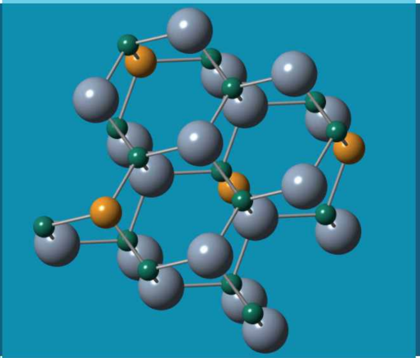
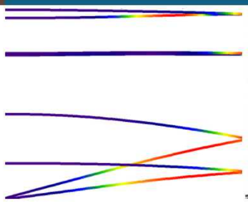
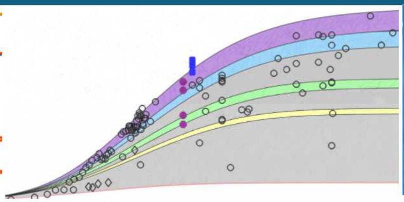
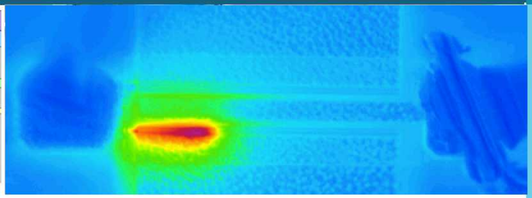
SAND2018-13439C

Size Dictated Thermal Conductivity of GaN and AlGaN









Thomas Beechem

Team

Chris Saltonstall, Hamid Seyf (GT), Asegun Henry (MIT), and Andrew Allerman

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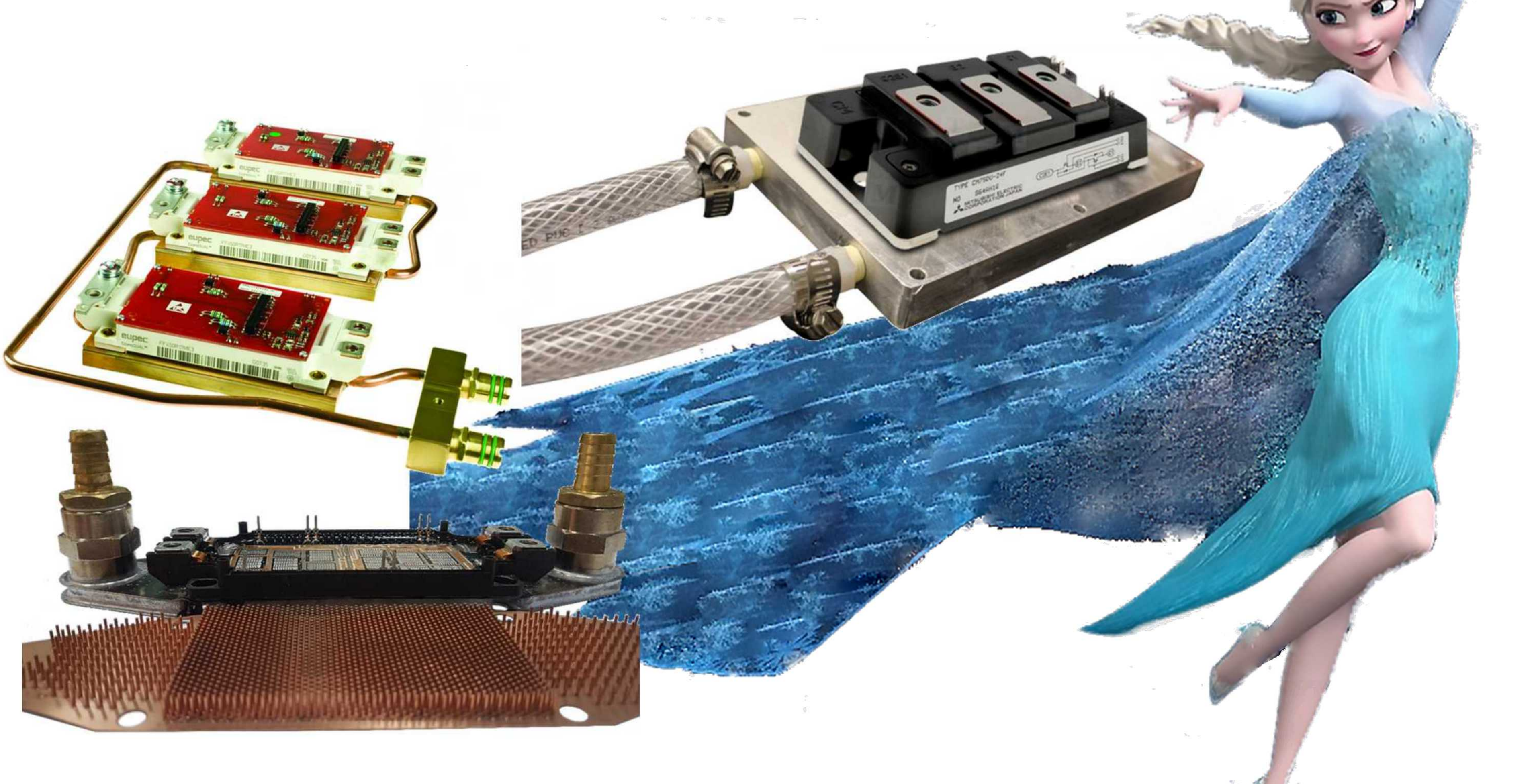
Typical Thermal Management

Frozen Approach ➠ Throw cold at the device



Images: Disney, HiFlux, Parker Hannifin, Advanced Thermal Solutions

Opportunity: Wide Bandgap Power Devices

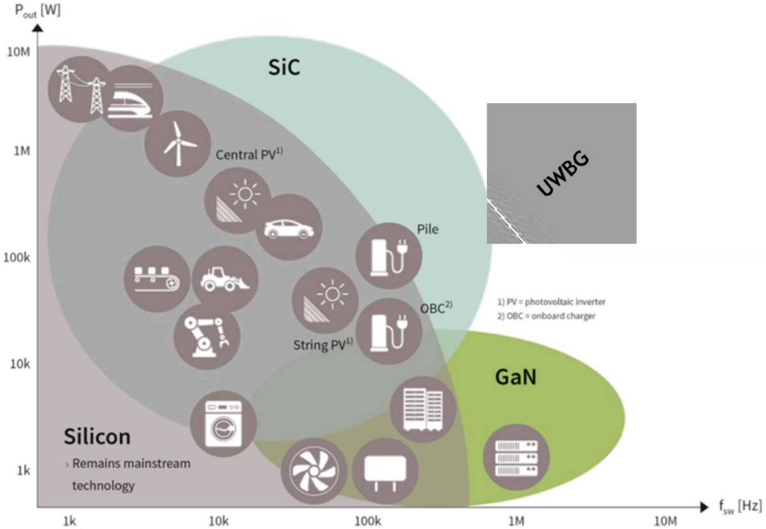


Image: Adapted from Infineon

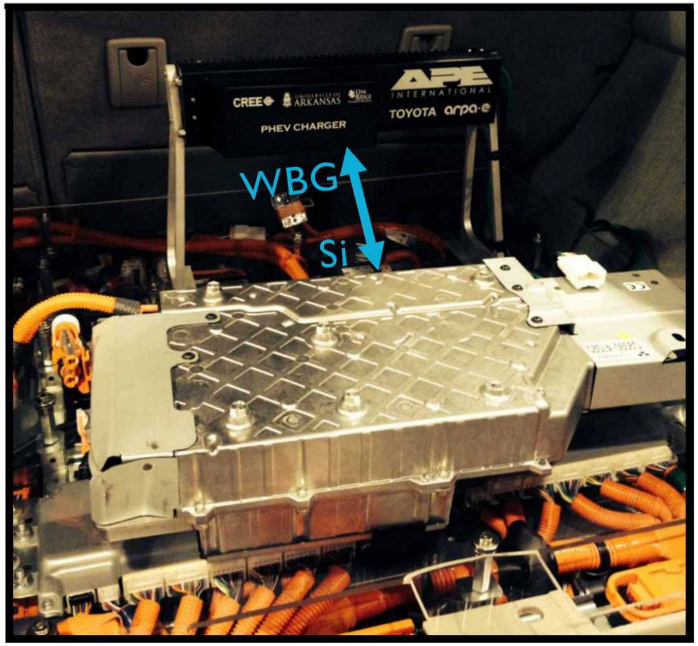
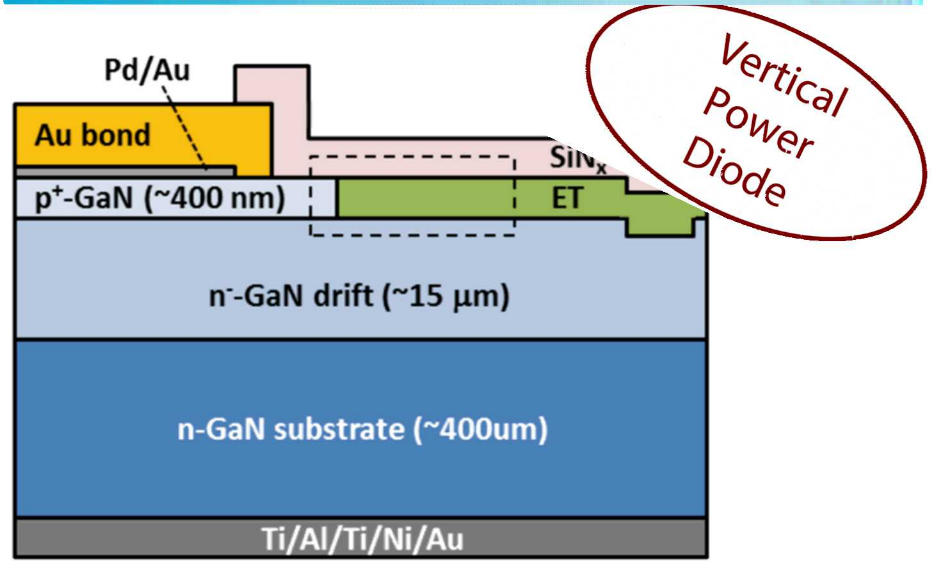


Image: Kiziyalli et al. WBG Semi. Based Power Elec. for Energy Efficiency. ARPA-E Report. 2018.

Thermal design from "growth up"



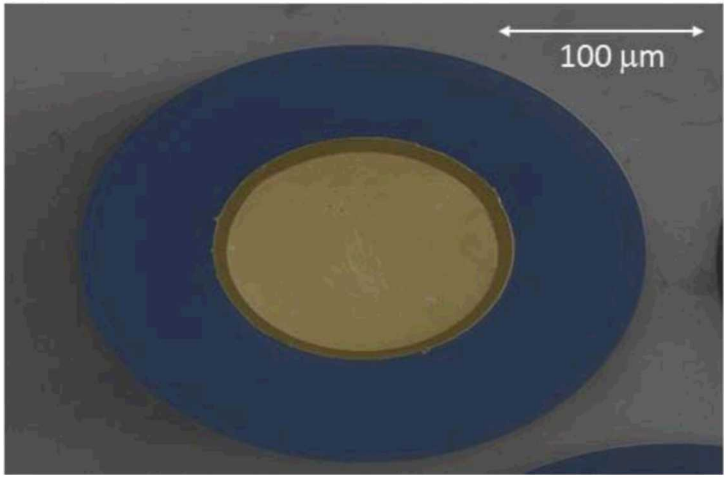


Image: Dickerson et al. IEEE Trans. Elec. Dev. (63) 419. 2016.

Do we know enough to design from "growth up"?

Phonon Gas (PG) Model RTA

$$k = \frac{1}{6\pi^2} \sum_s \int_0^{q_{m,s}} \frac{\hbar^2 \omega^2(q)}{k_B T^2} \frac{\exp\left(\frac{\hbar\omega(q)}{k_B T}\right)}{\left[\exp\left(\frac{\hbar\omega(q)}{k_B T}\right) - 1\right]^2} v^2(q) \tau_s(q) q^2 dq$$

Impurities

$\tau_I^{-1} \propto \omega^{-4}$

Size Effects

$\tau_L^{-1} \propto L^{-1}$

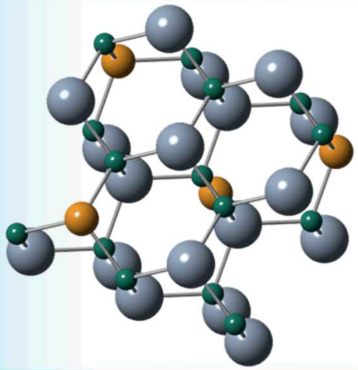
Dislocations

$\tau_D^{-1} \propto \omega^{-3}$

Goal: Understand what effects matter when in GaN and AlGaN

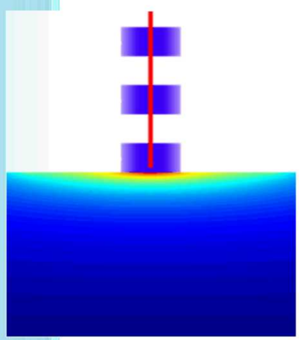
Approach: Make, Measure, Model

Make



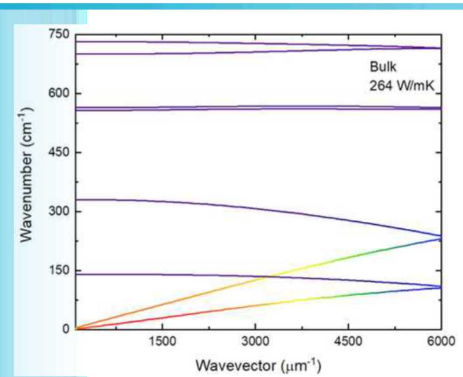
Material: MOCVD GaN/AlGaN
Variables: Doping, Alloying, Thickness

Measure



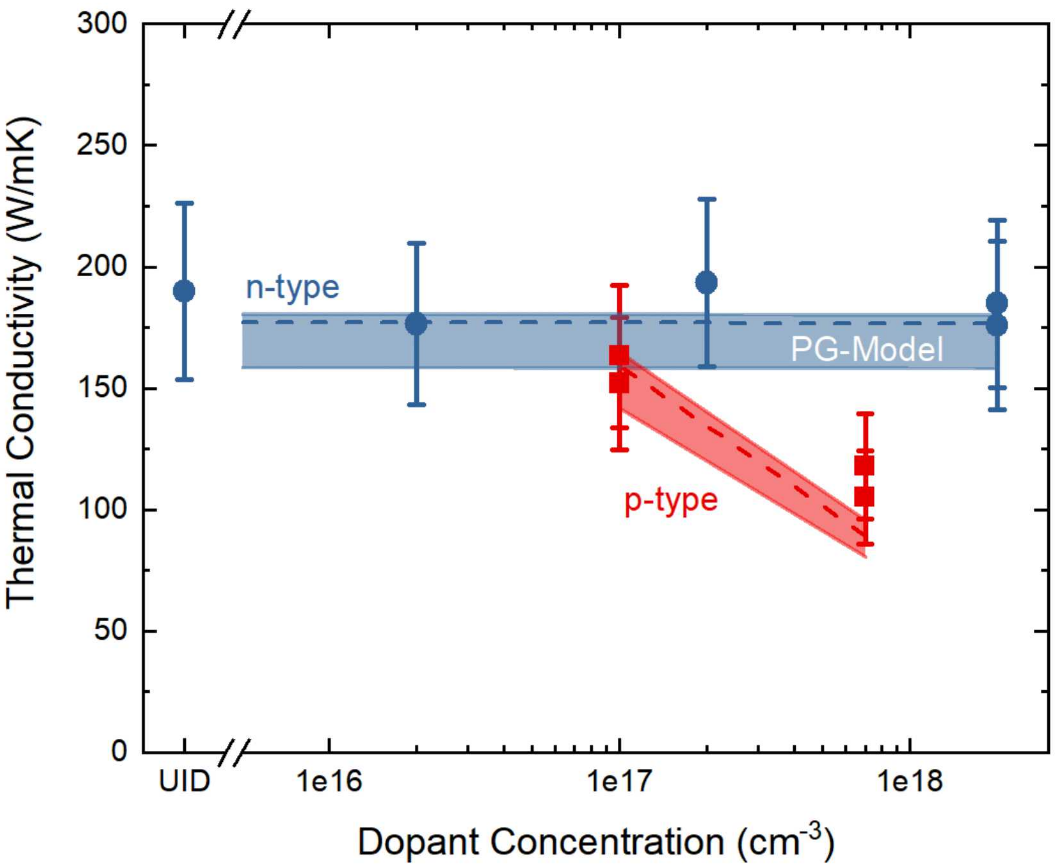
Tool: Time Domain Thermoreflectance

Model



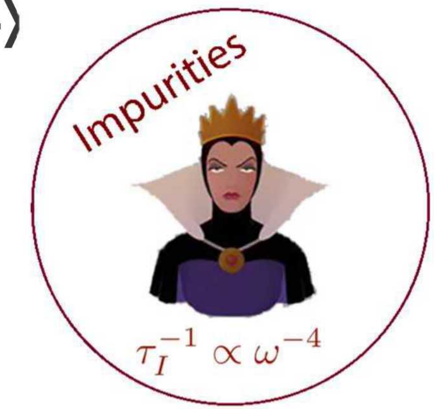
Approach:
Phonon Gas Model
DFT/Lattice Dynamics
Allen-Feldman Theory

Measure: An Unsuspected Insensitivity



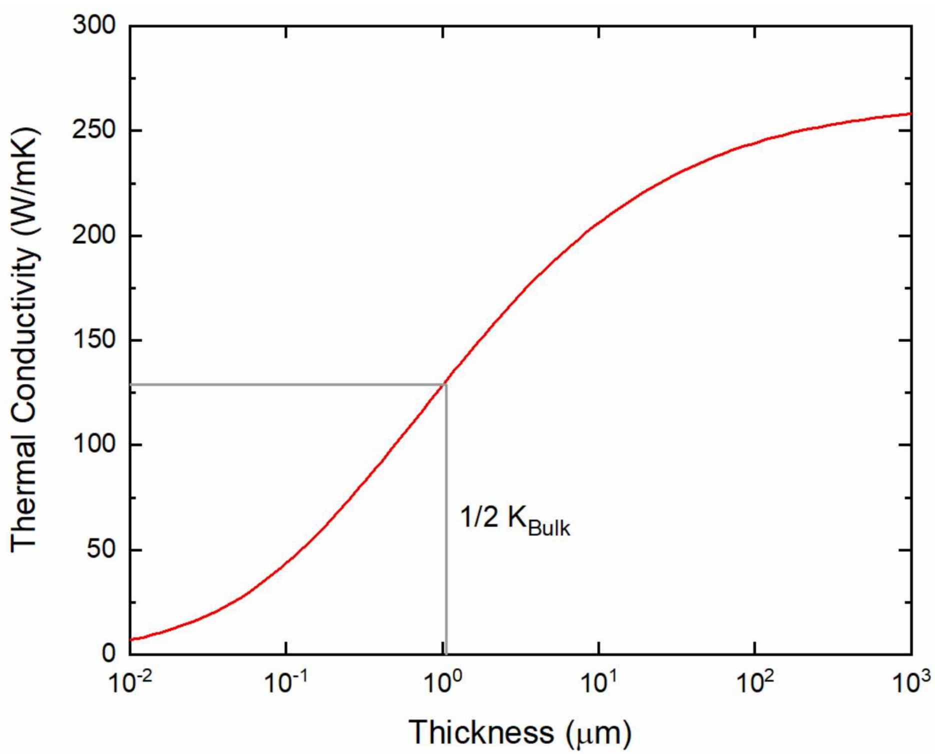
p-type
Sensitive

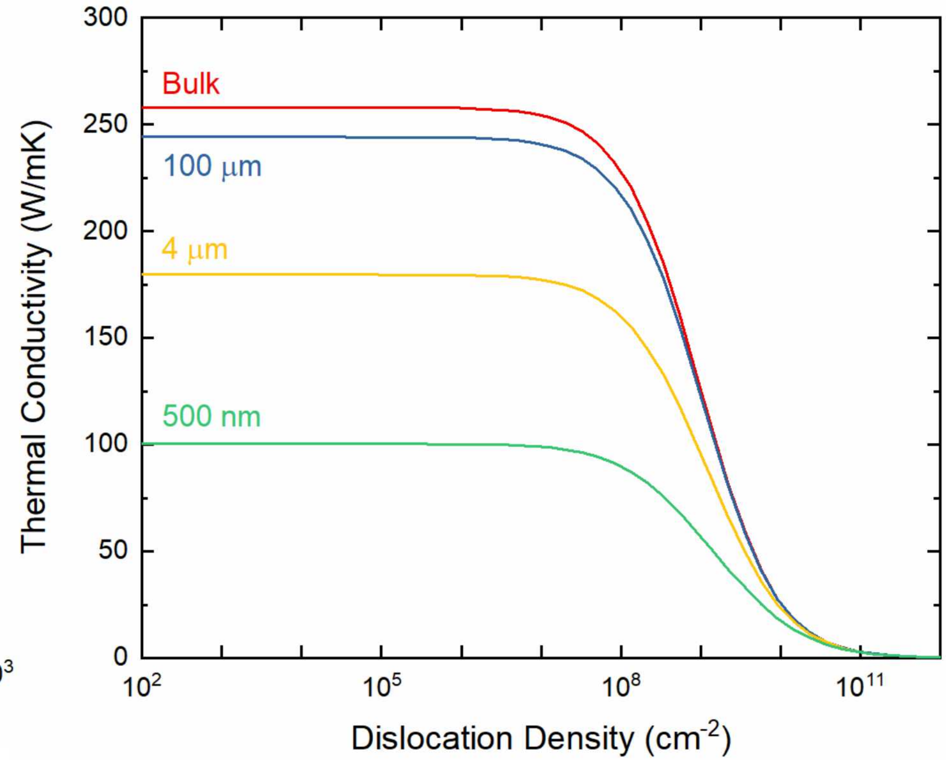
n-type
Immune?



Details: Beechem et al. JAP. (120) 095104. 2016

Phonon-Gas Model: Probing the Pain Points

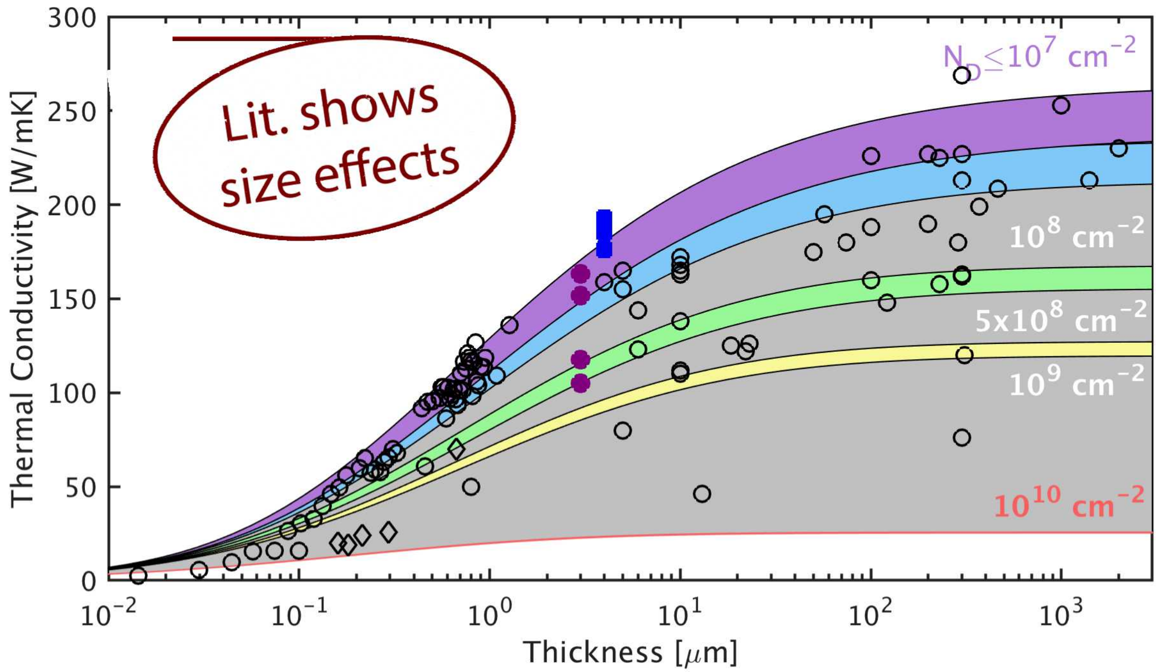


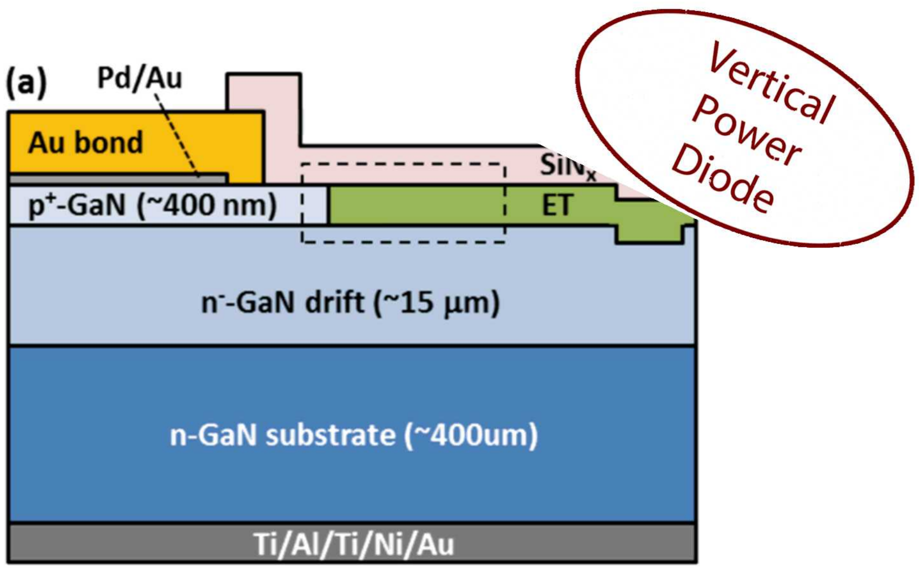


Takeaway: Size dictates thermal conductivity of GaN?

Details: Beechem et al. JAP. (120) 095104. 2016

Bottom Line: Implications on Device Design

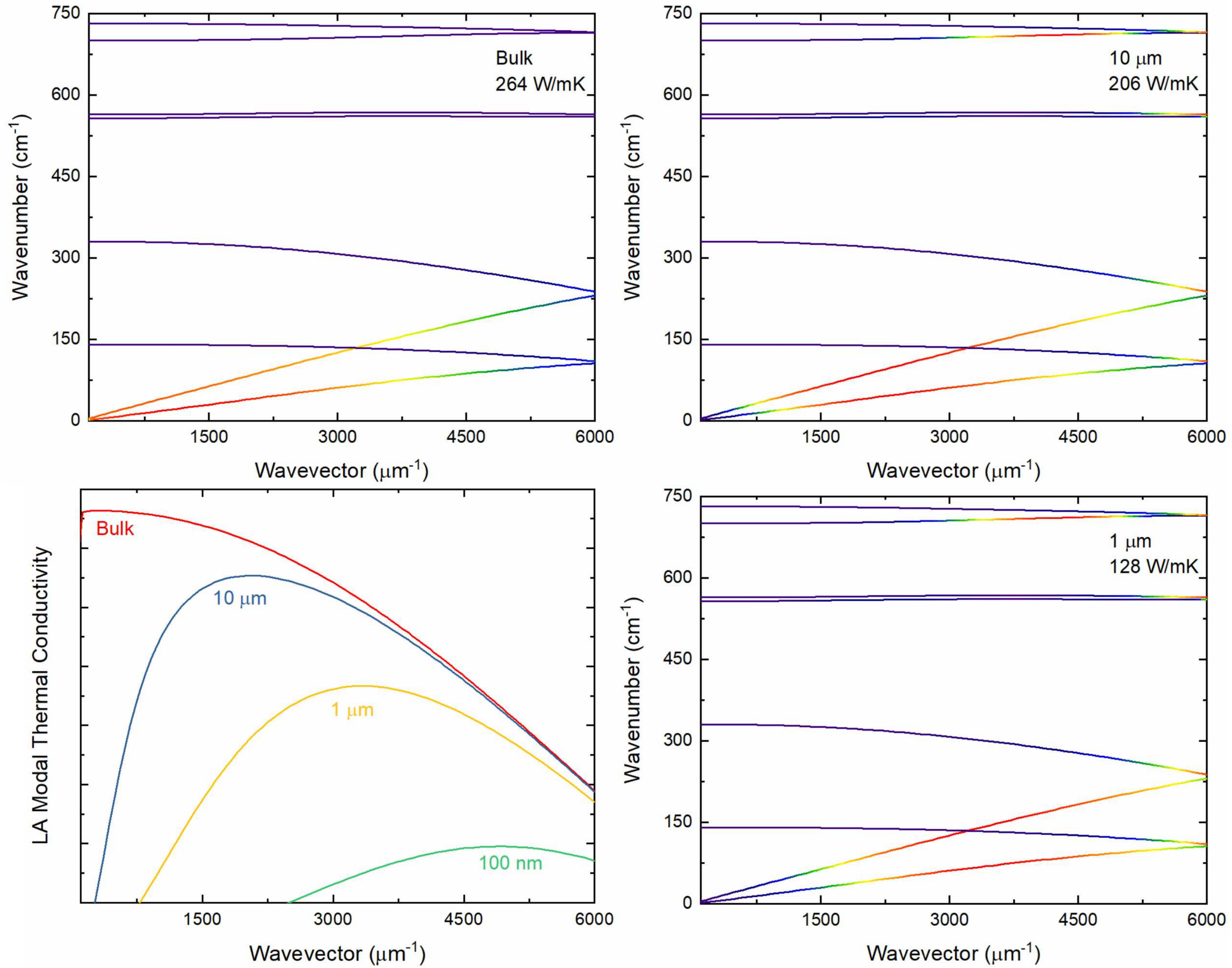




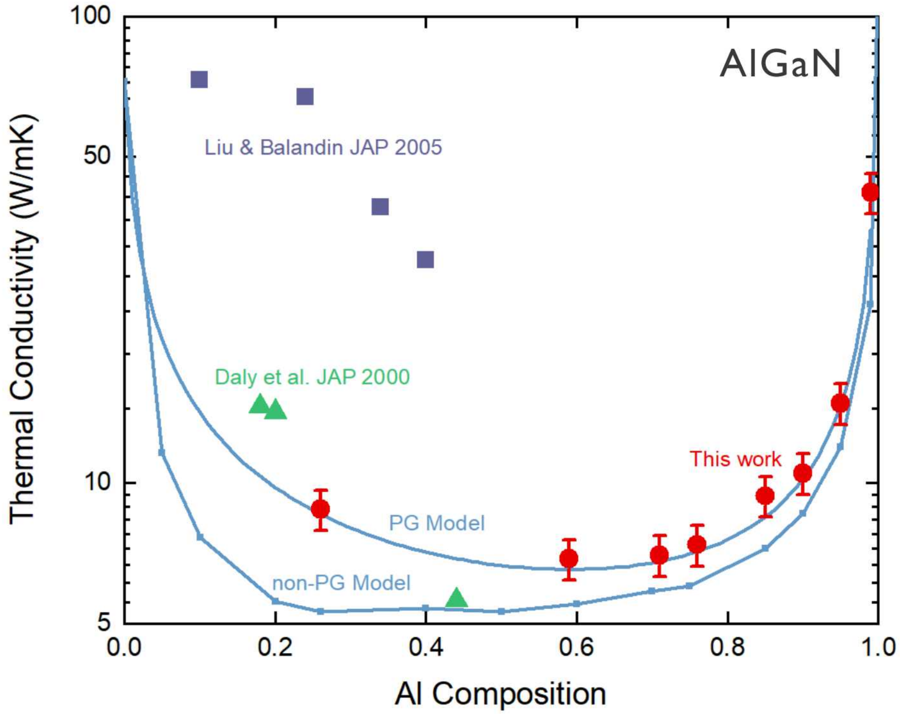
GaN conducts heat more like Si than GaN in most devices

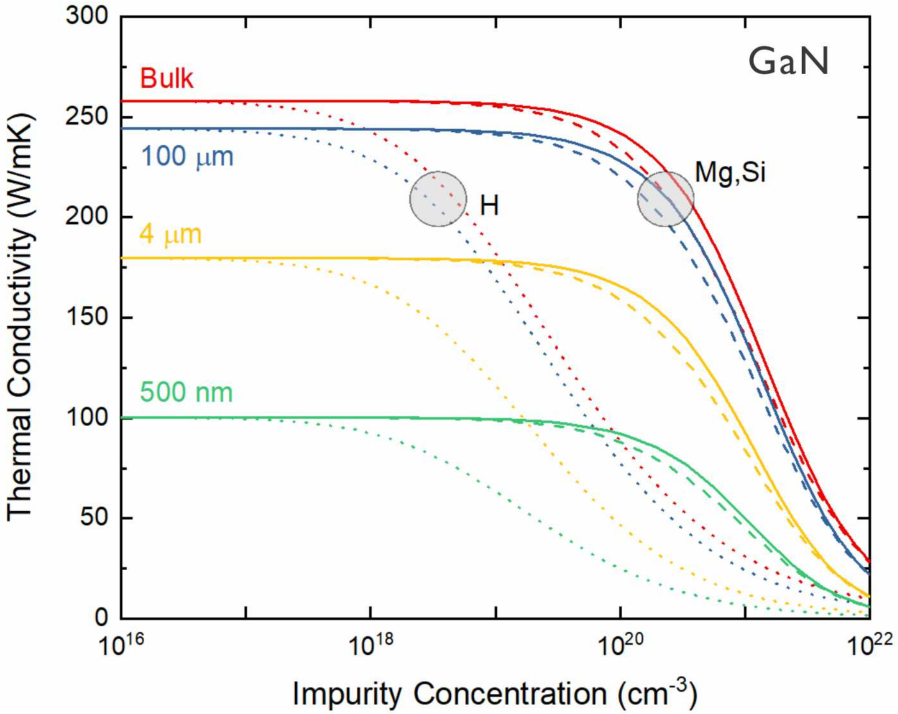
Image: Dickerson et al. IEEE Trans. Elec. Dev. (63) 419. 2016. Details: Beechem et al. JAP. (120) 095104. 2016

Visualize: Why do size effects dominate?



Measure: AlGaN…Impurities vs. Size Effects





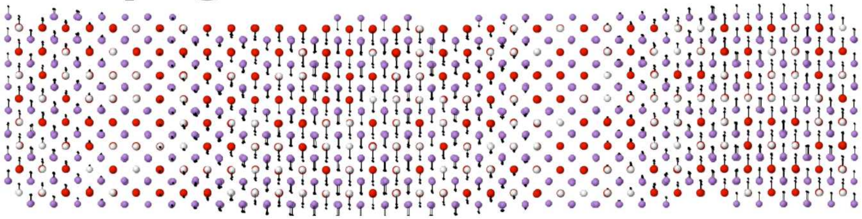
Takeaway: AlGaN acts like a "normal" alloy

Normal alloy, so what?

Data: Liu and Balandin. JAP (85) 5230. 2004. Daly et al. JAP (92) 3820. 2002. Saltonstall et al. In preparation.

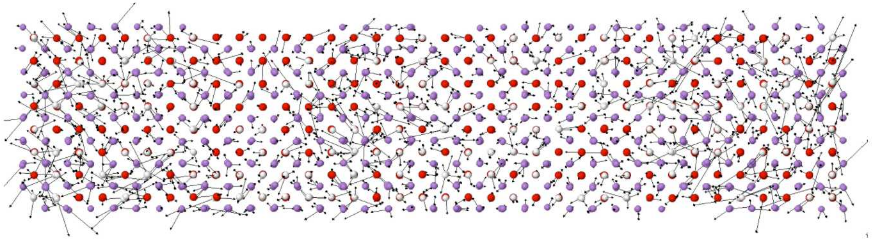
Model: Propagons, Diffusons, Locons & Virtual Crystals

Propagons: Phonon-ish



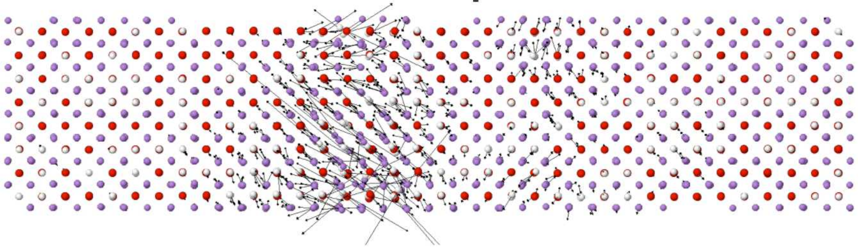
$$k = \frac{1}{6\pi^2}\sum_s \int_0^{q_{m,s}} \frac{\hbar^2\omega^2(q)}{k_B T^2} \frac{\exp\left(\frac{\hbar\omega(q)}{k_B T}\right)}{\left[\exp\left(\frac{\hbar\omega(q)}{k_B T}\right) - 1\right]^2} v^2(q)\tau_s(q) q^2 dq$$

Diffusons: Reluctant Carriers



$$k_{AF} \propto \sum_i C\left(\frac{\hbar\omega}{2k_B T}\right) D_i$$

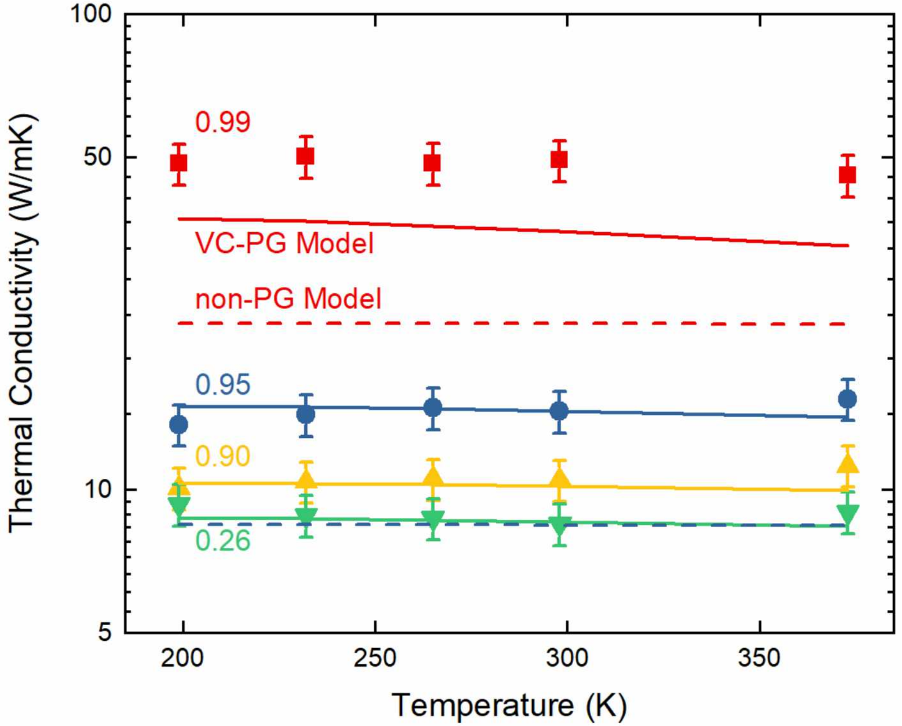
Locons: Heat Traps

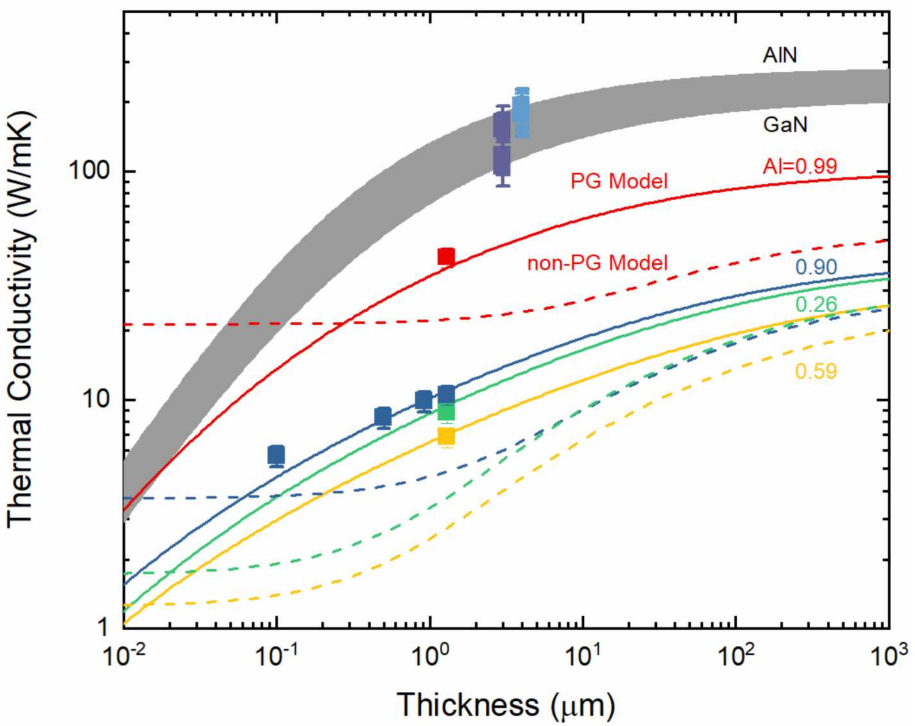


Transition between propagons & diffusons determined via modal analysis.

Animations: Seyf et al. npj Computational Materials. (3) 49. 2017. Approach: Braun et al. PRB (93) 140201. 2016.

AlGaN: Crystal Qualities in Alloy…Size Effects too

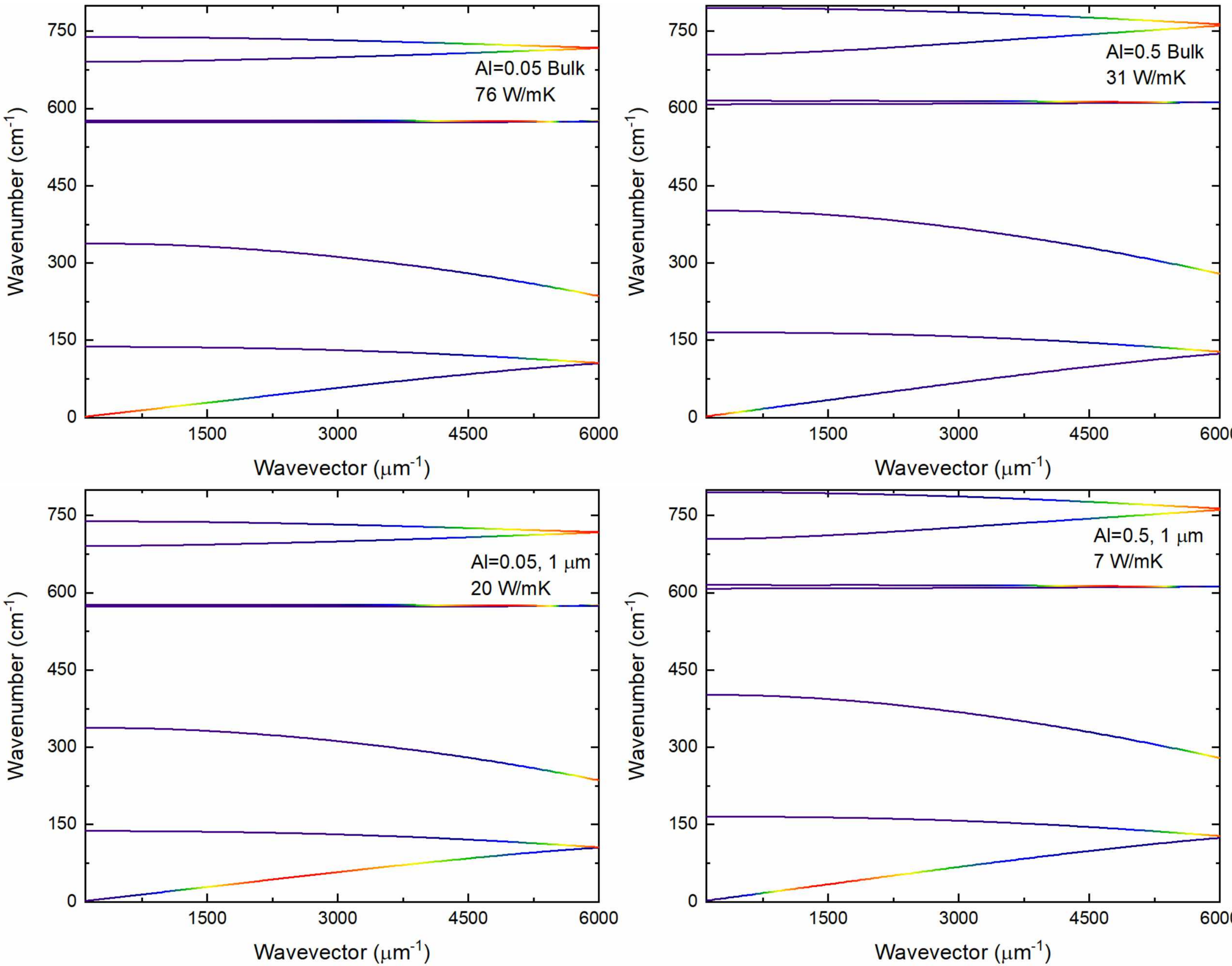




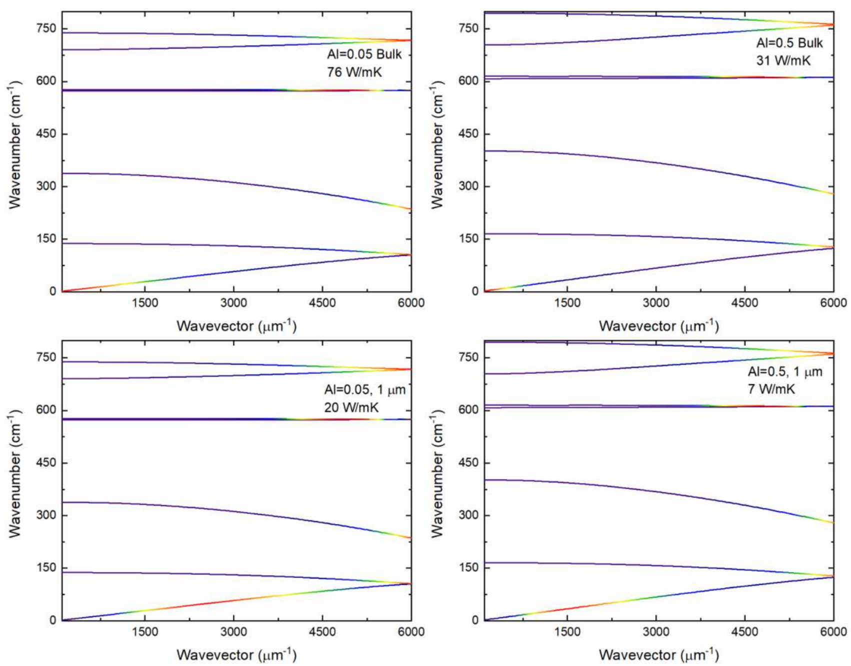
Takeaway: Size effects persist even more in alloy

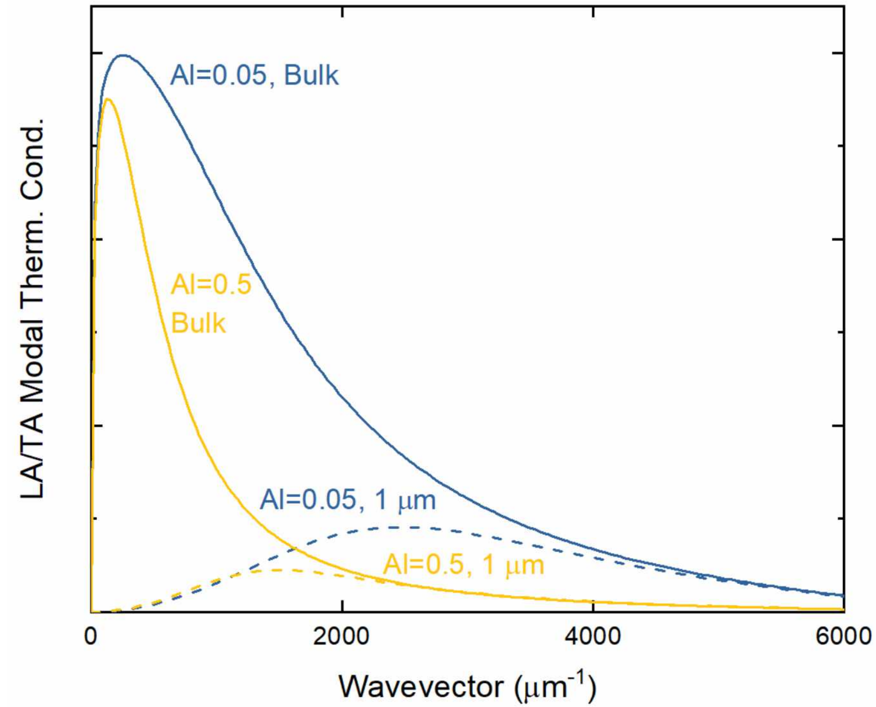
Saltonstall et al. In preparation.

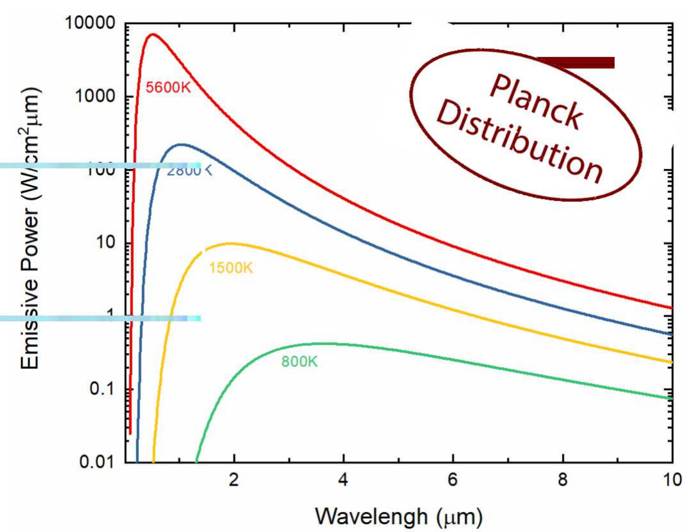
Visualize: Dominance of Acoustic Modes



Visualize: Dominance of Acoustic Modes

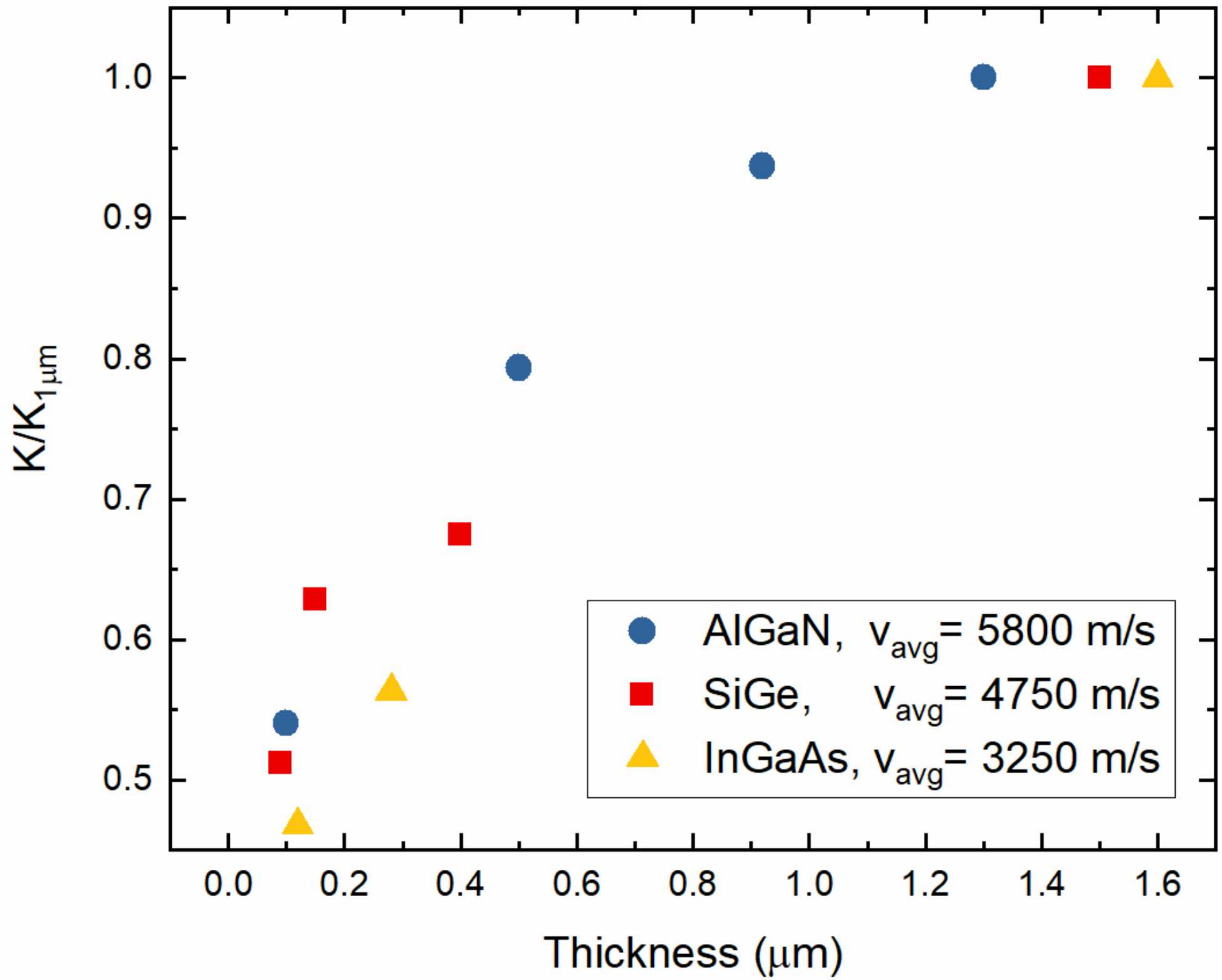






Takeaway: Long-wavelength acoustic modes curtailed with size

Generalize: Size Effects in Alloys

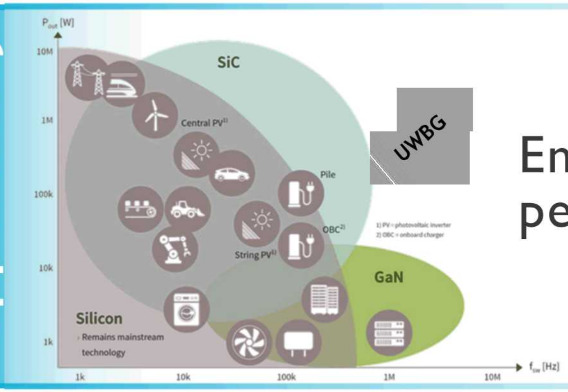


Takeaway: Size effects are similar across very different alloys

Data: AlGaN-Saltonstall et al. In preparation. SiGe-Cheaito PRL (109) 195901. 2012. Lee et al. APL (70) 2957. 1997. InGaAs-Seyf et al. npj Computational Materials. (3) 49. 2017.

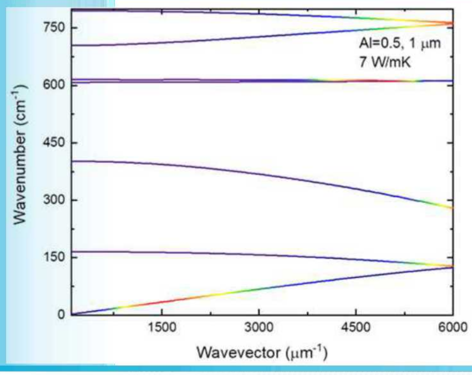
Take Home Message

Opportunity



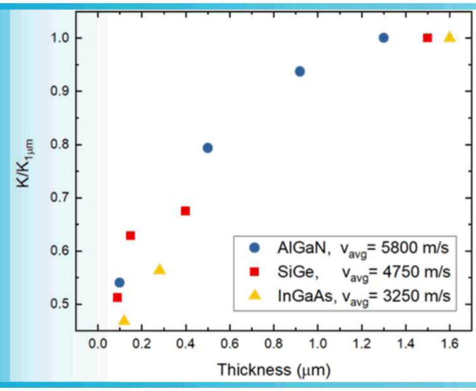
Emerging technologies provide opening to perform thermal design from "growth up."

Insight



Size effects dominate as boundaries wreck heat carrying acoustic phonons

Model



Alloys acutely affected owing to dominance of acoustic modes.