Practical application of Graphene for Thermal Management

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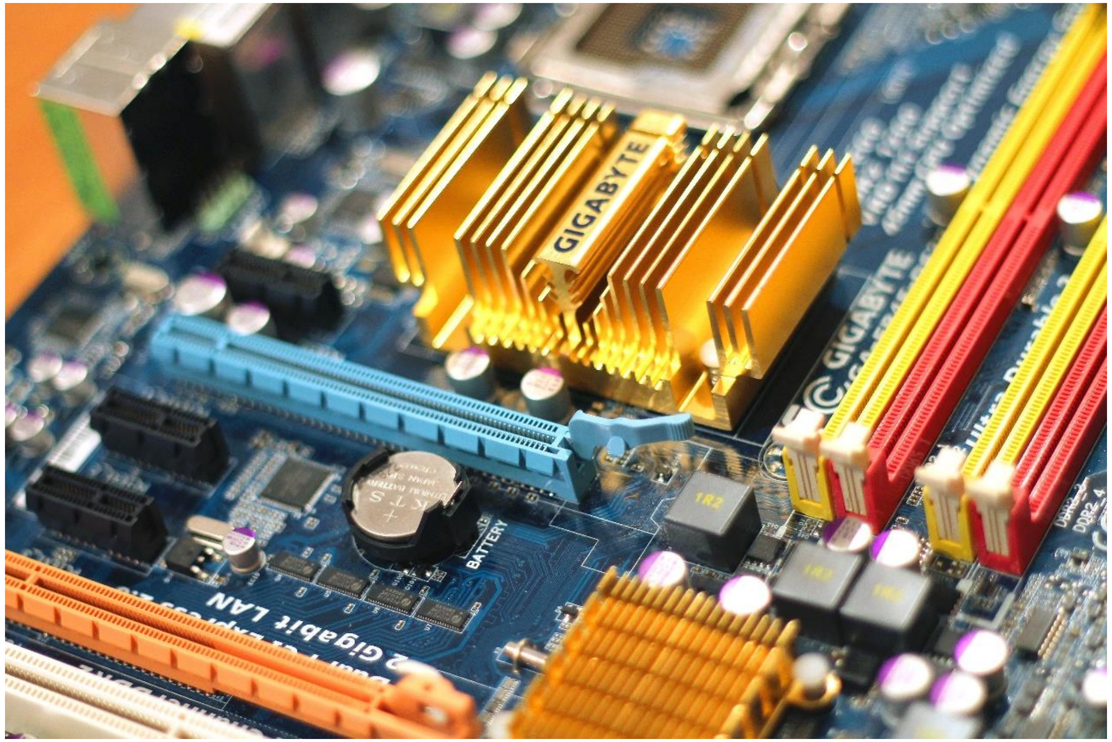
20220426

Thermal management



In the last decades the power density in microsystem has incresed strongly, due to:

- Higher complexity
- Smaller dimension

Fans, heat sinks, and heat pipes are all examples of hardware that have been employed over the years.

To address smaller electronic devices and ones that have multiple interfaces, heat spreader and thermal interface materials are needed.

Contents

- Heat spreader and thermal interface material
- Thermal performance of Graphene
- Graphene for heat spreading
- Graphene as thermal interface material

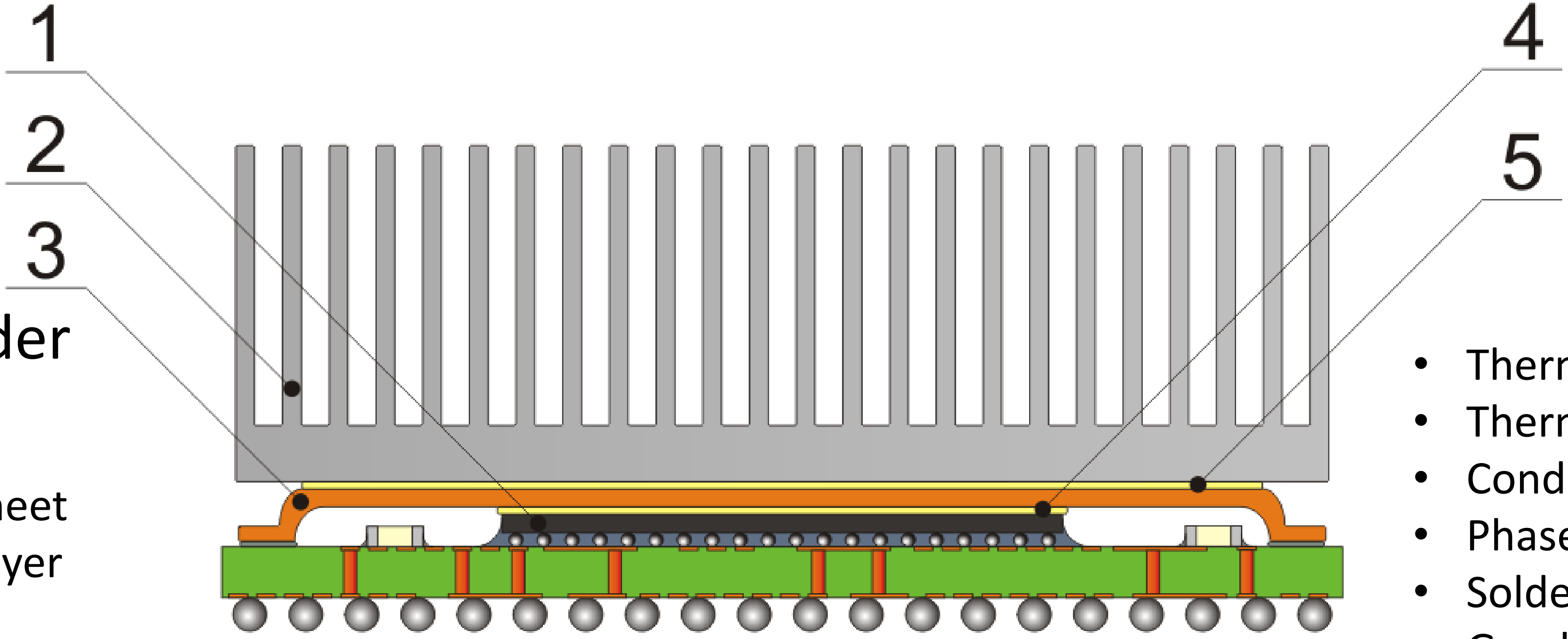
Thermal interface material and heat spreader

Die

Heat Sink

Heat Spreader

- Cu, Al plate
- Graphite sheet
- Diamond layer



TIM1

TIM2

- Thermal paste
- Thermal pad
- Conductive adhesive
- Phase change material
- Solder-based material
- Graphite sheet

Generic BGA package illustrating the basic Microelectronic components

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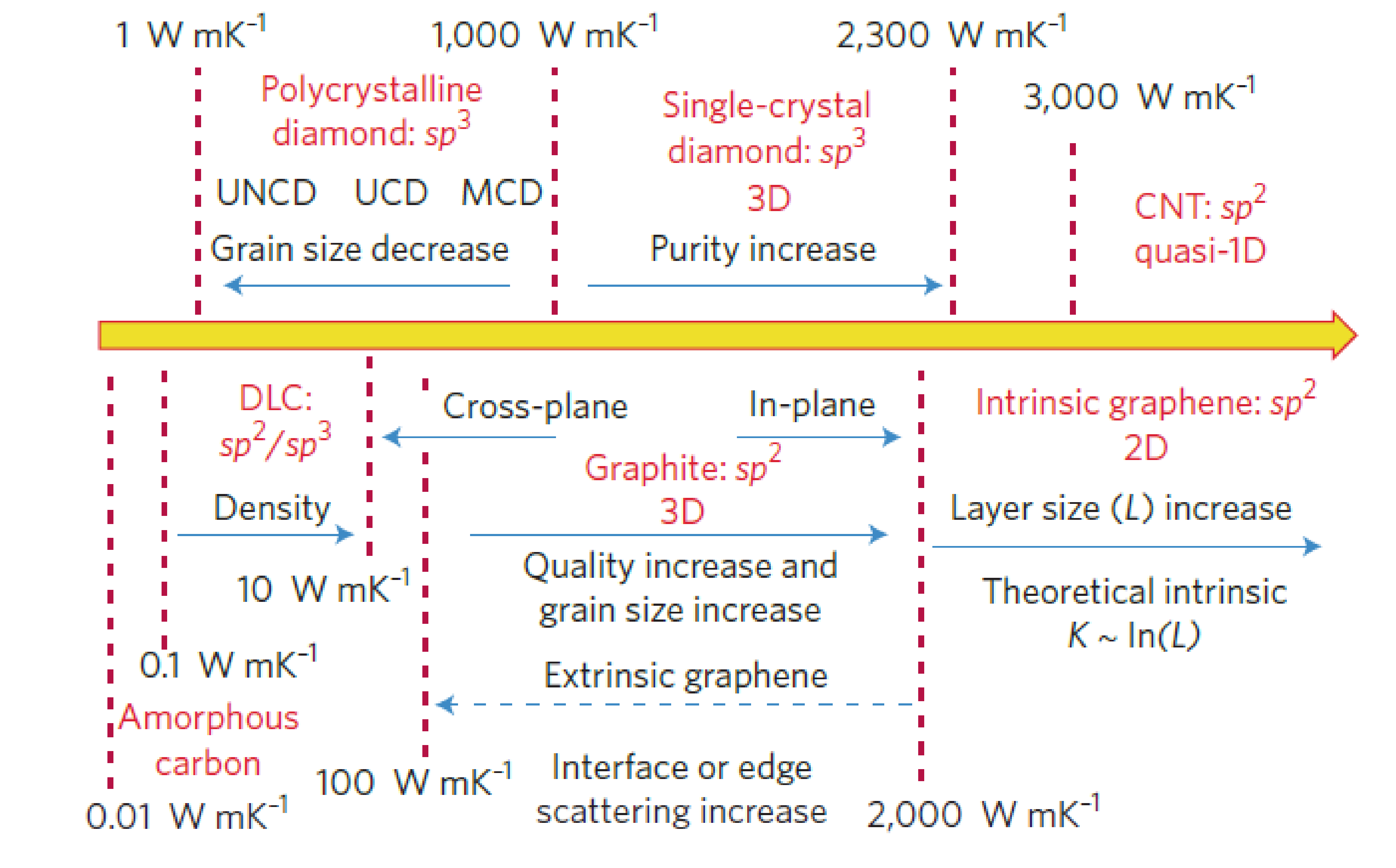
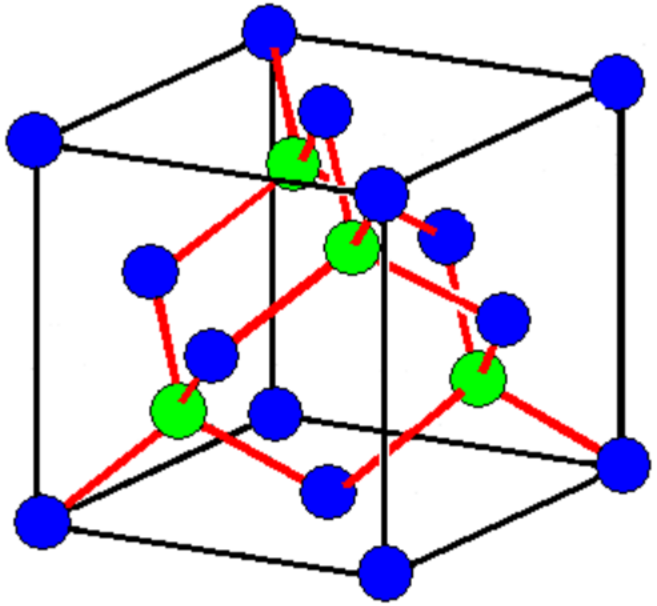
Thermal properties of carbon allotropes and their derivatives

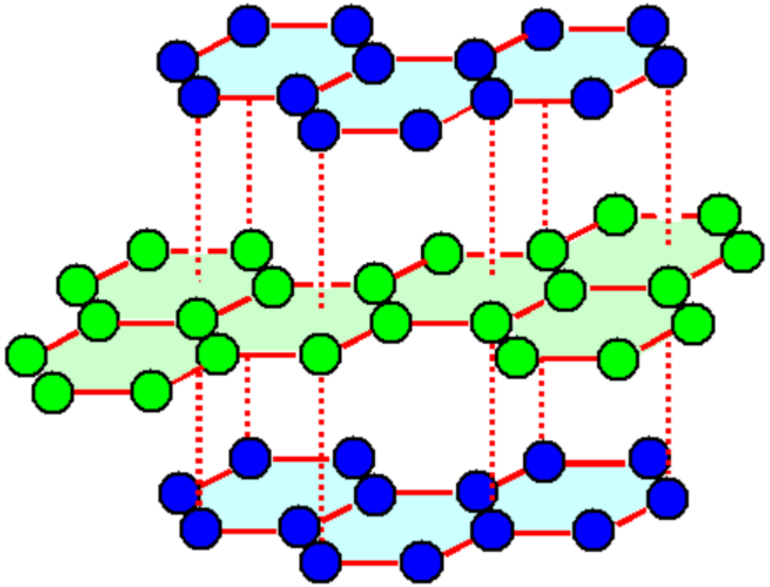


A. A.Baladin, Nature Mater., 10, 569, 2011.

Diamond and Graphite

- Crystal structure of diamond and graphite





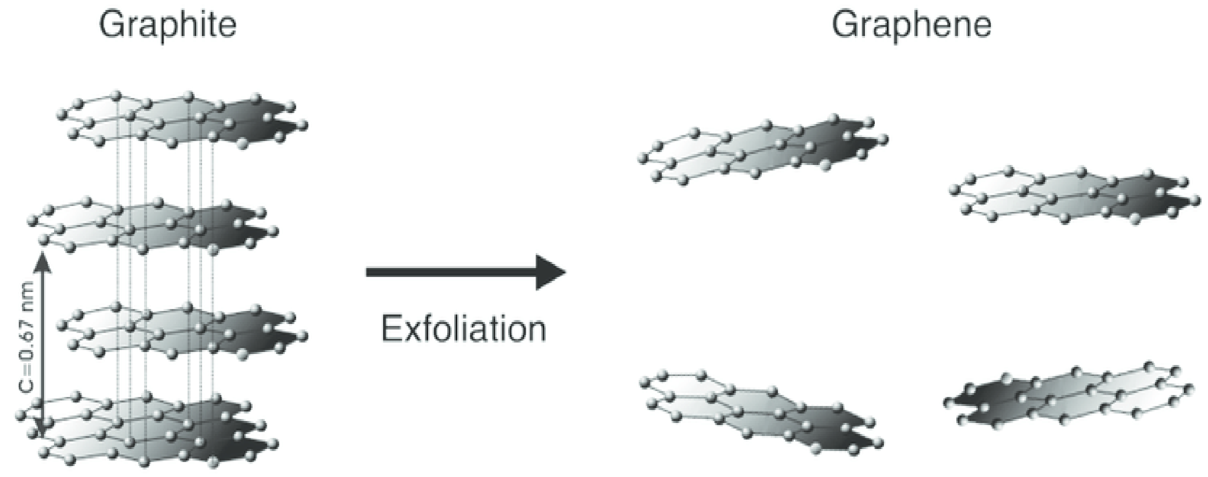
- Thermal property of diamond and graphite

    - ❖ Isotropic
    - ❖ 2300 W/(m·K) at room temp. for single crystal

    - ❖ Anisotropic
    - ❖ 1950 W/(m·K) at room temp. along in-plan direction for highly orientated pyrolytic graphite sheet (HOPGS)

What is graphene?

- Graphene is a two-dimensional atomic crystal made up of carbon atoms arranged in a hexagonal lattice.



- Monolayer
- Bilayer
- Multilayer (3-10 layers)

- GO- graphene oxide
- rGO- reduced graphene oxide
- FG(O) – functionalized graphene (oxide)

Graphene Related Materials (GRMs)

Mechanism behind super thermal conductivity of graphene

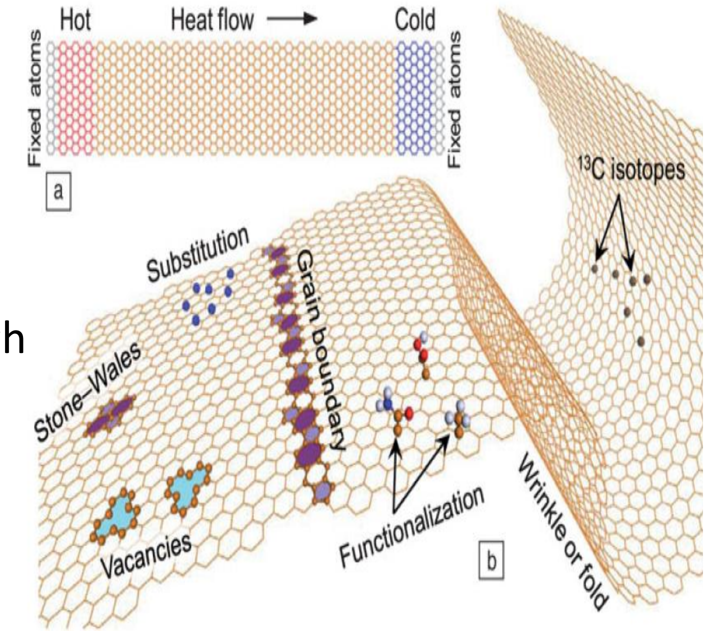
- In solid materials heat is carried by lattice vibration and free electrons, $K = K_p + K_e$, where K_p and K_e are the phonon and electron contributions, respectively.

- In metals, K_e is dominant owing to large concentrations of free carriers. Measurements of the electrical conductivity (σ) define K_e via the Wiedemann–Franz law, $K_e/(\sigma T) = \pi^2 k_B^2/(3e^2)$, where k_B is the Boltzmann constant and e is the charge of an electron.

- In carbon material, heat is usually dominated by phonons. For graphite, high in-plane thermal conductivity is due to covalent sp^2 bonding between carbon atoms, whereas out-of-plane heat flow is limited by weak van der Waals coupling (phonon umklapp scattering).

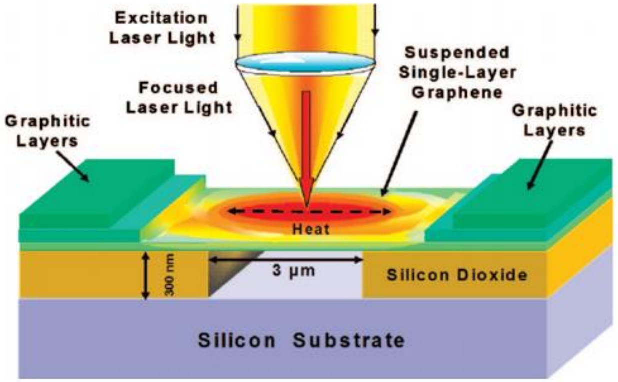
- Phonons can scatter on many different things: crystal defects, impurities, crystal boundaries, even other phonons.

- In monolayer graphene, the heat transfer is limited by the edge boundary scattering, and the phonon umklapp scattering is quenched.



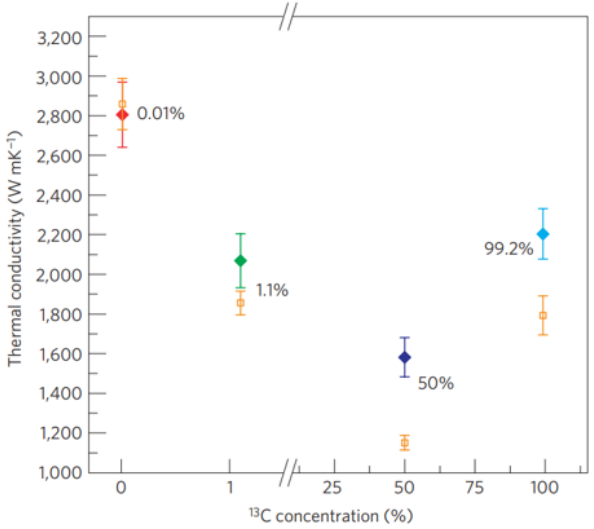
E. Pop, MRS Bullitin, 37, 1273, 2012.
S.Ghosh, Nature Mater. 9, 555, 2010.

Monolayer and multilayer graphene - Thermal property



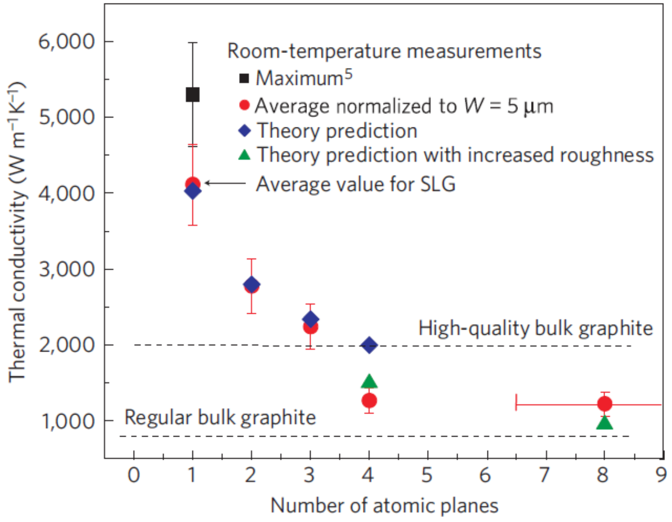
- Confocal micro-Raman spectroscopy
- The mechanical cleavage of bulk graphite
- K = 4840 to 5300 W/m·K

Alexander A. Balandin, Suchismita Ghosh, Wenzhong Bao, Irene Calizo, Desalegne Teweldebrhan, Feng Miao, and Chun Ning Lau, Nano Letters, 2008, 8, 902.



- High-quality monolayer CVD graphene
- The characteristic grain size ~200 μm
- Max K =4,120±1,410 W/m·K (Tm ~ 320 K)
- Avg K=2,805 W/m·K (Tm ~ 380 K)

Shanshan Chen, Qingzhi Wu , Columbia Mishra, Junyong Kang, Hengji Zhang, Kyeongjae Cho, Weiwei Cai, Alexander A. Balandin and Rodney S. Ruoff, Nature Material, 2012, 11, 203.



- The mechanical cleavage of bulk graphite
- Thermal conductivity changes from 2,800 to 1,300 W/m· K as the number of atomic planes increases from 2 to 4

S. Ghosh, W. Bao, D.L. Nika, S. Subrina, E. P. Pokatilov, C-N Lau and A. A. Balandin, nature Materials, 9, 555, 2010

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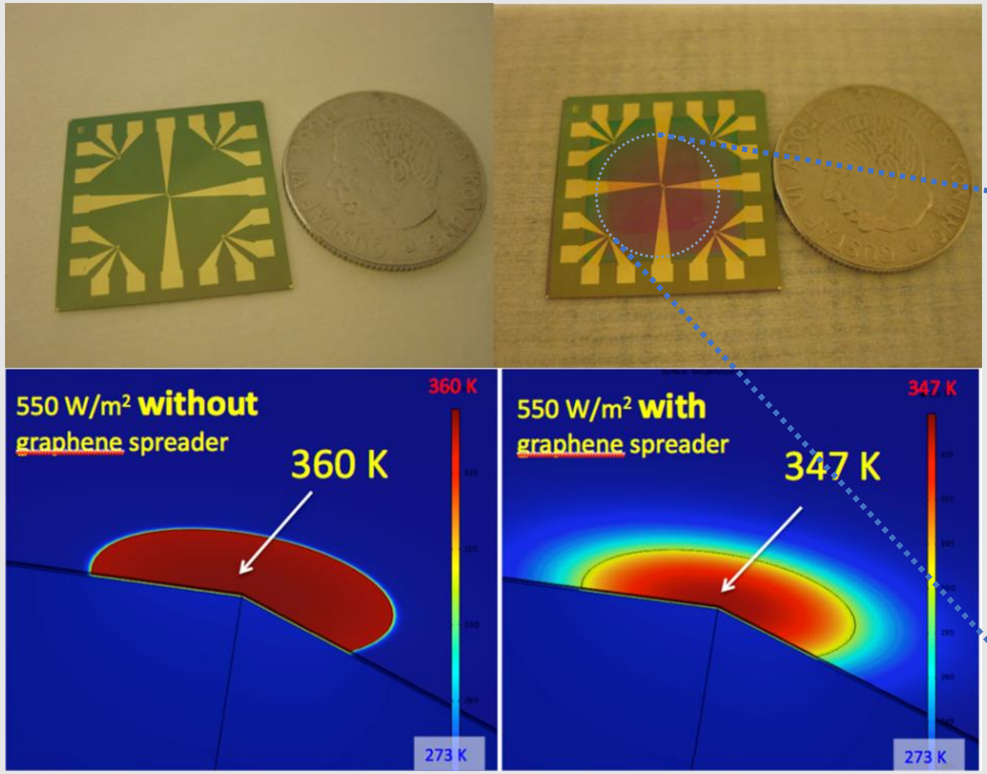
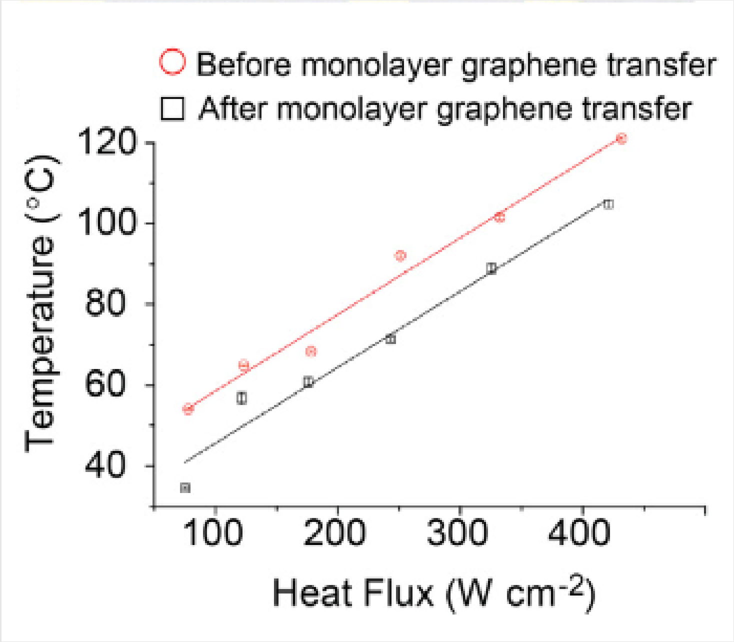
CVD graphene as heat spreader

As heat spreader, graphene can distribute heat generated from hot spots along its radial direction efficiently.

Potential challenges

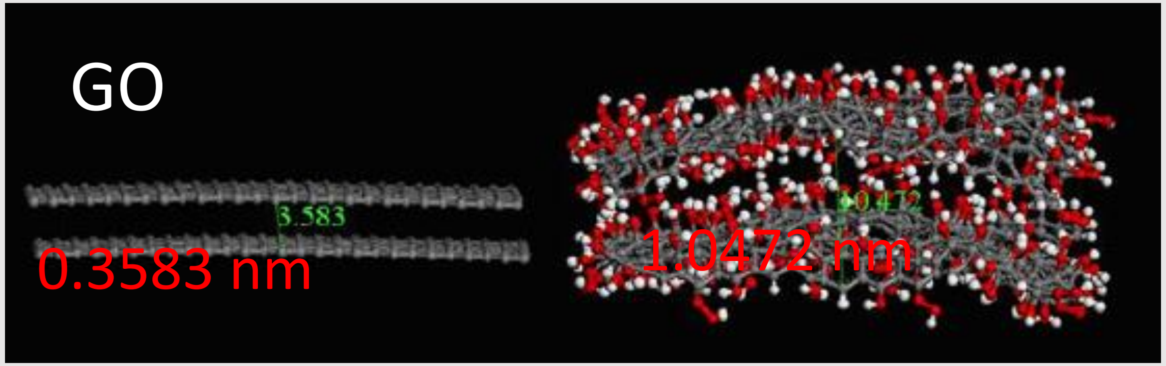
- Complexity of transfer process
- Relatively high cost
- Relatively low heat flux allowed to be dissipated

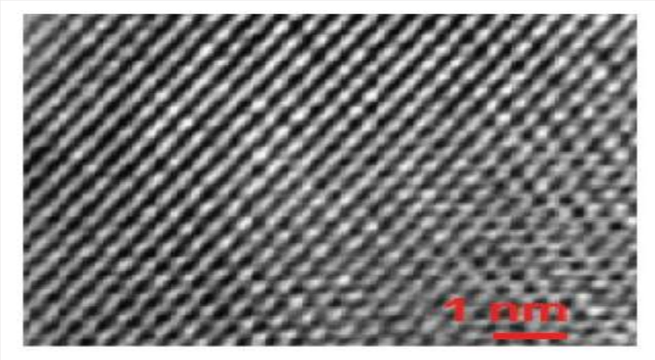


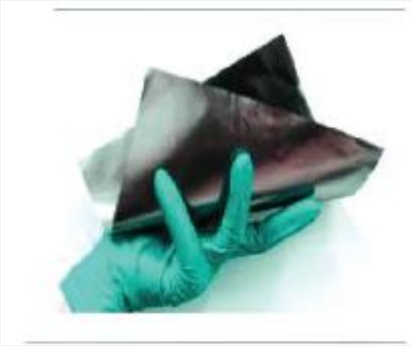


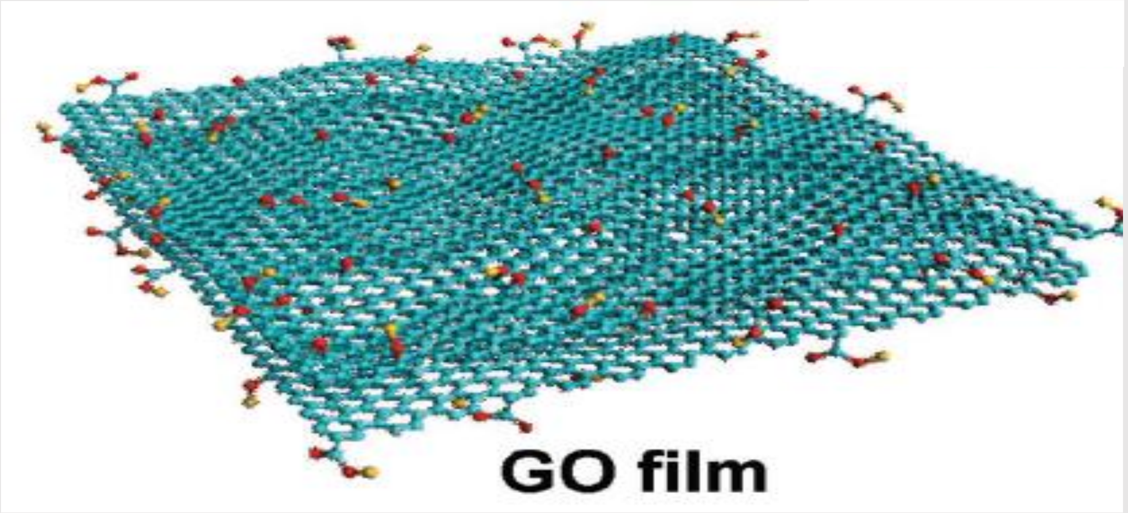
Z. Gao, Carbon, 61, 342, 2013.

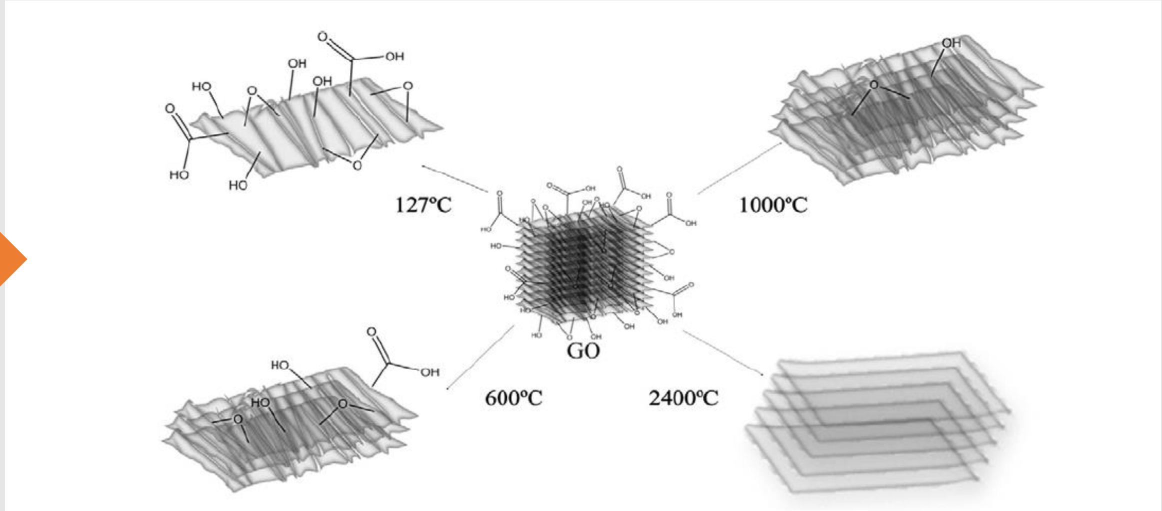
Graphene paper as heat spreader





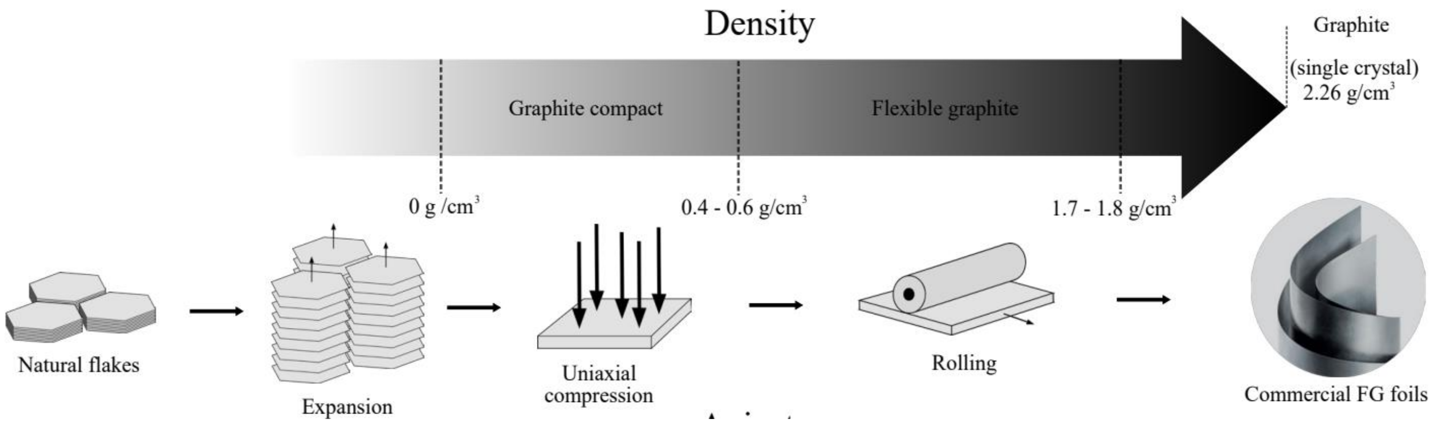






C. Botas, et al., Carbon 52 (2013) 476.
L. Peng, Adv. Mater. 1700589, 2017.

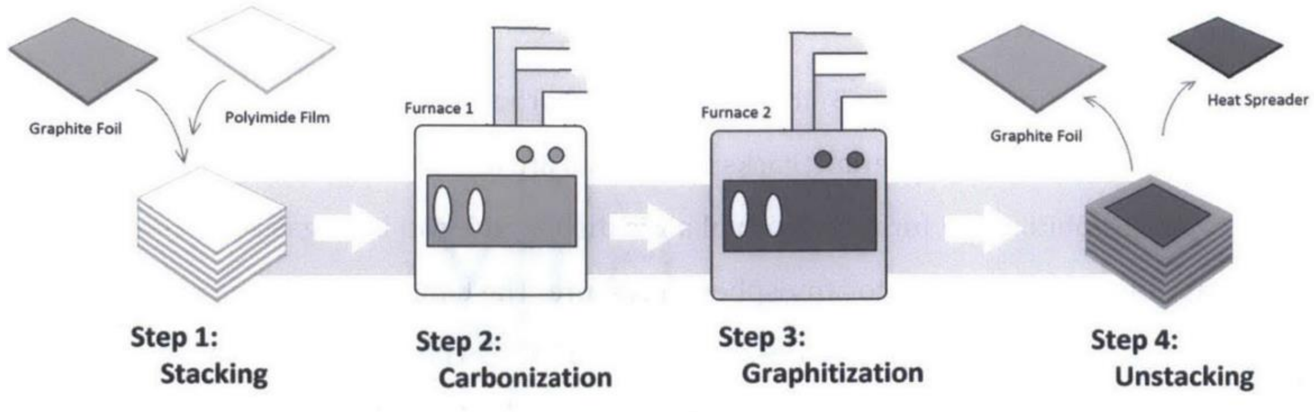
Graphite sheet/paper



- Tensile strength: ~10 MPa
- In-plane thermal conductivity: < 500 W/m·K
- Through-plane thermal conductivity: <10 W/m·K

E. Sofilti, Procidia Struct. Integrity, 26, 187, 2020

Graphite sheet from pristine graphite



- Tensile strength: ~25 MPa
- In-plane thermal conductivity: < 2000 W/ m·K
  Through-plane thermal conductivity: 5-10 W/ m·K

Pyrolytic graphite production : automation of material placement, 2014

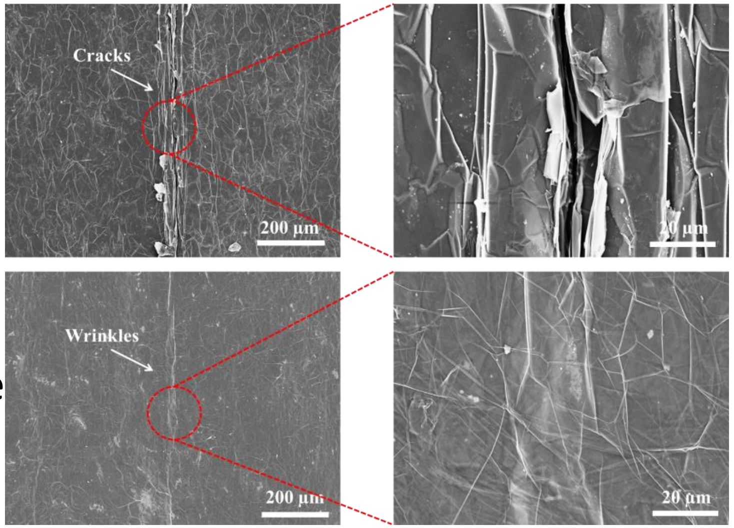
Pyrolytic graphite sheet (PGS)

Benefit of Graphene paper

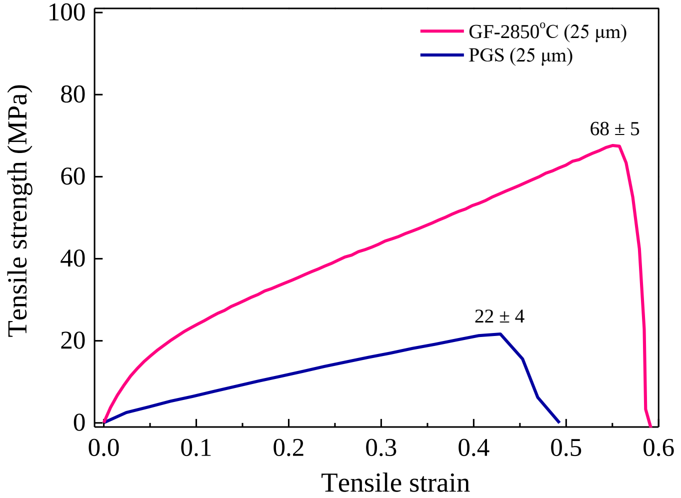
Folding reliability

PGS

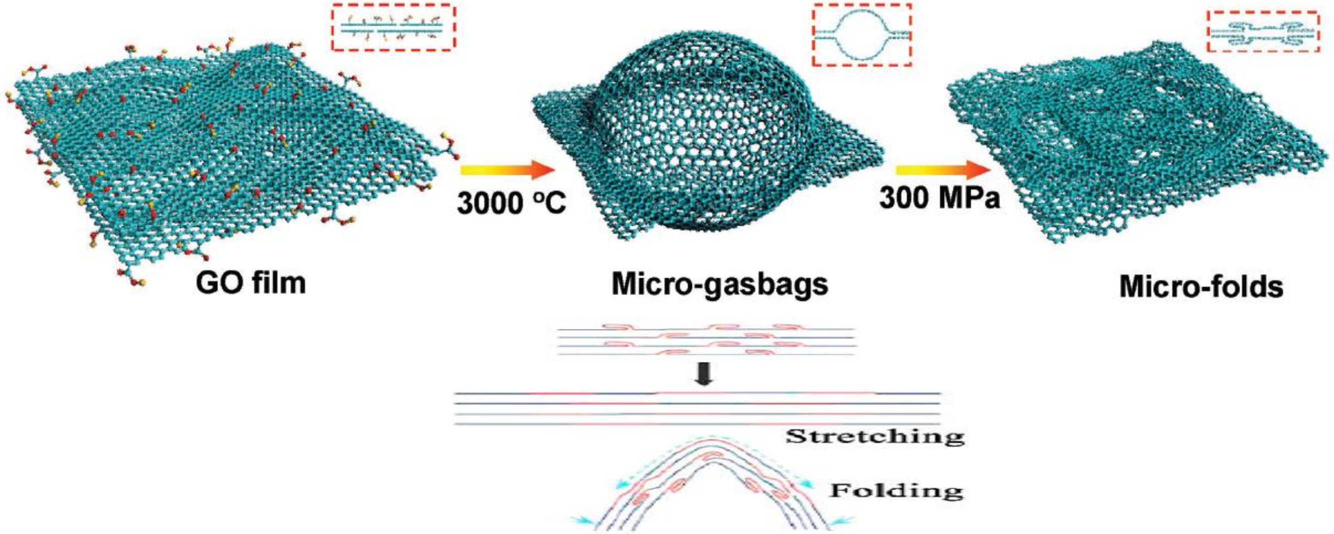
Graphene paper



Tensile strength



Introduction of microfolds to graphene paper



Schematic illustration for transforming GO film with abundant defects into recovered, defect-free graphene gasbag, and then highly flexible graphene sheet composed of folded graphene.

N. Wang, Small, **14**, 1801346, 2018.

L. Peng, Adv. Mater. 29, 1700589, 2017.

Graphene for cooling in the market

Graphene cooling in Smartphone

The Huawei Mate 20 X has applied graphene paper in its 'super cool system'.

https://www.techradar.com/news/dummy-40-ways-graphene-is-about-to-change-your-life

The Elesia Air Cooling Unit

Nanesa are using aluminium foam slices covered with a graphene-copper coating in evaporator and condenser unit.

Graphene Products | Graphene Flagship (graphene-flagship.eu)

AIR COOLING UNIT – Elesia

Thermal strap

Graphene thermal strap produced by Technology Application, Inc., is being tested in spaceflight by NASA.

X-Series® Thermal Straps - PGF & Graphene Foil (techapps.com)

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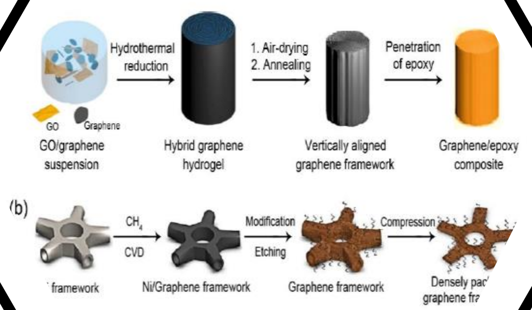
Dispersed Graphene/Polymers

- In earlier research, graphene was dispersed into a polymer matrix.
- To get the desired thermal conductivity beyond conventional TIMs (5 W/mK), 20–50 wt % of graphene loading in polymer is essential.
- Such high graphene content usually results in high viscosity and poor mechanical properties, hardly meeting the demands for practical applications.

Filler	Matrix	κ (W/mK)	Fraction	Yea
Graphite nanoplatelet	Epoxy	6.44	≈34 wt %	2007 [14,
Functionalized exfoliated graphite	Epoxy	5.80	20 wt %	2008 [15]
Graphene + CNT	Epoxy	0.32	1 wt %	2011 [16]
Graphene + Multilayer graphene	Epoxy	5.10	≈15 wt %	2012 [7]
Graphene + CNT	Epoxy	7.30	50 wt %	2012 [17]
Functionalized graphene flakes	Epoxy	1.53	10 wt %	2013 [18]
Graphene nanoflake	Polytetrafluoroethylene	10.00	≈24 wt %	2015 [19]
Graphene nanoplatelets	Polycarbonate	7.30	20 wt %	2016 [20
Multilayer graphene	Epoxy	1.50	5.7 wt %	2016

Graphene Framework/Polymers



- In recent years, the penetration of polymers into three-dimensional graphene frameworks has been considered as a promising solution to develop composites with improved thermal conductivity for TIM applications.

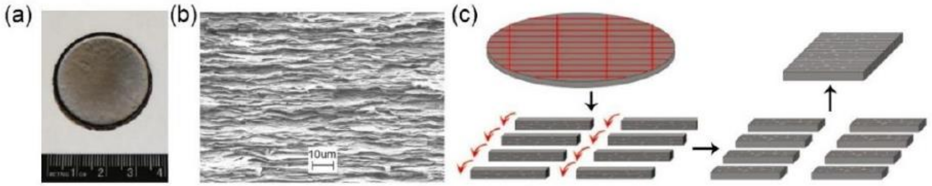
- So far, the approaches for the fabrication of a graphene framework can be mainly classified into two categories, the self-assembly method and the template-synthesis method.

- Graphene frameworks/polymers exhibit relatively higher thermal conductivity in comparison to their dispersed graphene/polymer counterparts at a similar filler content.

Filler	κ (W/mK)	Fraction	Form	
Graphene aerogel	2.13 (⊥) 0.63 (//)	≈1.4 wt %	Hard bulk	2014
Filtrated graphene framework	16.7 (//) 5.44 (⊥)	≈11.8 wt%	Hard bulk	2014 [29]
Templated graphene framework	1.51	5 wt%	Hard bulk	2016 [30]
Templated graphene framework	8.80 (//) 2.00 (⊥)	8.3 wt%	Hard lamella	2018 [25]
Filtrated graphene framework	10.0 (//) 5.40 (⊥)	5.5 wt%	Hard bulk	2018 [31
ertically aligned graphene framework	17.2 (//) 35.5 (⊥)	≈33 wt%	Hard bulk	201

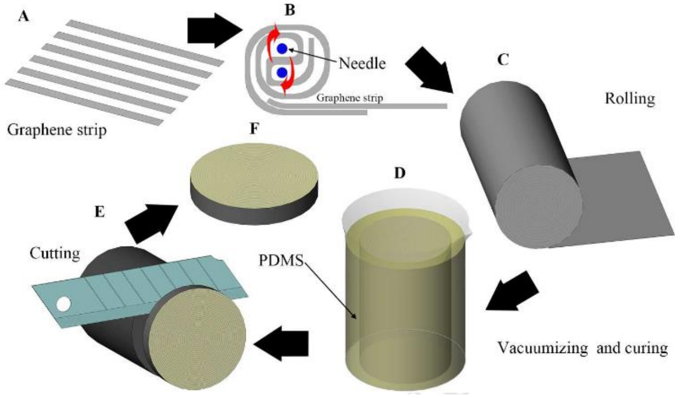
⊥: through-plane thermal conductivity, //: in-plane thermal conductivity.

Graphene-Based Monoliths



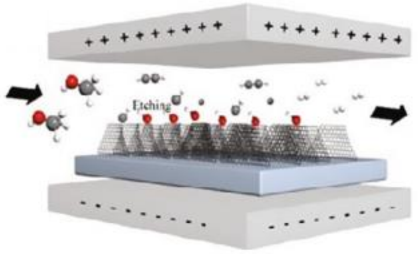
Vertically aligned graphene sheets, which was constructed via “rotating-reassembling” as-prepared graphene paper. With an indium coating on the surface, the obtained sample presents an equivalent through-plane thermal conductivity of 75.5 W/m·K and contact thermal resistant of 5.1 Kmm^2/W.

Q. Liang et al., ACS Nano 5, 2392, 2011.



Graphene sheets were rolled to form a cylinder. After dipping into PDMS and vacuum drying, the cylinder was cut into desired thickness for construction of TIMs. Through-plane thermal conductivity of 614.85 W/m·K.

Y. F. Zhang, et al., Carbon, 109, 552, 2016.

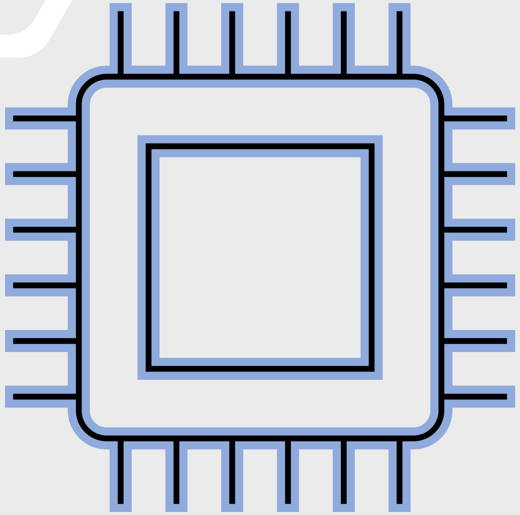


DC-PECVD to grow vertical graphene. The orderly arrangement of the fully erected sheets endowed the vertical graphene arrays with excellent thermal properties, with 53.5 W /m·K and a low contact resistance of 11.8 K/ mm^2 W .

S. C. Xu, et al., Adv. Funct. Mater. 30, 2003302, 2020.

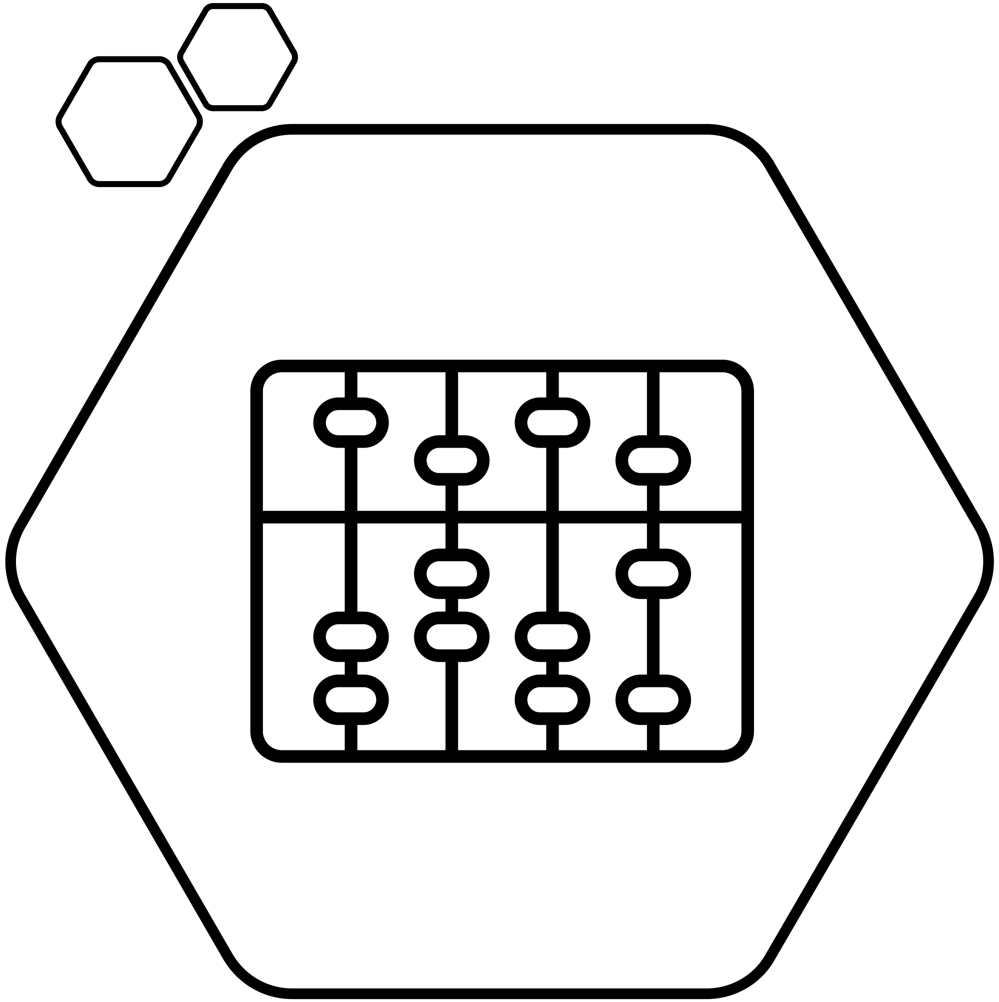
Challenges for framework/vertically aligned graphene as thermal interface material

- Graphene framework needs reversible deformation for maintaining high thermal conductivity while under packaging.
- Soft elastomer as matrix is required for good gap filler and decrease contact resistance.
- The samples ease of crushing and dropping out after compression, owing to the poor binding force of graphene layer structure. The slight dusting of carbon powder may cause a short circuit or contaminate some precision microelectronic and optoelectronic devices.



Summary

- Superior thermal conductivity
- Lightweight
- Flexible
- Versatile and efficient
- Durable and stable



Thank you!

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