

# Thermoelectricity: From Atoms to Systems

Week 4: Thermoelectric Systems

Lecture 4.5: Ballistic thermionic coolers and non-linear Peltier

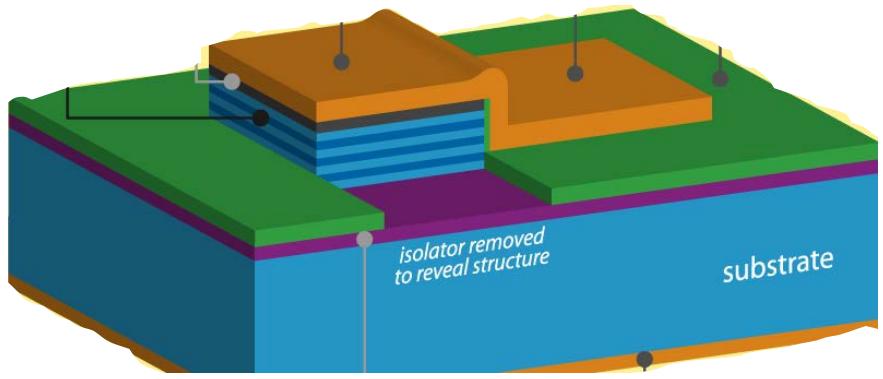
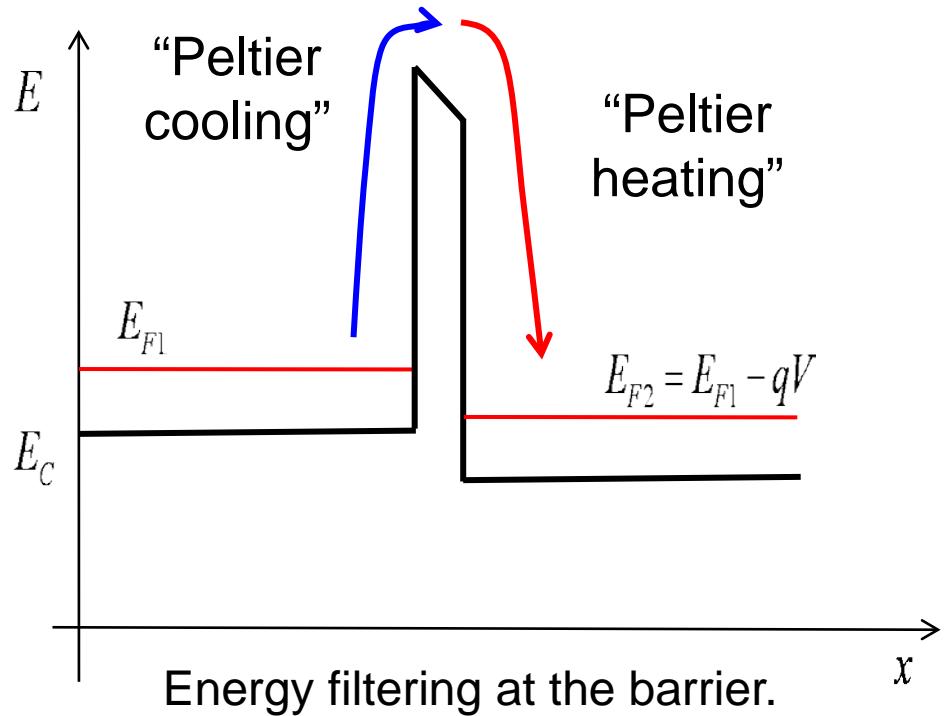
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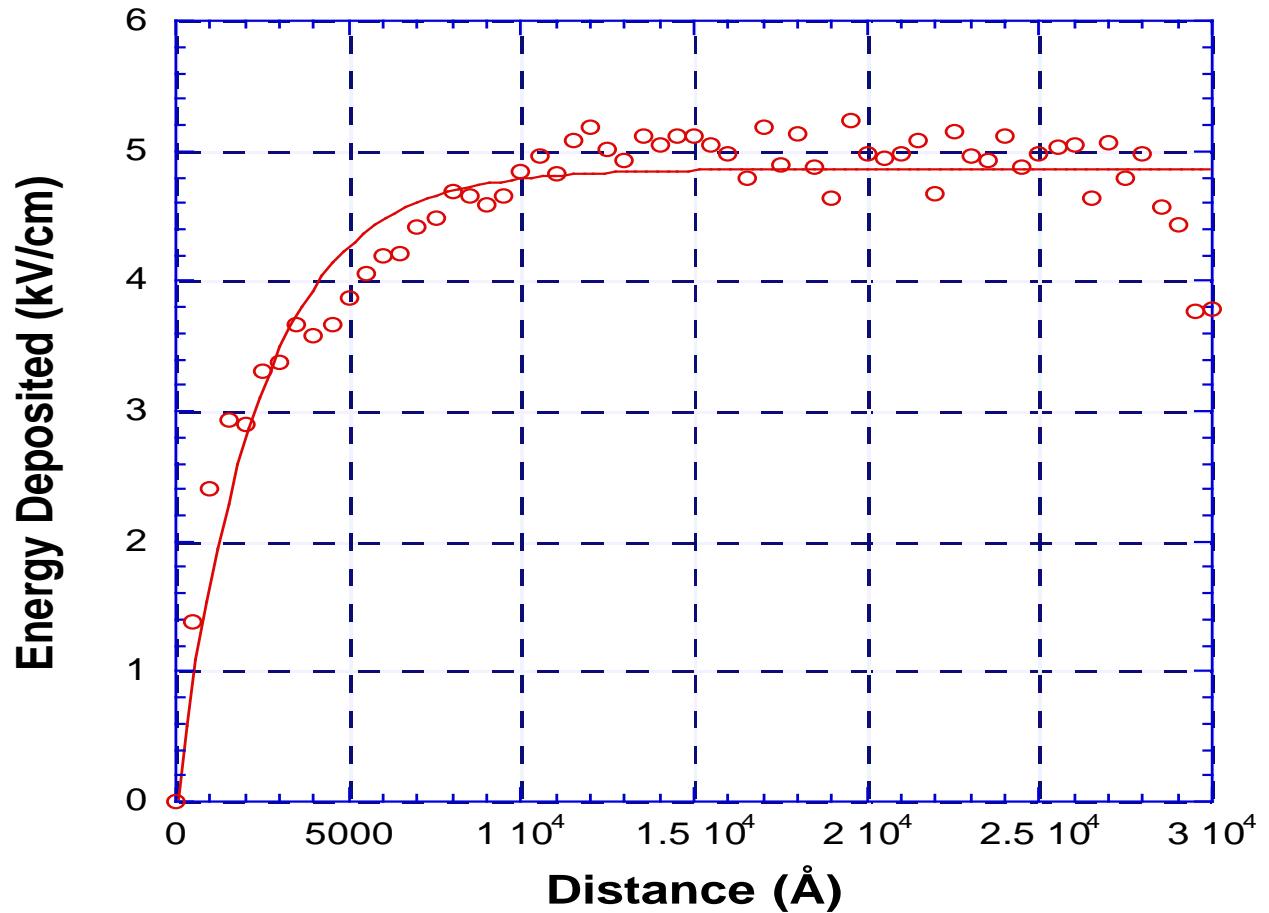
# System consideration of thermionic (thin film) devices



Lundstrom Week 2, Lecture 4 (2013)

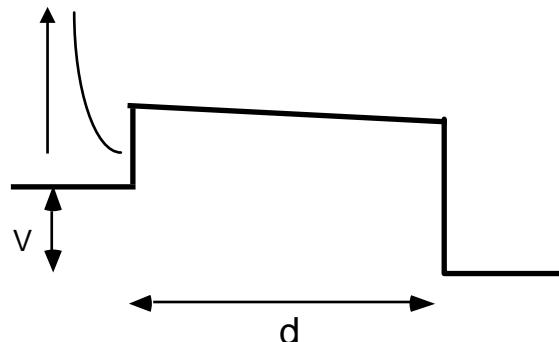
# Joule Heating in the Barrier

GaAs, 5000 electrons,  $E=5\text{kV/cm}$ ,  $\phi_c=0.1\text{eV}$



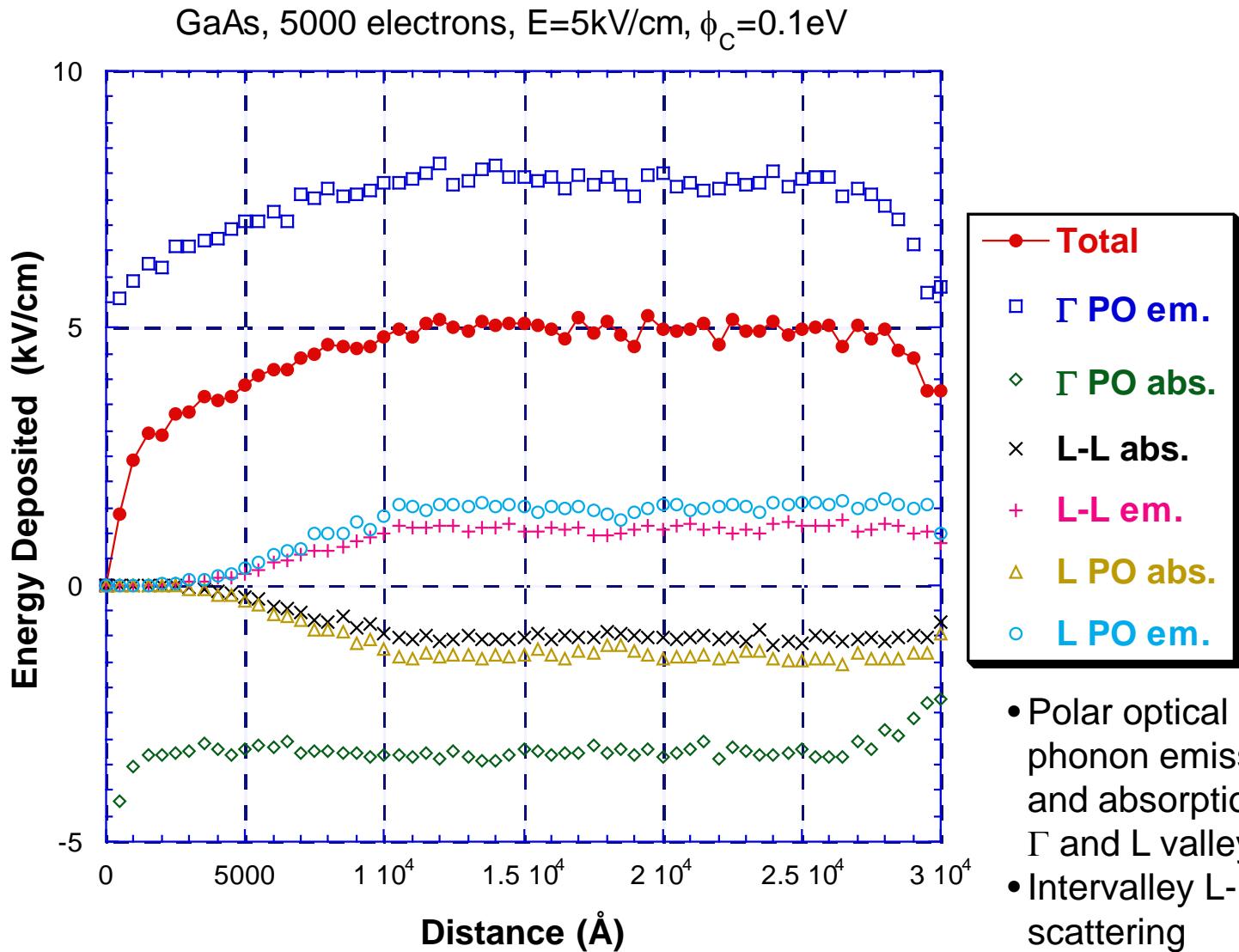
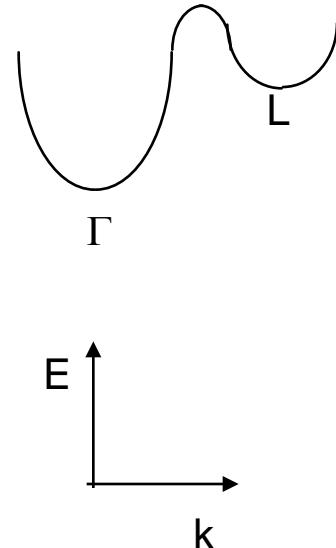
$\lambda_E$  = Energy relaxation length

$$\frac{dQ_{Joule}}{dx} = I \frac{V}{d} \left(1 - e^{-x/\lambda_E}\right)$$



A. Shakouri, et al.; Microscale Thermophysical Engineering, 2(1), January-March 1998, pp. 37-47.

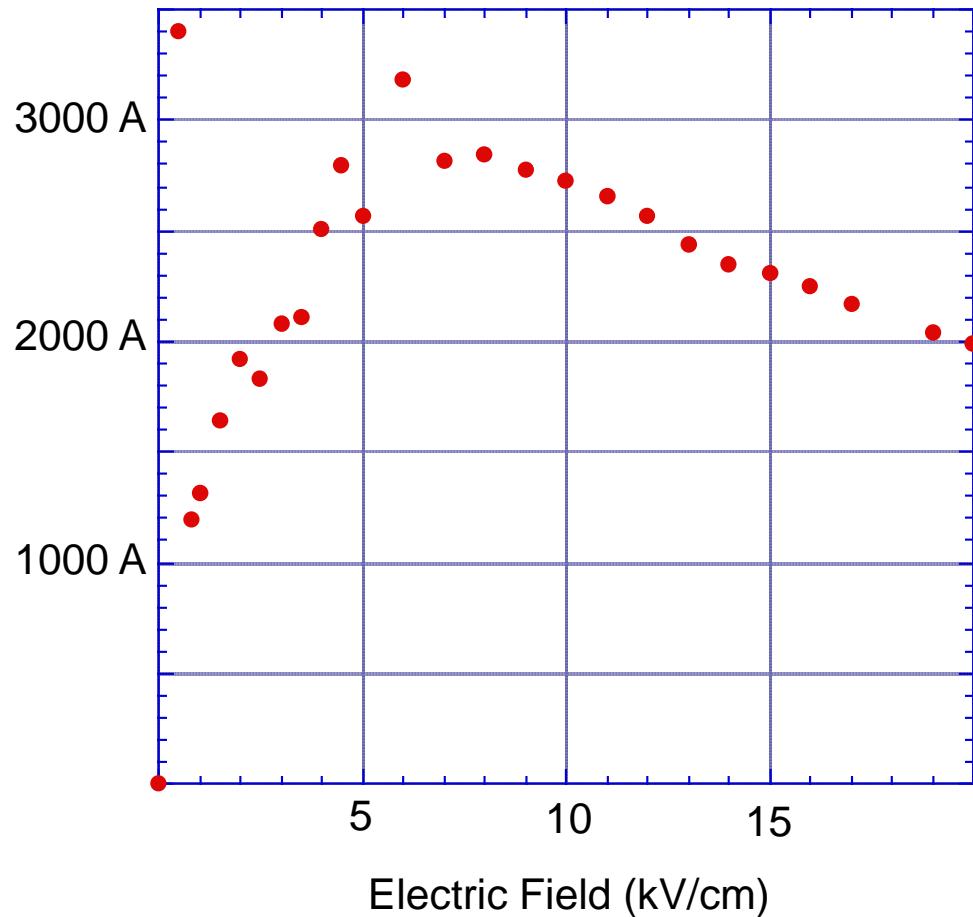
# Major Energy Relaxation Mechanisms in III-Vs



- Polar optical phonon emission and absorption in  $\Gamma$  and L valleys
- Intervalley L-L scattering

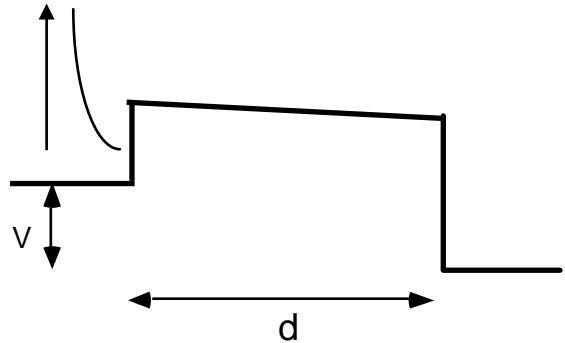
$\lambda_E$ : Energy relaxation length  
for electrons in GaAs

- Energy Relaxation length in III-V semiconductors has a maximum as a function of electric field.
- Interplay between Polar Optical Phonon Scattering and Intervalley Scattering.



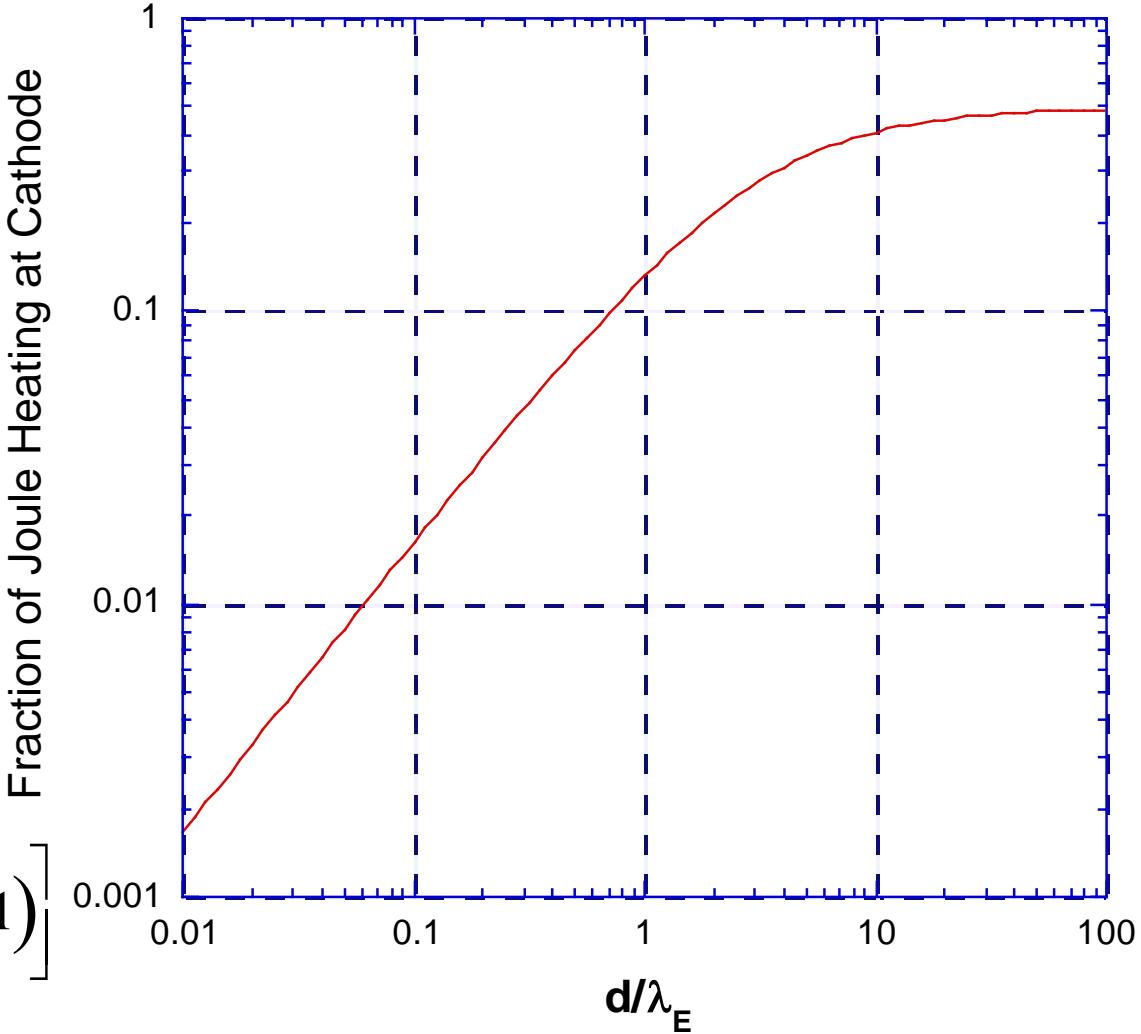
# Fraction of Joule heating going back to the Cathode

A. Shakouri, E. Y. Lee, D. L. Smith, V. Narayananamurti, and J. E. Bowers; Microscale Thermophysical Engineering, 2(1), January-March 1998, pp. 37-47.

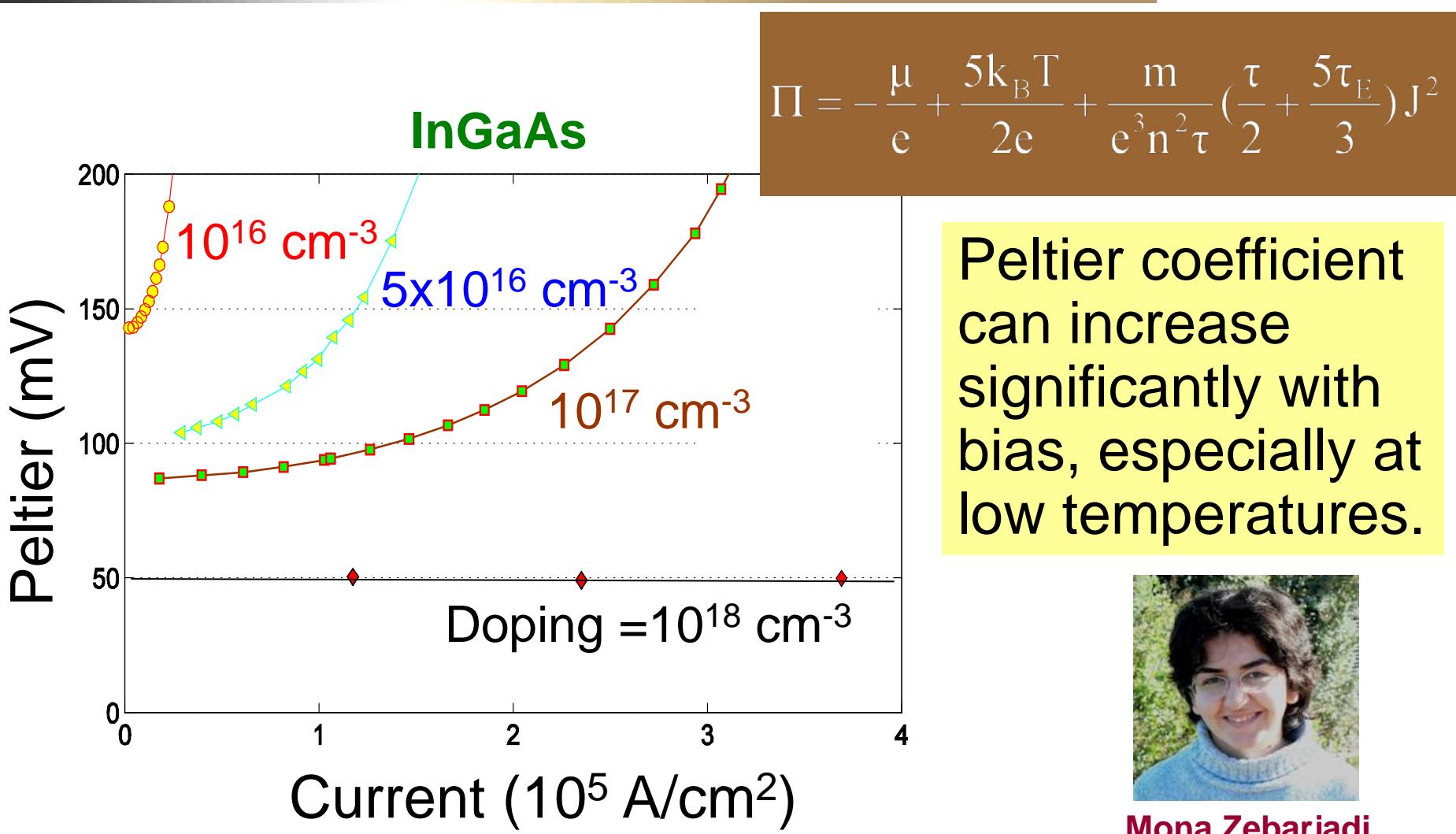


Energy relaxation length:  $\lambda_E$

$$Q_{Joule} = IV \left[ \left( \frac{1}{2} - \frac{\lambda_E}{d} \right) - \frac{\lambda_E^2}{d^2} \left( e^{-d/\lambda_E} - 1 \right) \right]$$

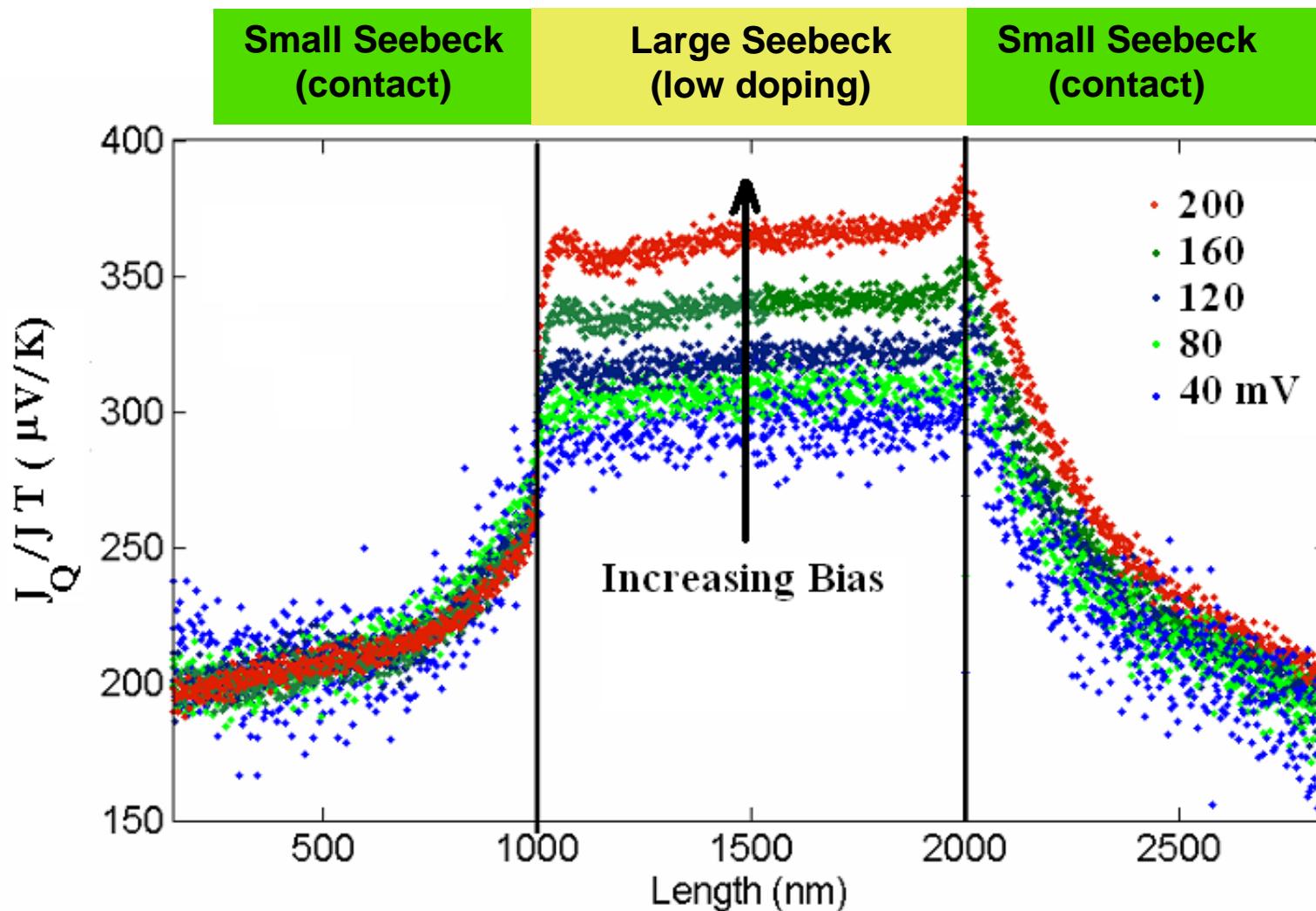


# Nonlinear Peltier Coefficient



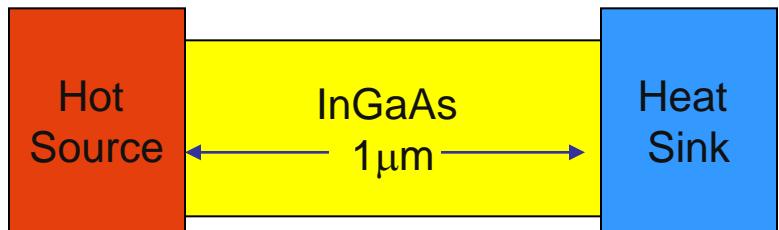
Mona Zebarjadi

M. Zebarjadi, K. Esfarjani & A. Shakouri , Appl. Phys. Lett., 91, 122104 (2007)

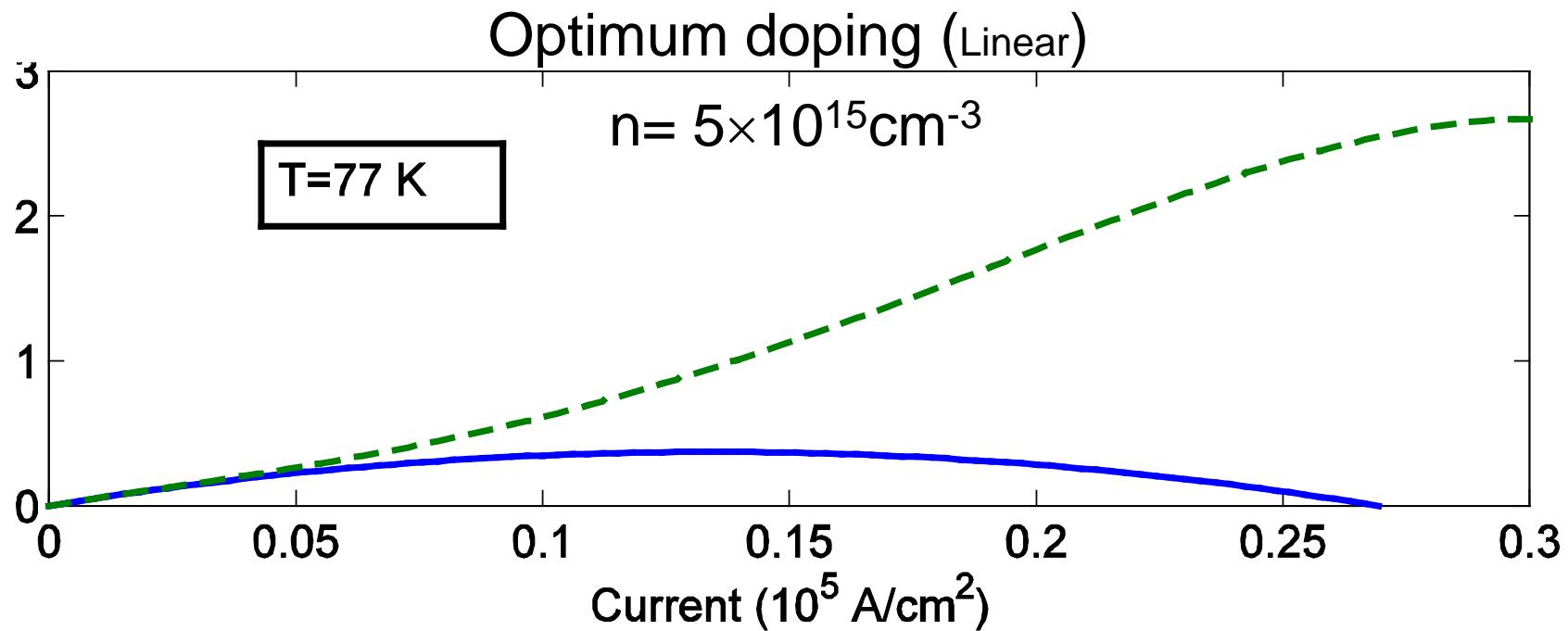


M. Zebarjadi, K. Esfarjani & A. Shakouri , PRB (2007)

# Potential enhancement of cooling power



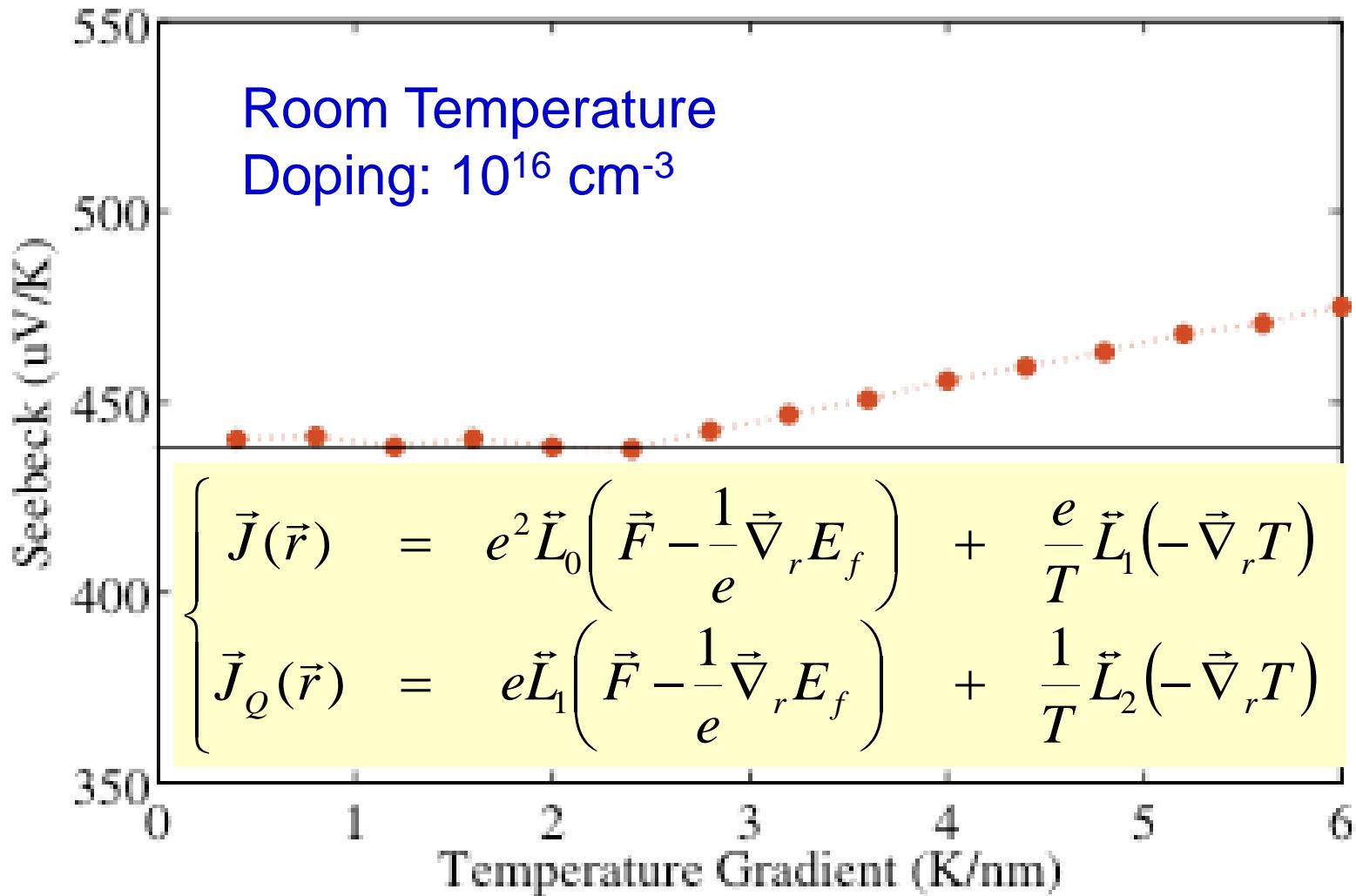
Nonlinearity of the Peltier coefficient can enhance the cooling power specially at cryogenic temperatures, if there is perfect heat sink.



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

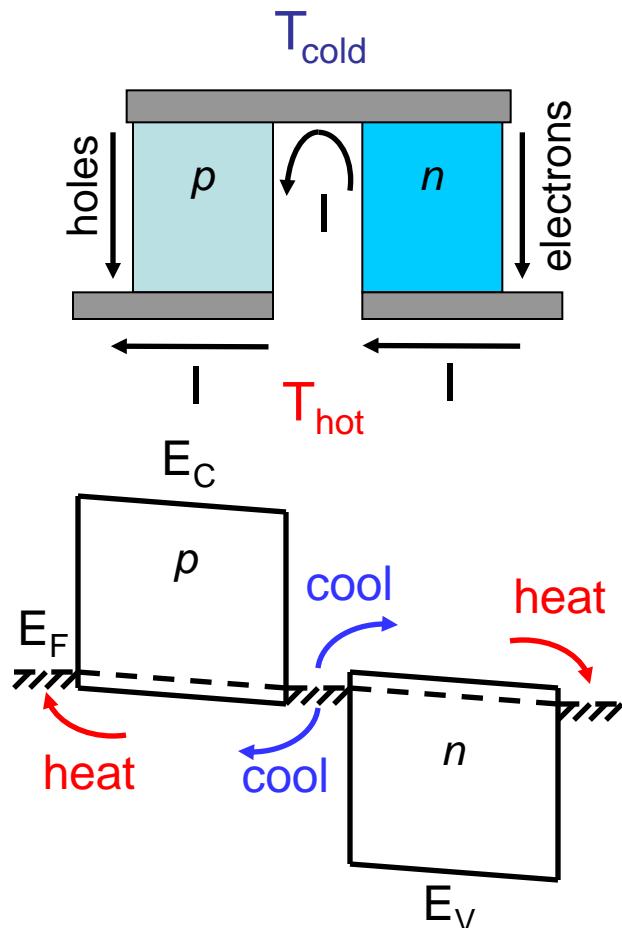
# Nonlinear Seebeck Coefficient

M. Zebarjadi, PhD Thesis, UC Santa Cruz

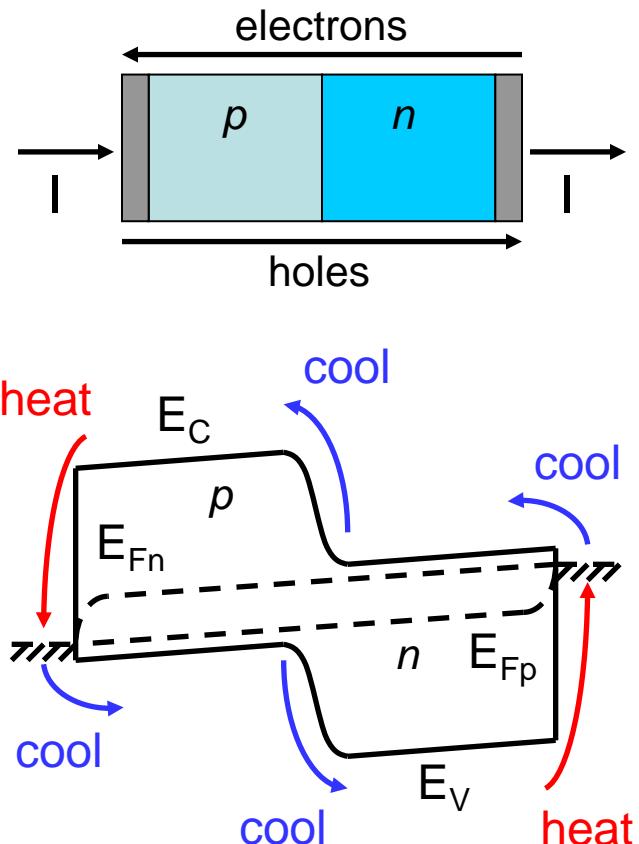


# Minority-Carrier Thermoelectric Effects

## Conventional TE Cooler

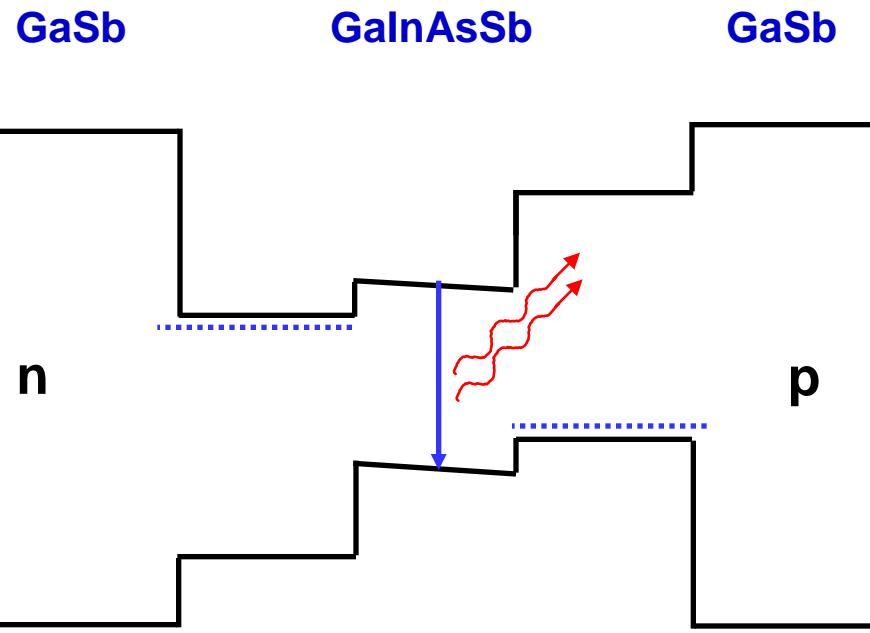


## P-N Diode

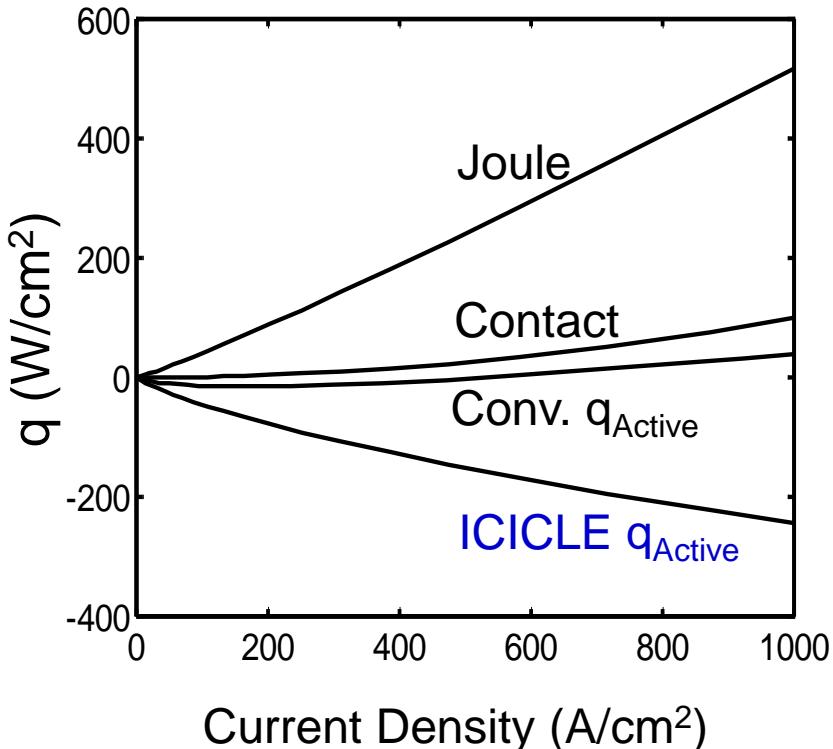


K. P. Pipe, R. J. Ram, and A. Shakouri,  
*Phys. Rev. B* 66, 125316 (2002)

# Injection Current Internally Cooled Light Emitter

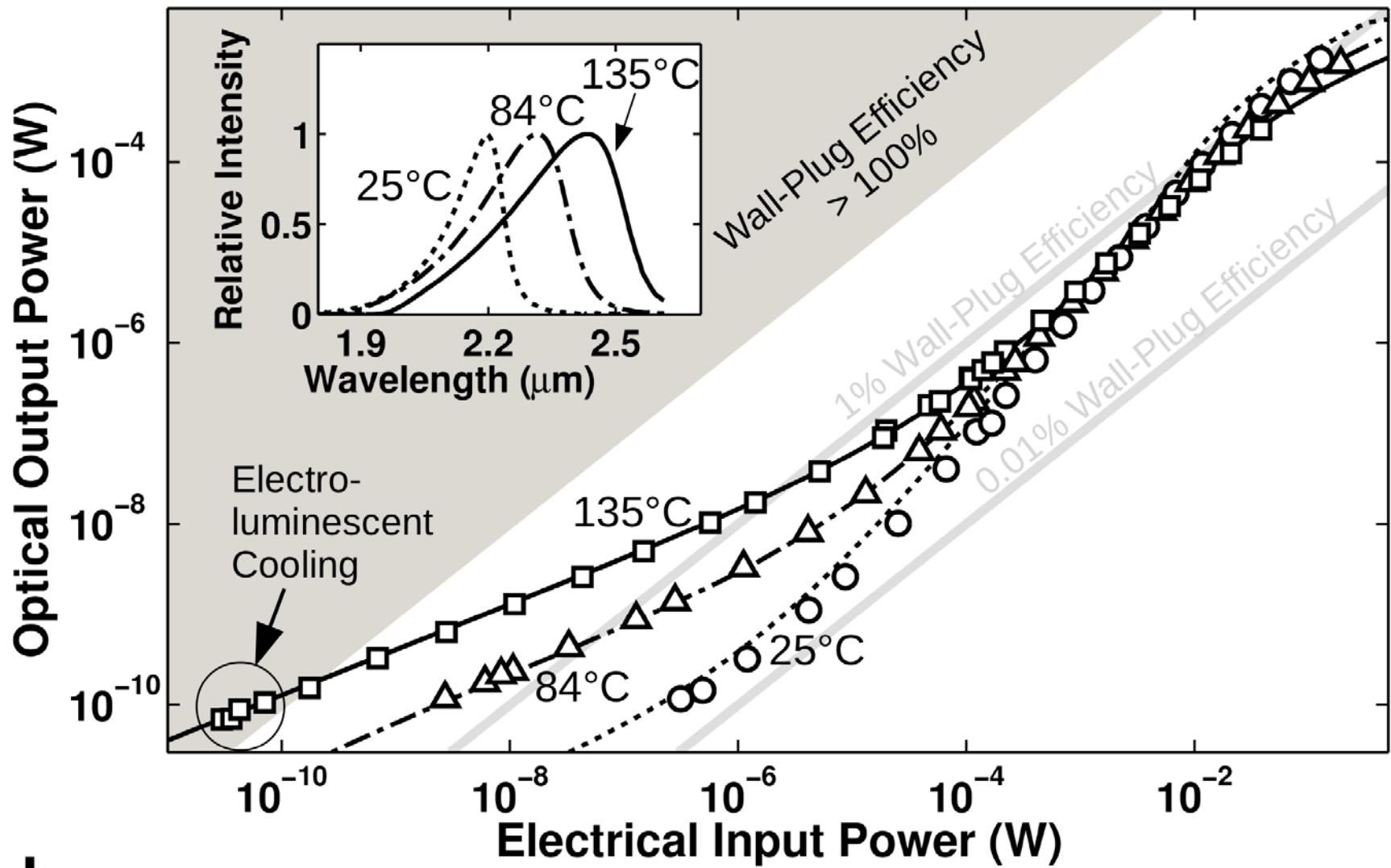


Electrically pumped  
“optical refrigeration”



Kevin Pipe, Rajeev Ram and Ali Shakouri,  
Photonic Techn. Lett., Apr. 2002

# TE Pumped LED with above Unity Efficiency



- System considerations of thin film/thermionic coolers (ballistic transport)
- Nonlinear Peltier effect
- Bipolar Peltier effect
- Internal cooling, thermoelectric energy conversion in optoelectronic devices