

FUSING LIGHT WITH HEAT

Foundations for Nanoscale Thermal Transport & Sensing

Thomas Beechem

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P. Hopkins, J. Ihlefeld



H. Seyf, A. Strachan



J. Caldwell



S. Choi



School of Mechanical Engineering

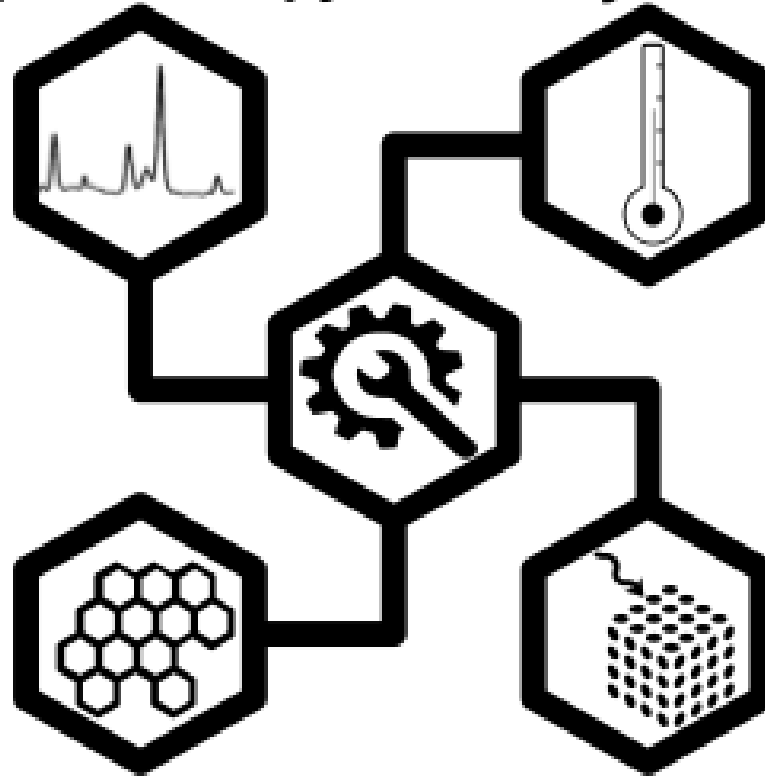
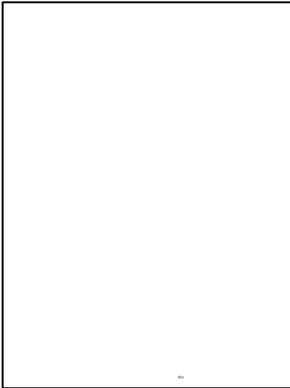


Our Perspective...

Vibrational Spectroscopy

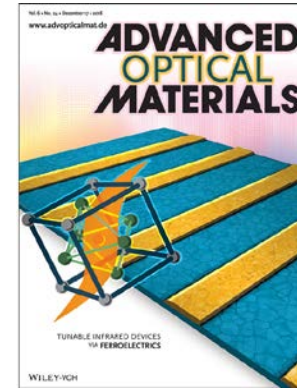
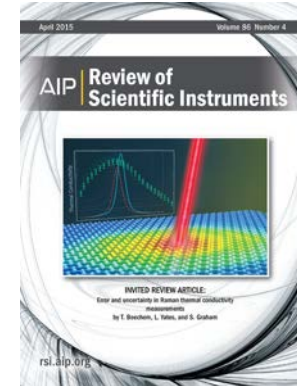
Thermal Physics

PURDUE
POLARITON
Group
Group



2D-Solids

Nanophotonics



Message Polaritonic Energy Transport

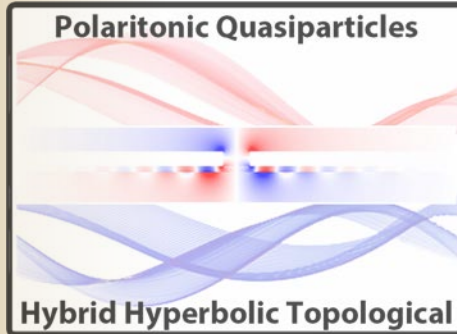
Problem



Clown Car Problem

Phonons and Electrons “bad” in small spaces ($< 1\mu\text{m}$) & at interfaces.

Premise



Fundamentally different energy carrier needed.

Polaritons are the carrier.

Reason

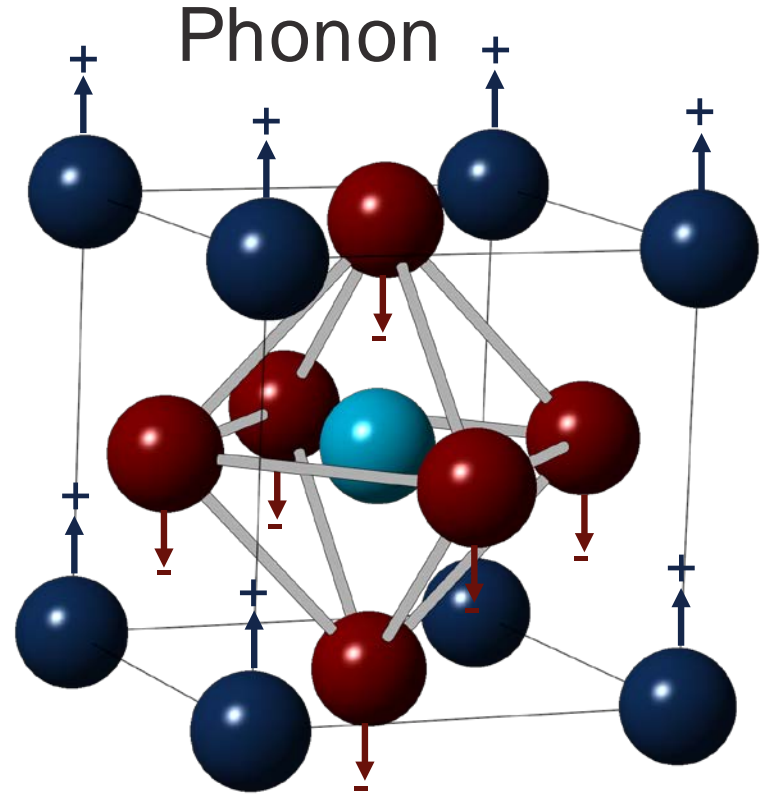
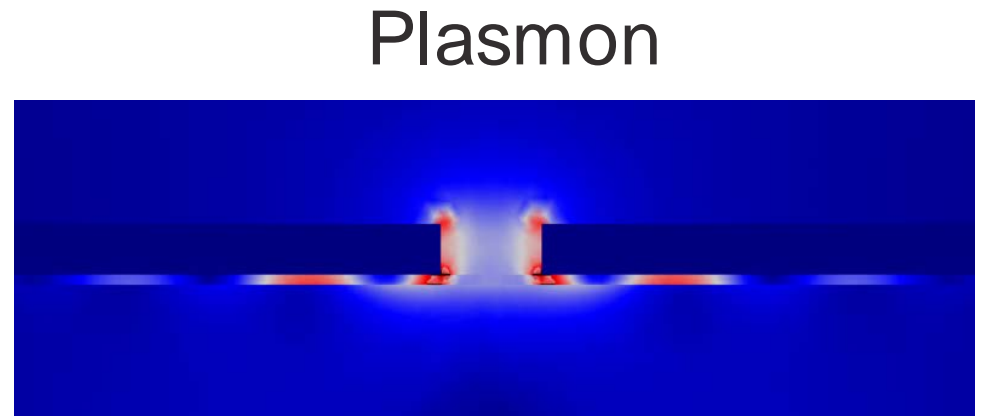
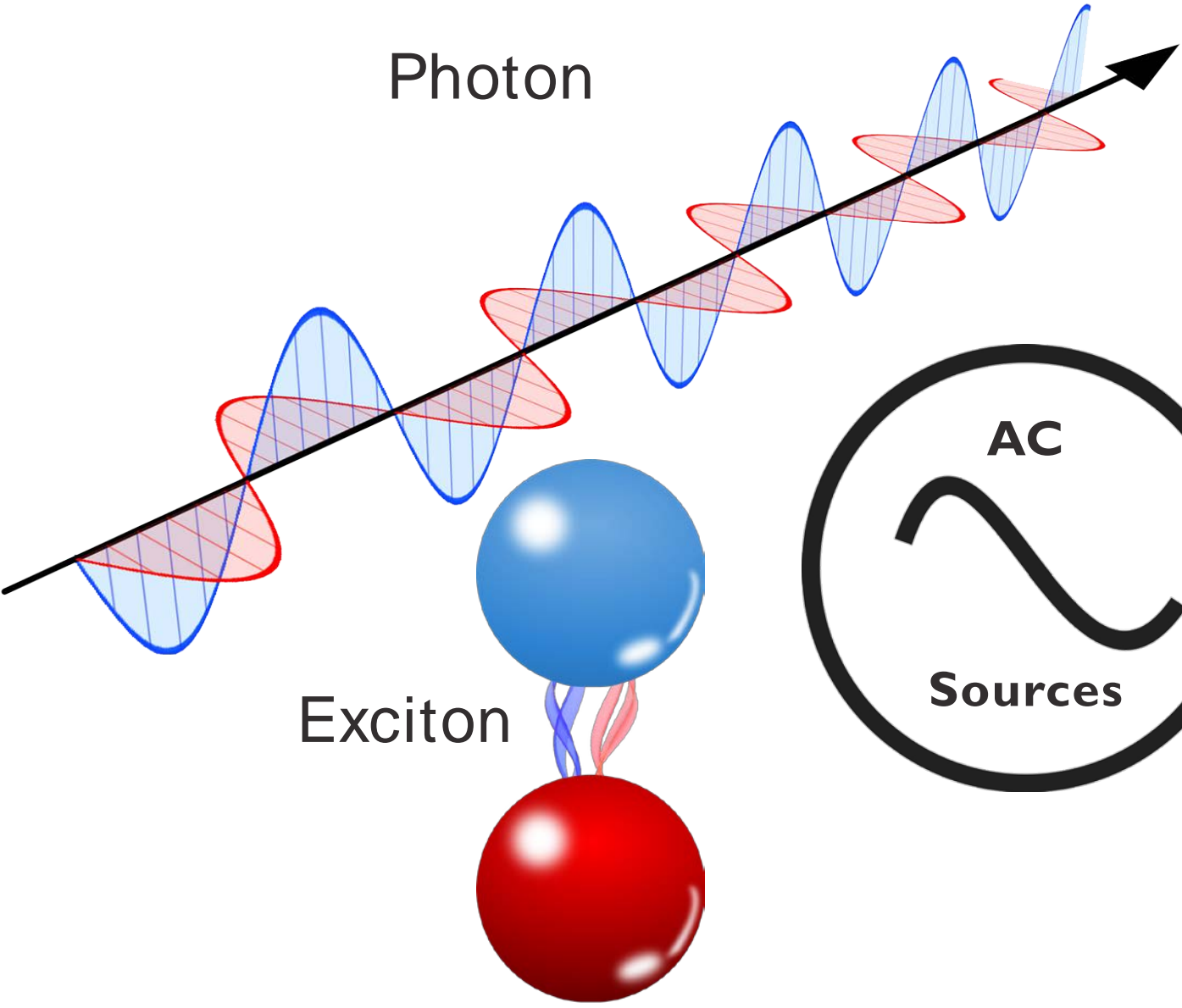


Polaritons get **better** in smaller spaces.

Dispersion Engineering of polaritons is doable.

Polaritons can be dynamically tuned.

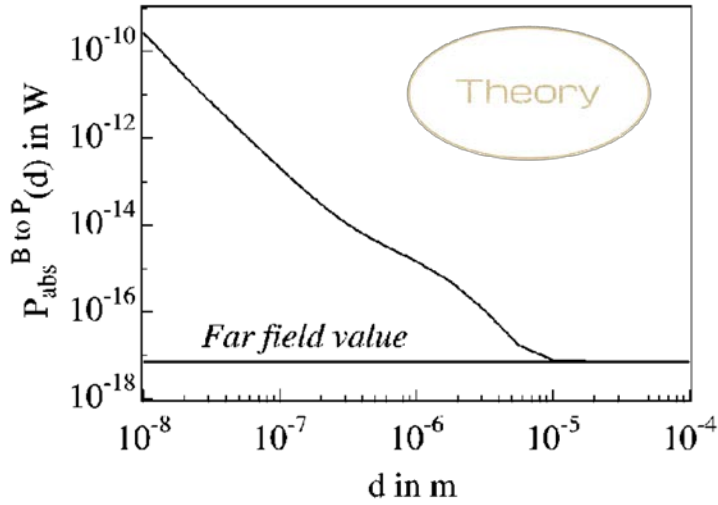
Photon . The Wave Det



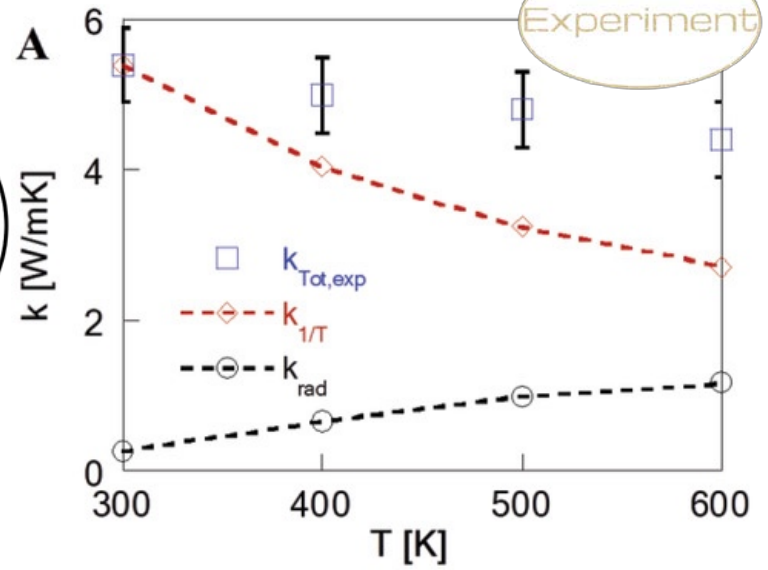
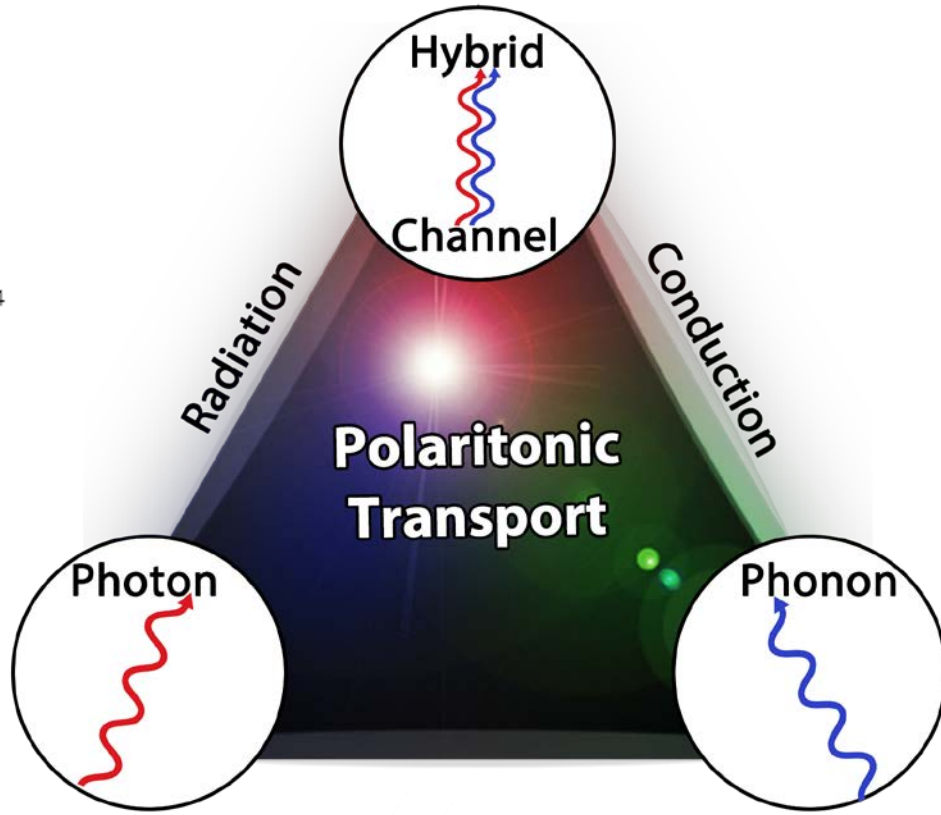
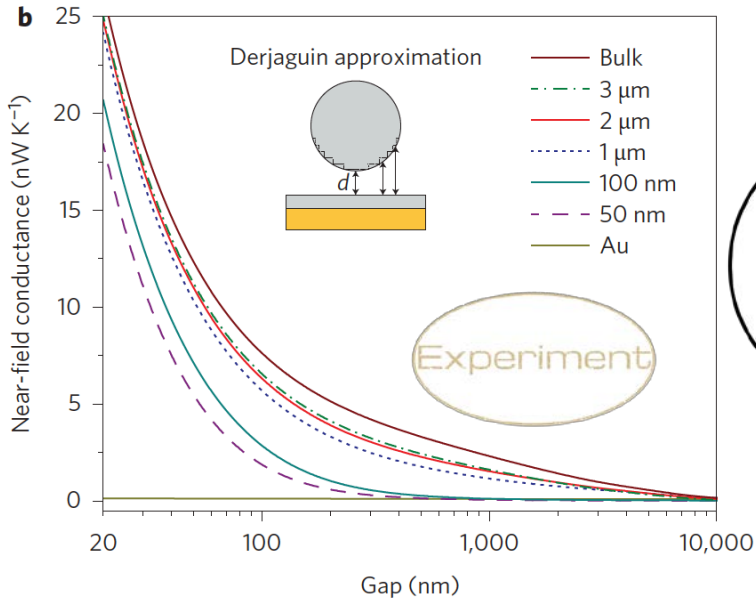
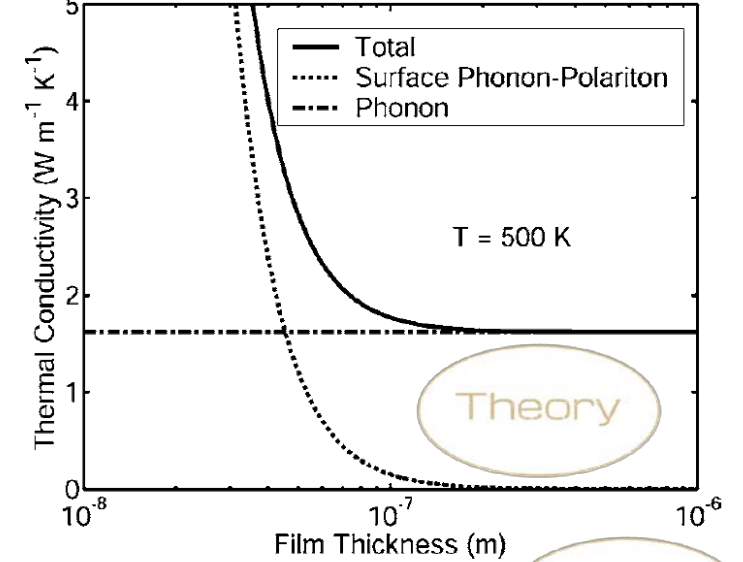
Polaritons carry heat.



Theory: Mulet et al. APL (78) 293. 2001.



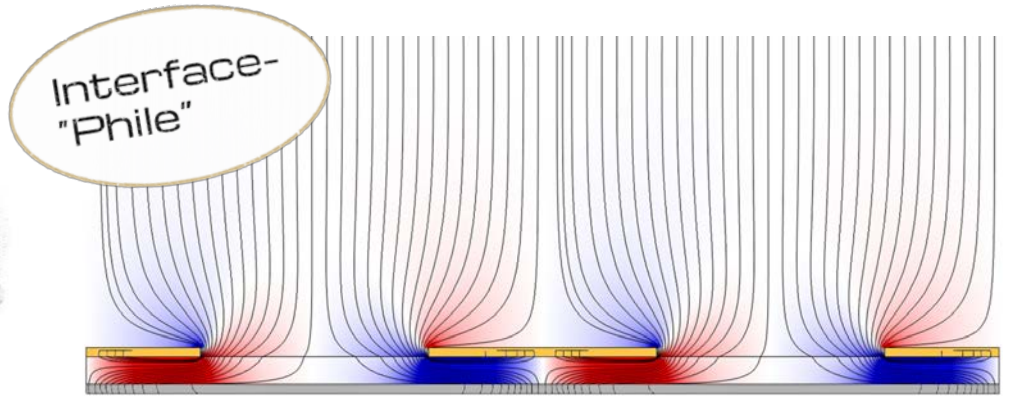
Theory: DY. Chen & G. Chen. PRB (72) 155435. 2005



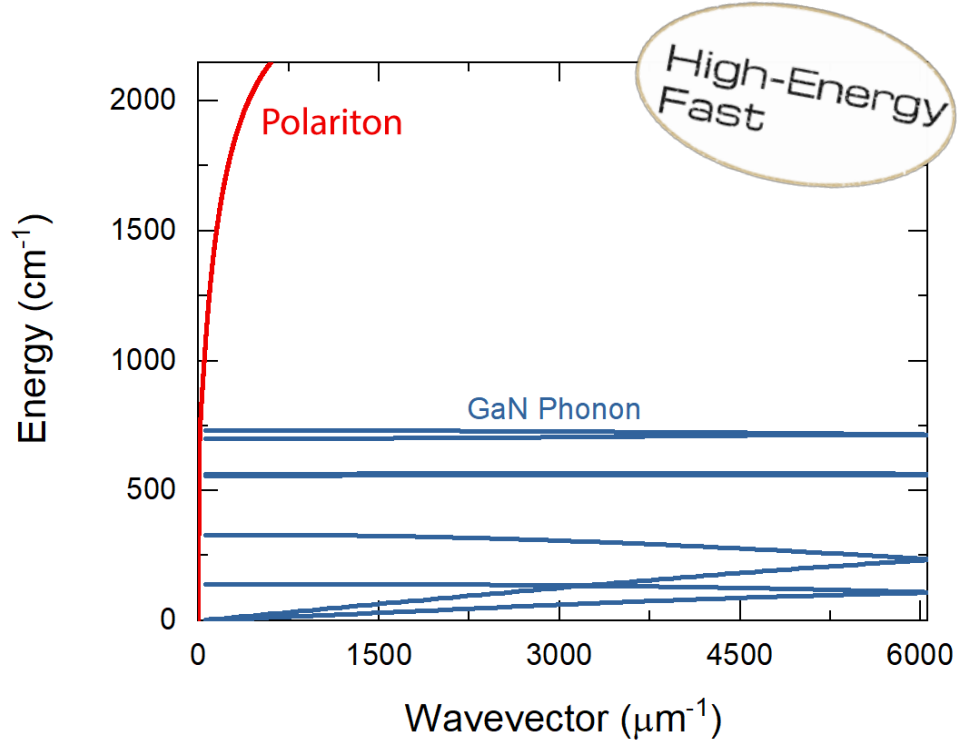
Expt: Song et al. Nat. Nano (10) 253. 2015.

Expt: Salihoglu..Xu. Adv. Fun. Mat. 1905830. 2019.

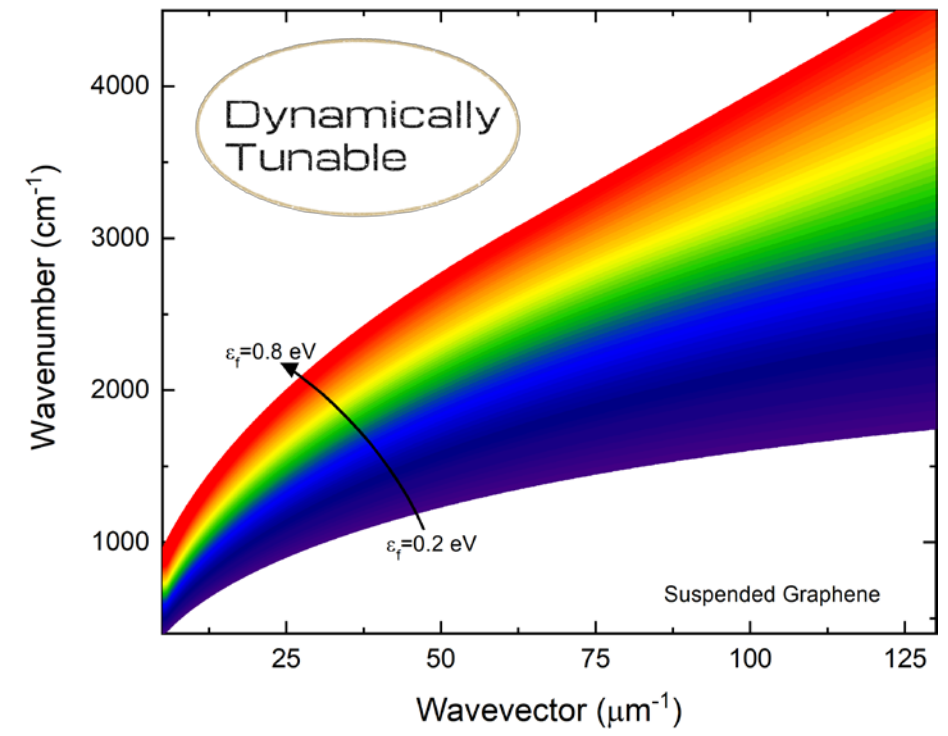
But Why Polaritons for Nanoscale Heat Transport?



Details: T. Beechem et al. Adv. Opt. Mat. 14, 1800062. (2018).



Maxwell (μm)
over
Newton (\AA)

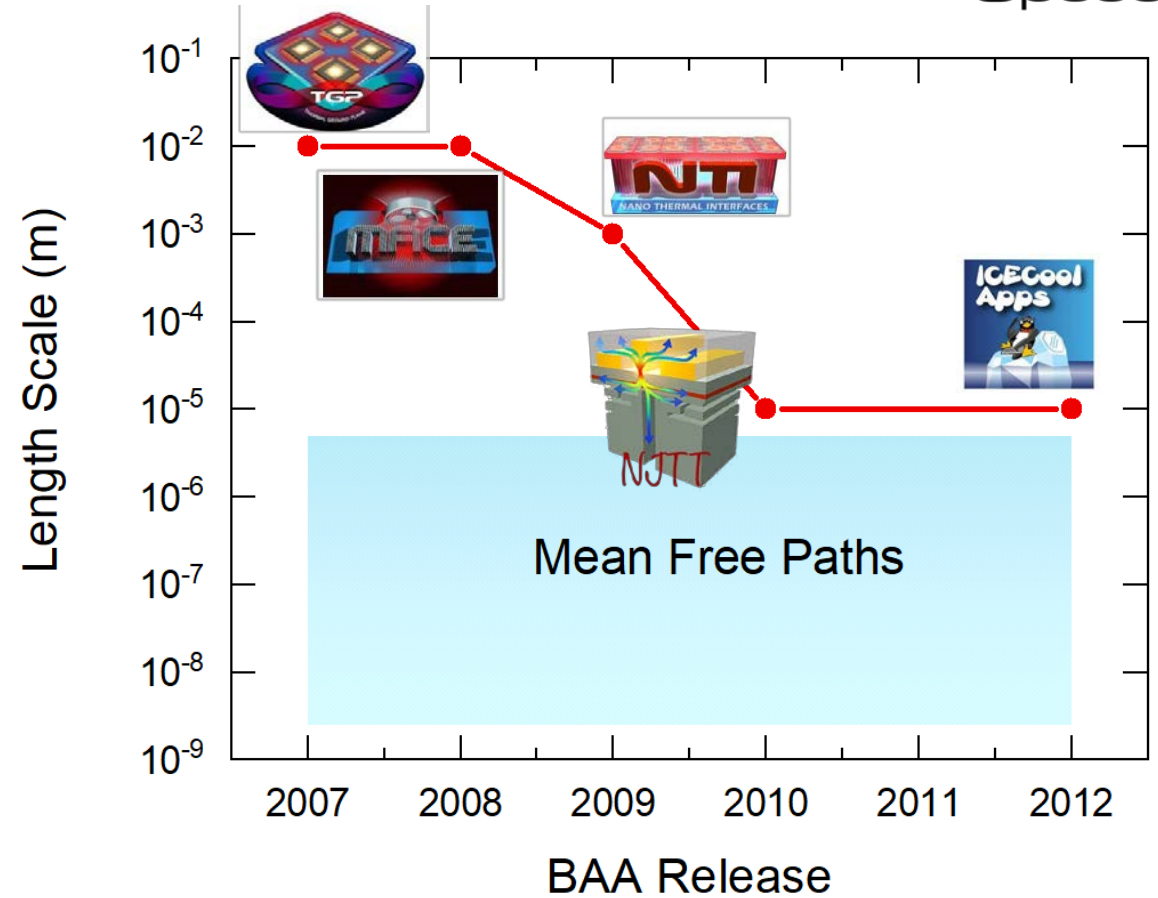
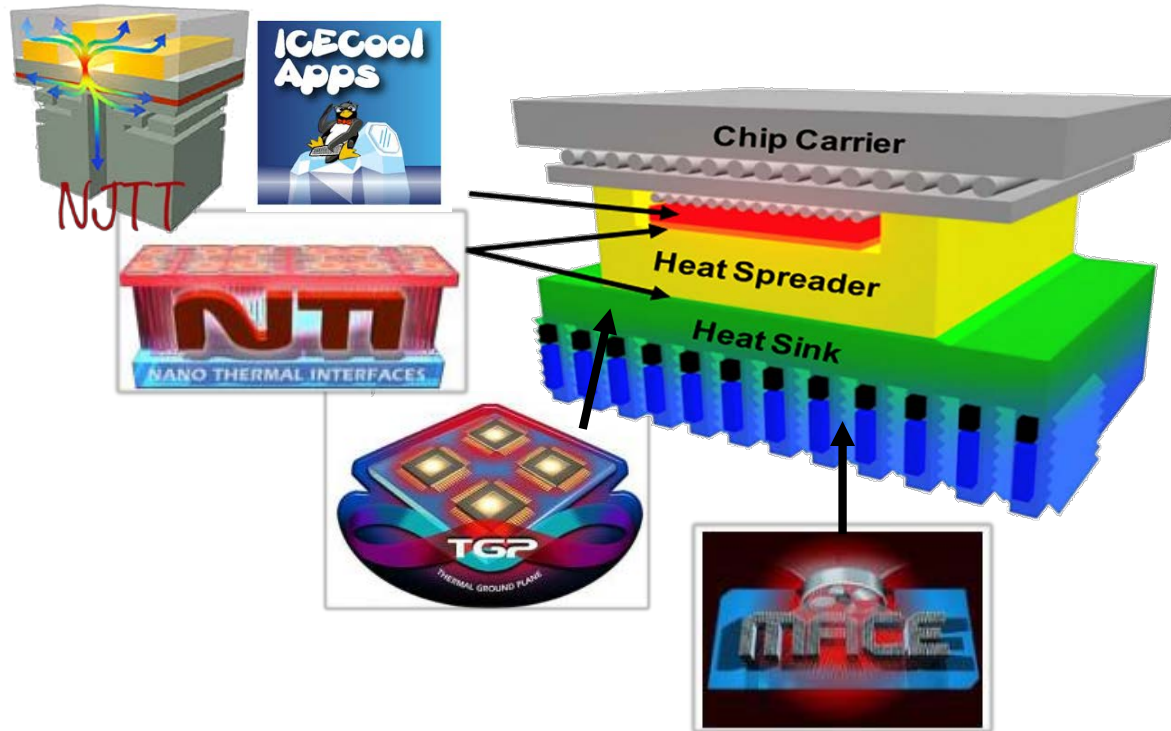


Details: A. Jarzembki... Beechem et al. Phys. Rev. Appl. 14, 034044 (2020).

Problem Solutions aren't scaling

Frozen Approach → Throw cold at the device





Paradoxical

Need solutions closer to source → Gotta get smaller.

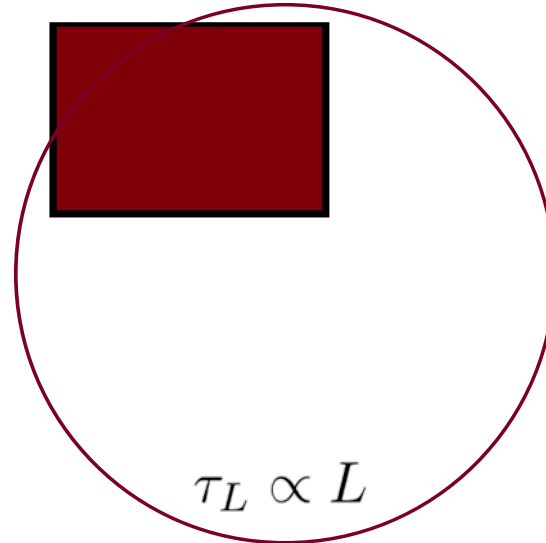
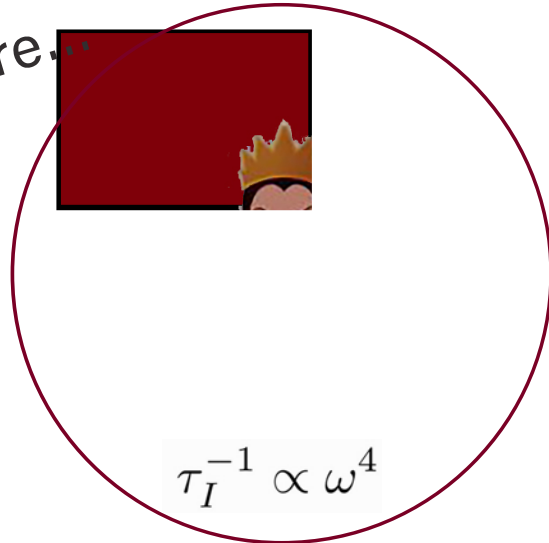
Problem Phonons Less Efficient in Small Places

Phonon Gas (PG)
Model
RTA

$$k_{PGM} = \frac{1}{VN_o} \sum_{\mathbf{q},s} (\hbar\omega) \frac{df_{\mathbf{q},s}}{dT} v_{\mathbf{q},s}^2 \tau_{\mathbf{q},s}$$



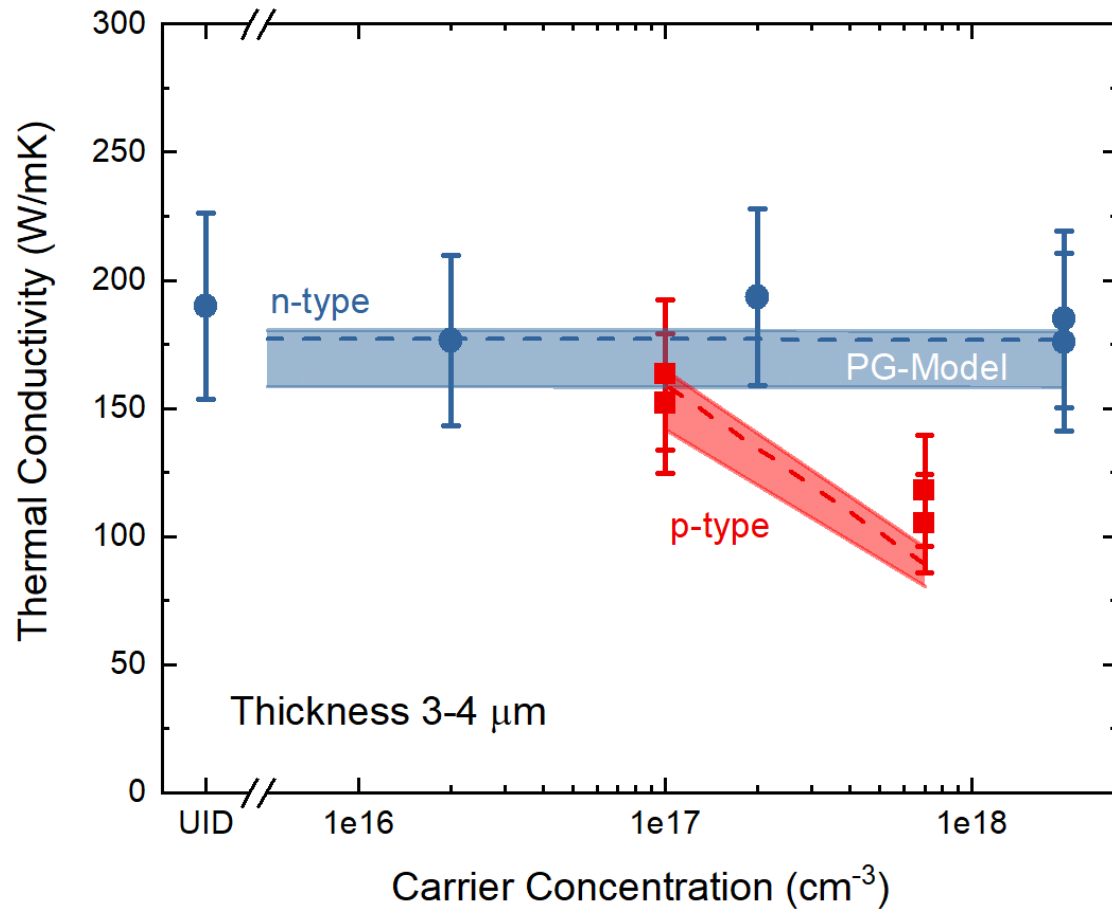
Question: What matters more,
size or "bad stuff"?



Dislocations

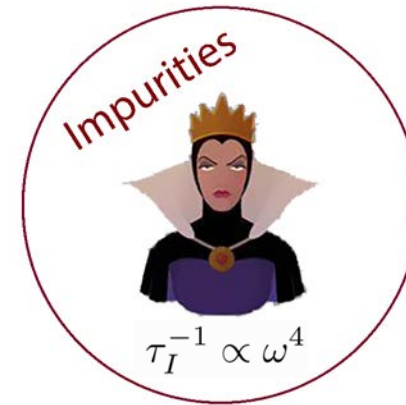


Thermal Conductivity

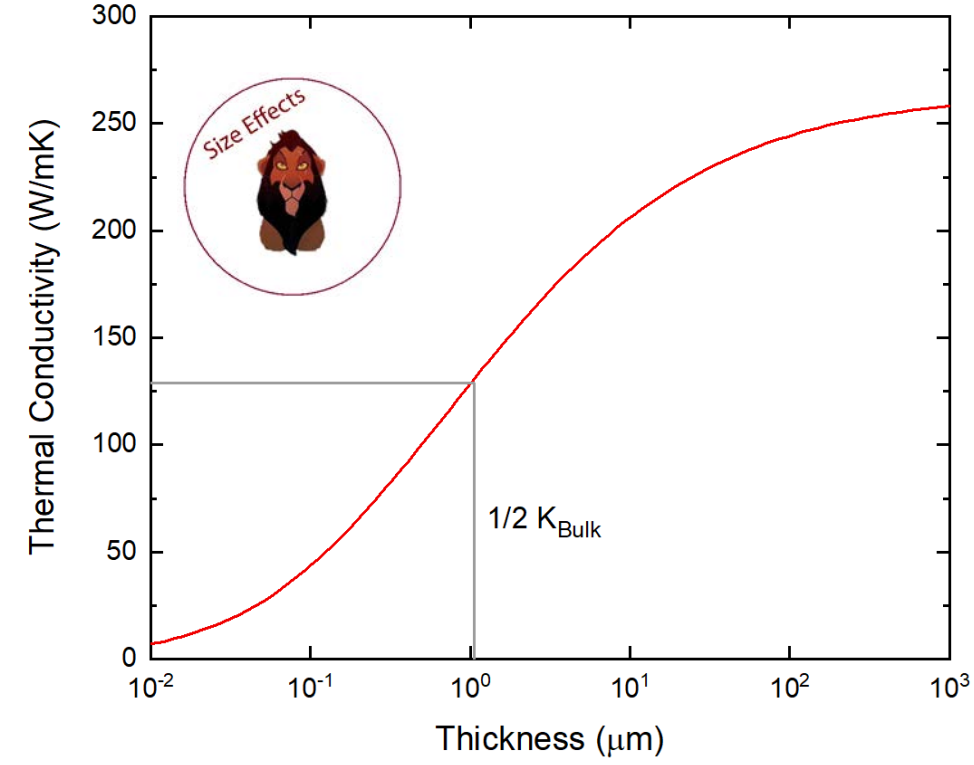
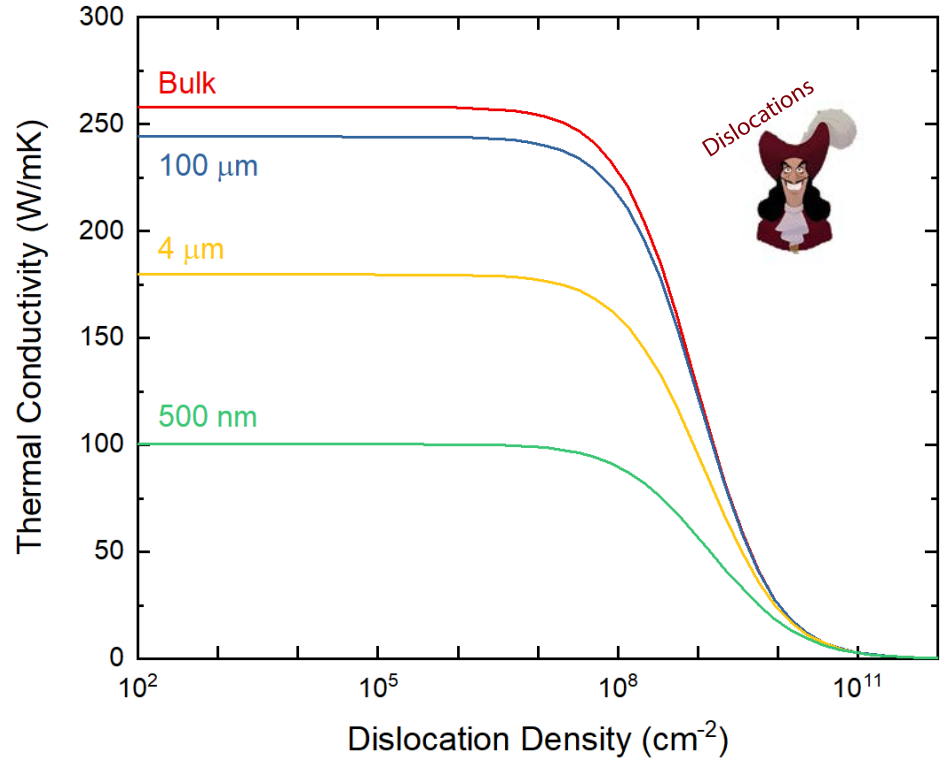


p-type
Sensitive

n-type
Immune?



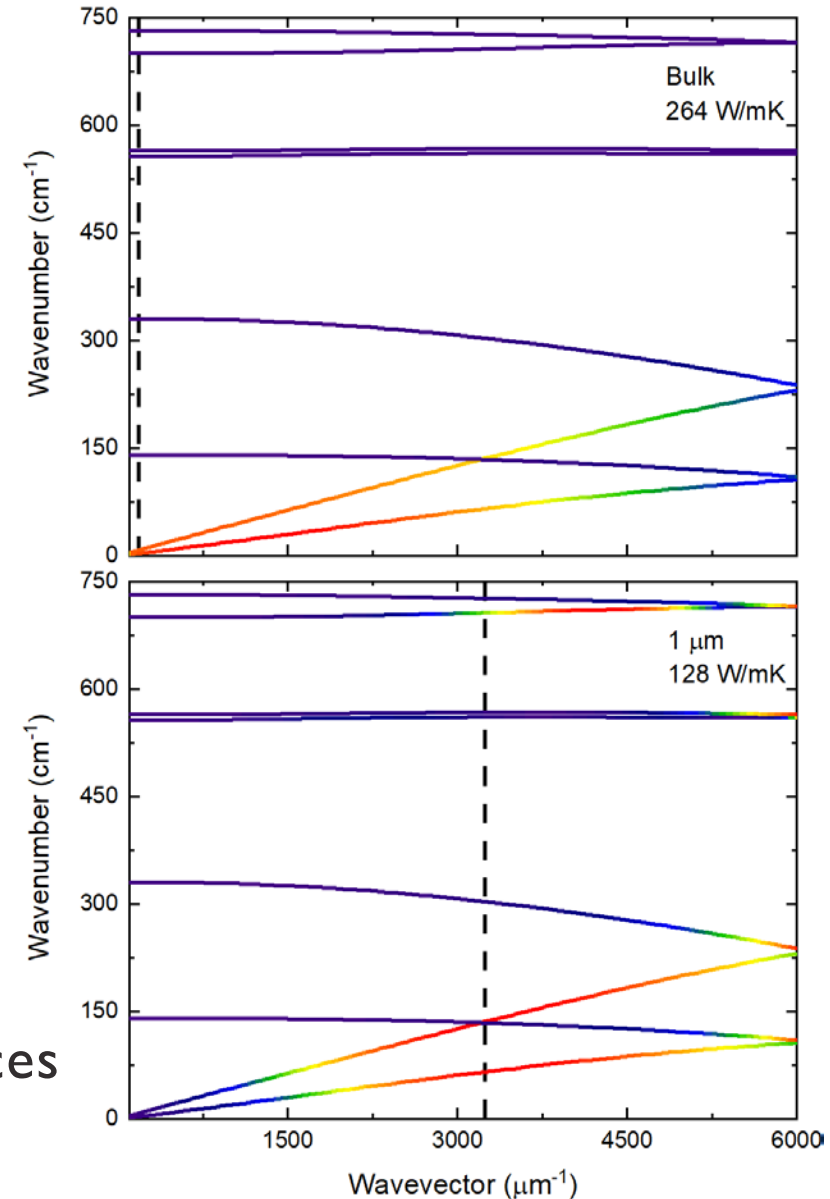
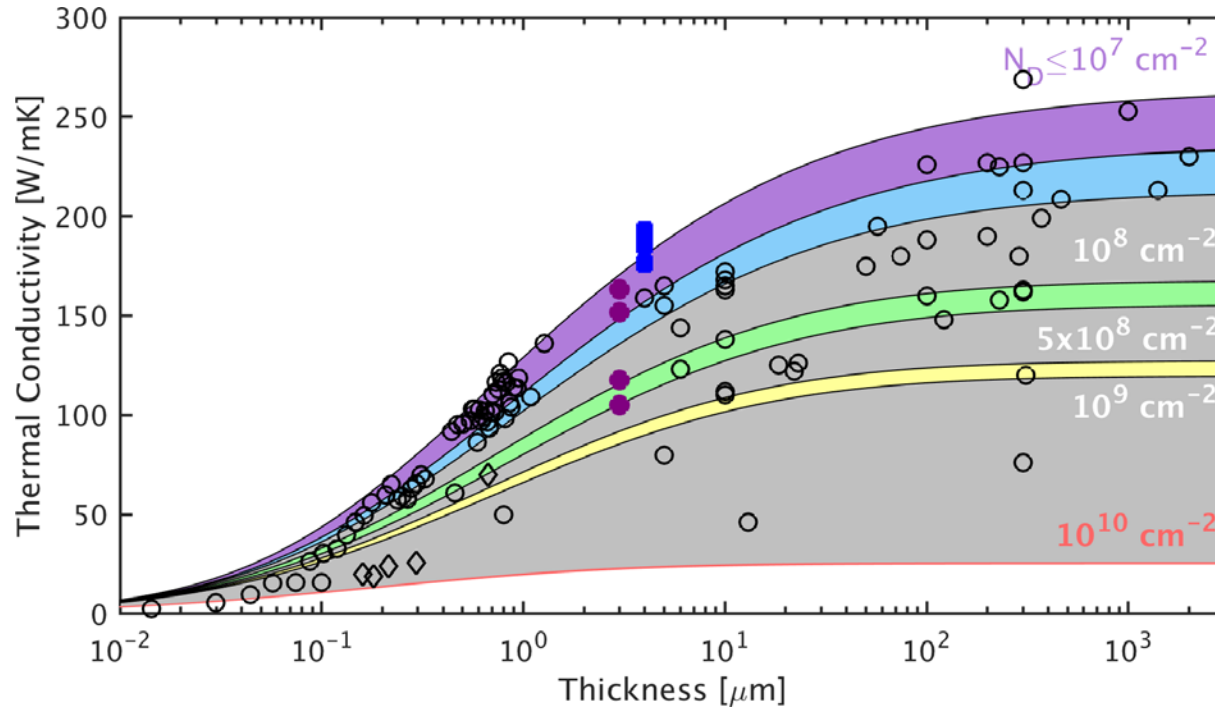
Phonon Gas Model: Probing the "Pain Points"



Phonon Gas (PG)
Model
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$$k_{PGM} = \frac{1}{VN_o} \sum_{\mathbf{q},s} (\hbar\omega) \frac{df_{\mathbf{q},s}}{dT} v_{\mathbf{q},s}^2 \tau_{\mathbf{q},s}$$

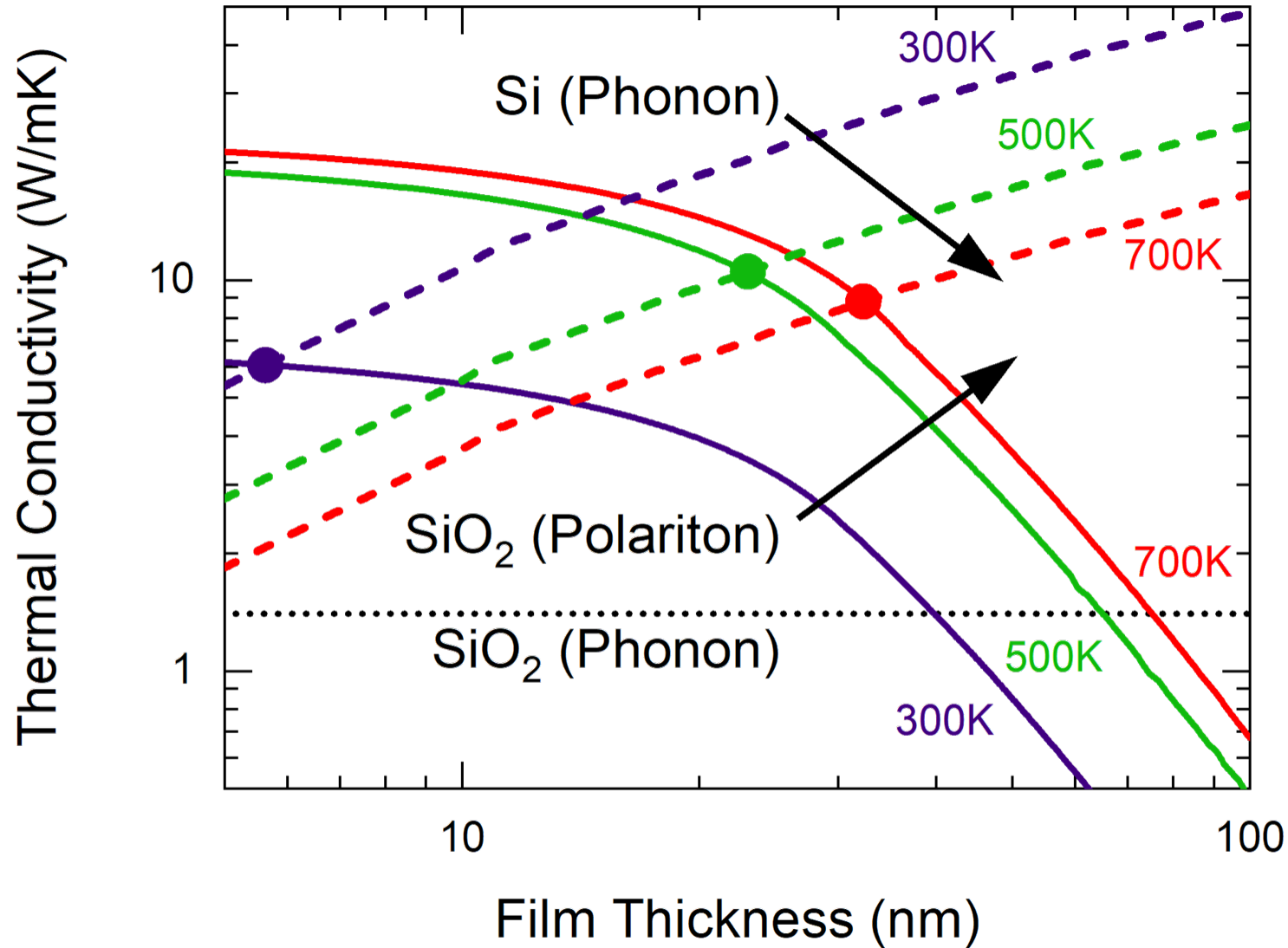
Size-Dependent Thermal Conductivity of GaN



Takeaway Textbook values don't exist in devices

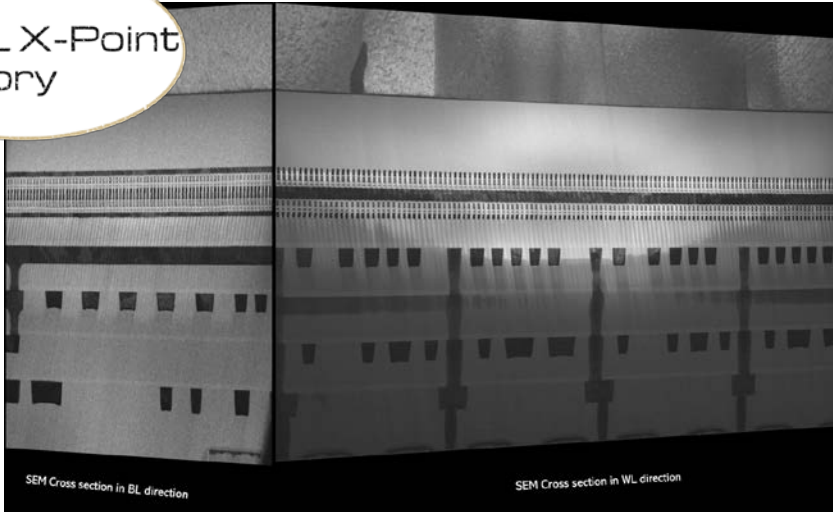
Takeaway Phonon transport scales opposite to devices

Polaritonic Transport Scales with Device Size



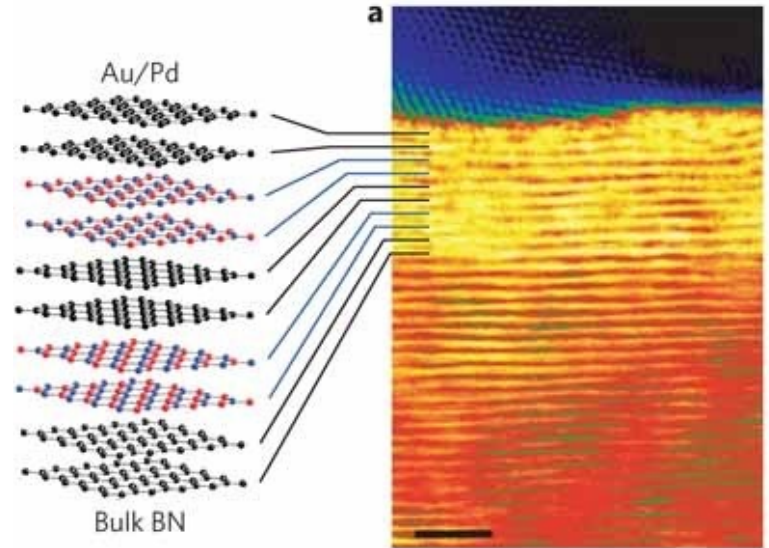
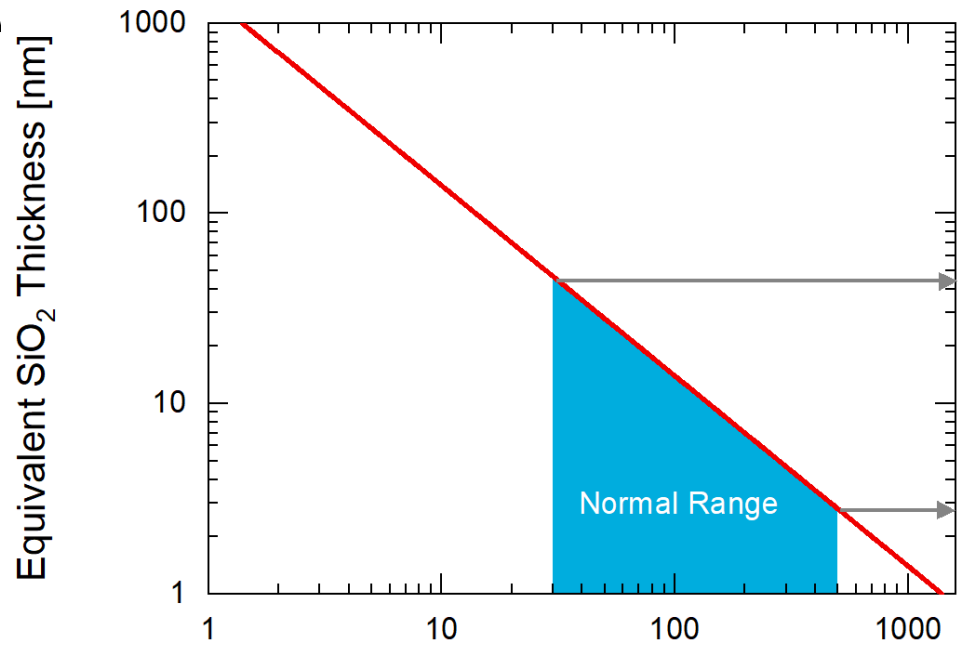
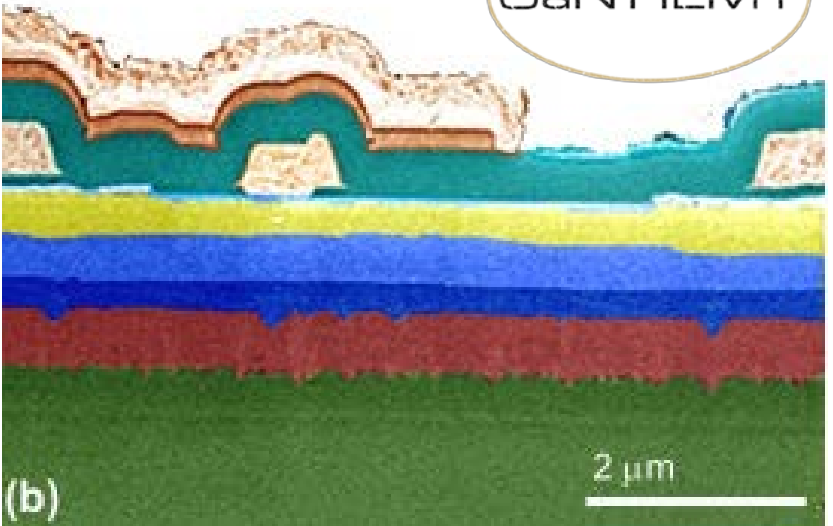
Problem 2 Interfaces are everywhere... and Bad

INTEL X-Point Memory



www.anandtech.com

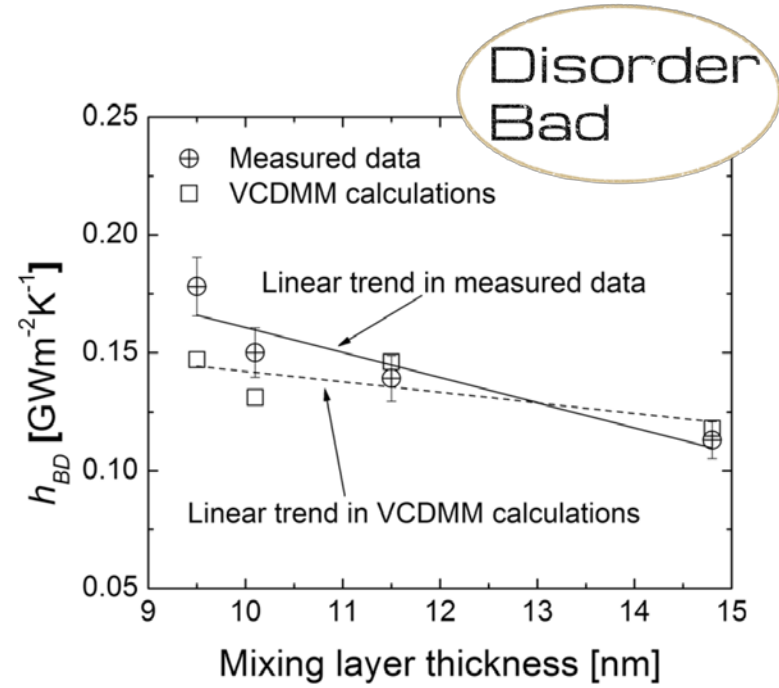
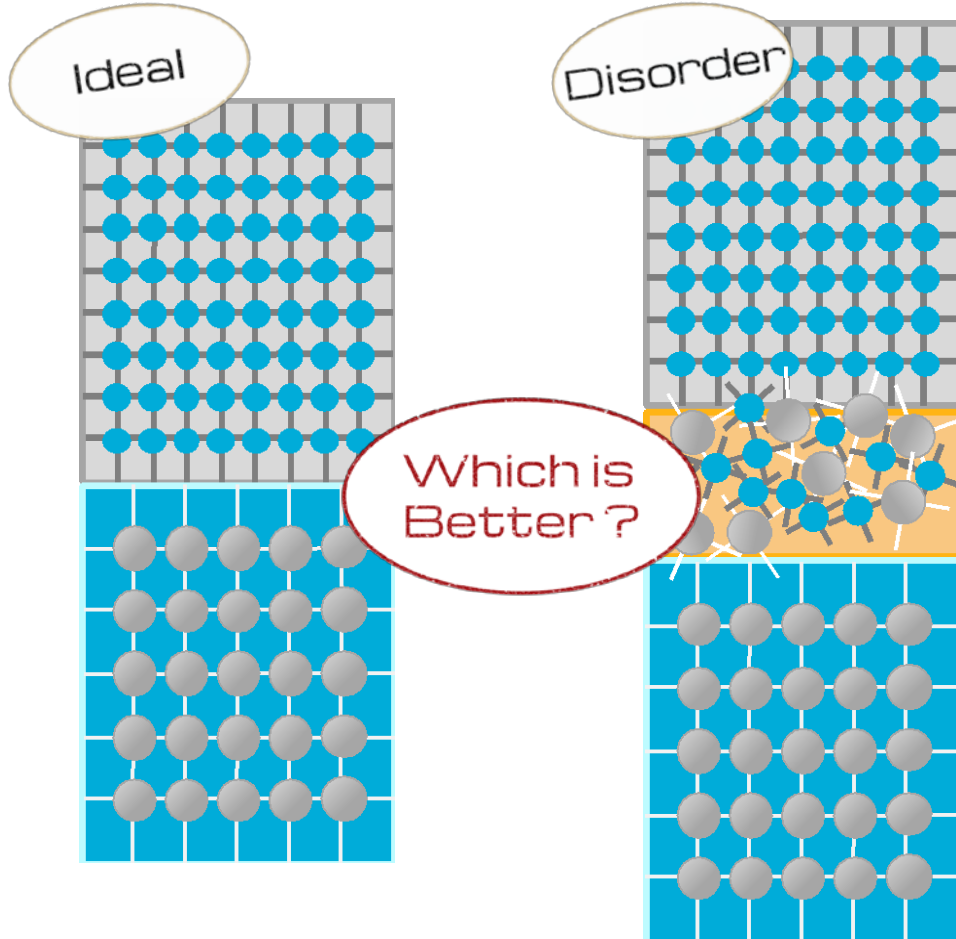
GaN HEMT



2D-Devices

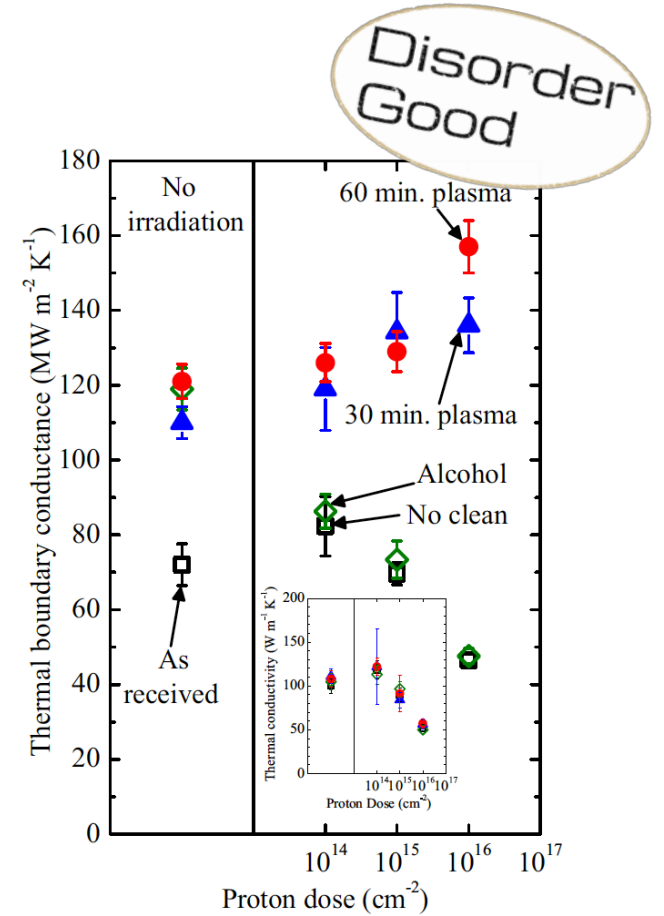
Haigh et al. Nat. Mat. (11) 764. 2012.

Interfaces Remain Confounding (Phonons)



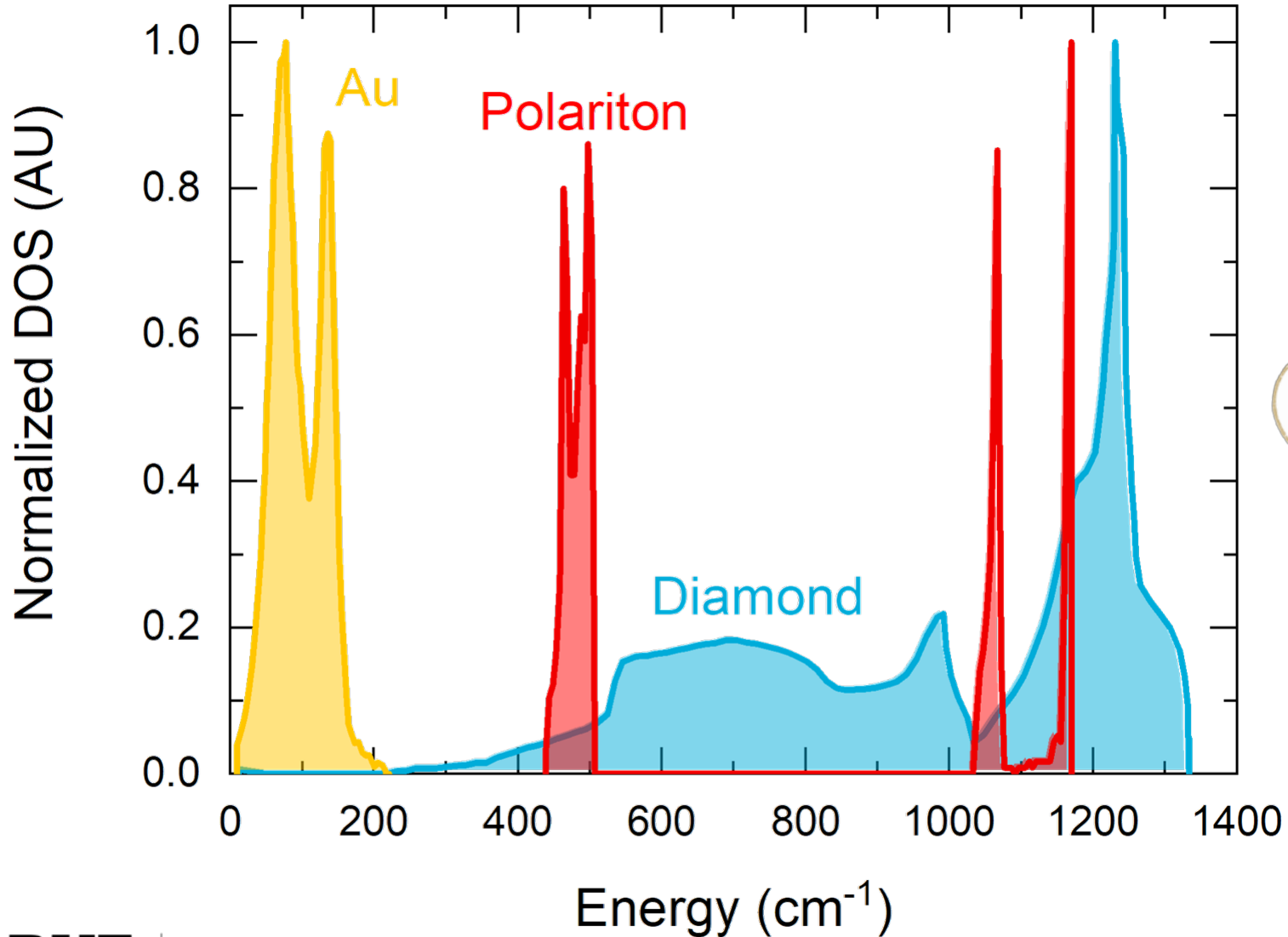
Expt. Details: Hopkins...Beechem...Graham. JHT (130) 0624402. 2008.

Theory Details: Beechem...Hopkins...Graham. APL (90) 054104. 2007.



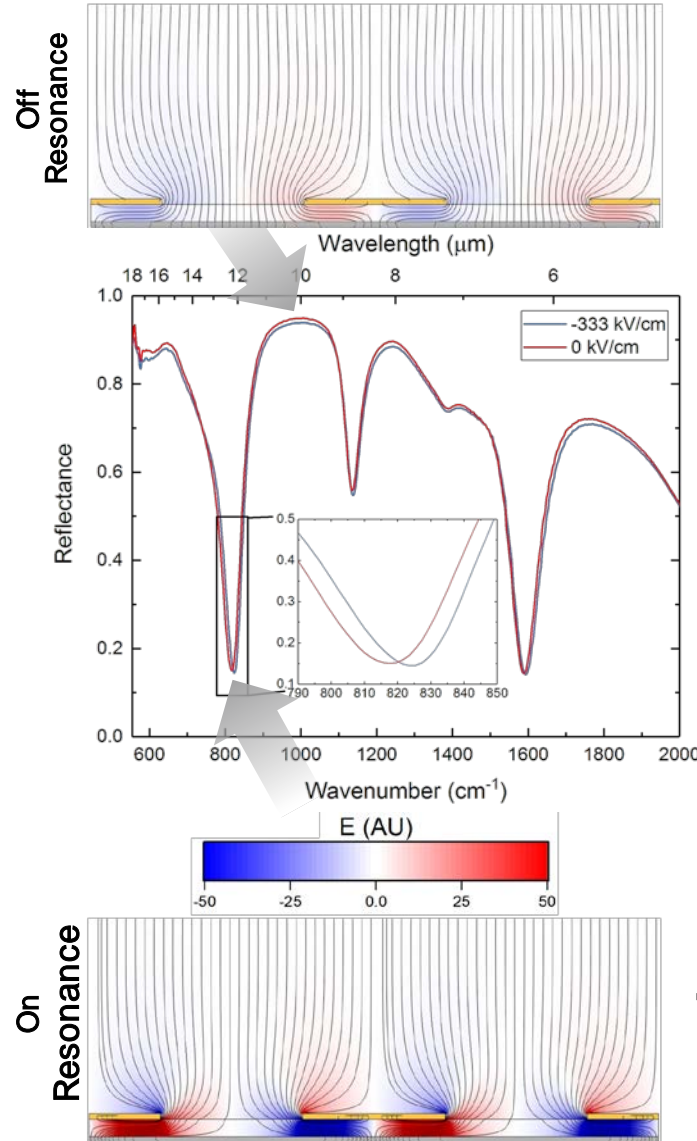
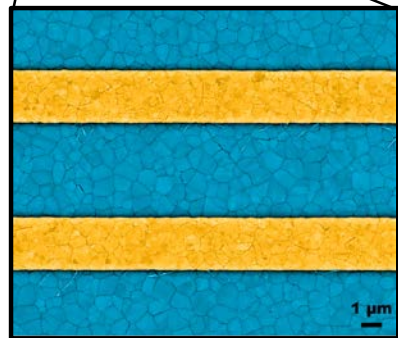
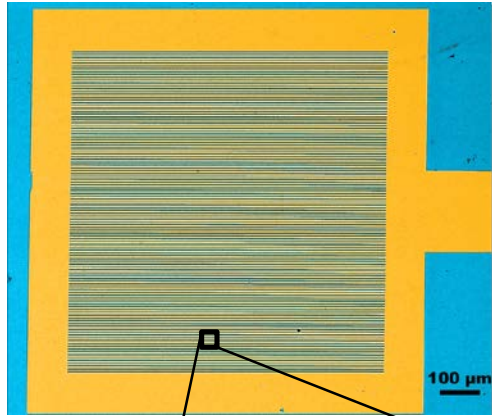
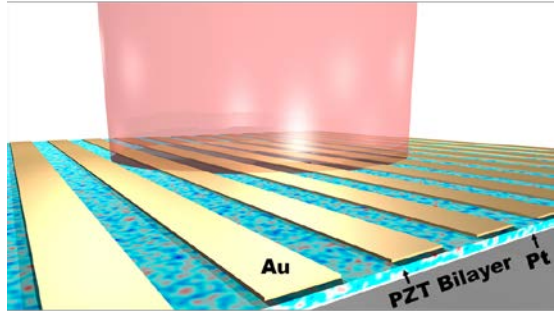
Details: Gorham...Beechem...Hopkins et al. PRB. (90) 024301. 2014.

Polariton Interfaces: "Translating" Heat?

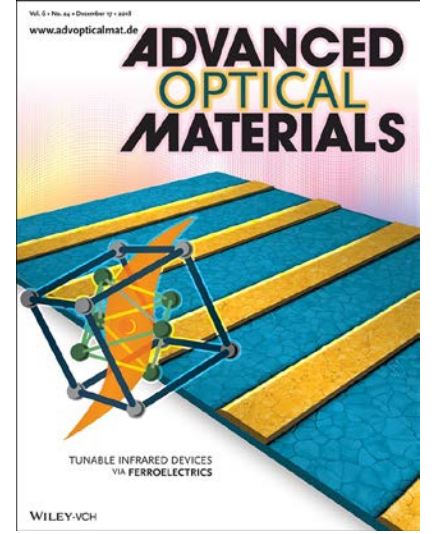
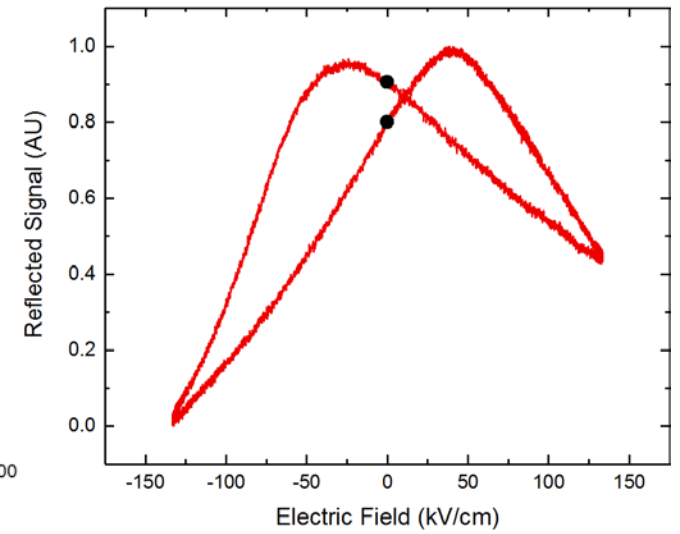


Link to Near-Field Transport?

Interfacial Transport via Polaritonic Hybridization?



Details: Beechem et al. Adv. Opt. Mat. (6) 1800062. 2018.



Opportunity for heat transfer!

Takeaway Polariton coupling links boundaries

Message Polaritonic Energy Transport

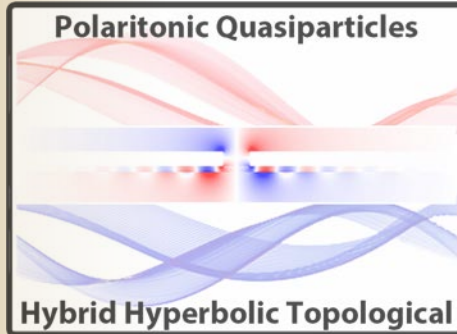
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Fundamentally different energy carrier needed.

Polaritons are the carrier.

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Dispersion Engineering of polaritons is doable.

Polaritons can be **dynamically tuned**.

WARNING Graphene Ahead



Iron Man

Why Iron man ditched iron for graphene



Are we one step closer to being able to use the world's strongest material?

By Nicola Casella, CNN
Updated 10:58 AM ET, Fri January 13, 2017

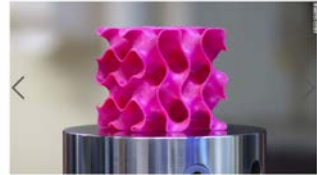


Photo: Innovative Properties. These materials could change the world.
Graphene's great: Researchers at the Massachusetts Institute of Technology have designed a new material that is 10 times stronger than steel.

The Washington Post

Why the graphene light bulb could switch on a new era of innovation

By Dominic Casullo
Updated 10:58 AM ET, Fri January 13, 2017



theguardian

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Home > science

Physics **Graphene - the new wonder material**

Scientists' interest rises in a material that is more solid than steel and a better conductor than copper

19
David Larousse

Page 22 November 2015
6:23 AM

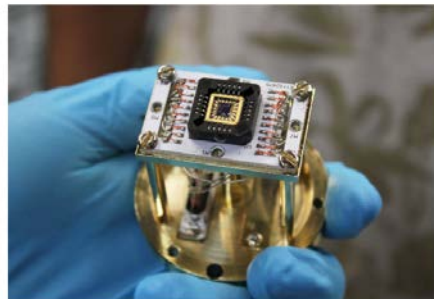
Most popular in US

- British spies were first to spot Trump team's links with Russia
- Arizona Sky Village's western June race rules: 'That's all you get! Goodward Light'
- United States' first female Muller judge: 'She's a real star'

The molecule is priceless but it is not a matter of cost - a few hundred dollars per kilo. The value lies in its potential. The molecule in question is called graphene and the EU is prepared to devote £1bn (£1.5bn) to it between 2011 and 2023 to find out if it can transform a range of sectors such as electronics, energy, health and construction. According to Scopus, the bibliographic database, more than 8,000 papers have been written about graphene since 2005.

A Physics Magic Trick: Take 2 Sheets of Carbon and Twist

The study of graphene was starting to go out of style, but new experiments with sheets of the ultrathin material revealed there was much left to learn.



A device containing an unusual form of carbon: two one-atom-thick sheets pressed together with the lattice of one rotated slightly. Experiments by Dmitri Efetov and his colleagues show that this material can exhibit different electronic properties, including superconductivity. ICFO - The Institute of Photonic Sciences

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Wonder material could harvest energy from thin air

By Peter Shattiloff, video produced by Curtis Brown and Jackson Luo, CNN
Updated 9:59 AM ET, Tue November 3, 2015



Story highlights

Researchers in the UK say a discovery involving wonder material graphene could revolutionize batteries.

Graphene is 300 times stronger than steel and a million times thinner than a human hair.

The material, which has the same atomic structure as the lead in pencils, is impermeable to atoms and molecules.

Scientists found that positively charged hydrogen atoms could pass through it with implications for fuel cell efficiency.

Billie's Mate. Originally published December 2014, updated November 2, 2015.

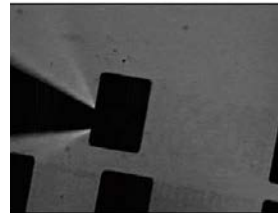
(CNN) — Bids claim for new battery technology have been around since the invention of the lead-acid battery more than 150 years ago.

But researchers at Manchester University in the UK say their latest discovery involving the new wonder material graphene could be the most revolutionary advance in battery technology yet.

According to a study published in the journal Nature.

Graphene is useful when...

2D "Win" Tuning (2DOS) Form & flexibility Heterogeneous integration



Graphene can be folded and cut into a microscopic kirigami spring. (Source: University of Michigan)

The New York Times

JULY 30, 2015

Graphene Origami

Graphene is a thin material with tremendous potential. Measuring only an atom-thick, it is harder than diamond, a better electrical conductor than copper, and 200 times as strong as steel.

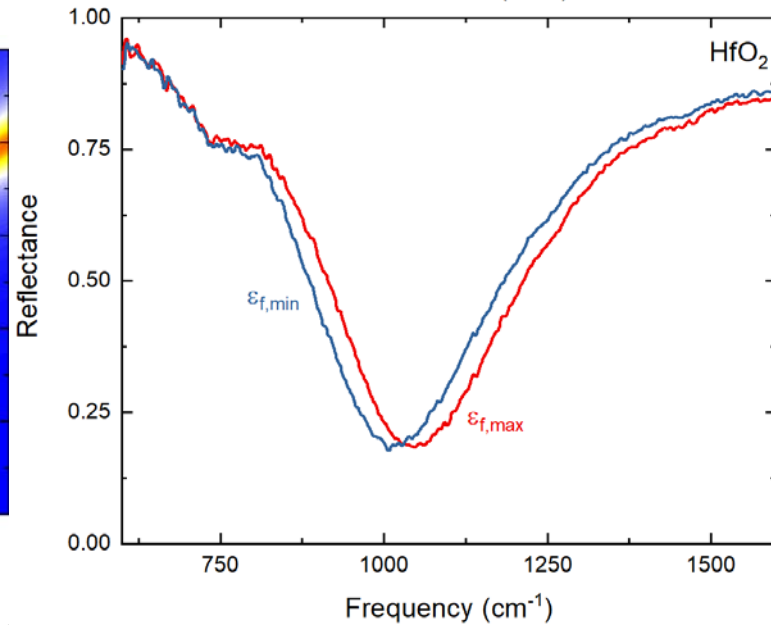
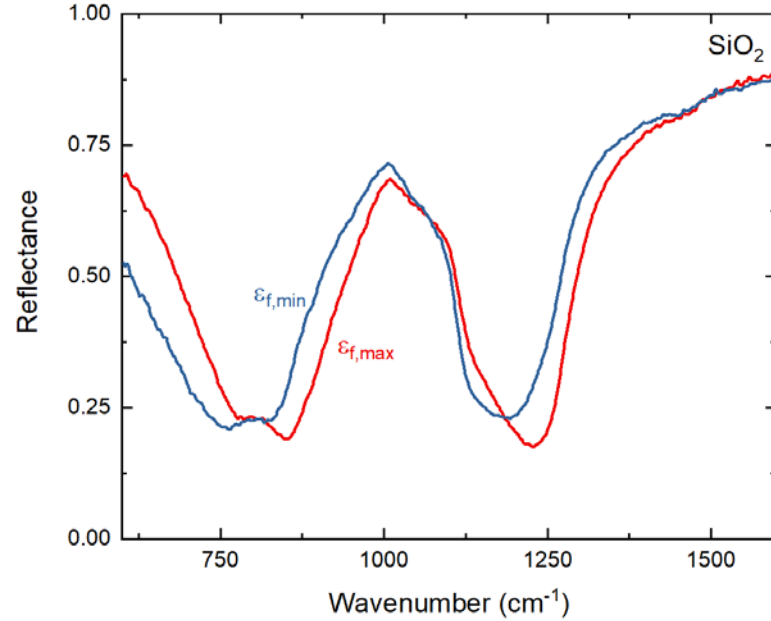
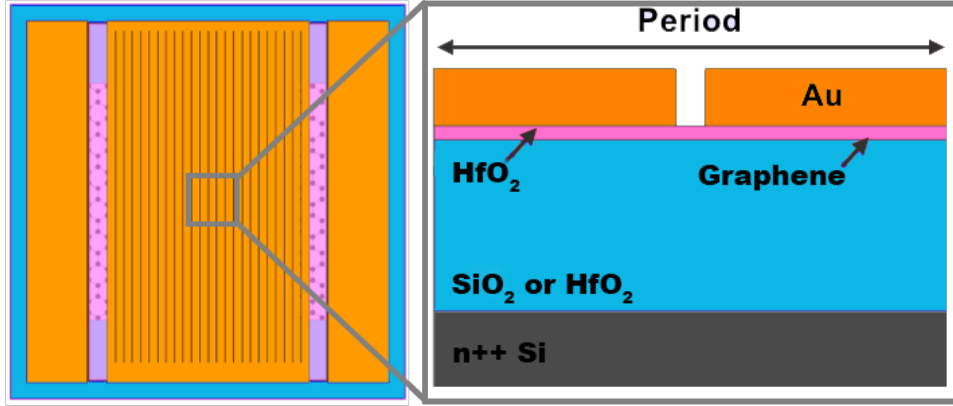
Graphene is so strong that a sheet of it stretched across a coffee-cup should be able to support the weight of a truck bearing down on a pencil point. Some researchers call it a "wonder material" that could be used in everything from batteries and biosensors to computers and condoms.

Now researchers have discovered another one of graphene's feats: It's as flexible as paper. Not only can graphene be crumpled and then perfectly flattened, but it can also be folded like origami, according to a report published Wednesday in Nature.

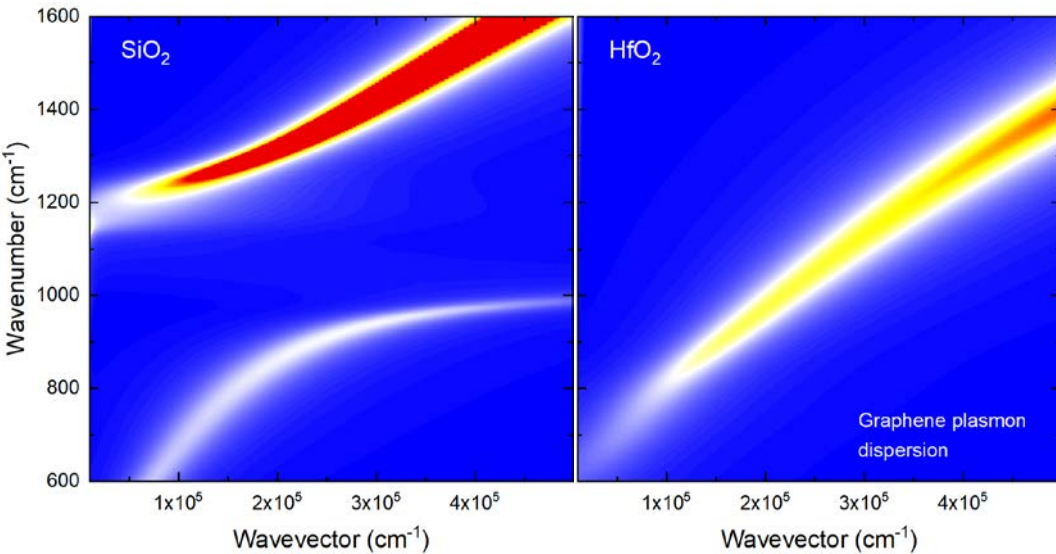
Using a style of origami that involves cuts and folds called kirigami, the researchers fashioned a sheet of graphene into a tiny spring. According to Nature, researchers may one day use kirigami to craft graphene sheets into microscopic weighing scales or nets small enough to wrap around living cells.

—NICHOLAS ST. FLEUR

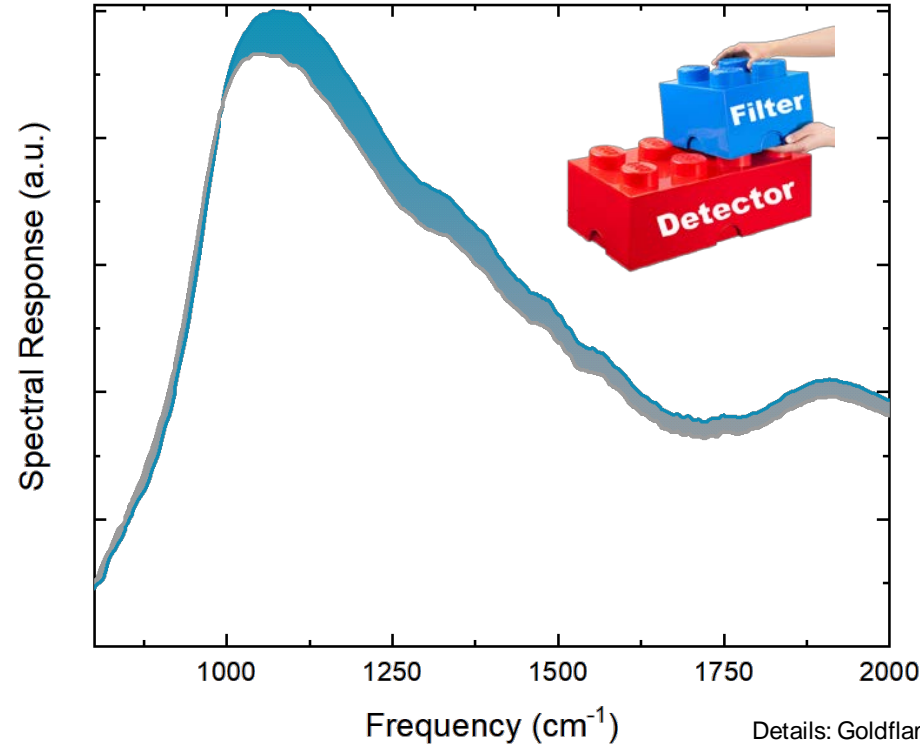
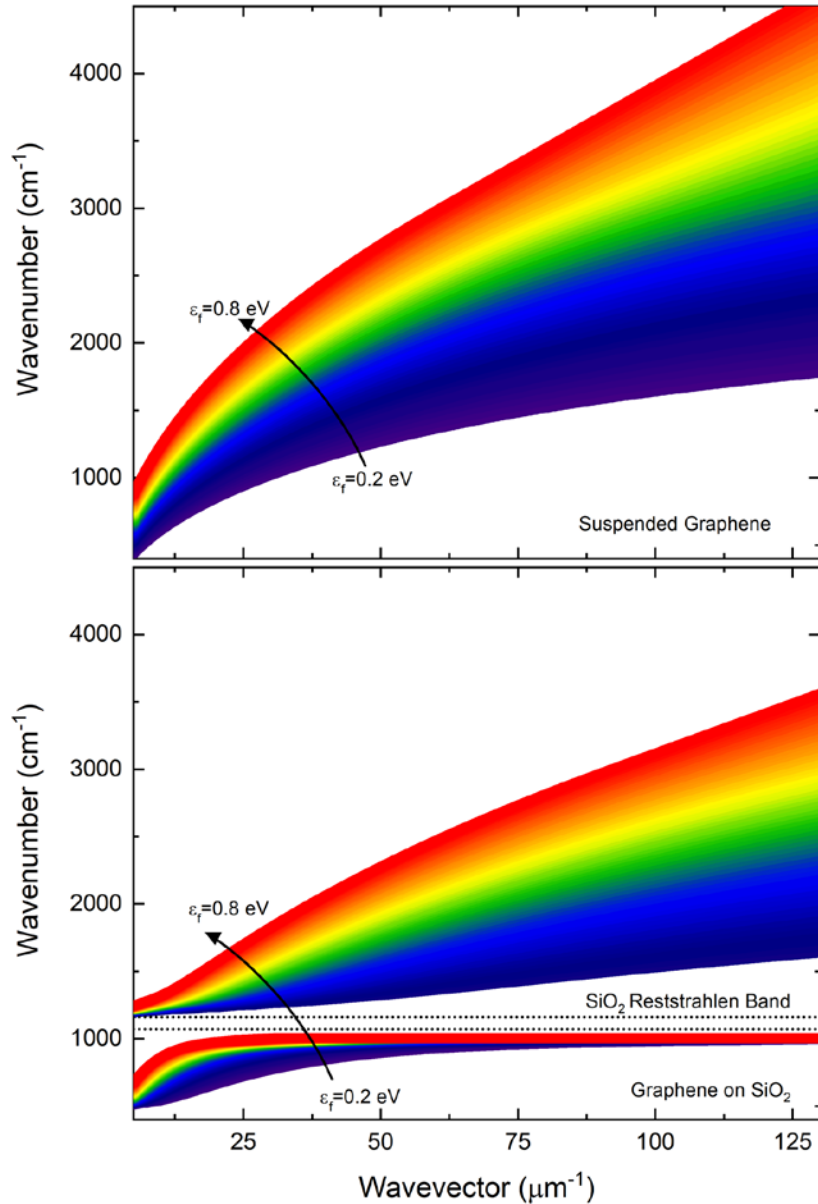
Plasmon Tailoring ... "Easy" Dispersion Engineering



Dispersion Change with Substrate



Polariton Tuning: "Push Button" Thermal Transport?



Details: Goldflam...Beechem et al. APL (116) 191102. 2020

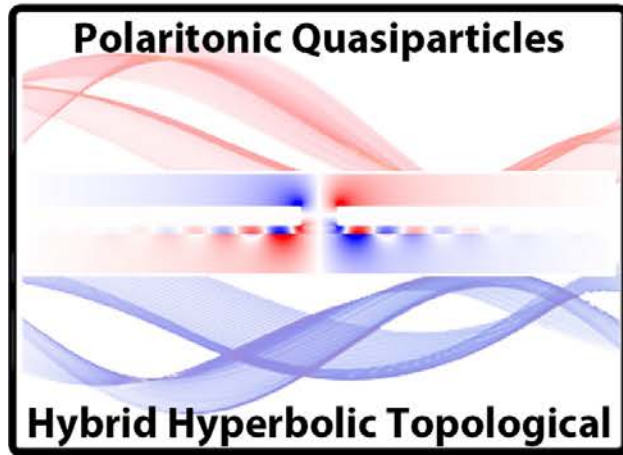
Opportunity for heat transfer!

Takeaway Polariton dispersions can be engineered

Takeaway Polariton dispersions can be switched.

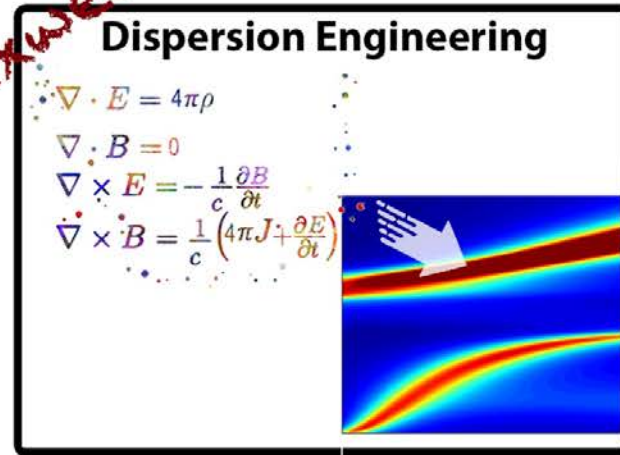
Details: A. Jarzembski...Beechem et al. Phys. Rev. Appl. 14, 034044 (2020).

Polaritonic Energy Transport: The Path



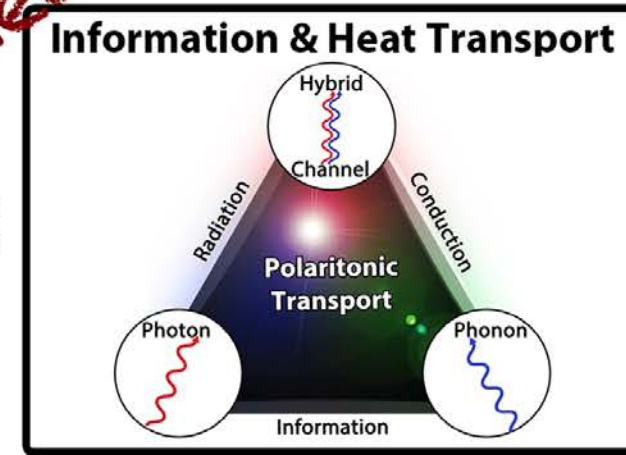
Maxwell

+

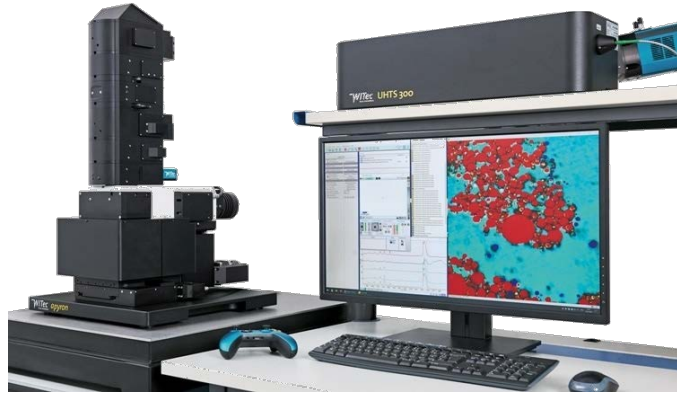


New

=

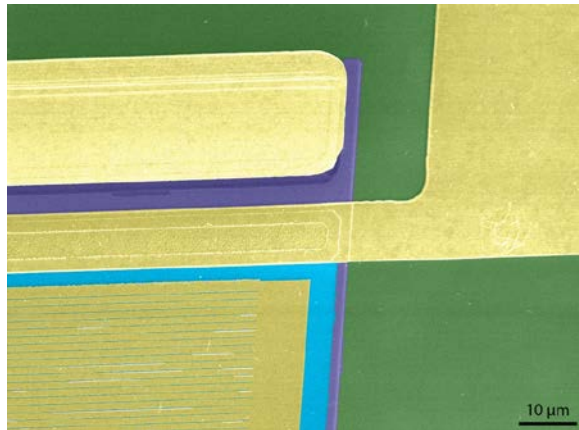
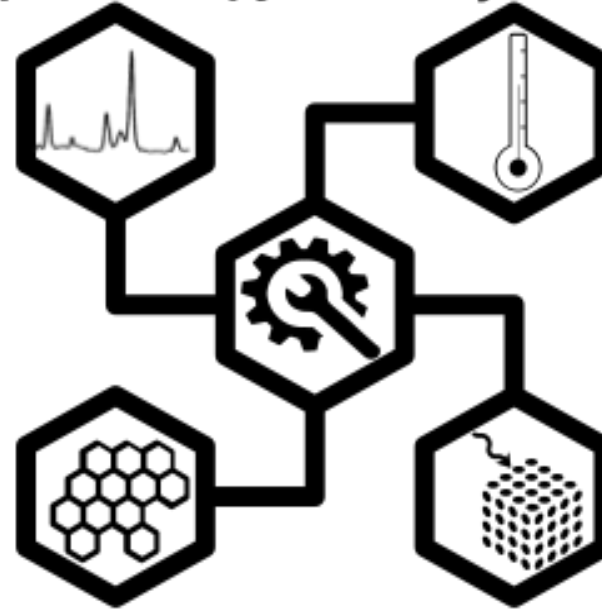


Paritonic Energy Transport: The Tools



Vibrational Spectroscopy

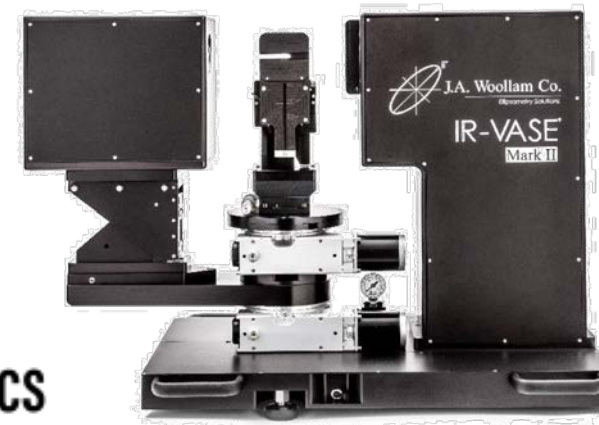
Thermal Physics



Details: Goldflam...Beechem. APL (116) 191102. 2020.

2D-Solids

Nanophotonics



Beyond Heat... Alternatives for Spectroscopy



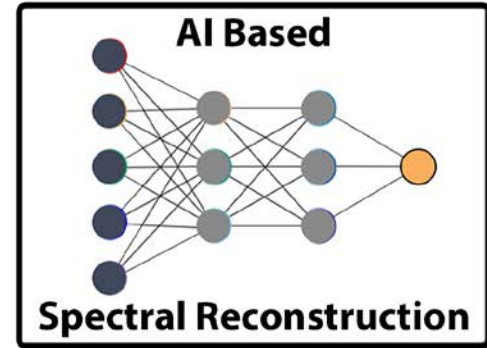
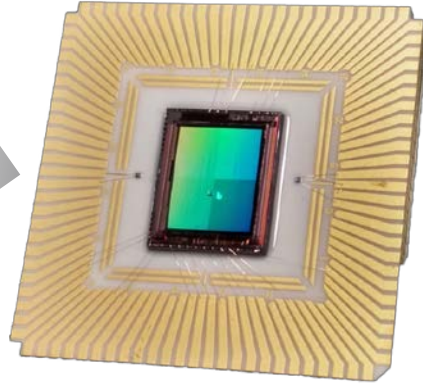
Problem #1
Spectrometers
are too big

Problem #3
Momentum

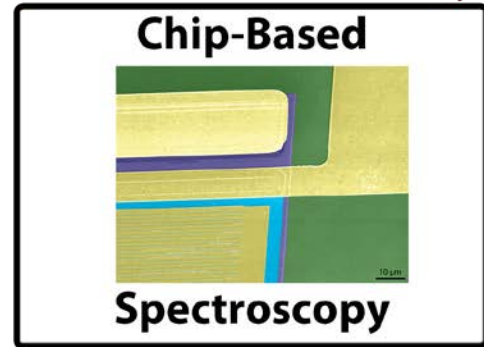
Problem #2
Spectrometers
are too general
purpose.



Beyond Heat. . . Radars for Spectroscopy



"More" Momentum || Made to Order





A light lab employing **infrared physics** to create **thermal, spectroscopic and sensing solutions.**

**HELP
WANTED**
Grad. Students



Thomas Beechem

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Birck Nanotechnology Center
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tbeechem@purdue.edu