ADVANCED ELECTRONIC MATERIALS

Supporting Information

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Graphene Field-Effect Transistors on Hexagonal-Boron Nitride for Enhanced Interfacial Thermal Dissipation

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1. Experimental details of carrier mobility calculation

The mobility was calculated from the linear regime of the transfer characteristics using the equation:

$$\mu = \left(\frac{L}{W C_i V_{ds}}\right)\left(\frac{\Delta I_{ds}}{\Delta V_g}\right)$$

Where C_i is the gate capacitance of the dielectrics, I_{ds} is the drain-source current, V_g is the gate voltage, and μ is the field-effect mobility. $\Delta I_{ds}/\Delta V_g$ was calculated from the slope between $V_g = -60$ V and V_{Dirac} (V_g at Dirac point).

The *h*-BN/SiO_2/Si has two dielectric layers. The thickness of SiO_2 used in this work is 300 nm, while the thickness of the *h*-BN is about 0.85 nm. The C_i of 300 nm SiO_2 is about 10 nF cm^{-2}. The capacitance of *h*-BN was calculated by:

$$C_{h\text{-BN}} = \mathrm{k}\,\varepsilon_0 / \mathrm{d}$$

where k is the dielectric constant of *h*-BN (the value is about 4.0), ε_0 is the permittivity, and d is the thickness of *h*-BN. As a result, the C_i of *h*-BN was about 4164 nF cm^{-2}.

Therefore, the two-layer system in series contributes to the total capacitance (C_{total}) of 9.98 nF cm^{-2} based on the equation:

$$1 / C_{total} = 1 / \mathrm{C}_{SiO2} + 1 / C_{h\text{-BN}}$$

2. Experimental details of differential 3ω measurement.

A 3 μm-wide Cr/Au (5 nm/50 nm) electrode was deposit onto graphene, through electron beam lithography and thermal evaporation process. Next, high dose O_2 plasma was used to oxide the graphene layer and remove *h*-BN layer, to make sure that heat dissipates only in vertical direction. This process is crucial for 3ω measurement where one should assume heat flow only in one direction.

An alternating current (AC) with a frequency of ω is applied on the electrode, which generates a fluctuation of Joule heat power with a frequency of 2ω and also a temperature fluctuation with a frequency of 2ω ($T_{2\omega}$). The resistance of the electrode (R) has a linear dependence with the temperature (T). As a result, an AC voltage with a frequency of 3ω ($V_{3\omega}$) is detected, and the temperature increase of the electrode can be calculated from:

$$T_{2\omega} = 2\frac{\mathrm{d}T}{\mathrm{d}R}\frac{R}{V}V_{3\omega}$$

where V and $V_{3\omega}$ are the measured voltage with frequency of 1ω and 3ω, respectively.

The calculated thermal resistance is the sum of the substrate thermal resistance and the interfacial thermal resistance. Therefore, the actual interfacial thermal resistance of P-G/*h*-BN/SiO_2 is lower than calculated thermal resistance. It is difficult to measure the interfacial thermal resistance of P-G/SiO_2 interface and P-G/*h*-BN/SiO_2 interface directly. However, the difference of the interfacial thermal resistance of P-G/SiO_2 interface and P-G/*h*-BN/SiO_2 interface can be detected by differential 3ω method. To carry out the differential 3ω method, the electrodes were fabricated both on P-G/SiO_2 interface and P-G/*h*-BN/SiO_2 interface. The differential interfacial thermal resistance can be calculated by:

$$R_{\mathrm{int}} = \frac{\Delta T_{2\omega}\cdot S}{P}$$

where R_{int} is differential interfacial thermal resistance between P-G/SiO_2 interface and P-G/*h*-BN/SiO_2 interface, S is cross-section area between electrode and P-G, P is the Joule heat power and $\Delta T_{2\omega}$ is the $T_{2\omega}$ difference between P-G/SiO_2 interface and P-G/*h*-BN/SiO_2 interface.

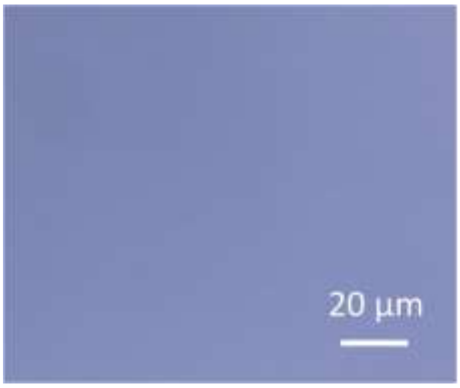

Figure S1. Optical image of *h*-BN film grown on SiO_2/Si by PECVD (30 min).

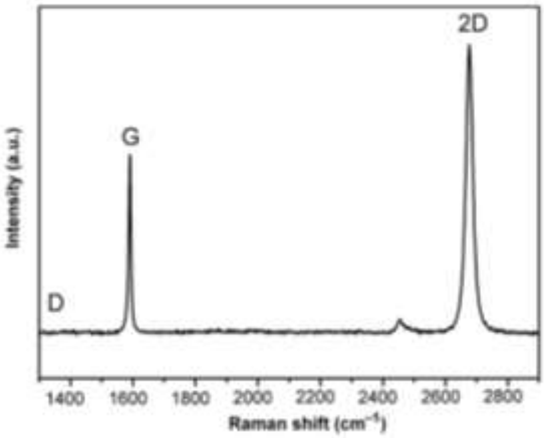

Figure S2. Raman spectrum of a P-G sheet on *h*-BN/SiO_2/Si.

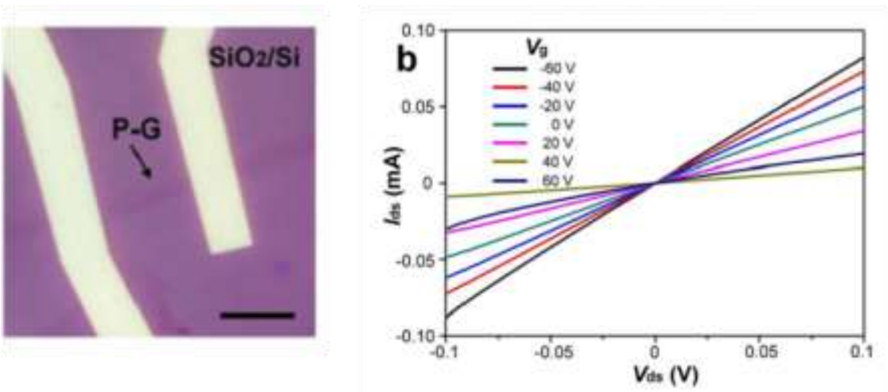

Figure S3. (a) The optical microscopy image of a P-G FET. (b) Output curve of a P-G FET produced on bare SiO_2/Si. The scale bar is 10 μm.

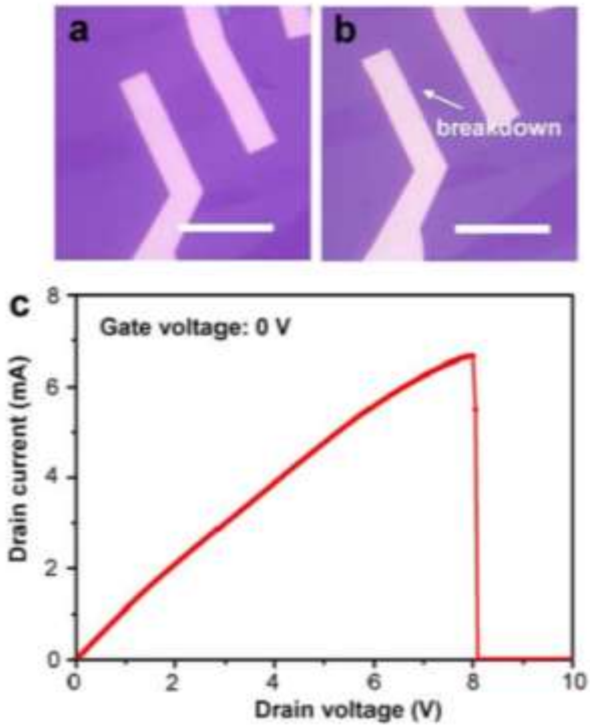

Figure S4. (a) Optical image of a P-G FET before and (b) after the current breakdown. (c) I_{ds}-V_{ds} curve of the current breakdown of the P-G FET device on SiO_2/Si. The scale bar is 20 μm in (c).

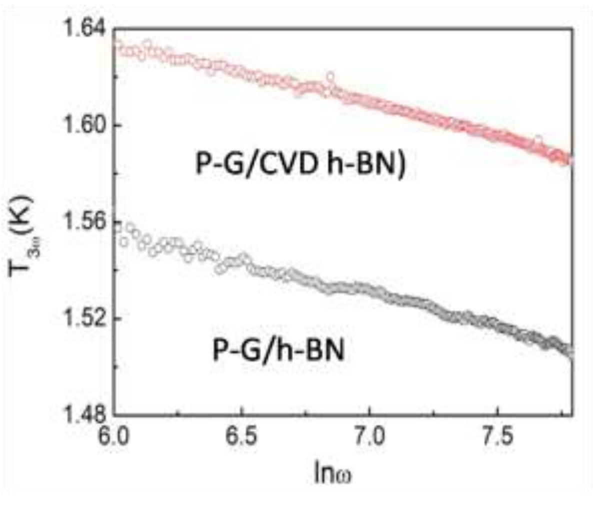

Figure S5. $T_{3\omega}$ versus ln ω curves of the P-G/*h*-BN (PECVD)/SiO_2 (black) and P-G/*h*-BN (post-growth transferred CVD *h*-BN)/SiO_2 (red) interfaces.