Ballistic to Diffusive Thermal Conduction in Graphene Ribbons

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Heat flow in nanomaterials is an important area of study, with both fundamental and technological implications. We developed a substrate-supported thermometry platform to measure thermal transport in graphene (Figure (a)). We find that the thermal properties of graphene can be tuned in sample sizes comparable to the phonon mean free path (mfp) [1]. Short, quarter-micron graphene samples reach ~35% of the ballistic thermal conductance limit [2] up to room temperature (Figure (b)), enabled by the relatively large phonon mfp (~100 nm) in substrate-supported graphene. In contrast, patterning similar samples into graphene nanoribbons (GNRs) leads to a diffusive heat flow regime that is controlled by ribbon width and edge disorder (b). In the edge-limited regime, the thermal conductivity scales with width as ~W1.8 ± 0.3, being about 100 Wm-1K-1 in 65-nm-wide GNRs, at room temperature (Figure (c)). These results are the first demonstration of how the manipulation of two-dimensional device dimensions and edges can be used to achieve full control of their heat-carrying properties, approaching fundamentally limited upper or lower bounds.

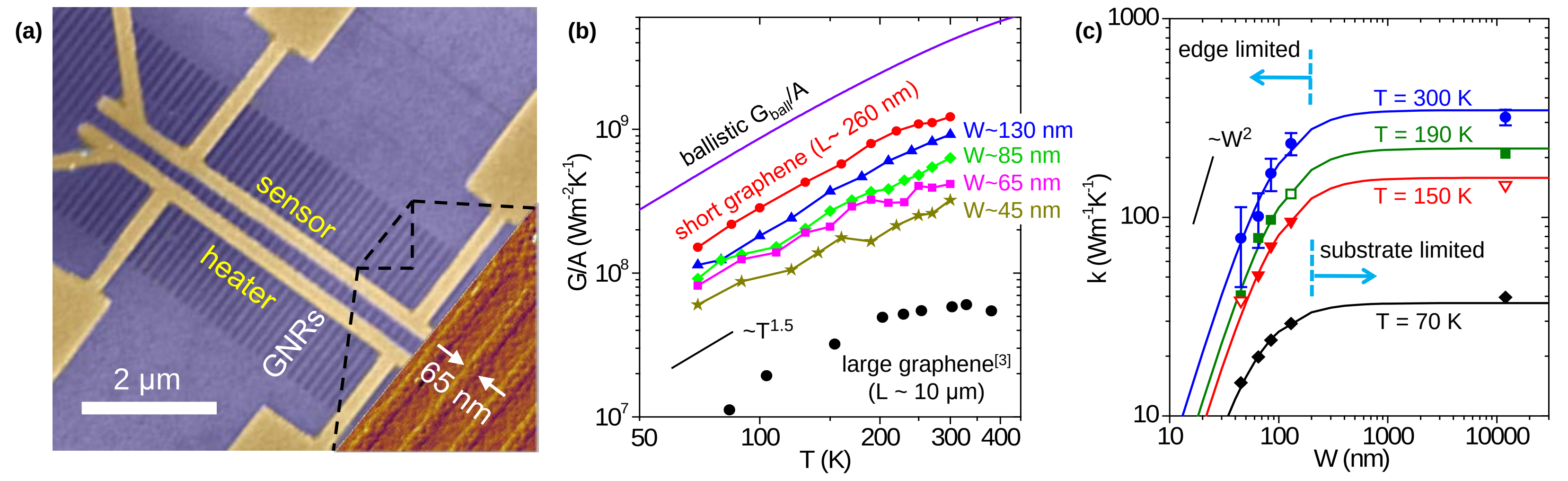

Figure (a): False-colored scanning electron microscopy image of parallel heater and sensor metal lines on top of an array of graphene nanoribbons (GNRs). Inset shows atomic force microscopy image of GNRs. **(b)** Thermal conductance per cross-sectional area (*G*/*A*) vs. temperature for our GNRs ($L \approx 260$ nm, *W* as listed), a "short" graphene sample ($L \approx 260$ nm, $W \approx 12$ µm), and a "large" graphene sample from Seol *et al.*[3] ($L \approx 10$ µm, $W \approx 2.4$ µm). The short but wide graphene sample attains up to ~35% of the theoretical ballistic heat flow limit[2]. **(c)** Thermal conductivity reduction with width for GNRs, all with $L \approx 260$ nm, showing a scaling of ~$W^{1.8\pm0.3}$ in the edge-limited regime.

[1] M.-H. Bae, Z. Li, Z. Aksamija, P. N. Martin, F. Xiong, Z.-Y. Ong, I. Knezevic, E. Pop, "Ballistic to Diffusive Crossover of Heat Flow in Graphene Ribbons," *Nature Communications*, DOI: 10.1038/ncomms2755 (2013).

[2] A. Y. Serov, Z.-Y. Ong, E. Pop, ""Effect of Grain Boundaries on Thermal Transport in Graphene," *Appl. Phys. Lett.* **102**, 033104 (2013).

[3] J. H. Seol *et al*., "Two-Dimensional Phonon Transport in Supported Graphene," *Science* **328**, 213 (2010).

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