The Heat Is On: Graphene Applications

Thermal management of nanoelectronics and 3-D electronics.

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IT IS WELL RECOGNIZED THAT POWER CONSUMPtion and heat removal in state-of-the-art integrated circuits (ICs) with the nanometer size of transistors is an urgent challenge. The electronic industry's transition to multicore designs, where the performance increase is achieved not via the increase in the clock frequency but rather through the increase in the number of processors, helped to alleviate some of the thermal issues but has not solved the problem of the nonuniformity of heat distribution inside a computer chip. The latter results in appearances of hot spots with heat fluxes exceeding $\sim$500 W/cm^2. The problems associated with the increased dissipated power densities have been encountered in optoelectronic and photonic devices as well. The thermal issues are further complicated by the fact that the material's ability to conduct heat deteriorates when it is structured at the nanometer scale [1]. For these reasons, thermal management has to be improved not only at the packaging level but also at the nanoscale materials and device levels.

THERMAL CHALLENGES AT NANOSCALE

One of the approaches to mitigate the self-heating problem at the device-structure level is to incorporate materials with very high thermal conductivity into the chip design, i.e., the high-heat flux thermal management approach. These thermally conductive materials can be used to build either the device channel or interconnects themselves, or can be utilized as heat spreaders together with conventional electronic materials. It is also expected that improvements in thermal interface materials (TIMs) can be made by the utilization of these highly thermally conductive materials as new fillers. Another approach is to use solid-state thermoelectric on-spot cooling, requiring efficient thermoelectric materials that can be integrated with the IC materials. Liquid cooling may also play a more important role in future thermal management technology.

GRAPHENE AS A THERMAL MANAGEMENT MATERIAL

Graphene is a carbon allotrope that consists of an individual atomic plane of sp^2-bound atoms. Conventional bulk graphite is

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Digital Object Identifier 10.1109/MNANO.2011.943327
Date of publication: 23 November 2011

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made up of graphene planes bound by weak van der Waals forces. In 2004, graphene was mechanically exfoliated by a research team from the University of Manchester, United Kingdom, and the Institute for Microelectronic Technology, Chernogolovka, Russia [2], [3].

Graphene reveals an extremely high room-temperature (RT) electron mobility and saturation velocity [2]–[4]. These excellent electronic properties mean that graphene can be potentially used for interconnects and high-frequency analog communication devices. Graphene's optical transparency coupled with high electrical conductivity can be used in transparent electrodes for photovoltaic solar cells, flexible electronics, and touch screens.

Owing to its geometry, graphene has a number of benefits compared with carbon nanotubes (CNTs). Graphene's planar geometry means that it is much easier to handle on a substrate, pattern, or coat with other materials, as well as make electrical contacts. Although graphene faces a number of challenges, such as development of controlled growth processes, quality Ohmic contacts, edge, and interface passivation control, its promise for becoming a viable electronic material looks good.

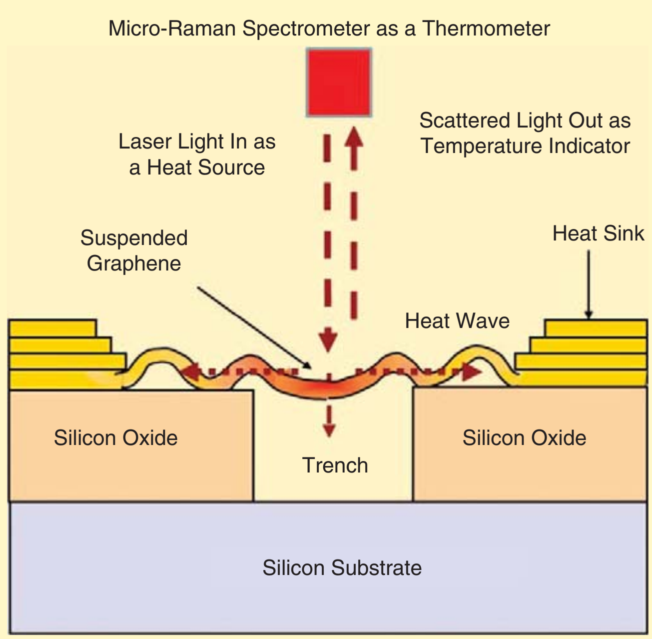


FIGURE 1 Illustration of the optothermal Raman experimental technique developed for measuring the thermal conductivity of suspended graphene. The suspended graphene or FLG is heated with laser light while the corresponding temperature rise is determined from the shift in the G or 2-D peaks in the Raman spectrum of graphene. The knowledge of temperature rise in response to the dissipated power and geometry of the graphene layer are sufficient for determining the in-plane thermal conductivity. The corrugations in the partially suspended graphene, which are depicted in the schematic, reduce graphene thermal coupling to the substrate but can lead to strain, which can affect heat conduction.

In addition to its unique electronic properties, graphene turns out to be an excellent heat-conduction material. The first experimental studies of thermal conductivity, K, of graphene were carried out at the University of California, Riverside (UCR), using an original optothermal Raman measurement technique developed specifically for graphene and few-layer graphene (FLG) [5]–[12]. Heating power ΔP was provided with a laser light focused in the middle of a suspended graphene layer that was connected to heat sinks at its ends (see Figure 1).

The temperature rise ΔT in response to ΔP was determined with a micro-Raman spectrometer. It was previously established by the same group that the G peak in graphene's Raman spectrum exhibits a strong temperature dependence [13]–[15]. The calibration of the spectral position the G peak with temperature, T, allows the utilization of the micro-Raman spectrometer as an optical thermometer.

During measurements, the graphene layer was heated by increasing the laser power. The amount of heat dissipated in graphene was determined via measuring the integrated Raman intensity of the G peak. Alternatively, it can be directly measured by a photodetector placed under the suspended graphene layers if the sample design allows for it. A correlation between ΔT and ΔP for the graphene sample with a given geometry can give K values via solution of the heat-diffusion equation. Details of the measurement procedures and experimental uncertainties for the optothermal Raman measurement technique for graphene are reported elsewhere [12].

It was found that the intrinsic thermal conductivity of the large-size freely suspended graphene varies in the range from ~2,000 to 5,000 W/m · K near RT [5]–[12]. The intrinsic thermal conductivity of graphene can be above the bulk graphite limit of ~2,000 W/m · K [12]. The thermal conductivity of graphene depends on the size of the flakes, edge roughness, and the strength of coupling to the substrate or matrix materials. The thermal conductivity values found for suspended graphene layers (see Figure 2) are closer to the intrinsic thermal conductivity. When graphene is incorporated between layers of dielectric, its thermal conductivity can be substantially reduced due to interface phonon scattering. For this reason, FLG may have advantages over the single-layer graphene. The use of FLG also increases the heat flux through the cross section of the thin film in heat-spreader applications.

The high thermal conductivity of graphene opens up new possibilities of practical applications of graphene in thermal management [12]. Even if the eventual thermal applications will use thin graphite films, which have high thermal conductivity (~2,000 W/m · K) when compared with that of silicon (~145 W/m · K), rather than graphene, it is due to the strong interest in graphene that crucial technologies of chemical vapor deposition (CVD) of carbon materials and liquid-phase exfoliation of graphite have been developed. Particularly promising are graphene and FLG applications as the top lateral heat spreaders for high-power density electronic devices such as GaN/AlGaN heterostructure field-effect transistors (HFETs).

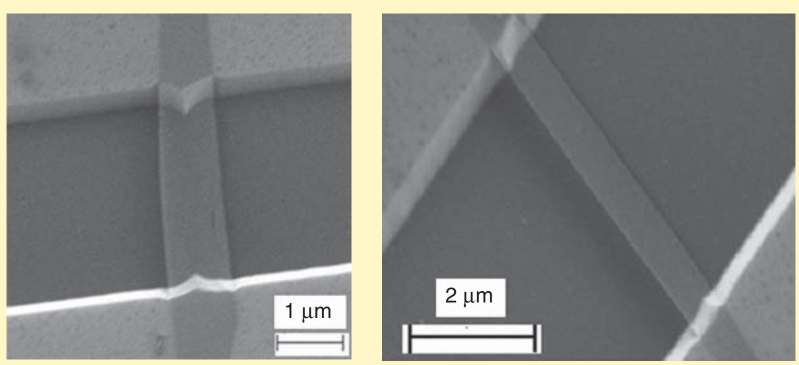
One of the approaches to mitigate the self-heating problem at the device-structure level is to incorporate materials with very high thermal conductivity into the chip design.

GRAPHENE FILLERS IN TIMs

The need for improved TIMs in modern electronic chip packaging and high-power density photonic devices stimulated an interest in carbon materials as fillers for TIMs. The current TIMs are based on polymers or greases filled with thermally conductive particles such as silver or silica, which require high volume fractions of filler (up to ~70%) to achieve thermal conductivities of the composite of about 1–5 W/m · K. Carbon materials, which were recently studied as fillers, include CNTs, graphite nanoplatelets, graphene oxide nanoparticles, and graphene flakes derived by chemical processes. Although both graphene flakes and CNTs have exceptional thermal conductivities, their geometries are markedly different. The properties of a composite material are strongly correlated with the aspect ratios of the fillers. The difference in the aspect ratios between graphene flakes and CNTs can substantially affect the effective properties of the corresponding composites.

To produce graphene in large quantities at affordable prices, we have adopted a simple surfactant-stabilized graphene-dispersion method that requires less chemical and thermal treatment compared with the other reported techniques [16]. This method offers several advantages and utilizes inexpensive and readily available source-graphene materials. The dispersions have been prepared by ultrasonication of natural graphite flakes in aqueous solutions. The thick graphite material was removed from the dispersion by centrifugation. The graphene dispersions were filtered, washed with distilled water, and air dried. The homogeneous mixture of epoxy and graphene flakes was loaded into a custom stainless steel mold, heated, and degassed in vacuum for curing. The samples were prepared with different volume fractions of graphene loading. The measurements of thermal conductivities of TIMs were performed by the transient-plane-source (TPS) hot disk and optical laser-flash techniques.

Improvements in thermal conductivity are conventionally characterized by the enhancement factor defined as $\eta = (K_e - K_b)/K_b$, where K_e is the thermal conductivity of the composite material and K_b is the thermal conductivity of the initial base material. In our experiments, we observed greater than 1,000% enhancement for



(a) (b)

FIGURE 2 Scanning electron microscopy image of (a) bilayer and (b) trilayer graphene suspended across trenches in Si/SiO_2 wafers. Note that the nearly ideal rectangular shape of the suspended graphene flakes simplifies the thermal data analysis. In the experiments, graphene is heated in the middle of the suspended part. For measurement details, see [12]. (Photo courtesy of Zahid Hossain, Nano-Device Laboratory, UCR.)

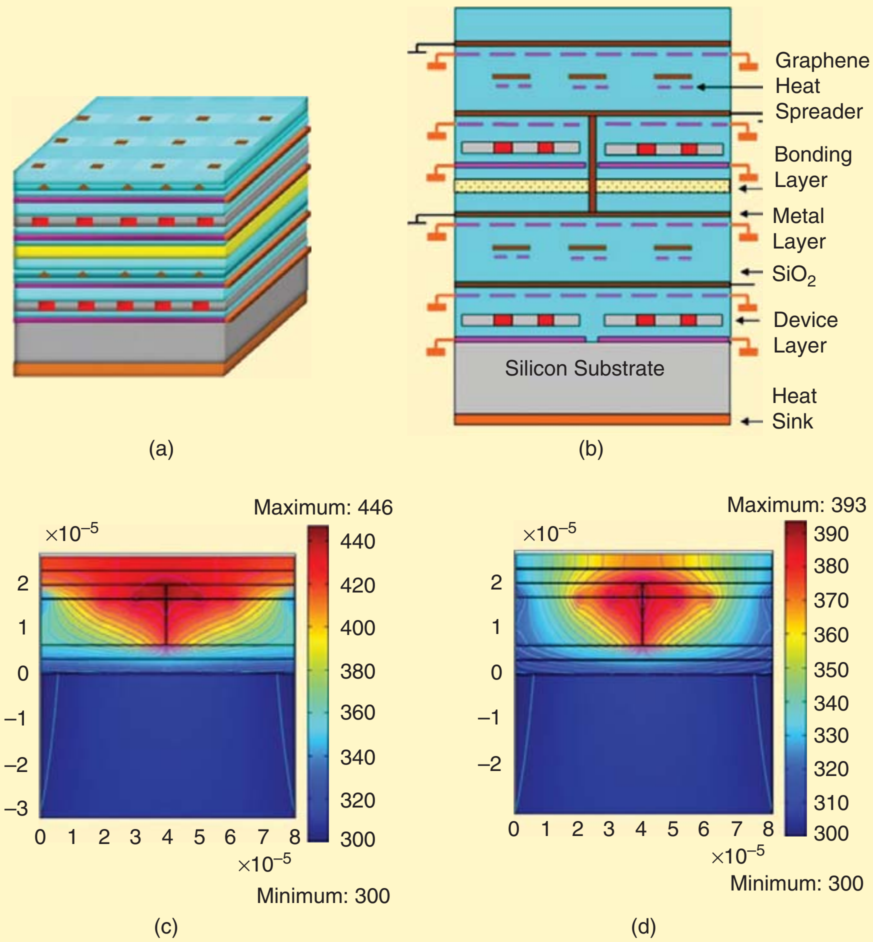


FIGURE 3 A schematic of the simulated 3-D chip with graphene heat spreaders. (a) A 3-D view and (b) cross section of the prototype 3-D chip showing graphene heat spreaders for heat removal from the inside-localized hot spots and interconnects. The main heat sink is in the bottom of the substrate, and additional heat sinks are used for the graphene heat spreaders. The vertical thermal via is also included in the design. The simulated temperature distribution across the 3-D chip with two strata, which consist of a device layer and two interconnect layers per stratum, are shown for the designs (c) without and (d) with graphene heat spreaders. The units of temperature are in degree kelvin. Note that the design with the incorporated graphene heat a spreaders has a substantially low temperature (~393 K) when compared with the design without graphene heat spreaders (~446 K).

graphene–epoxy composites and about 500% enhancement for graphene–silver epoxy composites at 5.0 vol.% graphene loading fraction. Our data indicate that graphene flakes can outperform CNTs and other carbon materials owing to their high intrinsic thermal conductivity and geometry, which leads to stronger enhancement at a given loading fraction, and thereby reduces cost. The observed enhancement factors with carbon materials are not achievable with conventional fillers.

Future applications of graphene in TIMs will eventually depend on many factors, such as viscosity of the composite, filler–matrix coupling, coefficient of thermal expansion, thermal interface resistance, and cost of production. Our initial data and strong practical motivations call for more research of graphene applications in TIMs.

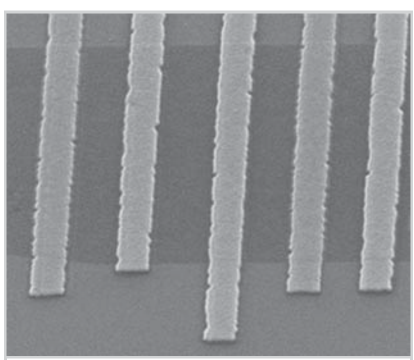


FIGURE 4 Scanning electron microscopy image of the graphene ribbon on an Si/SiO_2 wafer contacted by metal interconnects. The device, a prototype of a graphene global interconnect and heat spreader, was used to investigate the electronic and thermal properties. (Photo courtesy of Guanxiong Liu, Nano-Device Laboratory, UCR.)

GRAPHENE HEAT SPREADERS FOR NANO AND 3-D ELECTRONICS

The high thermal conductivity of graphene adds validity to its proposed transistor and interconnect applications owing to the potential benefit for thermal management (see Figures 3 and 4). Graphene layers incorporated into chip designs can also carry out the mission of high-heat flux cooling and help in the lateral heat spreading and hot-spot removal [17]–[20]. Graphene can be CVD grown on metal substrates, synthesized on SiC wafers, and incorporated within Si/diamond wafers. The graphene lateral heat spreaders can be combined in thermal network designs with the vertical thermal vias made of carbon fiber or CNTs. This approach can be extended to three-dimensional (3-D) integrated chips (Figure 3).

Graphene was tested for applications as an interconnect material, showing better results than CNTs or bundles of CNTs. The IC design, where the graphene layers separated by proper intercalation layers are used for both interconnects and heat spreaders, seems to be the most promising. Our physics-based modeling and simulation studies carried out with COMSOL [17]–[21] suggest that one can achieve a substantial reduction in the hot-spot temperature inside 3-D chips and silicon-on-insulator chips by using graphene as lateral heat spreaders (see Figure 3).

> Thermal management has to be improved not only at the packaging level but also at the nanoscale materials and device levels.

CONCLUSIONS

This article describes the thermal properties of graphene and the method of their measurements. Based on initial experimental and modeling studies, it is suggested that owing to their excellent heat-conduction properties, graphene and FLG can become the materials of choice for thermal management of future nanoelectronic and 3-D ICs. The particularly promising thermal applications of graphene are TIMs and lateral heat spreaders.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research through award N00014-10-1-0224 and the Corporation and Defense Advanced Research Project Agency through the Focus Center Research Program on Functional Engineered Nano Architectonics. The author acknowledges his group members (Dr. Samia Subrina and Ph.D. candidates Guanxiong Liu and Zahid Hossain) for providing the images for this review.

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