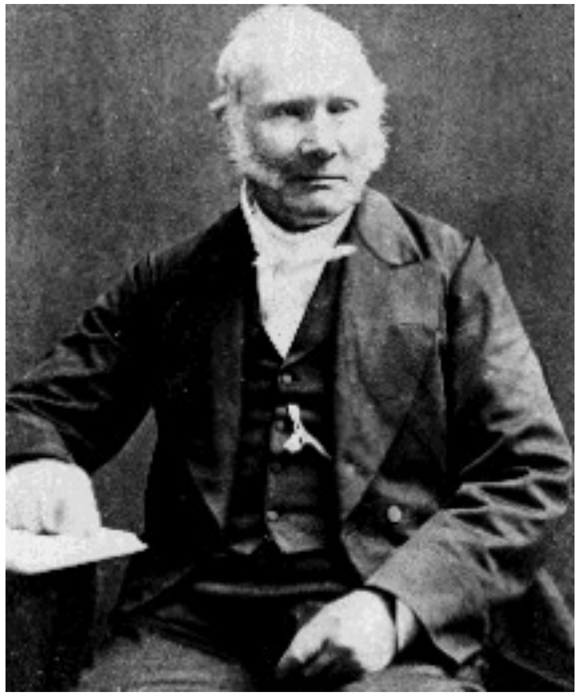
- 400 years in High Street
- Moved to Gilmorehill in 1870
- Neo-gothic buildings by Gilbert Scott

Famous Glasgow Scholars


William Thomson (Lord Kelvin)


James Watt


William John Macquorn Rankine


Rev Robert Stirling


Rev John Kerr


Joseph Black


John Logie Baird


Adam Smith

James Watt Nanofabrication Centre @Glasgow

Vistec VB6

E-beam lithography

Süss MA6 optical lith

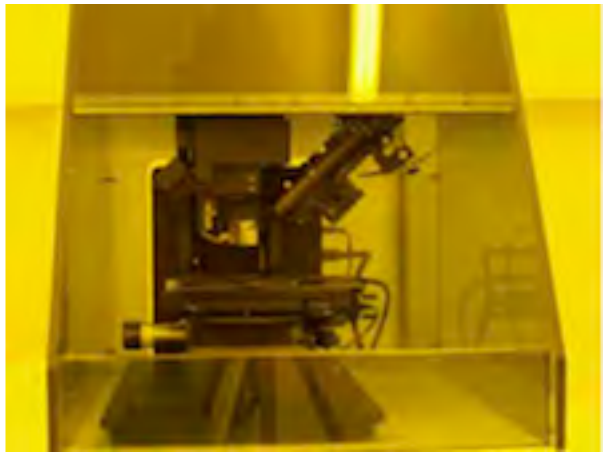
- 900 m^2 cleanroom - pseudo-industrial operation
- 14 technicians + 4 PhD research technologists
- Processes include: MMICs, III-V, Si/SiGe/Ge, integrated photonics, metamaterials, MEMS (microfluidics)
- Part of EPSRC III-V National Facility & STFC Kelvin-Rutherford Facility
- Commercial access through Kelvin NanoTechnology
- http://www.jwnc.gla.ac.uk/

14 RIE / PECVD / ALD

6 Metal dep tools

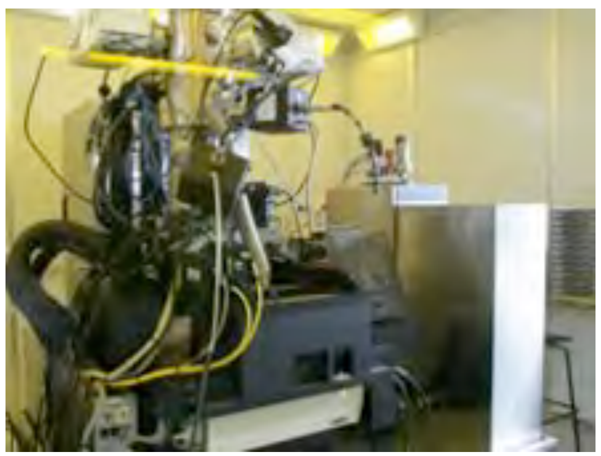
4 SEMs: Hitachi S4700

Veeco: AFMs



Electron Beam Lithography Capability

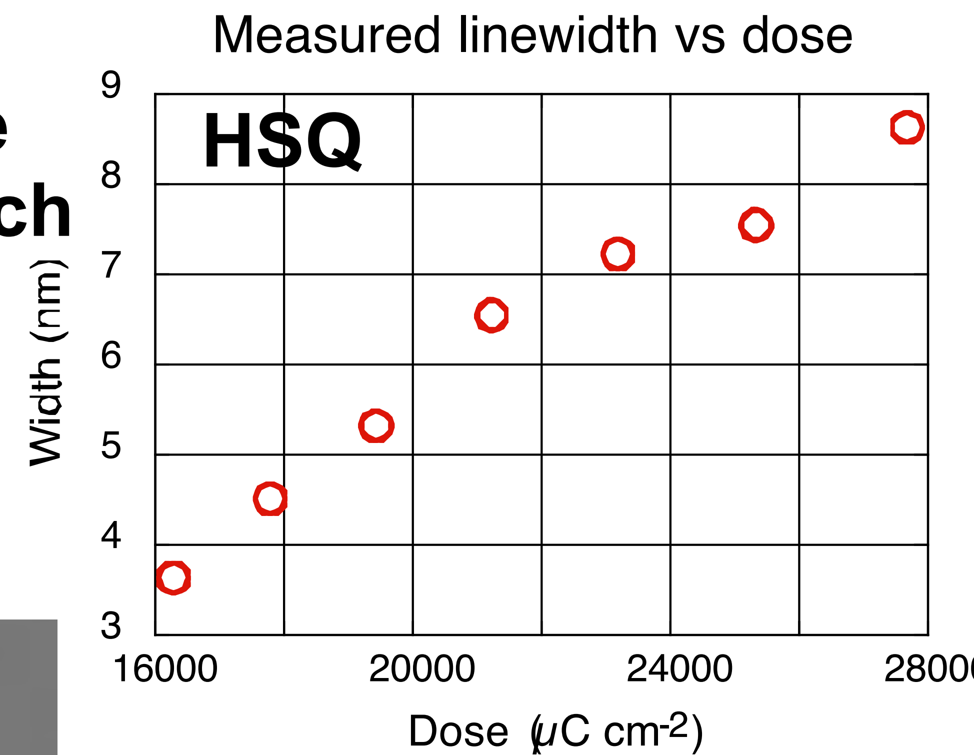
30 years experience of e-beam lithography

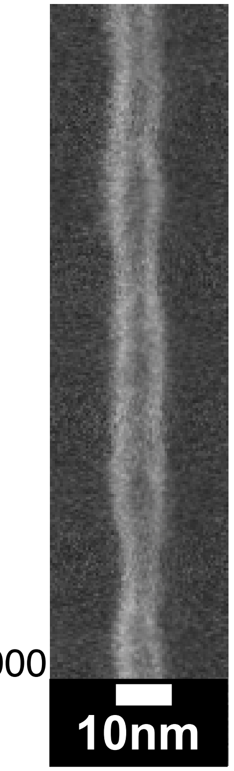


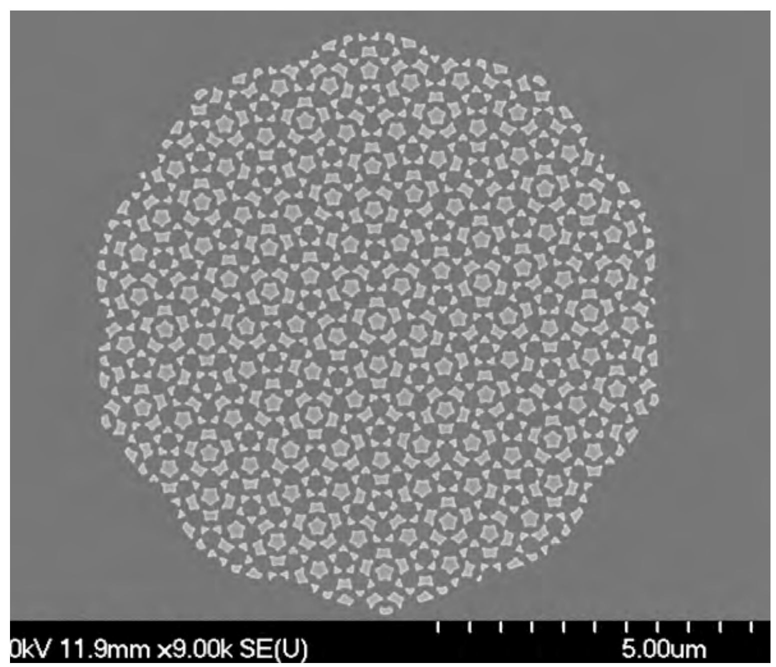
Vistec VB6

Vistec EBPG5

Sub-5 nm single-line lithography for research



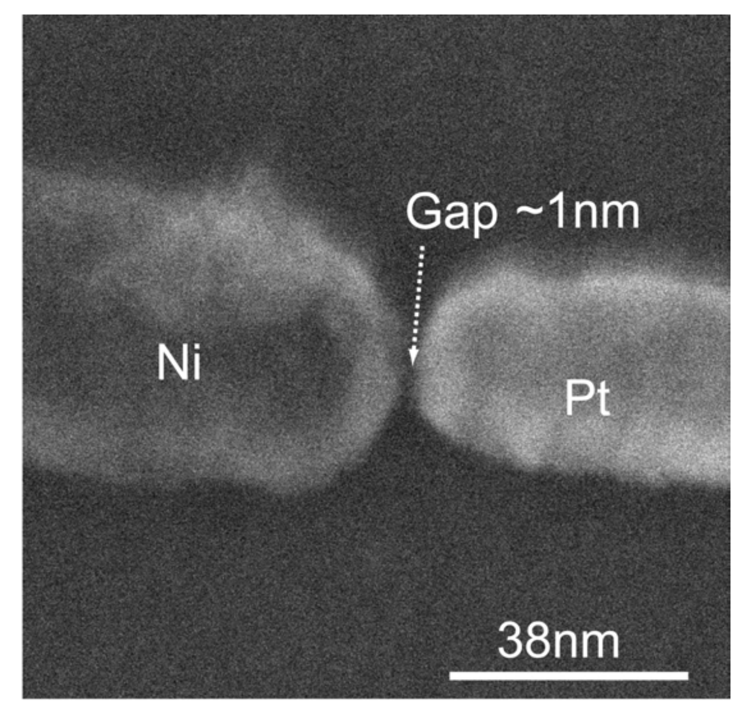




Penrose tile: layer-to-layer alignment 0.46 nm rms

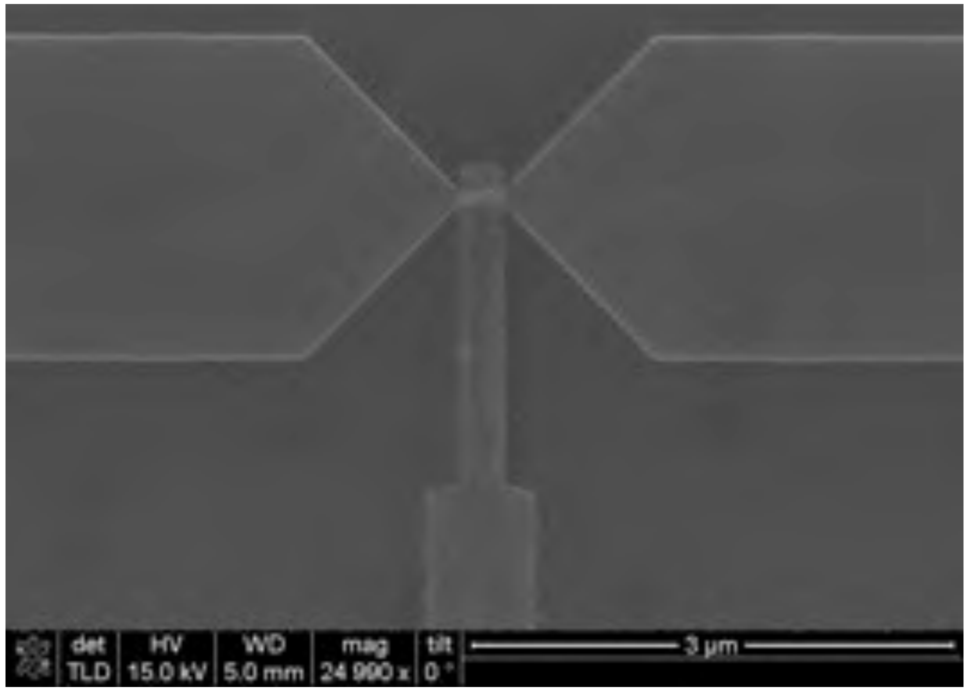
Alignment allows 1 nm gaps between different layers:

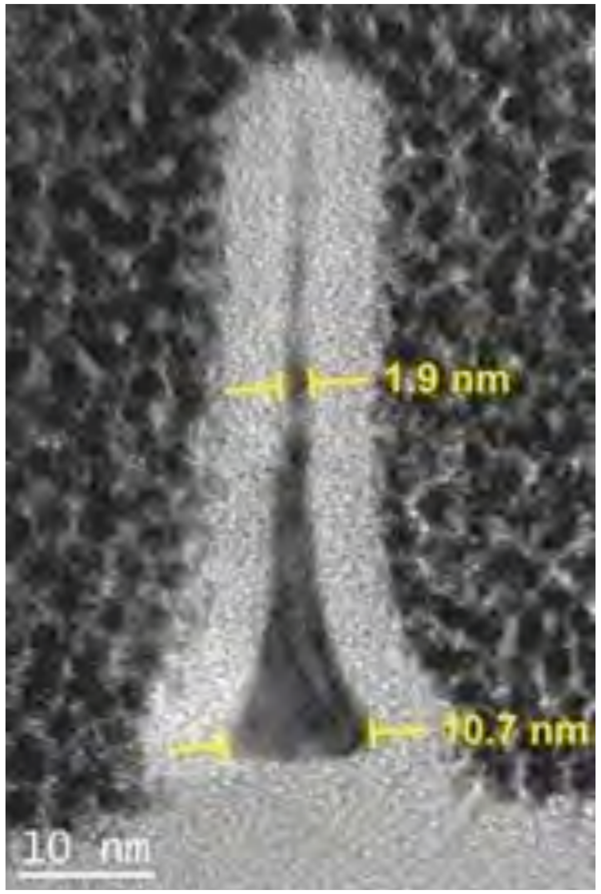
–> nanoscience: single molecule metrology

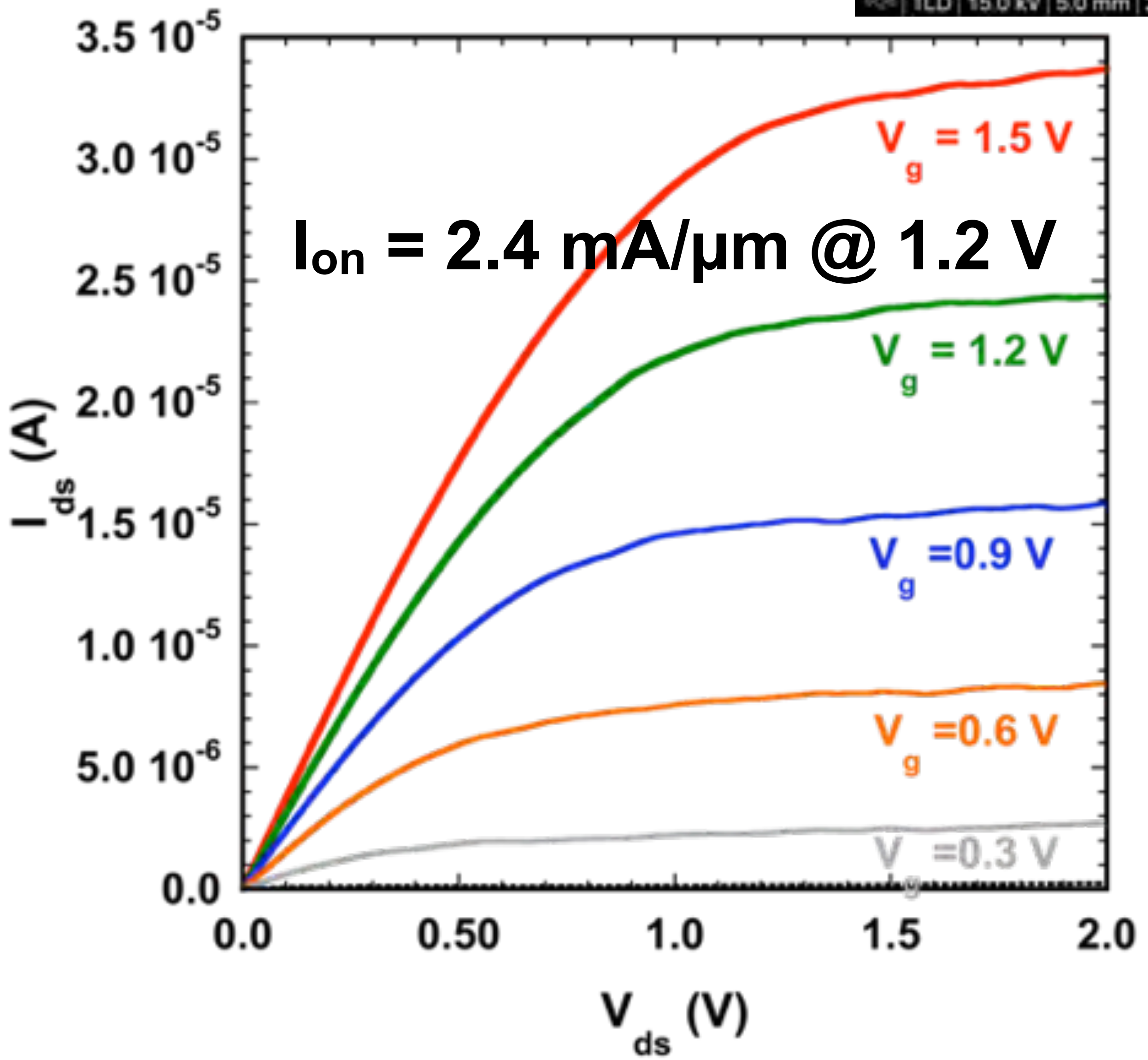


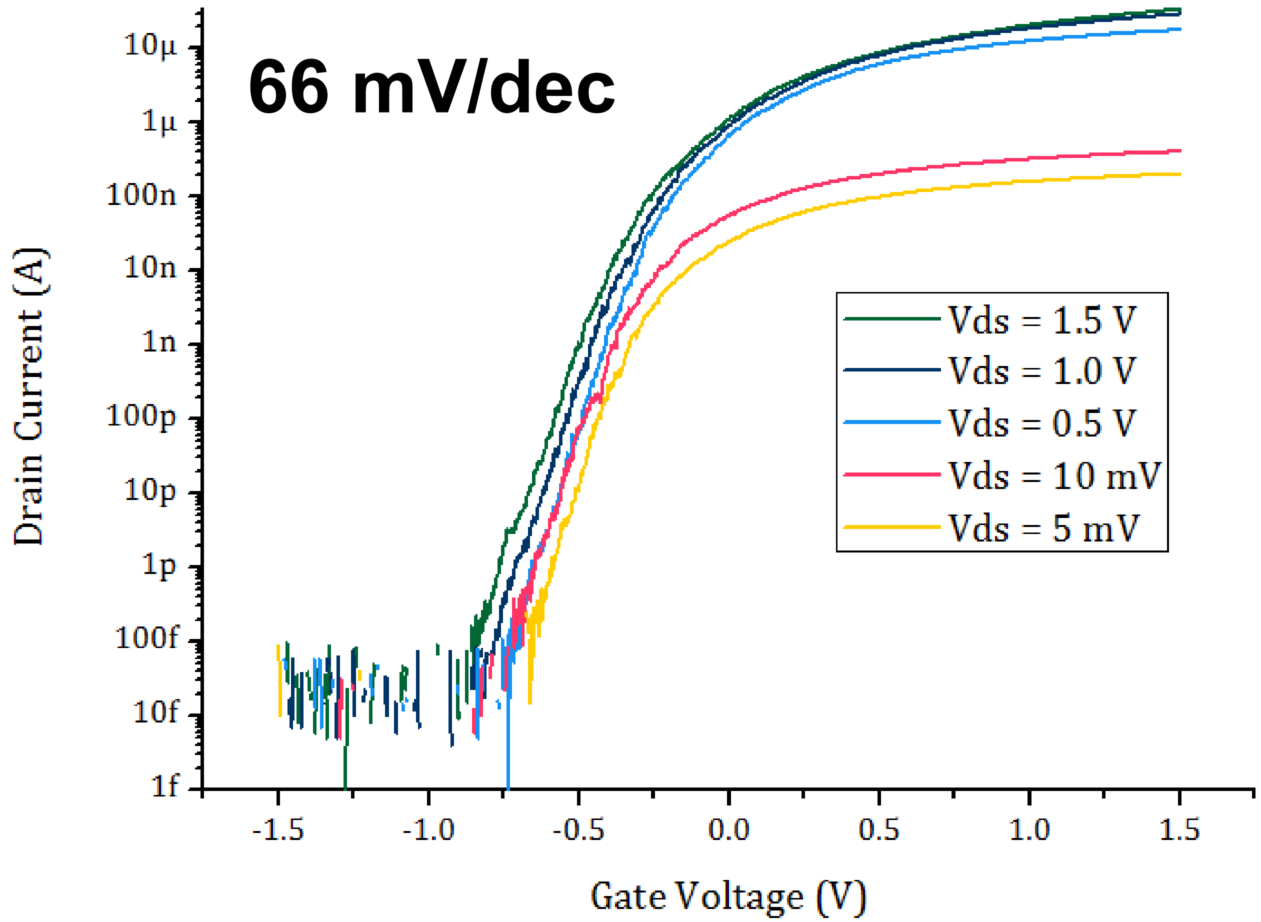
10 nm Width Si Nanowire FET

200 nm gate length
10 nm wide,
50 nm tall nanowire



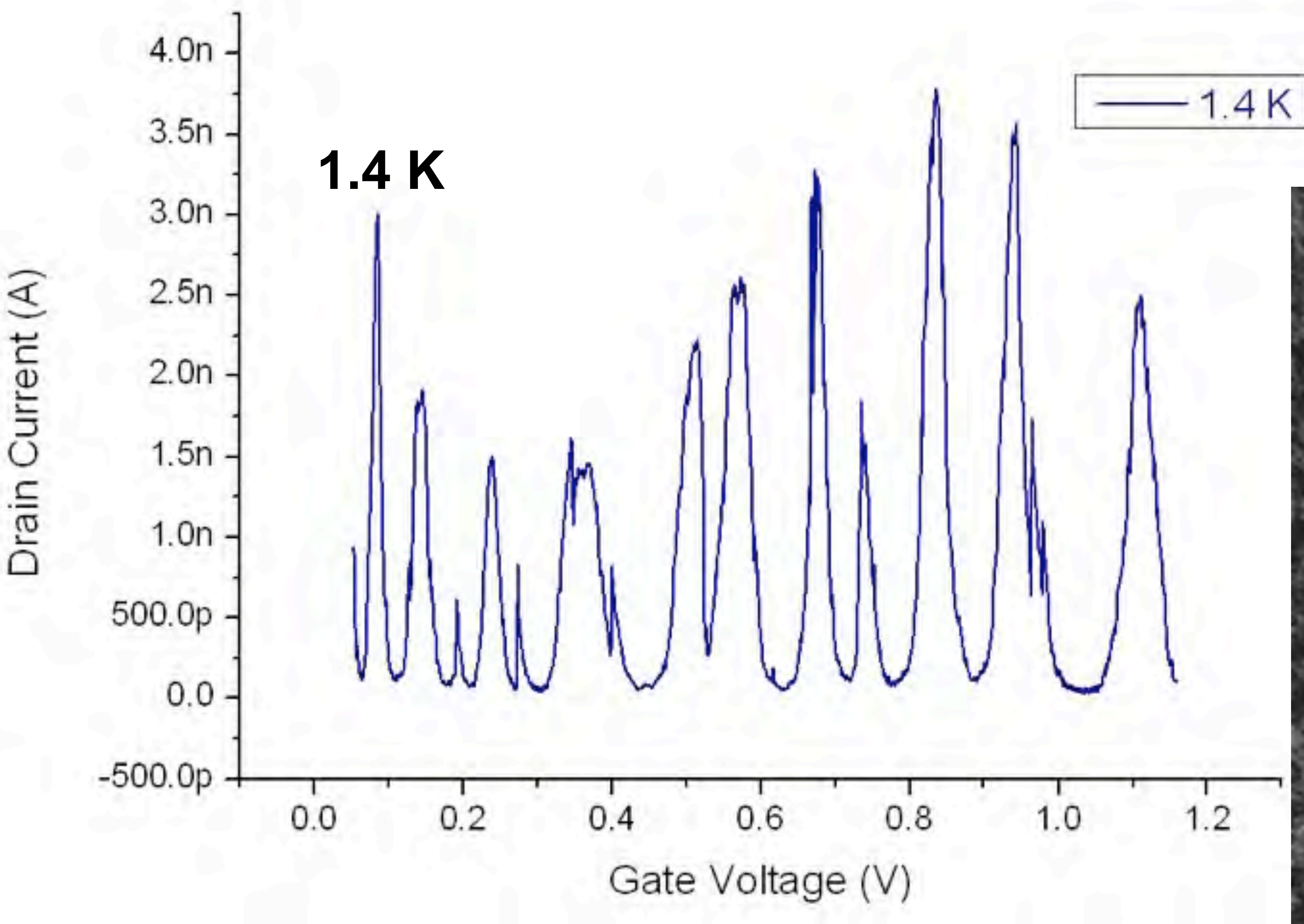


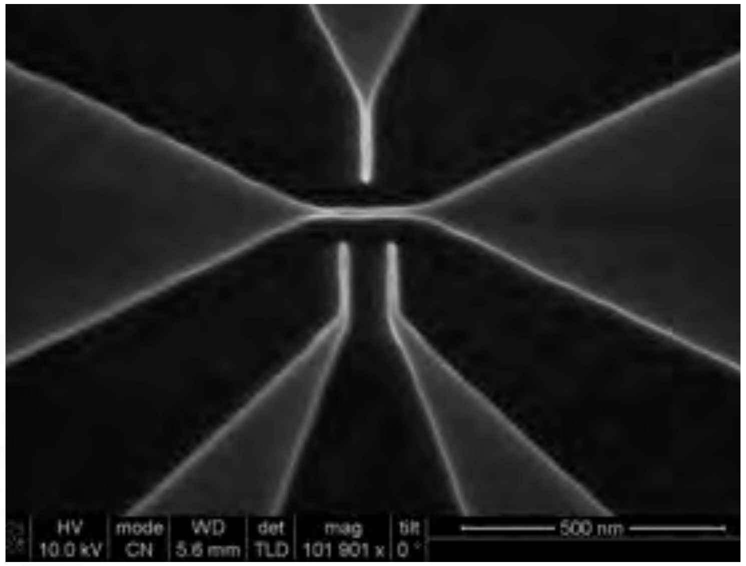


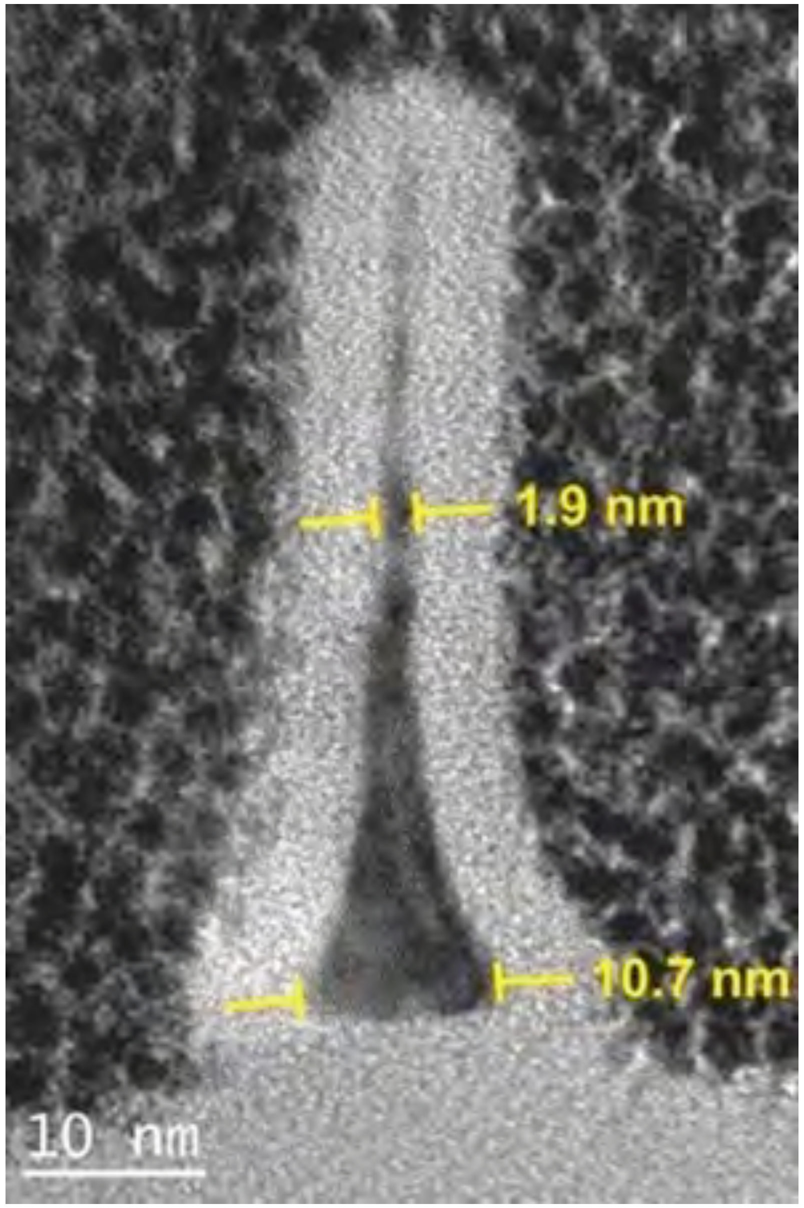


10 nm Wide Si Nanowire SET

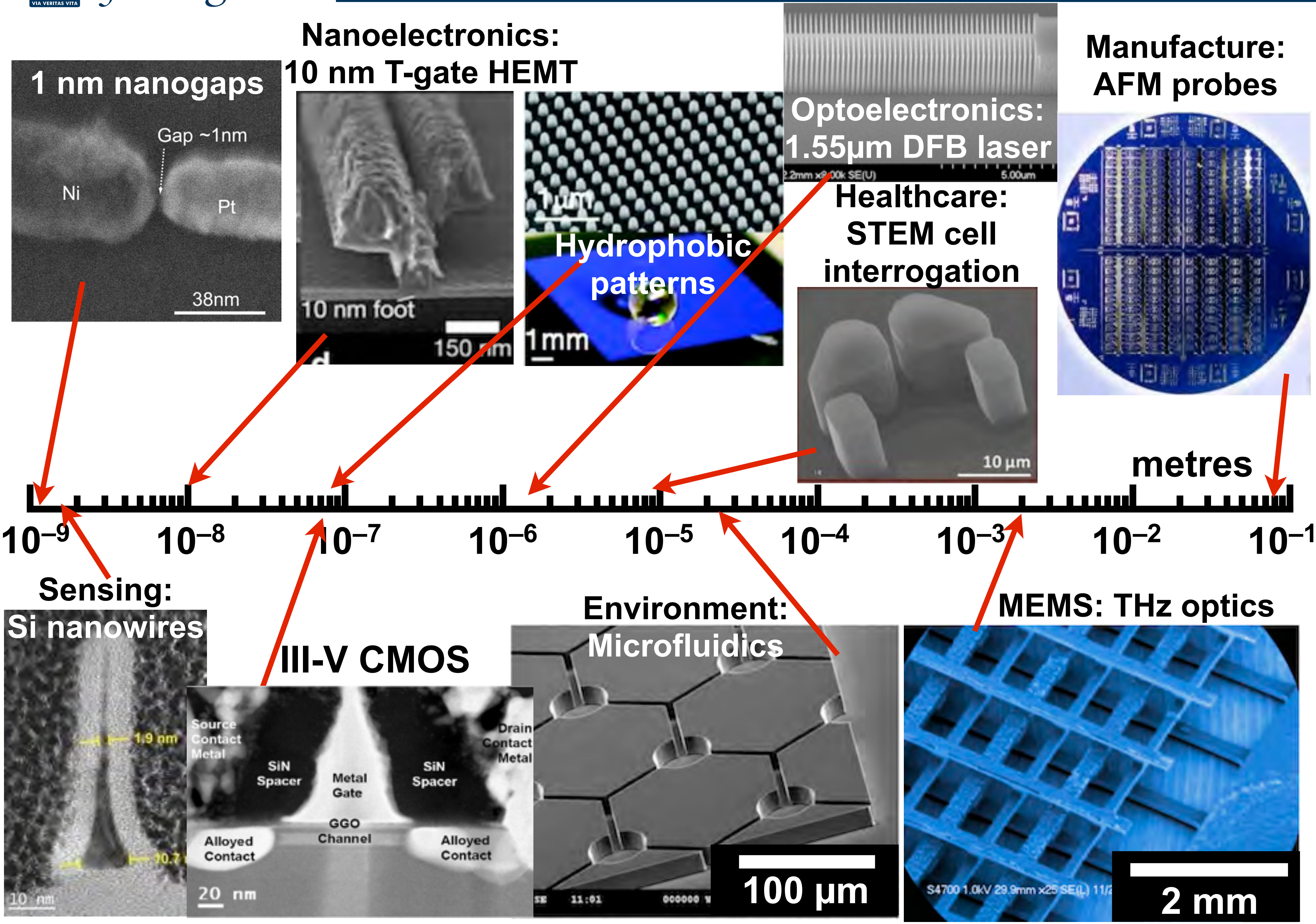
- Depletion mode nanowire







Micro and Nanotechnology from Glasgow

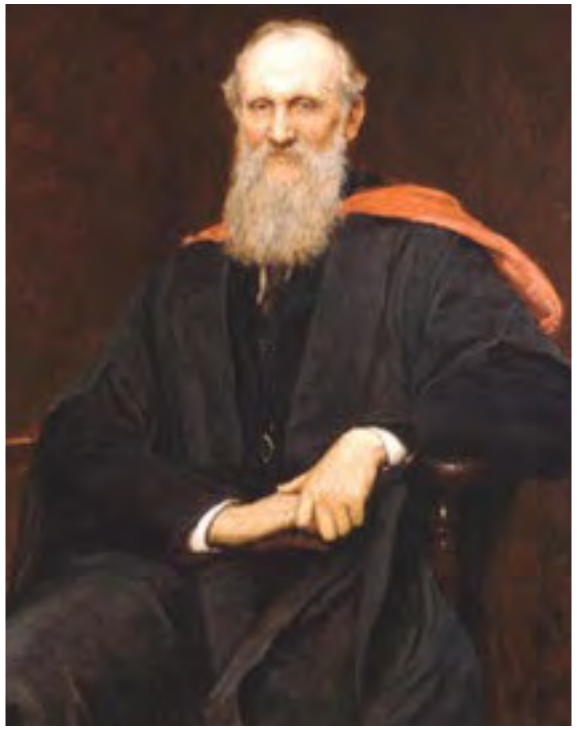


Thermoelectrics History

- History: Seebeck effect 1822

heat –> electric current

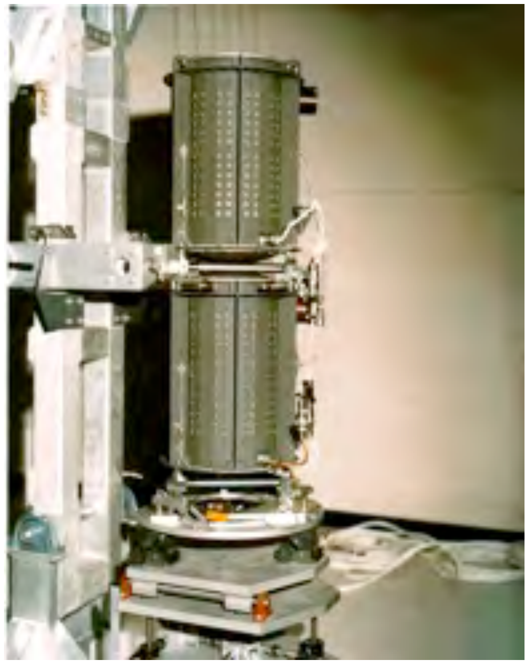
- Peltier (1834): current –> cooling



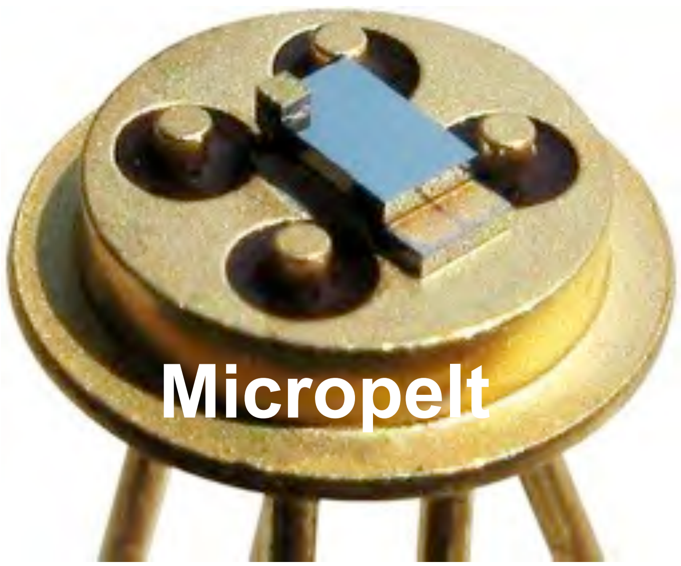
- Thomson effect: Thomson (Lord Kelvin) 1852

Thermoelectric Applications

NASA Voyager I & II



Peltier cooler: telecoms lasers



Cars: replace alternator

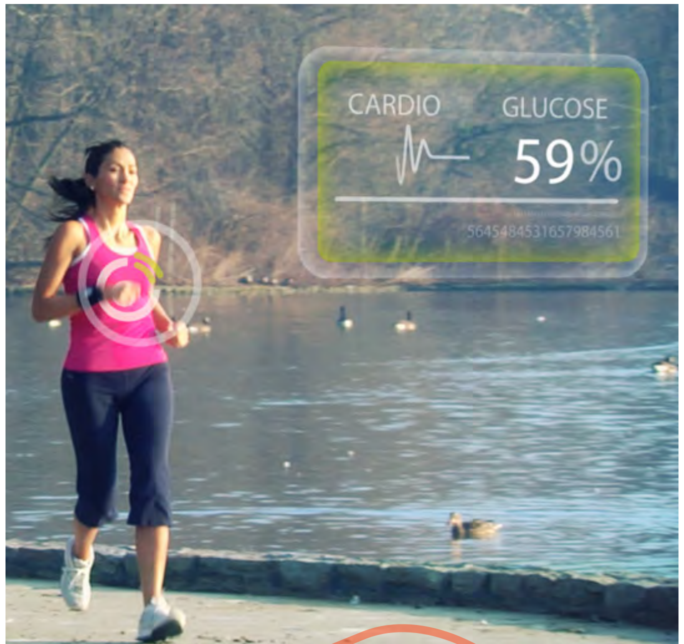
Temperature control for CO_2 sequestration

Buildings / industry temperature control – autonomous sensing

Energy Harvesting for Remote Sensing

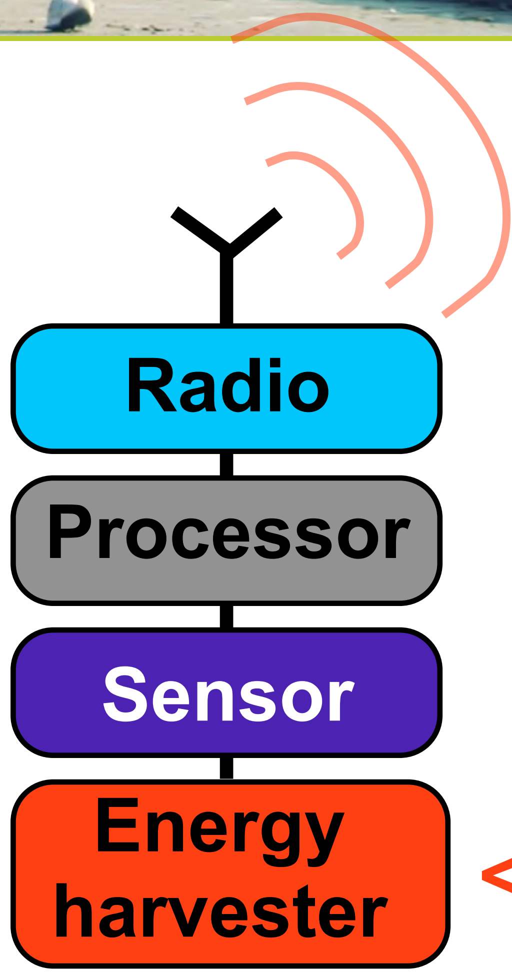
University of Glasgow

Sports performance sensors

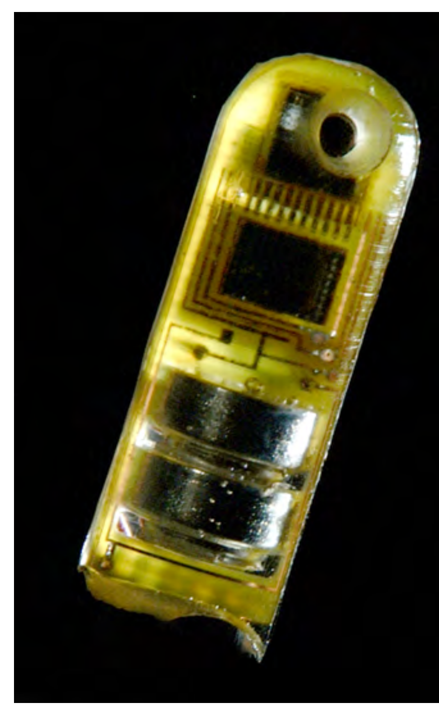


Flood sensors

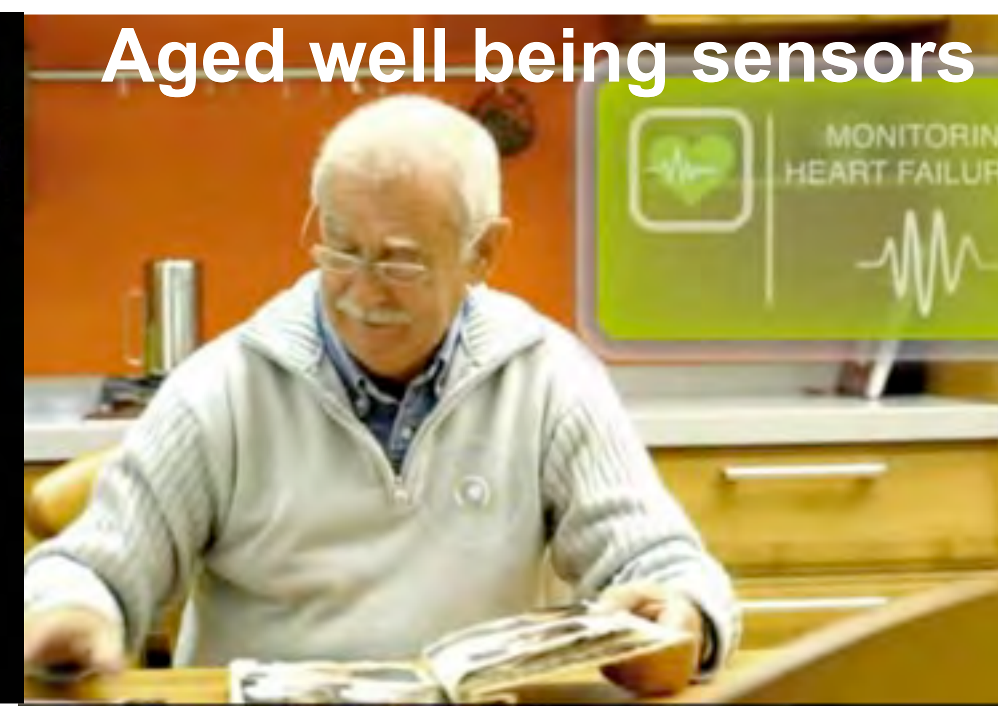
Weather monitoring



Radio	> 10 mW
Processor	> 100 µW
Sensor	> 10 µW
Energy harvester	< 100 µW/cm² !!!



Aged well being sensors



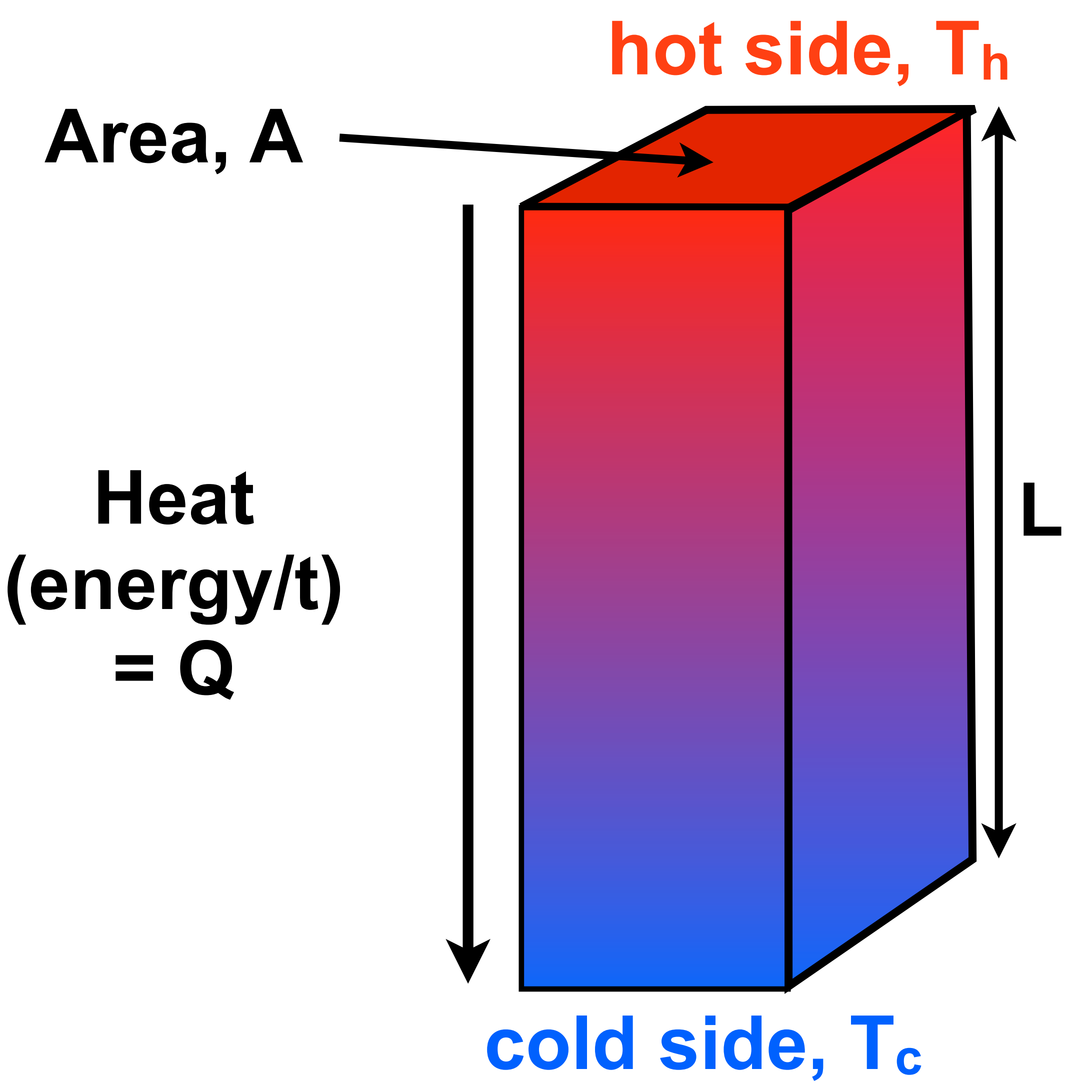
Battery free autonomous sensors: ECG, blood pressure, etc.

University of Glasgow

Background Thermal Physics

Fourier thermal transport

$$Q = -\kappa A \nabla T$$

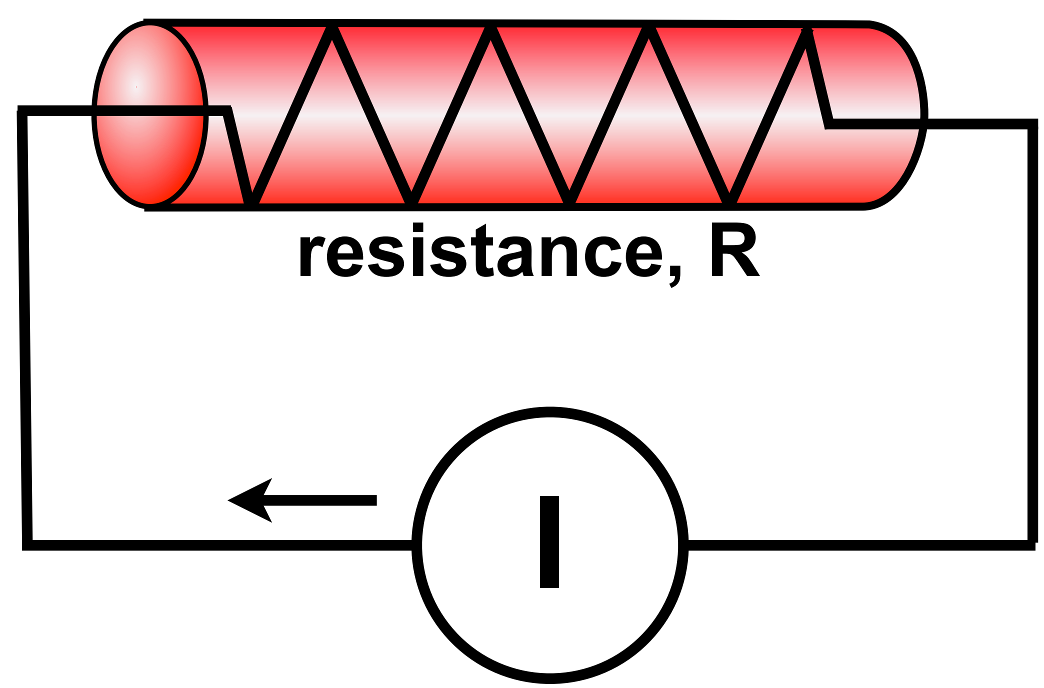


$$Q = -\kappa A \frac{T_c - T_h}{L}$$

Joule heating

$$Q = I^2 R$$

Q = heat (power i.e energy / time)



Background Physics

Fourier thermal transport

$$Q = -\kappa A \nabla T$$

Joule heating

$$Q = I^2 R$$

Q = heat (power i.e energy / time)

E_F = chemical potential

V = voltage

A = area

q = electron charge

g(E) = density of states

k_B = Boltzmann's constant

R = resistance

I = current (J = I/A)

κ = thermal conductivity

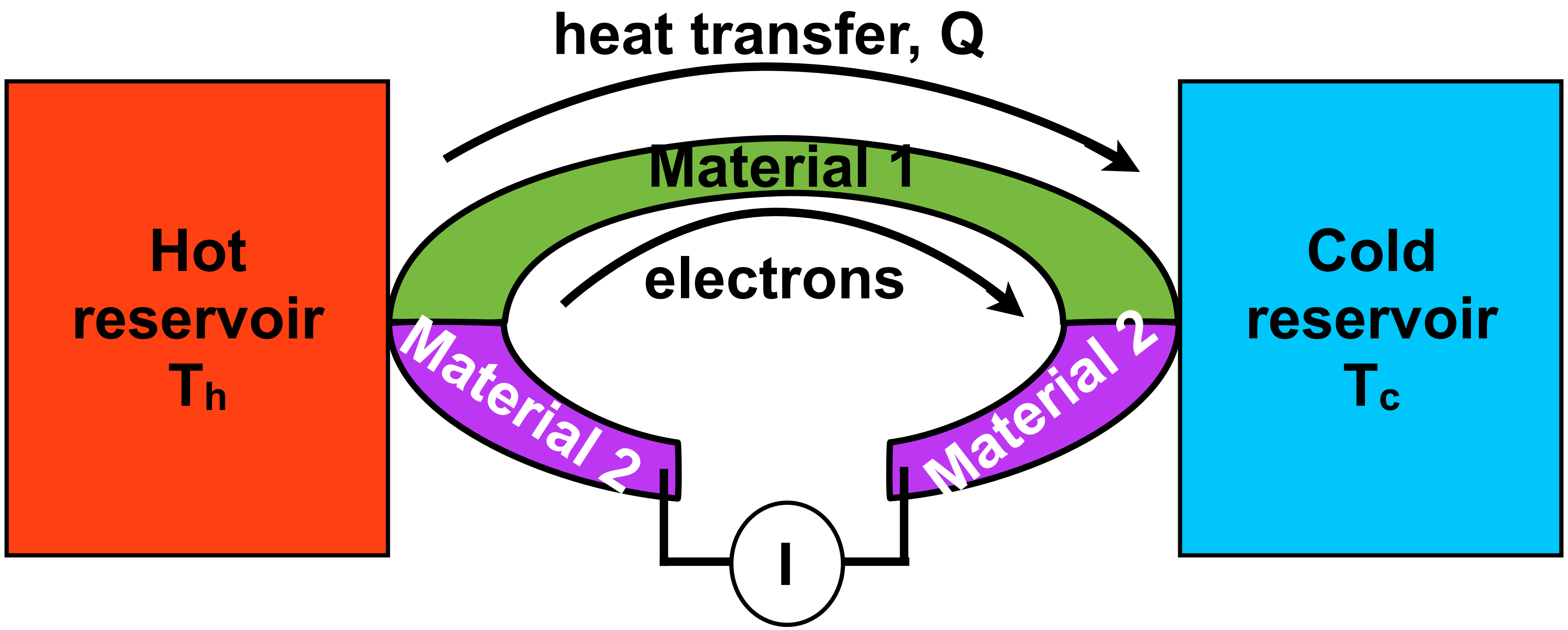
σ = electrical conductivity

α = Seebeck coefficient

f(E) = Fermi function

μ(E) = mobility

The Peltier Effect



Peltier coefficient, $\Pi = \frac{Q}{I}$

units: W/A = V

- Peltier coefficient is the heat energy carried by each electron per unit charge & time

The Peltier Coefficient

- Full derivation uses relaxation time approximation & Boltzmann equation

- $$\mathbf{\Pi = -\frac{1}{q}\int (E - E_F)\frac{\sigma(E)}{\sigma}dE}$$

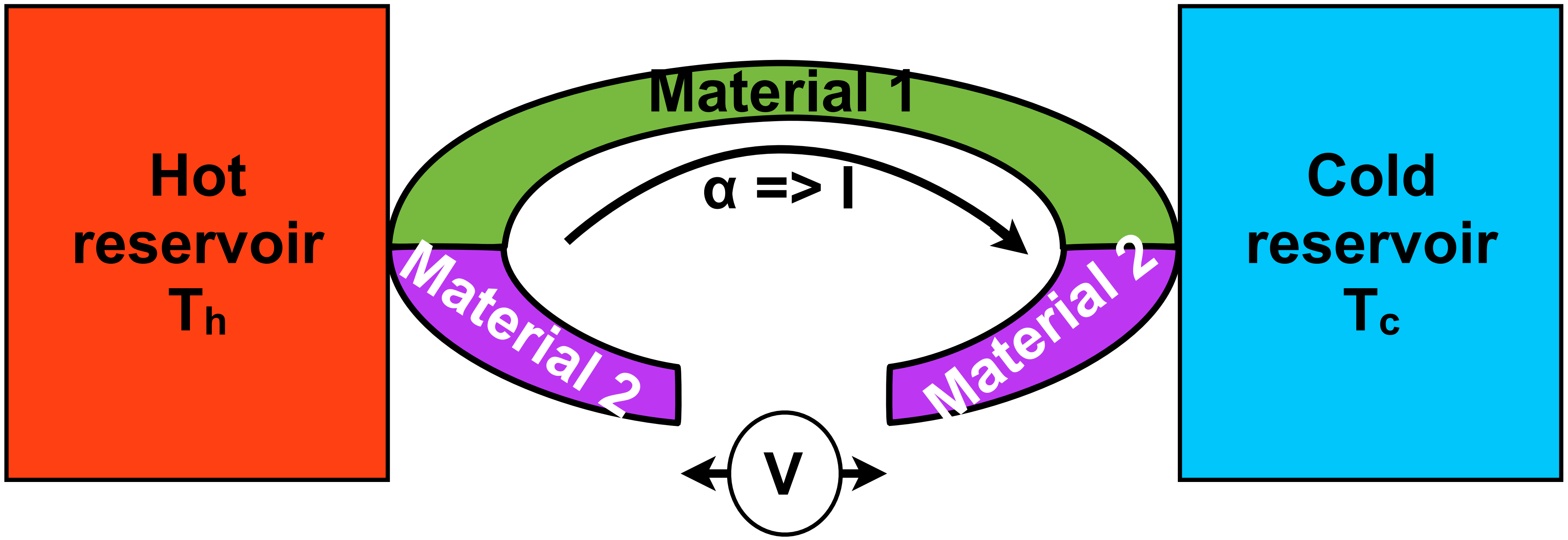
- $$\sigma = \int \sigma(\mathbf{E})\mathbf{dE} = \mathbf{q}\int \mathbf{g(E)}\mu(\mathbf{E})\mathbf{f(E)[1 - f(E)]dE}$$

- **This derivation works well for high temperatures (> 100 K)**

- **At low temperatures phonon drag effects must be added**

see H. Fritzsche, Solid State Comm. 9, 1813 (1971)

The Seebeck Effect



- Open circuit voltage, $V = \alpha (T_h - T_c) = \alpha \Delta T$

Seebeck coefficient, $\alpha = \frac{dV}{dT}$

units: V/K

- Seebeck coefficient = $\frac{1}{q}$ x entropy $\left(\frac{Q}{T}\right)$ transported with electron

The Seebeck Coefficient

- Full derivation uses relaxation time approximation, Boltzmann equation

- $$\alpha = \frac{1}{qT}\left[\frac{\langle E\tau\rangle}{\langle\tau\rangle} - E_F\right]$$

τ = momentum relaxation time

- $$\alpha = -\frac{k_B}{q}\int \frac{(E-E_F)}{k_B T}\frac{\sigma(E)}{\sigma}dE$$

$$\sigma = \int \sigma(E)dE = q\int g(E)\mu(E)f(E)[1-f(E)]dE$$

For electrons in the conduction band, E_c of a semiconductor

- $$\alpha = -\frac{k_B}{q}\left[\frac{E_c - E_F}{k_B T} + \frac{\int_0^\infty \frac{(E-E_c)}{k_B T}\sigma(E)dE}{\int_0^\infty \sigma(E)dE}\right]$$ for $E > E_c$

see Mott and Jones (1974) and H. Fritzsche, Solid State Comm. 9, 1813 (1971)

The Seebeck Coefficient for Metals

- $$\mathbf{f(1-f) = -k_B T \frac{df}{dE}}$$

- **Expand $\mathbf{g(E)\mu(E)}$ in Taylor's series at E = $\mathbf{E_F}$**

- $$\alpha = -\frac{\pi^2}{3q} k_B^2 T \left[\frac{d\ln(\mu(E)g(E))}{dE} \right]_{E=E_F}$$

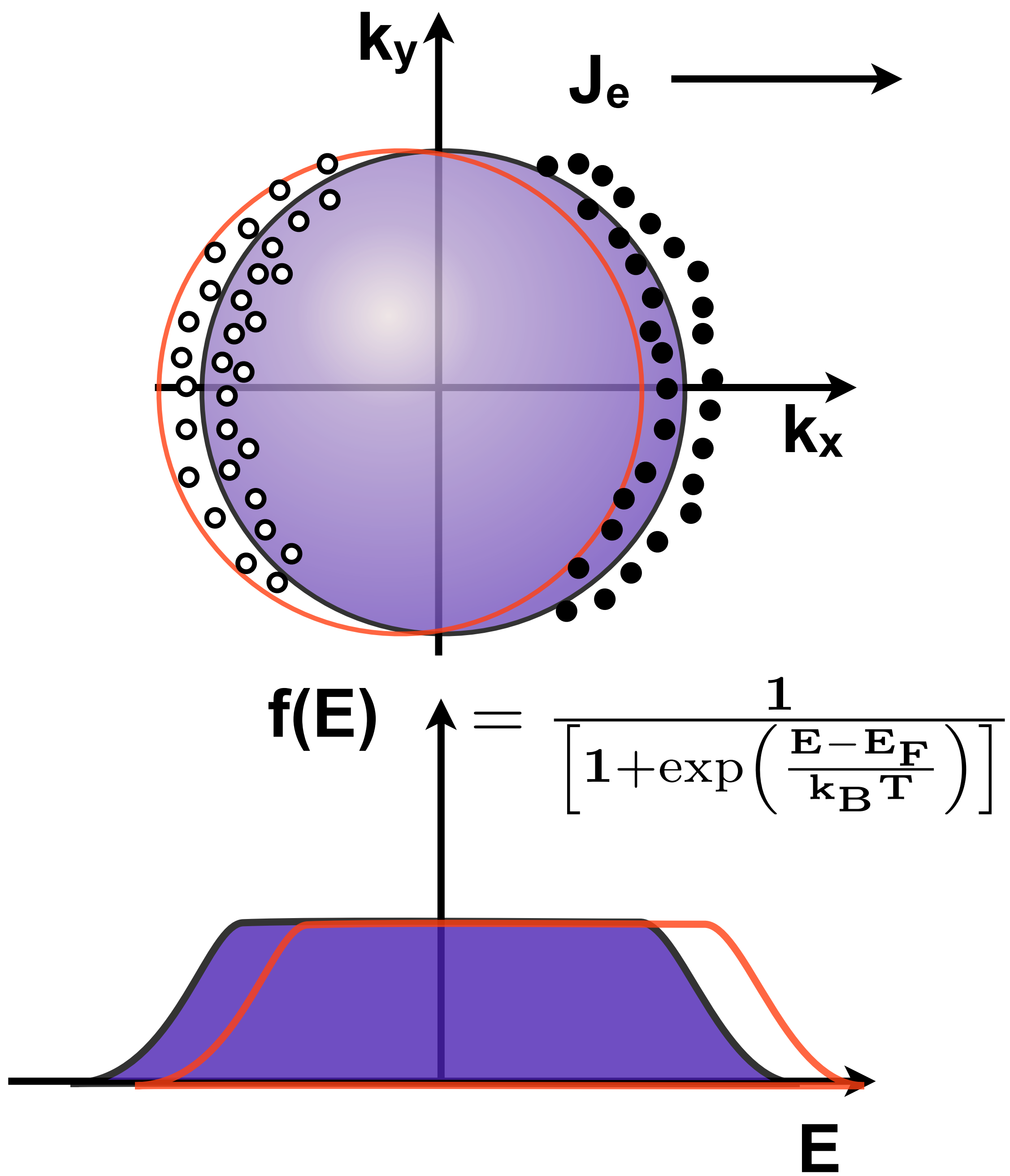
(Mott's formula for metals)

M. Cutler & N.F. Mott, Phys. Rev. 181, 1336 (1969)

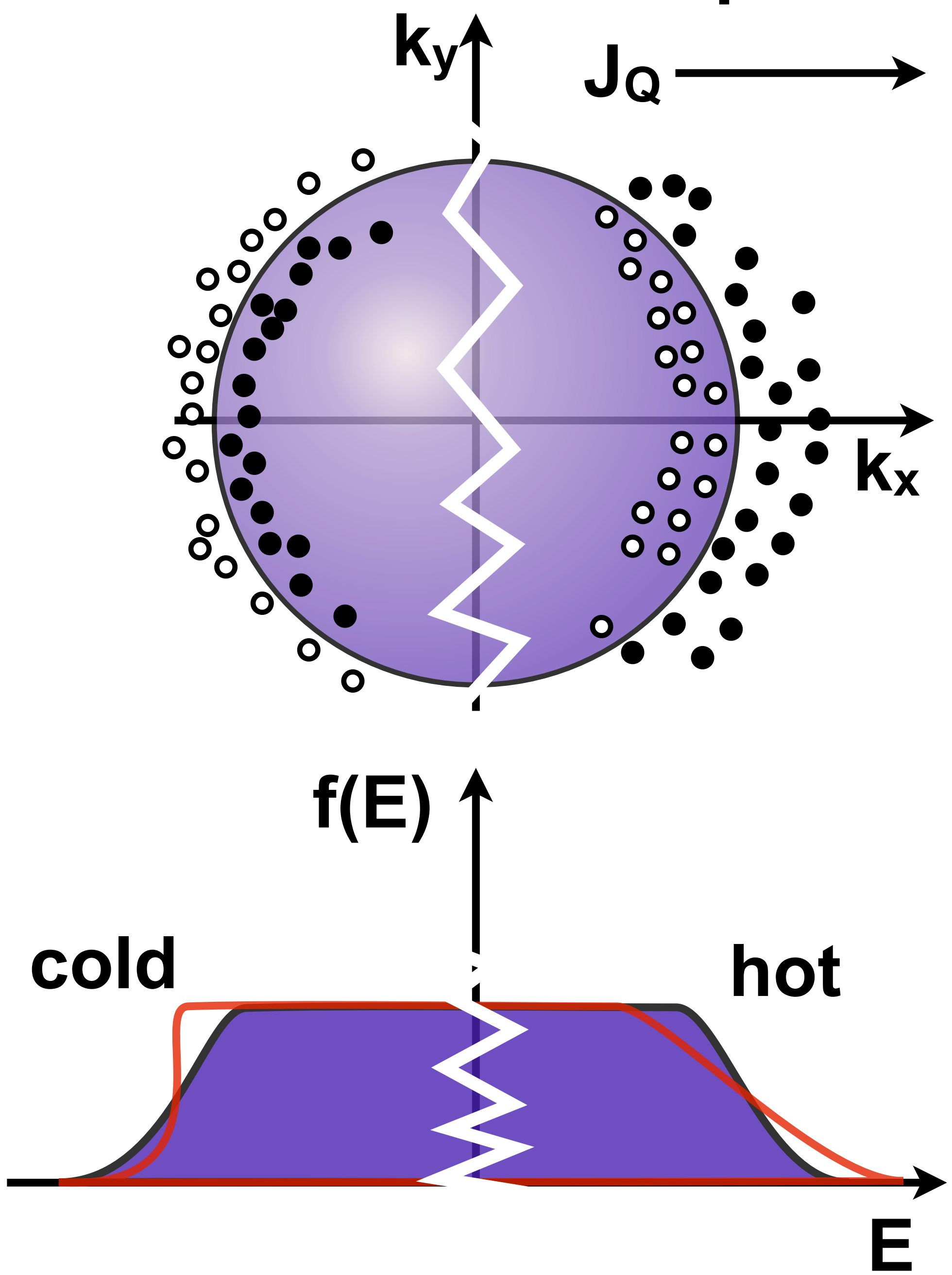
- **i.e. Seebeck coefficient depends on the asymmetry of the current contributions above and below $\mathbf{E_F}$**

3D Electronic and Thermal Transport

3D electronic transport



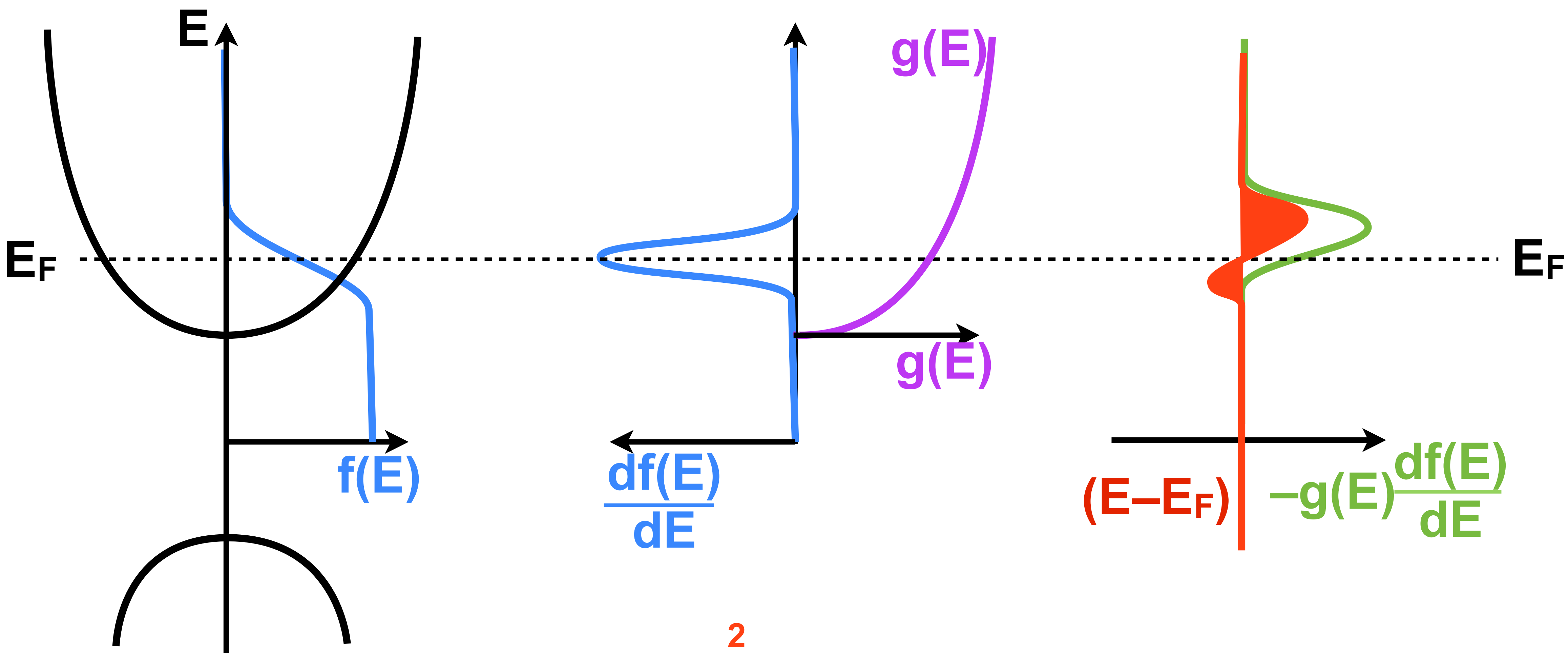
3D thermal transport



The Physics of the Thermoelectric Effect

- **If we ignore energy dependent scattering (i.e. τ = τ(E)) then from J.M. Ziman**

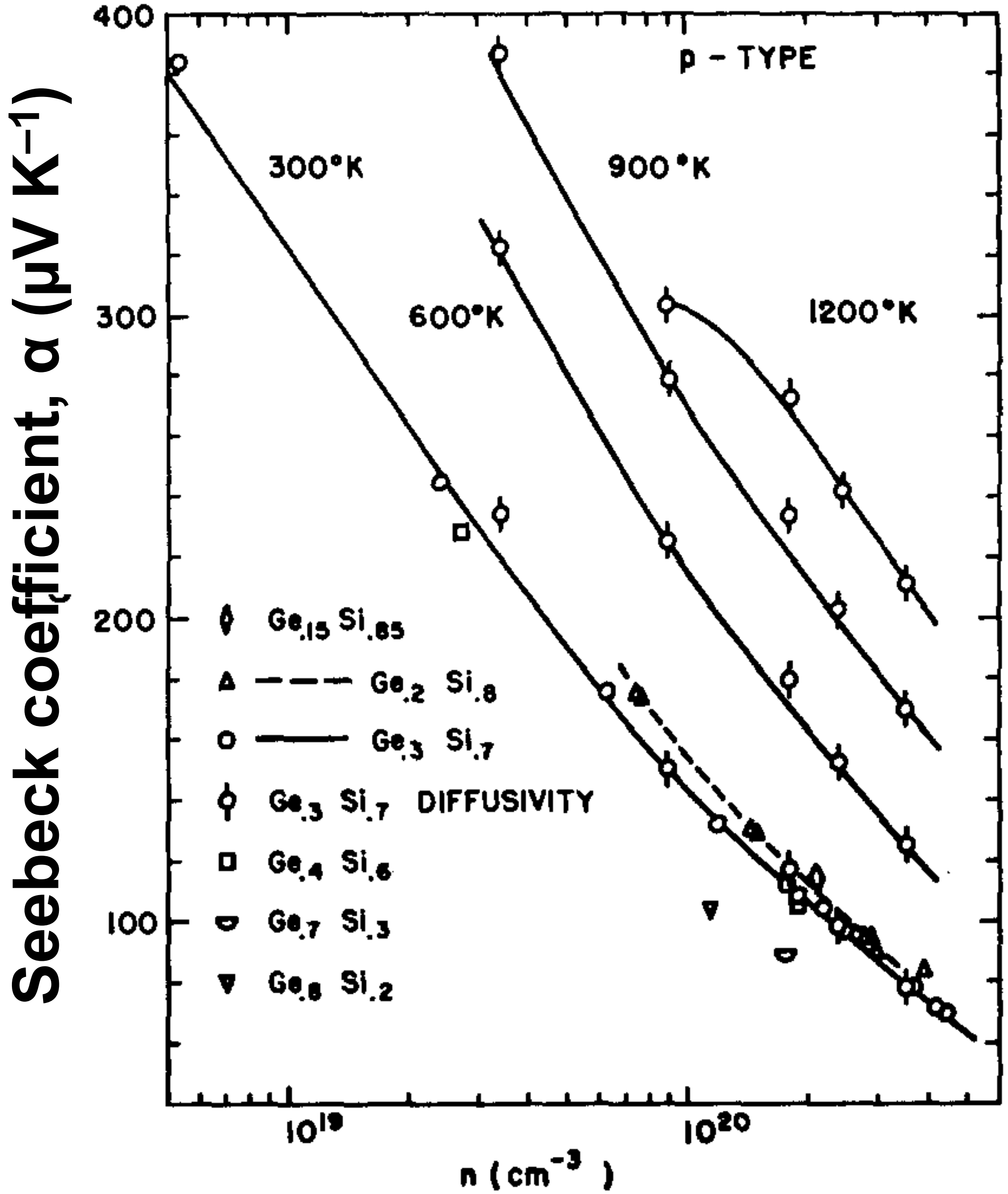
$$\sigma = \frac{q^2}{3}\int \tau(E)\nu^2(E)\left[-g(E)\frac{df}{dE}\right]dE$$



$$\alpha = \frac{q^2}{3T\sigma}\int \tau(E)\nu^2(E)\left[-g(E)\frac{df}{dE}\right](E-E_F)dE$$

- **Thermoelectric power requires asymmetry in red area under curve**

Semiconductor Example: SiGe Alloys

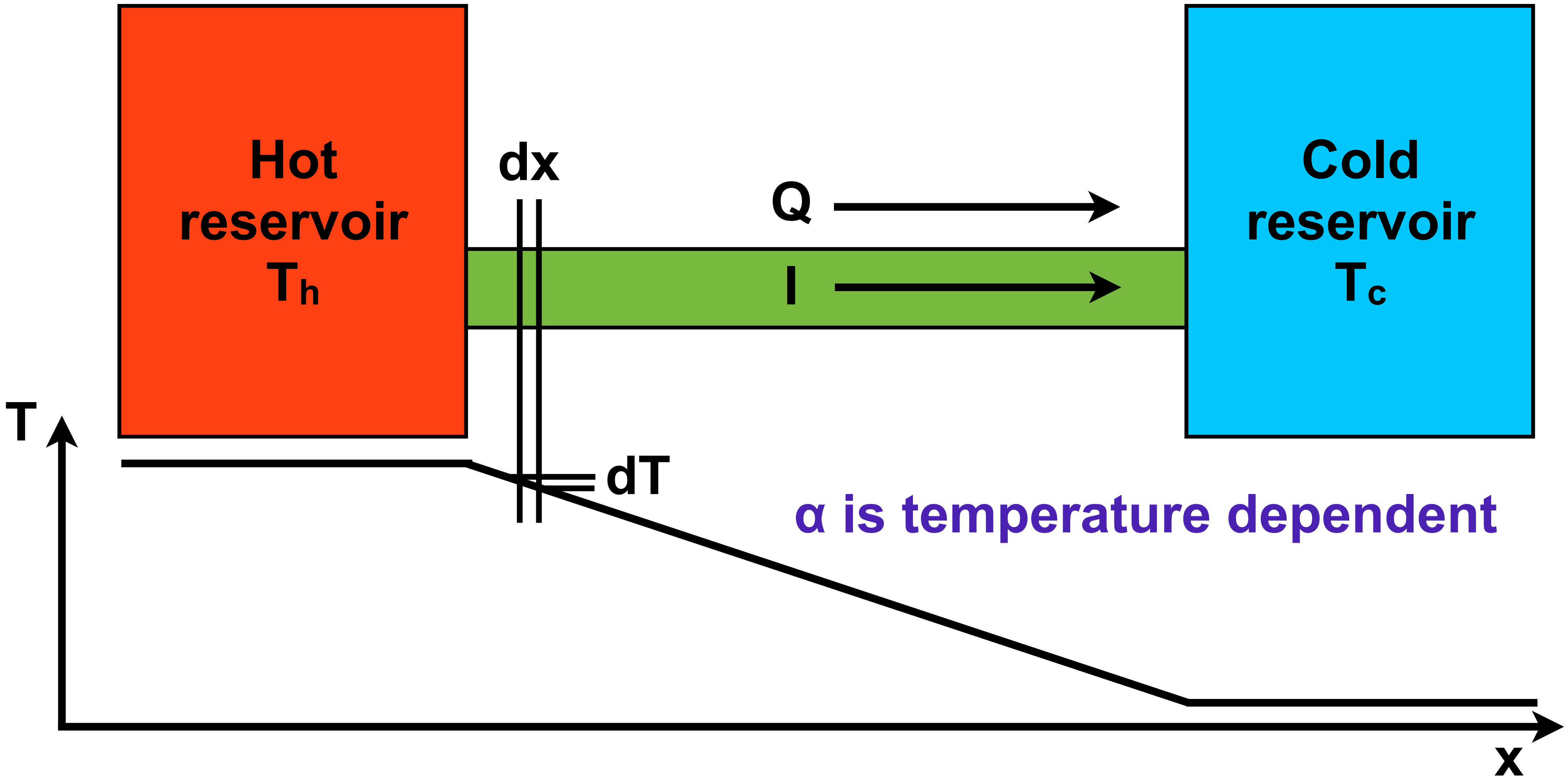


- Mott criteria ~ 2 x 10^{18} cm^{-3}
- Degenerately doped p-$Si_{0.7}Ge_{0.3}$
- α decreases for higher n
- For SiGe, α increases with T

$$\alpha = \frac{8\pi^2 k_B^2}{3eh^2} m^* T \left(\frac{\pi}{3n}\right)^{\frac{2}{3}}$$

J.P. Dismukes et al., J. Appl. Phys. 35, 2899 (1964)

The Thomson Effect



α is temperature dependent

$$\frac{\mathbf{dQ}}{\mathbf{dx}} = \beta \mathbf{I} \frac{\mathbf{dT}}{\mathbf{dx}}$$

Thomson coefficient, β: $dQ = \beta I dT$

units: V/K

The Kelvin Relationships

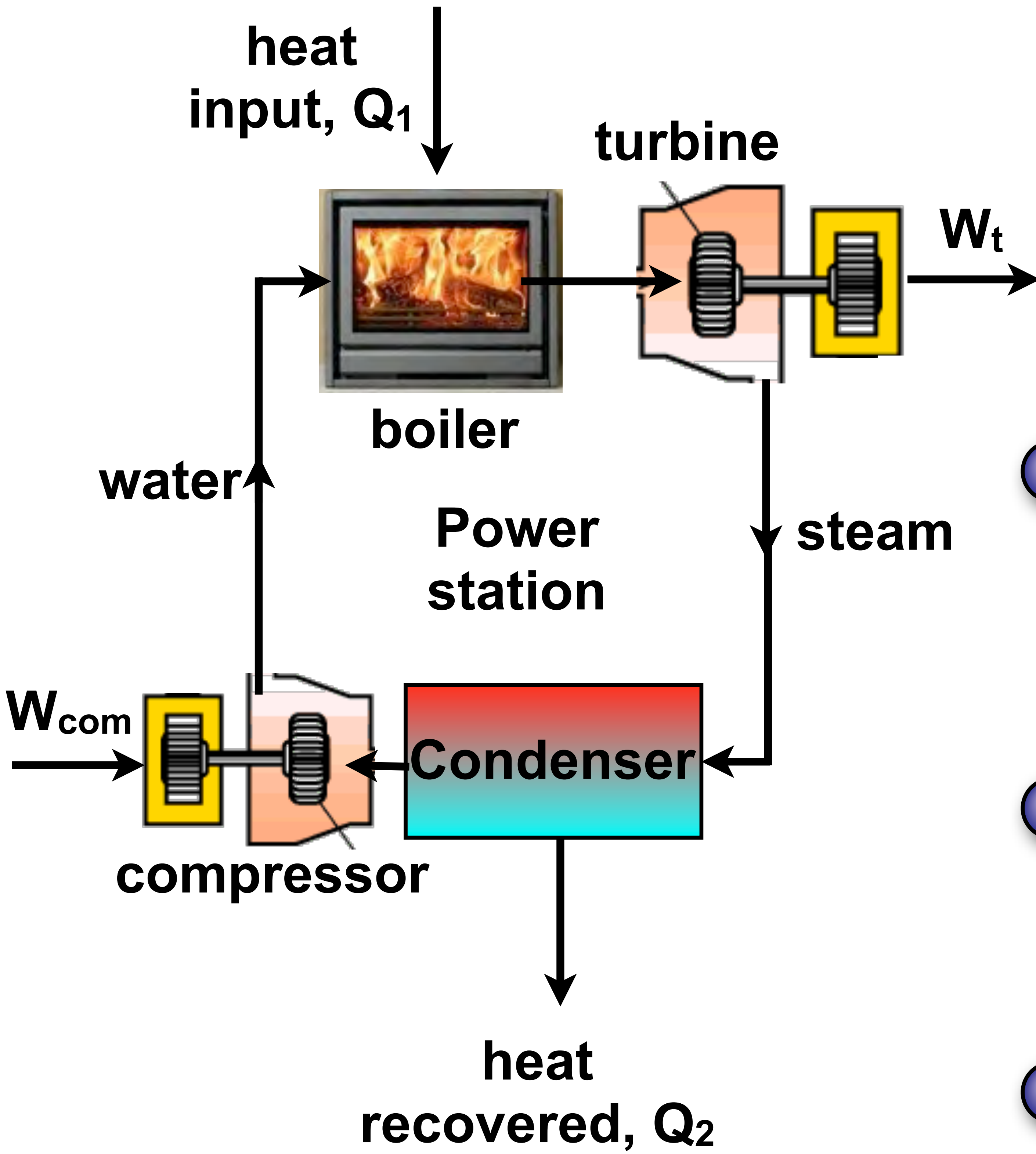
- Derived using irreversible thermodynamics

$$\Pi = \alpha \mathbf{T}$$

$$\beta = \mathbf{T}\frac{\mathbf{d}\alpha}{\mathbf{dT}}$$

- These relationships hold for all materials
- Seebeck, α is easy to measure experimentally
- Therefore measure α to obtain Π and β

Carnot Efficiency for Thermal Engines



$$\text{Efficiency} = \eta = \frac{\text{net work output}}{\text{heat input}}$$

$$= \frac{W_t - W_{com}}{Q_1}$$

- 1st law thermodynamics
  $(Q_1 - Q_2) - (W_t - W_{com}) = 0$
- $\eta = \frac{Q_1 - Q_2}{Q_1}$
- $\eta = 1 - \frac{Q_2}{Q_1}$

Carnot Efficiency

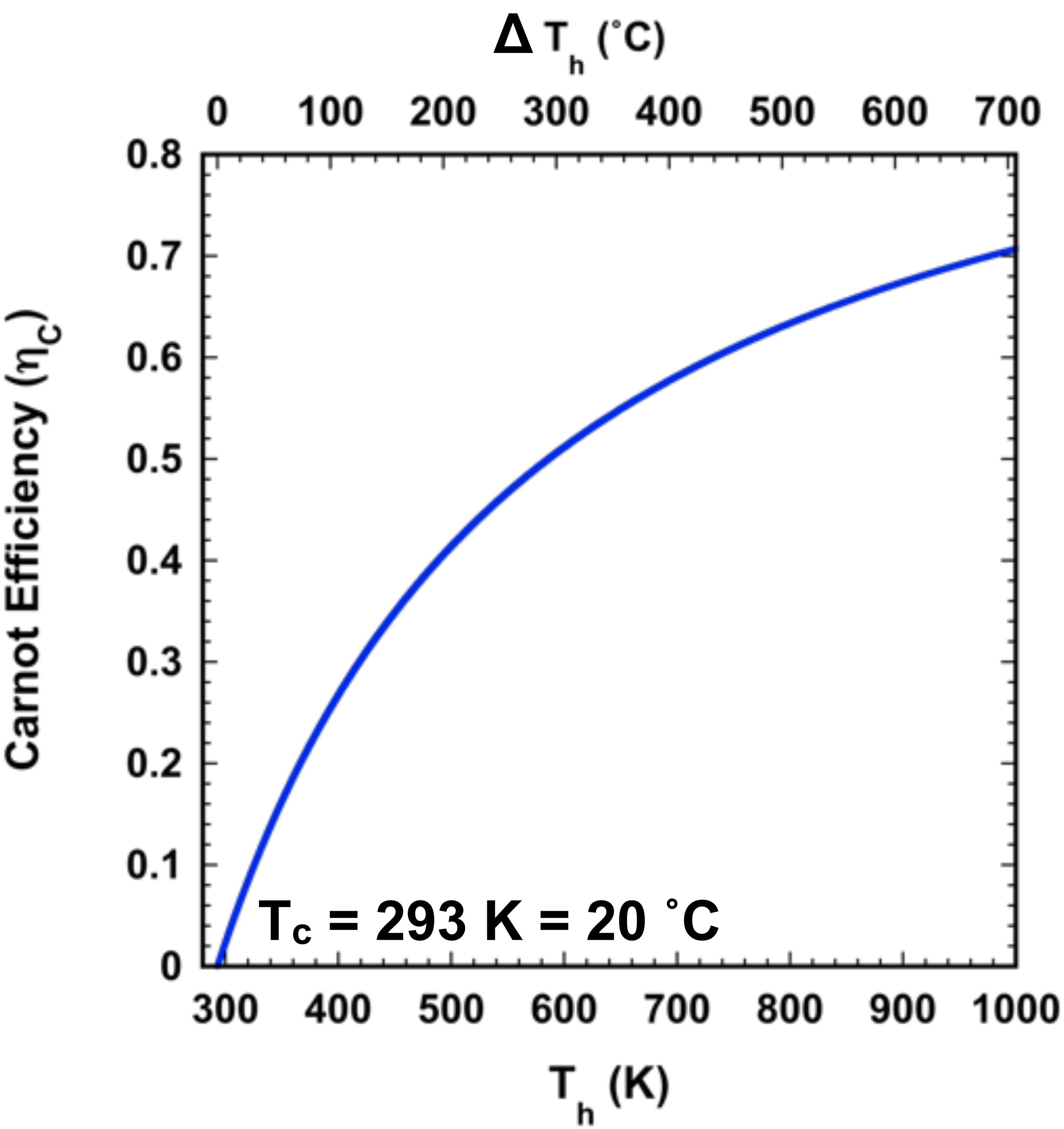
Efficiency =

$$\eta = \frac{\text{net work output}}{\text{heat input}}$$

$$\eta = 1 - \frac{Q_2}{Q_1}$$

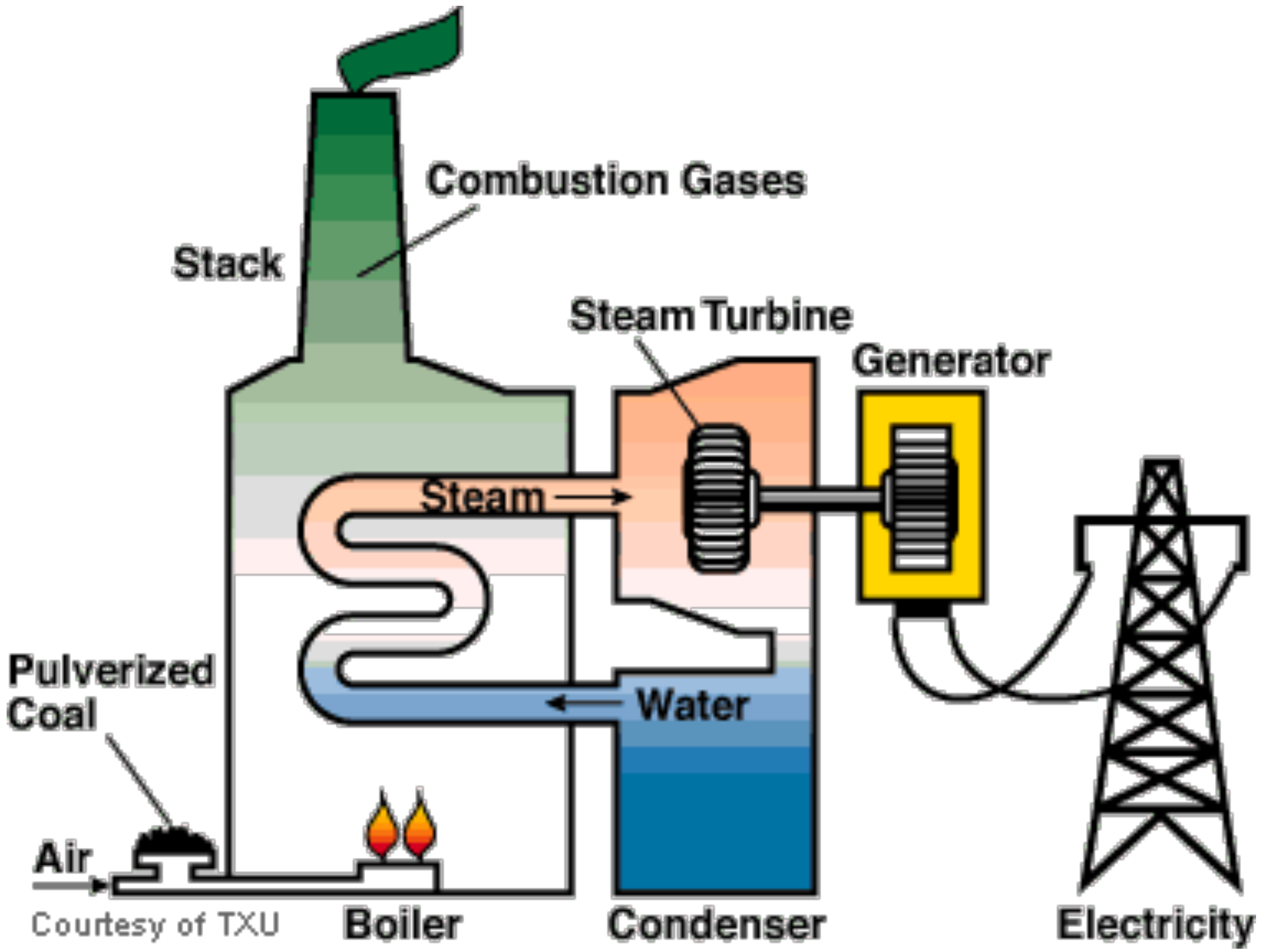
Carnot: maximum η only depends on T_c and T_h

$$\eta_c = 1 - \frac{T_c}{T_h}$$

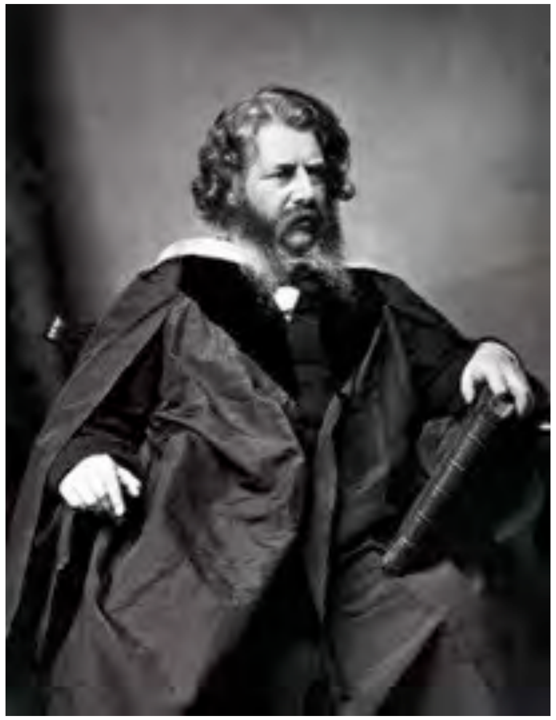


Higher temperatures give higher efficiencies

Energy Conversion: Electricity



The Rankine Cycle

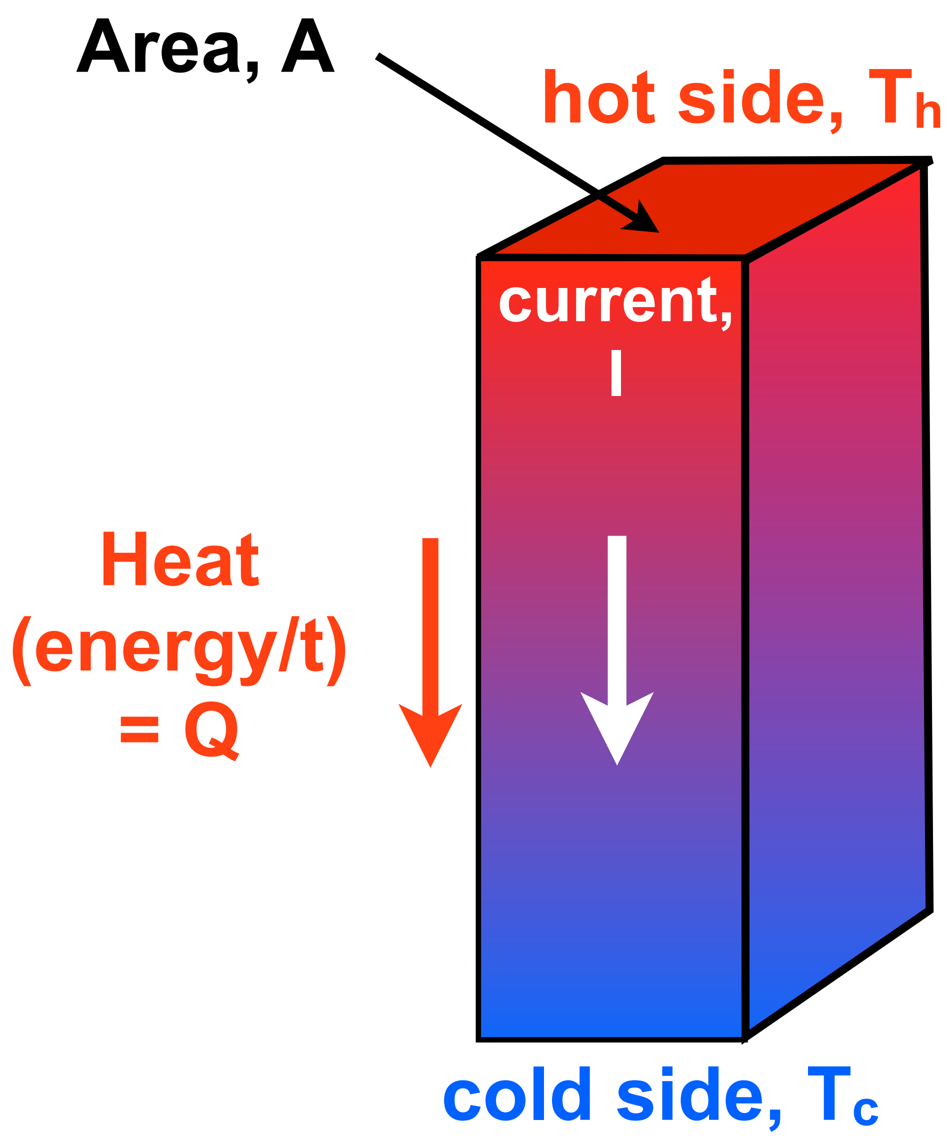


William John Macquorn Rankine

Energy stored in fuel → heat → kinetic energy → electric energy

Peltier Effect, Heat Flux and Temperature

- If a current of I flows through a thermoelectric material between hot and cold reservoirs:



- Heat flux per unit area =

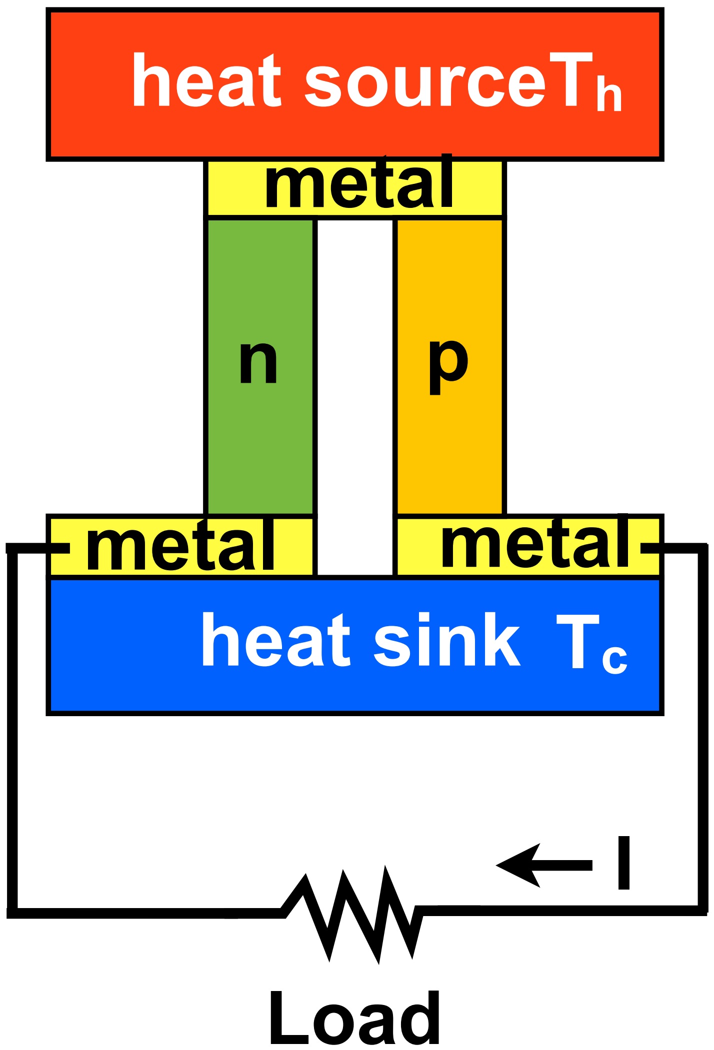
  (= Peltier + Fourier)

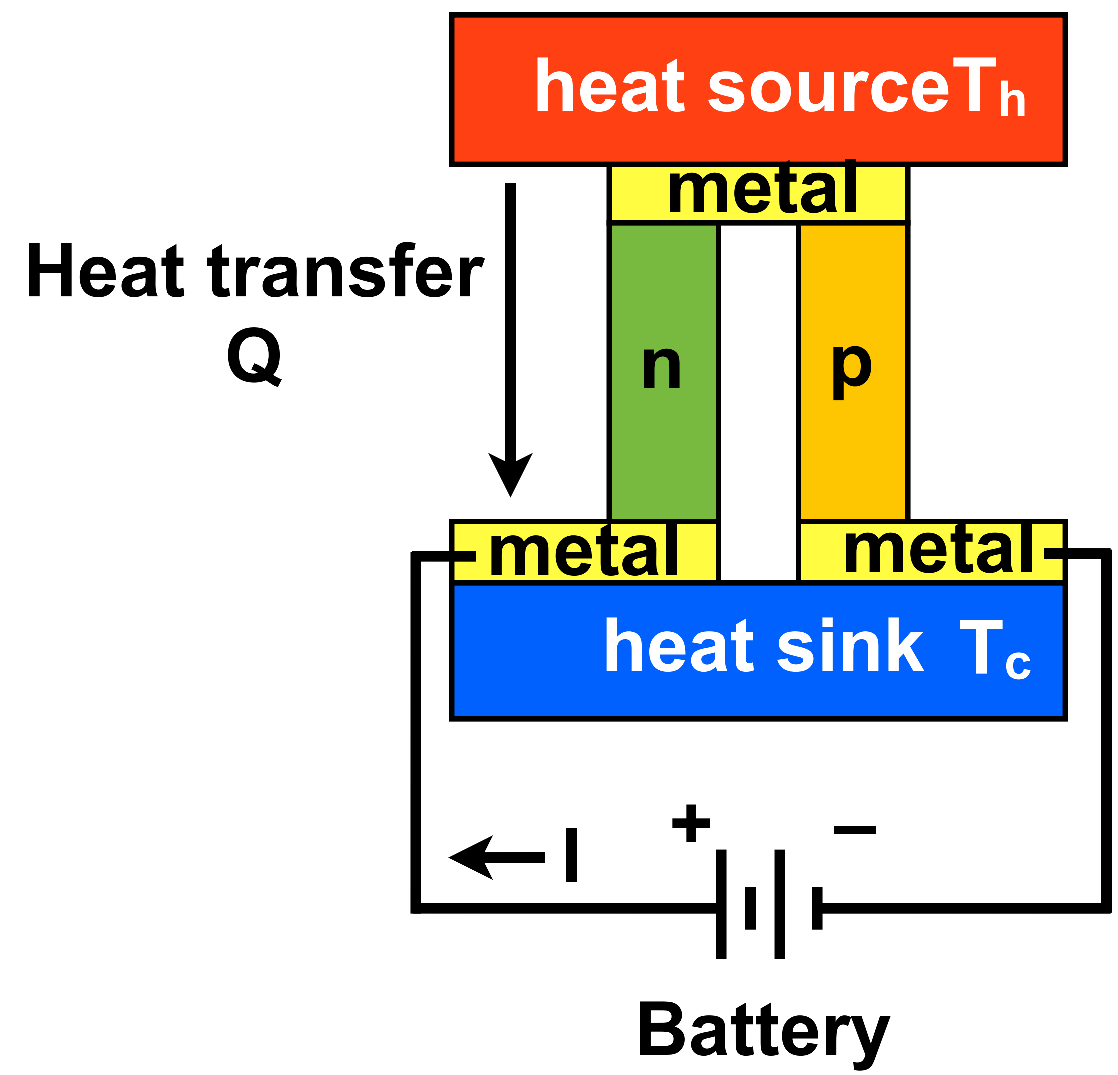
- $$\frac{\mathbf{Q}}{\mathbf{A}} = \mathbf{\Pi J} - \kappa \nabla \mathbf{T}$$

but $\mathbf{\Pi} = \alpha \mathbf{T}$ and $\mathbf{J} = \frac{\mathbf{I}}{\mathbf{A}}$

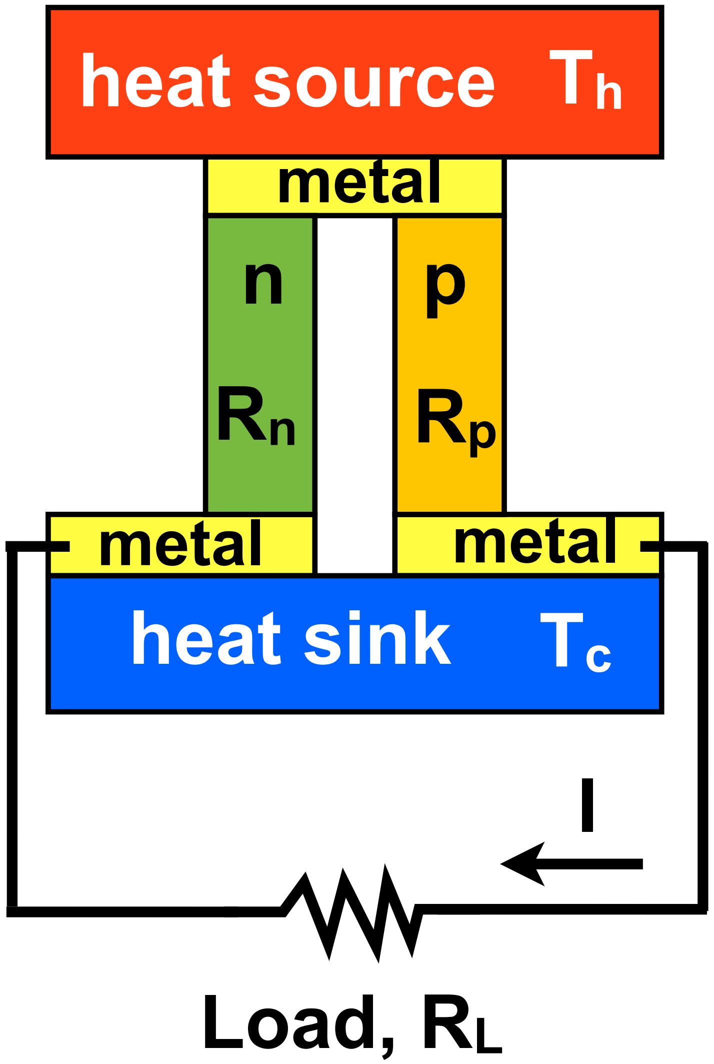
$$\mathbf{Q} = \alpha \mathbf{I T} - \kappa \mathbf{A} \nabla \mathbf{T}$$

Semiconductors and Thermoelectrics





Conversion Efficiency

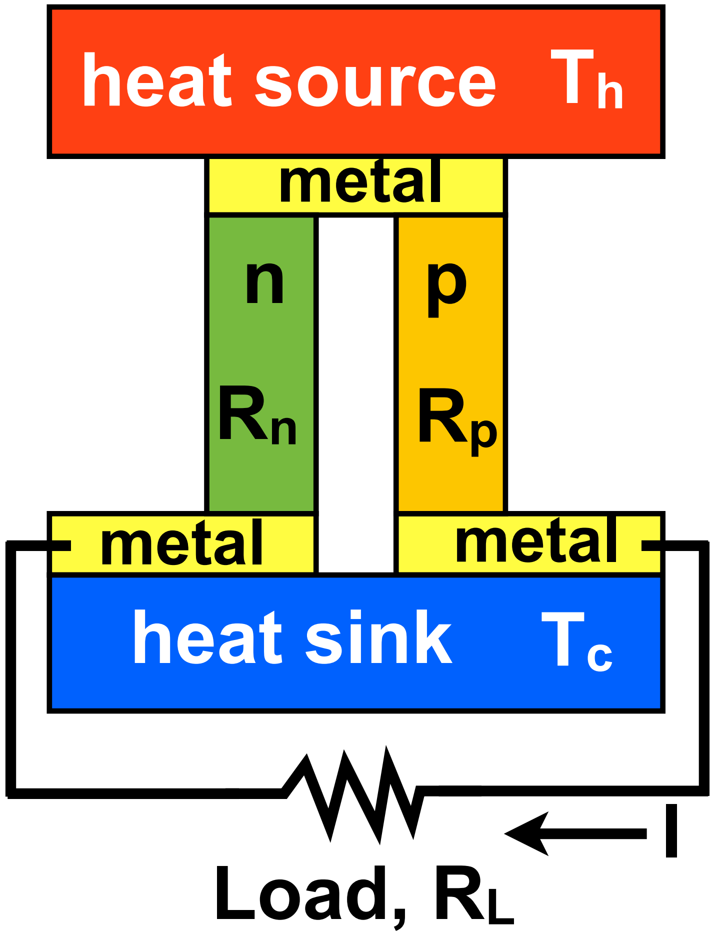


$R = R_n + R_p$

- $\eta = \dfrac{\text{power supplied to load}}{\text{heat absorbed at hot junction}}$
- Power to load (Joule heating) = I^2R_L
- Heat absorbed at hot junction = Peltier heat + heat withdrawn from hot junction
- Peltier heat $= \Pi I = \alpha I T_h$
- $I = \frac{\alpha(T_h - T_c)}{R + R_L}$ (Ohms Law)
- Heat withdrawn from hot junction $= \kappa A\,(T_h - T_c) - \frac{1}{2} I^2 R$

NB half Joule heat returned to hot junction

Thermoelectric Conversion Efficiency



- $\eta = \dfrac{\text{power supplied to load}}{\text{heat absorbed at hot junction}}$

  $= \dfrac{\text{power supplied to load}}{\text{Peltier + heat withdrawn}}$

$$\eta = \frac{I^2 R_L}{\alpha I T_h + \kappa A (T_h - T_c) - \frac{1}{2} I^2 R}$$

- For maximum value $\dfrac{d\eta}{d\left(\frac{R_L}{R}\right)} = 0$

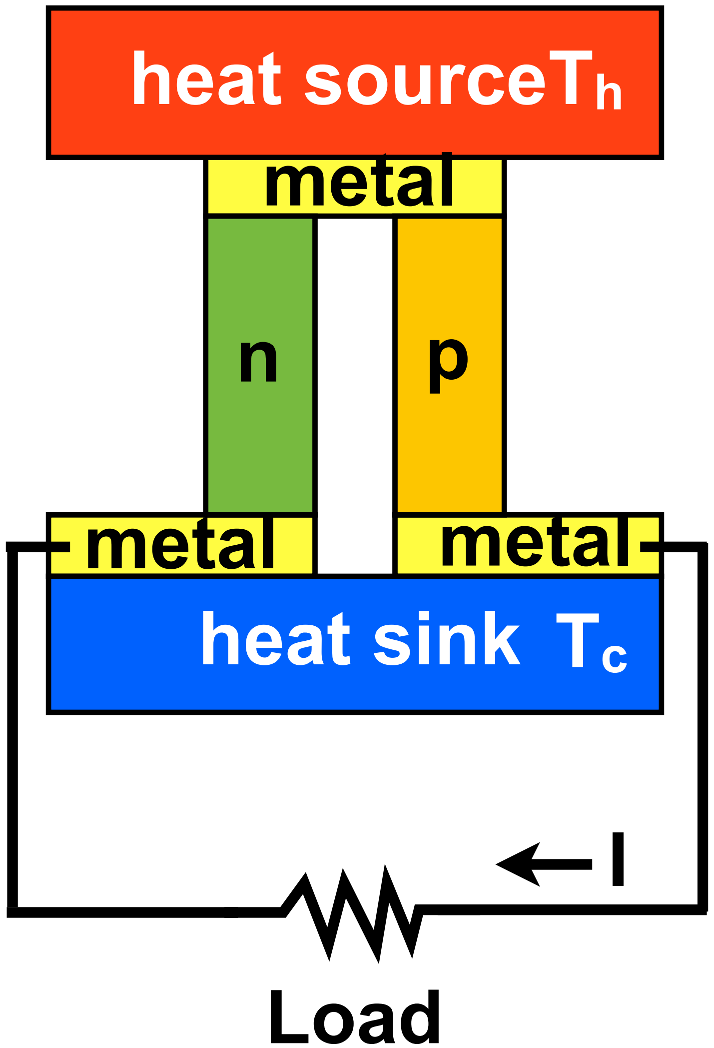
$$T = \frac{1}{2}(T_h + T_c)$$

$$\eta_{max} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_c}{T_h}}$$

where $Z = \dfrac{\alpha^2}{R\kappa A} = \dfrac{\alpha^2 \sigma}{\kappa}$

= Carnot x Joule losses and irreversible processes

Thermoelectric Power Generating Efficiency



$$\eta = \frac{\Delta T}{T_h} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}}$$

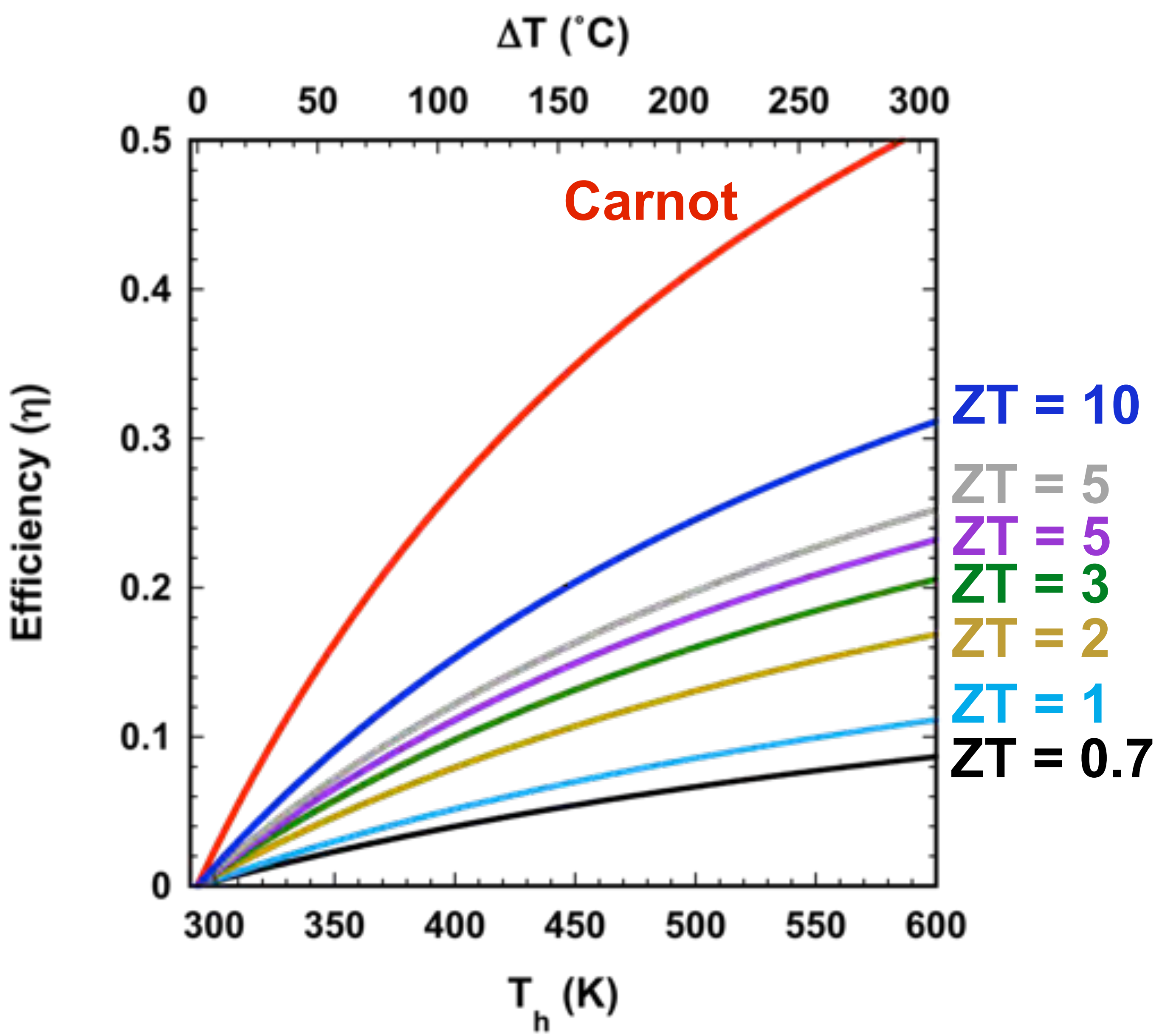


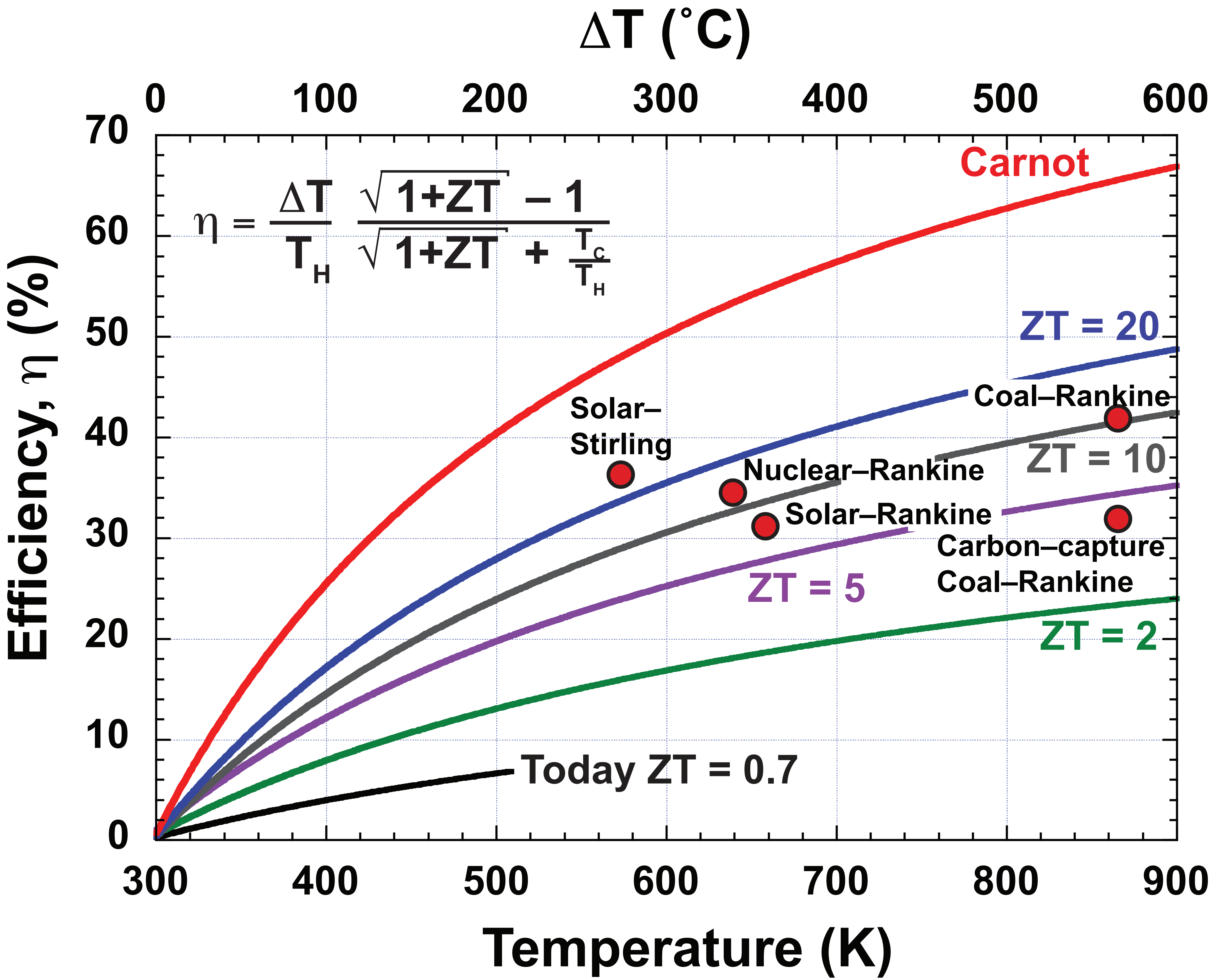
Figure of merit

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

Power factor = $\alpha^2\sigma$

Impedance matching and maximum power point tracking are key for thermoelectrics

Thermodynamic Efficiency

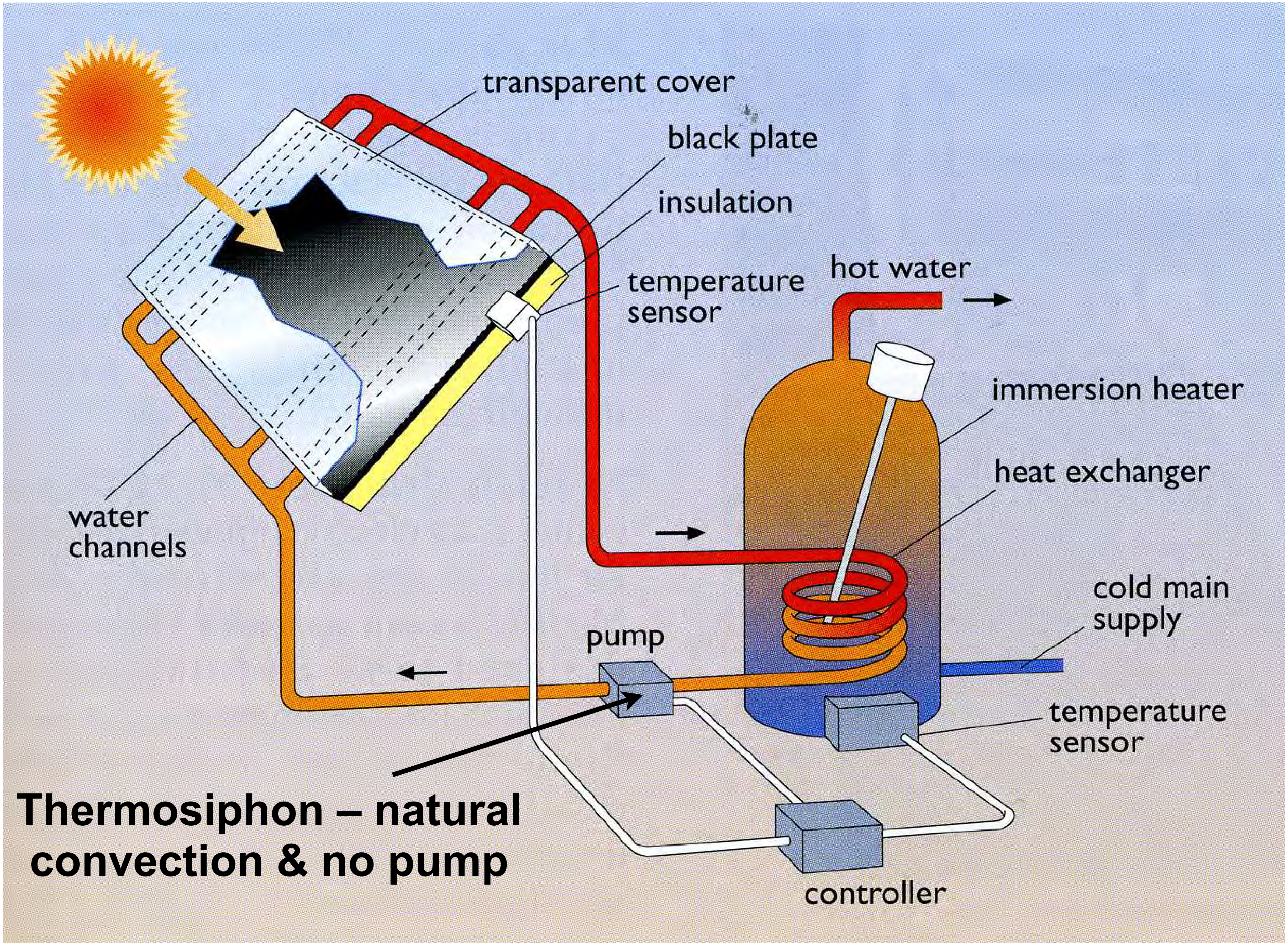


Energy Quality

Highest Quality
Electromagnetic
Mechanical (kinetic)
Photon (light)
Chemical
Heat (thermal)
Lowest Quality

- First proposed as availability by Kelvin in 1851 refined by Ohta
- Energy quality describes the ease (i.e. η) with which energy can be transformed
- A transition down the table will be more efficient than moving up the table
- Therefore solar heating is more efficient than photovoltaic electrical generation
- Expanded version from chemistry developed by Odum

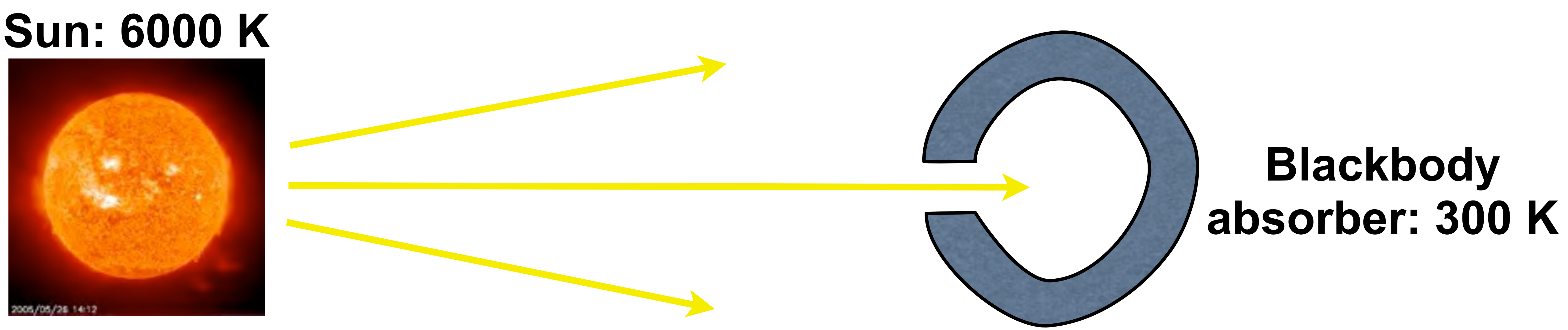
Solar Thermal Water Heating System



- **46% to 74% η for solar energy –> heat conversion are typical**

Carnot Limit for Radiative Absorption

- Thermal limit i.e. heating for the sun as a 6000 K black body emitter with a 300 K solar cell black body absorber

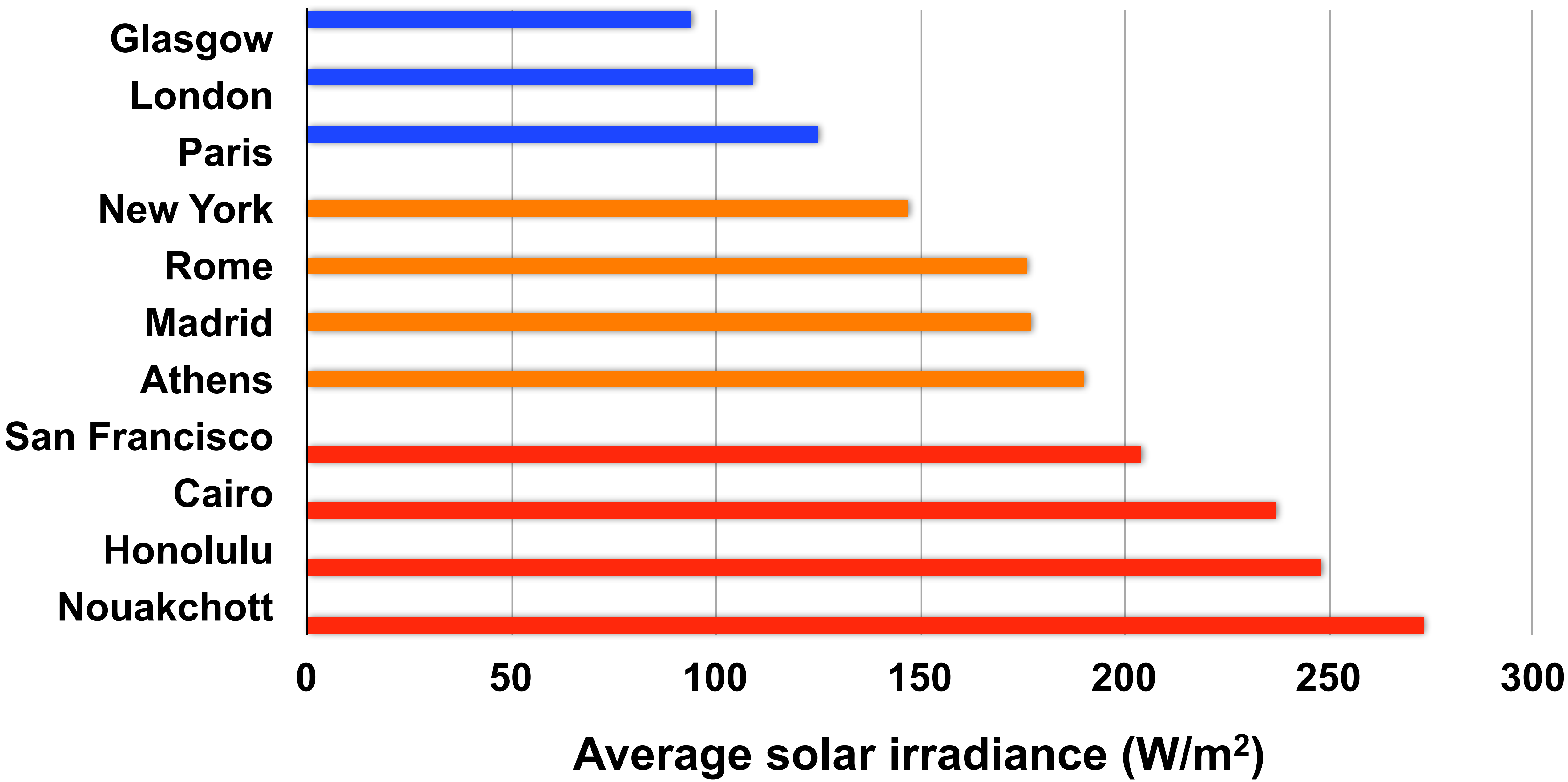


- Maximum Carnot efficiency is 85% for absorber at 2470 K:
  all photons absorbed
  maximum heat from every photon
  zero thermal dissipation from absorber

- Actual efficiencies for a room temperature absorber are < 85%

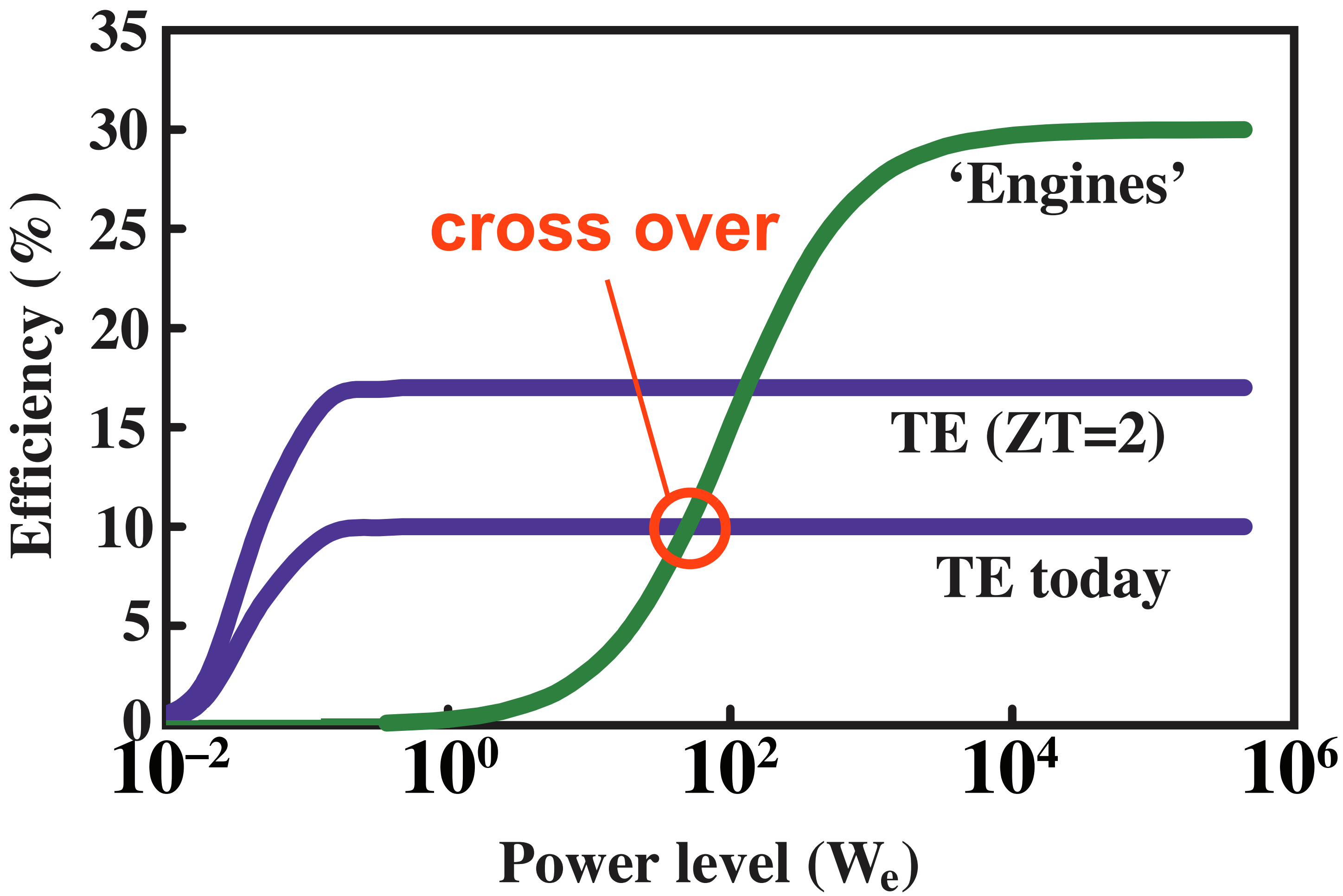
How Much Continuous Solar Energy?

- Due to clouds, day/night & seasons, average energy << peak energy
- Available energy needs to be averaged over 365 days and 24 hours



Power Generation From Macro to Micro

Illustrative schematic diagram



At large scale, thermodynamic engines more efficient than TE

ZT average for both n and p over all temperature range

Diagram assumes high ΔT

- At the mm and μm scale with powers << 1W, thermoelectrics are more efficient than thermodynamic engines (Reynolds no. etc..)

C.B. Vining, Nature Mat. 8, 83 (2009)

Maximum Temperature Drop

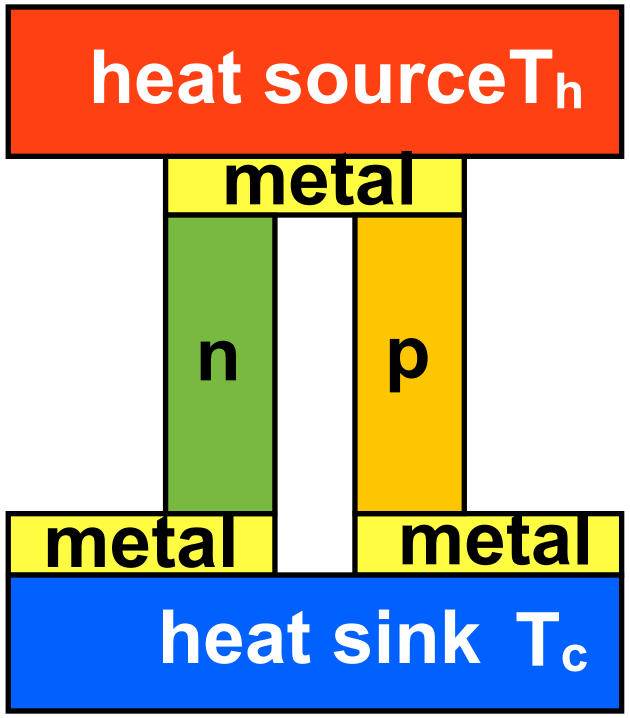
- As the system has thermal conductivity κ a maximum ΔT can be sustained across a module limited by heat transport

- $$\Delta T_{max} = \frac{1}{2} Z T_c^2$$

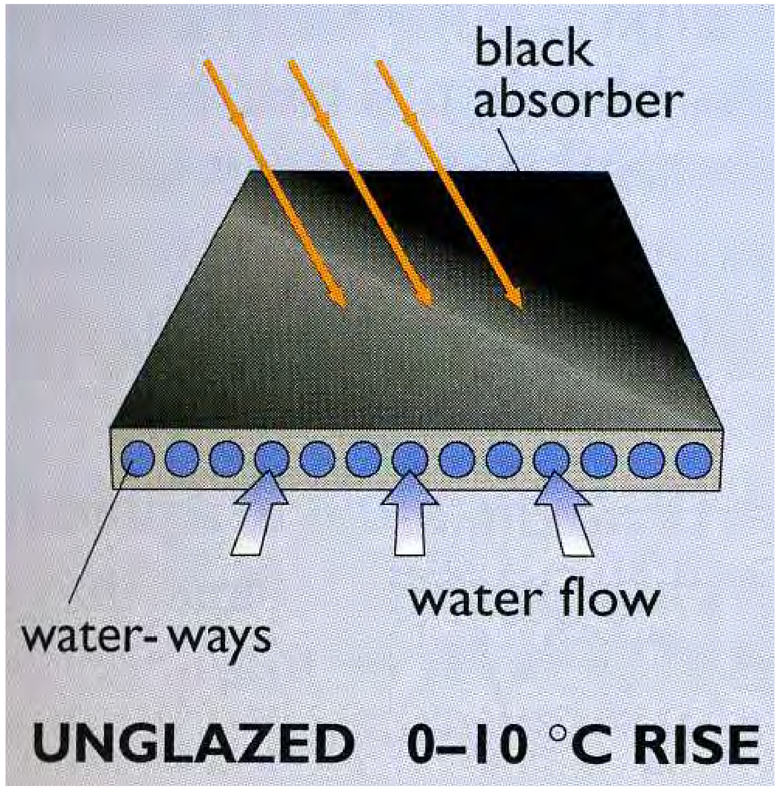
- The efficiency cannot be increased indefinitely by increasing T_h

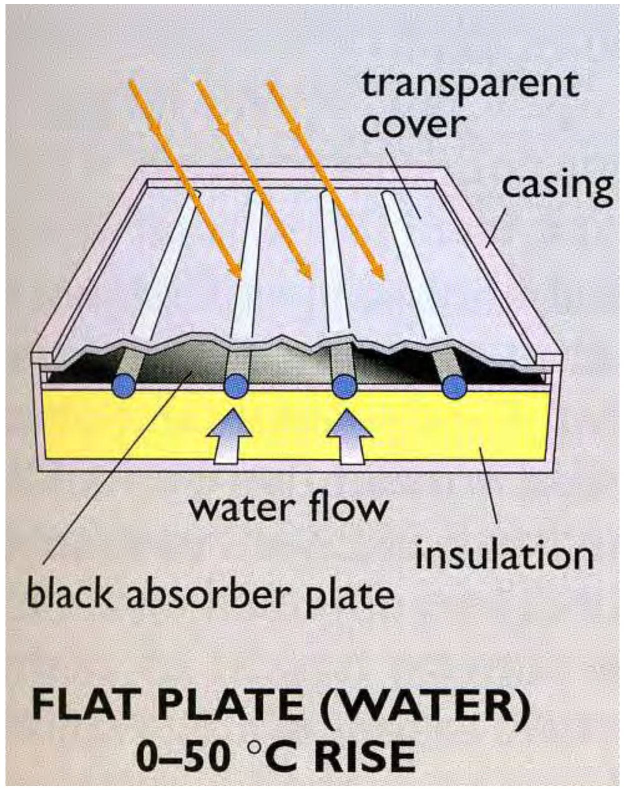
- The thermal conductivity also limits maximum ΔT in Peltier coolers

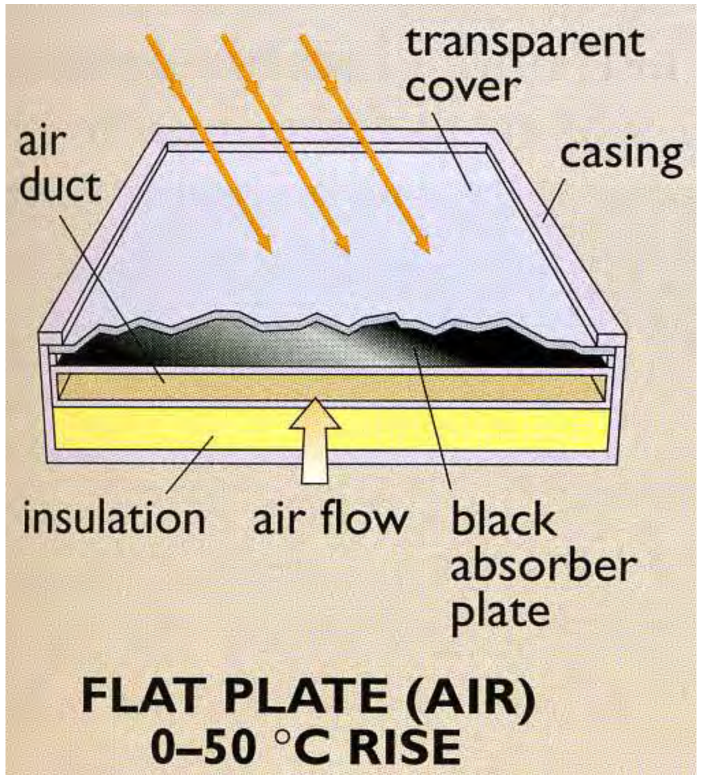
- Higher ΔT_{max} requires better Z materials



Solar Thermal Water Heating







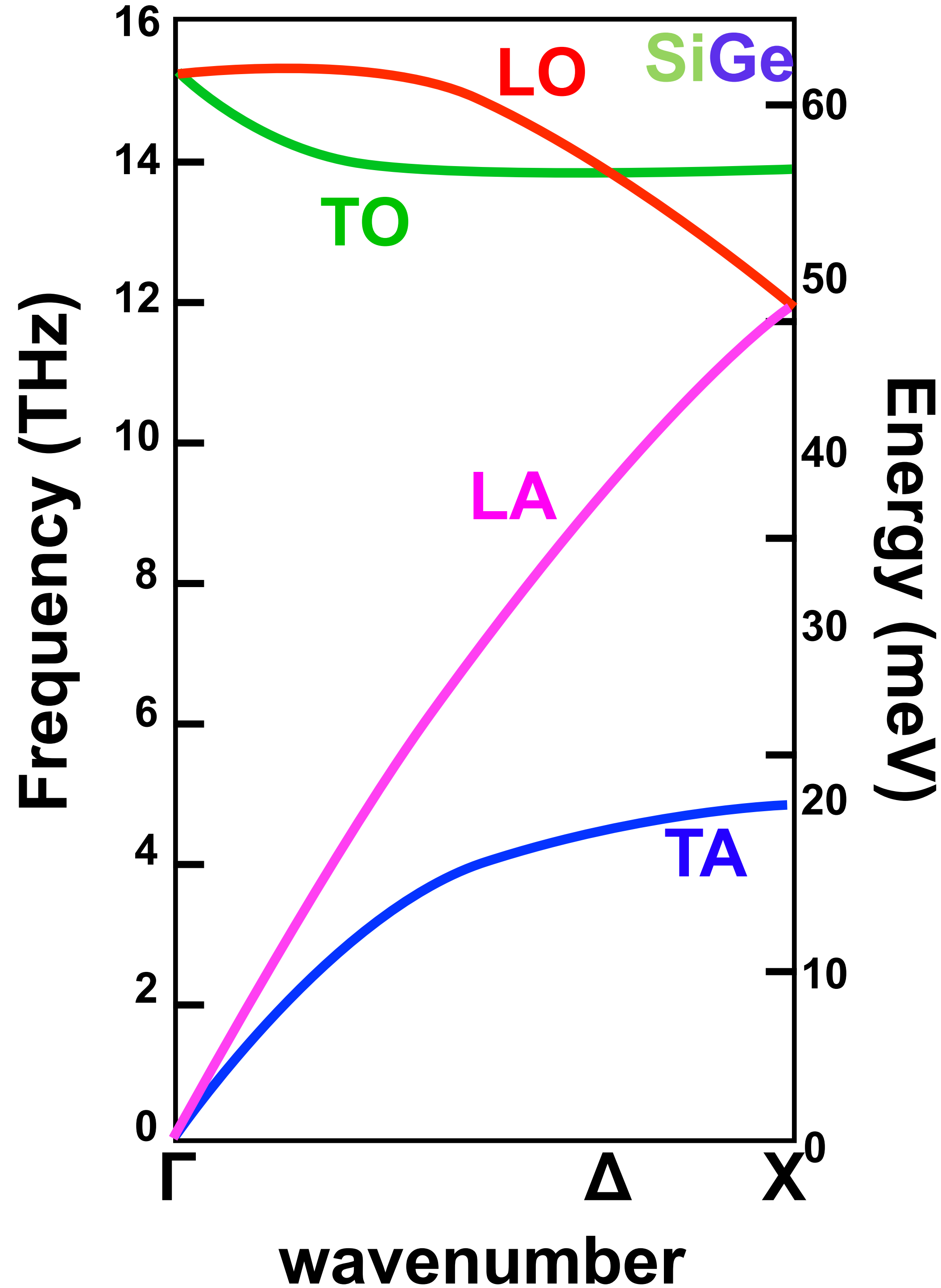
- **Efficiency can be high as η is dominated by absorption of photons**
- **Optimisation is all about maximum photon absorption and minimum heat loss**
- **46% to 74% η for solar energy –> heat conversion are typical**
- **η heavily dependent on amount of solar energy available and required hot water temperature**

Application Reality Check

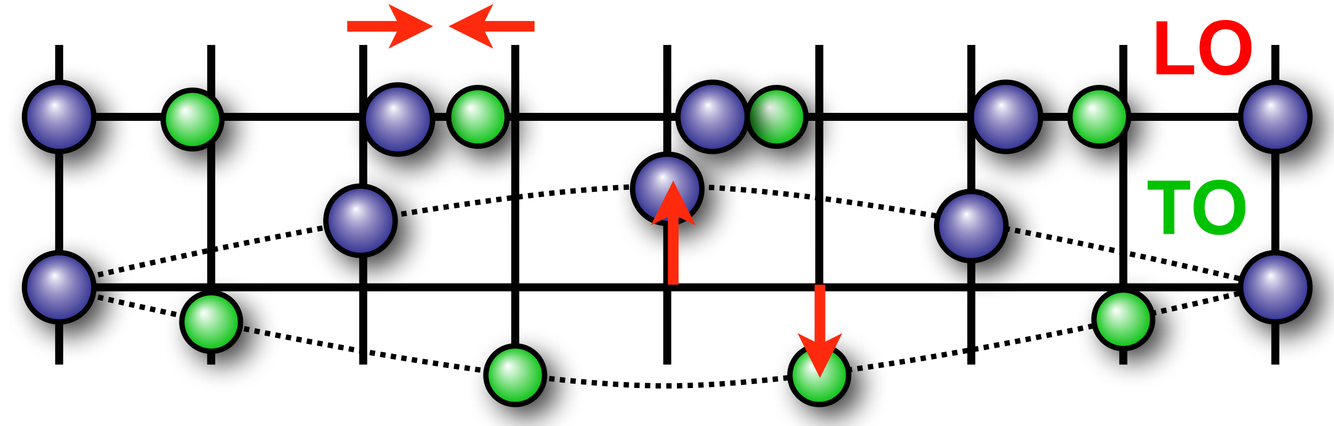
- NASA with finite Pu fuel for RTG requires high efficiency
- Automotive requires high power (heat is abundant)
- Industrial sensing requires high power (heat is abundant)
- Autonomous sensing requires high power (heat is abundant)
- As heat is abundant the issue is how to maximise power output NOT efficiency for most applications

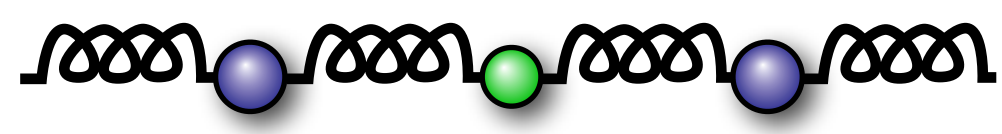
$$\text{Power} \propto \alpha^2\sigma$$

Phonons: Lattice Vibration Heat Transfer



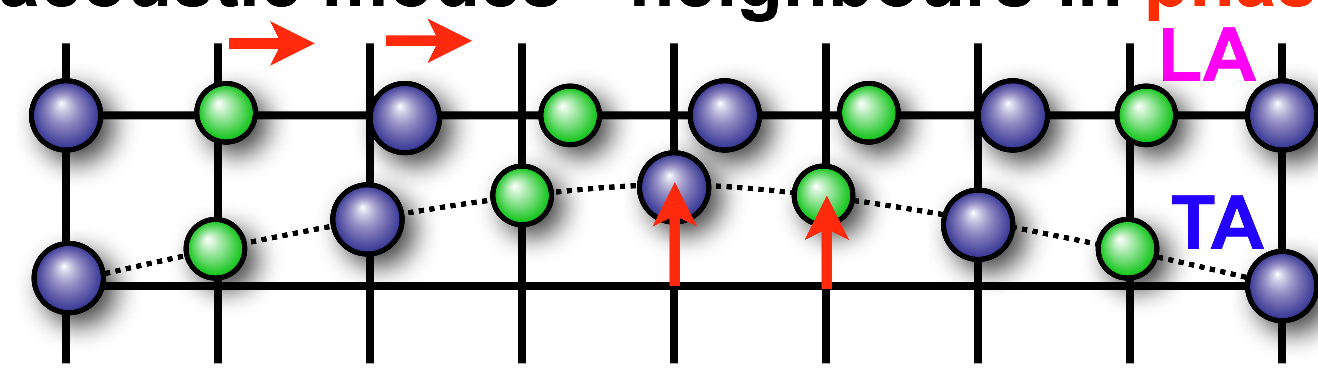
optic modes - neighbours in antiphase





NB acoustic phonons transmit most thermal energy

acoustic modes - neighbours in phase



- The majority of heat in solids is transported by acoustic phonons

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Thermal Conductivity

Lattice contribution:

- $$\kappa_{ph} = \frac{k_B}{2\pi^2}\left(\frac{k_B}{\hbar}\right)^3 T^3 \int_0^{\frac{\theta_D}{T}} \frac{\tau_c(x)x^4 e^x}{\upsilon(x)(e^x-1)^2}dx$$

θ_D = Debye temperature (640 K for Si)

$x = \frac{\hbar\omega}{k_B T}$

τ_c = combined phonon scattering time

$\upsilon(x)$ = velocity

J. Callaway, Phys. Rev. 113, 1046 (1959)

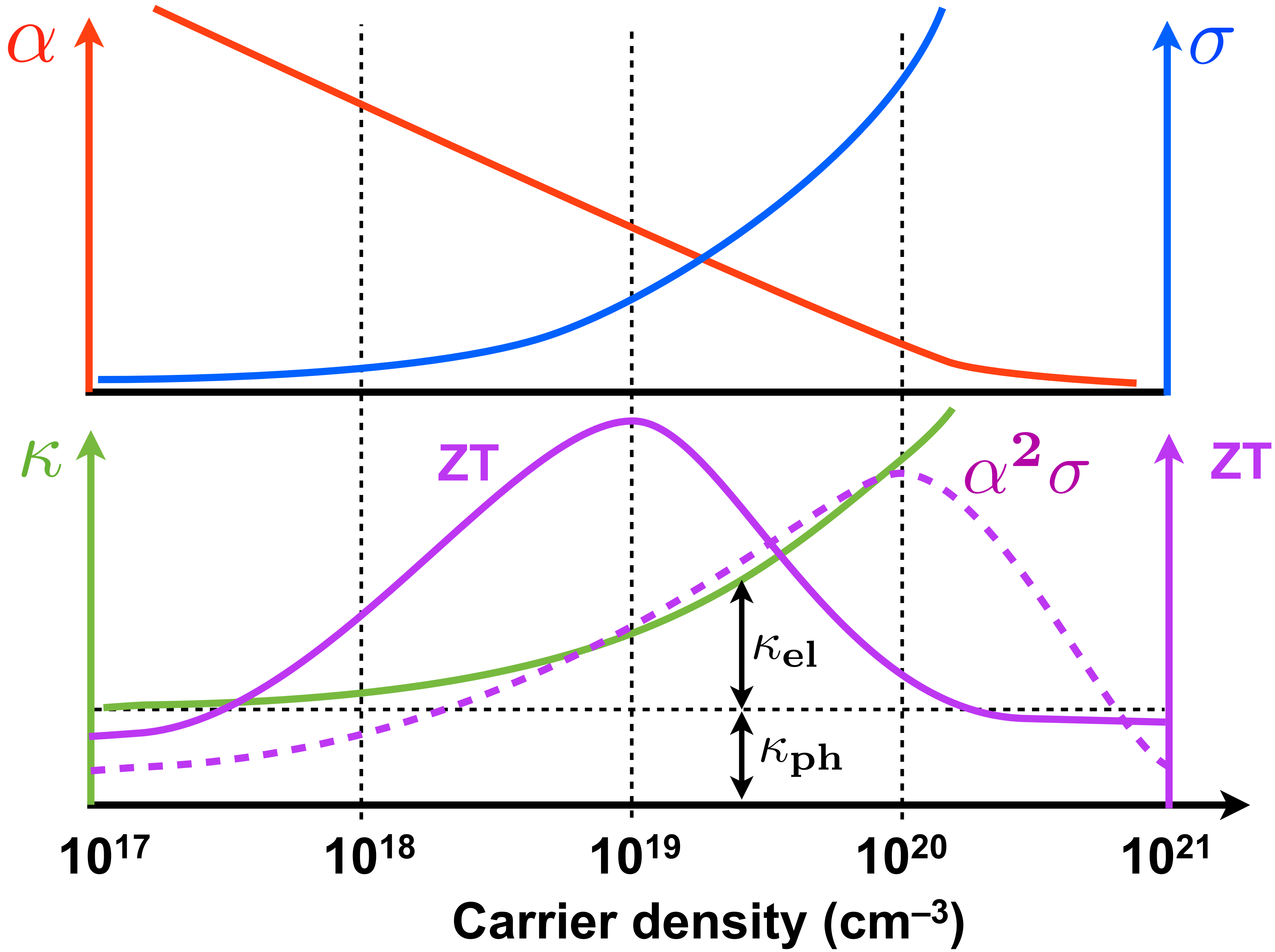
Electron (hole) contribution:

- $$\kappa_{el} = \frac{\sigma}{q^2 T}\left[\frac{\langle\tau\rangle\langle E^2\tau\rangle - \langle E\tau\rangle^2}{\langle\tau^3\rangle}\right]$$

$\tau(E)$ = total electron momentum relaxation time

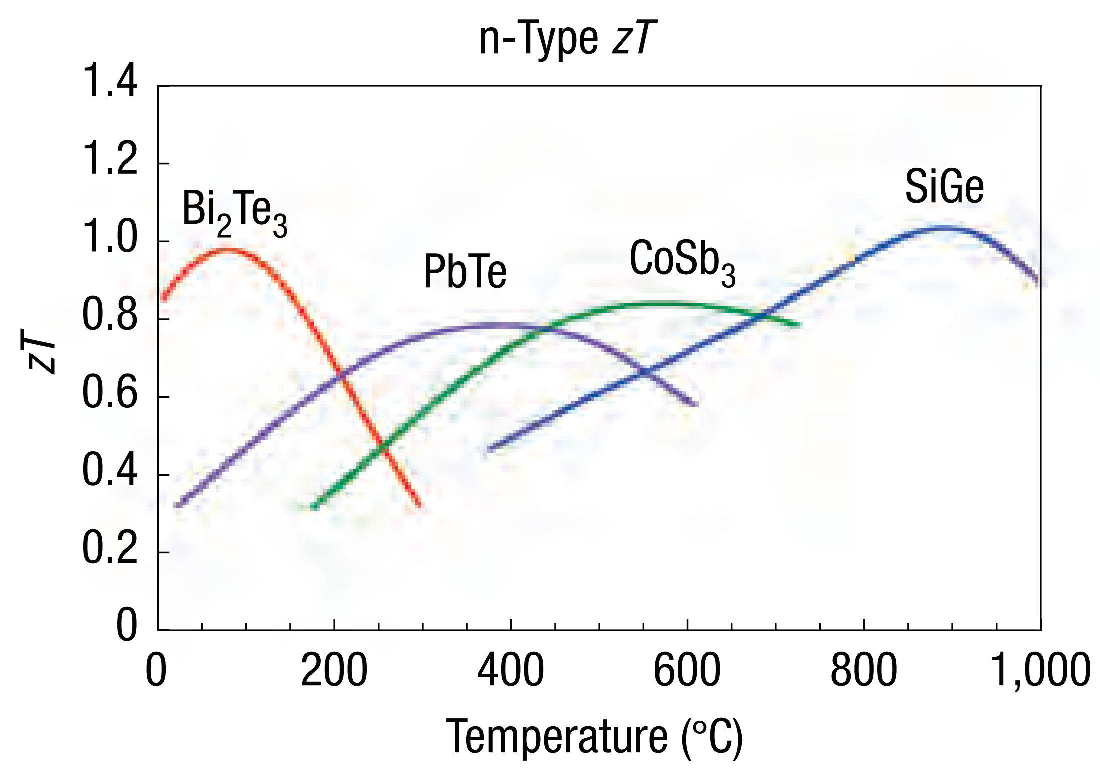
B. R. Nag, Electron Transport in Compound Semiconductors, (Springer-Verlag, New York USA, 1980)

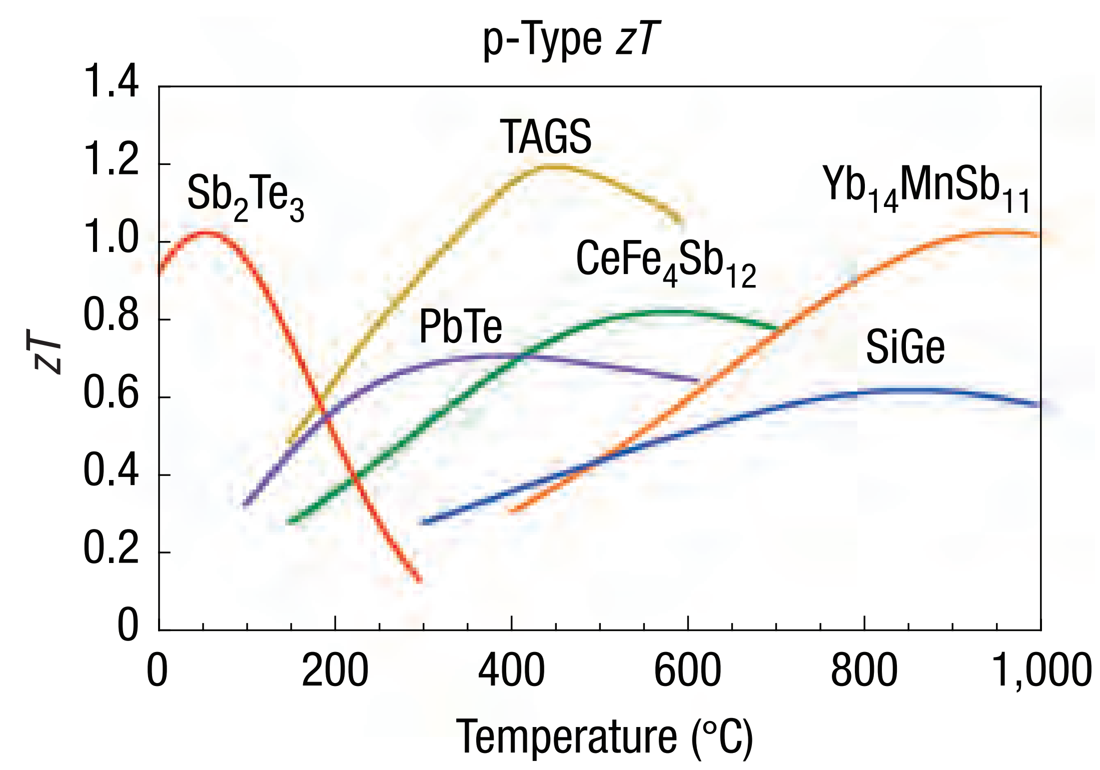
Thermoelectric vs Doping of Semiconductors



- Electrical and thermal conductivities are not independent
- Wiedemann Franz rule: electrical conductivity ∝ thermal conductivity at high doping

Bulk Thermoelectric Materials Performance





Nature Materials 7, 105 (2008)

- **Bulk n-Bi_2Te_3 and p-Sb_2Te_3 used in most commercial thermoelectrics & Peltier coolers**
- **But tellurium is 9th rarest element on earth !!!**
- **Bulk $Si_{1-x}Ge_x$ (x~0.2 to 0.3) used for high temperature satellite applications**

University of Glasgow

Main Strategies for Optimising ZT

Reducing thermal conductivity faster than electrical conductivity:

- e.g. skutterudite structure: filling voids with heavy atoms

Low-dimensional structures:

- Increase α by enhanced DOS ($\alpha = -\frac{\pi^2}{3q}k_B^2 T \left[\frac{d\ln(\mu(E)g(E))}{dE}\right]_{E=E_F}$)
- Make κ and σ almost independent
- Reduce κ through phonon scattering on heterointerfaces

Energy filtering:

enhance

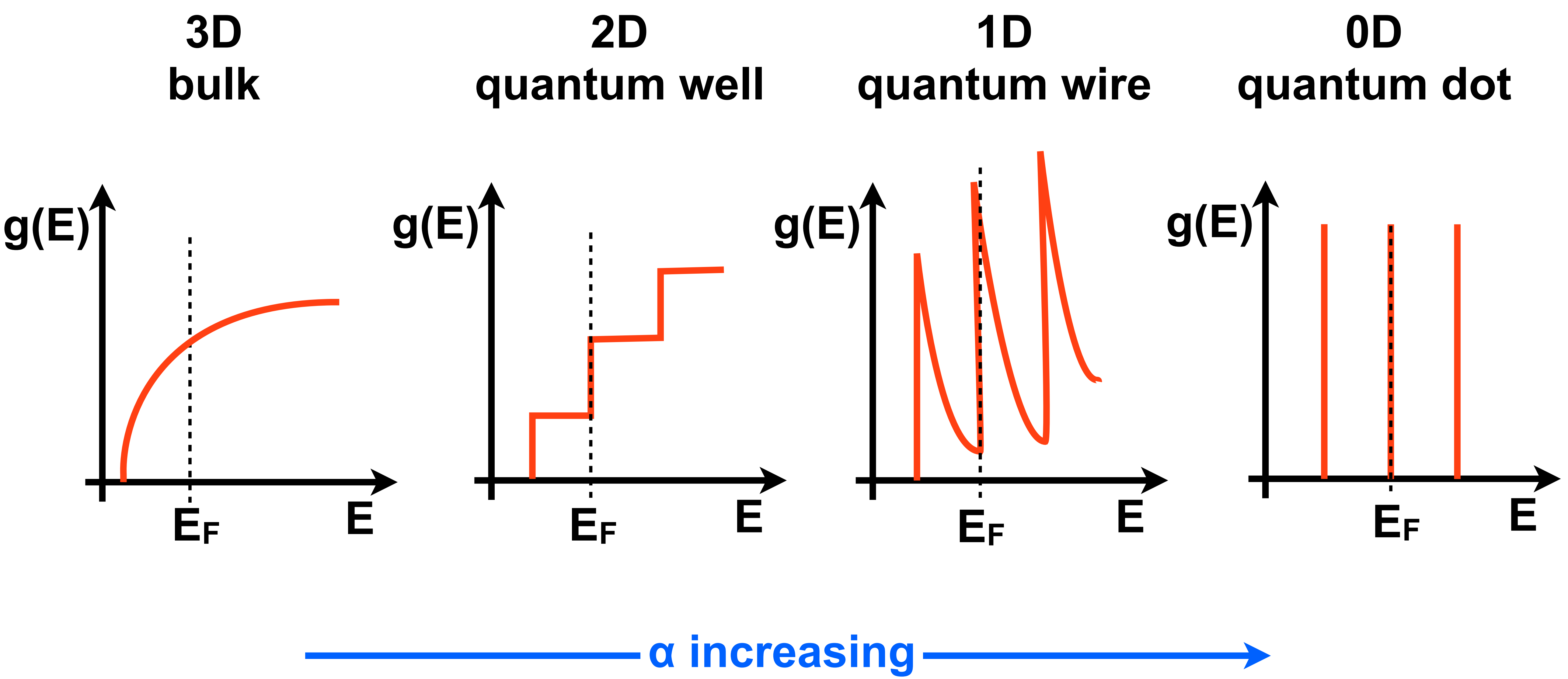
- $$\alpha = -\frac{k_B}{q}\left[\frac{E_c - E_F}{k_B T} + \frac{\int_0^\infty \frac{(E-E_c)}{k_B T}\sigma(E)dE}{\int_0^\infty \sigma(E)dE}\right]$$

Y.I. Ravich et al., Phys. Stat. Sol. (b) 43, 453 (1971)

Seebeck Enhancement at Low Dimensions

- **Increase α through enhanced DOS:**

$$\alpha = -\frac{\pi^2}{3q} k_B^2 T \left[\frac{d\ln(\mu(E)g(E))}{dE} \right]_{E=E_F}$$



M. Cutler & N.F. Mott, Phys. Rev. 181, 1336 (1969)

Length Scales: Mean Free Paths

3D electron mean free path $$\ell = \mathbf{v_F}\tau_\mathbf{m} = \frac{\hbar}{\mathbf{m}^*}(3\pi^2\mathbf{n})^{\frac{1}{3}}\frac{\mu\mathbf{m}^*}{\mathbf{q}}$$

$$\ell = \frac{\hbar\mu}{\mathbf{q}}(3\pi^2\mathbf{n})^{\frac{1}{3}}$$

3D phonon mean free path $$\Lambda_\mathbf{ph} = \frac{3\kappa_\mathbf{ph}}{\mathbf{C_v}\langle\mathbf{v_t}\rangle\rho}$$

- C_v = specific heat capacity
- $\langle v_t \rangle$ = average phonon velocity
- ρ = density of phonons

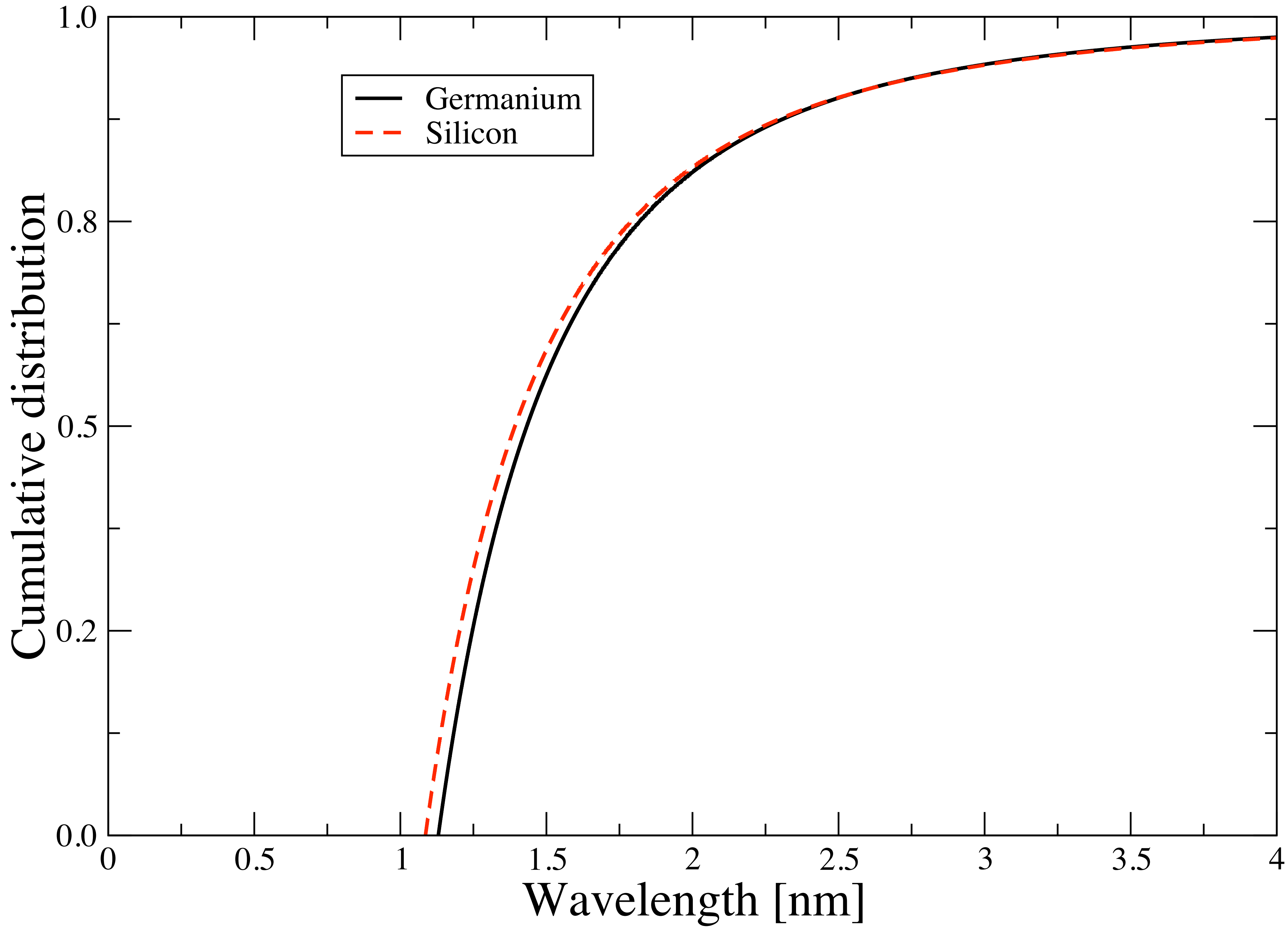
- A structure may be 2D or 3D for electrons but 1 D for phonons (or vice versa!)

Phonon Mean Free Paths

Material	Model	Specific Heat ($x10^6$ $Jm^{-3}K^{-1}$)	Group velocity (ms^{-1})	Phonon mean free path, Λ_{ph} (nm)
Si	Debye	1.66	6400	40.9
Si	Dispersion	0.93	1804	260.4
Ge	Debye	1.67	3900	27.5
Ge	Dispersion	0.87	1042	198.6

G. Chen, Phys. Rev. B 57, 14958 (1998)

Phonon Wavelengths that Carry Heat



- **Greater than 95% of heat conduction in Si / Ge from phonons with wavelengths between 1.2 and 3.5 nm**

Phonon Enhancements

Phonon scattering:

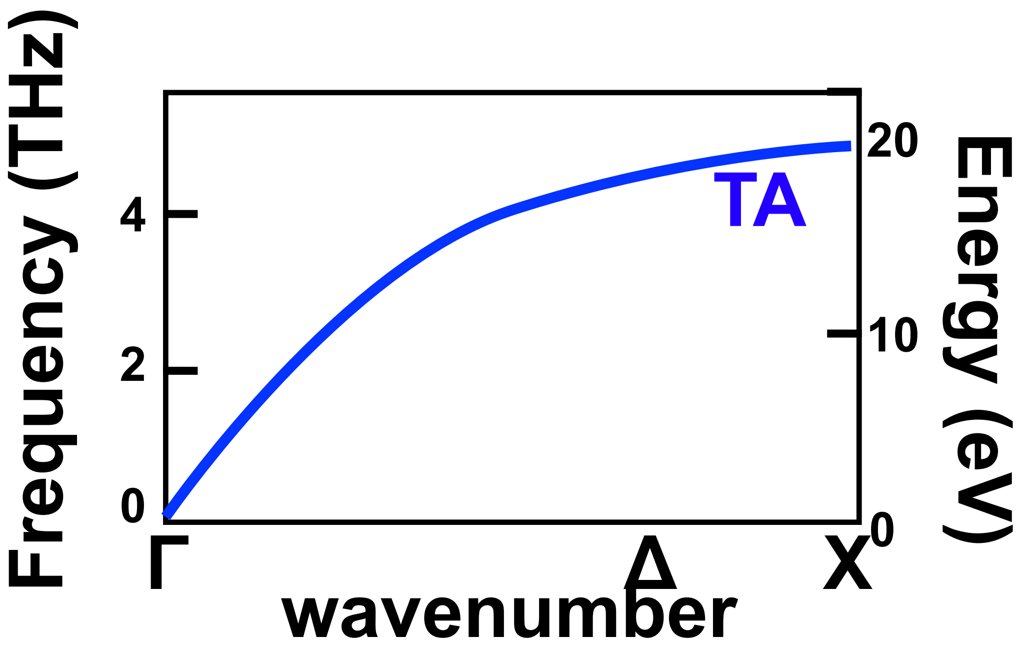
- Require structures below the phonon mean free path (10s nm)

Phonon Bandgaps:

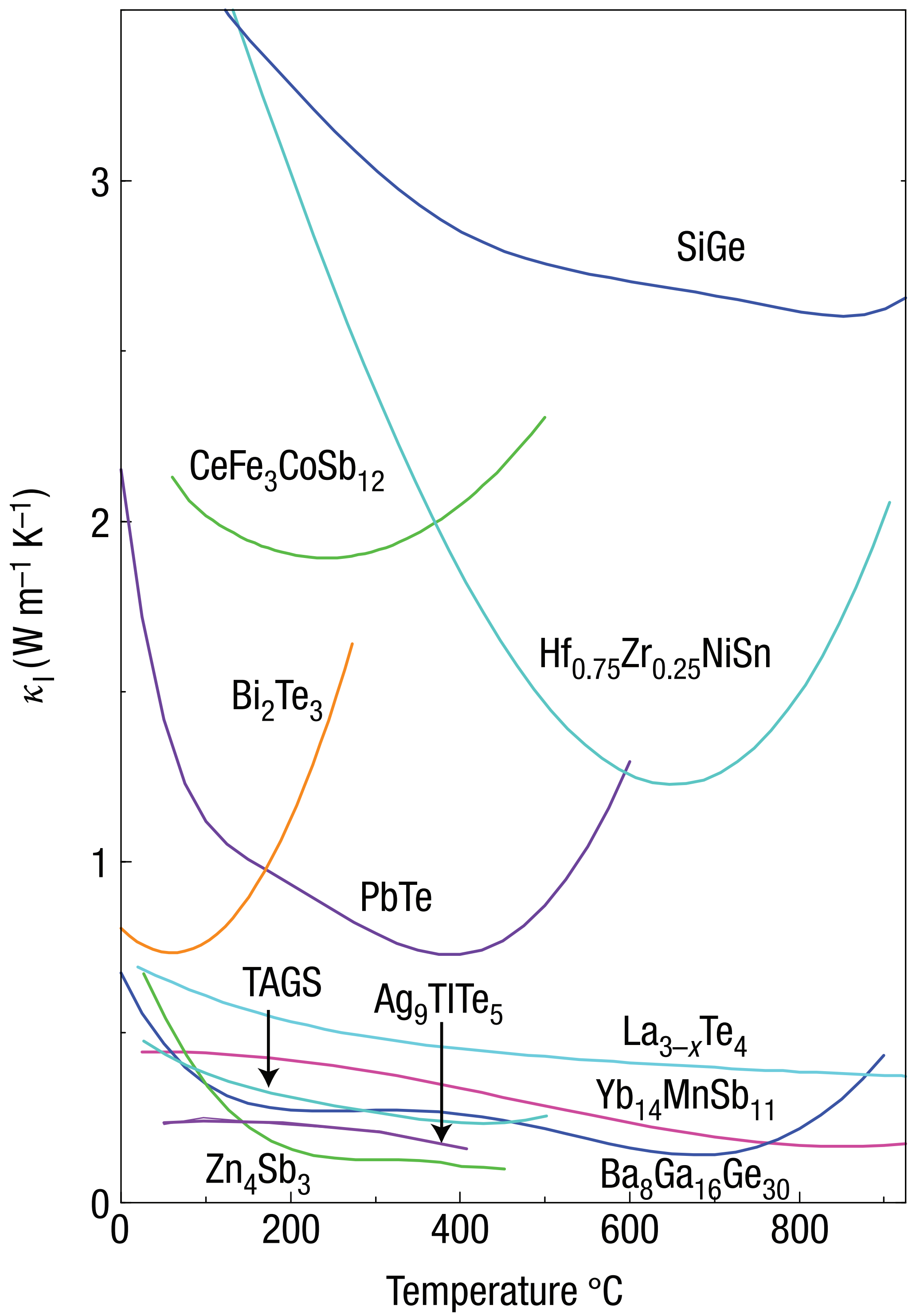
- Change the acoustic phonon dispersion –> stationary phonons or bandgaps

- Require structures with features at the phonon wavelength (< 5 nm)

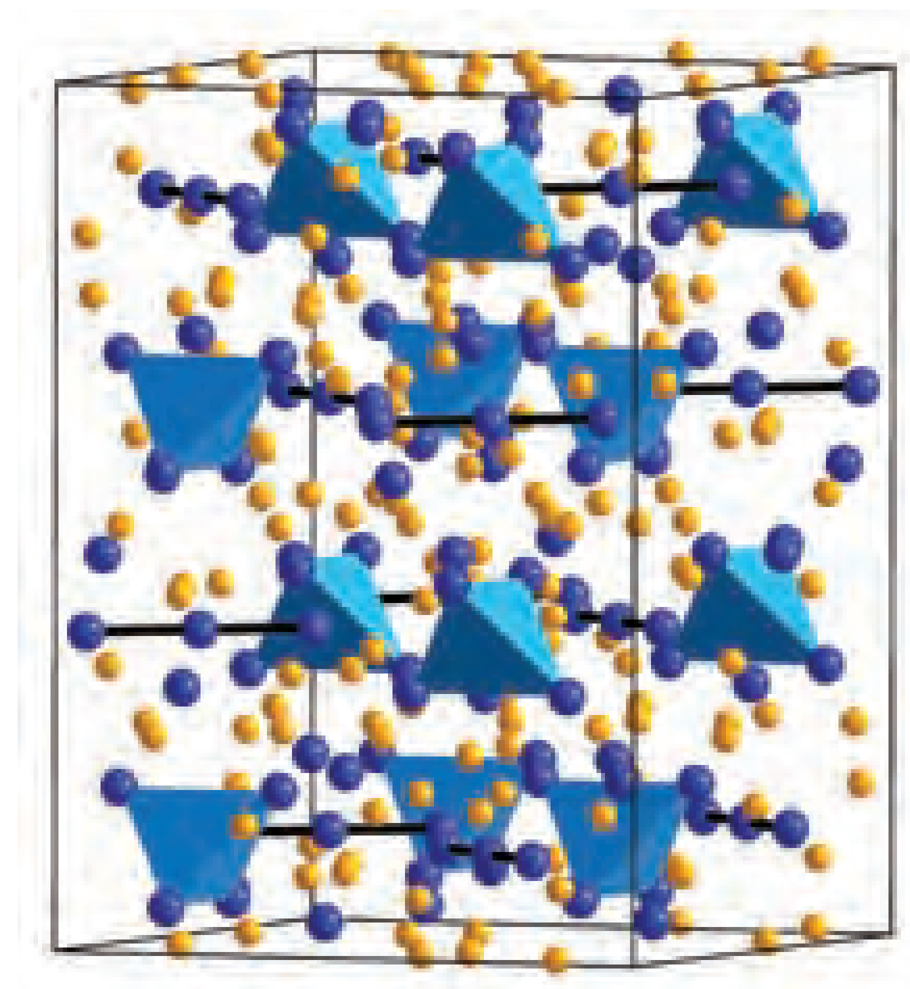
- Phonon group velocity $\propto \frac{dE}{dk_q}$



Complex Crystal Structures: Reducing κ_{ph}



Skutterudite structure: filling voids with heavy atoms

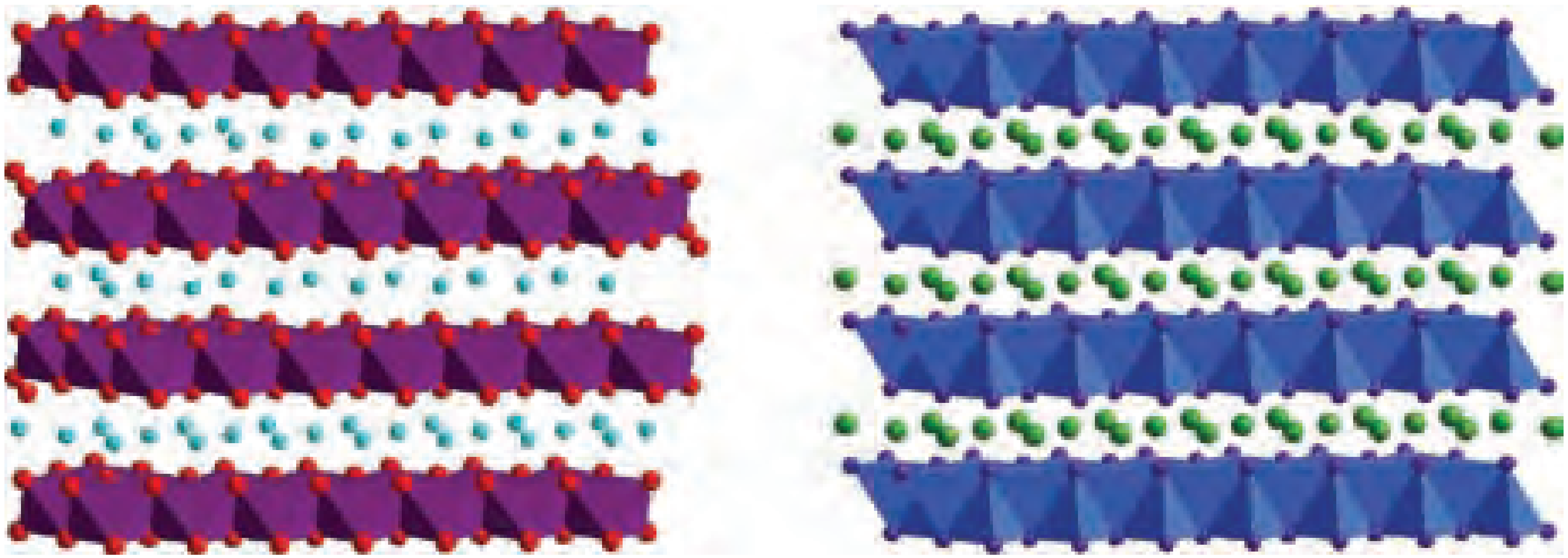


p-$Yb_{14}MnSb_{11}$ – ZT ~ 1 @ 900 ˚C

G.J. Snyder et al., Nat. Mat. 7, 105 (2008)

Electron Crystal – Phonon Glass Materials

- Principle: trying to copy "High T_c" superconductor structures
- Heavy ion / atom layers for phonon scattering
- High mobility electron layers for high electrical conductivity

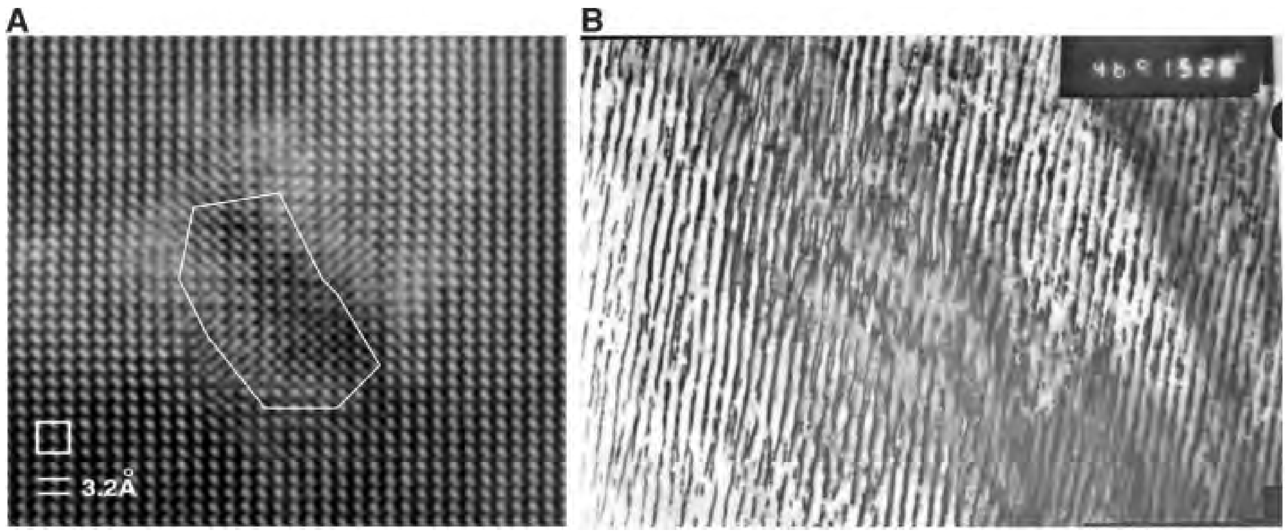


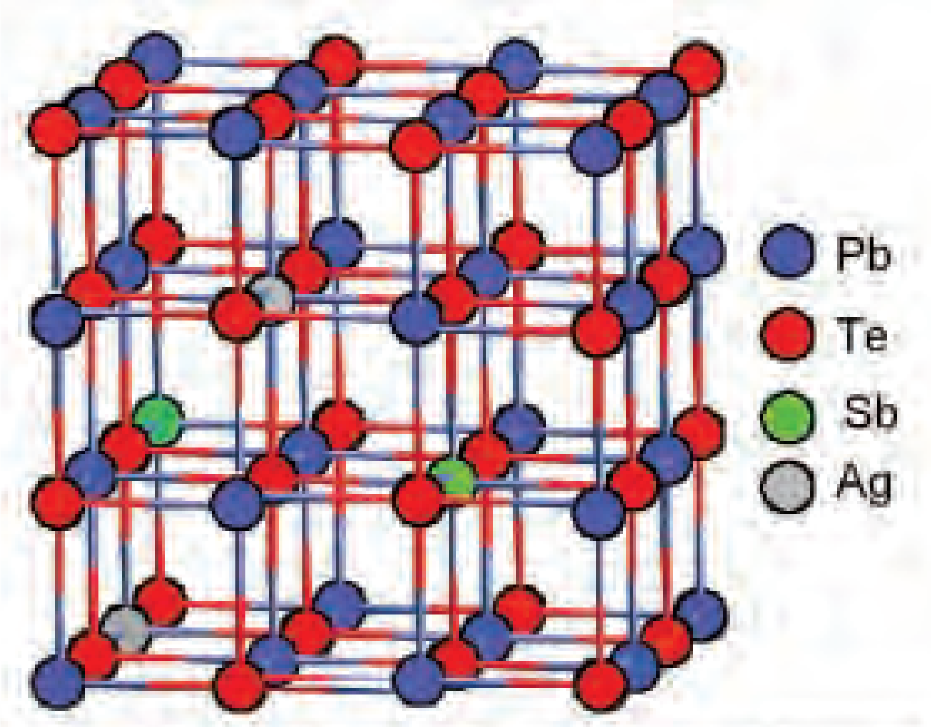
Na_xCoO_2 $Ca_xYb_{1-x}Zn_2Sb_2$

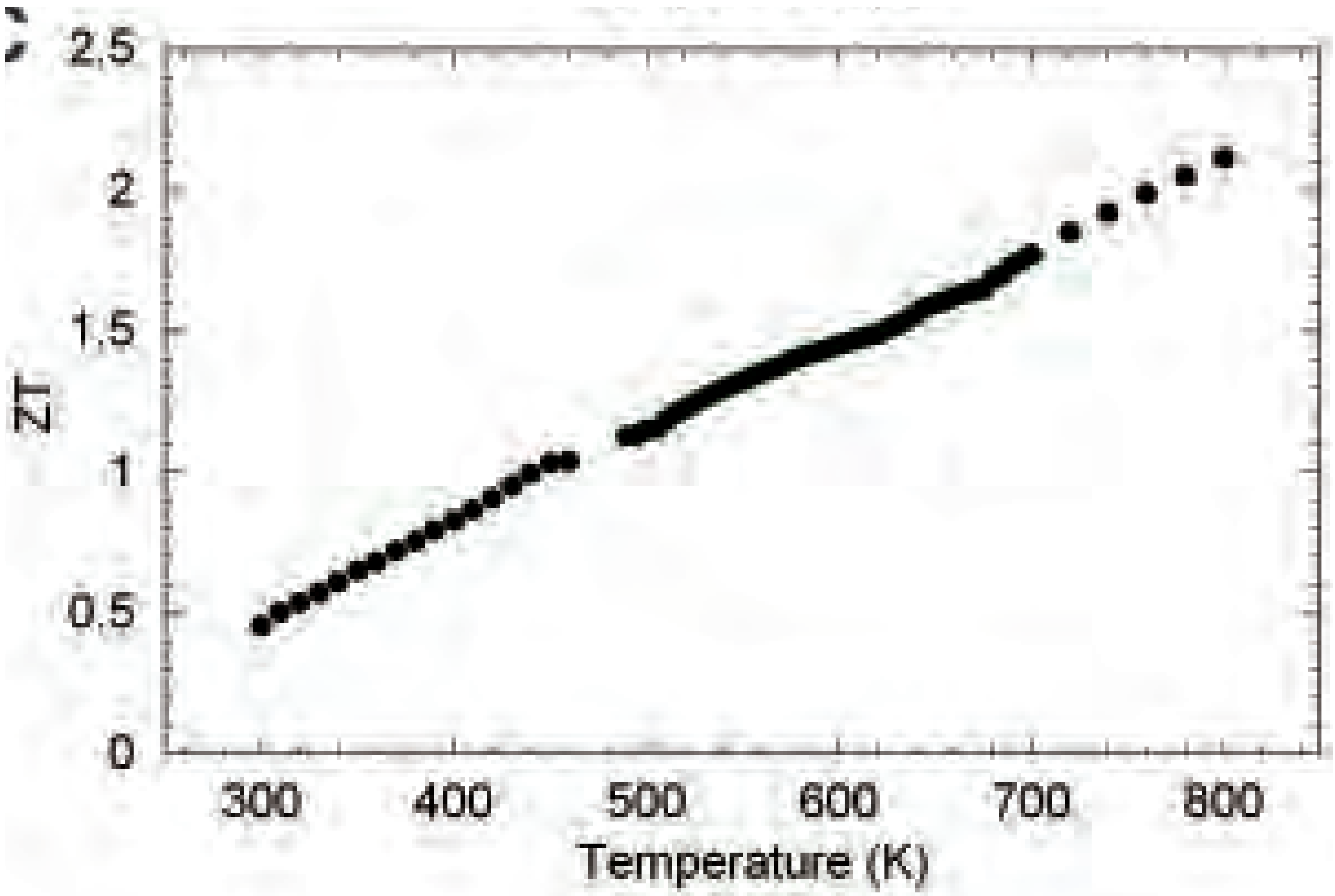
- Only small improvements to ZT observed

G.J. Snyder et al., Nat. Mat. 7, 105 (2008)

$AgPb_{18}SbTe_{20}$ – Nanoparticle Scattering?



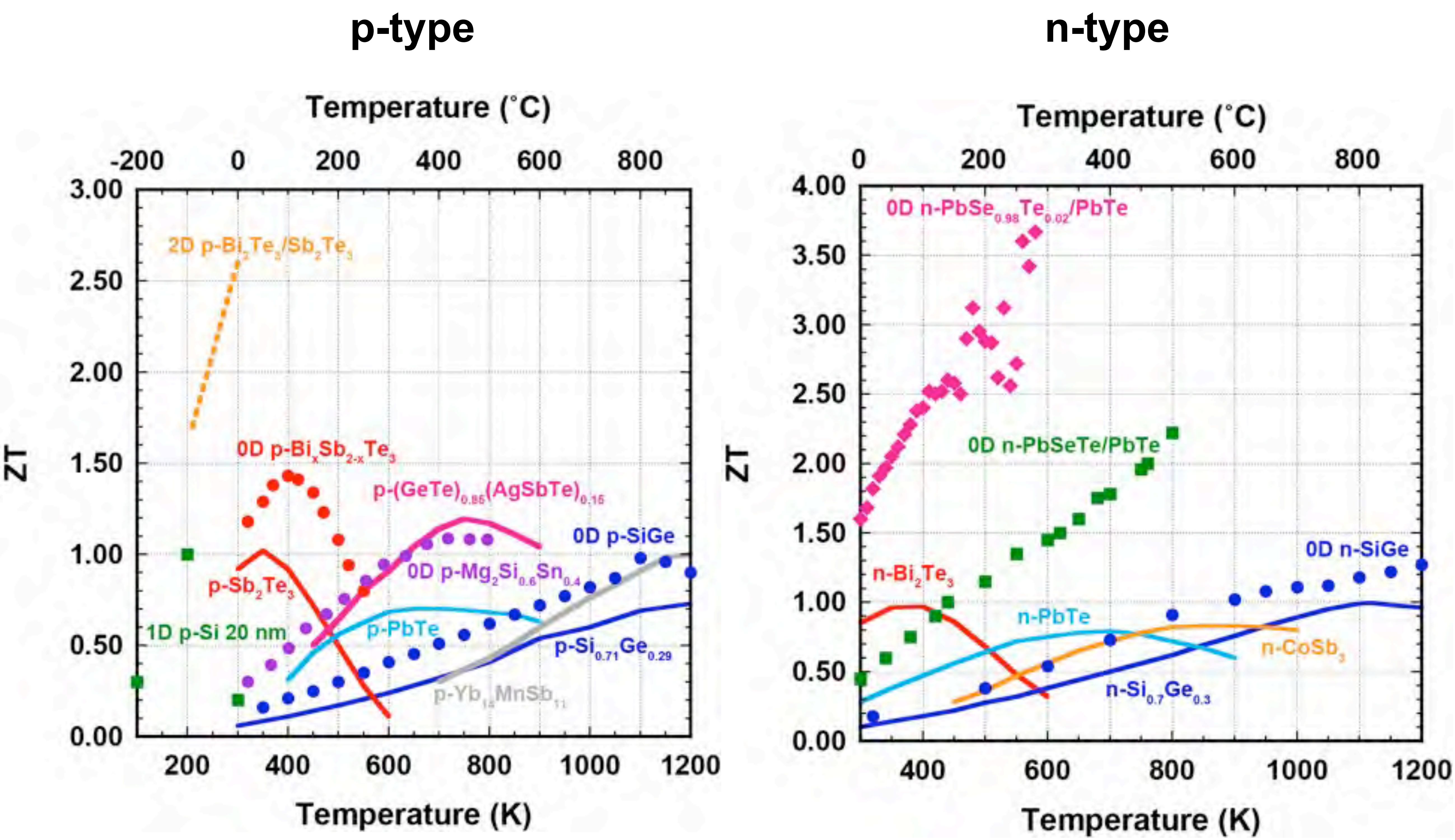




α = –335 μVK^{-1}
σ = 30,000 S/m
κ = 1.1 $Wm^{-1}K^{-1}$
at 700 K

K.F. Hsu et al., Science 303, 818 (2004)

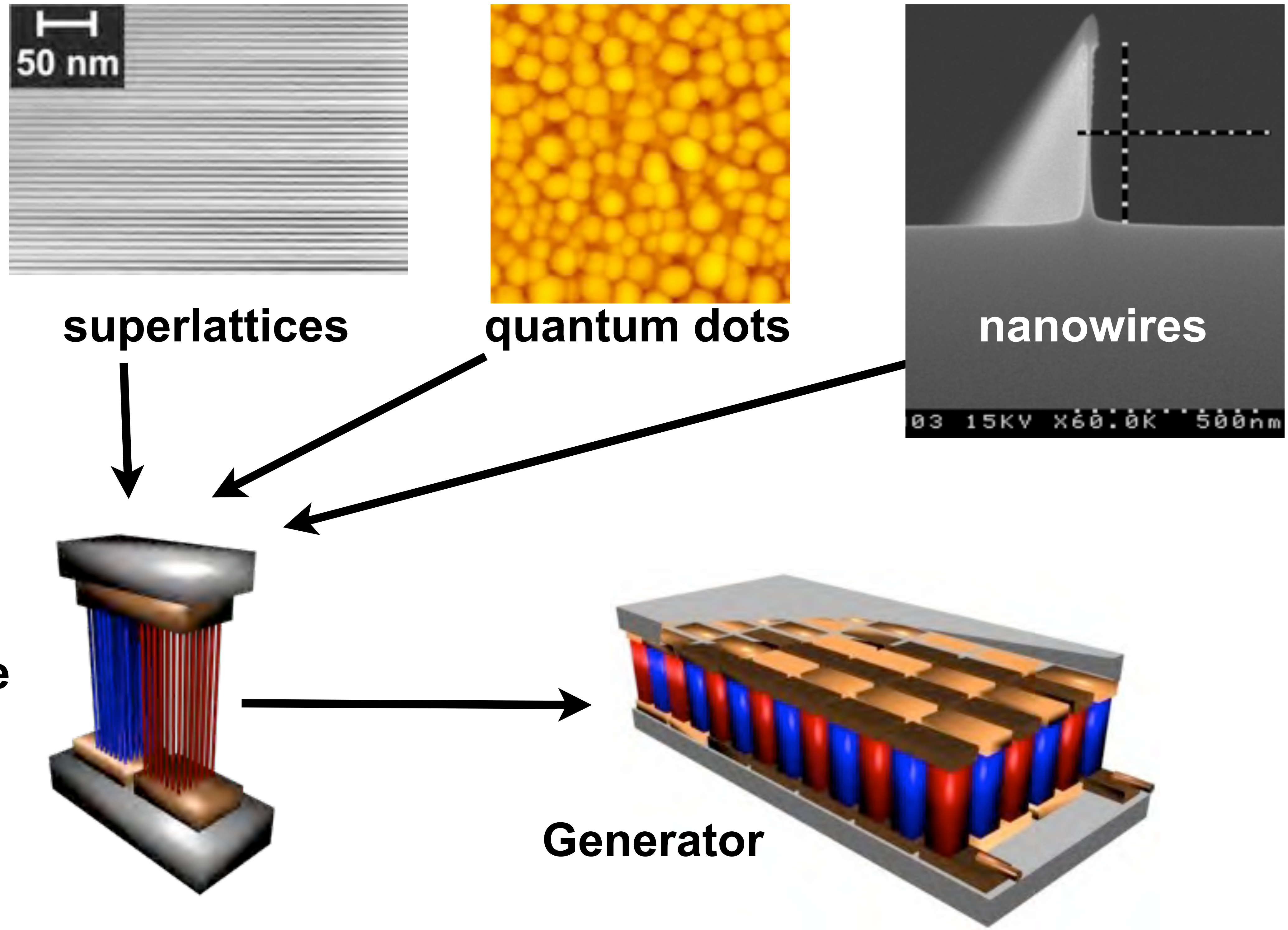
ZT versus Temperature



- **Nanostructures can improve Seebeck coefficient and/or decrease thermal conductivity**

GREEN Silicon Approach

Low dimension technology



Module

- **Si/SiGe technology –> cheap and back end of line compatible**

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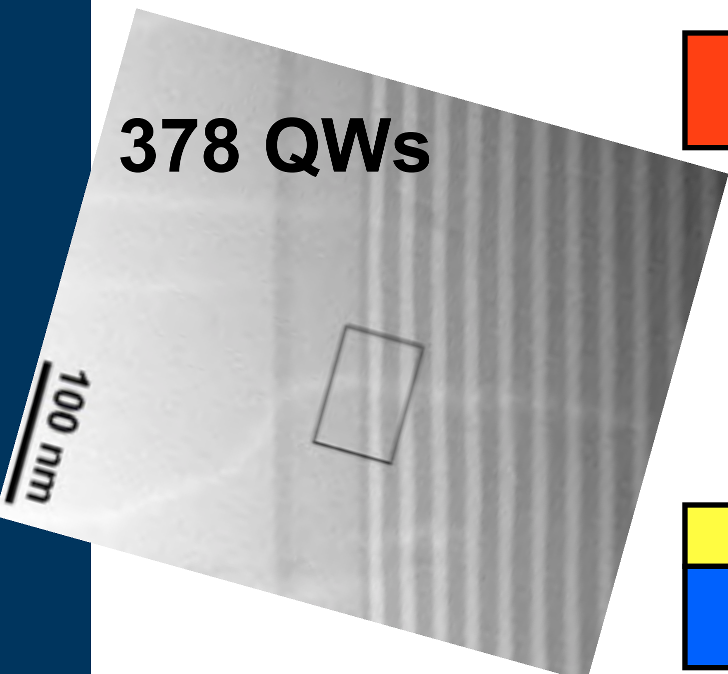
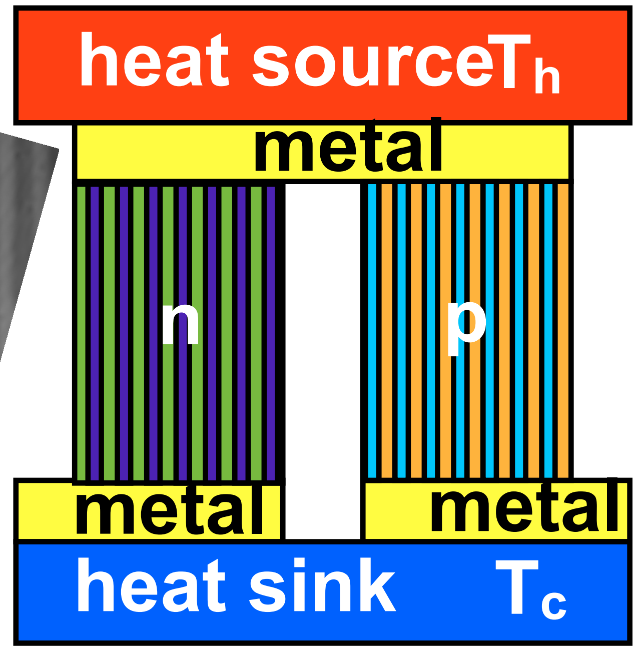
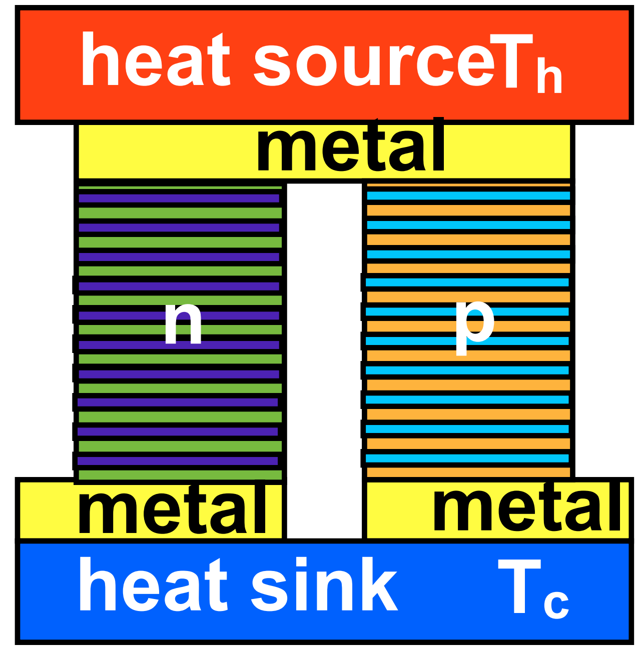
Thermoelectric Low Dimensional Structures

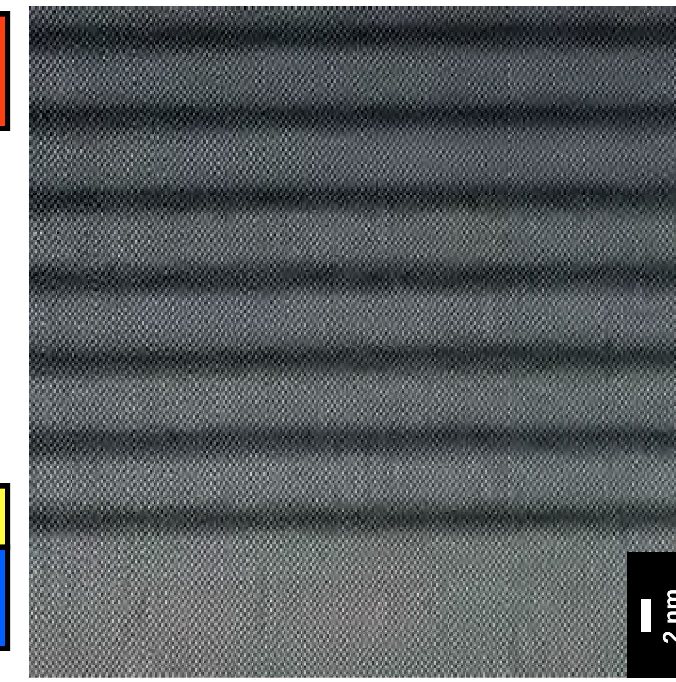


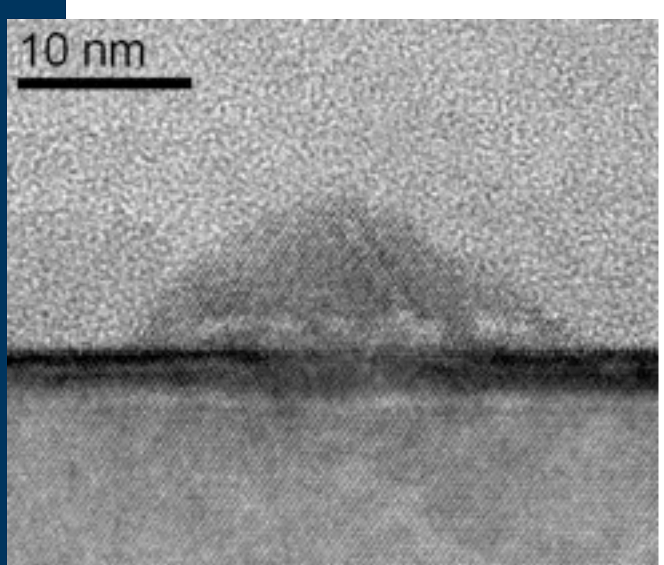
Lateral superlattice



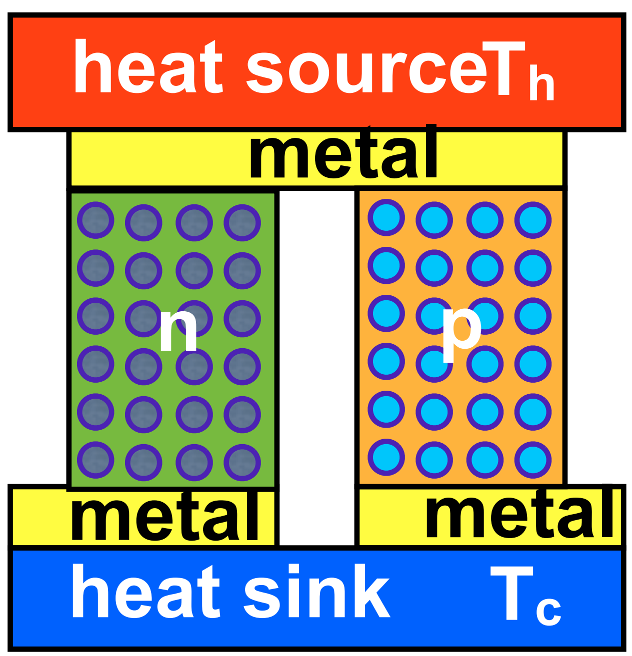
Vertical superlattice



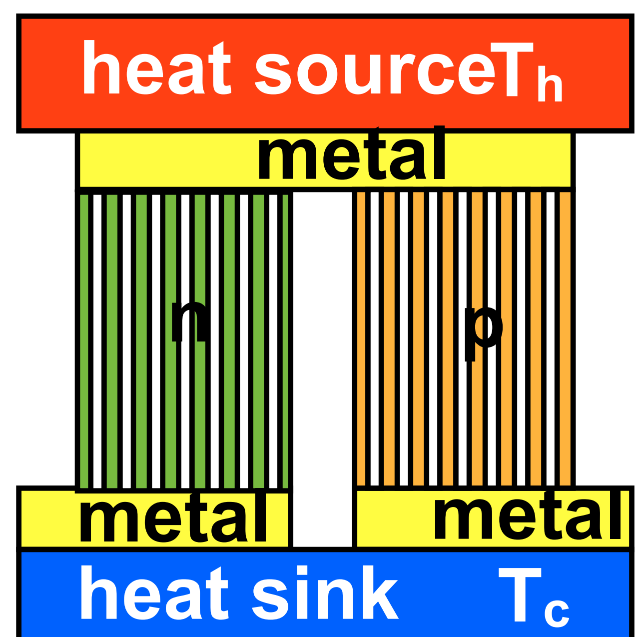


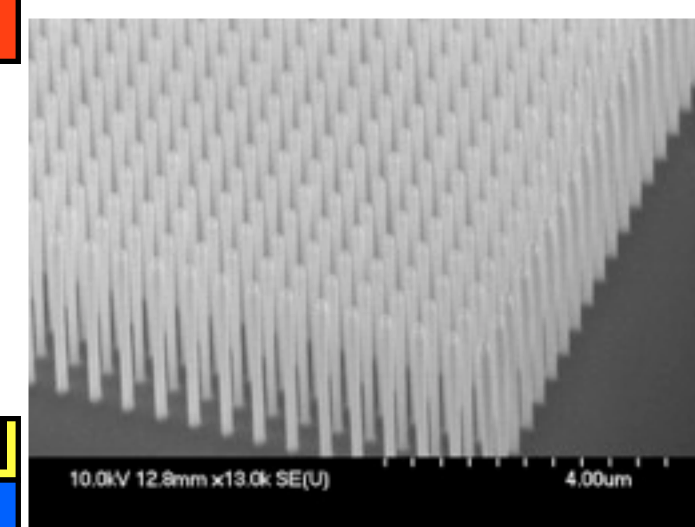


Quantum Dots



Nanowires





Vertical (Cross-plane) Superlattice TEs

- Use of transport perpendicular to superlattice quantum wells
- Higher α from the higher density of states
- Lower electron conductivity from tunnelling
- Lower κ_{ph} from phonon scattering at heterointerfaces
- Able to engineer lower κ_{ph} with phononic bandgaps
- Overall Z and ZT should increase

Vertical superlattice

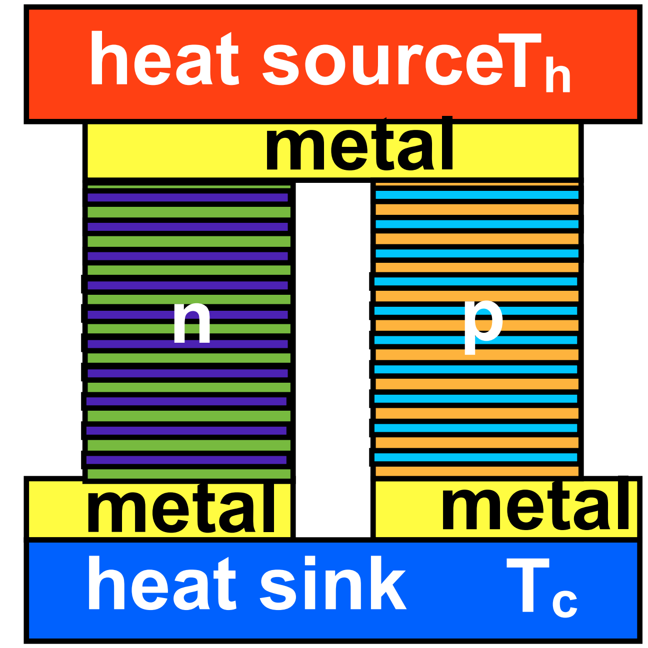
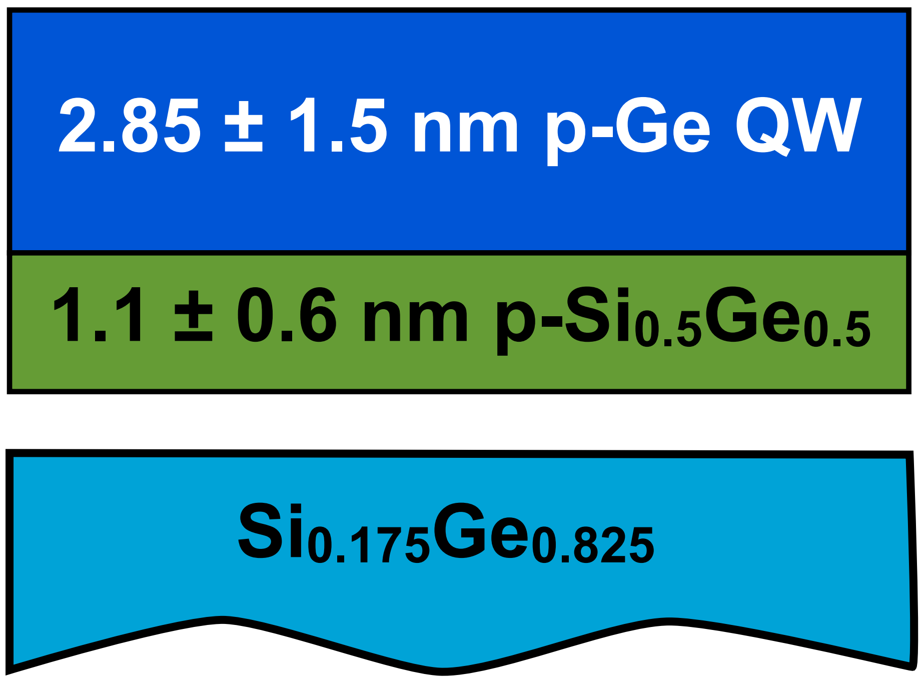


Figure of merit

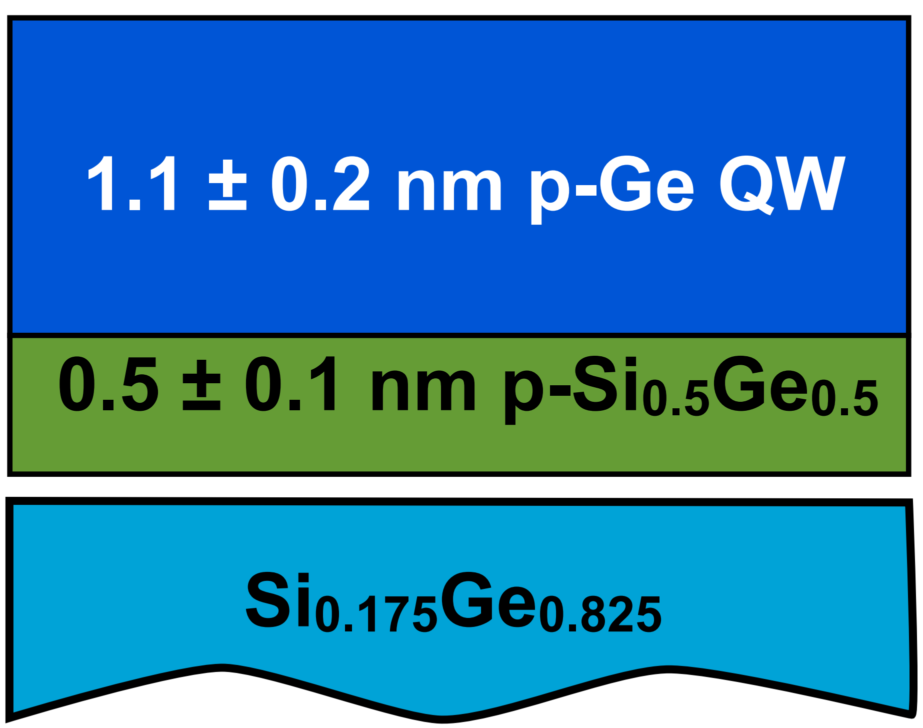
$$\mathrm{ZT} = \frac{\alpha^2 \sigma}{\kappa} \mathrm{T}$$

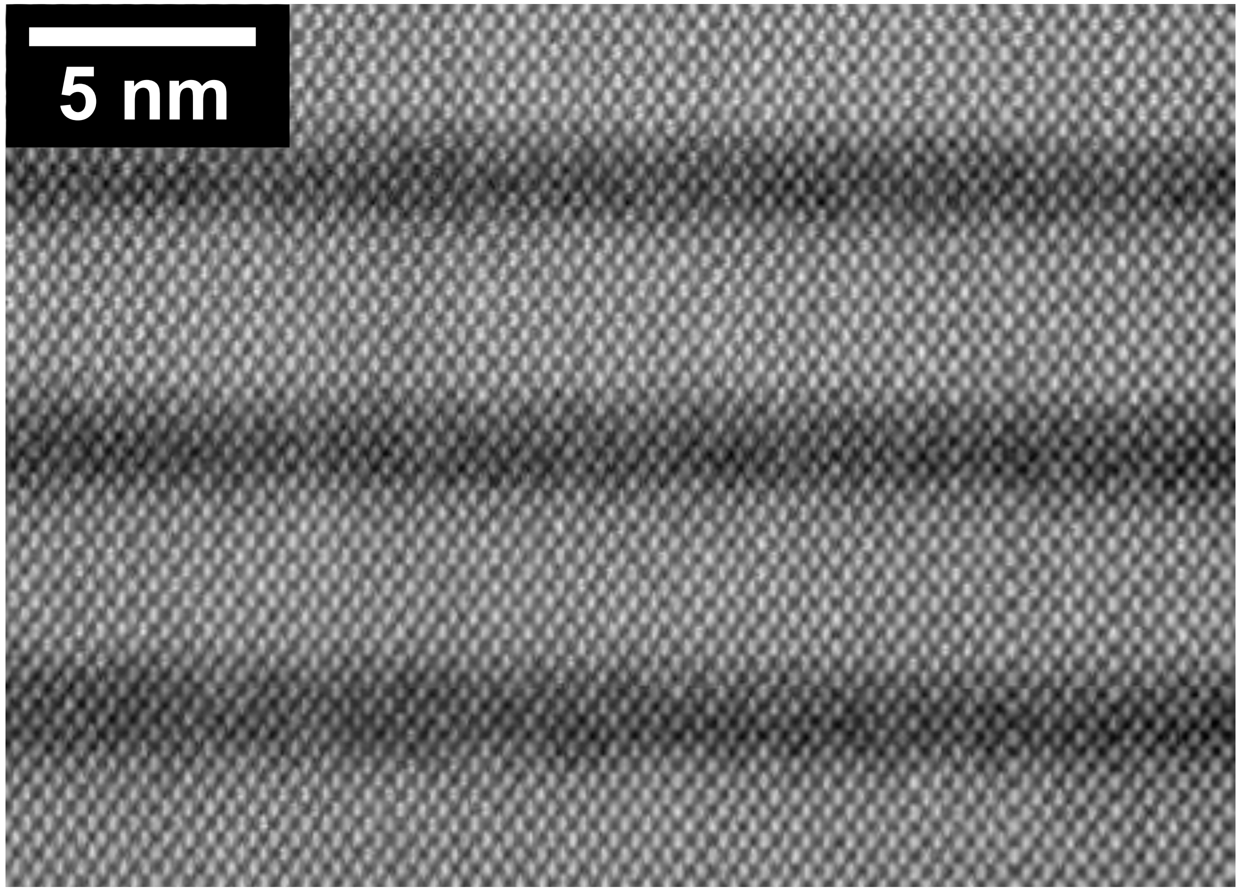
p-type Wafer Designs

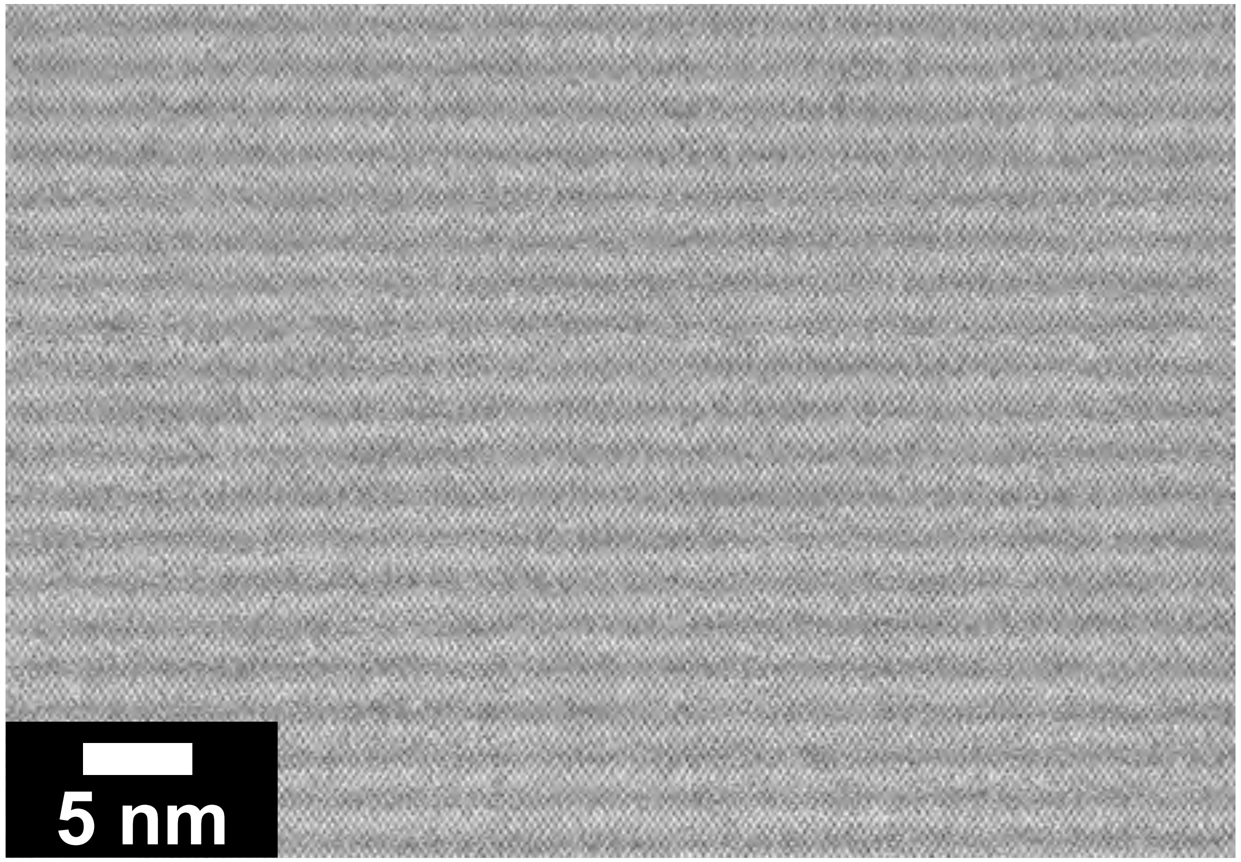
SL1 to SL4: 922 x



SL5: 2338 x

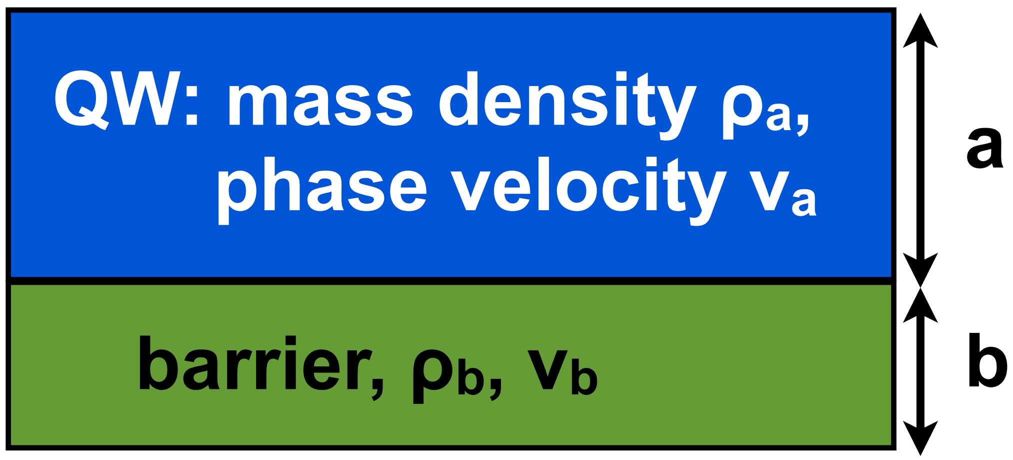






Rytov 1D Continuum Model for Layered Materials

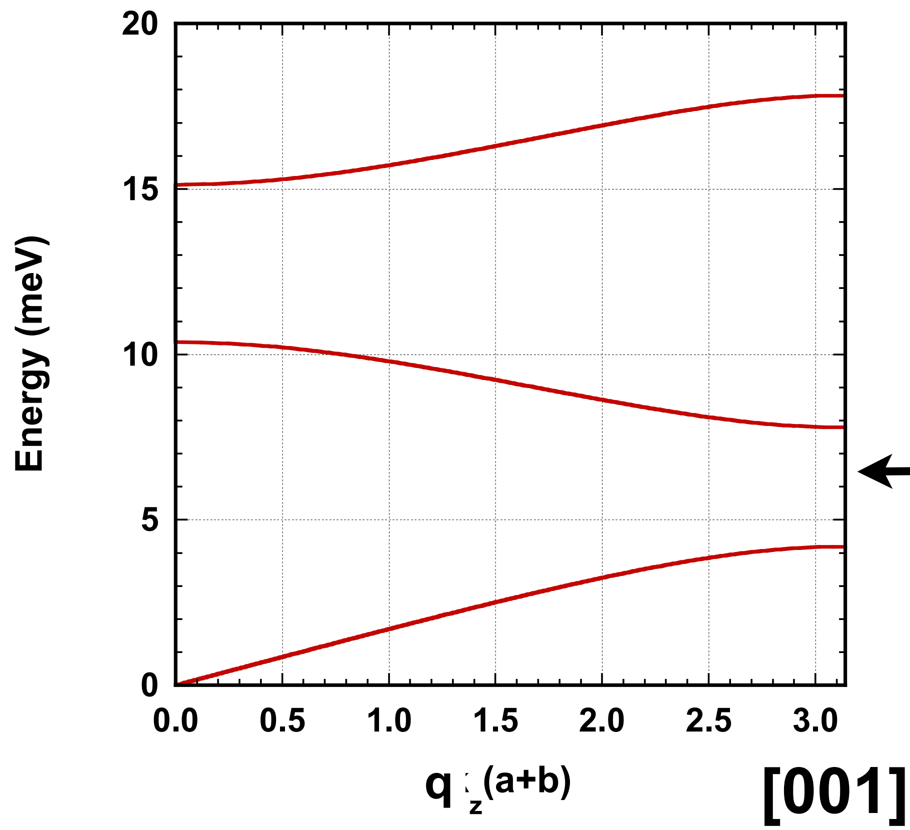
Superlattice N $\rightarrow\infty$



Acoustic mismatch: $\eta = \dfrac{\rho_b v_b}{\rho_a v_a}$

Superlattice zone boundaries: $q_z = \dfrac{n\pi}{a+b}$

$$\cos q_z(a+b) = \cos q_a a \cos q_b b - \left[\frac{1+\eta^2}{2\eta}\right] \sin q_a a \sin q_b b$$

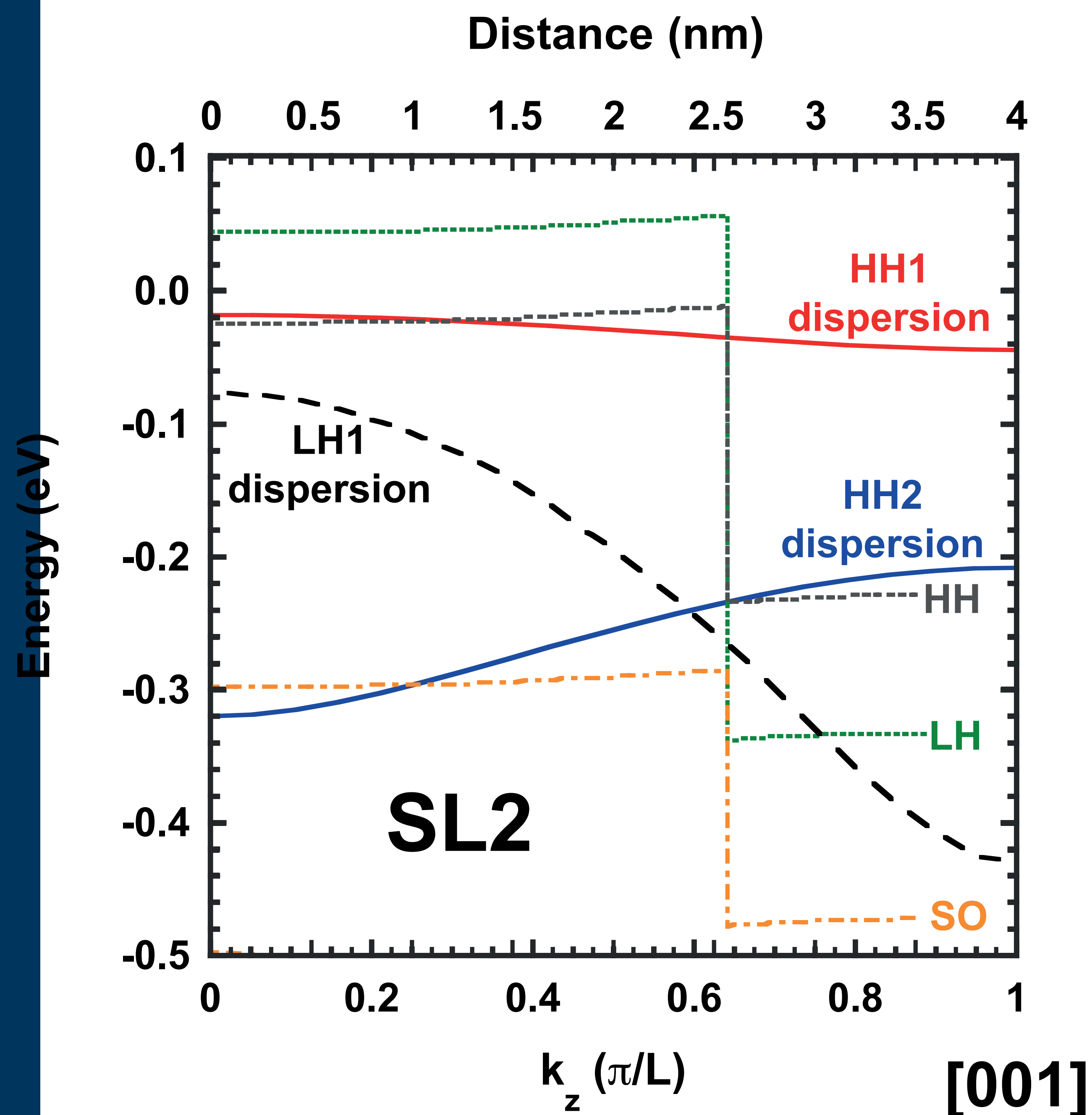


acoustic phonon bandgap

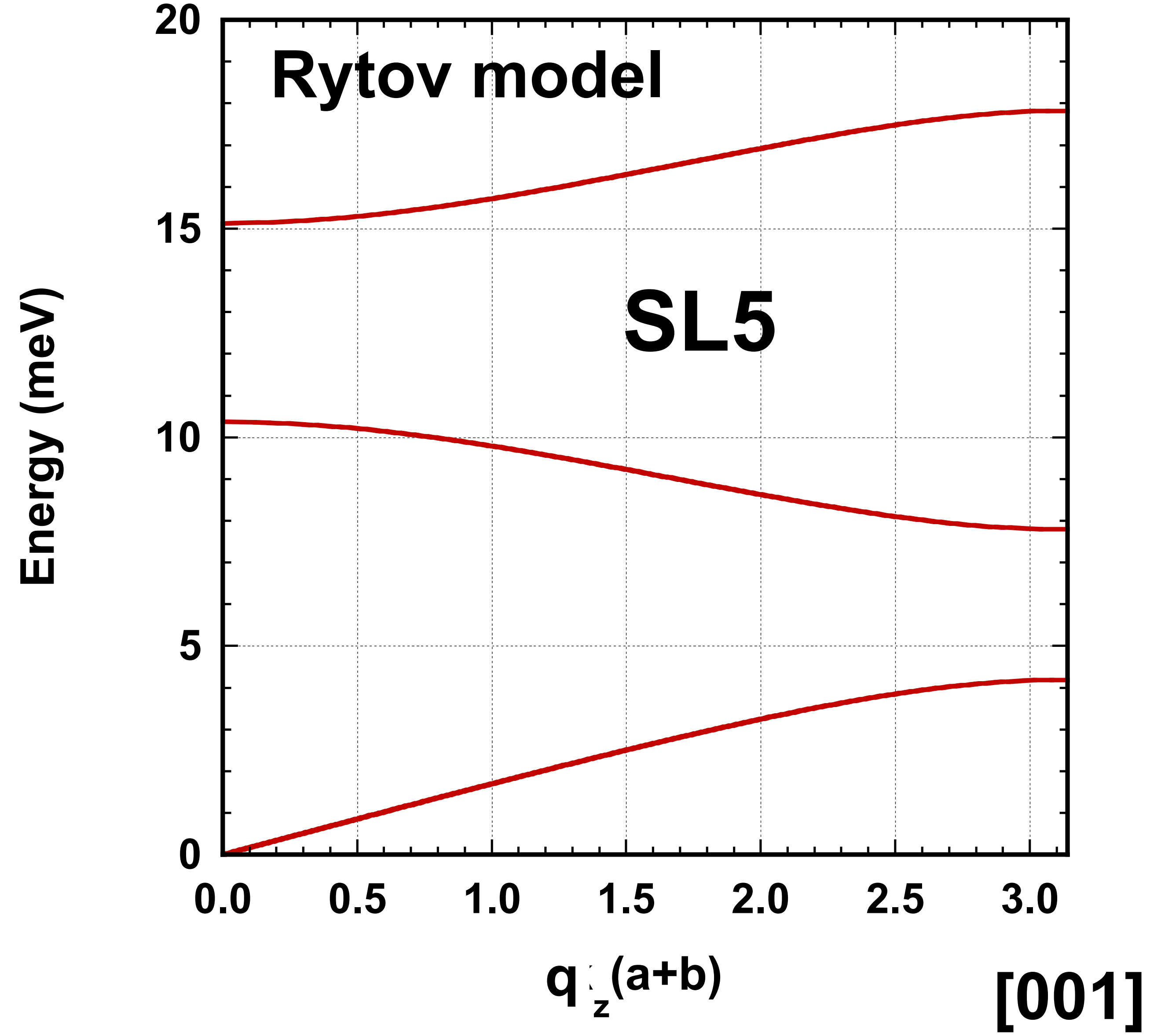
S.V. Rytov, Sov. Phys. Acoustics 2, 67 (1956)

Electron and Phonon Dispersion

Holes (Electronic Dispersion)

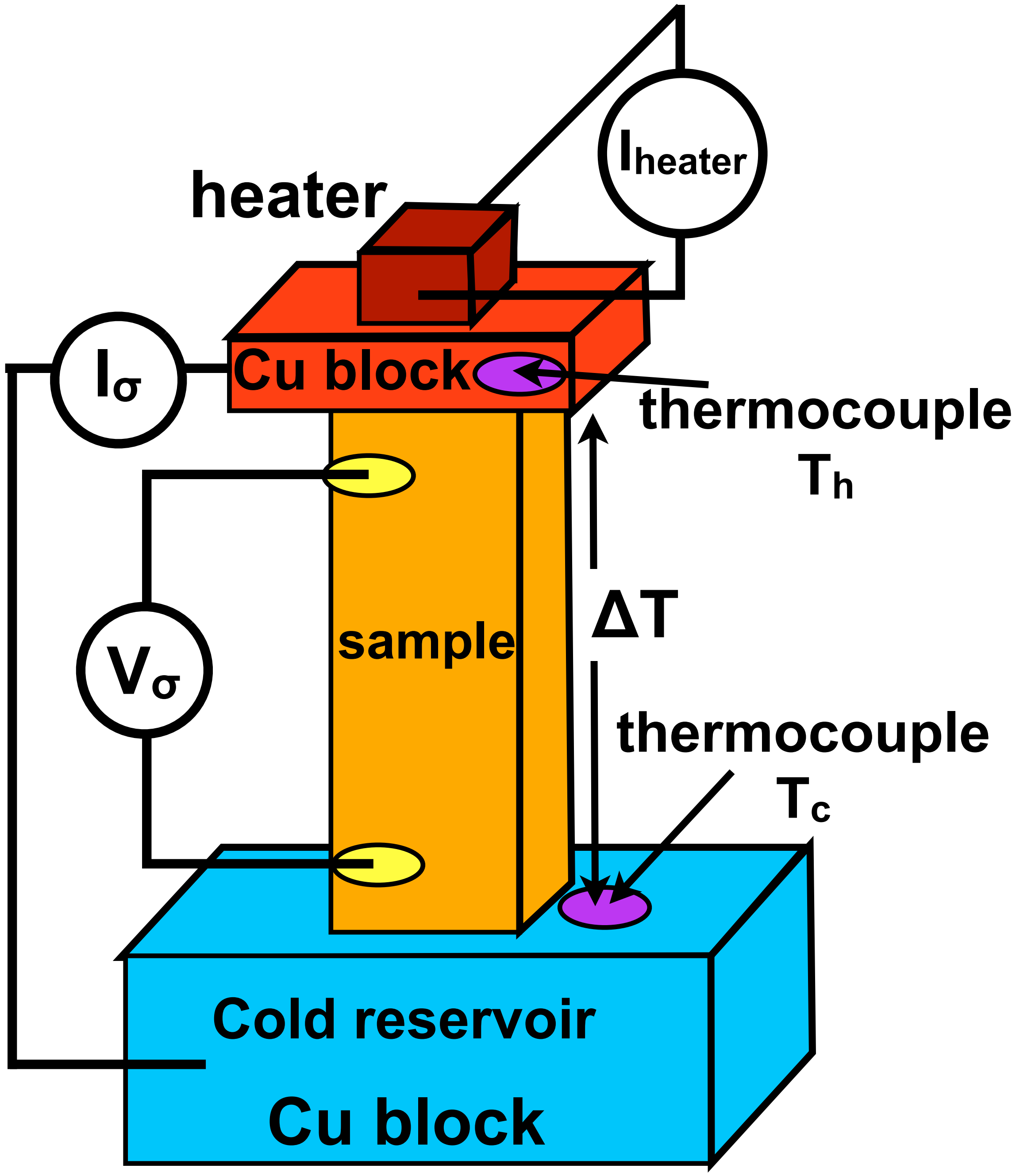


Phonon Dispersion



S.V. Rytov, Sov. Phys. Acoustics 2, 67 (1956)

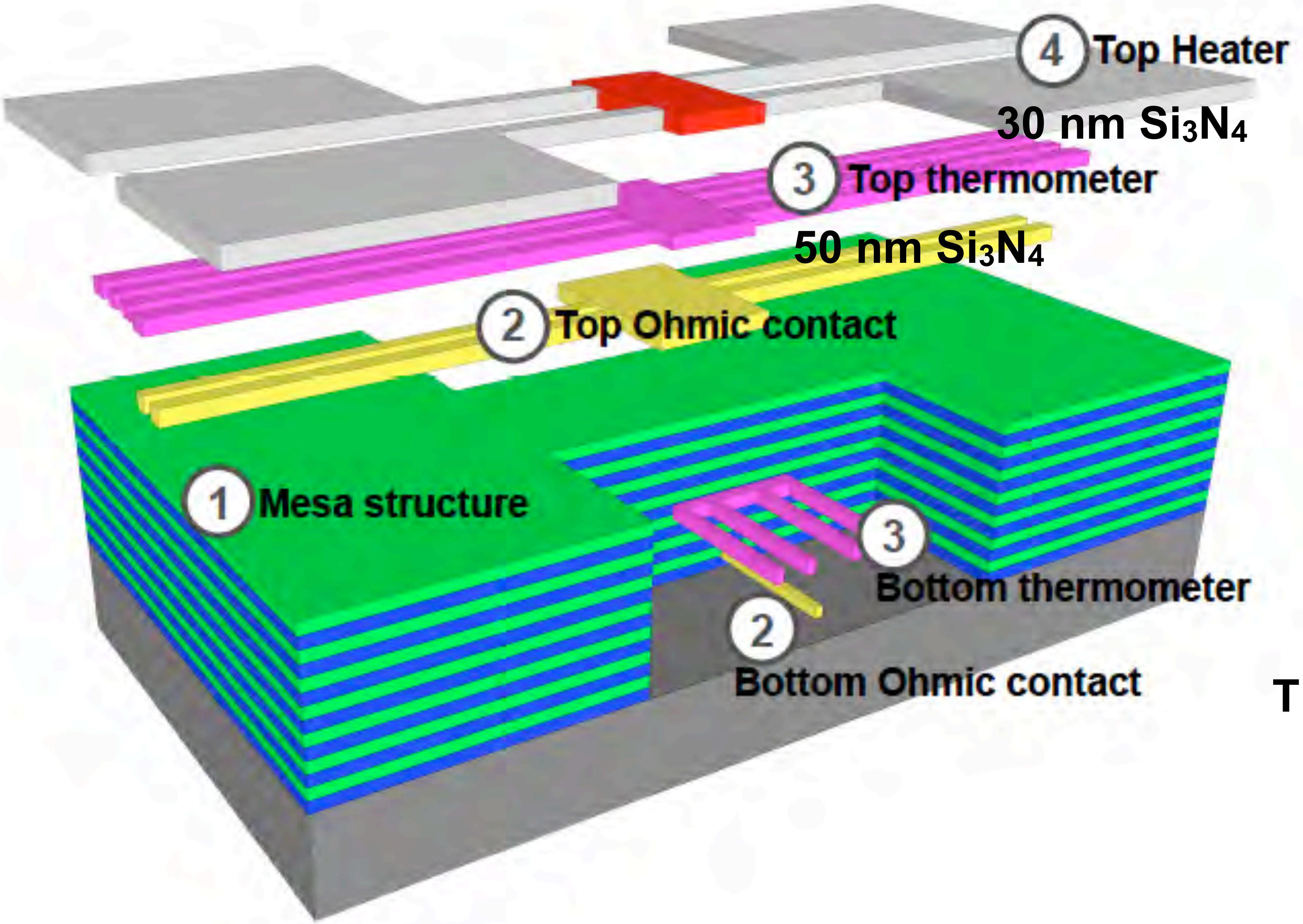
Measuring Seebeck Coefficient

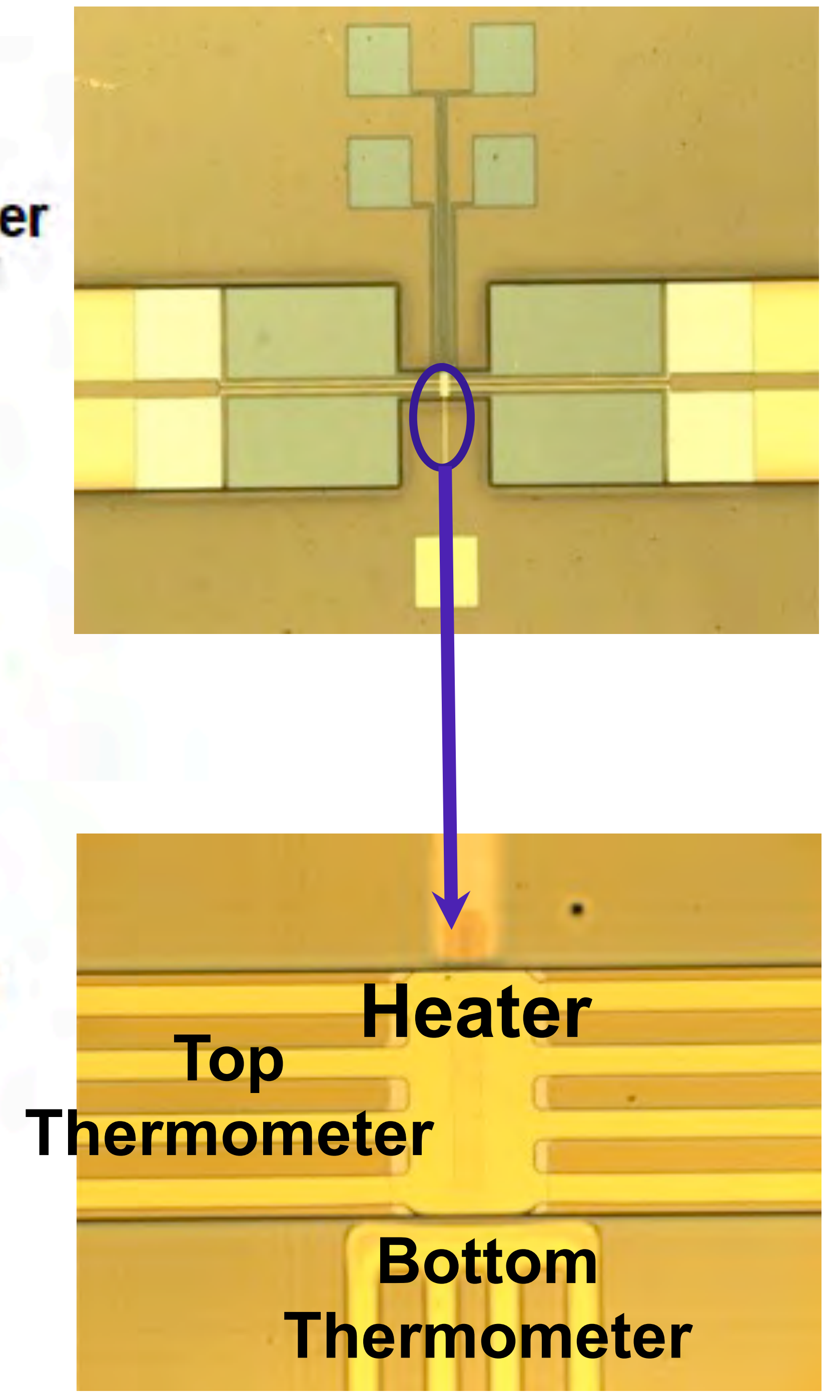


- Physically heat one side of sample
- Cold sink on other side of sample
- Thermocouples top and bottom to measure ΔT
- 4 terminal electrical measurements
- α and σ easy to measure

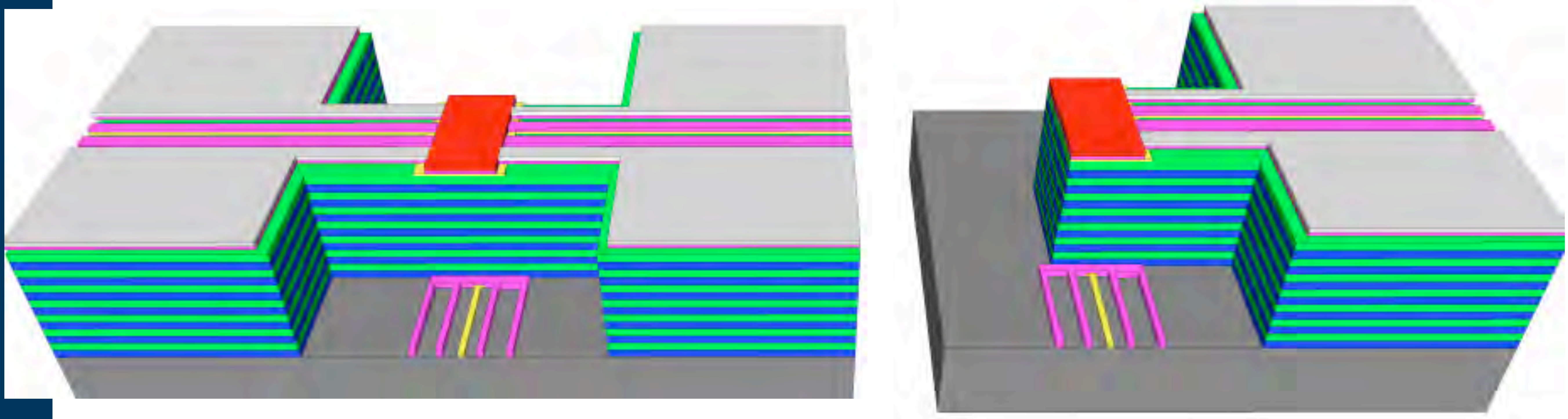
- Thermal conductivity, κ very difficult to measure

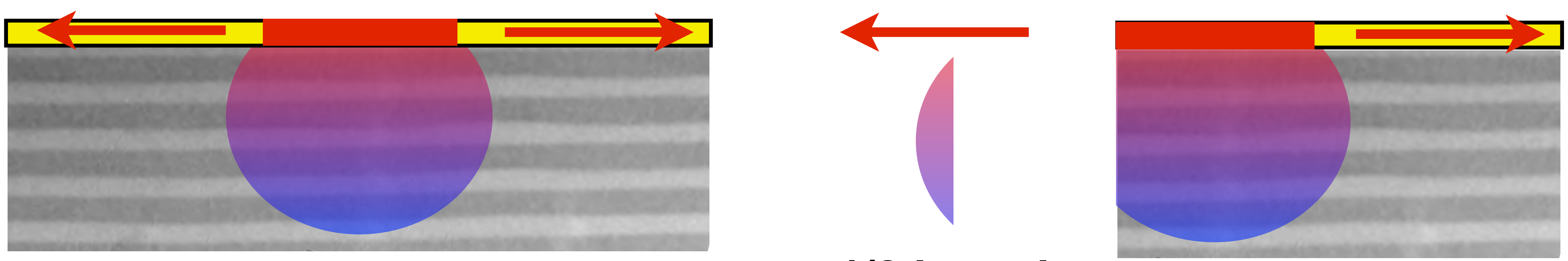
Vertical structure characterisation device





Thermal Parasitic Removal





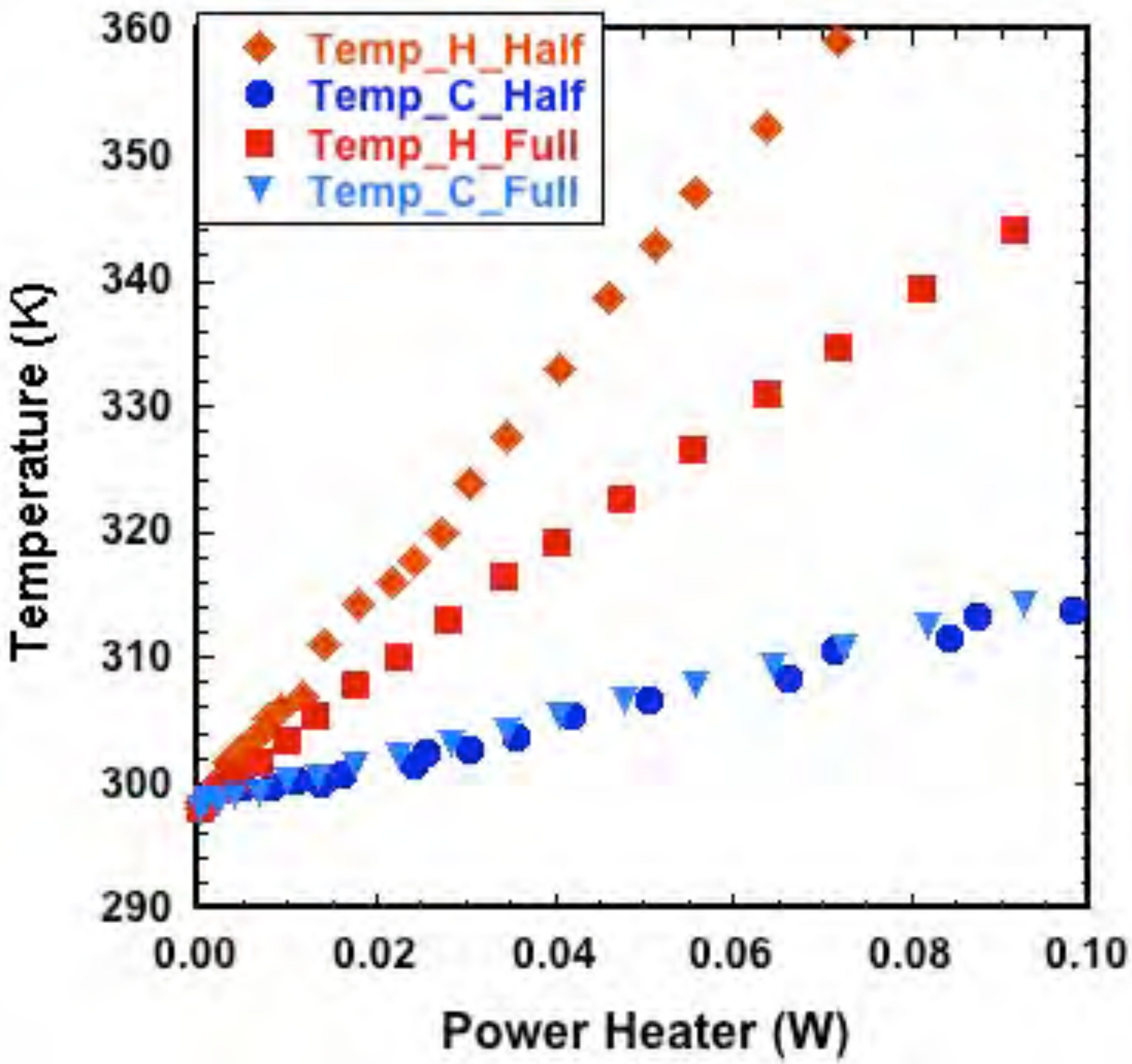
Isotropic structure

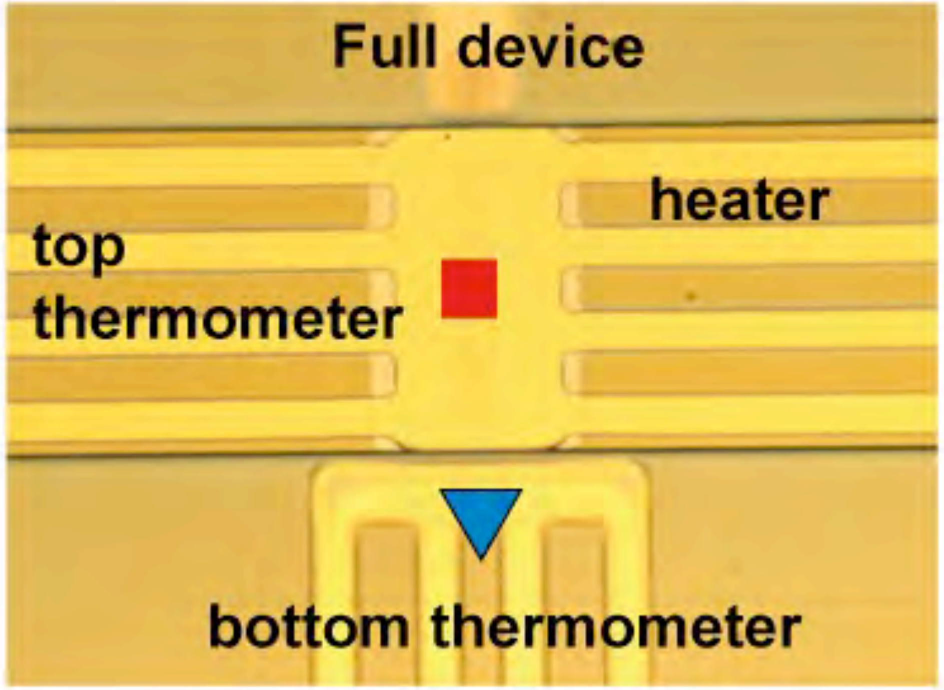
1/2 lateral parasitic contribution

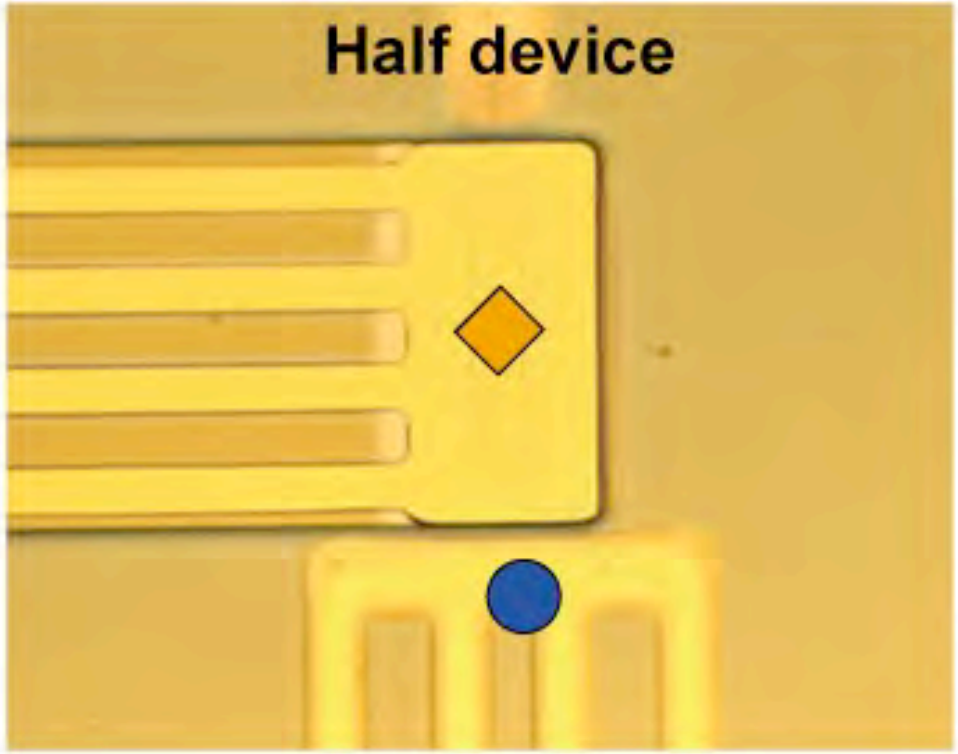
half structure

- **Half structure allows parasitics to be measured and removed for more accurate heat flux determination**

Thermal Measurements

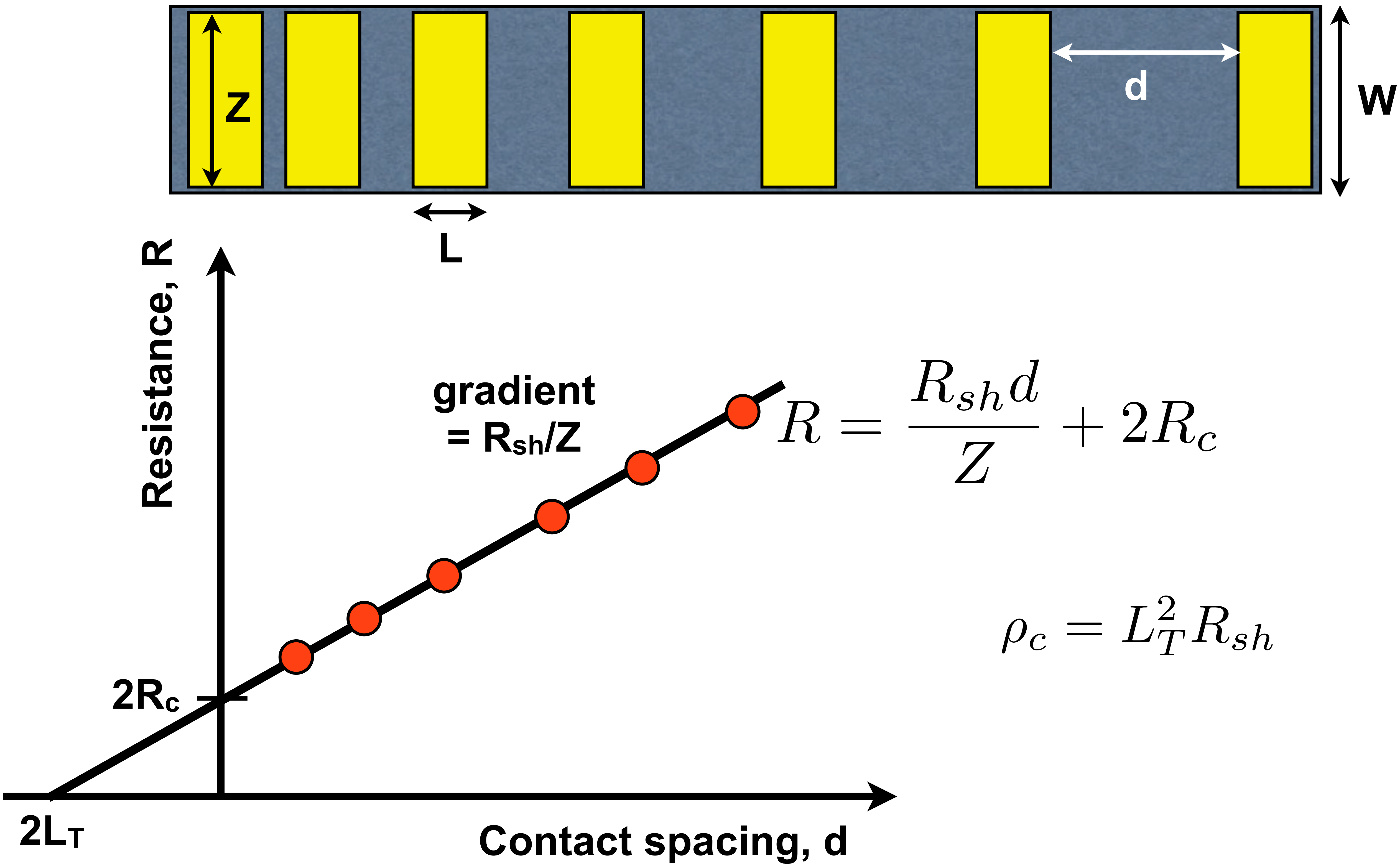






- **Measured 41% of heat in vertical transport**

Transfer Line Measurements (TLMs)

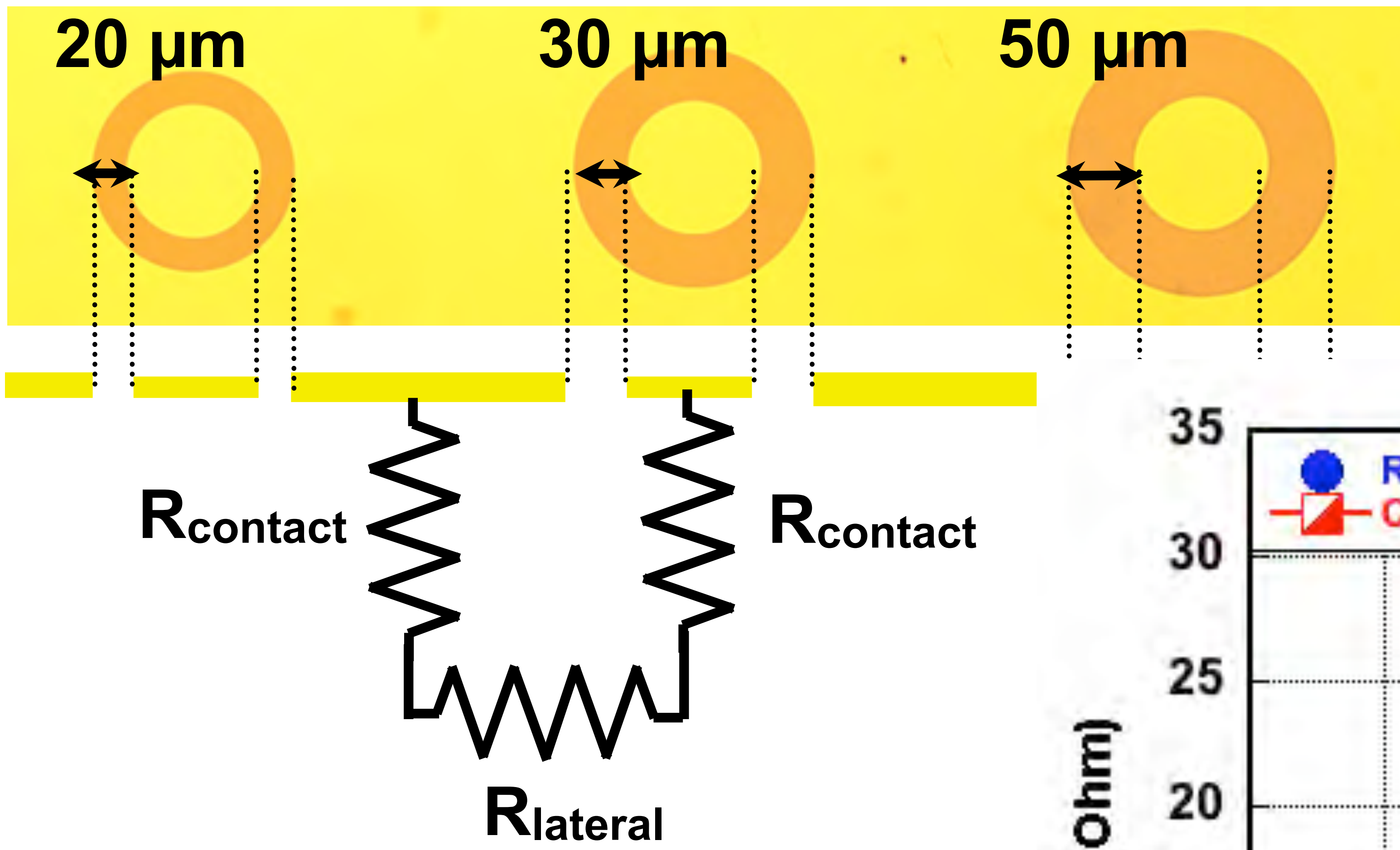


$$R = \frac{R_{sh} d}{Z} + 2R_c$$

$$\rho_c = L_T^2 R_{sh}$$

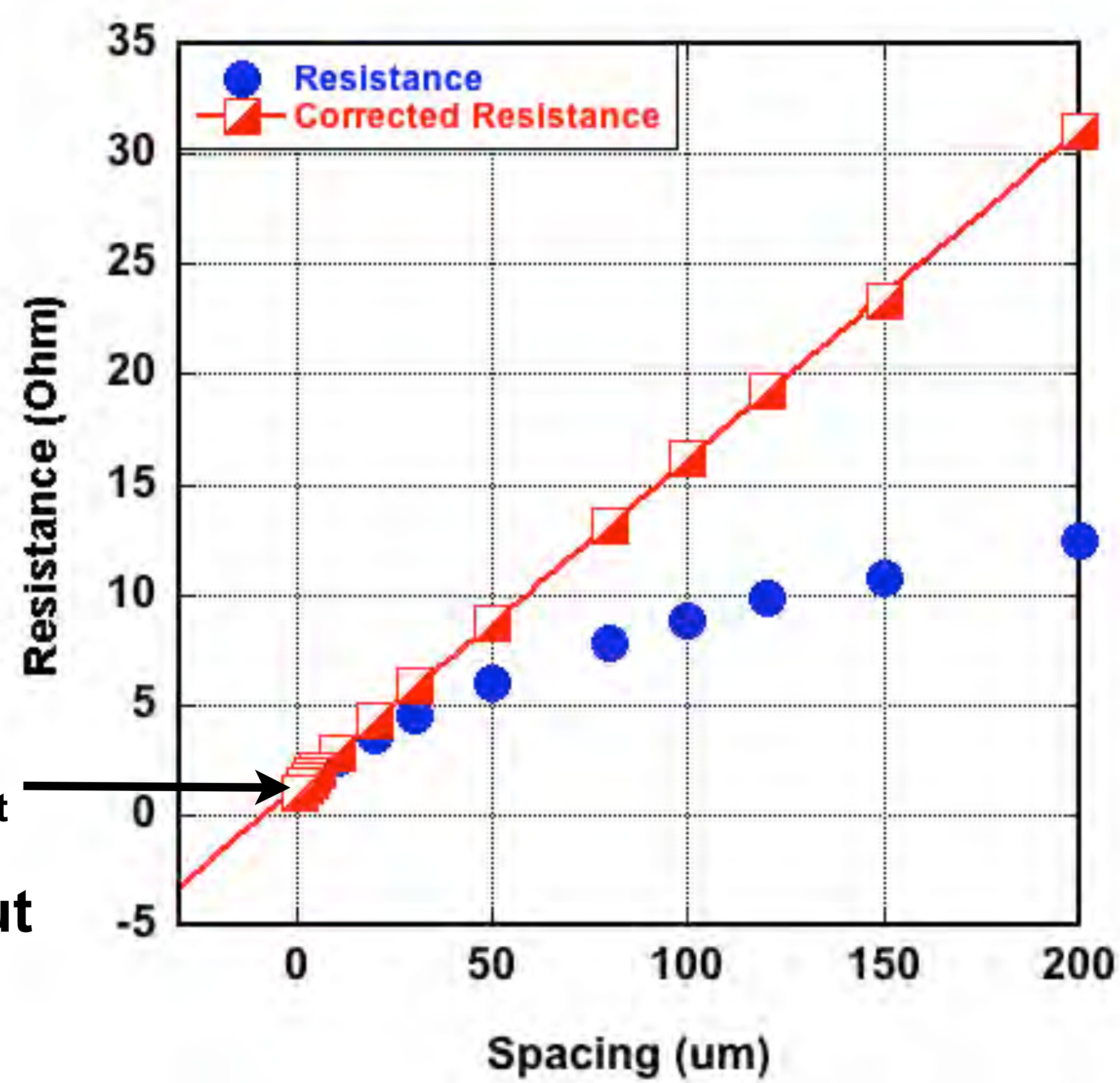
- Any misalignment or gaps results in errors –> circular TLMs

Vertical Electrical Conductivity I



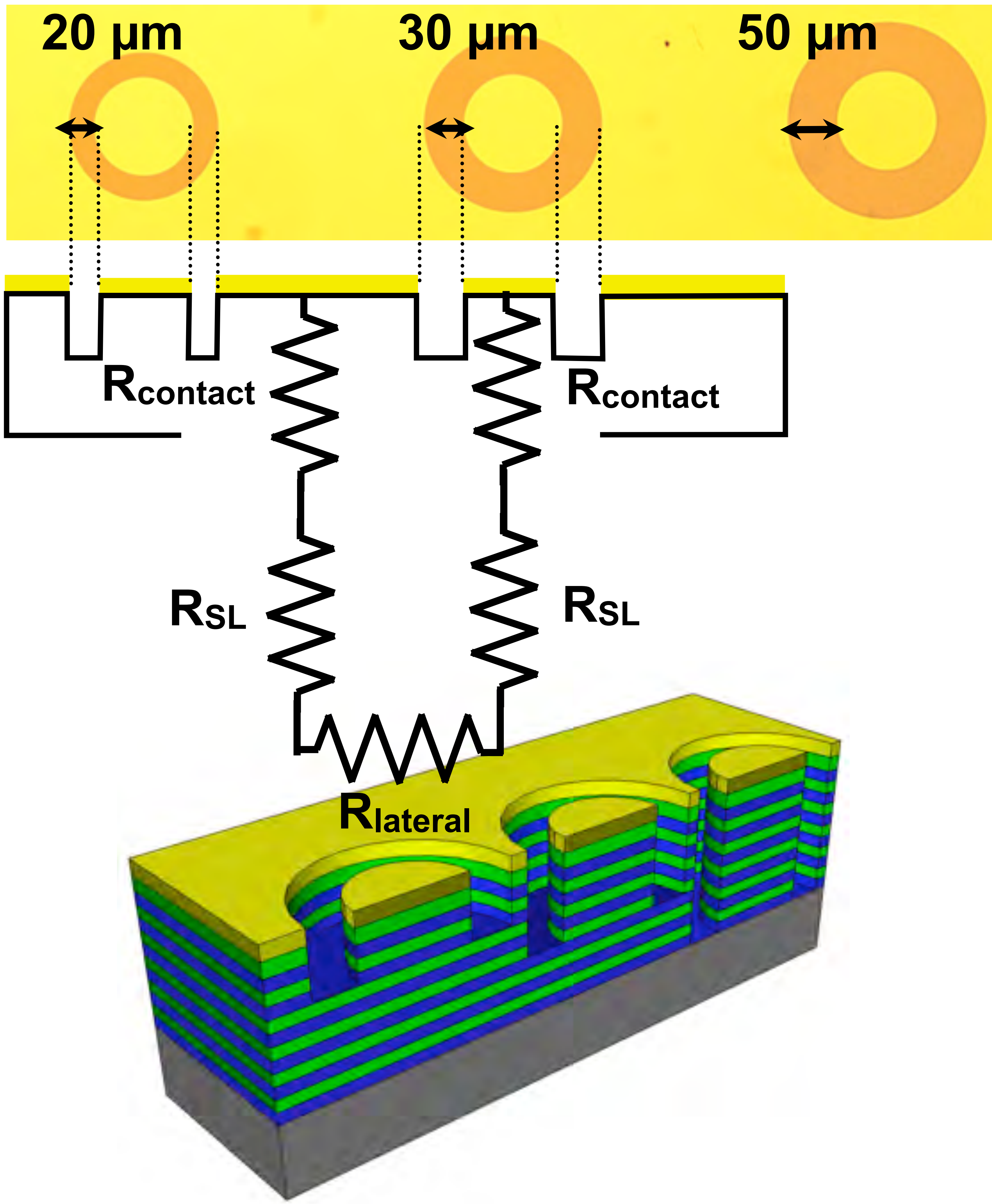
- Circular Transfer Line Method

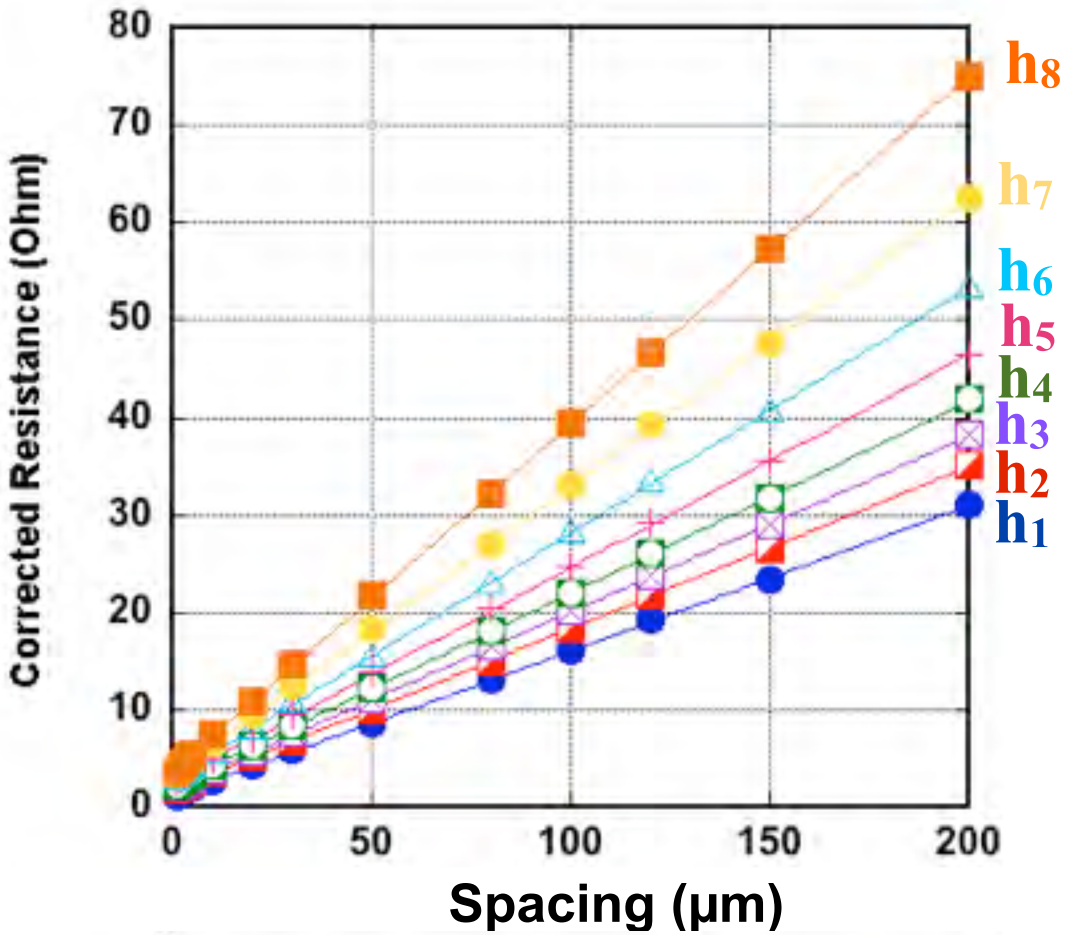
2Rcontact

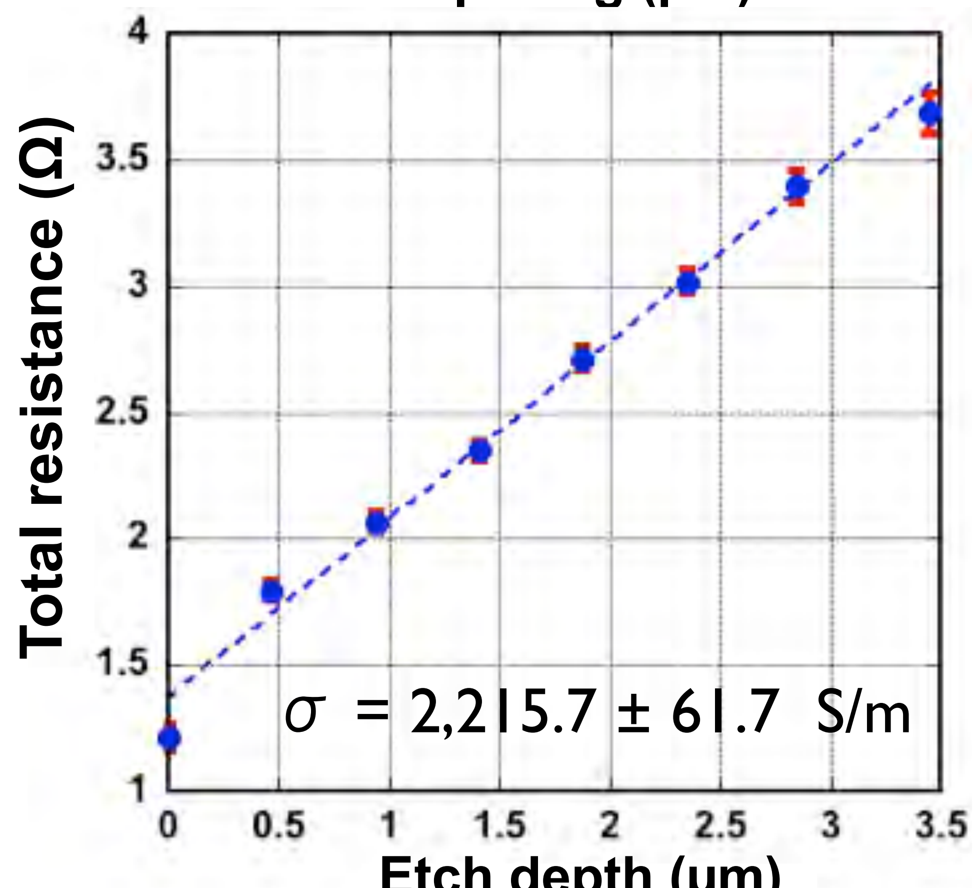


- Higher accuracy than TLM but correction factor required

Vertical Electrical Conductivity II







The Uncertainty in Measuring ZT

- Many materials with ZT > 1.5 reported
  but few confirmed by others (!)

- No modules demonstrated with such high efficiencies

- Due to: measurement uncertainty & complexity
  of fabricating devices

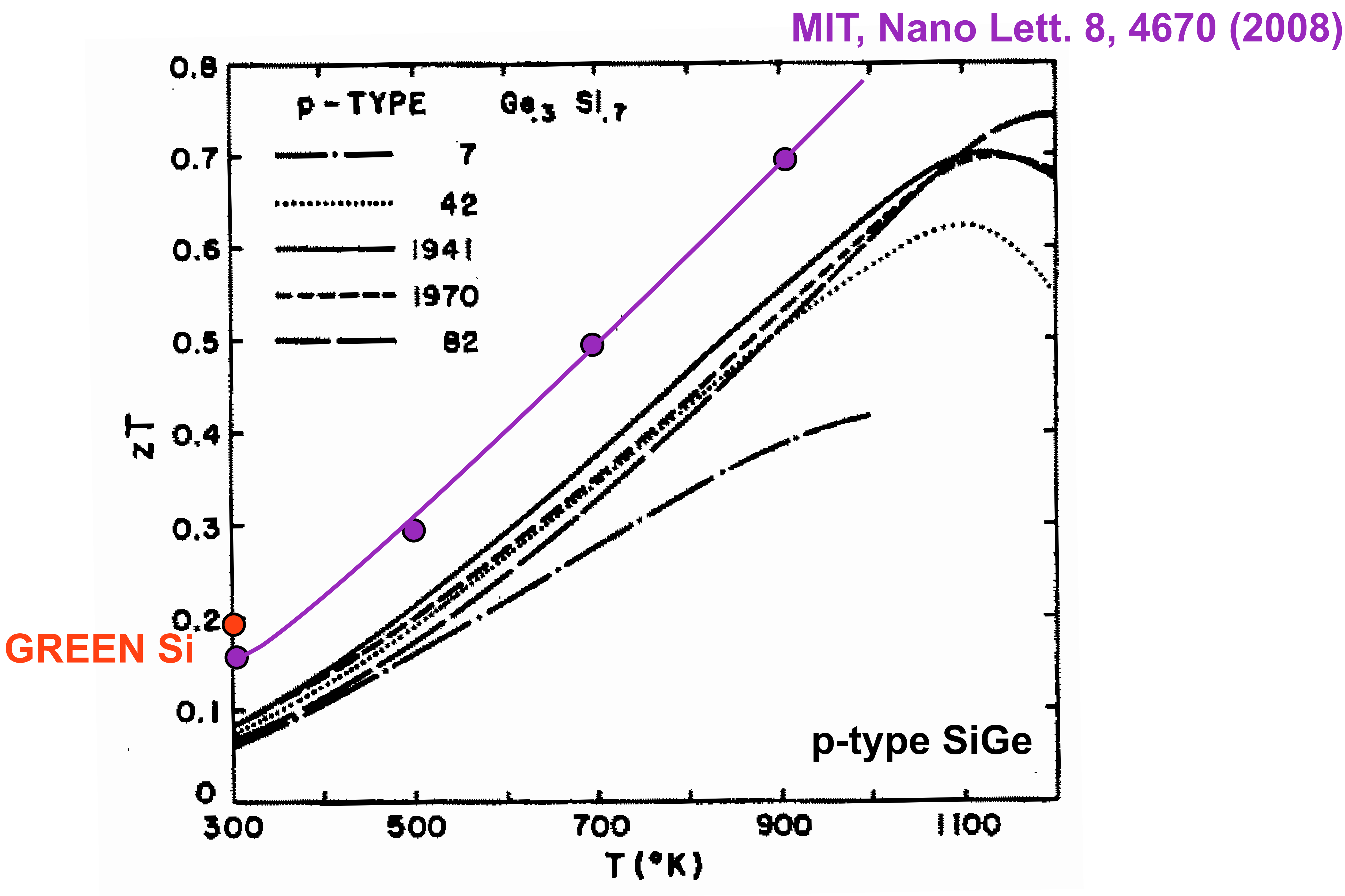
- $$\frac{\Delta(\mathrm{ZT})}{\mathrm{ZT}} = 2\frac{\Delta\alpha}{\alpha} + \frac{\Delta\sigma}{\sigma} + \frac{\Delta\kappa}{\kappa} + \frac{\Delta \mathrm{T}}{\mathrm{T}}$$

  Δx = uncertainty in x = standard deviation in x

- Measurements are conceptually simple but results vary considerably due to thermal gradients in the measurements –> systematic inaccuracies

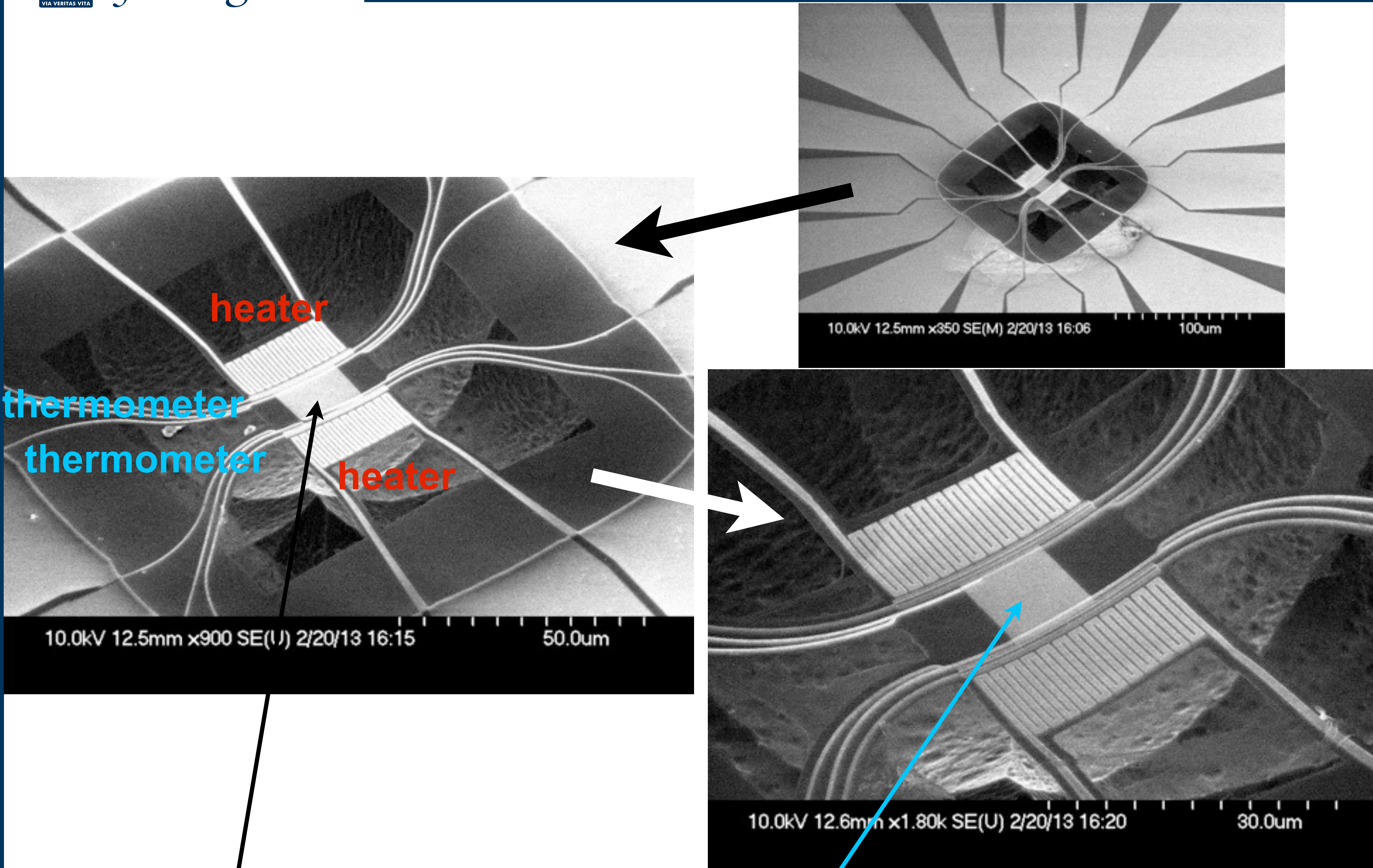
- Total ZT uncertainty can be between 25% to 50%

Bulk SiGe ZT Comparisons



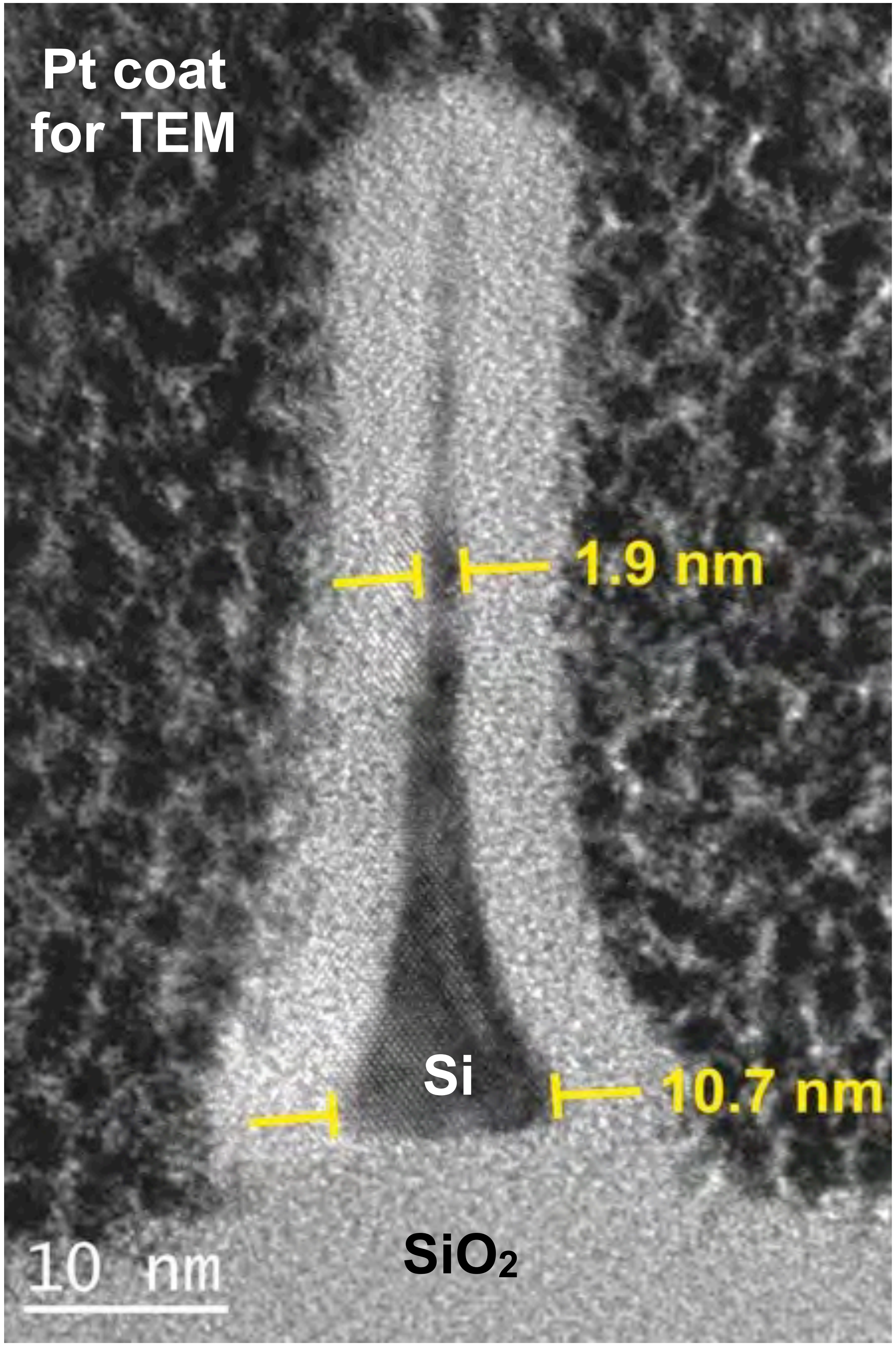
J.P. Dismukes et al., J. Appl. Phys. 35, 2899 (1964)

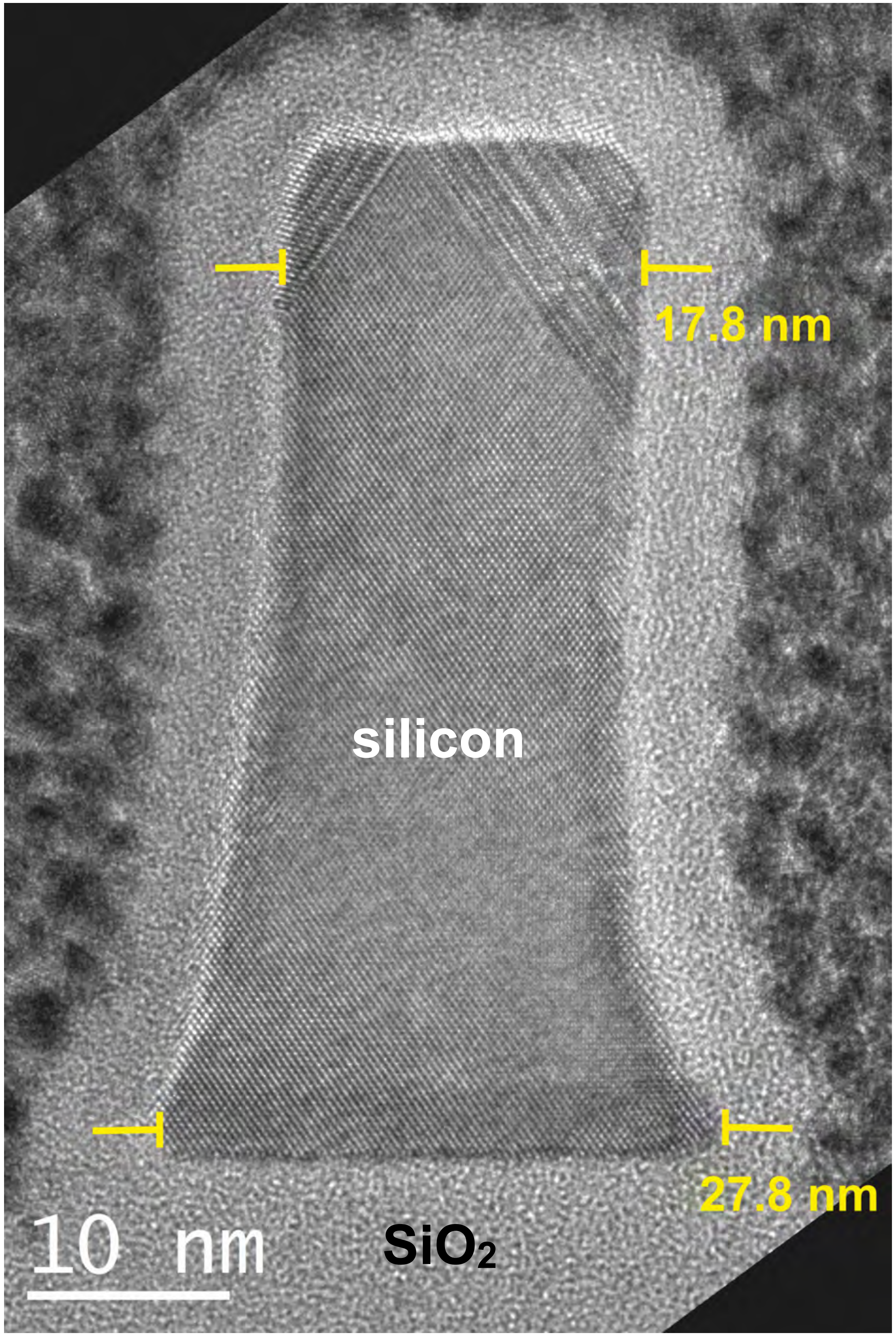
Nanowire Fabrication on Suspended Hall Bar



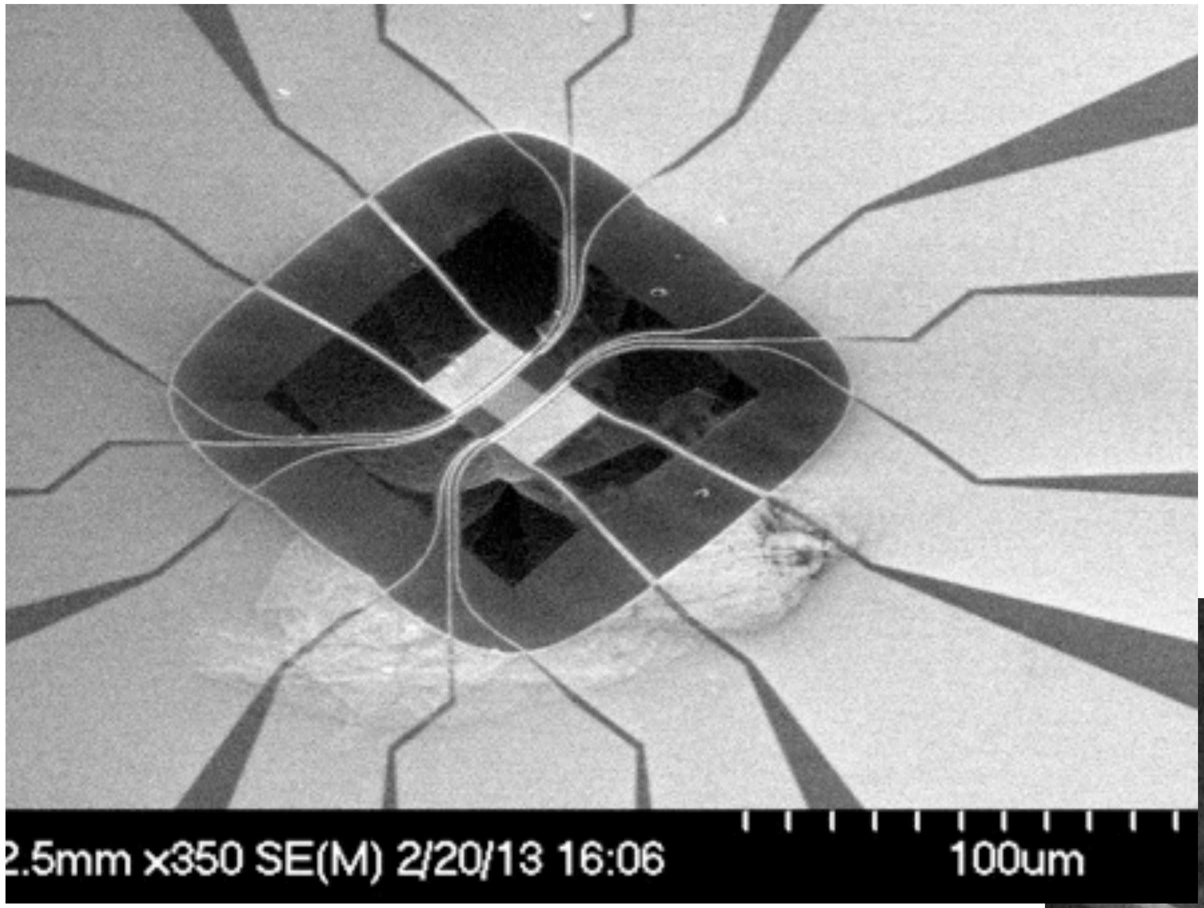
- **100 x 45 nm wide Si nanowires with integrated heaters, thermometers and electrical probes**

Si Nanowires: How many atoms wide?





45 nm Wide n-Silicon Nanowires



@ 300 K:

- σ = 20,300 S/m
  4 terminal
- κ = 7.78 W/mK
- α = –271 μV/K
- ZT = 0.057

- ZT enhanced by x117
- $\alpha^2\sigma$ = 1.49 mW $m^{-1}K^{-2}$
- What enhancements with SiGe ?

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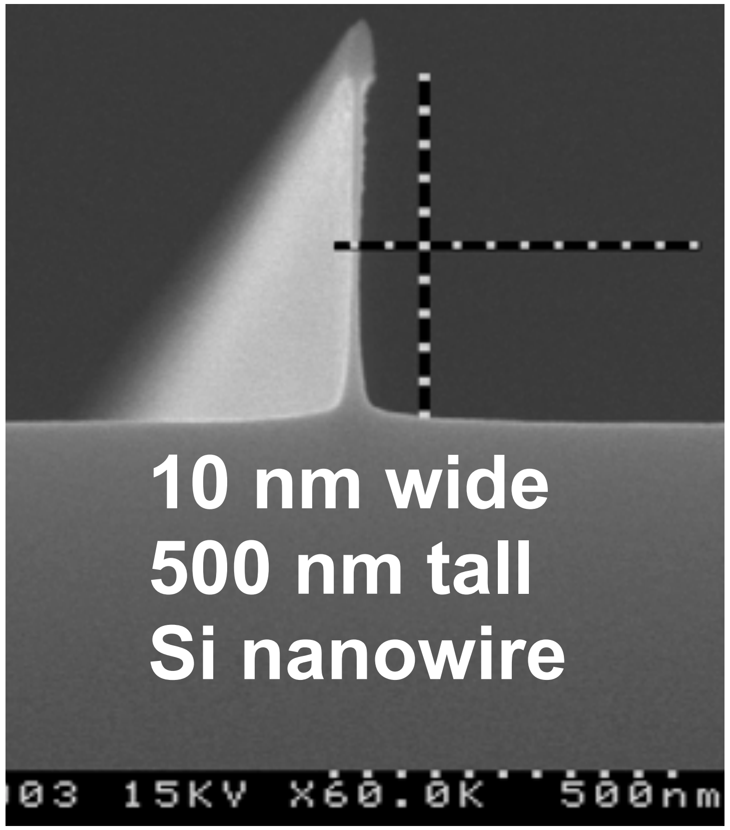
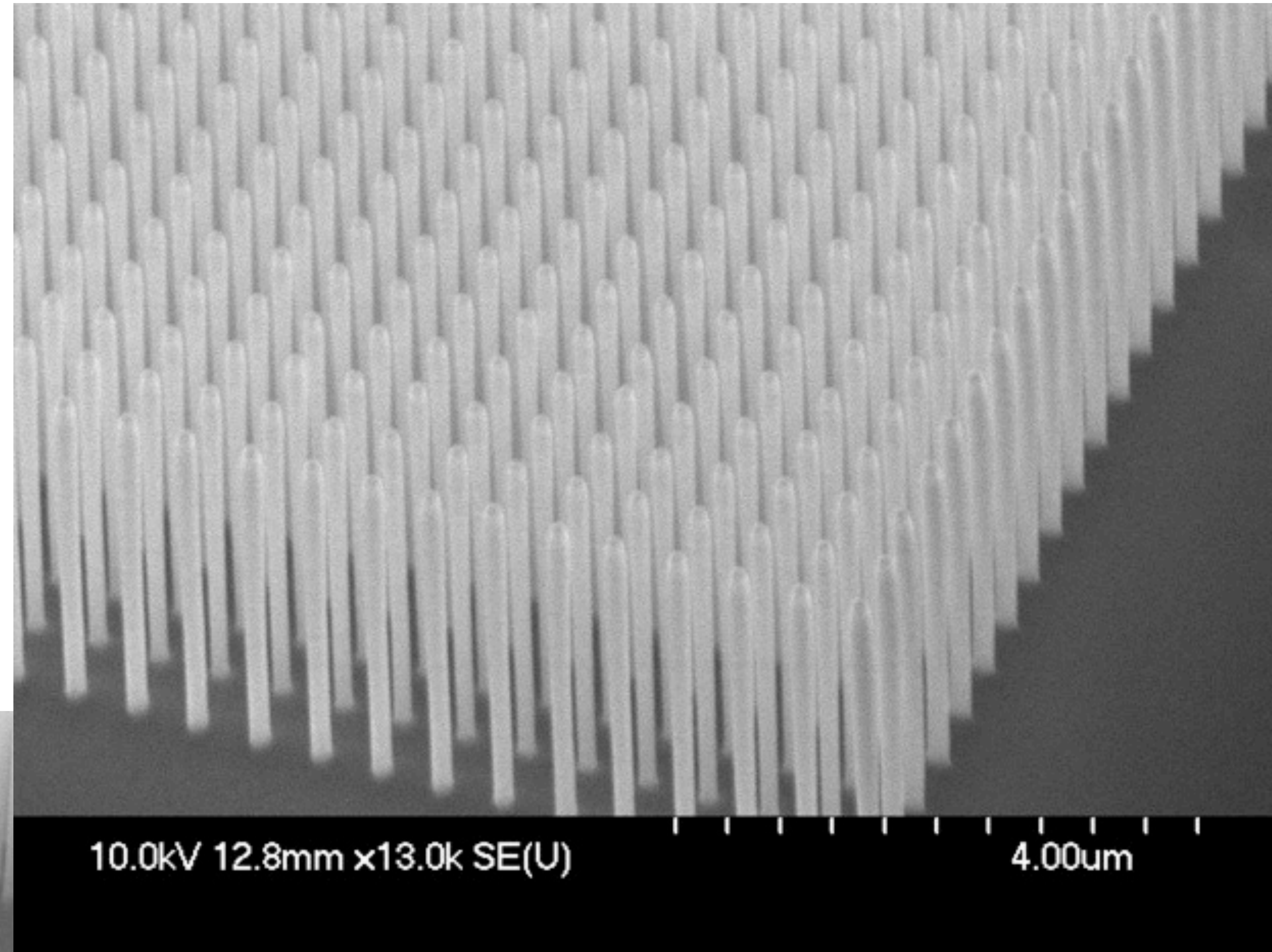
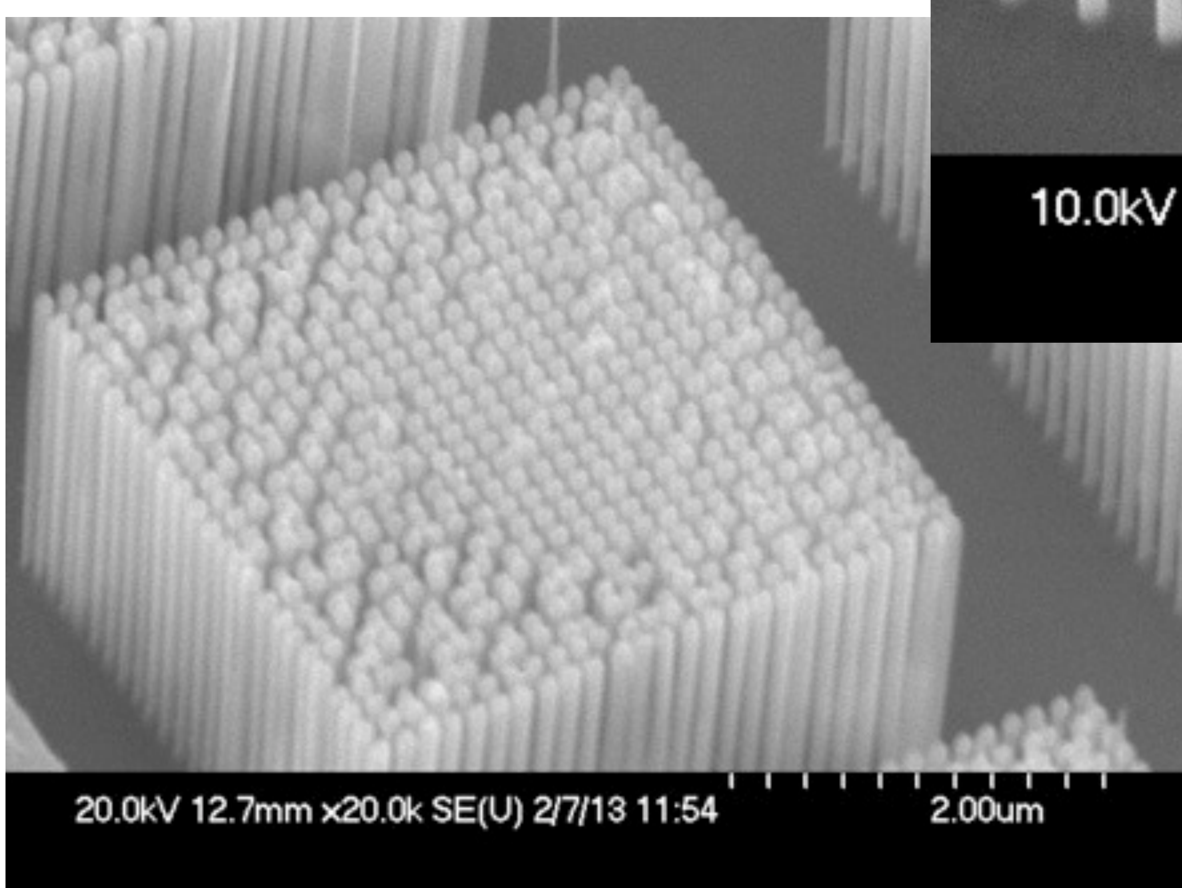
Nanowire Module Development



Si etch



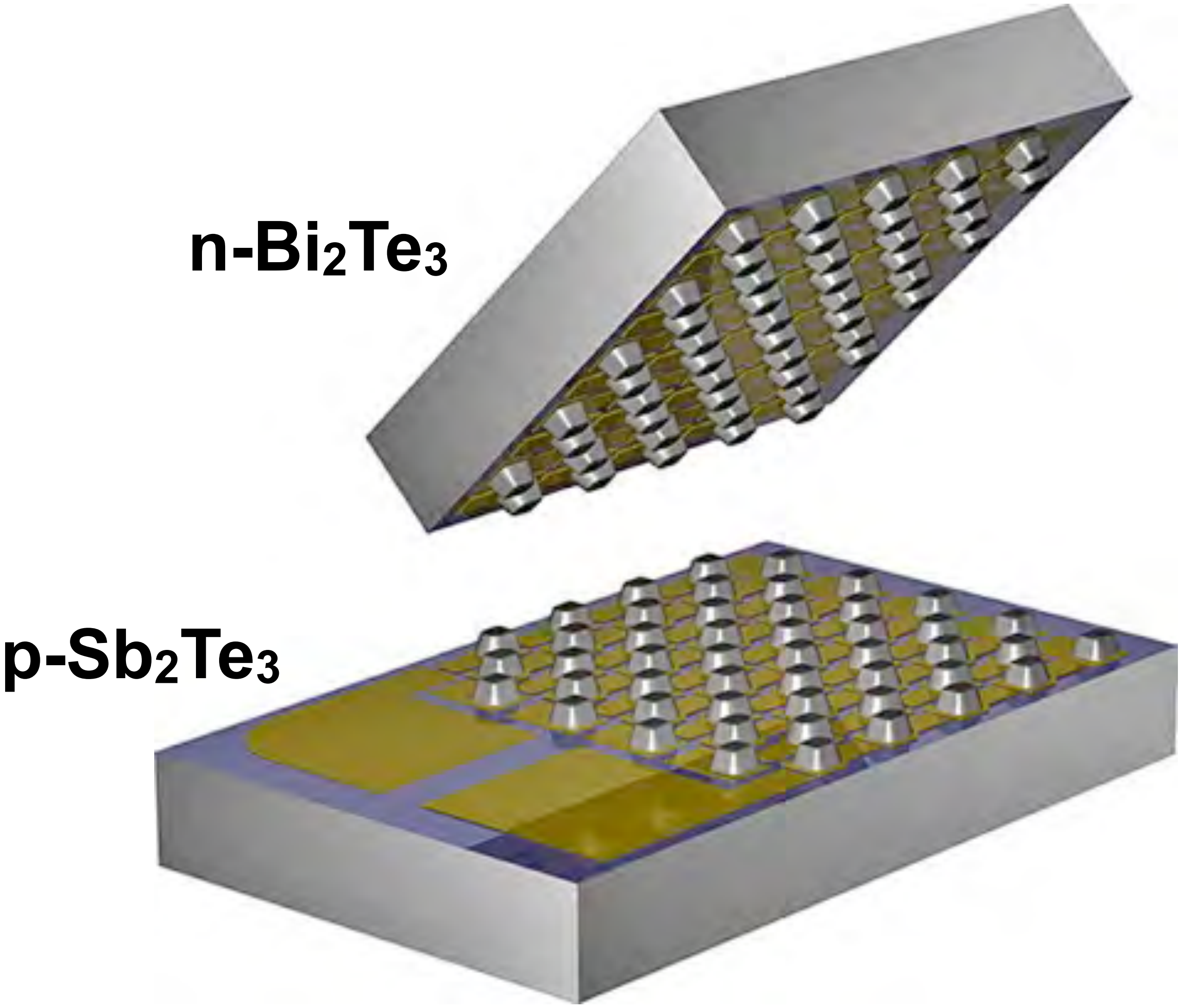


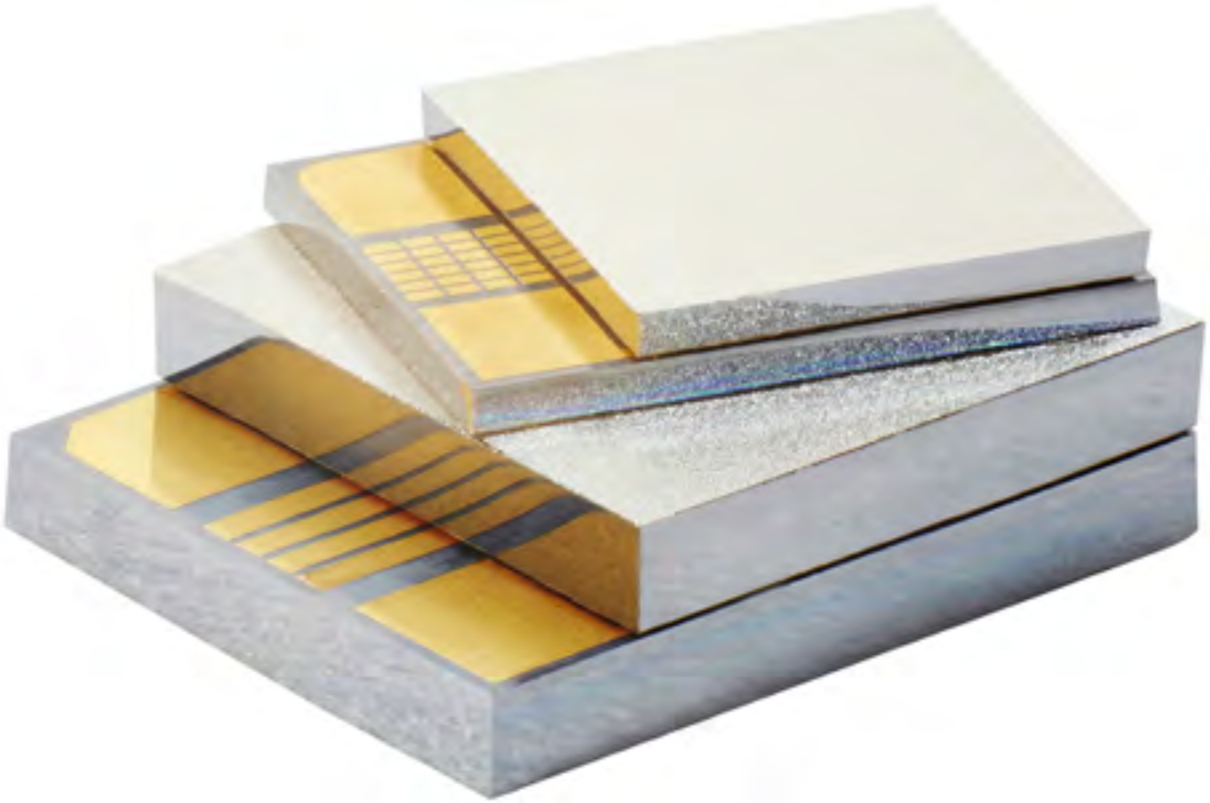
High density nanowires

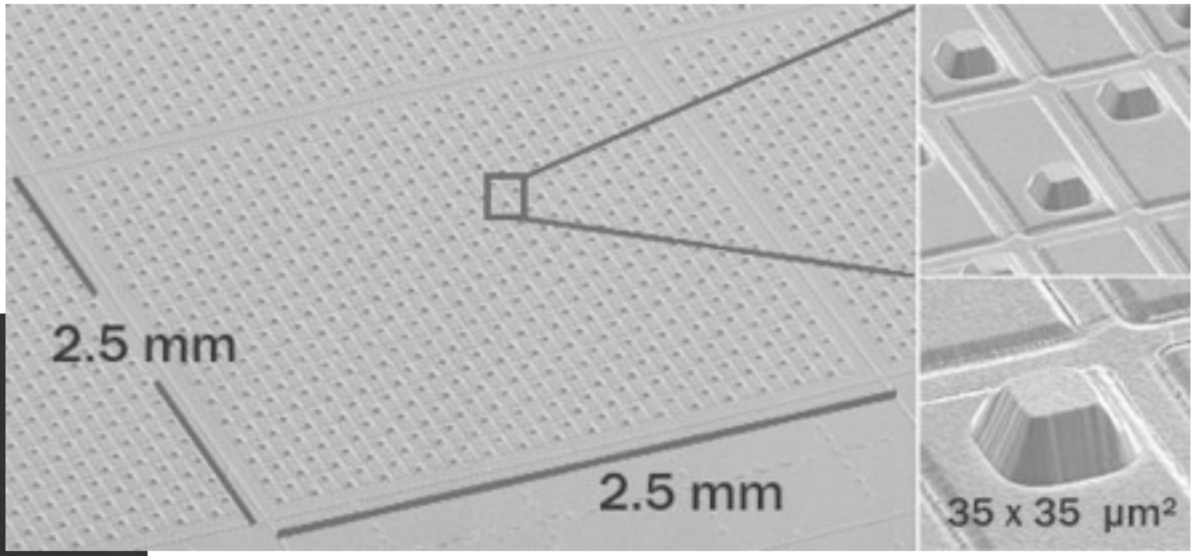
50 nm Ge/SiGe nanowires

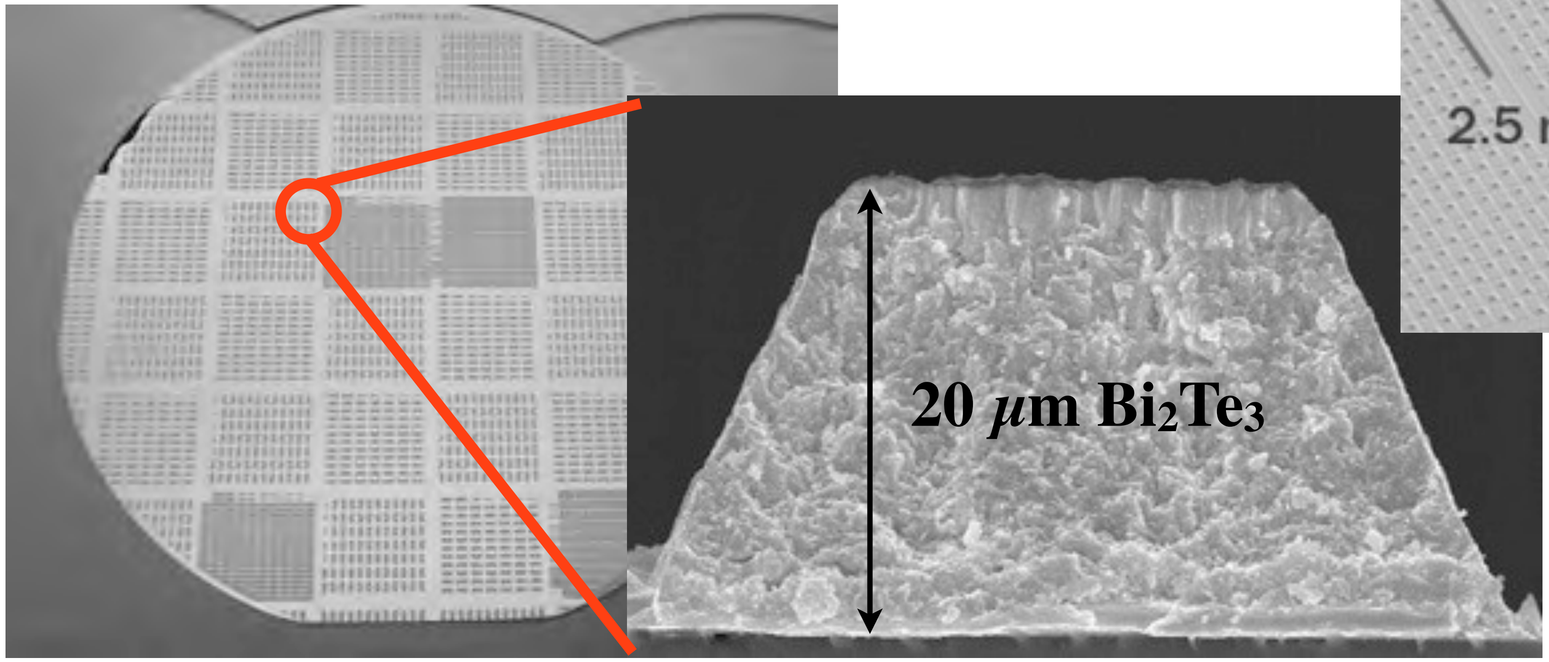
4 µm deep etched

Micropelt Microfabrication of BiTe Alloys



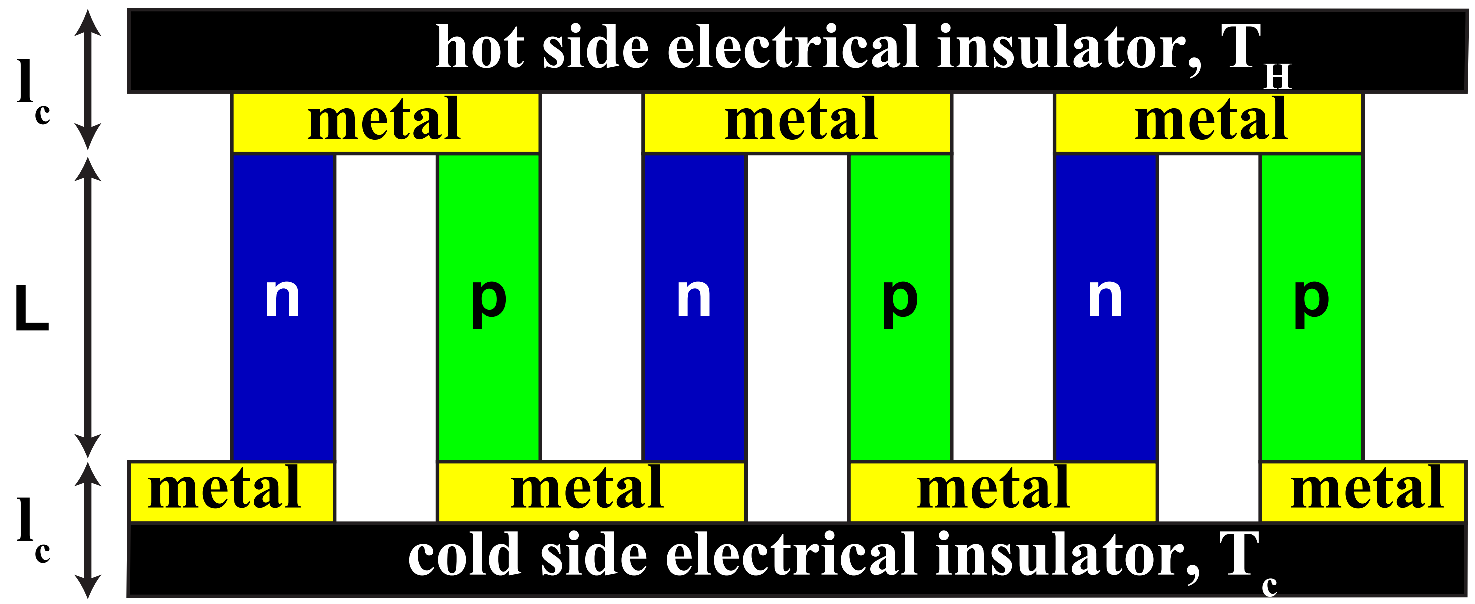






http://www.micropelt.com/

System Design: Power Output



A = module leg area

L = module leg length

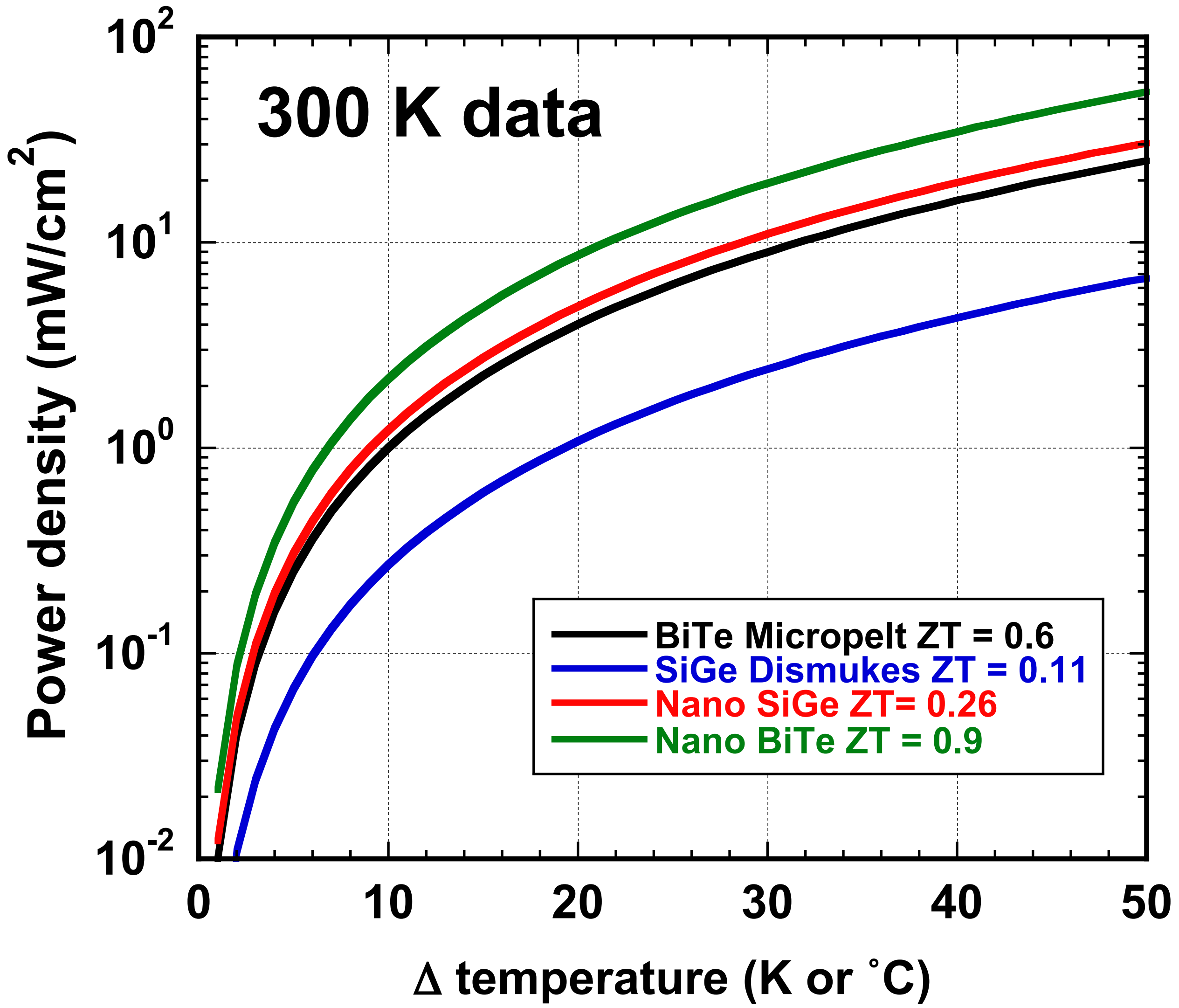
N = number of modules

κ_c = thermal contact conductivity

ρ_c = electrical contact resistivity

$$P = \frac{\alpha^2 \sigma A N \Delta T^2}{2(\rho_c \sigma + L)\left(1 + 2\frac{\kappa l_c}{\kappa_c L}\right)^2}$$

D.M. Rowe & M. Gao, IEE Proc. Sci. Meas. Technol. 143, 351 (1996)



- System: power in BiTe alloys limited by Ohmic contacts
- ρ_c (Bi_2Te_3) ≅ 1 x 10^{-7} Ω-cm^2
- ρ_c ($Si_{1-x}Ge_x$) = 1.2 x 10^{-8} Ω-cm^2

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Thermoelectric References

- D.M. Rowe (Ed.), "*Thermoelectrics Handbook: Macro to Nano*" CRC Taylor and Francis (2006) ISBN 0-8494-2264-2

- G.S. Nolas, J. Sharp and H.J. Goldsmid "*Thermoelectrics: Basic Principles and New Materials Development"* (2001) ISBN 3-540-41245-X

- M.S. Dresselhaus et al. "*New directions for low-dimensional thermoelectric materials*" Adv. Mat. 19, 1043 (2007)

- D.J. Paul, "*Thermoelectric Energy Harvesting*" Intech Open Access from "ICT - Energy - Concepts Towards Zero - Power Information & Communication Technology " (2014) - DOI: 10.5772/57347

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