Introduction

The development of two-dimensional (2D) heterostructures composed of graphene, hexagonal boron nitride (hBN) and transition metal dichalcogenides (TMDCs) has opened a new avenue beyond the current Si-based electronics. The presence of van der Waals (vdW) interactions between layers of 2D atomic crystals can be used in designing novel electronic, optoelectronic and photonic devices by enabling the manufacturer to control the thickness of the device on the atomic scale and to stack different 2D crystals in diverse ways [1–5]. To fully understand the operating mechanism of devices made of vdW heterostructures, it is crucial to study how heat is generated and dissipated in these devices, and how such generation and dissipation are affected by the transport of hot charge carriers and phonons through the different 2D layers. For example, the energy-relaxation process of photo-excited hot carriers has been studied in various vdW heterostructures such as MoS2/WS2, graphene/hBN/graphene and graphene/semiconducting TMDC/graphene [6–8]. Furthermore, the phonon transport through the vdW heterostructures has been studied in terms of the thermal boundary resistance (TBR) between dissimilar 2D materials [9, 10].

To develop energy-efficient 2D electronics, both electric transport and energy transport should be considered simultaneously in order to understand more comprehensively the role of the energy dissipation in the vdW heterostructures. While heat management has been extensively studied in conventional Si devices, III–V semiconductor-based heterostructures [11] and graphene (or MoS2)/SiO2 devices [12, 13], the study of the mechanism of energy dissipation in 2D vdW heterostructures is still in its infancy. For a graphene/hBN device, for example, since the power density per unit...
length along the graphene channel under a high bias is not uniform, one needs to measure temperature \( T \) profiles of both graphene and hBN together with carrying out proper numerical electro-thermal transport calculations in order to fully investigate the genuine role of energy dissipation in the vdW-heterostructure devices.

In this study, we performed spatially resolved Raman thermometry on biased graphene/hBN heterostructure devices in air to investigate the energy dissipation in the vdW heterostructure (see figure 1(a)). The measured temperature of the hBN \( T_{\text{BN}} \) underneath an operating graphene field-effect transistor (FET) with a channel length \( L \) of 26 \( \mu \text{m} \) agreed well with the \( T_{\text{BN}} \) estimated by an analytical calculation for \( T_{\text{BN}} \leq 100 \) °C. Furthermore, to explore power dissipation in an extreme case, we carried out studies in which we approached the break-down \( T \) of graphene (~600 °C) in air with a relatively short, \( L = 5 \mu \text{m} \), graphene device. By comparing the temperature profile along a biased graphene channel \( T_{\text{GR}} \) with that along the hBN substrate, we found the TBR between graphene and hBN to be in the range (1−2) \( \times 10^{-7} \text{ m}^2 \text{ K}^{-1} \text{ W}^{-1} \) for \( T = 100−600 \) °C. Also, by performing Raman thermometry together with numerical calculations using an electro-thermal transport model, we showed that the doping effect under a high-field transport limit significantly affected the energy dissipation in the graphene channel on hBN for the entire \( T \) range examined.

Results

Raman thermometry mapping

To realize a graphene device on an hBN layer, we placed mechanically exfoliated hBN flakes on top of a 90 nm thick SiO\(_2\)/Si substrate. Then, onto a selected 80 nm thick hBN flake (supplementary figure S1 (stacks.iop.org/TDM/5/025009/mmedia)), we placed a single layer of graphene using a transfer method [14]. We then used electron-beam lithography to deposit metal electrodes (Cr (5 nm)/Au (95 nm)) for the source and drain. For the electrical measurements, the highly p-doped Si substrate was used as an electrode to apply a back-gate voltage \( V_{\text{bg}} \). Figure 1(b) shows an optical microscope image of the completed device with a channel length \( L \) of 26 \( \mu \text{m} \) and width \( W \) of 6 \( \mu \text{m} \), where ‘S’ and ‘D’ mark the locations of the source and drain, respectively. The mobility of charge carriers in the graphene was measured to be \( \sim 7000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \) based on the fit of the resistance versus \( V_{\text{bg}} \) curve (supplementary section 1). For the Raman thermometry, we performed the \( T \) calibration process using a laser beam with an excitation wavelength of 633 nm \([9, 15]\). For this device, the intensities of the G and 2D peaks were not sufficiently strong to define the energy values through the graphene channel (supplementary figure S3). Thus, we obtained the experimental \( T_{\text{BN}} \) map from the hBN substrate based on the \( E_{2g} \) phonon energy of hBN beneath the graphene channel for a case of this device. The dependence of the \( E_{2g} \) phonon energy of hBN on \( T \) was determined by heating the graphene/hBN FET device on a hot plate, which gave a slope, \( S_{\text{BN}} \), of \(-0.0218 \text{ cm}^{-1}/\text{°C} \) (supplementary figure S4(a)). We also confirmed that the 633 nm wavelength laser did not result in any significant photo-induced doping of the graphene channel on hBN [16] (supplementary section 2). In all of hBN thermometry experiments, we did not apply a finite \( V_{\text{bg}} \).

Figure 1(c) shows the representative Raman spectra of the hBN underneath the graphene FET at \( V_{\text{sd}} = 0, 10, −10, 15 \) and \(-15 \text{ V} \), which were recorded at the middle of the channel. The dashed vertical line indicates the location of the \( E_{2g} \) phonon energy at \( V_{\text{sd}} = 0 \) V. For finite \( V_{\text{sd}} \), the \( E_{2g} \) phonon energy showed a red-shift behavior. For example, the \( E_{2g} \) phonon energy shifted downward from 1366.22 to 1364.55 \text{ cm}^{-1} \) when \( V_{\text{sd}} \) was changed from zero to \(-15 \text{ V} \), where the peak energies were obtained from the Lorentzian fit as shown by the red curves on the Raman spectra. From the value of \( S_{\text{BN}} \) indicated above and the 22.4 °C value of the ambient \( T \), \( T_{\text{bn}} \), we estimated the \( T_{\text{BN}} \) at the middle of the channel to be \(-100 \) °C at \( V_{\text{sd}} = -15 \text{ V} \) based on a relation of \( T = T_{\text{bn}} + (\omega_{\text{BN}} - \omega_{\text{BN}}^0)/S_{\text{BN}} \), where \( \omega_{\text{BN}}^0 \) and \( \omega_{\text{BN}} \) are the \( E_{2g} \) energies of the hBN at zero and finite \( V_{\text{sd}} \), respectively. Based on this process, we produced maps, with pixel dimensions of \( 1 \times 1 \mu \text{m}^2 \), of the \( T_{\text{BN}} \) underneath the graphene channel for various \( V_{\text{sd}} \) values (figure 1(d)) by scanning the laser beam over the entire graphene channel. Supplementary figure S5 shows \( E_{2g} \)-energy maps of the hBN underneath the graphene channel at corresponding \( V_{\text{sd}} \) values including the zero bias condition. The average \( T \) of the entire hBN area underneath the graphene channel was found to increase with increasing \( V_{\text{sd}} \), i.e. to 43.2 °C (47.7 °C) and 76.4 °C (92.3 °C) at \( V_{\text{sd}} = 10 \) and 15 (−15) V, respectively. Interestingly, the left side was hotter than the right side with a difference of \sim 30 °C at \( V_{\text{sd}} = 15 \text{ V} \), in contrast to a nearly homogeneous \( T \) distribution through the entire hBN channel at \( V_{\text{sd}} = -15 \text{ V} \), and this issue is discussed below.

For a detailed analysis, we plotted, as shown in figures 2(a)−(d), profiles of \( T_{\text{BN}} \) (triangles or solid circles) along the hBN beneath the graphene channel at \( V_{\text{sd}} = 10, −10, 15 \) and −15 V, respectively, where the \( T_{\text{BN}} \) shown at each indicated x position was calculated as the average of the \( T \) values over the y axis in figure 1(d). The average \( T_{\text{BN}} \) showed relatively similar values of \sim 45 °C and \sim 50 °C for \( V_{\text{sd}} = 10 \text{ V} \) and −10 V (see figures 2(a) and (b)), respectively, but rather dissimilar values of \sim 81 °C and 96 °C for \( V_{\text{sd}} = 15 \) and −15 V (see figures 2(c) and (d)), respectively. To gain insight into the measured \( T \) values for graphene and hBN, we analytically calculated \( T \) values based on the schematic shown in figure 2(e). In the steady state, the average \( T \) of the graphene \( (T_{\text{GR}}) \) for a given electrical power \( (P) \) was calculated from the total thermal resistance \( (R_{\text{tot}}) \) from the graphene to the heat sink of the Si substrate according to the equation...
\[ T_{\text{AG}} = R_{\text{tot}}P + T_0, \]

where \( R_{\text{tot}} = R_{\text{GB}} + R_{\text{BN}} + R_{\text{ox}} + R_{\text{Si}} \) \( R_{\text{GB}} \approx (1.35 \times 10^{-7} \text{ m}^2 \text{ K W}^{-1}) \) [9], \( R_{\text{BN}} \approx (2.2 \times 10^{-8} \text{ m}^2 \text{ K W}^{-1}) \) [17], and \( R_{\text{ox}} \approx (10^{-8} \text{ m}^2 \text{ K W}^{-1}) \) [18] are the thermal resistances of the hBN, SiO2 and Si substrate, respectively [12]. Here, \( k_{\text{BN}} \approx (3 \text{ W m}^{-1} \text{ K}^{-1}) \), \( k_{\text{ox}} \approx (1.3 \text{ W m}^{-1} \text{ K}^{-1}) \) and \( k_{\text{Si}} \approx (50 \text{ W m}^{-1} \text{ K}^{-1}) \) are the thermal conductivities of hBN (out-of-plane) [19], SiO2 and the highly doped Si, respectively [12]. We obtained \( R_{\text{tot}} \approx 2480 \text{ K W}^{-1} \), resulting in a \( T_{\text{AG}} \) of \( \approx 63.8 \text{ °C} \) with a \( P \approx (1.67 \text{ mW}) \) at \( V_{\text{sd}} = \pm 10 \text{ V} \), and with \( R_s \approx (950 \Omega) \) being the series resistance. At \( V_{\text{sd}} = \pm 15 \text{ V} \), we obtained a \( T_{\text{AG}} \) of \( \approx 116 \text{ °C} \). Then, we estimated the \( T \) drop through the interface between graphene and hBN, using the relationship \( \Delta T_{\text{GB}} = P R_{\text{GB}}/(LW) \), to be \( \approx 14.5 \text{ and } \approx 32.8 \text{ °C} \), resulting in \( \approx 49 \) and \( \approx 83 \text{ °C} \) values for \( T_{\text{BN}} \) at \( V_{\text{sd}} = \pm 10 \text{ V} \) and \( \pm 15 \text{ V} \), respectively. The analytically calculated \( T_{\text{BN}} \) values for \( V_{\text{sd}} = 10, -10 \) and 15 V, as shown by the dashed horizontal black lines in figures 2(a)–(c), respectively, were found to be consistent with the corresponding measured \( T_{\text{BN}} \) values (solid triangles or solid circles) near the middle of the channel. Partial disagreements at the ends of channel are because the model does not consider the cooling effect by the electrodes.

**High-field induced local doping**

The averaged measured \( T \) values of hBN at \( V_{\text{sd}} = \pm 15 \text{ V} \), however, as shown by the solid circles in figure 2(d) were found to be as much as \( \approx 10 \text{ °C} \) greater than the analytically estimated values (dashed horizontal line). We attributed this difference to a local doping under the condition of high-field transport with a relatively high \( V_{\text{sd}} \) value. For graphene on a SiO2 substrate, a locally high electric field has been shown to induce trapped charges in SiO2 near the interface between graphene and SiO2, and to hence result in the local doping [20]. The local doping was itself be manifested by the appearance of another new local resistance maximum aside from the original local resistance maximum observed at the charge neutral gate voltage \( (V_{\text{g0}}) \) in the \( R-V_{\text{bg}} \) curves. In the case of graphene on hBN, there was only one local resistance maximum at \( V_{\text{g0}} \approx 13 \text{ V} \) in the beginning of the thermometry experiment as shown in figure 3(a). After

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**Figure 1.** (a) Schematic of the measurement configuration in a laser scanning mode. (b) Optical microscope image of a graphene field-effect transistor (\( L = 26 \mu \text{m} \) and \( W = 6 \mu \text{m} \)) on an hBN/SiO2/Si substrate. The dashed lines indicate the boundary of the graphene channel. The scale bar is 10 µm. (c) Raman spectra with the hBN E2g peaks at \( V_{\text{sd}} = 0, 10, -10, 15 \) and \( -15 \text{ V} \), which were taken at the middle region of the channel. Red curves are the Lorentzian fits. The vertical dashed line indicates the location of the peak at zero bias. (d) \( T_{\text{BN}} \) maps underneath the graphene channel for various \( V_{\text{sd}} \) values. The left and right ends are the drain (D) and source (S), respectively.

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applying a $V_{sd}$ of 10 V for the Raman thermometry, however, an additional local resistance maximum at $V_{bg} \sim 0$ V appeared (see a blue curve in figure 3(b)). Then, it disappeared after applying a $V_{sd}$ of $-10$ V and was again observed after applying a $V_{sd}$ of 15 V (see blue curves in figures 3(c) and (d)). Thus, we concluded that there was a local doping caused by the locally high field in the graphene on the hBN layer based on the above history-related doping effect, as has previously been observed for graphene on SiO$_2$ layer [20].

The $-10 \mu m < x < 3 \mu m$ region of the channel was measured to be hotter than the other regions when the $V_{sd}$ was 15 V, as shown in figure 1(d). The greater $T$ of this region reflects the electric field of the...
corresponding graphene region being stronger than that of the other regions [12], which may have led to a high-field-induced doping effect in this left (or drain) side of the graphene on hBN. Furthermore, the Joule-heat-induced high T likely resulted in local annealing, which could have led to the additional local doping in the graphene. Such local doping leads to different Fermi energy levels along the graphene channel, as shown in the upper panel of figure 2(f) with \( V_{sd} = 0 \) V, where the dashed line indicates the Fermi energy level. The portion of channel near the drain has less hole doping than that near the source, according to the observation of a newly appeared local resistance maximum in the \( R-V_{bg} \) curve located near \( V_{bg} \sim 0 \) V together with the maintenance of the original local resistance maximum at \( V_{bg} \sim 13 \) V (see figure 3(d)).

With the non-uniform carrier density profile along the graphene channel as an initial condition, applying a \( V_{sd} \) of \(-15\) V led to a change in the Fermi level along the graphene channel, as shown in the lower panel in figure 2(f). Interestingly, in that case, the carrier density resided near the charge-neutral condition along the entire graphene channel, in contrast to the case for which a \( V_{sd} \) of 15 V was applied (see the lower panel of figure 2(f)). This resulted in a relatively uniform and high resistance through the entire channel, and thus a higher average experimentally determined \( T \) (solid circles in figure 2(d)) than expected from the calculations (dashed horizontal line in figure 2(d)).

**Electro-thermal transport model**

The analytical approach based on equation (1) assumed that the graphene channel was exposed to a uniform electric field or homogeneous power density. But, the electric field would be expected to vary along the channel under a high-\( V_{sd} \) regime due to the carrier density significantly varying along the channel (see the lower panel of figure 2(f)). Thus, to reveal the genuine \( T \) profile of the graphene channel and the local field strength causing local doping at graphene on hBN, we performed a numerical simulation based on the electro-thermal transport model. We numerically calculated the \( T \) profile along the graphene and hBN by considering the local electric field \( F_x \) as given by the equation \( F_x = -dV_x/dx \), where \( V_x \) is the local voltage in the graphene channel with \( x = -L/2 \sim L/2 \) [12]. The local \( T \) \( (T_x) \) along a channel of interest with a local power density per unit length \( p'_x \), calculated using the equation \( p'_x = IF_x \), and a current \( I \) is given by the steady-state heat equation

\[
AK \frac{d^2T_x}{dx^2} + P_x - \frac{1}{\th} (T_x - T_0) = 0, \tag{2}
\]

where \( A \) is the cross-sectional area of the heat channel, \( k \) is the in-plane thermal conductivity of the heat channel and \( R_{th} \) is the thermal resistance from the material of interest to the heat sink. In the case of graphene, the \( F_x \) was calculated by the drift velocity and mobility with local carrier density based on \( R-V_{bg} \) curves (with the calculation details provided elsewhere [12]). Figures 3(d) and (e) show \( R-V_{bg} \) curves (blue) after thermometry performed at \( V_{sd} = 15 \) V and \(-15\) V, respectively. For the numerical calculations of \( T \) profiles, we used red curves of the fits to get mobility and \( V_{bg} \) in corresponding data. We also obtained the voltage \( (V_x) \) drop along the graphene by integrating \( F_x \) along the channel length. In this way, we calculated \( I-V_{sd} \) curves (solid curves), which are shown along with the experimental data (scattered points) in supplementary figure S6: the \( I-V_{sd} \) curves were obtained while the bias voltage reached to \( V_{sd} = \pm 10 \) V and \pm 15 V.

Figures 2(a)–(d) show the \( T \) profiles of graphene (dashed red curves) and hBN (solid red curves) obtained by carrying out simulations at \( V_{sd} = 10, -10, 15, \) and \(-15\) V, respectively. In equation (2), we considered \( R_{bg} = R_{th} \) with \( k = k_c = 700 \) W m\(^{-1}\) K\(^{-1}\) to calculate the \( T \) profile in the graphene channel on the hBN, where \( k_c \) is the thermal conductivity of graphene [21] on hBN. Here, we used an \( R_{bg} \) value of \( 1.35 \times 10^{-7} \) m\(^2\) K\(^{-1}\) for the calculations based on a recent report [9], although the value could be lowered by improving the quality of the graphene/hBN interface [10]. The result showed a local maximum (or hot spot) in the graphene channel for all conditions, where the location of the hot spot depended on the \( V_{bg} \) and \( V_{sd} \) conditions. For example, a hot spot was located at the drain when a \( V_{sd} \) of 15 V was used (see dashed curve in figure 2(c)). The presence of a hot spot here was attributed to the local minimum in the hole carrier density at the drain in a hole-doped region (see the lower panel of figure 2(f)), resulting in a local maximum drift velocity \( (V_{sd}) \) with a continuity equation for a current density of \( j = n_e e d \), where \( n_e \) and \( e \) are a local total carrier density and elementary charge, respectively. This also led to a local maximum \( F_x \) at the drain with the relationship \( T_{th} \sim F_x \), accompanied by a local maximum power density and hot spot in that region. On the other hand, the hot spot in the graphene was located at the source at \( V_{sd} = -15 \) V in figure 2(d) because the minimum hole carrier density is located at the source [12].

On the other hand, the experimentally obtained \( T \) profiles along the hBN (triangles or solid circles) in figures 2(a)–(d) did not show such sharp hot spots as the \( T \) profiles calculated for graphene channel. This difference was related to the ratio between the heat dissipation rates through lateral and substrate directions. The length scale of the lateral heat dissipation is the lateral heating length, \( L_H = L \sqrt{R_{th}^\parallel} / R_0^\parallel \), where \( R_0^\parallel = (k^\parallel A/L)^{-1} \) is the in-plane thermal resistance of the material of interest [12]. For the hBN with in-plane thermal conductivity [22] \( k_{BN} \) of 400 W m\(^{-1}\) K\(^{-1}\) and a thickness of 80 nm, we obtained an \( L_{BN} \) (healing length of hBN layer) value of \( \sim 2.4 \) \( \mu \)m. Here, a total thermal resistance from hBN to a Si heat sink is given by \( R_{th,BN} = R_{th} + R_{BN} \). In the case of the graphene, on
the other hand, an $L_{HG}$ value of $\sim 0.3 \mu m$ was obtained for $k_G = 600 - 900 \text{ W m}^{-1} \text{ K}^{-1}$ with a total thermal resistance from graphene to a heat sink of $R_{HG} = R_{os}$, resulting in relatively sharp hot spots as shown by the dashed lines in figures 2(a)–(d). For the numerical calculation of the $T$ profile along the hBN, we used $A = W \times l_{BN}$ as the cross-sectional area for the lateral heat flow. The heat flux density $p_x^T$ used for hBN was the same as that calculated from the graphene channel. The calculated $T$ profiles along the hBN channel denoted by the solid red curves in figures 2(a)–(c) showed good agreement with the experimental data for $V_{sd} = 50 \mu V$, $-10 \mu V$, and $15 \mu V$, respectively.

At $V_{sd} = -15 \text{ V}$, the experimentally obtained $T$ profile of hBN deviated significantly from the calculation (solid red curve in figure 2(d)) at the drain region but not at the source region. In the electro-thermal calculation, we assumed a uniform doping with a single local resistance maximum at $V_{g0} = 12 \text{ V}$ (see the red curve in figure 3(e)). However, the experimentally obtained $R-V_{bg}$ curve (blue curve in figure 3(e)) showed an additional local maximum (vertical arrow) at $V_{bg} \sim 3 \text{ V}$, which indicated a local doping phenomenon. This local doping apparently resulted in another hot spot near the drain region, and hence led to $T$ rising in the drain as much as at the source in the hBN, as shown in figure 2(d) (solid circles). This result is consistent with the analytic analysis in the previous section.

To determine the field-strength range causing the local doping, we plotted the electric-field strength ($F_x$) along the graphene channel when using a $V_{sd} = 15 \text{ V}$ (solid curve), as shown in figure 3(f). The region indicated to be locally doped, i.e. corresponding to the relatively high-$T$ region in the panel for $V_{sd} = 15 \text{ V}$ as shown in figure 1(d), is indicated by the double-headed arrow in figure 3(f); the magnitude of $F_x$ throughout this region was found to be greater than $0.4 \text{ V m}^{-1}$. On the other hand, we also observed two local resistance maxima in the $R-V_{bg}$ curves after applying a $V_{sd}$ of 10 V, as shown in figure 3(b) (blue curve). At $V_{sd} = 10 \text{ V}$, the magnitude of the calculated electric field strength (dashed curve in figure 3(f)) in the drain part was determined to be about $-0.35 \text{ V m}^{-1}$. These results indicated an electric field strength of $-0.35 \text{ V m}^{-1}$ to be sufficient to produce local doping in graphene on hBN. In the case of graphene on SiO$_2$, the local doping due to the electric field occurred with higher fields of $F > 2 \text{ V m}^{-1}$ [20] than that of graphene on hBN. While further study is needed to understand the difference between the activation electric field needed to induce a local doping in graphene on hBN and that in graphene on SiO$_2$, a similar situation was also observed in photo-induced doping experiments, i.e. the charge-trap energy of $\sim 2.6 \text{ eV}$ was obtained for SiO$_2$ [23], larger than that for hBN ($\sim 2.3 \text{ eV}$) [16].

Heat dissipation near the graphene break-down $T$ in air

To explore the heat dissipation at an extreme case near the graphene break-down $T$ of $\sim 600 \text{ °C}$ in air [24], we fabricated another graphene device on an 8nm thick hBN flake/290 nm thick SiO$_2$/Si substrate and having $L = 5 \mu m$ and $W = 2 \mu m$ (top panel of figure 4(a)), i.e. with an area an order of magnitude smaller than that of the device described in previous sections. For this smaller-area device, the Raman 2D peak of graphene was clearly observed through the entire channel (see figure 4(b) and supplementary figure S7); thus, we successfully obtained the $T$ maps of graphene and hBN simultaneously. The solid black circles in figure 4(b) show $E_{2g}$ and 2D modes of hBN and graphene, respectively, which were taken without bias voltage from the location of the channel indicated by the laser beam in the top panel of figure 4(a). When a bias voltage ($V_{sd} = 8.5 \text{ V}$) was applied, the $E_{2g}$ and 2D modes were shifted to lower energies (see solid red circles in figure 4(b)). By following a $T$-calibration process, plots of $T$ versus the $E_{2g}$ and 2D mode energies gave slopes $S_{BG} = -0.0341 \text{ cm}^{-1}/\text{°C}$ [15] and $S_{GR} = -0.0428 \text{ cm}^{-1}/\text{°C}$, respectively (supplementary section 3). Based on these $S_{BG}$ and $S_{GR}$ values and data in figure 4(b) (solid curves: Lorentzian fit results), we estimated the temperatures of graphene and hBN at the position indicated by the laser spot to be, respectively, $\sim 470 \text{ °C}$ and $\sim 180 \text{ °C}$ when applying a $V_{sd} = 8.5 \text{ V}$ at $T_0 = 24 \text{ °C}$. Based on this process, we mapped $T_{GR}$ and $T_{BG}$ at $V_{sd} = 8.5 \text{ V}$, by scanning the laser beam over the entire device channel (see middle (graphene) and bottom (hBN) panels in figure 4(a)). While the hBN showed gradual changes in $T$ along the channel was changed, there was a rather marked change in $T$ at the middle of the graphene channel. For further analysis, we plotted $T$ profiles for the graphene (squares) and hBN (circles) channels in figure 4(c), where the error bars reflect the variation in $T$ along the channel width at a given $x$ location. The steep change in $T$ of graphene occurred between $x = -1 \mu m$ and $x = 0 \mu m$, as indicated by grey squares; this marked change in $T$ was attributed to a local doping effect as discussed below.

In figure 4(d), the resistance changed in some regions during the course of the Raman scanning for hBN and graphene, and these changes were attributed to changes in $V_{g0}$ during the scanning process (supplementary figure S8). Note that the resistance did not change with considerable time periods with two resistance values of $\sim 6.3 \text{ kΩ}$ and $\sim 7.5 \text{ kΩ}$, respectively, marked (i) and (ii). These resistance levels are denoted by red and green points in the figure, respectively. The resistance changed with time between these regions (denoted by the grey points). The red, grey and green squares in figure 4(c) for the graphene were
obtained in the same colored-graphene time zones in figure 4(d), respectively. The region scanned during the time period in which the resistance increased with time (grey points after ~0.5 h in the graphene scanning region in figure 4(d)) coincided with a region showing a steep change in T with change in position (grey squares between x ~ 1 µm and x ~ 0.5 µm for the graphene channel in figure 4(c)). An I–Vsd curve (scattered green dots in figure 4(e)) was obtained as soon as finishing the Raman scanning. It indicated a resistance of ~7.5 kΩ at Vsd = 8.5 V together with the conditions of region (i). The dashed grey curve was obtained with RGB = 2 × 10^{-8} m^2 K W^{-1} together with the conditions of region (ii). (d) Resistance as a function of Raman thermometry scanning time values with a Vsd of 8.5 V. (e) Scattered orange points: I–Vsd curve for Vsd values up to 8.5 V applied for the thermometry. Scattered green points: I–Vsd curve just after the thermometry, and corresponding to region (ii) in (d). Red curve: I–Vsd curve satisfying the condition R = 6.3 kΩ at Vsd = 8.5 V and corresponding to region (i) in (d). Solid green and dashed orange curves: calculated fits to the corresponding experimentally derived I–Vsd curves.

On the other hand, when the scanning was started from the drain region, the resistance of the graphene was included in region (i) as shown in figure 4(d). This condition gave the TGR profile for −2.5 µm < x < −1 µm (red squares) in figure 4(c). To calculate the TGR profile for region (i), we first plotted its calculated I–Vsd curve (as shown by a solid red curve in figure 4(e)), from which we derived an R of ~6.3 kΩ at Vsd = 8.5 V. Here, Vg0 was determined to be 10.6 V for the calculation, in contrast to the 5.6 V value determined for the case of region (ii) (see a dashed red curve in supplementary figure S8(b)). This change in Vg0 perhaps resulted from the high-field-induced doping effect, since the field strength was already greater than 1 V µm^{-1} through the entire channel. Thus, there is no additional local maximum resistance unlike the L = 26 µm device case as shown in figure S8. The calculation taking into account the doping effect yielded results found to be in good agreement with the experimental TGR profile for −2.5 µm < x < −1 µm (solid red curve in figure 4(c)). From region (i) to region (ii), i.e. from x = −1 to 0.5 µm, TGR was observed to decrease from ~450 °C to ~350 °C (figure 4(c)), due to a doping effect. This result indicated the energy dissipation in the graphene channel to be strongly affected by a doping effect near the graphene break-down T. We also calculated the TRBN profile (circles: experiment; red and green curves on hBN data: calculations in figure 4(c)), by considering the change in resistance between regions (i) and (ii) in figure 4(d). While the graphene showed a steep T change with a doping effect, the hBN showed a relatively flat temperature profile, which is because of the different lateral healing length in graphene and hBN, as discussed already.

Note that R = 5.5 kΩ at the initial state in figure 4(d) quickly changed to the region (i) as soon as the Raman scanning was started. The experimentally determined I–Vsd curve (orange dots) was obtained for bias conditions up to Vsd = 8.5 V before the scanning. We calculated an I–Vsd curve (a dashed orange curve...
in figure 4(e)) and $T_{GR}$ profile (a dashed orange curve in figure 4(c)) at this condition, and the $T_{GR}$ nearly reached $\sim 600 \, ^\circ\text{C}$. Fortunately, the resistance quickly increased and reached the region (i) before the graphene channel disintegrated. Changing the bias polarity from 8.5 V to $-8.5 \, \text{V}$ left the sample resistance at $\sim 5.5 \, \text{k}\Omega$ (supplementary figure S9). At this condition, however, a doping effect did not occur and the graphene channel finally disintegrated in 50 s. The AFM image of figure 4(a) was obtained after the break-down event with $V_{sd} = -8.5 \, \text{V}$, and showed a graphene-broken region near the source. During the calculation, TBR values between graphene and hBN in the range of $(1-2) \times 10^{-7} \, \text{m}^2 \, \text{K} \, \text{W}^{-1}$ were obtained for $T = 100-600 \, ^\circ\text{C}$, consistent with values previously obtained at a $T$ of $\sim 100 \, ^\circ\text{C}$ [9]. We also plotted the $T_{GR}$ calculated with $R_{GR} = 2 \times 10^{-8} \, \text{m}^2 \, \text{K} \, \text{W}^{-1}$ (dashed grey curve in figure 4(c)) with the condition of region (ii); this $R_{GR}$ value is the lowest $R_{GB}$ value measured by experiment so far to the best of our knowledge [10]. We found that a reduction of the TBR by one order of magnitude resulted in a reduction of the local Joule heating effect by a factor of 1.3 at the same power.

Conclusion

We performed in situ Raman thermometry of the graphene and hBN in graphene/hBN 2D heterostructure devices, and these results together with consideration of an electro-thermal transport model indicated that a strong electric field induced doping and hence significantly affected how energy was dissipated in these devices. The TBR between graphene and hBN was determined to be in the range $(1-2) \times 10^{-7} \, \text{m}^2 \, \text{K} \, \text{W}^{-1}$ from 100 °C up to the graphene break-down $T$ of 600 °C in air. Although the estimated TBR was found to be an order of magnitude higher than that recently measured [10], using a high-quality 2D material/hBN interface is nevertheless essential for realizing efficient heat management in future heterostructure 2D electronics, as shown by our electro-thermal transport model. We expect our Raman thermometry of hBN to be easily extended to various 2D vdW heterostructure devices based on TMDC materials and black phosphorous, which we expect to provide useful information for the design of energy-efficient 2D heterostructure devices.

Experimental methods

Raman thermometry

The in situ Raman measurements were taken using a backscattering geometry. Incident light from an He–Ne laser with a wavelength of 632.8 nm was focused on the graphene/hBN FET channel surface through an optical microscope objective lens (50×/0.55NA). Scattered light was dispersed through a spectrometer equipped with a 1200 groove mm$^{-1}$ grating and detected using a thermoelectrically cooled charge-coupled device detector. For the spatially resolved Raman measurements, the sample was placed on a computer-controlled piezoelectric stage that was moved over the entire transport channel in either 0.5 or 1 µm intervals. During the Raman thermometry measurements, the excitation laser power was maintained at less than 1 mW, which corresponded to a power density of approximately $0.6 \times 10^7 \, \text{mW} \, \text{cm}^{-2}$. Heating effects on the sample due to laser absorption were not observed. The data for each map were acquired over the course of about 2 h. For the $T$-dependent Raman measurements, the sample was placed on a heating plate.

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