Advanced Thermal Interface Materials: Assembly and Integration for System in Package

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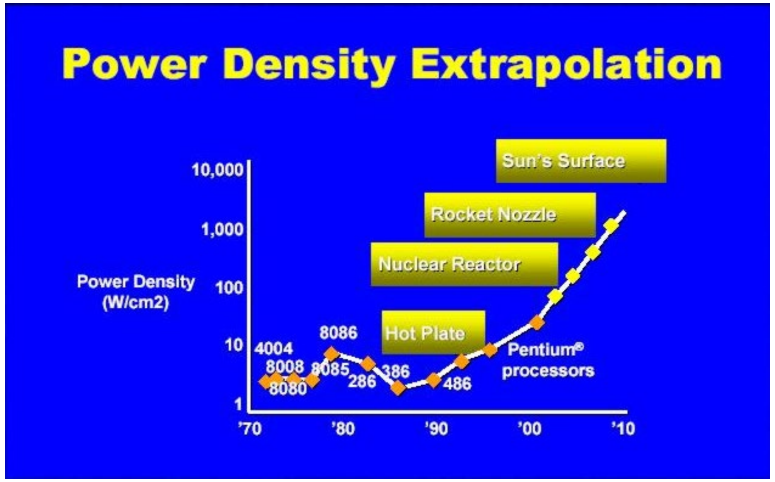
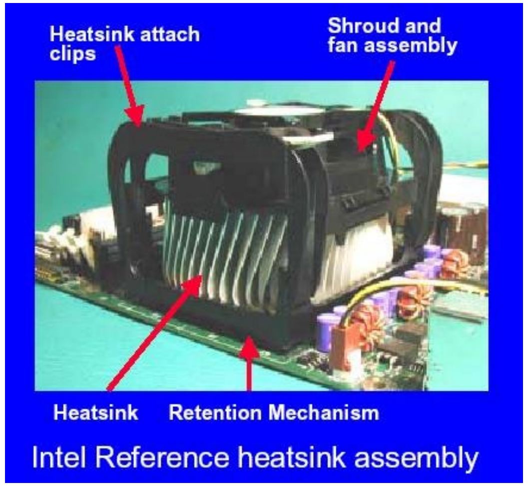
Power Dissipation

Power dissipation is perhaps the greatest challenge facing modern electron devices.

Intel on Devices ~ 2001



Intel on Packaging ~ 2001



Power dissipation, or self-heating, has limited the performance of integrated circuits for nearly two decades[1].

We often solve this via **packaging**, since self-heating is deeply rooted in charge transport in imperfect semiconductors at normal temperatures[2].

1. S. Salahuddin, et al. The era of hyper-scaling in electronics. Nature Electronics 2018.
2. S. Data. Quantum Transport: Atom to Transistor. Cambridge University Press 2005.

Packaging Requirements

The thermal requirements on packaging are becoming more demanding.

Material Requirements[3]

	Power Electronics/ Electrification Packaging Material Requirements		
Attributes	**Current**	**5 years**	**10-15 years**
Packaging platforms	Laminate & LF based (QFN, LGA, BGA, SiP) Power QFN, specialized package (TO)	Laminate & LF based (QFN, LGA, BGA, SiP) Flip chip/ (HD) FOWLP	Laminate & LF based (QFN, LGA, BGA, SiP) Contact-less package (example: EM energy transfer) Flip chip/ (HD) FOWLP/PLP
Pkg Dimensions	2x2 to 7x7mm	1x1 to 2x2 mm	Chip Scale
Device Material	Si	GaN, SiC	GaN, SiC
Max Junction Temperature	175C	200C	200C and beyond
Max Voltage	1300V	>2000V	TBD
Interconnect/via material/surface finish	WB- Au wire,Cu wire, Multiple Cu vias, Cu Pillar, OSP, ENIG, ENEPIG, Electrolytic NiAu	WB-Cu wire, OSP, SOP, ENIG, ENEPIG, Electrolytic NiAu, Cu Pillar interconnect, Thicker Cu-via/ Larger surface area (clips)	Cu Pillar, OSP, SOP, ENIG, ENEPIG, Electrolytic NiAu New Materials (graphite, etc)
Die attach materials	Epoxy, Solder (Leadfree & Leaded) Sintering Adhesive (Pb-free)	Sintering Adhesive (Pb-free) Diamond and Graphite loaded materials	TLPS (Transient Liquid Phase Sintering) New Materials (graphite, etc.)

Diamond and Graphite loaded materials

Thermal Requirements[3]

Table 3: Thermal Management Requirements. (Green: Solution available for manufacturing. Yellow: Additional development work needed. Red: Significant development effort needed for HVM. White: Information only)

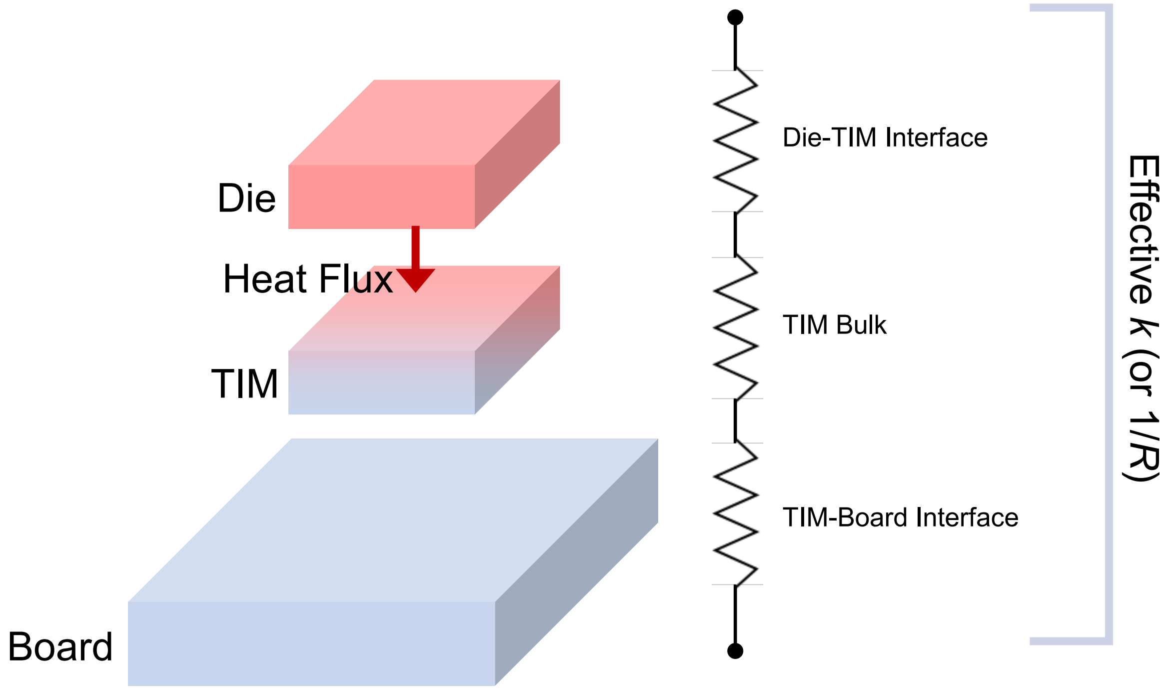
	Thermal Management		
	>2023	>2028	2033 and +
Ingredients			
Thermal Interface Materials (TIMs)	Thermal interface materials with low thermal resistance and high resilience to package and board level assembly techniques (50% or greater reduction especially in effective thermal resistance under reliability conditions)		
Heat Spreaders	High conductivity (2x or greater than copper), low-cost materials for interfacing which are capable of being cost effectively manufactured into integrated heat spreaders on the package	High conductivity spreaders for integration within a 3D stack which are process compatible. Thermal conductivities >= 3000 W/m/K with a thickness of 50mm to 200mm	

Thermal conductivities >= 3000 W/m/K with a thickness of 50mm to 200mm

3. National Institute of Standards and Technologies. Microelectronic and Advanced Packaging Technologies Roadmap. Interim Edition 2023.

Die Attachment

The thermal conductivity (k) of the thermal interface material (TIM) is directly related to the device's temperature rise (ΔT) at a given operating power or heat flux (q).



Fourier's law

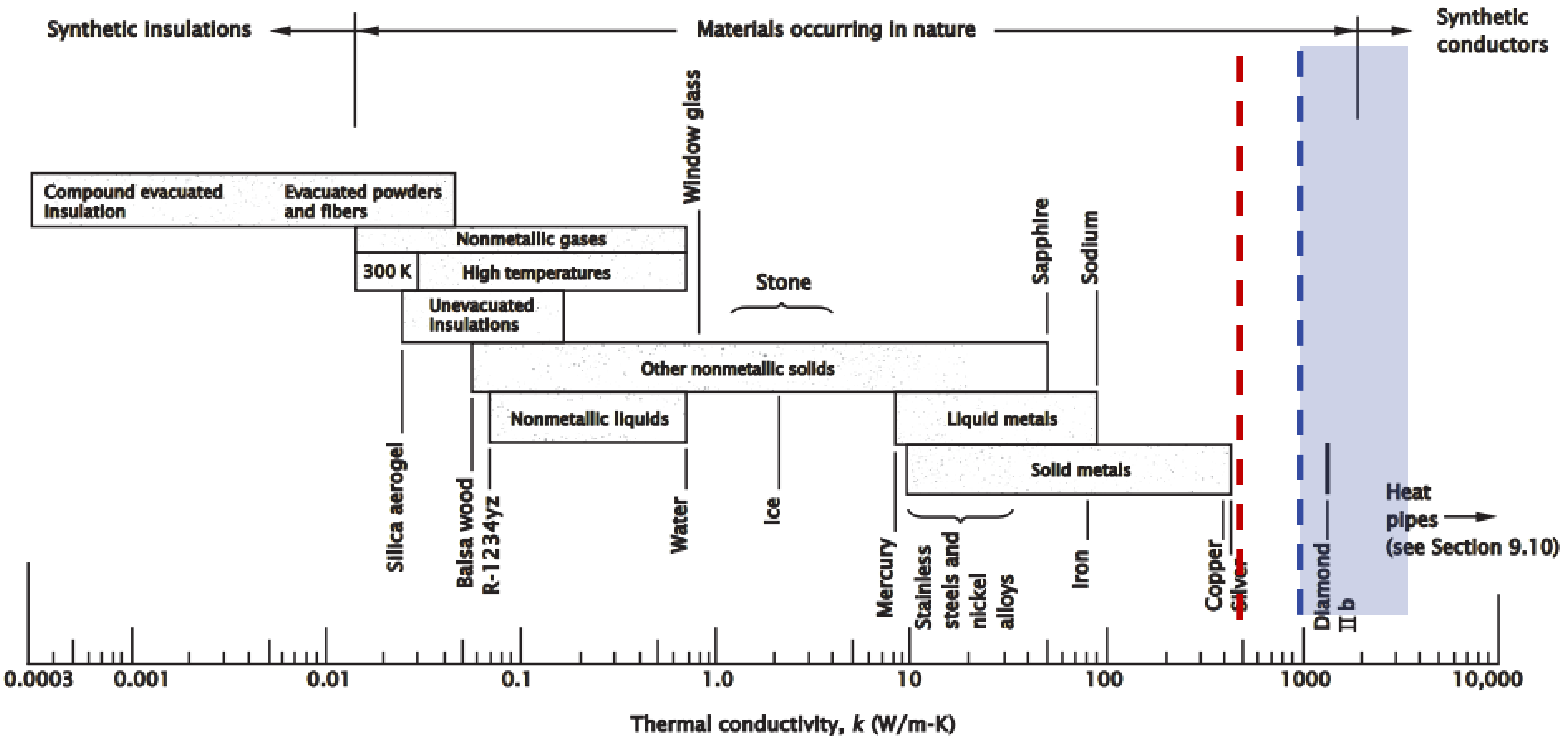
$\Delta T = qL/k$ where L is the ~ 100 mm thickness of the TIM

As devices push heat fluxes of ~ **10^5 W/m^2**, thermal conductivities of ~ **10^3 W/mK** are required for acceptable temperature rises[3].

3. National Institute of Standards and Technologies. Microelectronic and Advanced Packaging Technologies Roadmap. Interim Edition 2023.

Moving Beyond Metals

Metals are limited to k ~ 10^2 W/mK and few materials can tap into the 10^3 W/mK range[4].

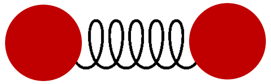


4. G. Chen. Nanoscale Energy Transport and Conversion: A Parallel Treatment of Electrons, Molecules, Phonons, and Photons. Oxford University Press 2005.

Why Carbon Materials?

Why are carbon materials (graphene, graphite, carbon nanotubes, diamond) seemingly alone on many roadmaps for advanced passive/conductive thermal packaging?

$$\omega = \sqrt{\frac{k}{m}}$$

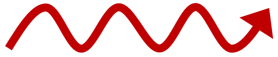


From mechanics, the vibrational frequency (ω) of a harmonic oscillator is related to the atomic mass and stiffness of the interatomic potential.

Carbon has light atoms and stiff bonds

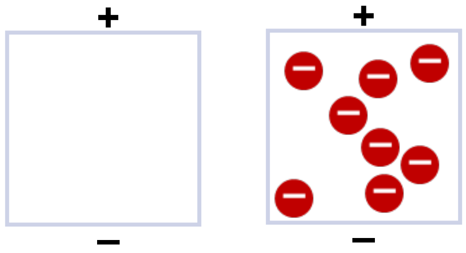
$$k = \sum^{\text{modes}} C v \lambda$$

Heat Capacity (C) — Phonon Mean-Free Path (λ)



From kinetic theory, the thermal conductivity is related to the group velocity ($v \propto \omega$) of the phonons.

Carbon has high thermal conductivity



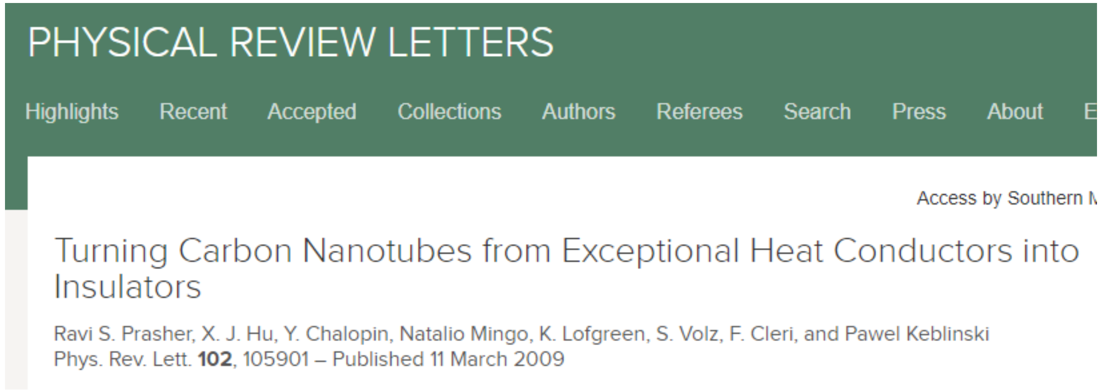
From nature, electrical insulating (diamond) and conducting (graphite) forms exist.

Carbon has electrically insulating and conducting forms

Many synthetic conductors, like heat pipes or microfluidics, may not be compatible with highly integrated systems. For example, back-end-of-the-line compatibility for monolithic 3D integration.

Constructing Bulk Carbon-Based TIMs

The atomic-scale interfaces within the TIM are major challenges.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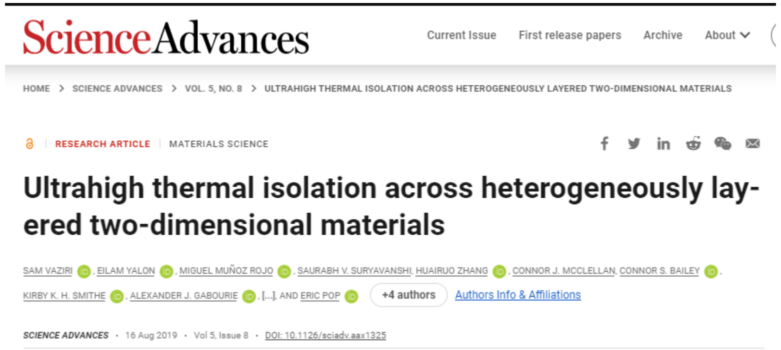
Turning Carbon Nanotubes from Exceptional Heat Conductors into Insulators

Ravi S. Prasher, X. J. Hu, Y. Chalopin, Natalio Mingo, K. Lofgreen, S. Volz, F. Cleri, and Pawel Keblinski

Phys. Rev. Lett. **102**, 105901 – Published 11 March 2009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RESEARCH ARTICLE | MATERIALS SCIENCE

Ultrahigh thermal isolation across heterogeneously layered two-dimensional materials

SAM VAZIRI, EILAM YALON, MIGUEL MUÑOZ ROJO, SAURABH V. SURYAVANSHI, HUAIRUO ZHANG, CONNOR J. MCCLELLAN, CONNOR S. BAILEY, KIRBY K. H. SMITHE, ALEXANDER J. GABOURIE, [...], AND ERIC POP +4 authors Authors Info & Affiliations

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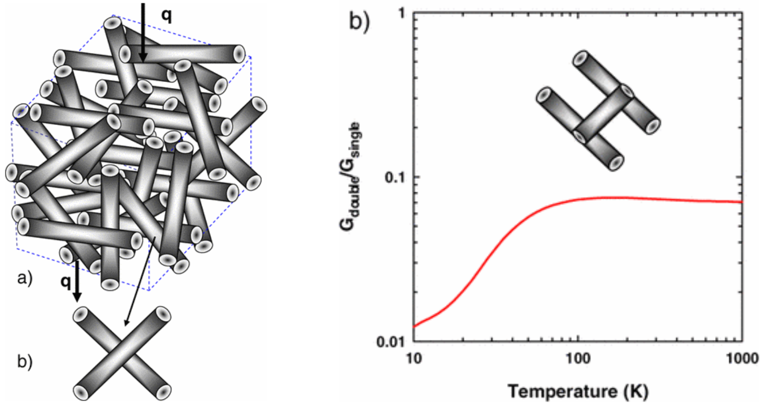
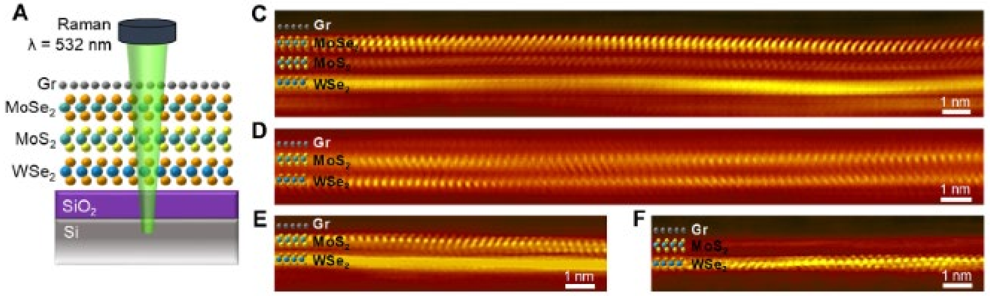




Under some conditions, the interface of graphite is **3× more thermally resistive than air**!

5. S. Prasher, et al. Turning Carbon Nanotubes from Exceptional Heat Conductors into Insulators. Physical Review Letters 2009.
6. S. Vaziri, et al. Ultrahigh thermal isolation across heterogeneously layered two-dimensional materials. Science Advances 2019.

The Integration and Assembly Challenges

Heterogeneous integration of these TIMs is limited by many areas.

Fabrication
How do we build these carbon-based materials?

- controlling interface chemistry
- controlling material quality
- controlling material uniformity

Metrology
How do we characterize these materials?

- mapping nanoscale thermal profiles
- measuring thermal boundary resistance
- relating thermal, structural, and chemical properties

Integration
How do we integrate these materials?

- preventing damage
- avoiding thermal expansion mismatch

Table 5.1: Illustration of the current State of the Art and future needs for different metrology requirements.

Metrology Technology	Current		5 years	10 years	15 years
Atomic-level characterization of new materials and devices	Aberration corrected STEM Automated FIB sample preparation with consistent lamella thickness APT SPM	Advanced electron diffraction methods Advanced energy dispersive X-ray spectroscopy Backscattered electron diffraction	Aberration corrected SEM AI/ ML analysis of characterization data i.e. strain analysis ML-based analysis of crystal phase and orientation in nanostructures Reduced time to analysis	Continued improvement	Continued improvement via invention
			Increase in wavelength range	Increased X-ray source Intensity for In-fab X-ray	

AI/ ML analysis

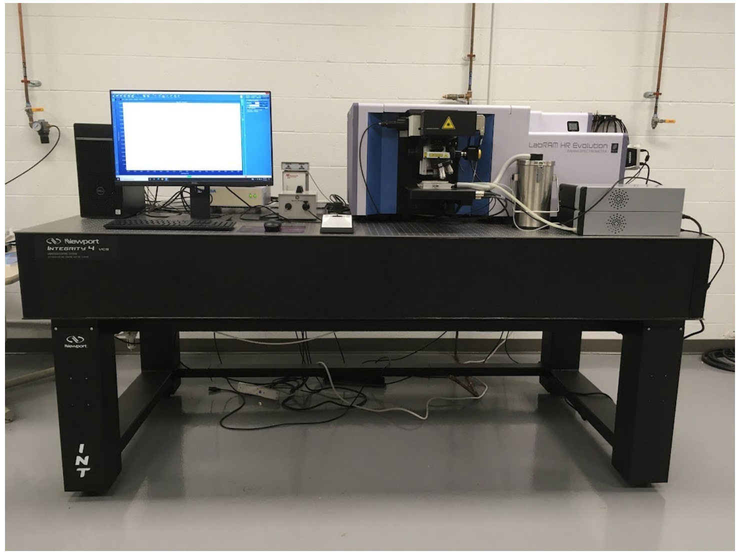
ML-based analysis

3. National Institute of Standards and Technologies. Microelectronic and Advanced Packaging Technologies Roadmap. Interim Edition 2023.

Metrology Limitations

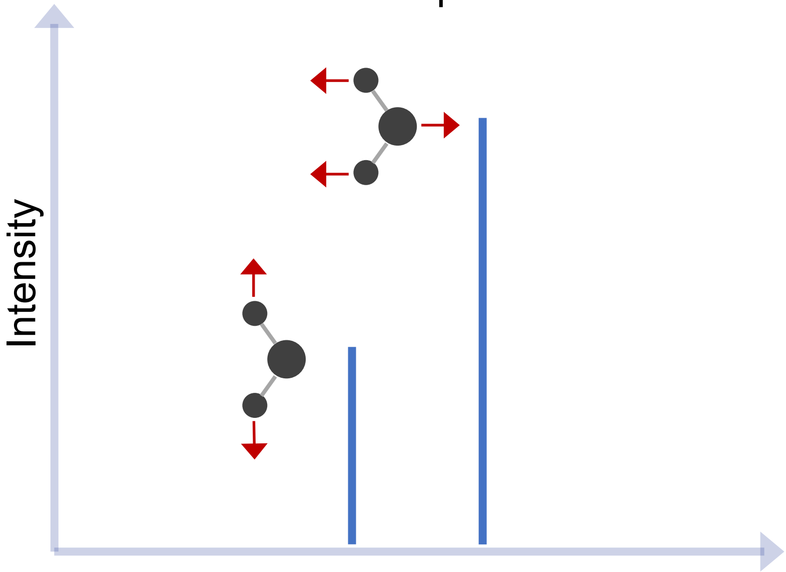
Raman spectroscopy is a powerful metrology that probes the vibrational modes of materials.

Raman Spectrometer

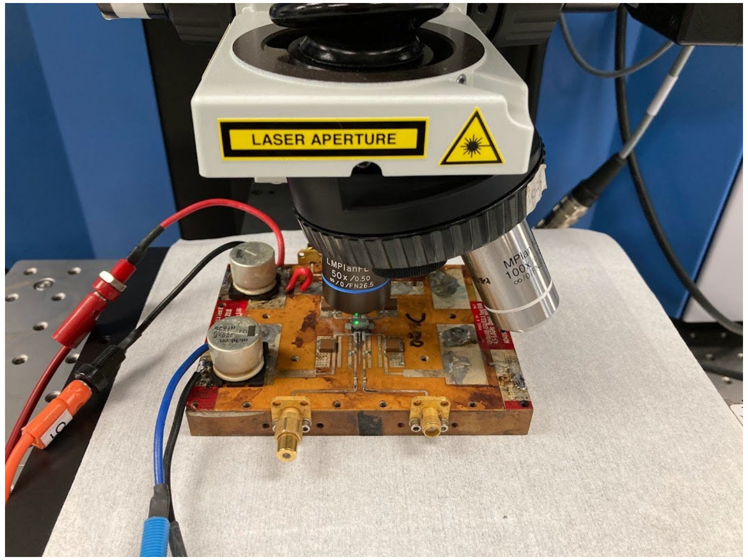


A ~ 600 nm optical laser beam that can be moved (or rastered) with nanoscale resolution and can see through transparent layers (like GaN, SiC, or oxides).

Raman Spectra



Applied Research



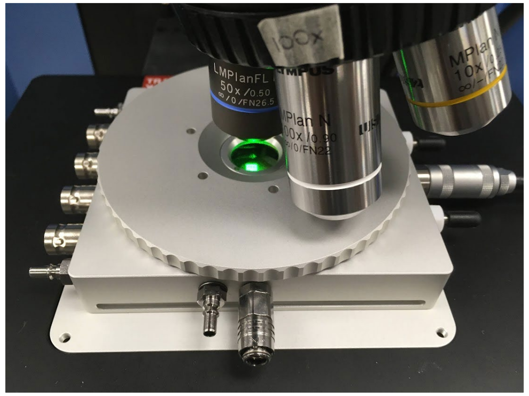
The peak intensity, width, and frequency can tell us:

- **temperature**
- composition
- defects
- strain

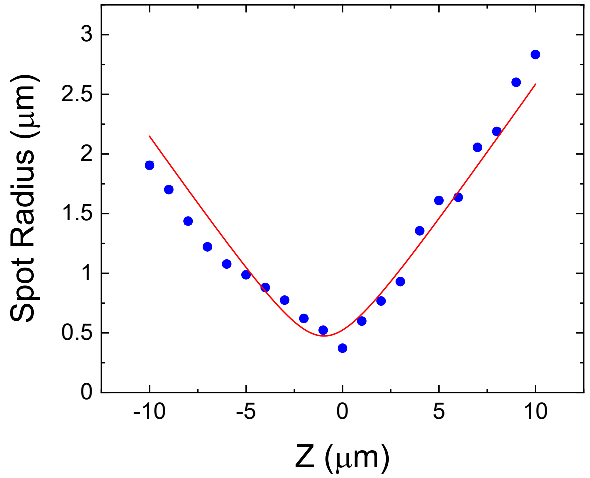
Raman Thermometry on Silicon

Raman thermometry is the method of using the Raman spectrum to characterize temperature (*T*).

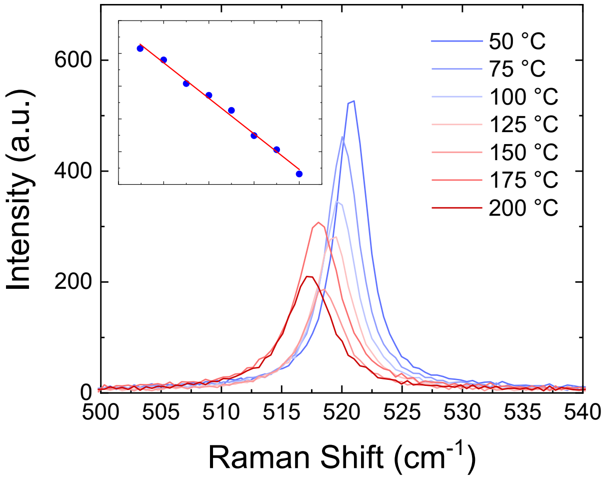
Thermal Stage



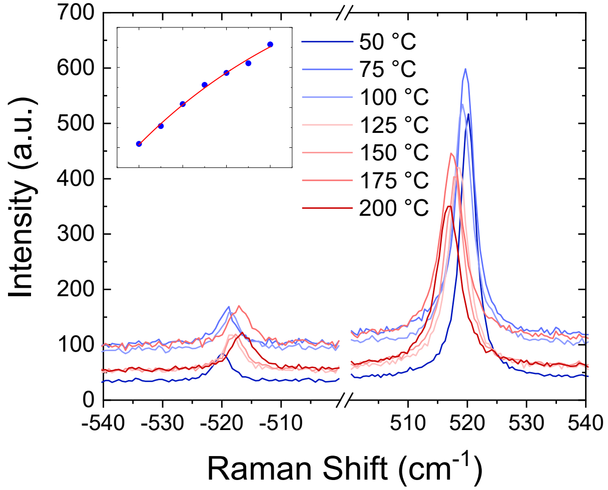
Beam Size Calibration



Peak Position vs. *T*

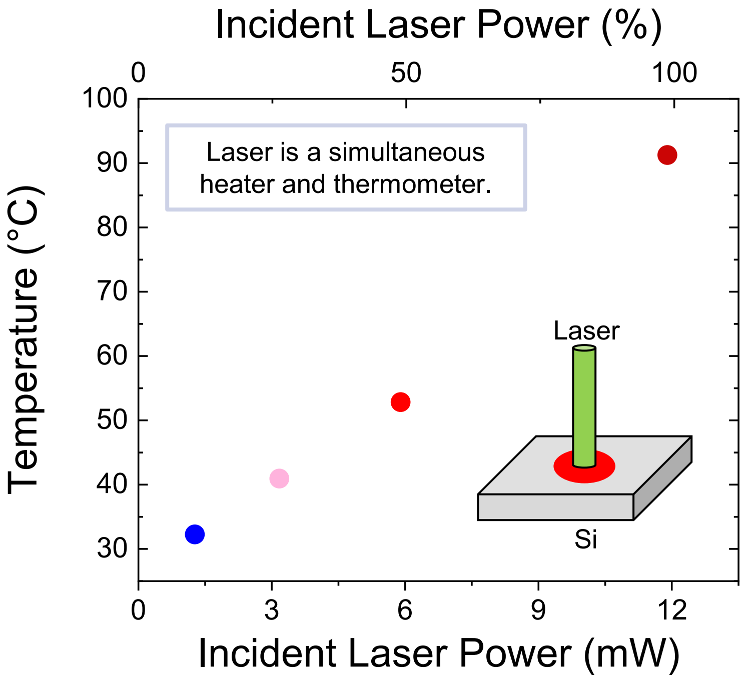


Peak Intensity vs. *T*

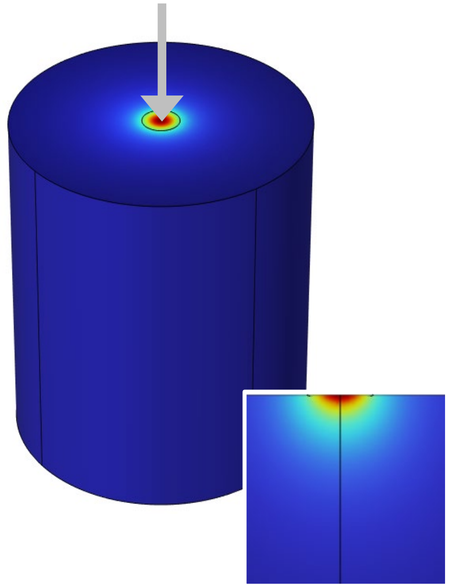


Raman-Based Thermal Conductivity Measurements

On materials with complex or delicate morphologies, Raman thermometry can be expanded to an optical thermal conductivity extraction.

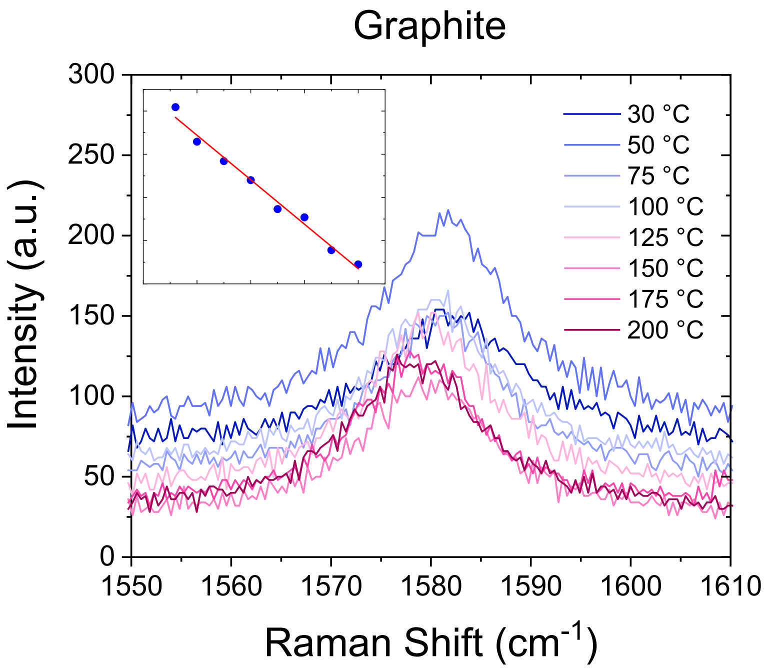


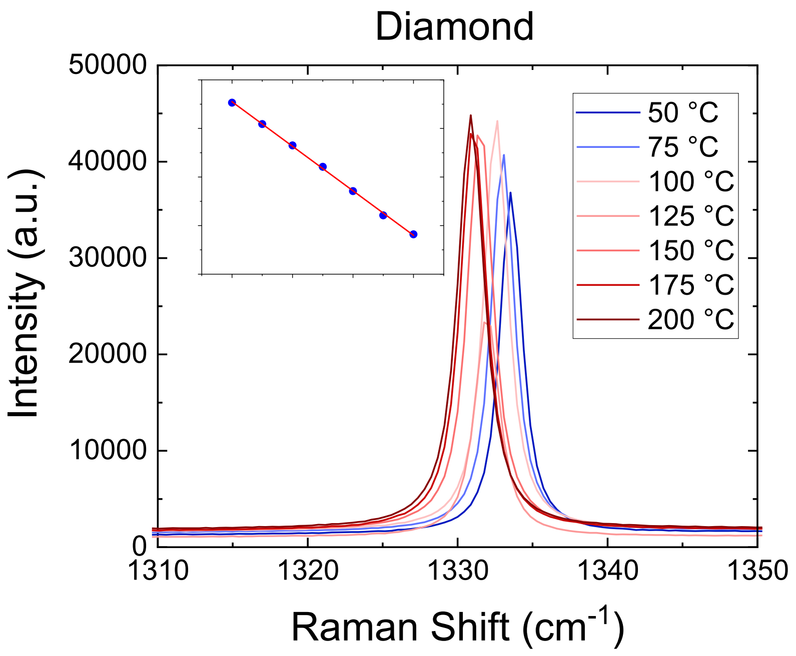
93 °C at 7.3 mW ∴ k ~ 140 W/mK



Calibrations on Carbon Materials

The temperature of graphite and diamond can be calibrated, providing a framework for investigating carbon-based thermal packaging.

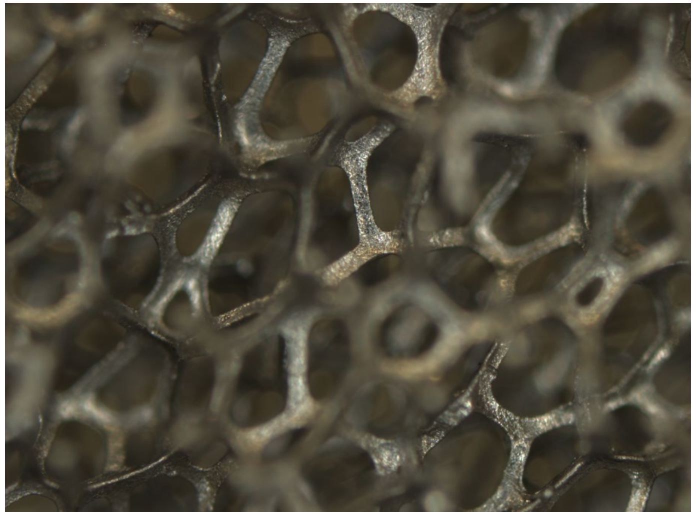




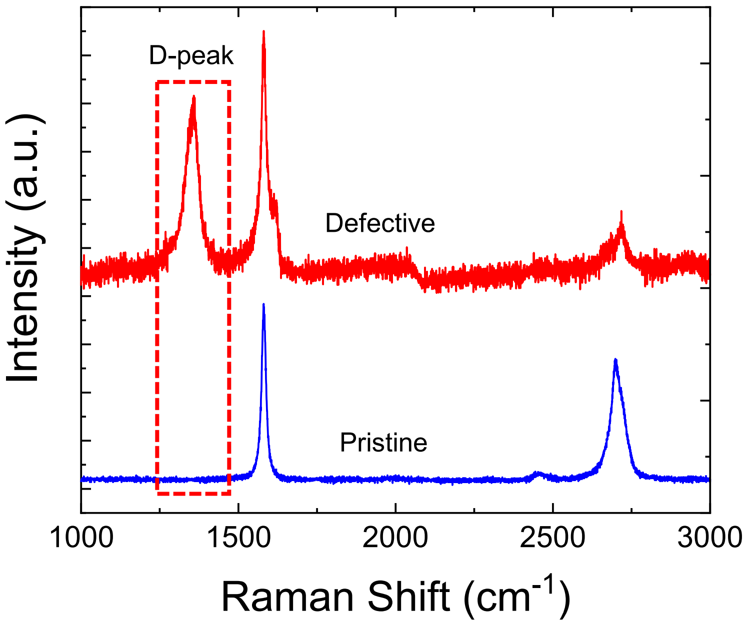
Thermal Conductivity vs. Structure and Chemistry

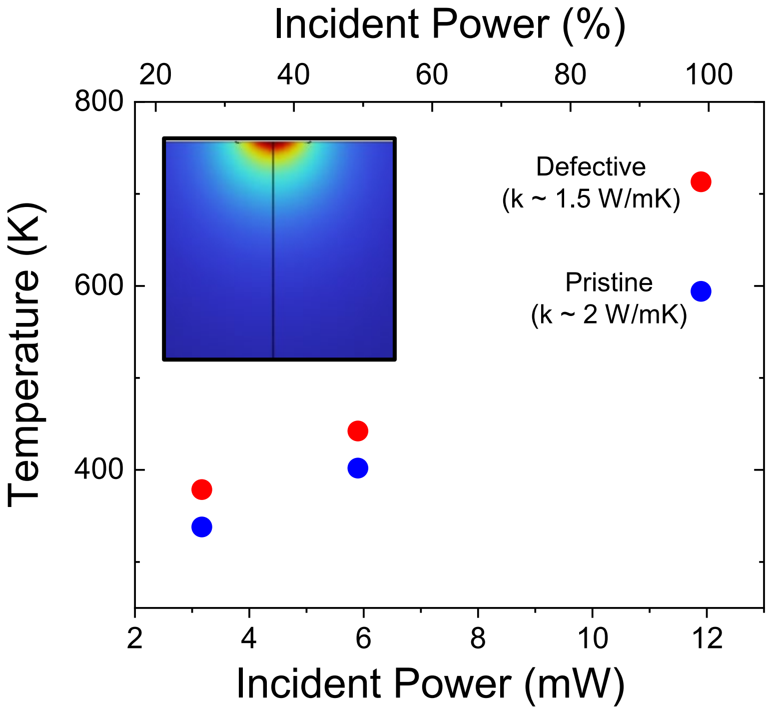
While temperature is characterized with peak shifts, peak broadening (or new peaks) can characterize the structure and chemistry.

Graphite-Metal Composite



Comparing Raman Spectra



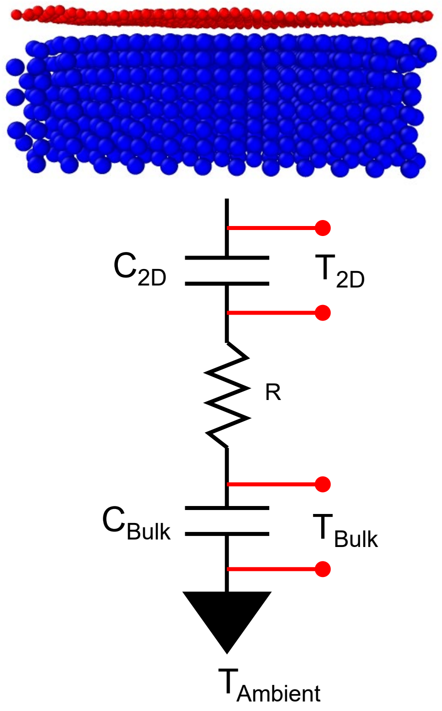


The Raman laser is now a simultaneous **heater**, **thermometer**, and **characterizer** of structural/chemical details!

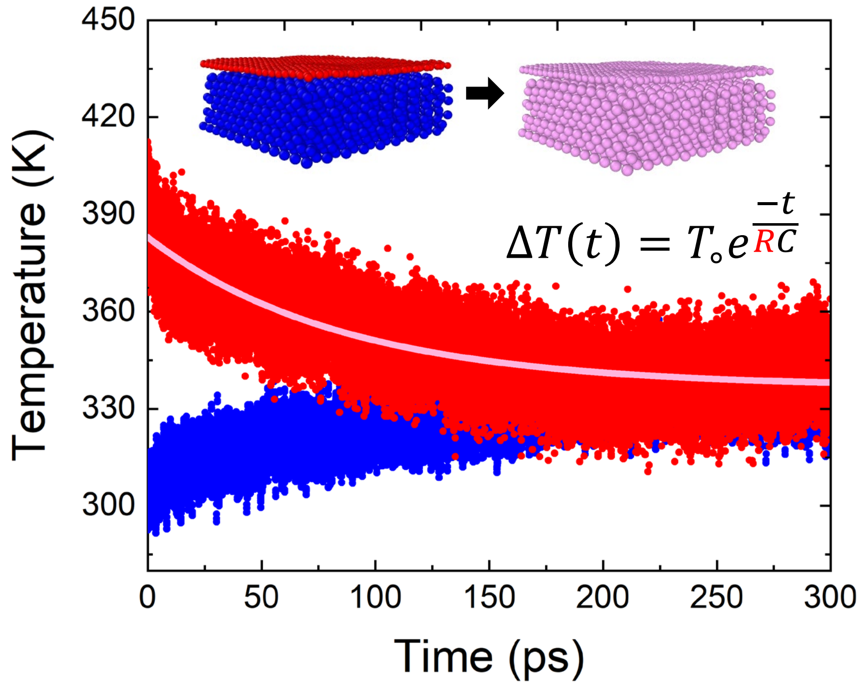
Molecular Dynamics Simulations

Raman thermometry can be coupled with molecular dynamics simulations to investigate the structure-(thermal) property relationships of interfaces.

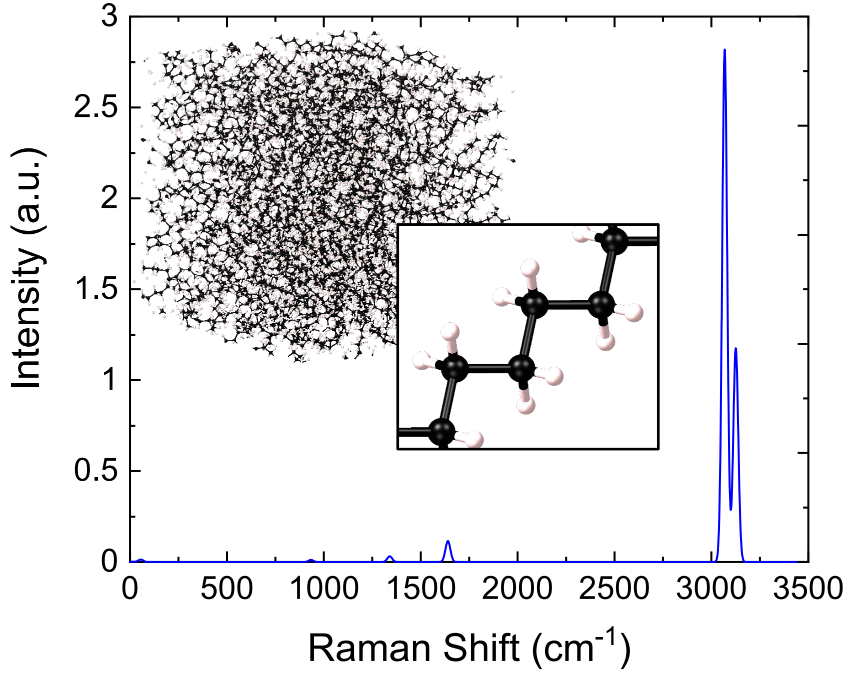
Equivalent Thermal Circuit



Approach to Equilibrium



Computing the Raman Spectra

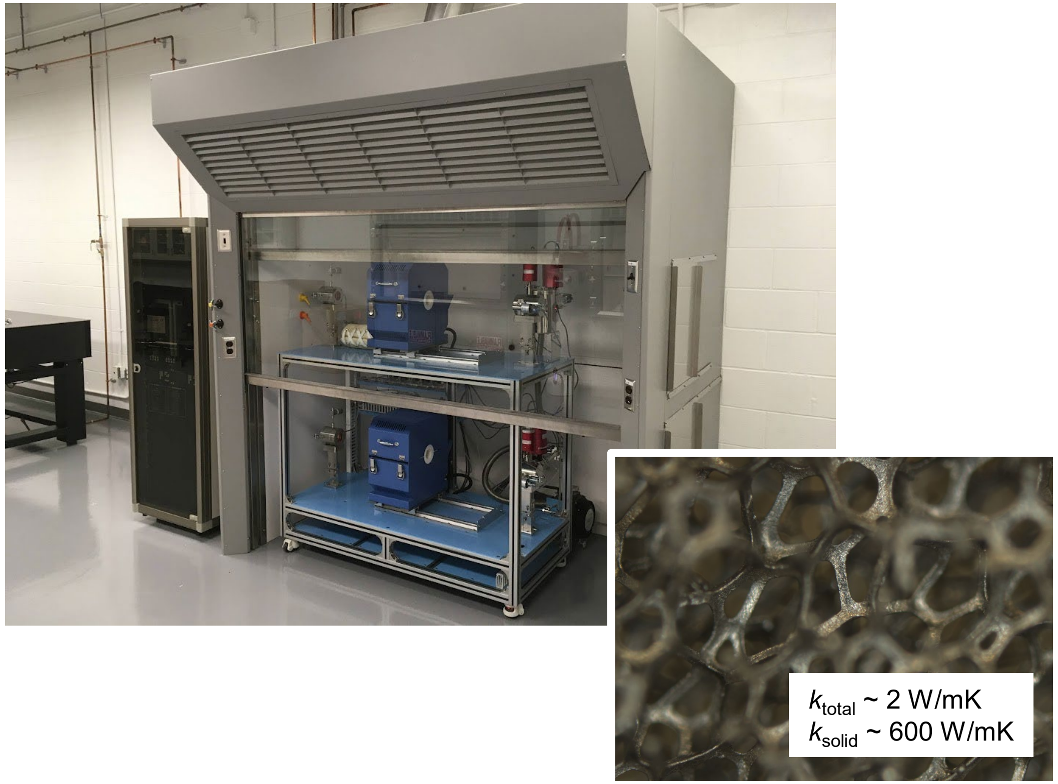


Promising Developments

There are a variety of promising avenues for carbon-based thermal packaging.

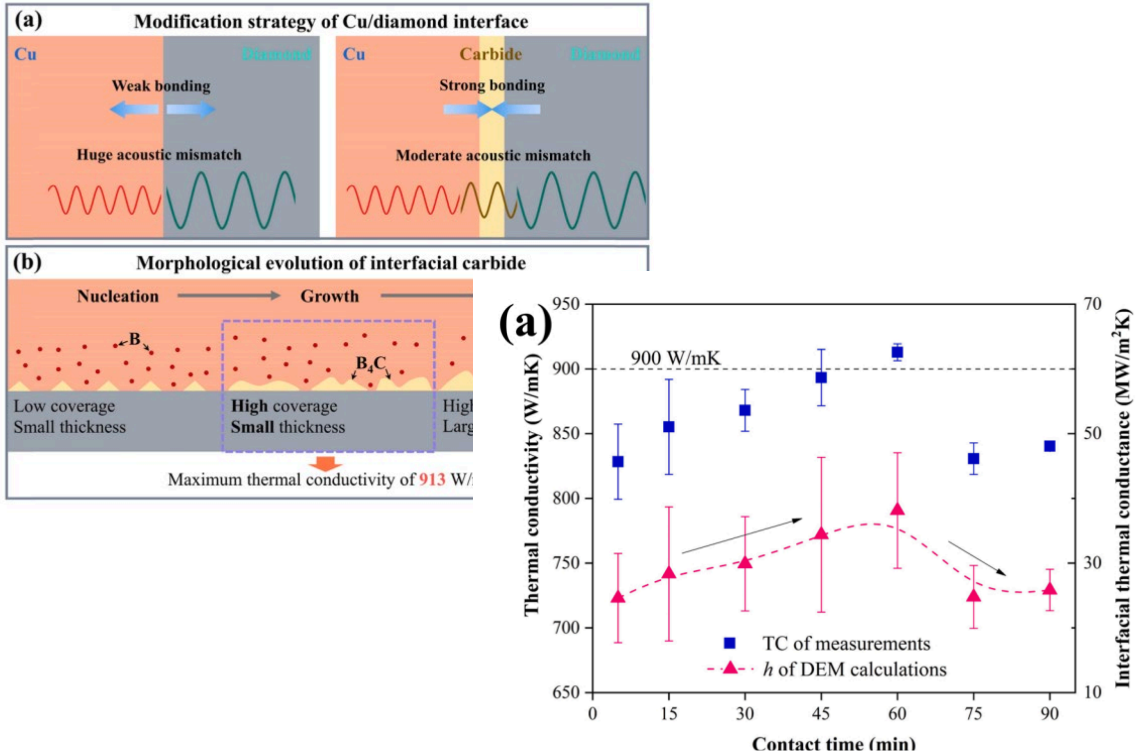
Graphene/Graphite Grown Directly on Metals

Templated Growth?



Successful Engineering of Carbon-Metal Interfaces

Interfaces can be controlled?



7. M. Pettes, et al., "Thermal Transport in Three-Dimensional Foam Architectures of Few-Layer Graphene and Ultrathin Graphite." Nano Letters 2012.
8. Y. Zhang, et al. Manipulating in-situ discrete carbide interlayer to achieve high thermal conductivity in Cu-B/diamond composites. Materials Today Communications 2022.

Takeaways and Future Work

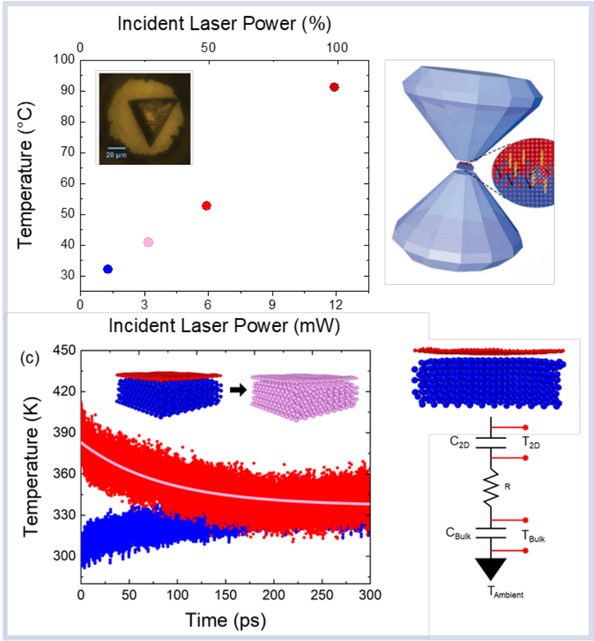
- **Power dissipation** will continue to be a major limiter of electron devices, and likely require packaging solutions.

- Materials with thermal conductivities of **~ 10^3 W/mK** are needed, and carbon-based materials are the best options

- Integration and assembly of carbon-based packaging materials are limited by **interfaces** and require new metrology and fabrication approaches.

Example Work from Our Lab

Tuning interfaces with extreme pressure (DACs)



Questions

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