# Thermionic and Thermoelectric Power Generators

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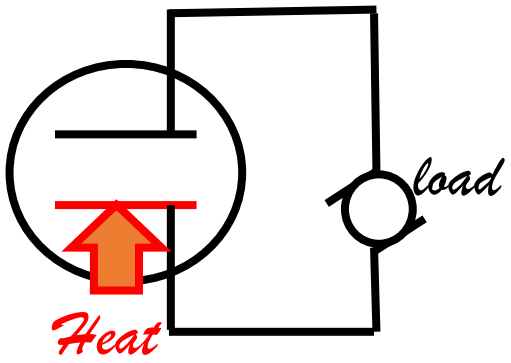
ARPA-E workshop

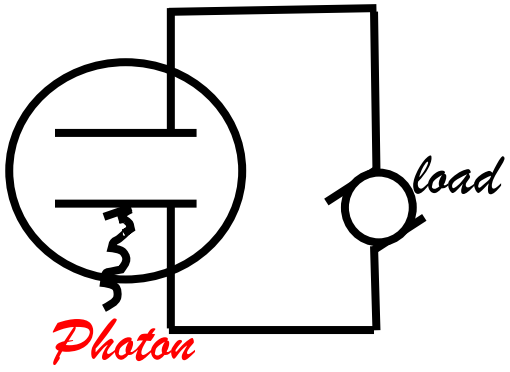
San Francisco, CA, Dec 14

University of Virginia Engineering
School of Engineering & Applied Science

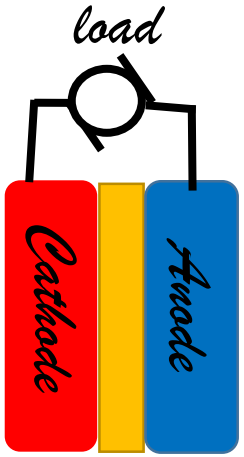
# Thermal to Electrical vacuum & Solid State Devices



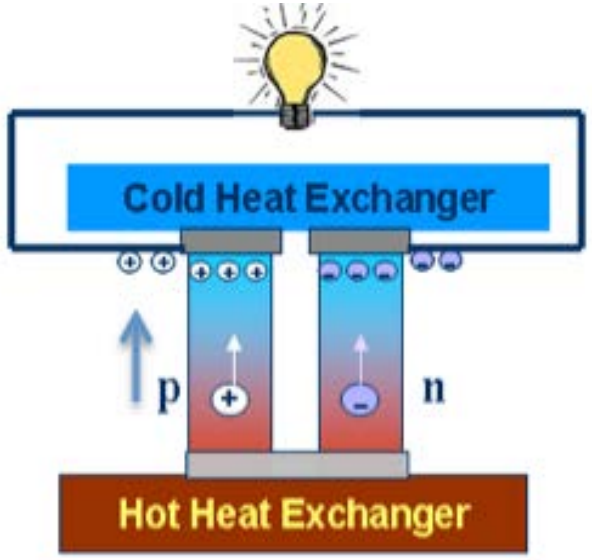

Vacuum Thermionic
1904 Fleming
1956 Hatsopoulos




Photoemissive converter
1959 Von Doenhoff &
Premo



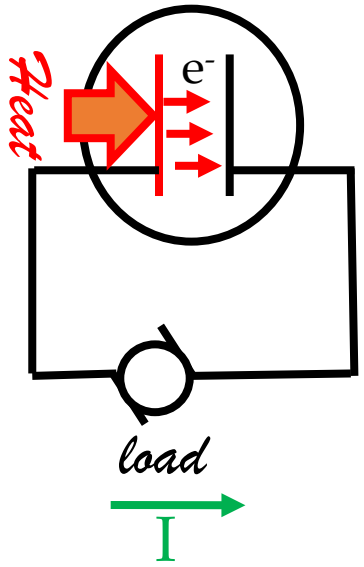

Solid-State
Thermionic
Mahan 1994
Shakouri 1997

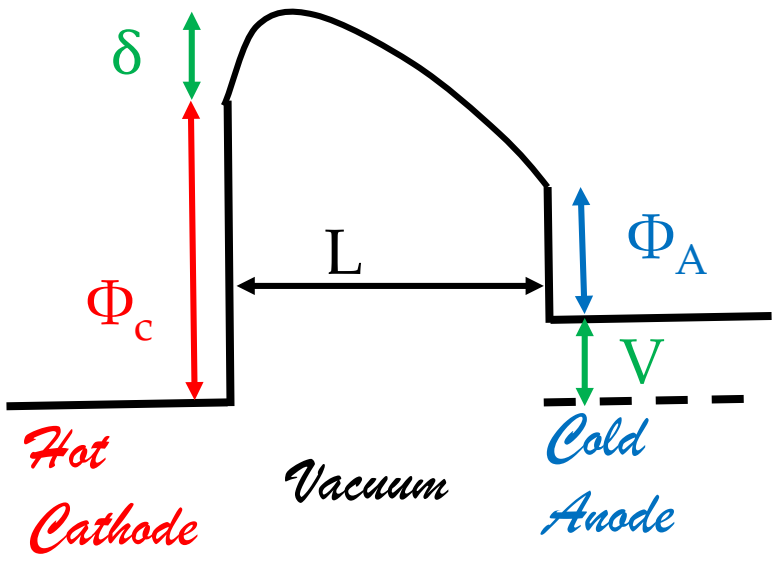


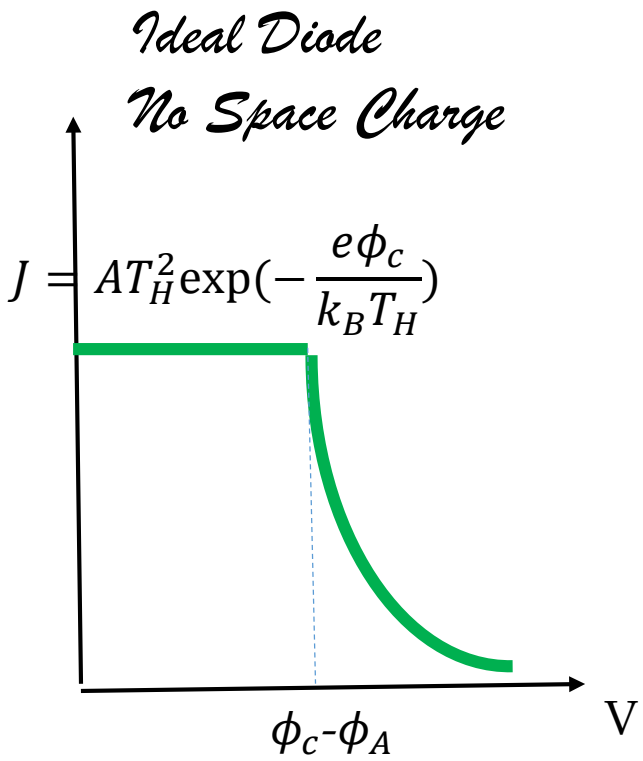

Thermoelectric
1821 Seebeck
1926 Grondahl
1950 Ioffe,
Goldsmid, …

Hybrid
PETE: Photon Enhanced
Thermionic Emission
Melosh, 2010

# Vacuum Thermionic devices



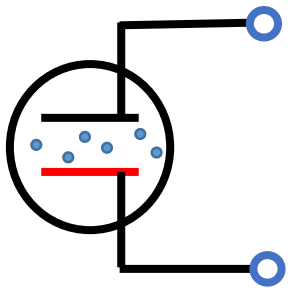



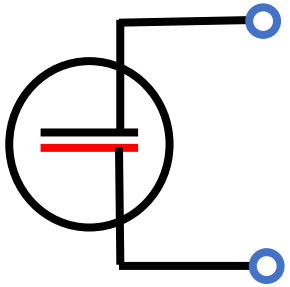

Theoretical efficiency as high as 90% of Carnot
Experimentally obtained efficiency 16% in 1950~1960 Wilson, Hatsopoulos

# Challenges to operate below 600°C

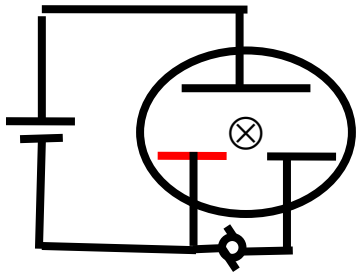
- Effective cooling of anode
- Work function limitations (~1eV)
- Space charge effect



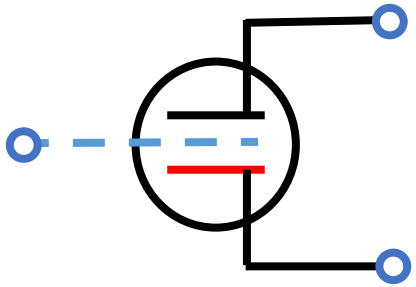
Positive ions (Cesium)



Closely spaced



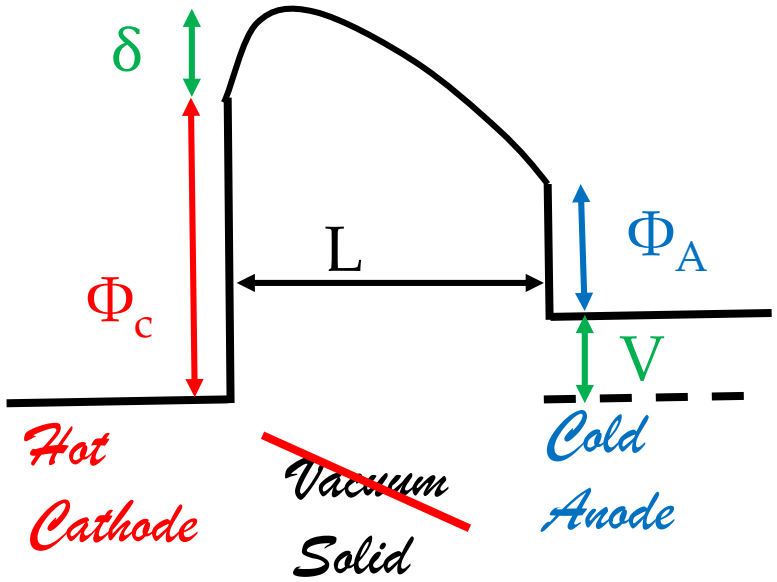
E-B Field



Triode

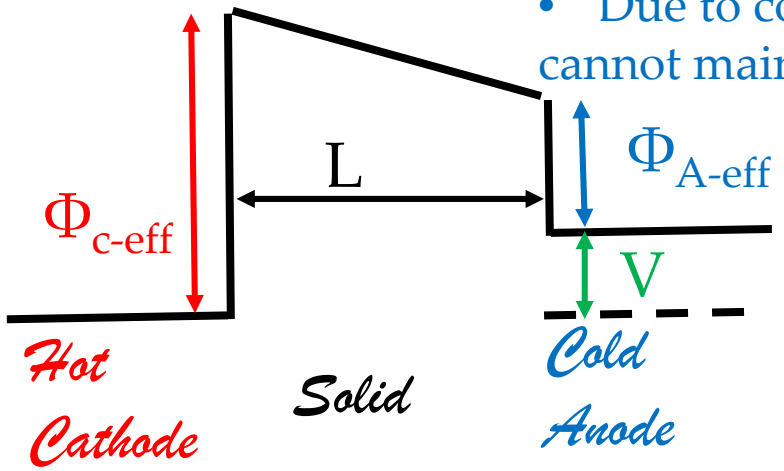
# Solid State Thermionic

- Mahan et al. view point



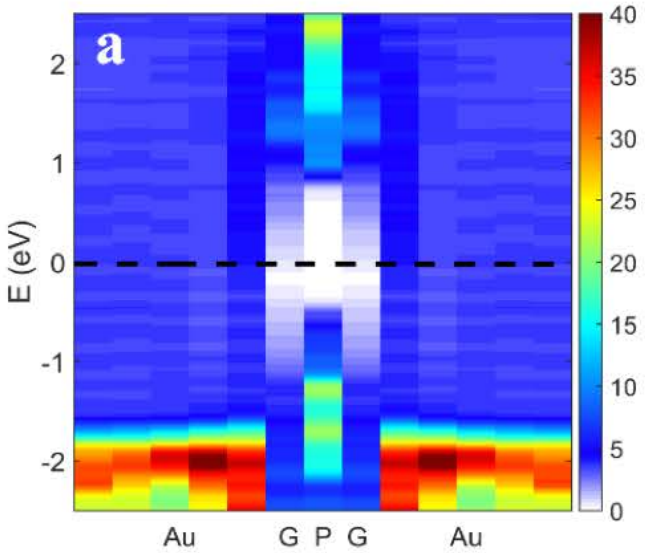

- No Vacuum! √
- Lower barrier heights √
- No Space charge √

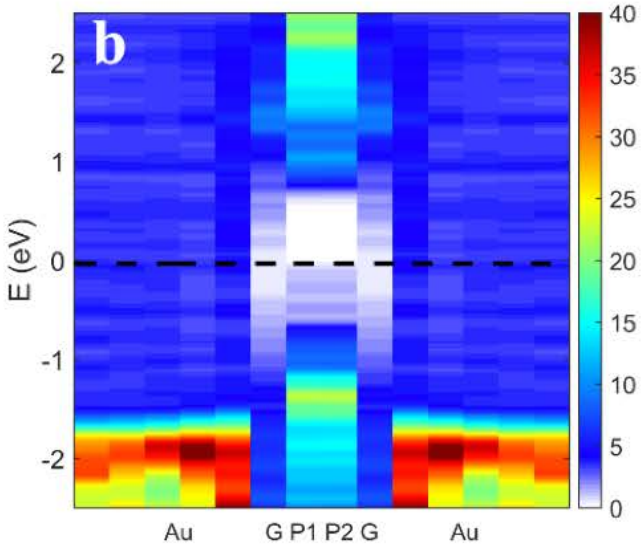
- $L_{tunnel} < L < L_{mean\text{-}free\text{-}path}$
- Ballistic Vs. Diffusive
- Due to conduction, cannot maintain large ΔT

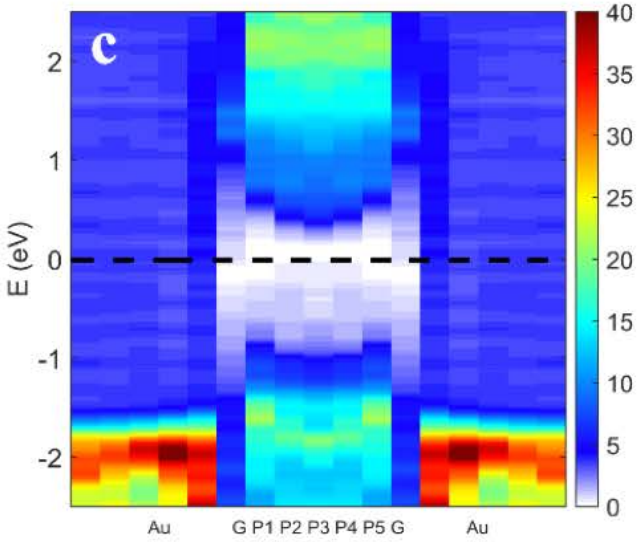


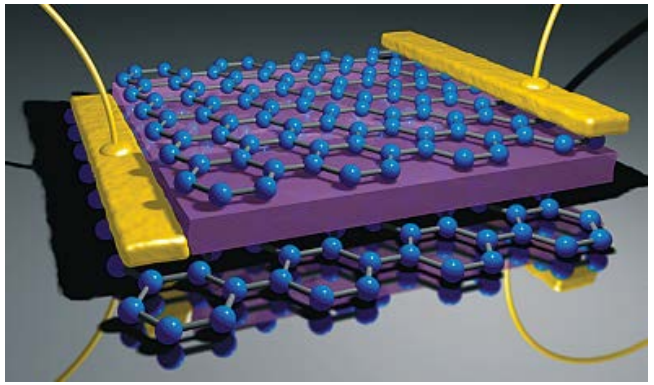

Optimum barrier height of few KT
Multi-barriers are needed
Thermoelectrics are better!

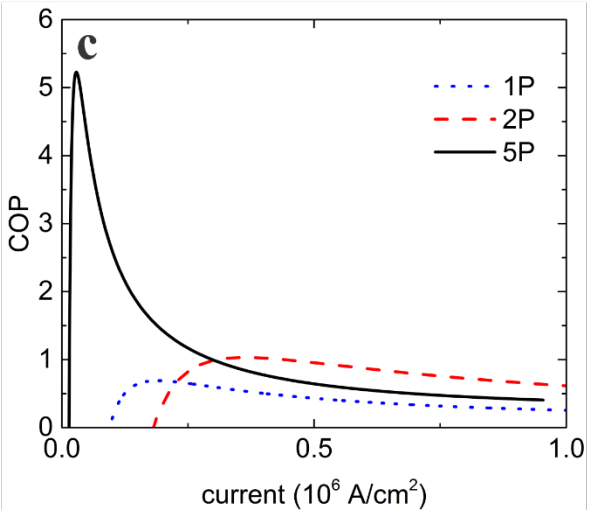
# 2D Layered materials

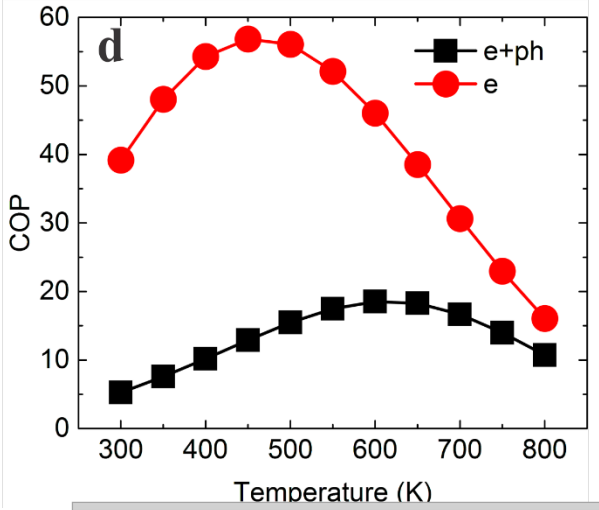




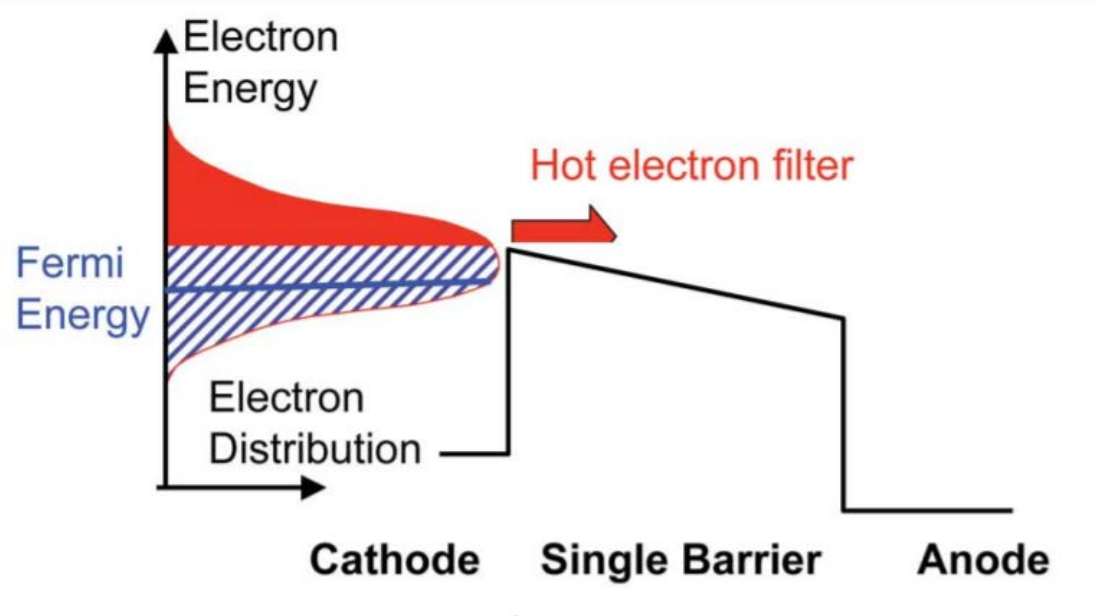



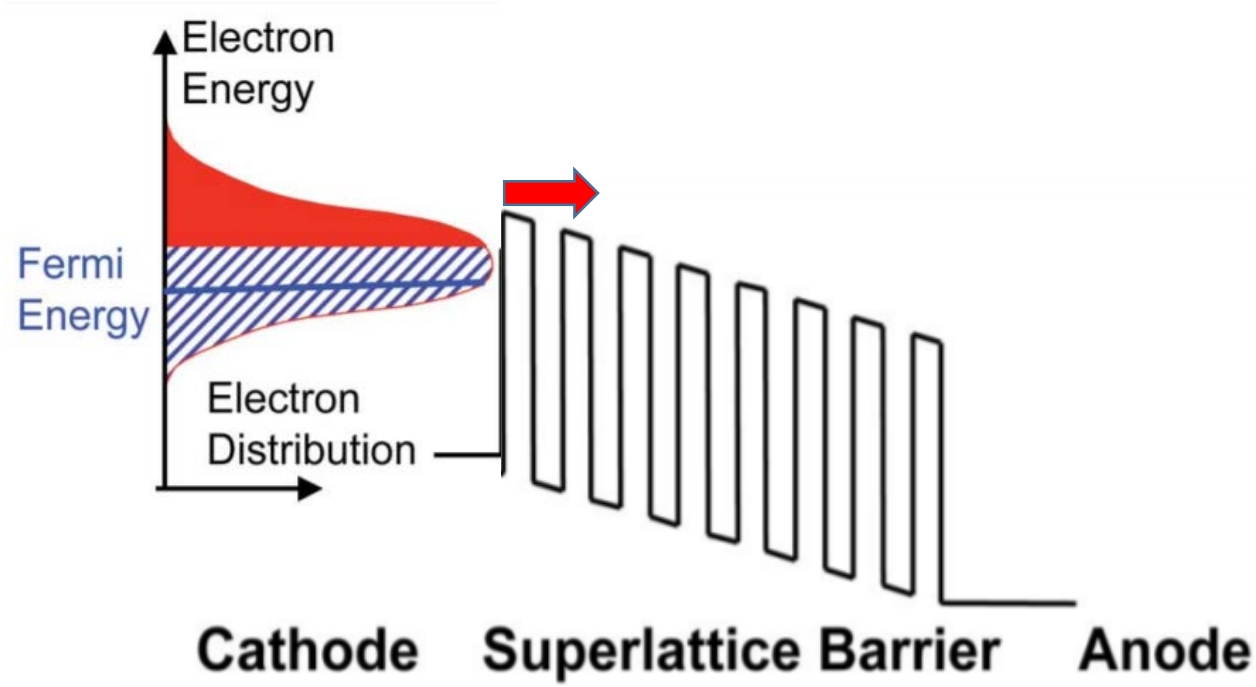



Wang, Zebarjadi, Esfarjani, Nanoscale, 2016

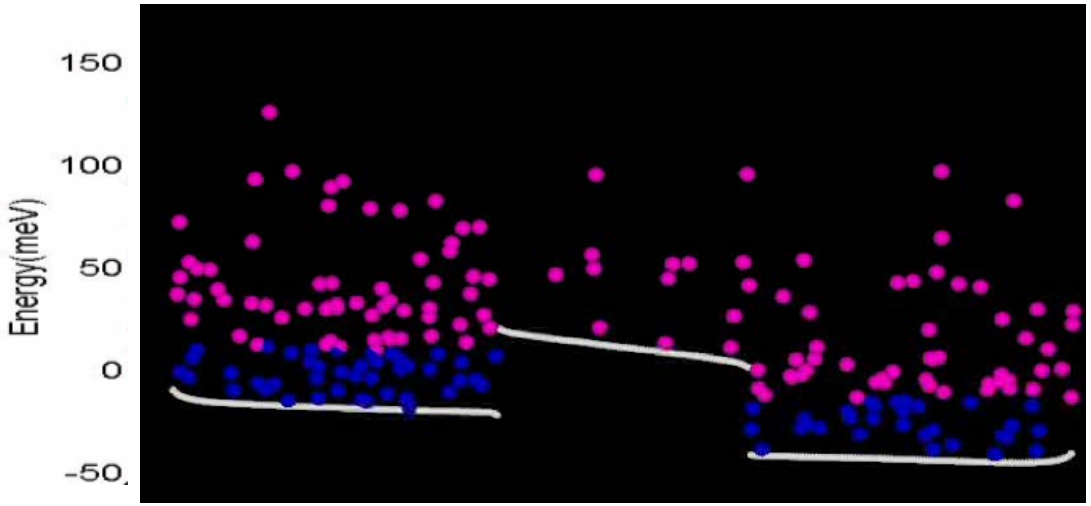
# Solid State Thermionic devices

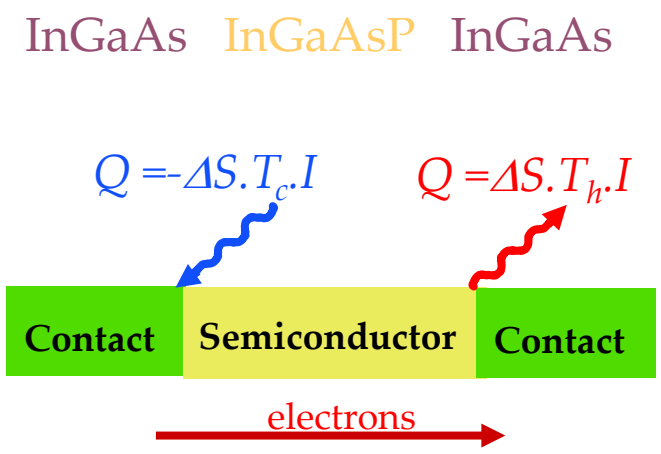
- Shakouri et al. view point

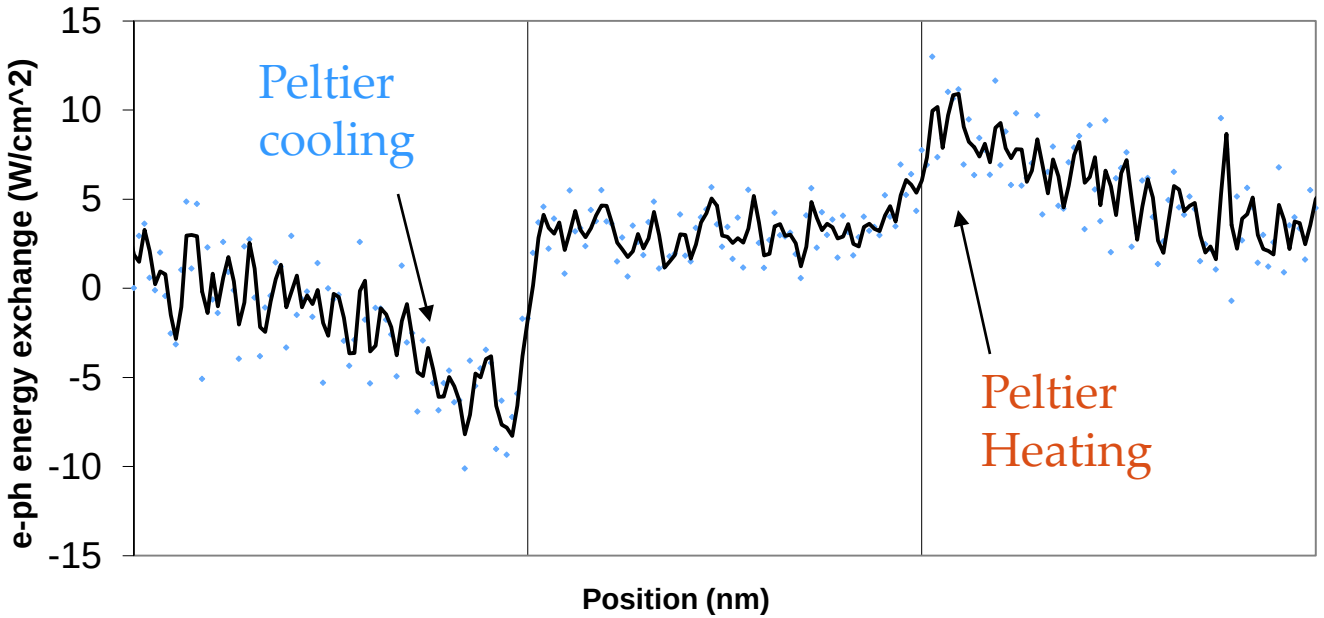


# Thermionic devices



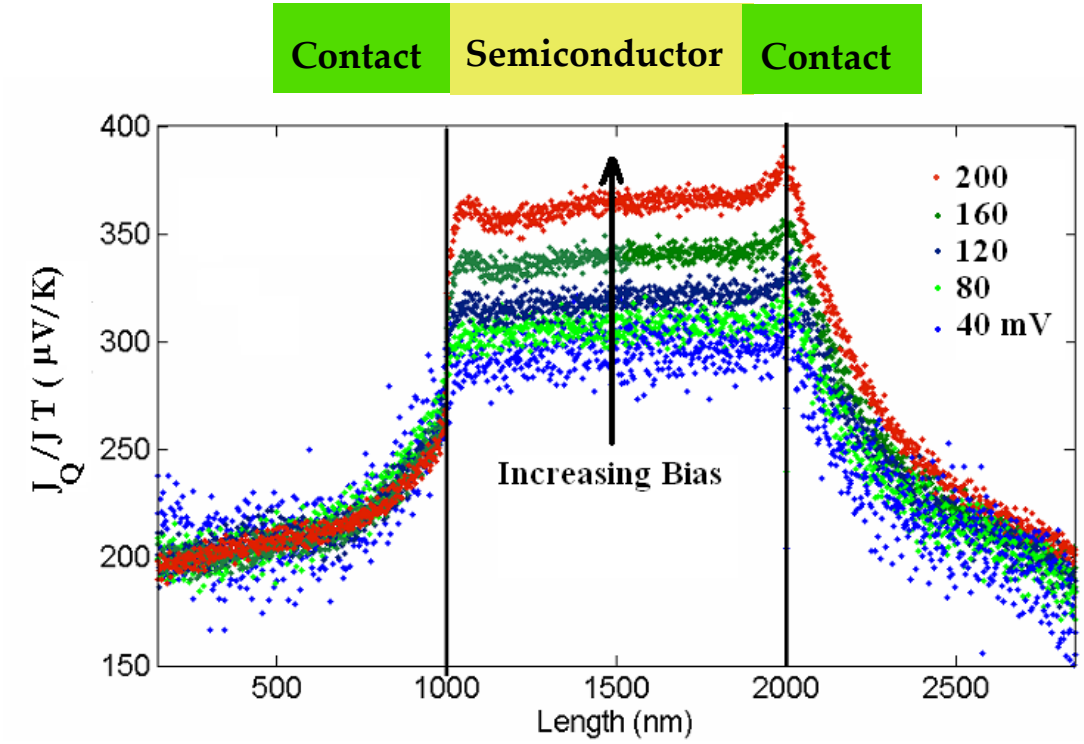






Zebarjadi et al., Phys. Rev. B, Vol 74, 195331 (2006)

# Nonlinear Solid State Thermionic

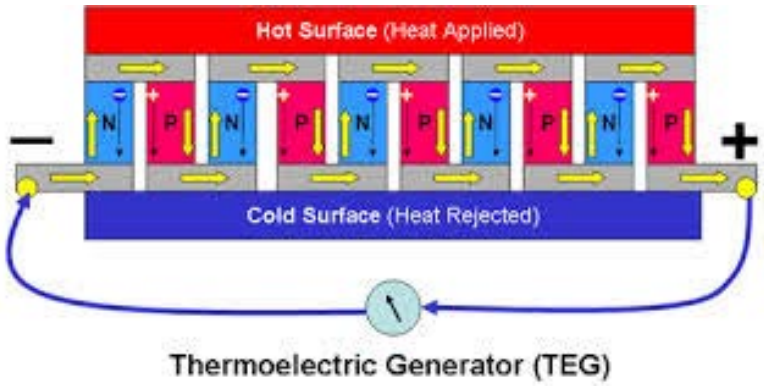
- Due to large Joule heating, only efficient when e-ph interaction is very weak (low temperatures; low carrier concentrations)






Zebarjadi et al., Appl. Phys. Lett., 91, 122104 (2007)

# Thermoelectric Materials




- Diffusive transport as opposed to ballistic
- Bulk property independent of contacts

# Thermoelectric Devices

- Device efficiency
  - Materials (ZT)
  - Contact electrical and thermal resistance
  - Impedance matching
  - Efficient heating/cooling of the device

# Materials Design

Orders of magnitude

$\sigma \sim 10^5$ S/m

$S \sim 100\ \mu V/K$

$\kappa \sim 1$ W/mK

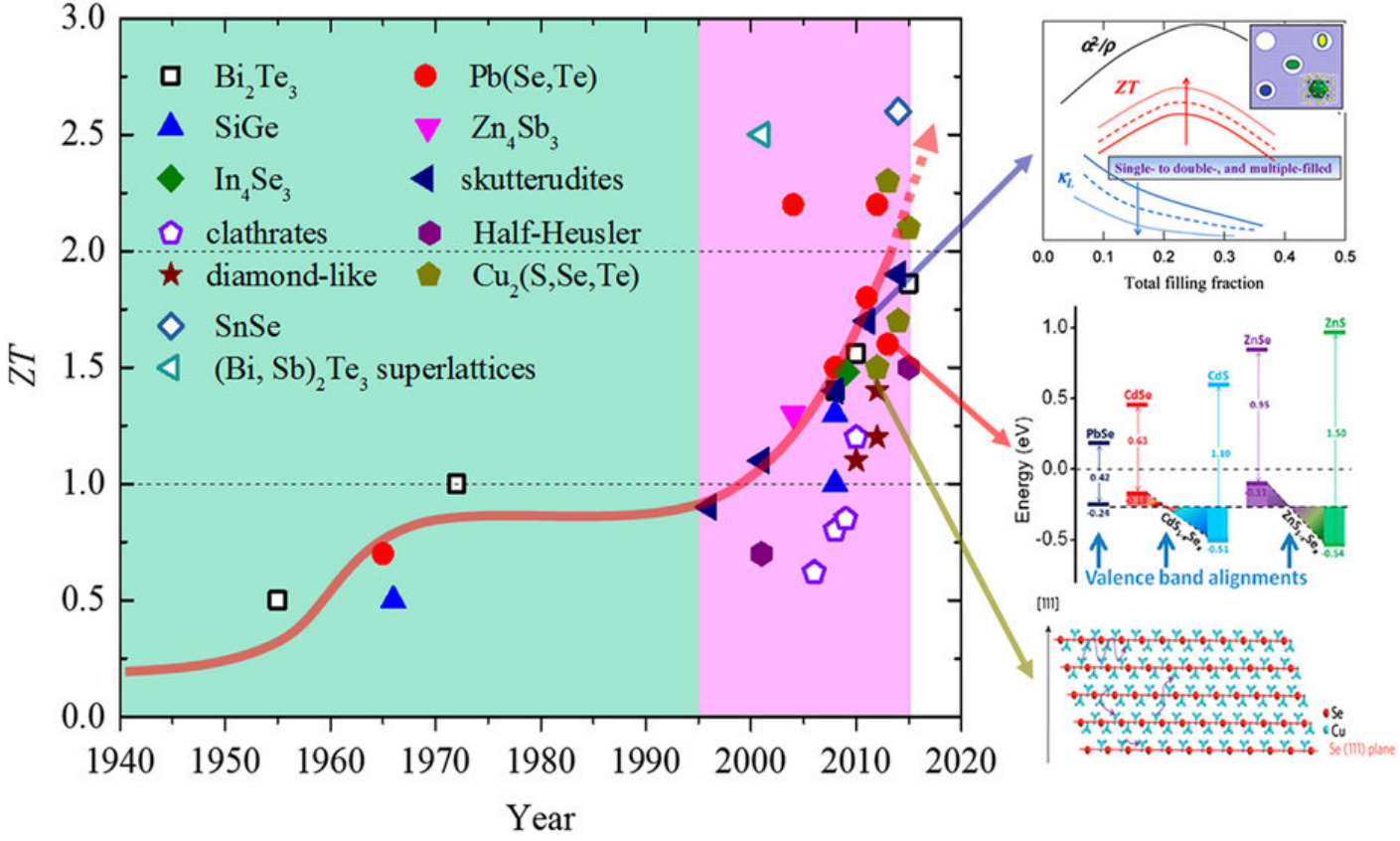
$\sigma S^2 \sim 10^{-3}$ W/mK$^2$

$$Z = \frac{\sigma S^2}{\kappa}$$

Power factor

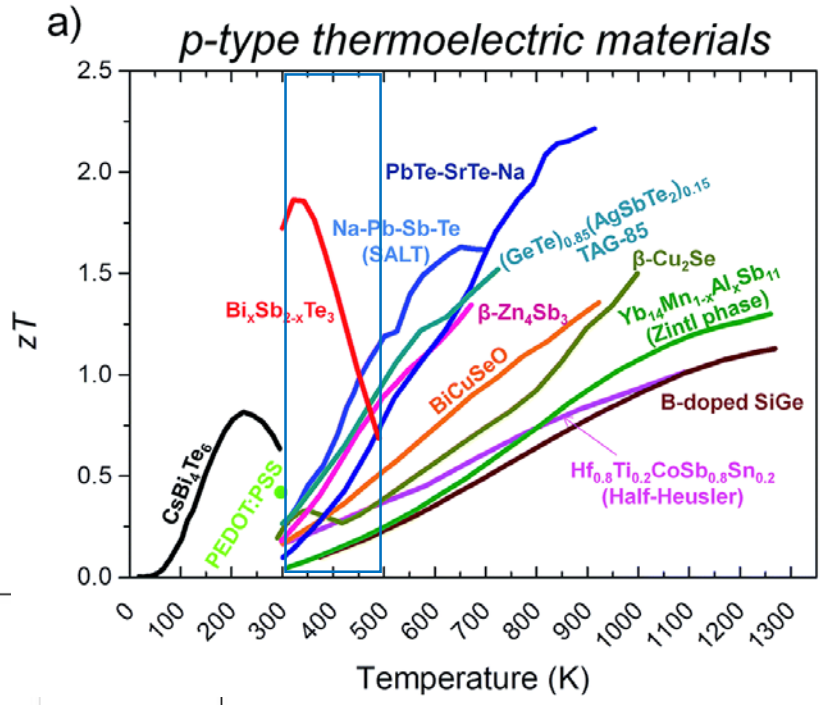
Thermal Conductivity

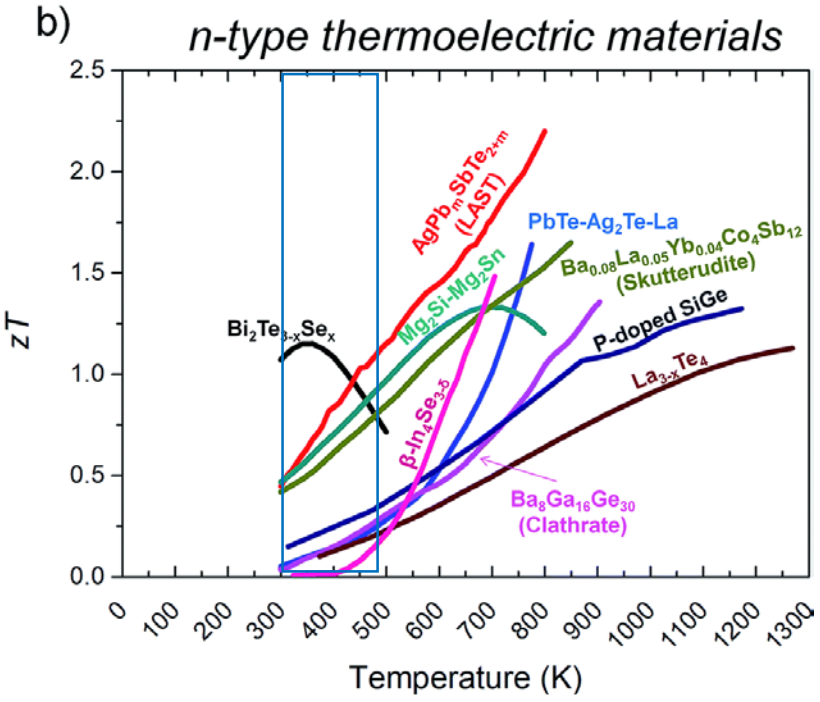
ZT Dimensionless

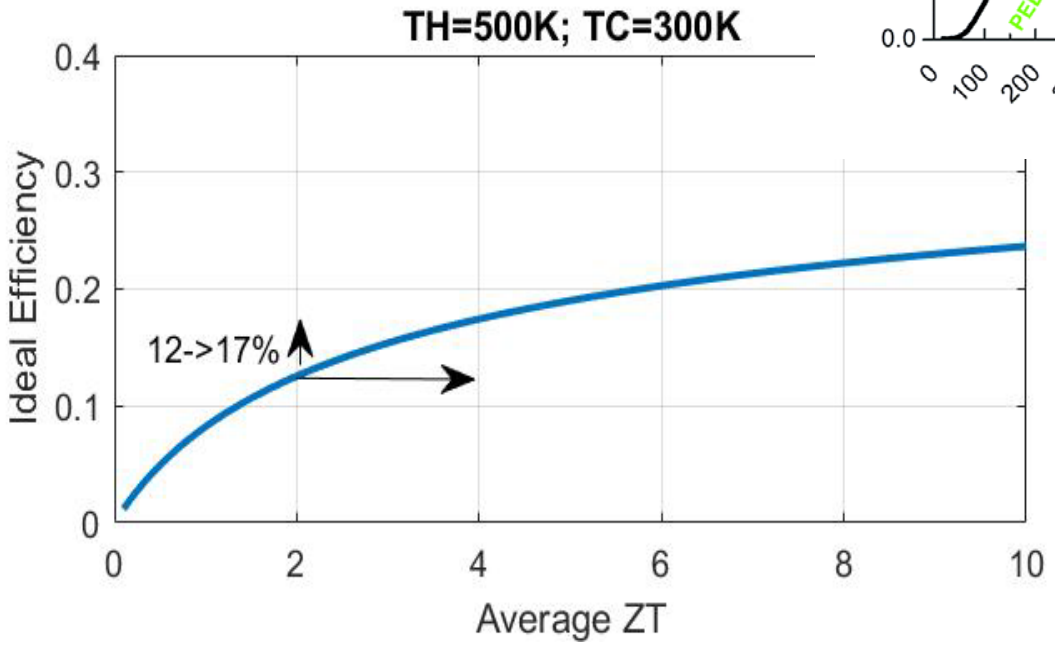



*Yang et al. npj Computational Materials 2016*

# Efficiency

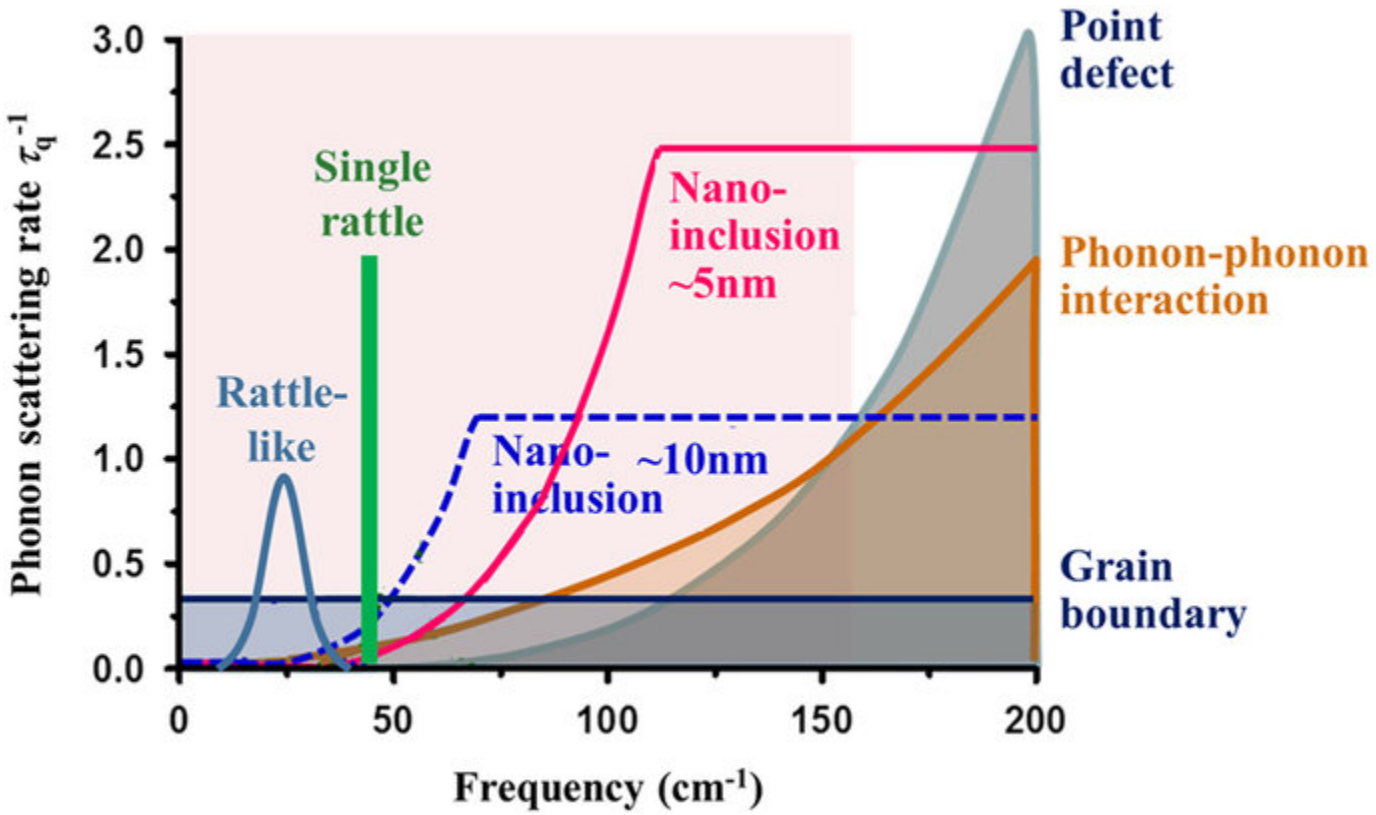


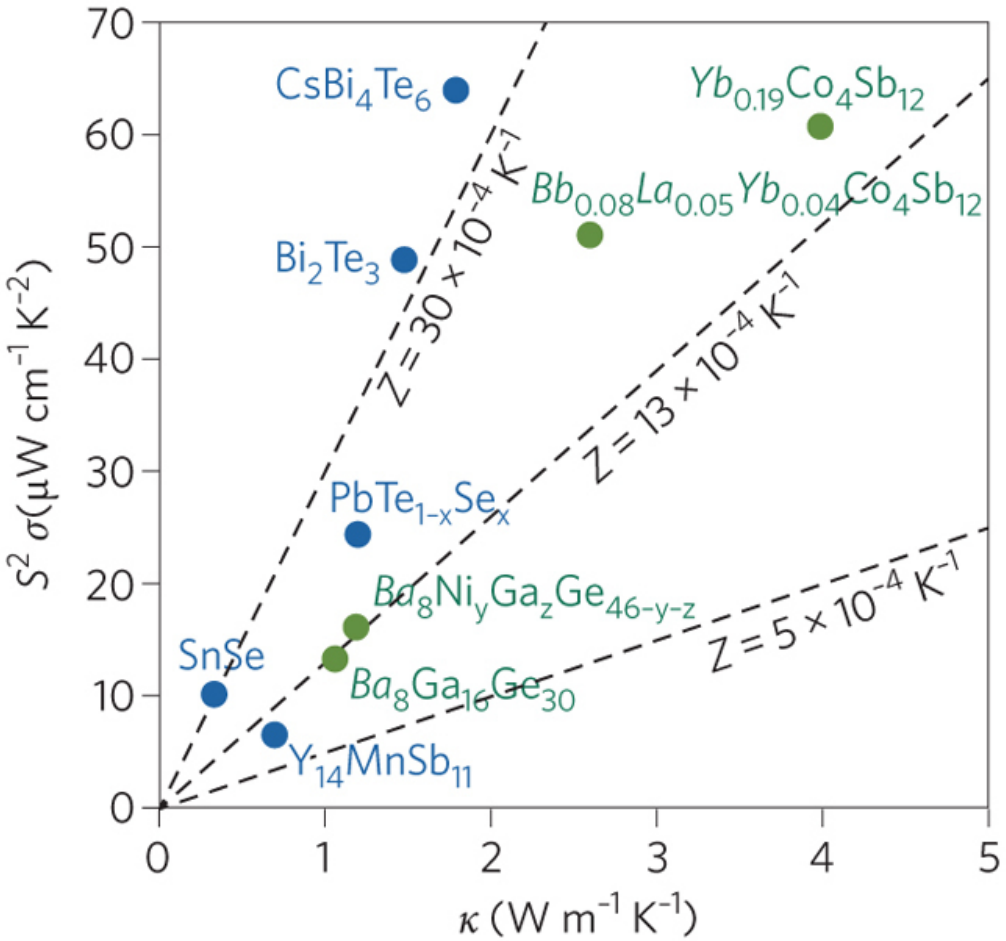

***Rull-Bravo et al.***, *RSC Adv.*, 2015

# Thermal conductivity Reduction

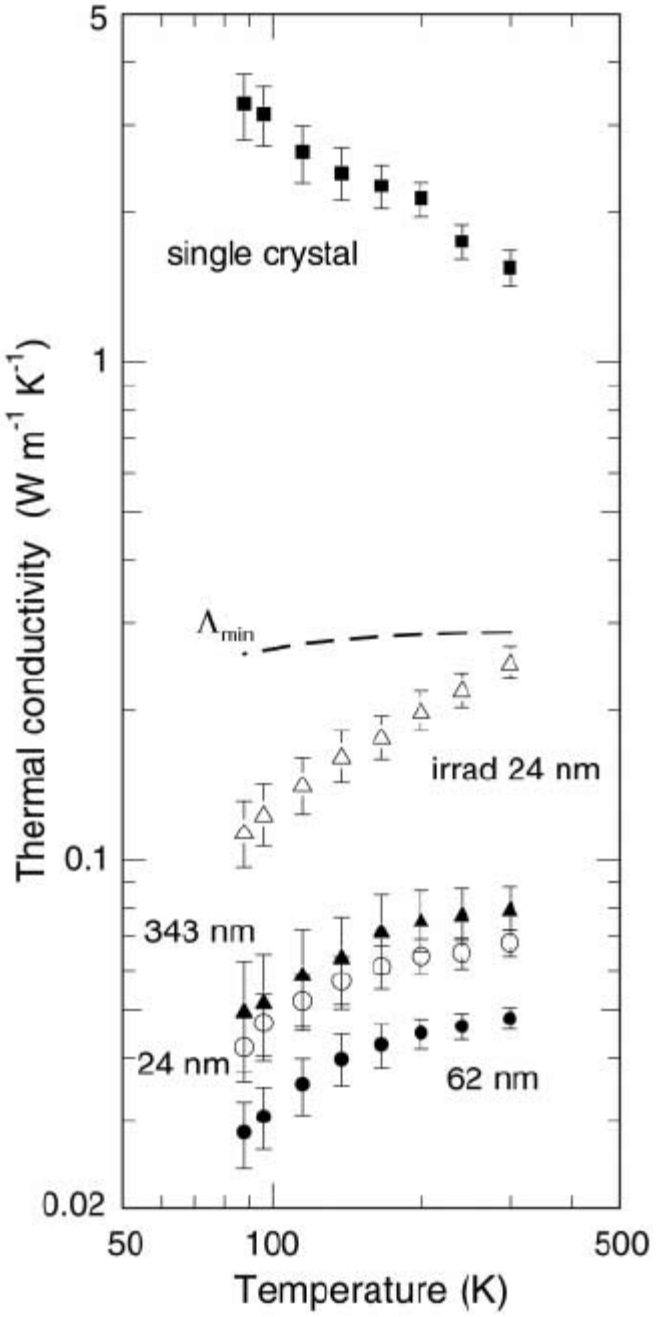



*Yang et al. npj Computational Materials 2016*

# Thermal conductivity




*Beekman, Morelli, Nolas, Nature Materials 2016*




*Cahill Science 2007*



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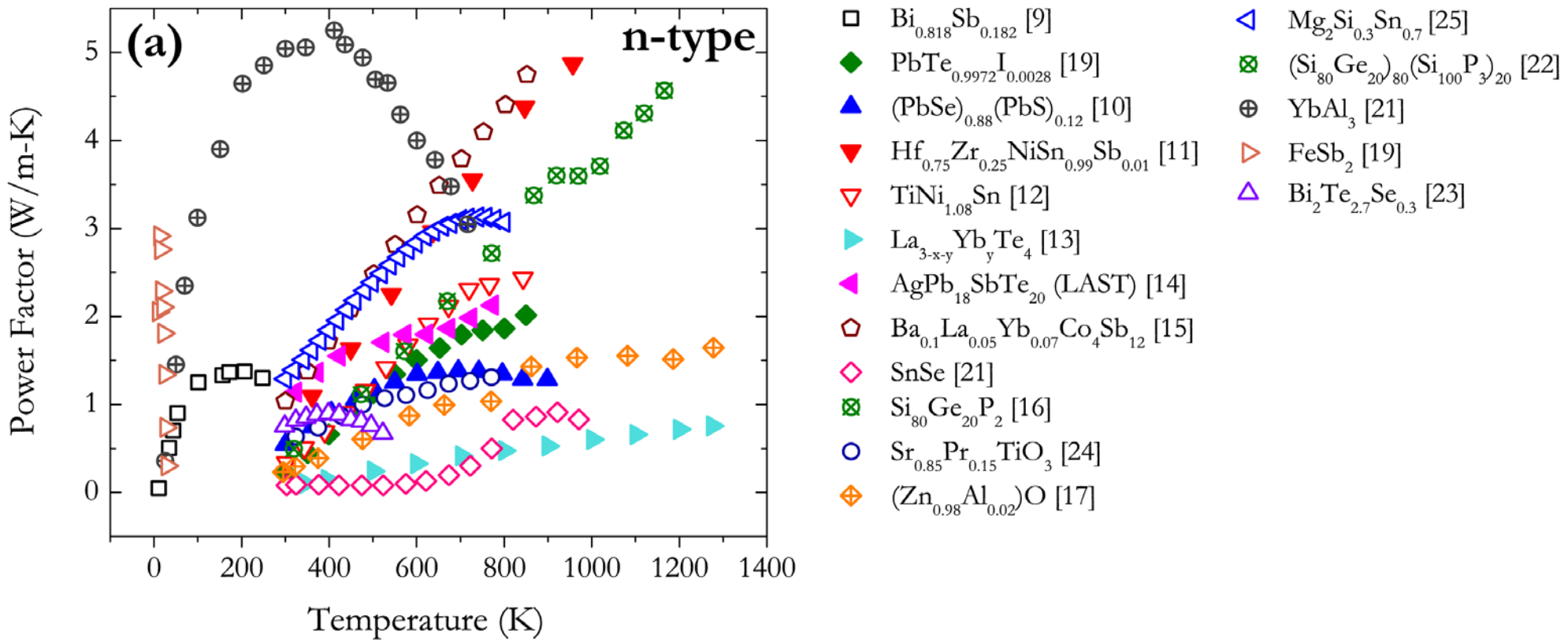
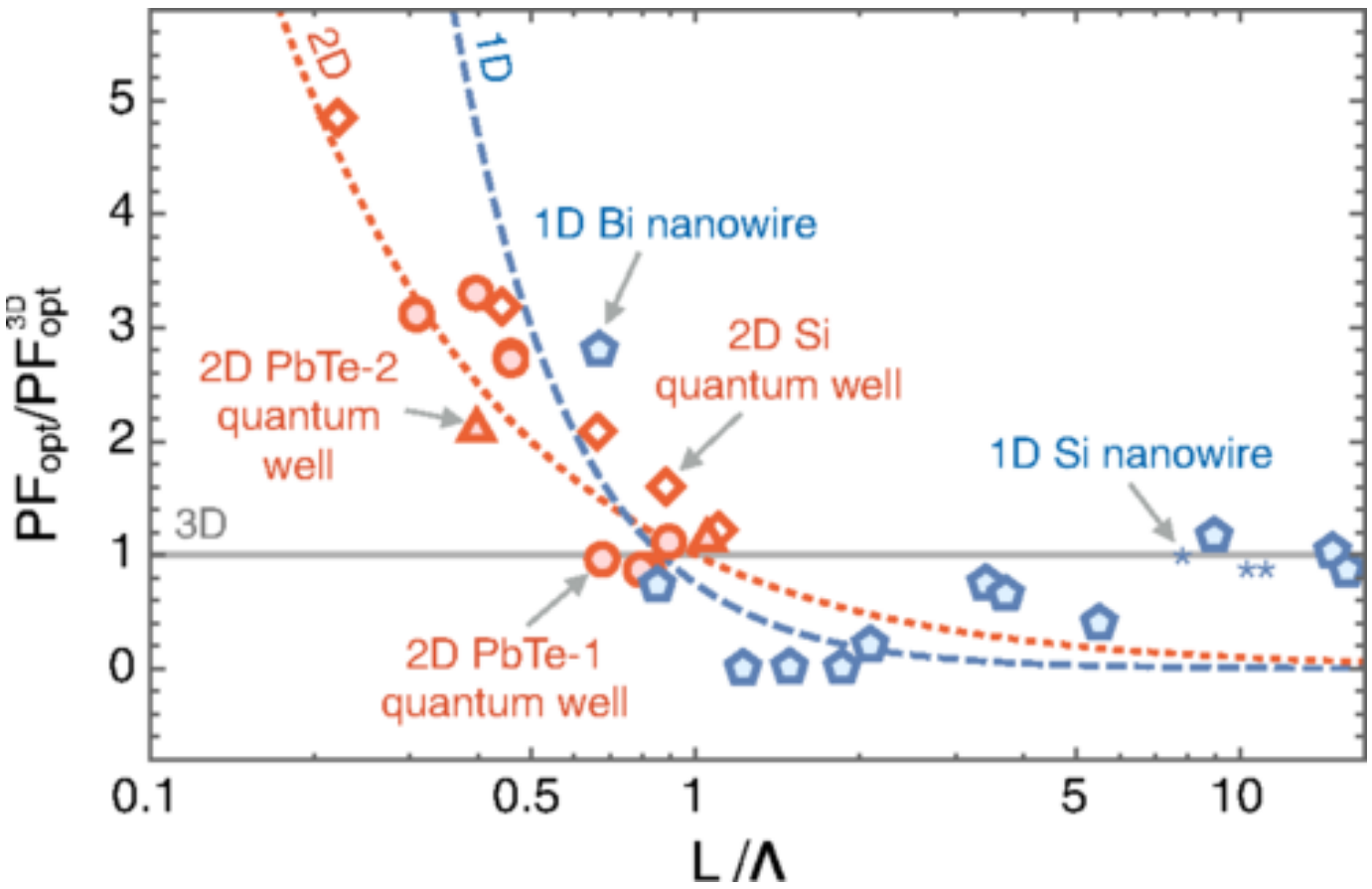
# Power Factor times T

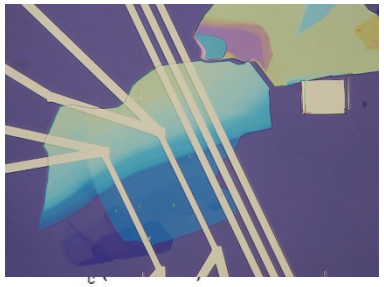


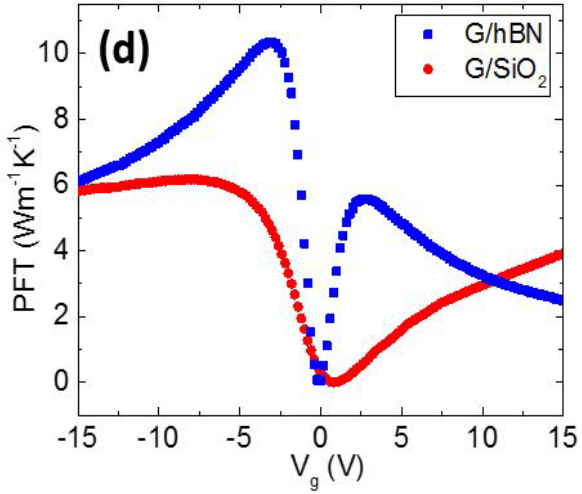

Dehkordi, Zebarjadi, Tritt, MSE:R (2015)

# Confinement




Hung et al. PRL (2016)



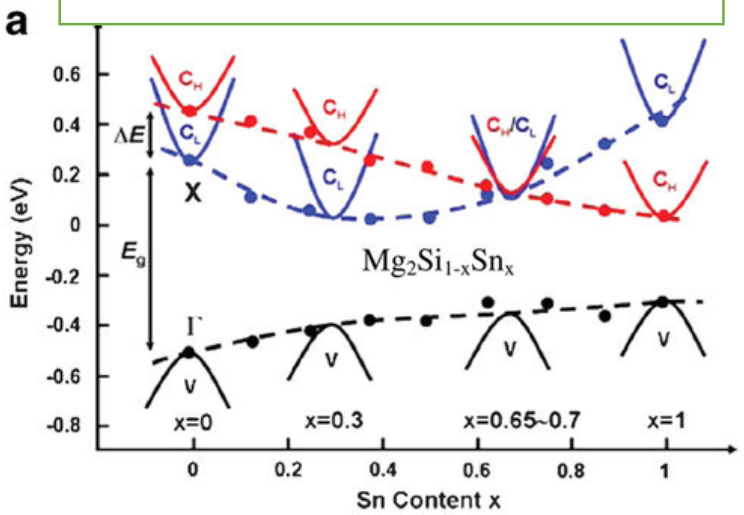



Duan et. al. PNAS 2016

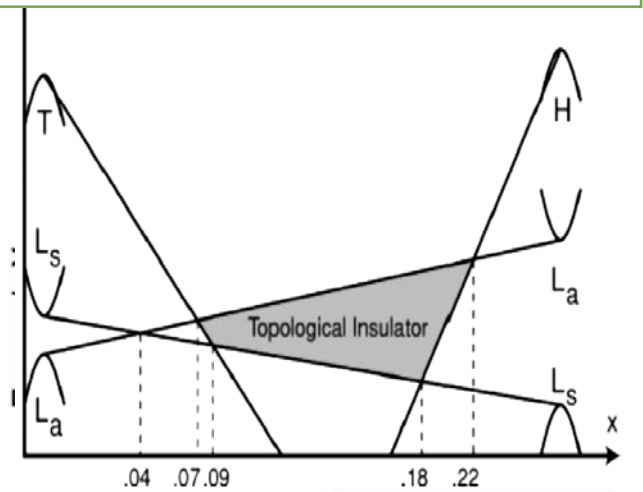
# Band Engineering

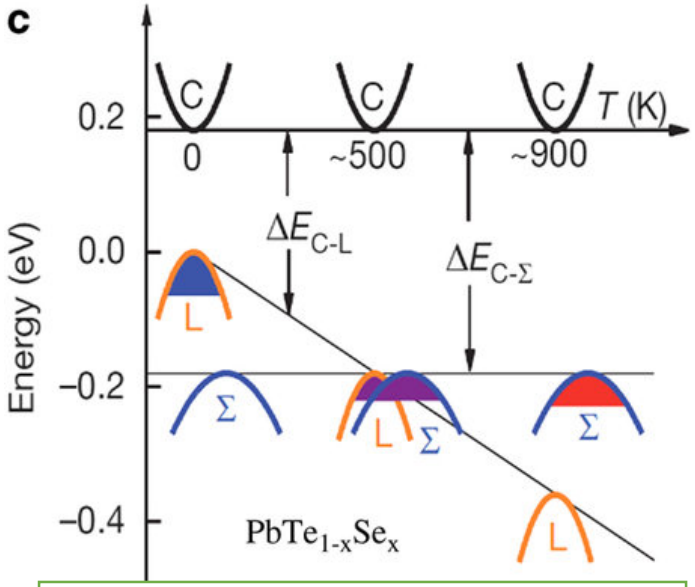
- Degenerate bands
- Resonant States
- Change of bands with T
- Alloying

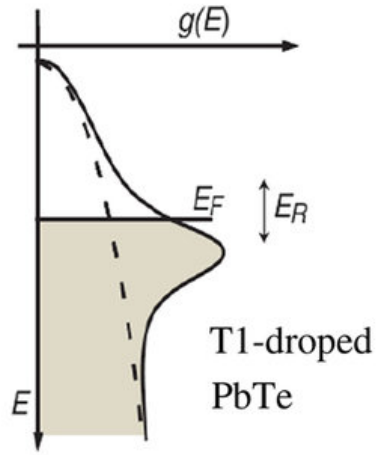
Solid Solution
Zhang et al




Phase diagram of Bismuth antimony Surface states



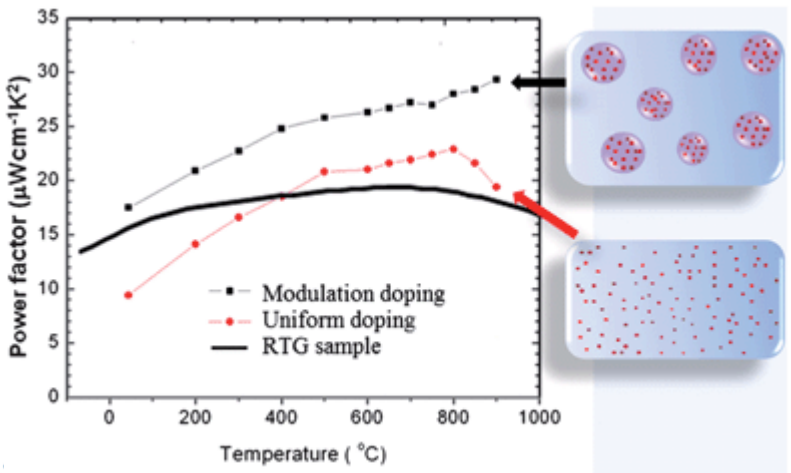



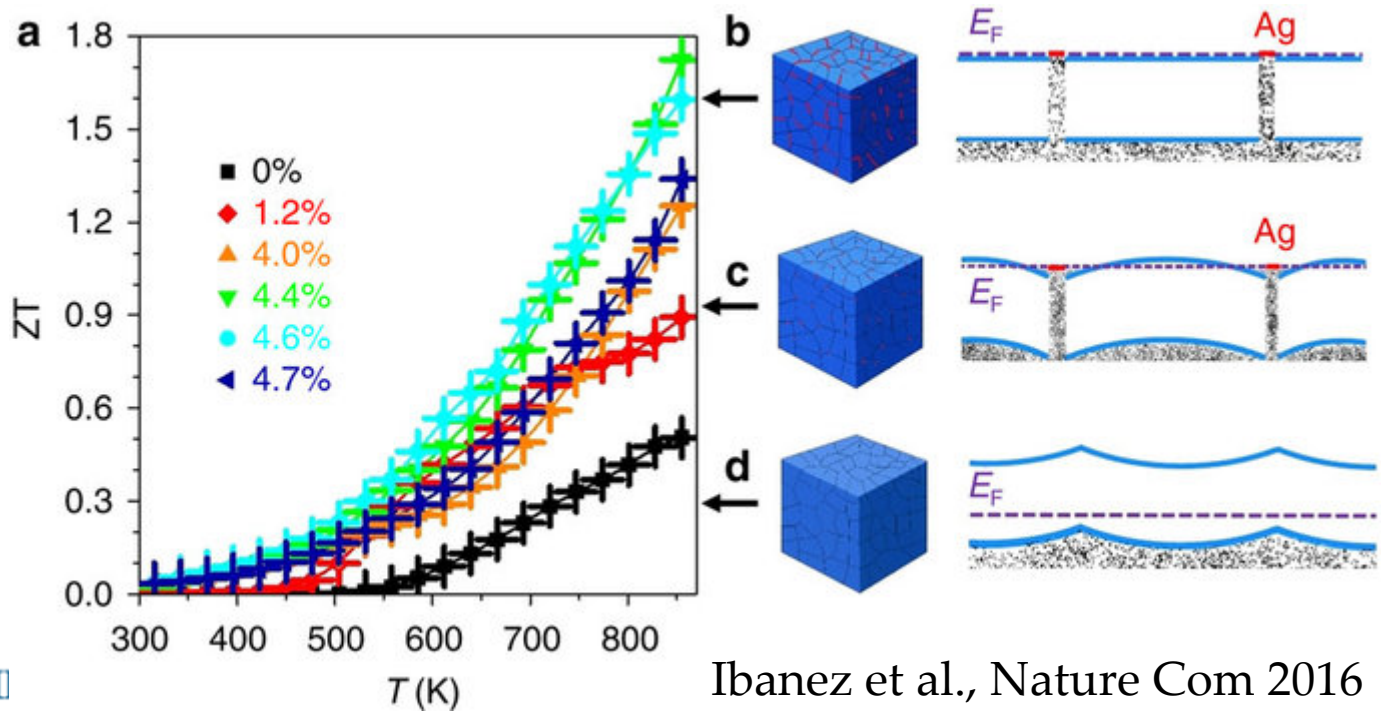

Temperature induced band order , Snyder et. al.

Resonant States, Heremans et al.

# Unconventional Doping

- Nanoparticles with aligned bands with host
- Resonant Doping
- Surface doping (Modulation doping)
- Cloaking




Ibanez et al., Nature Com 2016

# Summary

- Vacuum Thermionic Challenges
  - Suffer from presence of vacuum; Space Charge; large work function
- Solid State Thermionic Challenges
  - Thermal resistance; need investigation of Nonlinear Transport
- Thermoelectric Materials
  - Need high average ZT materials at room temperature
  - Need to focus on device aspects