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Thermal Transport in Graphene and Few-Layer Graphene: Applications in Thermal Management and Interconnects

Alexander A. Balandin

Nano-Device Laboratory
Department of Electrical Engineering and Materials Science and Engineering Program
Bourns College of Engineering
University of California – Riverside
Riverside, California 92521 USA

Phone: +1-951-827-2351 E-mail: balandin@ee.ucr.edu

1. Introduction

In 2008 we discovered experimentally that graphene, in addition to its unique electronic and optical properties, reveals unusually high thermal conductivity at room temperature [1-2]. In a follow up study we investigated the evolution of thermal conductivity in few-layer graphene with addition of the atomic planes and its transition to the bulk graphite limit [3]. We explained the high thermal conductivity of graphene by the two-dimensional nature of the acoustic phonon transport and suppression of the phonon Umklapp scattering [4-5]. It was also established that the thermal conductivity of graphene layers and ribbons depends strongly on the geometrical size of the layers and their coupling to the substrate. The superior thermal properties of graphene are beneficial for all proposed electronic applications of graphene and few-layer graphene. We have shown that graphene layers incorporated within electronic chips can act as lateral heat spreaders for hot-spot removal in advanced 2-D and 3-D integrated chips [6-7]. Specific designs where graphene ribbons play simultaneously the role of interconnects and heat spreaders in advanced ICs, hybrid carbon - silicon chips and 3-D electronics have also been investigated [7-9]. Here, I briefly outline our experimental and theoretical results.

2. Specifics of Heat Conduction in Graphene

To measure thermal conductivity of "free" graphene we suspended long graphene flakes across trenches in Si/SiO_2 wafers. The flakes were attached to the side graphite or metal heat sinks (see Fig. 1). The graphene flakes were heated with the laser beam focused in the middle of the suspended part of the flake. The corresponding temperature rise was measured by the shift in the Raman G peak [1]. Knowing the geometry of the graphene flake, dissipated power and temperature rise allowed us to determine the thermal conductivity. We found that the thermal conductivity of "free" graphene exceeds that of bulk graphite provided that the size of the flake is sufficiently large [2].

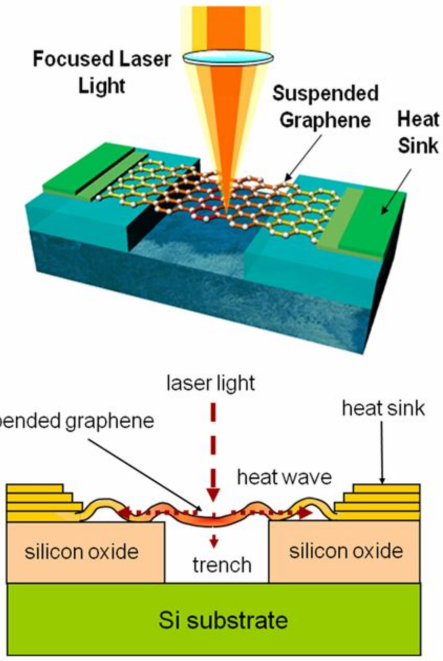

Fig. 1: (a) Schematic of the experimental set up used for the first measurements of the thermal conductivity of graphene (see for details A.A. Balandin, *et al.*, *Nano Letters*, **8**, 902 (2008); or feature article about this experiment in IEEE Spectrum October, 2009). The excitation laser light focused on graphene suspended across a trench in Si wafer. Laser power absorbed in graphene induces a local hot spot and generates heat wave propagating toward the heat sinks. (b) Illustration of the micro- and nanoscale corrugation formed in the suspended flake, which further reduce the thermal coupling to the substrate.

We developed a detail theory of the phonon thermal conductivity of single-layer graphene. It was found that the near room-temperature thermal conductivity of single-layer graphene, calculated with a realistic Gruneisen parameter, is in the range ~2000–5000 W/mK depending on the flake width, defect concentration and roughness of the edges. The obtained theoretical results [4-5] were in agreement with our measurements [1-2]. Owing to the long phonon mean free path the graphene edges produce strong effect on thermal conductivity even at room temperature.

Based on the results of our investigation, we proposed graphene as a material for heat removal. To test the feasibility of this approach we simulated heat propagation in silicon-on-insulator (SOI) circuits with and without graphene lateral heat spreaders. The analysis was focused on the prototype SOI circuits with MOSFETs [6]. It was found that the incorporation of graphene or few-layer graphene (FLG) layers with proper heat sinks can substantially lower the temperature of the localized hot spots. The approach was extended to 3-D integrated circuits with incorporated graphene lateral heat spreaders (see Fig. 2).

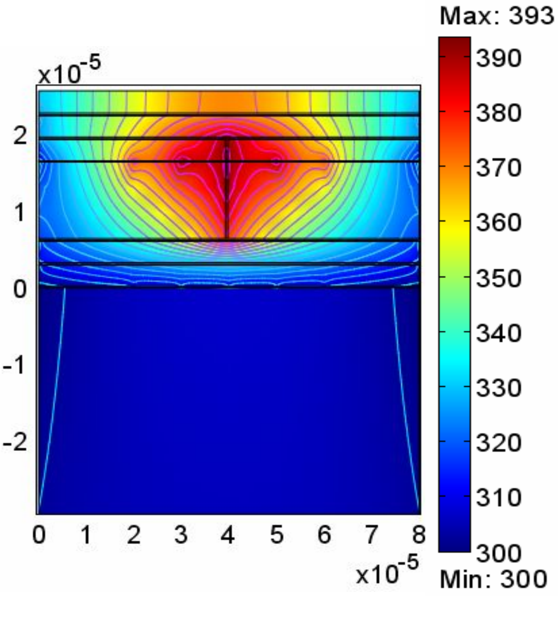

Fig. 2: Temperature distribution in 3D chip with graphene lateral heat spreaders. The simulation results show that incorporation of graphene can lead to substantial decrease in the hot-spot temperature.

In 2008, we tested graphene interconnects and investigated the temperature dependence of their electrical resistance [6]. Most recently we built proto-type devices where graphene layers simultaneously played a role of interconnects and heat spreaders (see Fig. 3). The results show that graphene can sustain very high current densities while improving thermal management of interconnects [9].

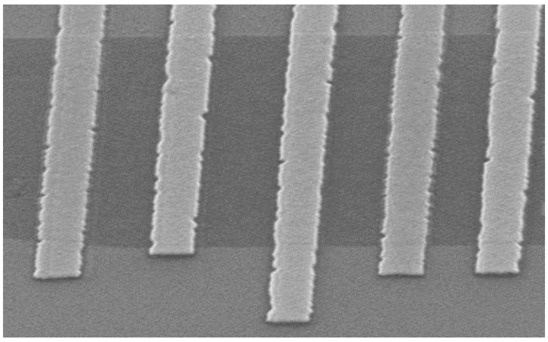

Fig. 3: Prototype graphene interconnect and heat spreader contacted by metal electrodes. Our results show that graphene is promising material for incorporation within 3-D circuits and may lead to substantial improvement of thermal management.

3. Conclusions

We described the first experimental investigation of heat conduction in graphene and graphene's possible applications as materials for interconnects and heat spreaders.

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