Thermally-Limited Current Carrying Ability of Graphene Nanoribbons

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Graphene nanoribbons (GNRs) are essential building blocks of future graphene electronics [1], however many unknowns persist about their electrical and thermal properties. Among these, the maximum current density of GNRs and their behavior under high-field transport are of both fundamental and practical importance. Here, we measure current densities of GNRs up to ~3 mA/µm near breakdown, but ultimately find that heat dissipation is the key mechanism limiting transport and reliability. Finally, we extract the GNR thermal conductivity for the first time, k ~ 80 W/m/K or more than an order of magnitude lower than that of 2-D graphene [2-4], most likely limited by edge roughness scattering.

GNRs devices (predominantly bilayer) with two-terminal Pd contacts were prepared from multi-wall carbon nanotubes [1] on SiO_2(300 nm)/Si substrates (Fig. 1). High-field measurements were combined with breakdown thermometry analysis [5] used previously for carbon nanotubes. Breakdown was carried out by applying an increasing DC voltage between source and drain until the device breaks irreversibly from Joule heating and oxidation in air (Fig. 1B). The breakdown temperature of graphene and nanotubes in air is known, T_{BD} ~ 600 °C [5]. In addition, the gate voltage is set at V_G = -40 V to minimize hysteresis (Fig 1C). Similar devices of micron-sized 2-D exfoliated graphene (ex-G) were studied as well.

We find that the device breakdown power (P_{BD}) increases with the square root of the device surface area (Fig. 2A). To understand this trend, a self-heating model is used to predict the breakdown power, P_{BD} in our devices. The calculations take into account the Joule heat dissipated into the oxide, the contacts, as well as within the GNR itself. We note that our model is in good agreement with our data. Examining Fig. 2A, we note that data for GNRs < 0.3 µm varies more than that for graphene > 0.3 µm. The spread in the data can be described by varying the graphene thermal conductivity, k in the model, thus pointing out the increased role this parameter has on power dissipation at small dimensions.

In Fig. 2B we plot the breakdown current density (I_{BD}/W) vs. device width. The results show that the maximum current density scales inversely with width, and can reach >3 mA/µm for GNRs ~15 nm wide. To find the cause of this trend, we study how the total thermal conductance per unit area, G'' and the thermal conductance per unit area into the underlying substrate, h scale with width in Figs. 3A and 3B. From both figures, we observe a similar inverse scaling with width for both h and G'' as we did for the current density. Such dependence can be explained by Figs. 3C-E. Figure 3C diagrams how heat is dissipated both into the contacts and into the underlying substrate. In addition, we find that for larger 2-D graphene sheets >0.3 µm (Fig. 3D), dissipation occurs mainly 'vertically down' into the SiO_2. However for narrow GNRs (Fig. 3E), the lateral heat spreading into the SiO_2 becomes a significant contributor for dissipation, leading to an increase of G'', the total thermal conductance per unit area.

Likewise, heat dissipated in GNRs at high field depends on the thermal conductivity (k) and length (L) of each sample, as indicated by Figs. 3A and 3B. Here, GNR lengths were L = 0.2-0.7 µm. By fitting the measured breakdown power and current density with our thermal breakdown model, we extracted the GNR thermal conductivity for the first time. We found the range k = 63-450 W/m/K for our 15 GNR samples, with a median k ~130 W/m/K at T_{BD} ~ 600 °C, or k ~ 78 W/m/K at 20 °C, estimated from the T dependence of heat capacity [5]. The thermal conductivity of such GNRs is an order of magnitude lower than that of "large" 2-D graphene [2-4] on SiO_2 (Fig. 4). The reduction of k suggests a strong effect of edge scattering on high-field and thermal transport in narrow GNR transistors.

References

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Figures

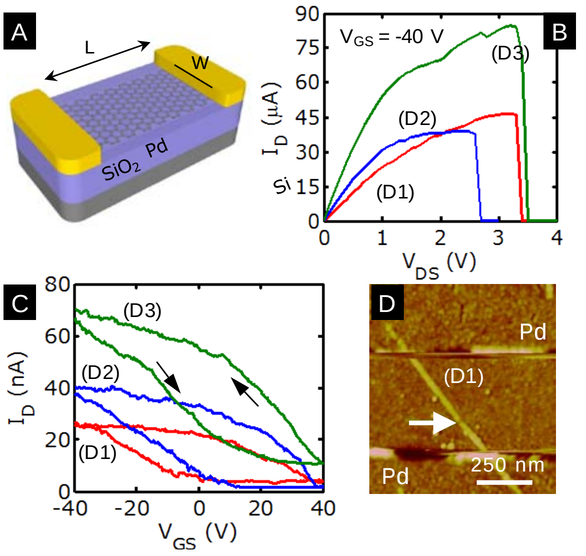

Fig. 1. (A) Schematic of typical graphene device used in this work. (B) Measured current-voltage (I_D-V_{DS}) up to breakdown of GNRs in air; dimensions are (D1) W = 20 nm, L = 510 nm, (D2) W = 16 nm, L = 590 nm, and (D3) W = 38 nm, L = 390 nm. (C) Corresponding I_D-V_{GS} transfer curves display typical hysteresis in air (arrows show sweep direction). Data in (B) were taken at V_{GS} = -40 V where hysteresis is minimal. (D) AFM image of GNR device D1 after high-current sweep; white arrow shows breakdown location.

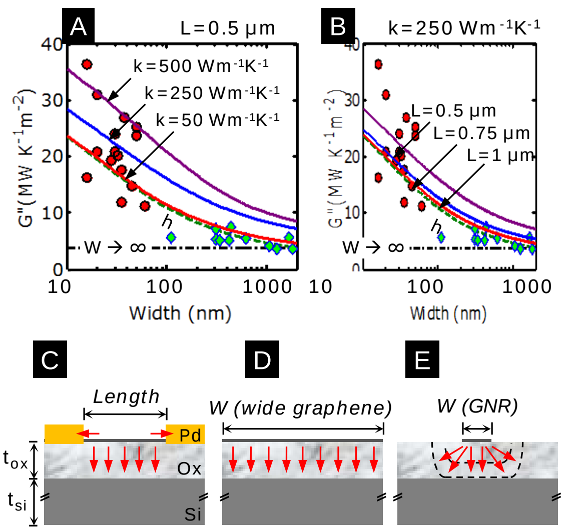

Fig. 3. Thermal conductance of device per unit area (G'') vs. width for graphene of varying (A) thermal conductivity and (B) length. Both parameters affect heat sinking along the device, as illustrated in (C), affecting sensitivity to in-plane k. Dashed lines show the modeled contribution from the graphene/SiO_2 thermal boundary conductance h; horizontal dash-dotted line is the limit for $W \to \infty$ which applies to the case shown in (D), only "vertical" heat sinking through oxide. The significance of lateral heat spreading from GNRs is shown in (E).

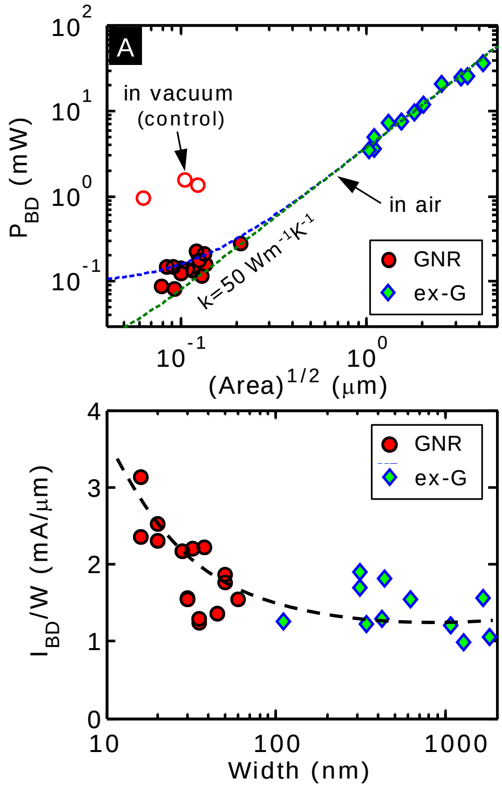

Fig. 2. (A) Scaling of breakdown power with square root of device footprint. Dashed lines are thermal model with k = 50 and 500 W/m/K. Lateral heat sinking and in-plane GNR thermal conductivity begin to play a role in devices < ~0.3 μm (also see Fig. 3). Heat sinking from larger 2-D exfoliated devices (ex-G) is entirely limited by the SiO_2. A few GNRs were broken in vacuum as a control group. (B) Scaling of maximum current vs. device width, demonstrating greater current density in narrower GNRs that benefit from 3-D heat spreading and lateral heat flow along the GNR (also see Fig. 3). Dashed line drawn to guide the eye.

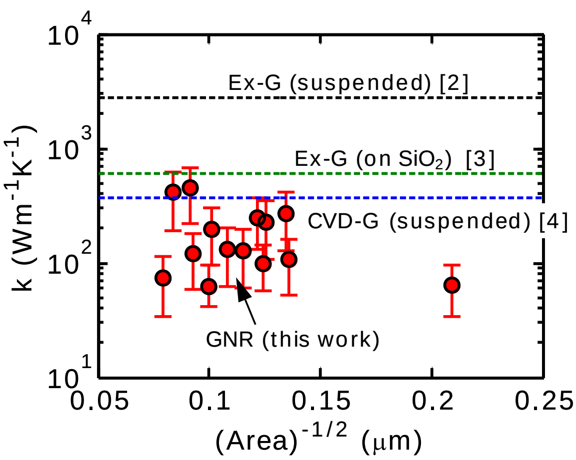

Fig. 4. Thermal conductivity of GNRs from this work, compared to large-area graphene measurements from literature [2-4]. The range obtained is 63–450 $Wm^{-1}K^{-1}$ with a median of 130 W/m/K at the breakdown temperature (600 ^oC). The median value at room temperature is ~40% lower, or ~78 W/m/K, nearly an order of magnitude below that of large-sized exfoliated graphene on SiO_2 [3], illustrating the role of phonon-edge scattering.