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Carbon-Based Thermal Interface Materials for High-Power Device Packaging

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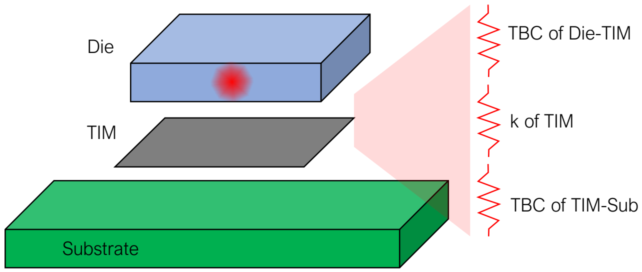
Problem

High-power devices, like high-frequency GaN and GaAs devices for communication, produce extreme thermal fluxes (Q) that must be sunk to the substrate via packaging to avoid degrading temperature rises.

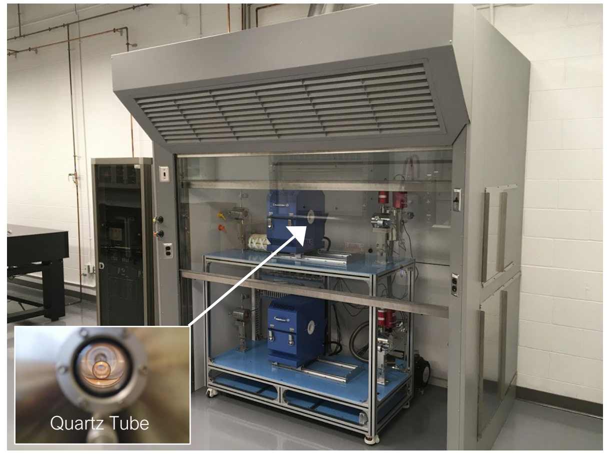


From Fourier's law, the temperature rise at the die is directly related to the thermal conductivity (k) of the thermal interface material (TIM) used as a die attach, as well as the thermal boundary conductivity (TBC) at the two interfaces.

$Q = k(\Delta T/L)$ where L is the TIM thickness

What materials can provide sufficient thermal conductivity while also satisfying the electrical and mechanical needs of the die attach?

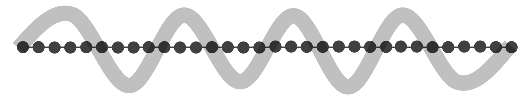
Producing Graphene

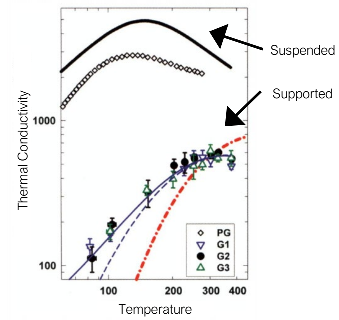


Large and continuous graphene sheets can be grown directly onto 3D metal templates using chemical vapor deposition (CVD). The metal can be chemically etched to produce freestanding graphene films.

Roadblock: Phonon Damping in Graphene

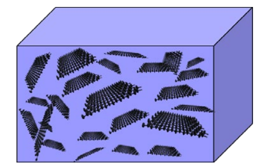
Unlike 3D materials, a significant part of graphene's thermal conductivity comes from out-of-plane flexural phonons (unique to 2D materials). These important vibrations can be dampened when touching other materials.





J. Seol, et al. Science 328 (2010).

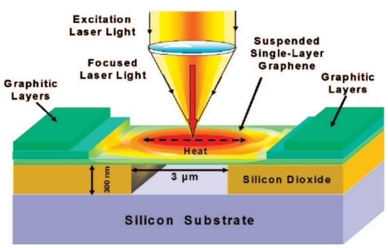
Simply placing a graphene on a substrate can reduce its thermal conductivity by 10X! Same phenomena occurs when mixing graphene flakes into composites.



Why Carbon Nanomaterials?

Despite their challenges, they are unmatched in regards to their intrinsic thermal, electrical, and mechanical properties, where they <u>outperform bulk metals by at least and order of magnitude</u>.

In nonmetals, the thermal conductivity is generally related to strength of the chemical bonds and mass of the atoms. The sp^2 hybridized bonds in graphene are among the strongest in nature and carbon is a relatively light atom…



A. Balandin, et al. Nano Letters 8 (2008).

Graphene: k ~5,000 W/mK*

compared with

Cu: k ~400 W/mK

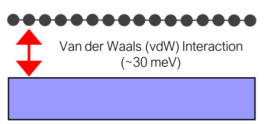
*Impractical amounts of care are taken to coax these values out of the material, like suspending it or working with isotopically pure samples.

Roadblock: Anisotropy in Graphene

While the in-plane thermal conductivity is excellent, it is extremely <u>difficult to get heat in or out of graphene</u> (i.e., poor cross-plane thermal conductivity). As such, there is nearly a 100X thermal anisotropy in the material.

The poor cross-plane thermal conductivity arises for two reasons.

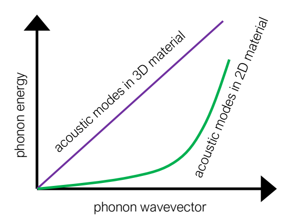
1. Weak Chemical Interaction



The chemically-inert surface of graphene interacts with other materials through a vdW interaction. This makes it difficult for phonons to interact between the two materials.

Weak Chemical Interaction
↓
Weak Phonon Coupling
↓
Low Cross-Plane k

2. Mismatched Phonon Modes



2D materials, like graphene, vibrate differently from 3D materials. This makes it difficult for the acoustic phonons that carry heat to move between 2D and 3D materials

Mismatched Phonon Modes
↓
Phonon Reflection
↓
Low Cross-Plane k

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Engineering Avenues

We are exploring a variety of methods of overcoming these roadblocks.

1. Pressure – Using pressure to hybridize the phonon modes between the 2D graphene and the 3D host material
2. Templated Growth – CVD of graphene on Cu templates to ensure the orientation and density of graphene in the TIM, while also allowing us to remove the metal and leave freestanding graphene with undamped phonon modes
3. Metal-Graphene Contact Engineering – Adjusting the metal deposition method to tailor defects at the interface, which can promote a more intimate contact (reducing the vdW gap) and relax phonon wavevector conservation rules.