Graphene:
Applications in Thermal Management

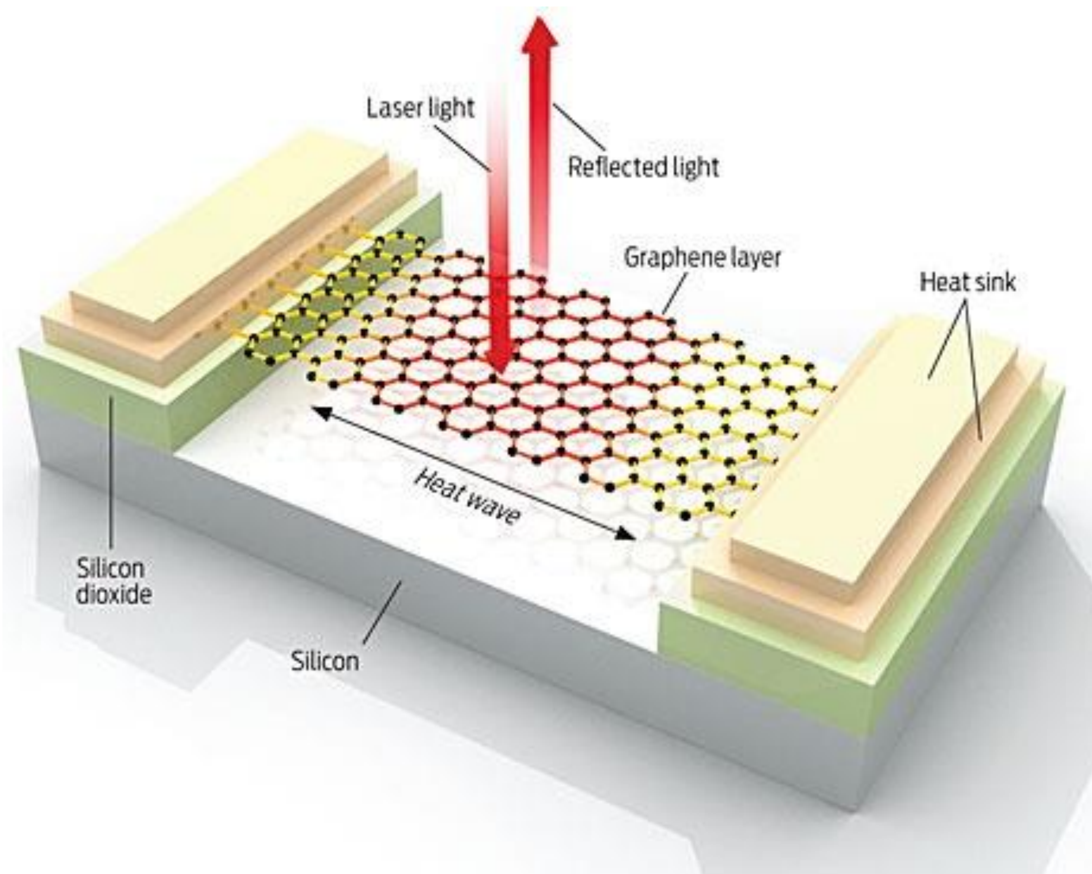
Alexander A. Balandin

Nano-Device Laboratory: NDL
Center for Phonon Optimized Engineered Materials: POEM
Department of Electrical and Computer Engineering
Materials Science and Engineering Program
University of California – Riverside

NSF and DARPA-SRC FAME

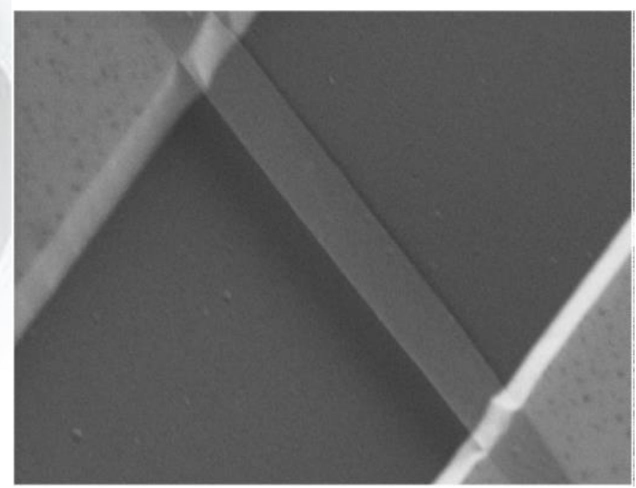
CPMT Panel Discussion – May 2015

Discovery of the Unique Heat Conduction Properties of Graphene



←*IEEE Spectrum* illustration of the first measurements of thermal conductivity of graphene carried out at UCR.

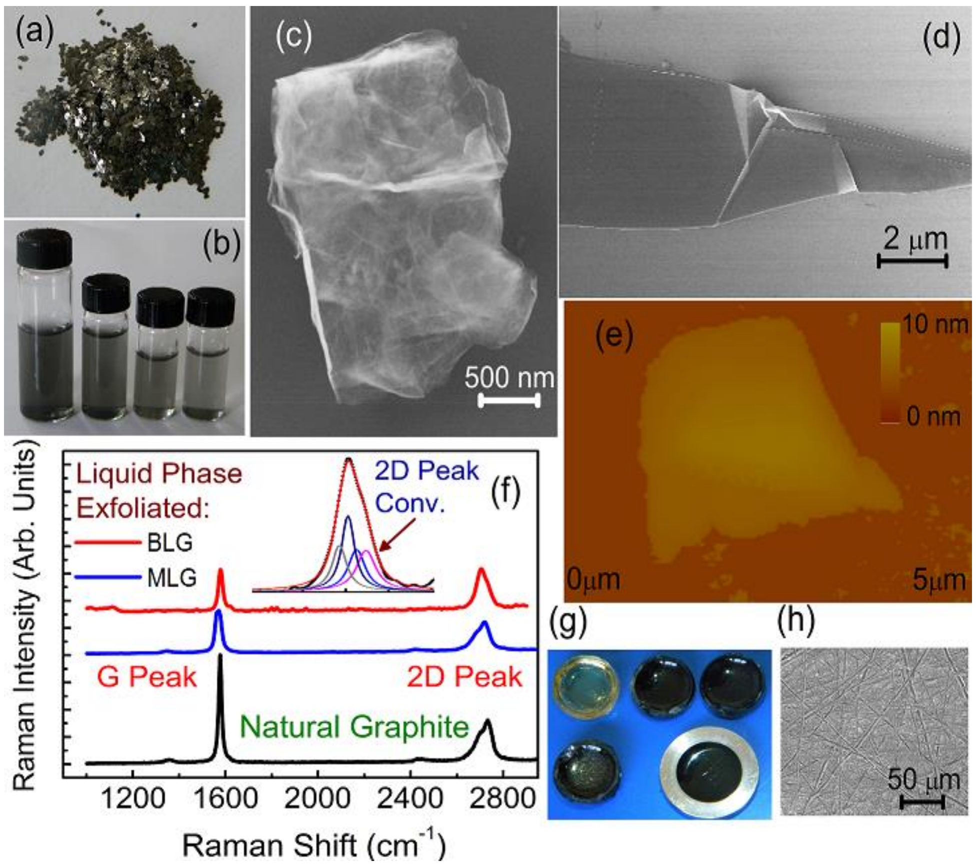
Details: A.A. Balandin et al., *Nano Letters*, 8, 902 (2008); A.A. Balandin, *Nature Mat.*, 10, 569 (2011).

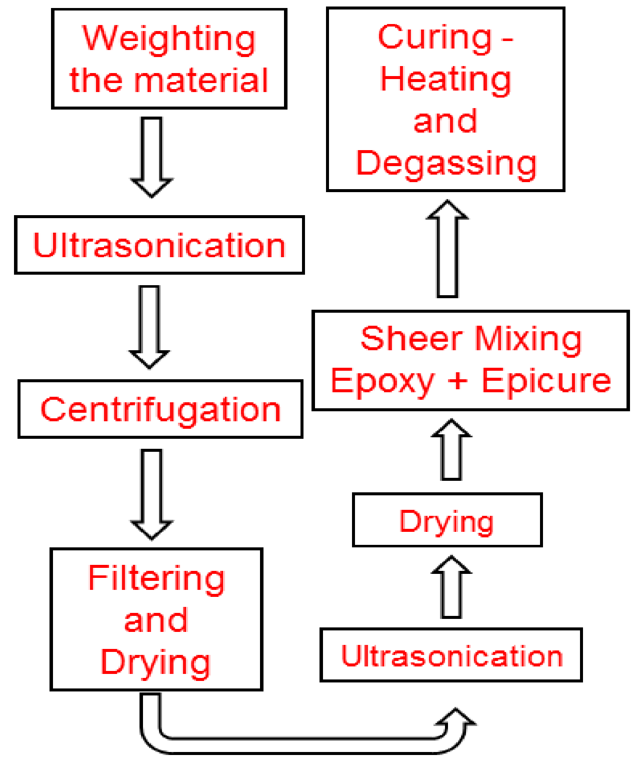


SEM image of the suspended graphene flake connected to heat sinks →

Graphene Enhanced TIMs

Definitions: “graphene” vs. FLG vs. thin film of graphite

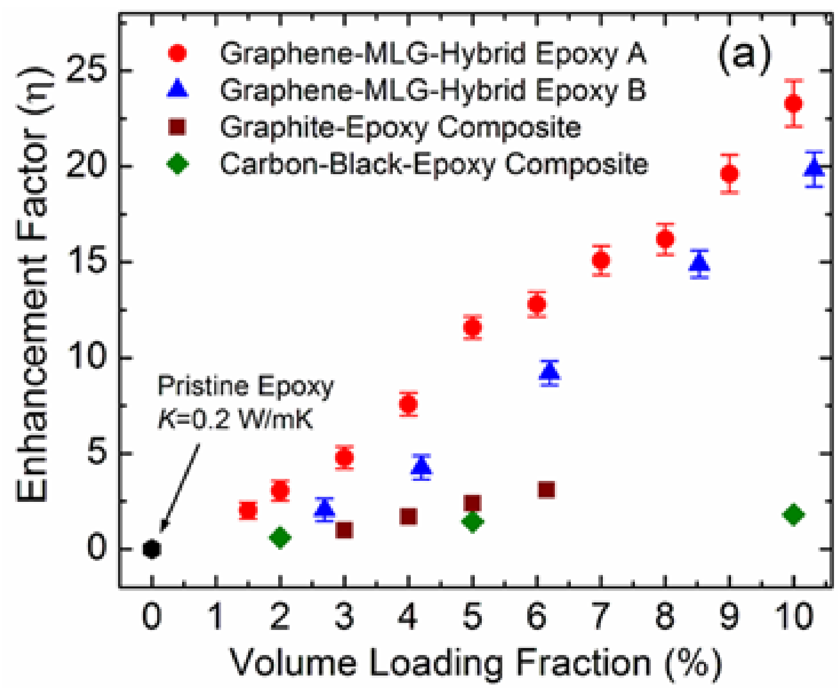




aqueous solution of sodium cholate

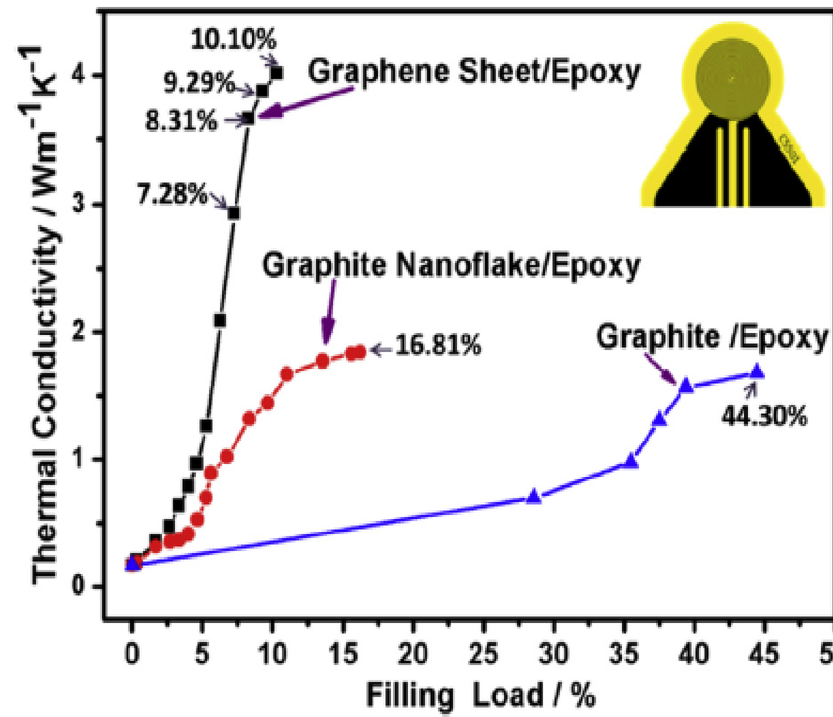
K.M.F. Shahil and A.A. Balandin, "Graphene - multilayer graphene nanocomposites as highly efficient thermal interface materials," *Nano Letters*, 12, 861 (2012).

Graphene TIMs with Strongly Enhanced Thermal Conductivity



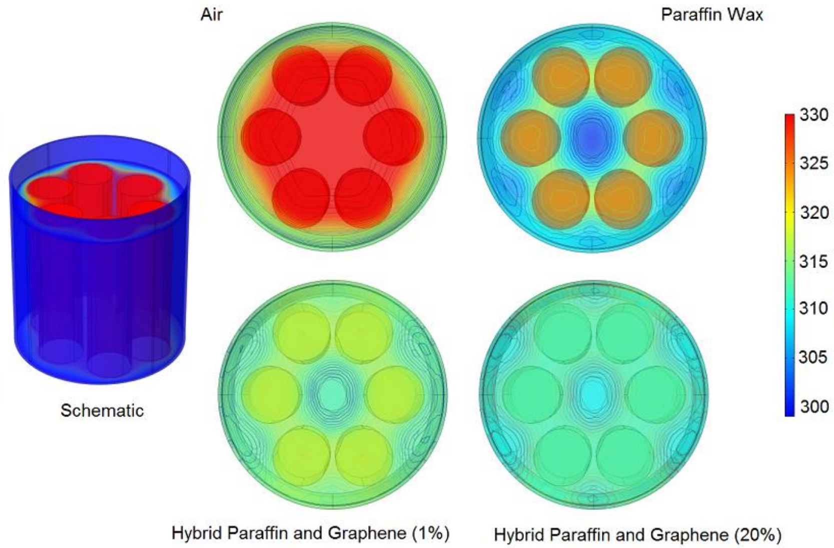
K.M.F. Shahil and A.A. Balandin, "Graphene - multilayer graphene nanocomposites as highly efficient thermal interface materials," *Nano Letters*, 12, 861 (2012).

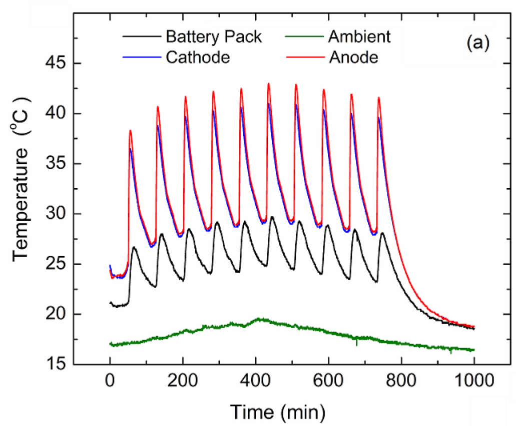
Independent Experimental Confirmation:

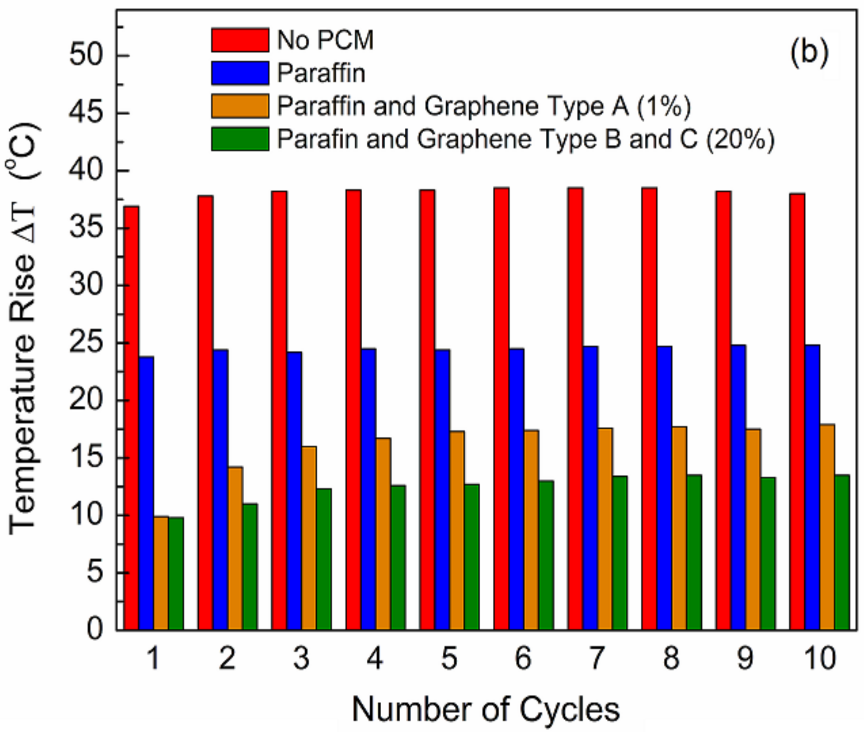


Y.-X. Fu et al. / International Journal of Thermal Sciences 86 (2014) 276–283

Testing C_nH_{2n+2} – Graphene Composites for PCM for Battery Thermal Management



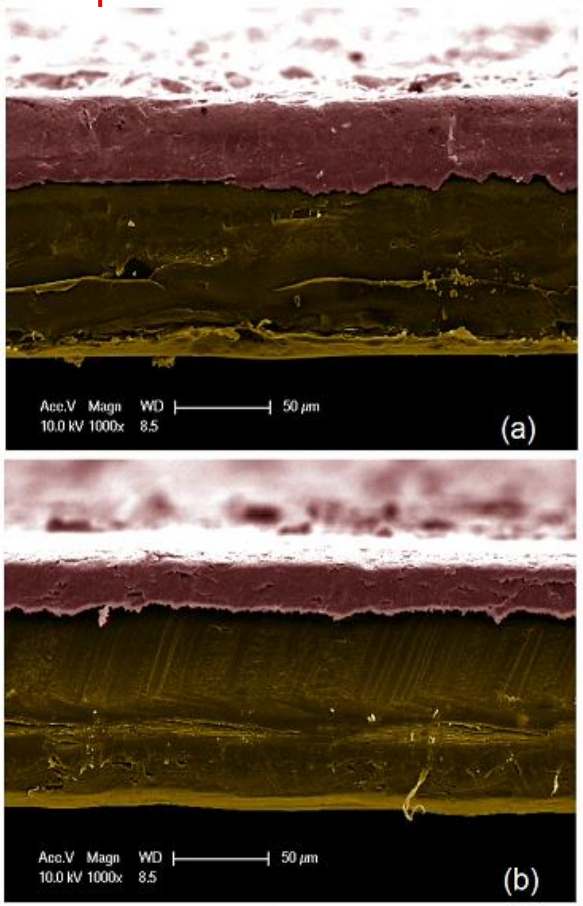


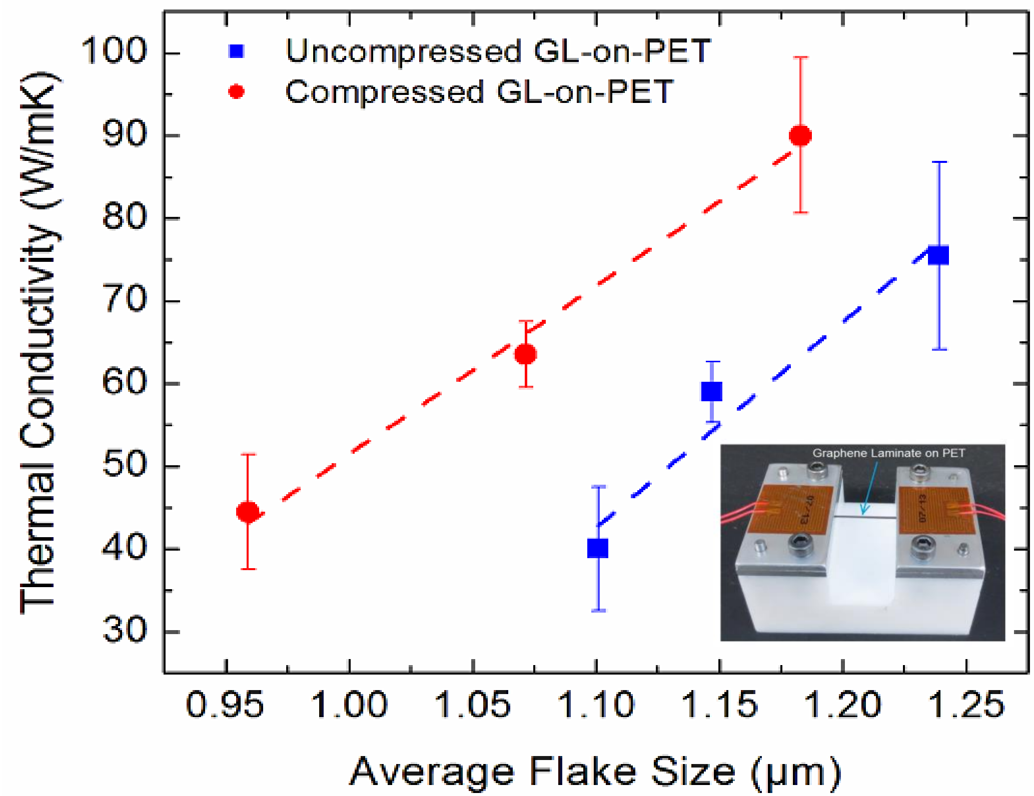


P. Goli, et al., "Graphene-Enhanced Hybrid Phase Change Materials for Thermal Management of Li-Ion Batteries" Journal of Power Sources, 248, 37 – 43 (2014)

Thermal Conductivity of Graphene Laminate

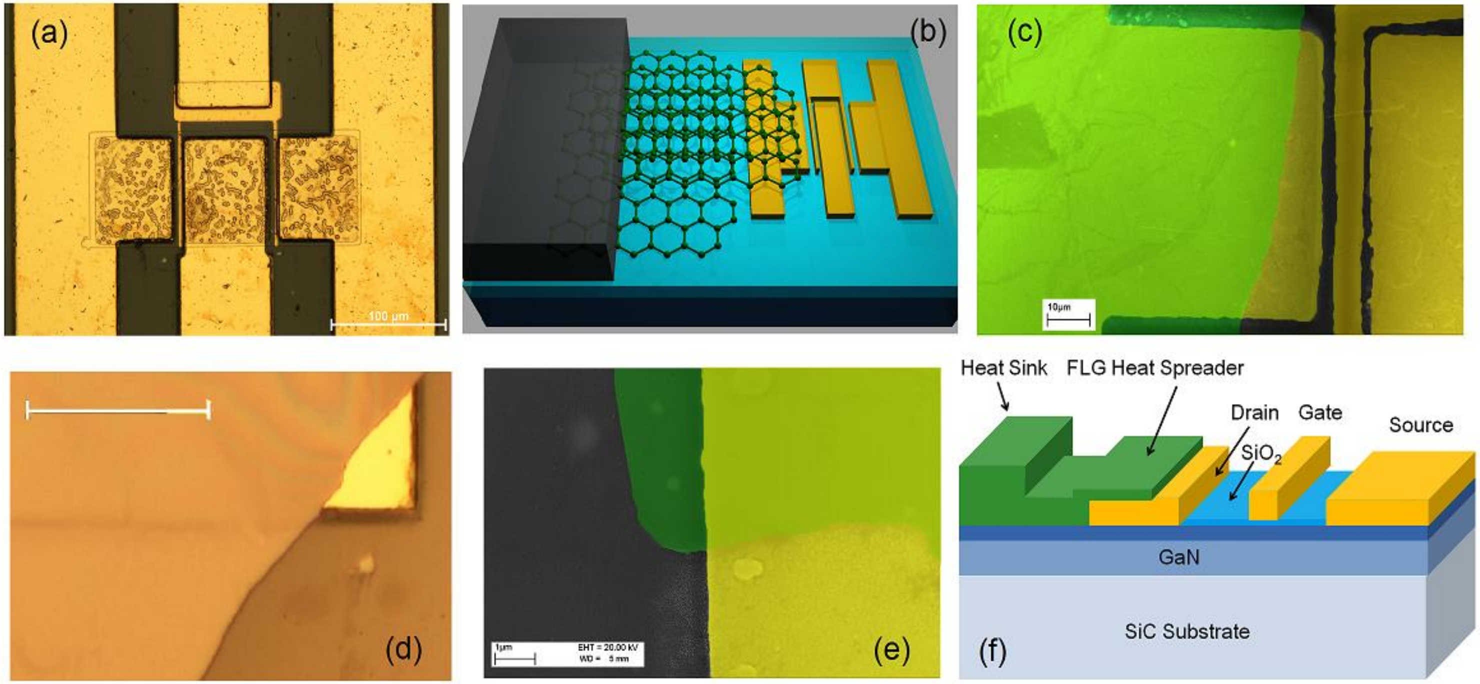
Cooperation with Prof. Konstantin Novoselov and Bluestone Global Tech





H. Malekpour, K.-H. Chang, J.-C. Chen, C.-Y. Lu, D.L. Nika, K.S. Novoselov and A.A. Balandin, "Thermal conductivity of graphene laminate," Nano Lett., 14, 5155–5161 (2014).

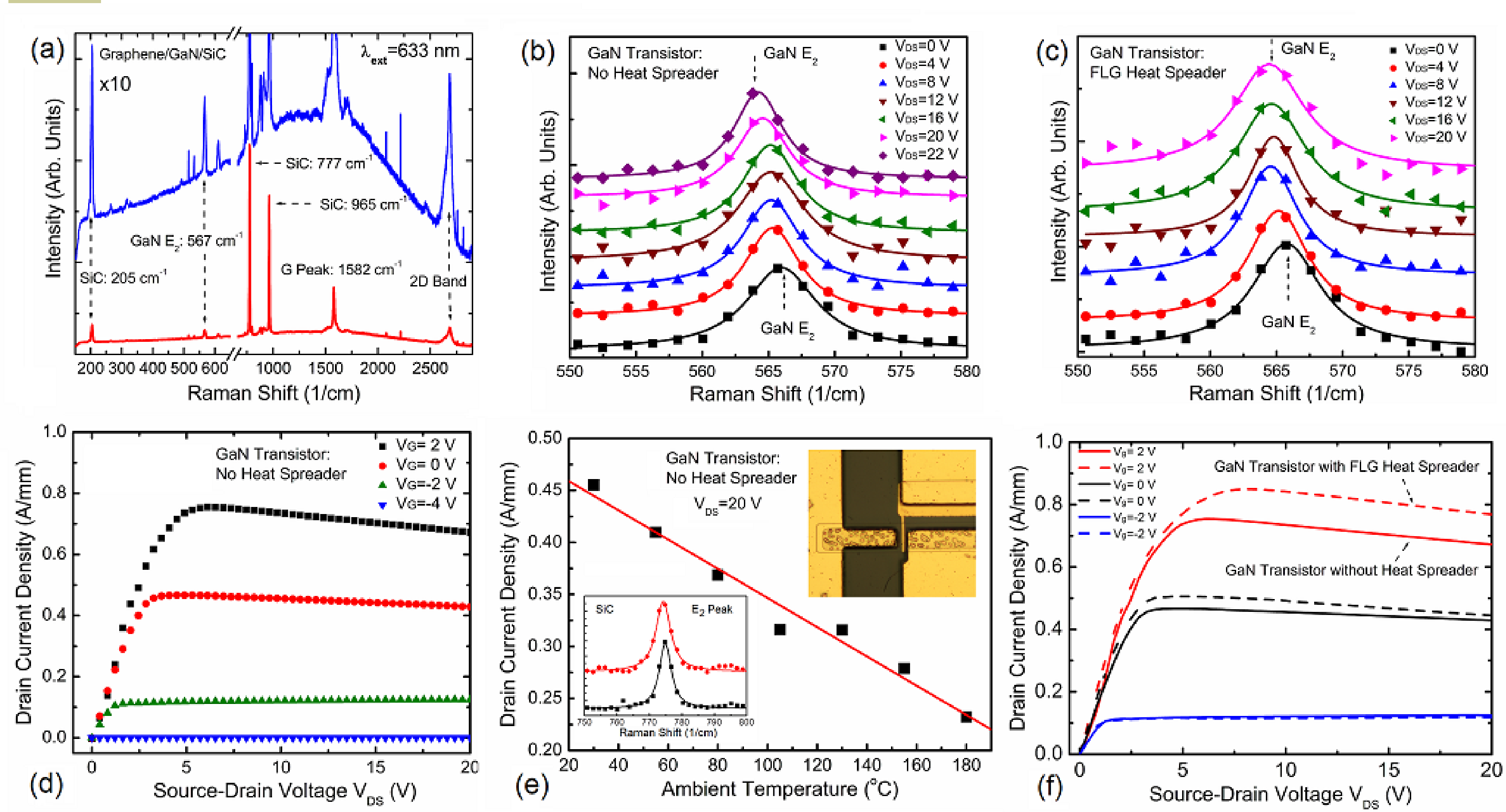
Graphene *Quilts* for Thermal Management GaN Technology



GaN HFETs were used as examples of high-power density transistors; PMMA was utilized as the supporting membrane for graphene transfer to a desired location; the alignment was achieved with the help of a micromanipulator

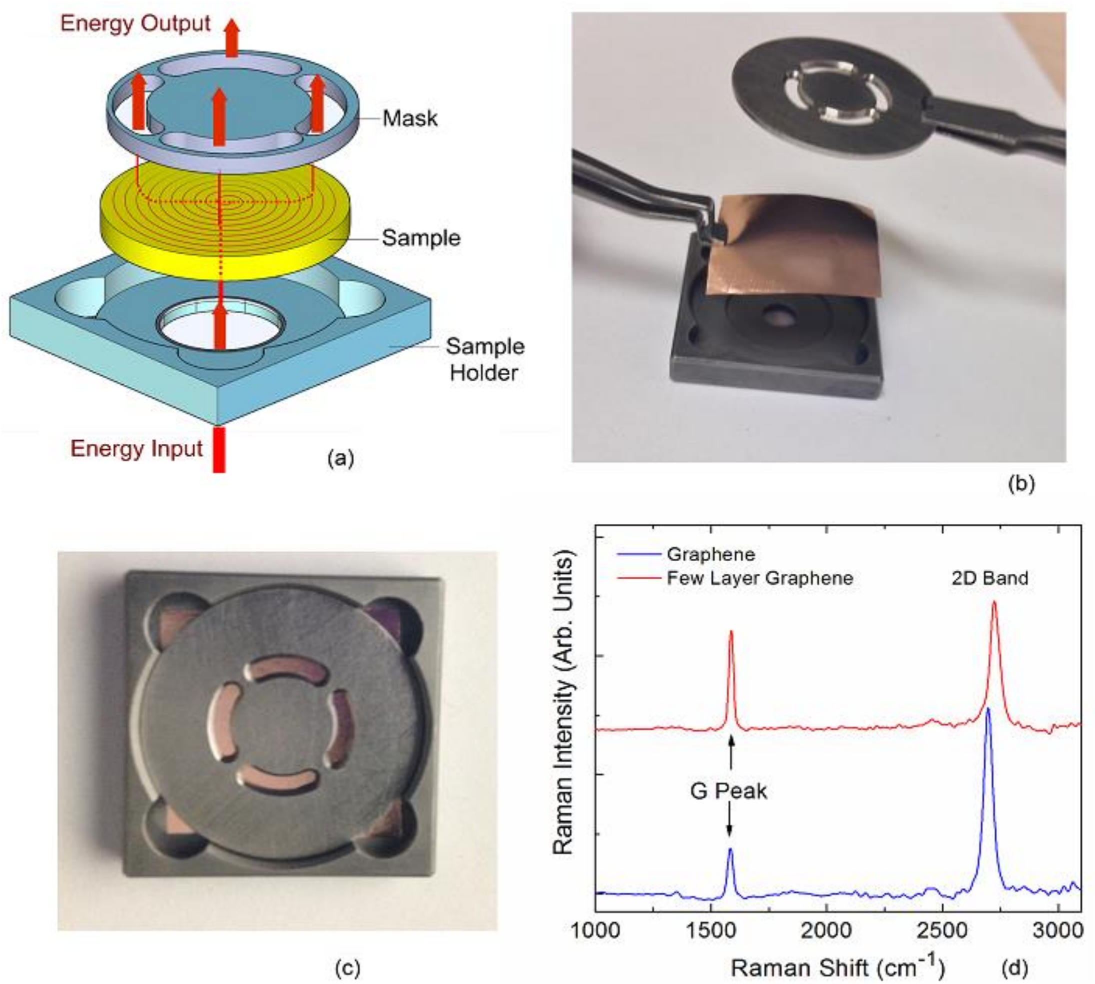
Z. Yan, G. Liu, J.M. Khan and A.A. Balandin, Graphene-Graphite Quilts for Thermal Management of High-Power Transistors, *Nature Communications* **3**, 827 (2012).

Reduction of the Hot-Spot Temperature



The hot-spots temperature near drain contacts can be lowered by as much as ~ 20^{o}C in such devices operating at ~13-W/mm – translates to an order of magnitude improvement in MTTF

Thermal Properties of Copper Foils Coated with CVD Graphene



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(a) Schematic of the modified "laser flash" experimental setup for measuring in-plane thermal diffusivity.
(b) Cu film coated with CVD graphene placed on the sample holder.
(c) Back side of the sample holder with the slits for measuring temperature.
(d) Raman spectrum of graphene and few-layer graphene on Cu. The data is presented after background subtraction.

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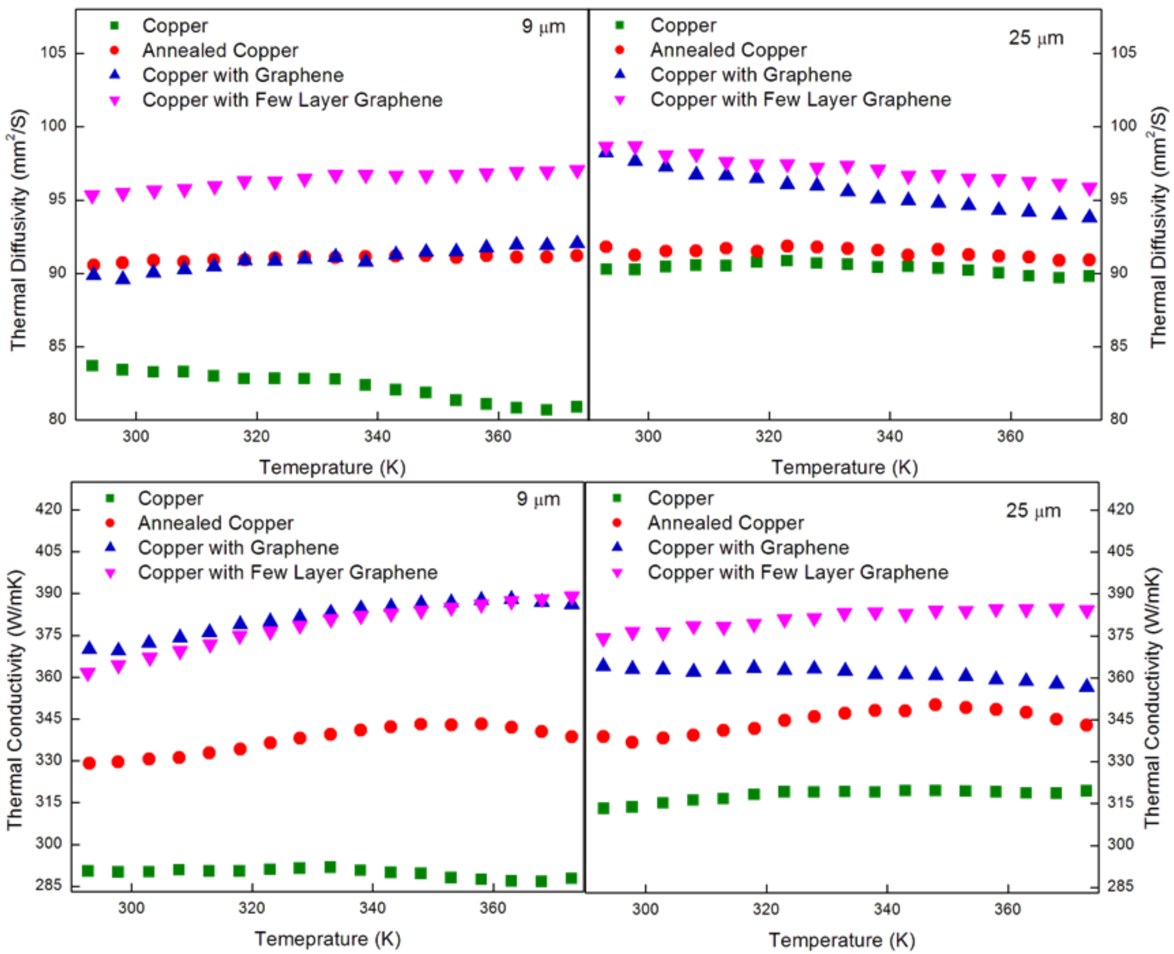
Thermal Properties of Graphene – Copper – Graphene Hetero-Films



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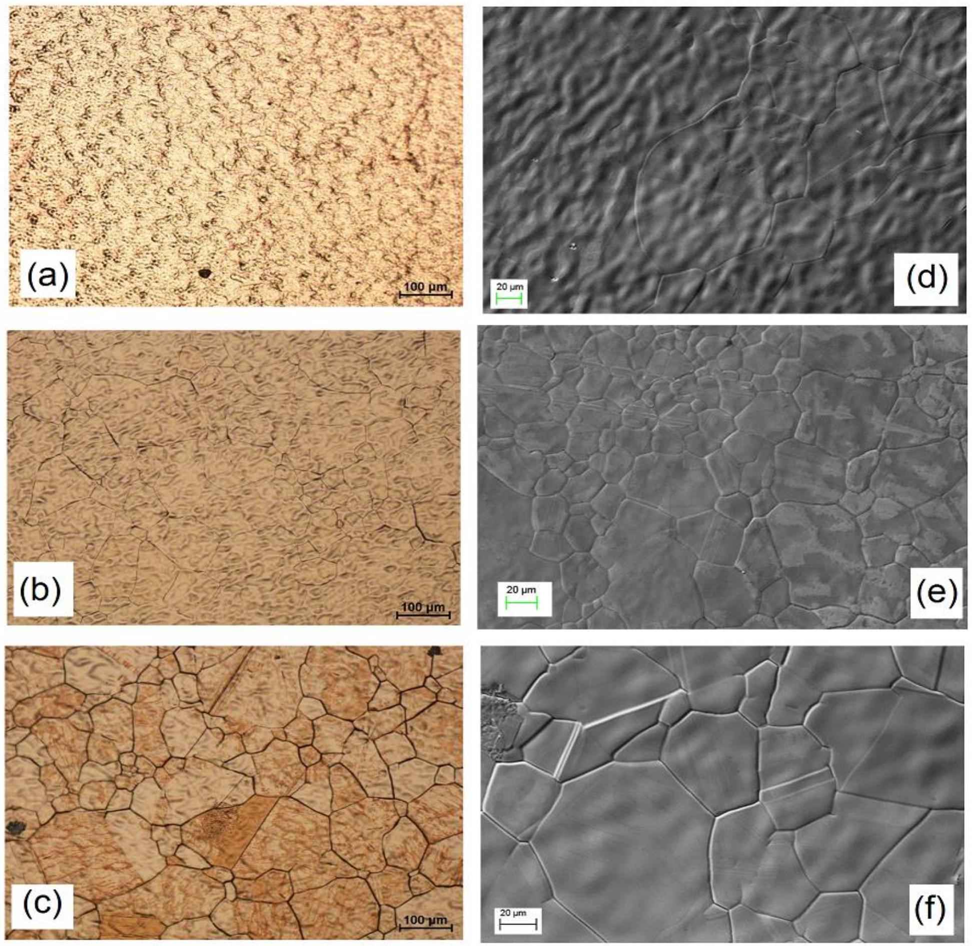
→ CVD of graphene on both sides of 9-μm-thick Cu films increases their thermal conductivity by 24% near room temperature.

→ Thermal resistance R=L/(KhW) of the additional heat conduction channel via graphene is much larger than via Cu film.

P. Goli, H. Ning, X. Li, C.Y. Lu, K.S. Novoselov and A.A. Balandin, Nano Letters, 14, 1497 (2014)

Enlargement of Cu Grain Size During CVD of Graphene



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Thermal conductivity *K* of a polycrystalline metal through that of a single-crystal metal:

$$K = (1 + \Lambda / D)^{-1} K_B$$

$$\frac{\tilde{D}}{D} = \frac{1 - (\Delta K / K)}{1 + (\Delta K / K)(D / \Lambda)}$$

If one assumes that the average grain diameters are in the range D≈1-10 µm, the measured ΔK/K=0.2 can be achieved for if the ratio varies from ~0.13 to 0.016, which corresponds to the grains in reference Cu on the order of 130 – 160 nm.

P. Goli, H. Ning, X. Li, C.Y. Lu, K.S. Novoselov and A.A. Balandin, Thermal Properties of Graphene−Copper−Graphene Heterogeneous Films, Nano Letters, 14, 1497 (2014)

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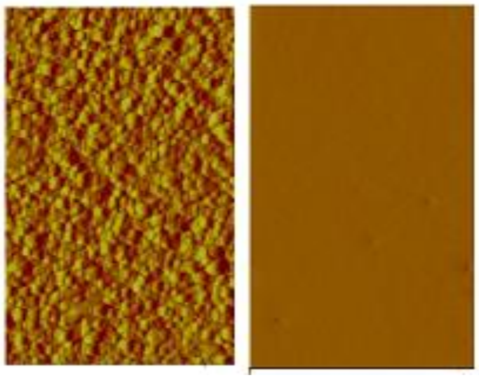
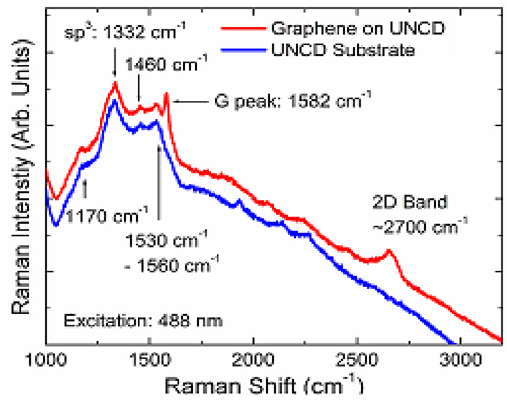
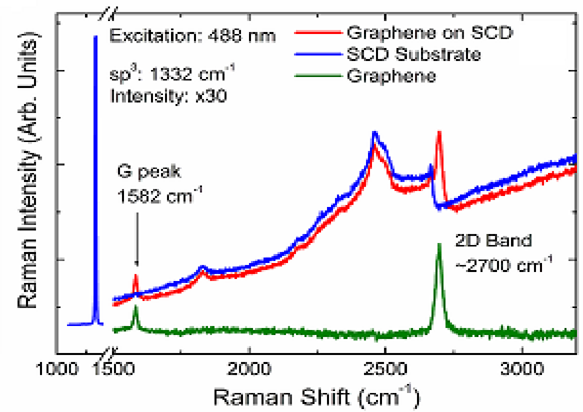
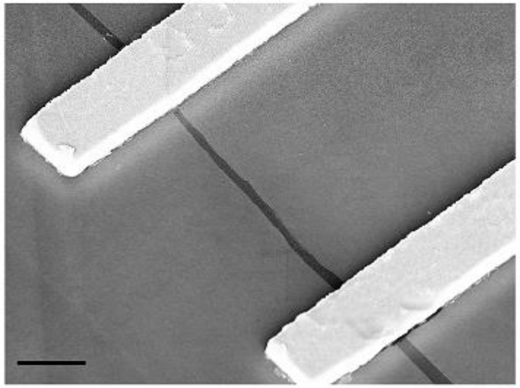
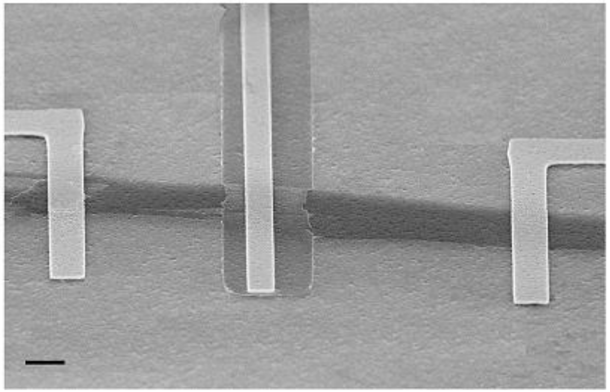
Graphene-on-Diamond: Carbon-on-Carbon Technology

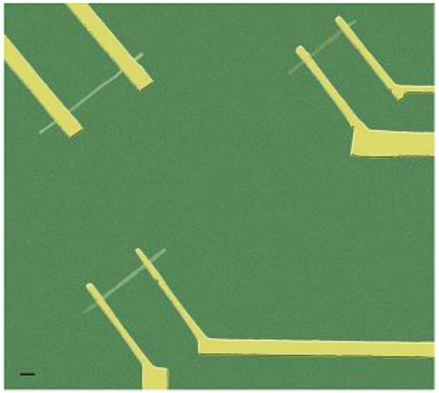






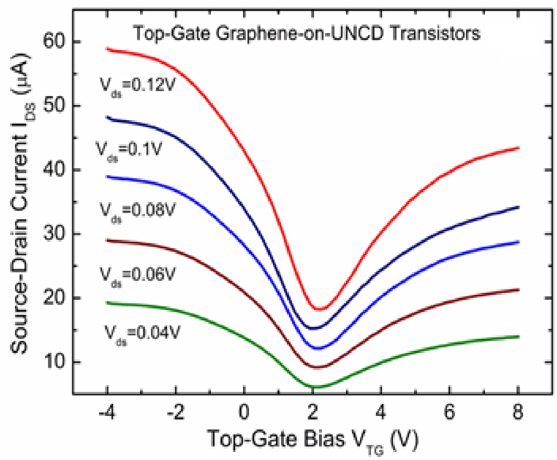


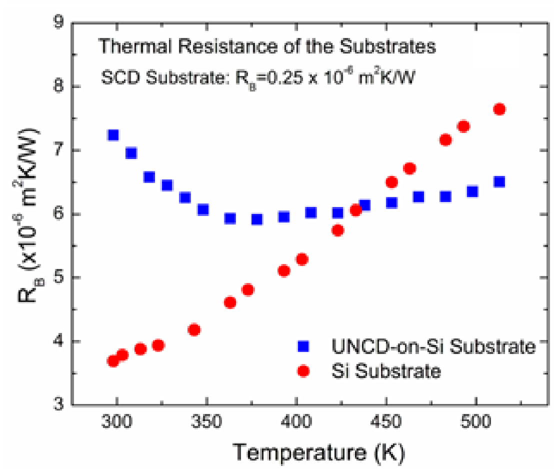


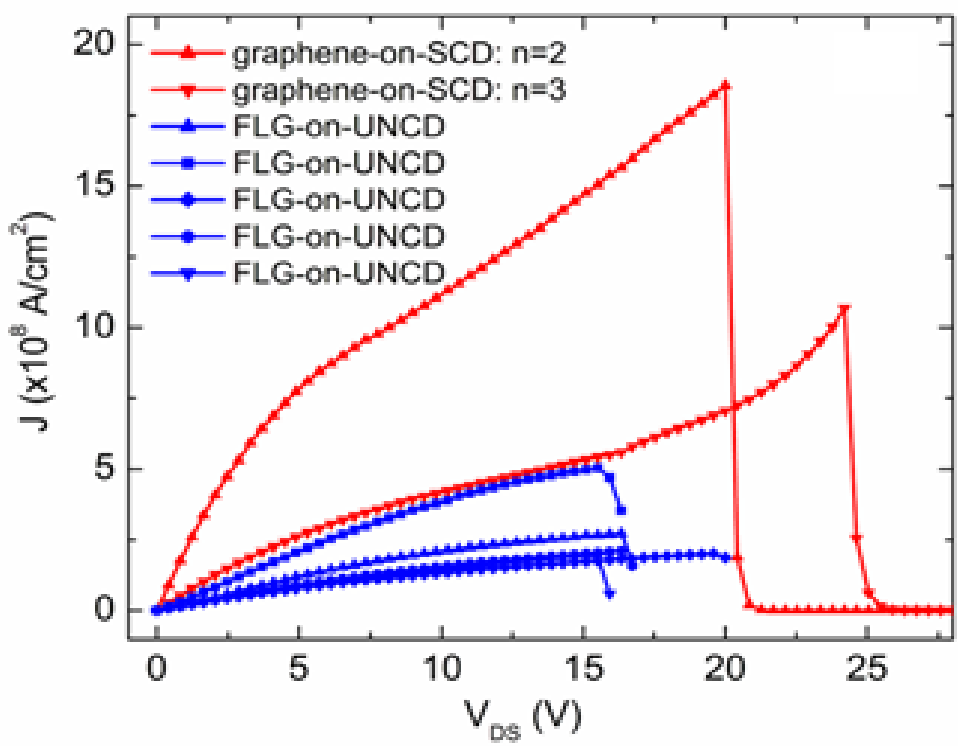


Typical graphene FETs on SiO_2/Si reveal J_{BR} on the order of 10^8 A/cm^2, which is ~100$\times$ larger than the limit for the metals but still smaller than the maximum achieved in CNTs

Graphene Interconnects with Increased Breakdown Current Density

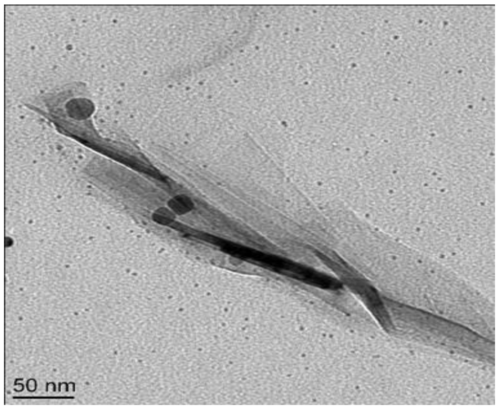


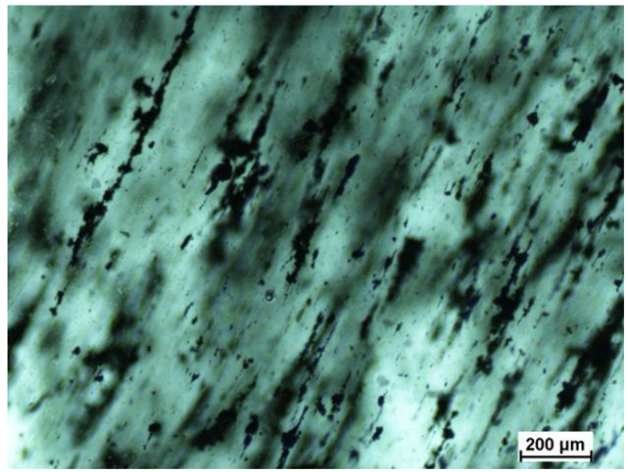


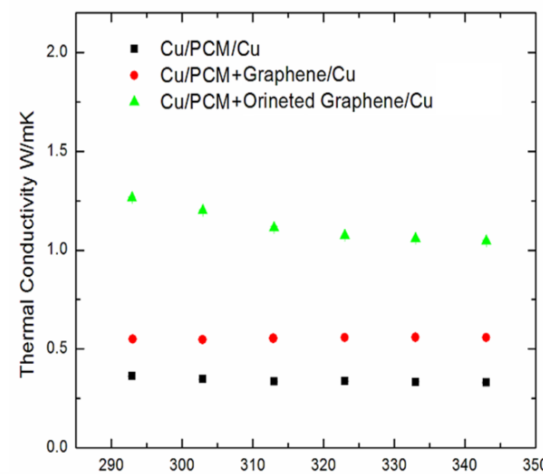


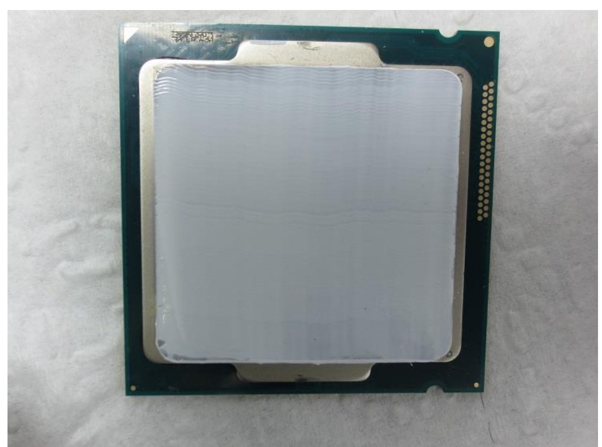
J. Yu, G. Liu, A. Sumant and A.A. Balandin, Graphene-on-diamond devices with increased current-carrying capacity: Carbon sp^2-on-sp^3 technology, *Nano Letters,* 12, 1603 (2012).

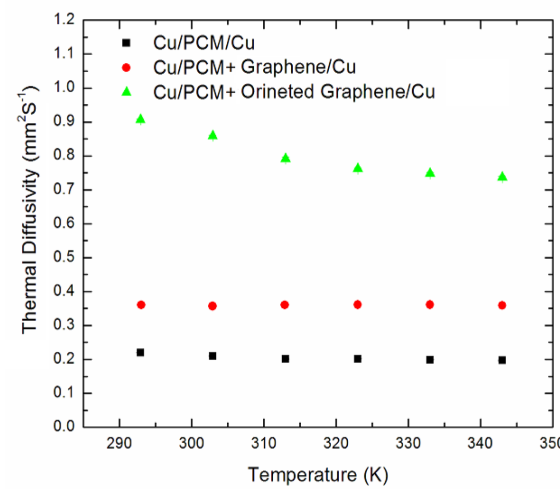
Demonstration of the Aligned Graphene Fillers in Various Matrix Materials





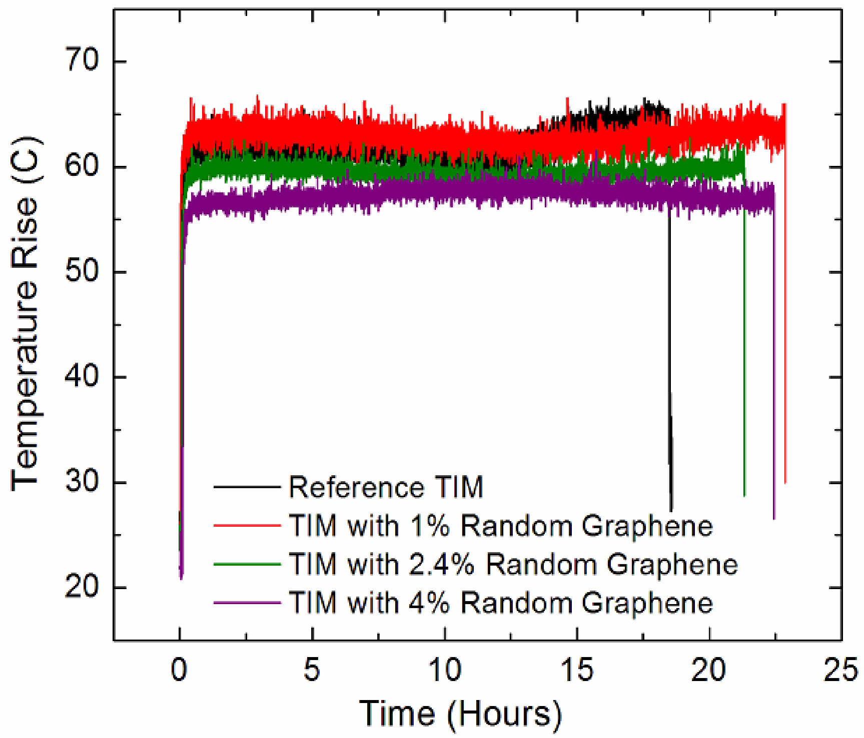


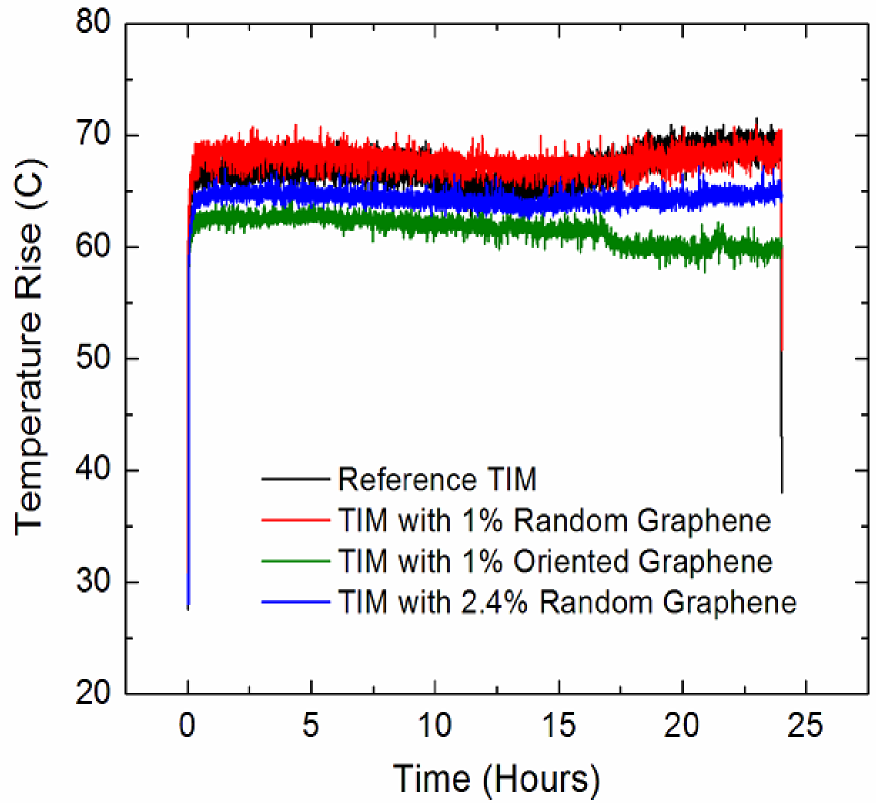




Testing of Graphene-Enhanced TIMs in Computer CPUs

Only 1% of oriented graphene fillers in TIMs can reduce the CPU temperature by 10 ºC. Filler orientation is achieved using special application pack in a process compatible with industry standards.





Take Home Messages

- *Thermal conduction in 2D crystals is different from that in 3D bulk owing to specifics of long-wavelength phonon transport*
- *Thermal conductivity of the atomically thin films depends on the interplay of the intrinsic and extrinsic effects*
- *Graphene can be used as filler for thermal composites*
- *Graphene laminate can be used as thermal coating*
- *CVD graphene increases thermal conductivity of copper*
- *Graphene and FLG can be used as local heat spreaders*
- *Graphene is superior to CNTs owing to better matric coupling, lower cost and 2D geometry*

→ Thermal applications of graphene are much closer to commercialization than other applications of graphene

A.A. Balandin and D.L. Nika, *Materials Today*, **15** 266 (2012).
A.A. Balandin, Nature Materials, 10, 569 - 581 (2011).

Acknowledgements

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