

# High Velocity Saturation in Graphene Encapsulated by Hexagonal Boron Nitride

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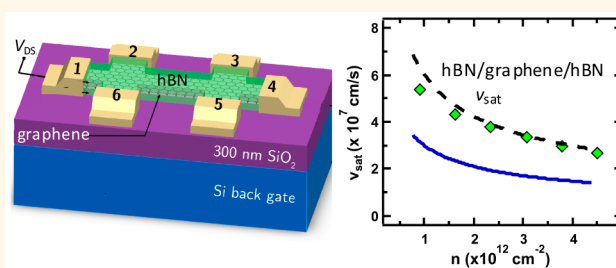
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## Supporting Information

**ABSTRACT:** We measure drift velocity in monolayer graphene encapsulated by hexagonal boron nitride (hBN), probing its dependence on carrier density and temperature. Due to the high mobility ( $>5 \times 10^4$  cm<sup>2</sup>/V/s) of our samples, the drift velocity begins to saturate at low electric fields ( $\sim 0.1$  V/ $\mu$ m) at room temperature. Comparing results to a canonical drift velocity model, we extract room-temperature electron saturation velocities ranging from  $6 \times 10^7$  cm/s at a low carrier density of  $8 \times 10^{11}$  cm<sup>-2</sup> to  $2.7 \times 10^7$  cm/s at a higher density of  $4.4 \times 10^{12}$  cm<sup>-2</sup>. Such drift velocities are much higher than those in silicon ( $\sim 10^7$  cm/s) and in graphene on SiO<sub>2</sub>, likely due to reduced carrier scattering with surface optical phonons whose energy in hBN ( $>100$  meV) is higher than that in other substrates.

**KEYWORDS:** graphene, boron nitride, drift velocity saturation, high field, phonon scattering



Graphene-based electronic devices have been extensively investigated,<sup>1–10</sup> inspired by the material's unusual band structure,<sup>11</sup> high intrinsic mobility,<sup>12</sup> high thermal conductivity,<sup>9,13</sup> and ability to withstand high current densities.<sup>14</sup> Electron flow in graphene under low (lateral) electric fields shows distinctive behavior such as Klein tunneling<sup>15</sup> and the half-integer quantum Hall effect.<sup>16</sup> At low field, the electron or hole drift velocity is simply proportional to the electric field magnitude, through the mobility. In contrast, under high electric field, the drift velocity approaches a constant saturation velocity,  $v_{\text{sat}}$ , at which the rate of energy gain from the electric field is balanced by the rate of energy loss *via* inelastic phonon emission.<sup>17,18</sup> Transport under high electric fields should enable probing the electron– or hole–phonon interaction and could depend on high-energy details of the band structure. High saturation velocity is also vital for practical applications of graphene in radio frequency amplifiers<sup>19</sup> and high-current graphene interconnects.<sup>14,20</sup> For example, the intrinsic transit frequency of a transistor is limited by the saturation velocity:  $f_T \approx v_{\text{sat}}/(2\pi L)$ , where  $L$  is the channel length.

Due to graphene's atomically thin nature, the saturation velocity can be limited by both intrinsic graphene phonons and remote substrate phonons,<sup>21,22,39</sup> with lattice heating<sup>4,8–10</sup> and interfacial charged impurities also playing a role.<sup>4,8,10</sup> Reported room-temperature saturation velocities in graphene in contact

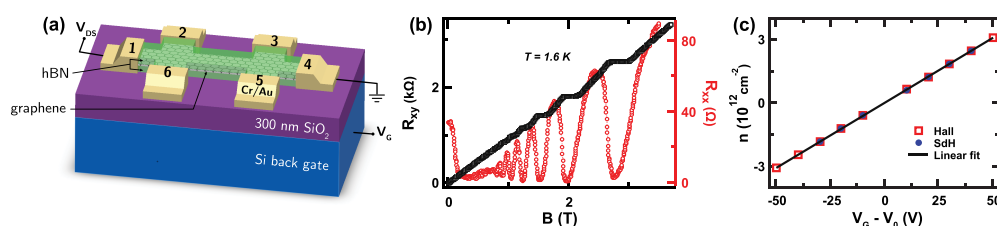
with hBN and SiO<sub>2</sub> substrates, and on a SiO<sub>2</sub> substrate with an additional Al<sub>2</sub>O<sub>3</sub> top gate dielectric are  $2 \times 10^7$ ,<sup>23</sup>  $1.9 \times 10^7$ ,<sup>4</sup> and  $10^7$  cm/s,<sup>24</sup> respectively, at a common carrier density of  $5.0 \times 10^{12}$  cm<sup>-2</sup>. Encouragingly, velocities approaching the Fermi velocity of  $\sim 10^8$  cm/s in graphene have been estimated in suspended samples<sup>5</sup> or by applying rapid bias pulses,<sup>21</sup> but these approaches are not relevant for most circuit applications.

hBN is a good candidate substrate for enhancing graphene saturation velocity for multiple reasons: (i) Its surface optical phonon (OP) energy of  $\sim 102$  meV compared to 59 meV in SiO<sub>2</sub><sup>8</sup> should suppress the phonon emission process which is most commonly thought to limit  $v_{\text{sat}}$ . (ii) The high thermal conductivity of hBN<sup>25</sup> may limit self-heating, further decreasing electron–phonon scattering.<sup>10</sup> (iii) Graphene on hBN has shown mobility<sup>26</sup> much higher than that on other substrates, due to reduced impurity scattering. (iv) The Fermi velocity ( $v_F$ ) of graphene, known to be dependent on the substrate dielectric constant, has been measured to be nearly  $1.5 \times 10^8$  cm/s in graphene on hBN;<sup>27</sup> this is comparable to the  $v_F$  on SiO<sub>2</sub> and greater than that on substrates with a higher dielectric constant such as SiC, Al<sub>2</sub>O<sub>3</sub>, and HfO<sub>2</sub>. Theoretical modeling considering the effects of lattice heating and substrate

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**Figure 1.** (a) Schematic of six-contact Hall bar on monolayer graphene device encapsulated by hBN. Data in main text are presented from a device with  $2\ \mu\text{m}$  channel width and  $4\ \mu\text{m}$  center-to-center separation between voltage probes. (b) Hall effect and longitudinal resistance as a function of perpendicular magnetic field at 1.6 K ambient temperature. (c) Extracted carrier density as a function of gate voltage, showing consistent results between Hall effect and Shubnikov–de Haas (SdH) measurements.

impurities predicts velocity saturation at  $\sim 2.5 \times 10^7$  cm/s in graphene on hBN at fields beyond  $1\ \text{V}/\mu\text{m}$ .<sup>10</sup> The same model predicts lower velocities of  $2 \times 10^7$  and  $1.5 \times 10^7$  cm/s on  $\text{Al}_2\text{O}_3$  and  $\text{HfO}_2$ , respectively.

Despite these earlier studies, there are so far no direct measurements of graphene saturation velocity in samples encapsulated by hBN, which ought to provide nearly the best of all possible scenarios discussed earlier, including best heat spreading, lowest impurity density, and highest phonon energy, though the Fermi velocity may be slightly lower than that in samples with no top dielectric.

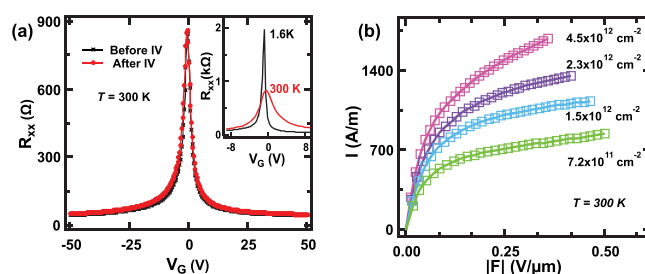
## RESULTS AND DISCUSSION

Here, we created hBN-encapsulated monolayer graphene samples with Cr/Au edge contacts to achieve ultraclean, high-mobility devices, as shown in Figure 1a and Figure S1 (see Methods and Supporting Information). We employed gated multi-terminal test structures to directly probe charge transport as a function of carrier density and lateral electric field within the graphene Hall bars. Data were collected at ambient temperatures between 2 and 300 K with carrier densities up to  $4.4 \times 10^{12}$  electrons/cm<sup>2</sup> and  $4.2 \times 10^{12}$  holes/cm<sup>2</sup>. We observe that the drift velocity saturates at a density-dependent value between  $2.7 \times 10^7$  and  $6 \times 10^7$  cm/s at room temperature (RT), higher than that in previous reports for graphene on other substrates and nearly 1.5 times higher than that predicted by theoretical models for graphene on hBN for similar carrier densities.<sup>10</sup> (Note, however, that our graphene encapsulated in hBN has substantially higher mobility than that envisioned in those models.) The saturation velocity is nearly independent of temperature and likely limited primarily by emission of hBN surface OPs, whose energy ( $\sim 102$  meV) is far above the ambient thermal energy.

For this paper, we systematically studied two devices without applying biases high enough to cause irreversible changes in transport. Results from one of these devices are presented in the main text, and  $v_{\text{sat}}$  data from the other are included in the Supporting Information. In the process of learning the phenomenology of our high-field measurements, we fabricated and studied 12 additional devices and on 8 of them collected significant data before causing irreversible changes. All such data were broadly consistent with those featured in the main text.

Figure 1 b shows the typical low electric field transport properties of the graphene device in perpendicular magnetic fields with a 100 nA (17.9 Hz) AC current flowing from source to drain (contacts 1 to 4 in Figure 1a). Both the longitudinal resistance  $R_{xx}$  between contacts 2 and 3, and Hall resistance  $R_{xy}$  between contacts 2 and 6 were measured.  $R_{xx}$  is a strong function of back gate voltage ( $V_G$ ) at zero magnetic field and

300 K. As shown in the inset of Figure 2a, with decreased temperature the resistance peak at the charge neutrality point



**Figure 2.** (a) Characteristic gate voltage sweep showing consistent  $R_{xx}$  curves before and after measurement. The charge neutrality point (CNP) occurs at  $V_G = V_0 = -1$  V. The maximum resistance modulation (on/off) is  $\sim 18.5$  at RT. Inset shows data at 300 and 1.6 K zoomed in near the CNP to better illustrate the temperature dependence of  $R_{xx}$ . (b) Measured current density vs field for various average carrier densities at RT.

(CNP) becomes higher and narrower due to suppression of thermally induced ambipolar conduction, and resistance at high density becomes lower due to reduced electron–phonon scattering. The resulting maximum resistance on/off ratio is  $\sim 18.5$  at RT and  $\sim 445$  at 1.6 K. At 1.6 K in a perpendicular magnetic field  $B$ ,  $R_{xx}$  exhibits typical Shubnikov–de Haas (SdH) quantum oscillations equally spaced in  $B^{-1}$ , and  $R_{xy}$  is quantized at filling factors  $\nu = 2, 6, 10$ , etc. (Figure 1b), as generally reported for high-mobility graphene devices.<sup>28,29</sup> Figure 1c displays the linear dependence of carrier density on gate voltage, and extraction from Hall effect or SdH oscillations gives mutually consistent results.

Current–voltage ( $I$ – $V$ ) measurements at high lateral electric fields were carried out in a four-terminal configuration to eliminate contributions from contact resistance. DC bias was applied between source and drain, and both current in the channel and four-terminal voltage between contacts 2 and 3 were measured (Figure 1a). We made most measurements with source–drain bias polarity ( $V_{\text{DS}}$ ) chosen to increase rather than decrease carrier density for a given polarity of gate voltage ( $V_G$ ). Care was taken to ensure all measurements were repeatable after high-field measurements, as high-field stress can drive such devices into a regime with shifted CNP or even multiple CNPs (see Supporting Information). Thus, before and after each high electric field measurement, we performed a gate voltage sweep at low source–drain bias to locate the CNP (Figure 2a) and ensure that it had not shifted.

Current was normalized by device width (to yield current density  $I$ ), and four-terminal voltage was normalized by center-to-center separation between voltage probes (to obtain the

lateral field  $F$  in the channel), as shown in Figure 2b. Due to the high mobility of our devices (see below), the current increases rapidly with electric field at low fields, and current saturation begins at fields much lower ( $\sim 0.1$  V/ $\mu\text{m}$ ) than those in previous studies.<sup>4,21</sup> The largest current density measured here was  $\sim 1.7$  mA/ $\mu\text{m}$  or  $5.15 \times 10^8$  A/ $\text{cm}^2$ , higher than that in previous reports for graphene on hBN<sup>8</sup> (and much higher than typical Cu interconnects at  $\sim 10^7$  A/ $\text{cm}^2$ ) but limited by the lateral fields, which were kept moderate to avoid sample instability and breakdown.

We use current density to calculate drift velocity,  $v_d = I/(en)$ , where  $e$  is the elementary charge,  $n \approx (C/e)(V_G - V_0 + V_{DS}/2)$  is the average carrier density,<sup>4</sup> and  $C = 1.152 \times 10^{-8}$  F/ $\text{cm}^2$  is the capacitance per unit area over the hBN and SiO<sub>2</sub> layers, as obtained from Hall and SdH measurements (Figure 1c). This approximation justifiably neglects the low residual density of carriers near the CNP<sup>30</sup> caused by charged impurities and thermal generation (see Supporting Information). Due to the low impurity density of hBN-encapsulated graphene,<sup>31</sup> thermal carrier generation dominates the uncertainty of the carrier density calculation, which is estimated to be  $<1\%$  here for  $|V_G| > 10$  V, even at RT.<sup>4</sup> The possible maximum error in  $v_d$  caused by the potential variation along the channel is estimated to be between 5 and 15%, depending on the carrier density (see Supporting Information).

As shown in Figure 3, the mobility  $\mu = \sigma/(ne)$  extracted from the curves in Figure 2b is consistent with the value calculated

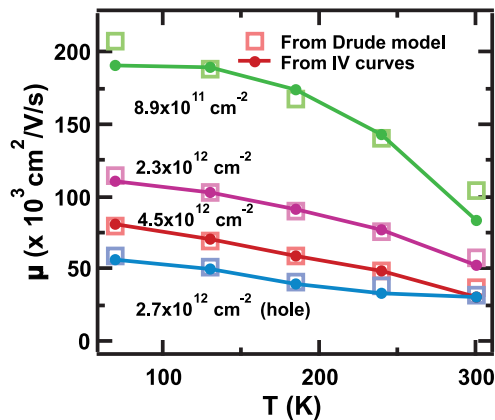


Figure 3. Temperature- and density-dependent mobility shows good correlation between estimates from linear fits to  $v_d$  vs  $|F|$  curves at low field (lines) and from the Drude model (square symbols).

from the Drude model, where  $\sigma$  is the conductivity at zero magnetic field. Electron mobility increases with decreasing temperature, ranging from  $80 \times 10^3$  cm<sup>2</sup>/Vs at 300 K to  $207 \times 10^3$  cm<sup>2</sup>/Vs at 70 K, in both cases at a density of  $0.8 \times 10^{12}$  cm<sup>-2</sup>. The mobility also increases with decreasing carrier density. Hole mobility is lower than electron mobility in all devices measured in this study (see Figures 2a and 3). With carrier densities between  $0.8$  and  $1.4 \times 10^{12}$  cm<sup>-2</sup>, the RT mean free path ranges from  $0.6$  to  $1.2$   $\mu\text{m}$  at low fields (see Supporting Information), always smaller than the geometry of our Hall bar. Further, the mean free path is much smaller at high fields, suggesting that throughout our room temperature measurements the sample is in or near the diffusive transport regime appropriate for extracting an average drift velocity.

Figure 4a displays the drift velocity as a function of lateral electric field at several carrier densities, showing that velocity

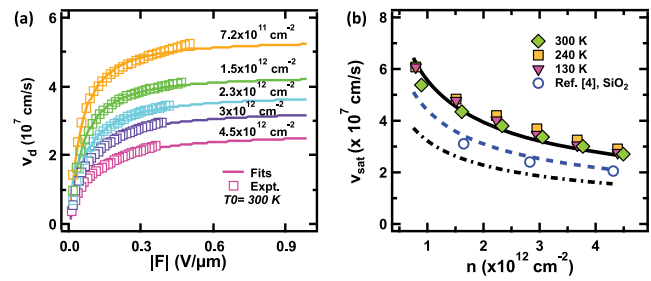


Figure 4. (a) Room temperature electron drift velocity vs field at several average carrier densities. Square symbols are experimental data; lines are fits to and extrapolations from eq 1. (b) Extracted saturation velocity vs electron density at various ambient temperatures. Color filled symbols are experimental data on hBN, whereas white filled circles are data from ref 4,  $v_{\text{sat}}$  of graphene on SiO<sub>2</sub>. Lines are eq 3 with OP energies of 59 meV for SiO<sub>2</sub> (black dashed-dotted line), 102 meV for hBN (black solid line), and 81 meV (blue dashed line) as an intermediate fit for graphene on SiO<sub>2</sub> as in ref 4.

does not fully saturate at the accessed fields, which were limited by device instability at higher fields. The slope of drift velocity versus lateral field at low field represents the device mobility, such that the steeper dependence of drift velocity on field in our device compared to that in samples of graphene on SiO<sub>2</sub><sup>4</sup> corresponds to the much higher low-field mobility of graphene encapsulated by hBN.

To extract saturation velocity  $v_{\text{sat}}$  we fit drift velocity data in Figure 4a to the commonly used equation<sup>4,21,32,33</sup>

$$v_d(F) = \frac{\mu F}{\left[1 + \left(\frac{\mu F}{v_{\text{sat}}}\right)^\gamma\right]^{1/\gamma}} \quad (1)$$

where  $\mu$  is the mobility and  $\gamma$  is a temperature-dependent fitting factor.<sup>32</sup> Qualitatively,  $\gamma$  tunes the “sharpness” of the turnover from the low-field linear to the high-field saturation regime. For each density and temperature, we fix  $\mu$  based on the slope of low-field  $v_d$  versus  $F$  data, leaving  $v_{\text{sat}}$  and  $\gamma$  as free fitting parameters. When we fit  $\gamma$  and  $v_{\text{sat}}$  in eq 1 to the experimentally derived drift velocity versus field at each carrier density, the resulting  $v_d(F)$  surprisingly undershoots the experimental drift velocity for high fields, as can be seen at  $|F| > 0.3$  V/ $\mu\text{m}$  in Figure 4a. If heating were significant, the opposite would be expected because at high fields heating would lower experimental drift velocity relative to the predictions of eq 1. Ignoring this subtlety, and thus likely slightly underestimating  $v_{\text{sat}}$ , least-squares fitting yields  $v_{\text{sat}}(n)$  (Figure 4b). The saturation velocity decreases with increasing carrier density, consistent with previous results.<sup>4,8,23</sup>  $\gamma$  is between 0.7 to 1.2 and displays both density and temperature dependence (see Supporting Information), in line with Thornber’s prediction.<sup>32</sup>

Velocity saturation in graphene depends on carrier density, but the peak values measured here are higher than those in most other materials. At low carrier densities,  $v_{\text{sat}}$  measures  $\sim 6 \times 10^7$  cm/s. At a carrier density of  $4 \times 10^{12}$  cm<sup>-2</sup>,  $v_{\text{sat}} \approx 3 \times 10^7$  cm/s at 300 K. At similar densities in graphene on SiO<sub>2</sub>,  $v_{\text{sat}}$  reaches only  $2 \times 10^7$  cm/s.<sup>4</sup> For other commonly studied materials such as MoS<sub>2</sub>, Si, and Ge, saturation velocities of only  $0.27 \times 10^7$ ,<sup>34</sup>  $10^7$ ,<sup>33</sup> and  $0.6 \times 10^7$  cm/s,<sup>35</sup> respectively, have been realized at RT, with little dependence on carrier density.



Only for InSb do measured  $v_{\text{sat}}$  values reach comparably high: up to  $5 \times 10^7$  cm/s at 300 K and  $\sim 5.5 \times 10^7$  cm/s at 77 K.<sup>36</sup>

Several mechanisms can cause velocity saturation. At low fields, elastic scattering with charged impurities at the graphene–hBN interface can lower mobility and drift velocity.<sup>37</sup> However, charged impurities are expected to play a less significant role in limiting the velocity saturation at high fields,<sup>4</sup> especially in hBN-encapsulated graphene, which has a lower density of interfacial impurities. From low-field resistivity measurements, we estimate the impurity density  $n_{\text{imp}}$  in our device to be  $4.54 \times 10^{10}$  cm<sup>-2</sup> (see Supporting Information), much lower than previously reported  $n_{\text{imp}} \approx 8.86 \times 10^{11}$  cm<sup>-2</sup> for graphene on SiO<sub>2</sub>.<sup>4</sup> Further, our device mobilities continue to increase with reducing temperature down to 50 K (Figure 3), in contrast to the mobility in graphene on SiO<sub>2</sub>, which is constant below 200 K and is dominated by impurity scattering.<sup>38</sup> This suggests that charged impurities are not the dominant scattering mechanism in hBN-encapsulated graphene except at temperatures below 50 K.

Therefore, scattering due to intrinsic (graphene) and remote (hBN) phonons, specifically surface OPs, is the most likely mechanism for limiting the saturation velocity in our samples. Such OPs are expected to limit saturation velocity in graphene due to their higher energy, which enables them to inelastically scatter and relax the energy of electrons much more efficiently than acoustic phonons (APs).<sup>39</sup> In addition, the deformation potentials for OP scattering are higher than those for AP scattering,<sup>8,10</sup> rendering the rate of OP emission stronger than that of AP emission. In atomically thin materials like graphene, scattering can occur with both the intrinsic phonons of graphene and the (dynamically screened<sup>7,10</sup>) surface OPs of the substrate. Typically, the lower-energy of these phonons, here the hBN phonons, limit the saturation velocity.

As charge carriers accelerate to high energies in high electric fields, an energy difference arises between “forward” populated and unpopulated states.<sup>4,6</sup> When this energy difference exceeds the OP energy  $\hbar\omega_{\text{OP}}$ , high-energy carriers can emit OPs, scattering inelastically back into the lower-energy states. At source–drain separation of 4  $\mu\text{m}$ , even at fields below 0.1 V/ $\mu\text{m}$ , the total potential difference is high enough to allow emission of graphene or hBN surface OPs, so the field rather than the total potential is the important parameter. At high field,  $v_{\text{sat}}$  can be related to the OP frequency  $\omega_{\text{OP}}$ :<sup>4,40</sup>

$$v_{\text{sat}} = \frac{2}{\pi} \frac{\omega_{\text{OP}}}{\sqrt{\pi n}} \sqrt{1 - \frac{\omega_{\text{OP}}^2}{4\pi n v_{\text{F}}^2} \frac{1}{N_{\text{OP}} + 1}} \quad (2)$$

The dependence of  $v_{\text{sat}}$  on temperature is related to the phonon occupation,  $N_{\text{OP}} = 1/(\exp(\hbar\omega_{\text{OP}}/k_{\text{B}}T) - 1)$ . At high carrier densities and neglecting self-heating, eq 2 can be simplified<sup>4,24,40</sup> to

$$v_{\text{sat}} \approx \frac{2}{\pi} \frac{\omega_{\text{OP}}}{\sqrt{\pi n}} \quad (3)$$

In Figure 4b, extracted  $v_{\text{sat}}$  values closely follow eq 3 with  $\hbar\omega_{\text{OP}}$  corresponding to the lowest hBN surface OP energy of  $\sim 102$  meV,<sup>8</sup> suggesting that the emission of remote OPs is the dominant high-field scattering mechanism in our devices. The significance of phonon scattering is further supported by device mobilities, which are consistent with theoretical calculations of remote phonon-limited mobility proposed by Ong and Fischetti.<sup>7,41</sup> Considering the temperature dependence of  $N_{\text{OP}}$  in eq 2,  $v_{\text{sat}}$  is predicted to change only 1.2% as the temperature

changes from 100 to 300 K, given a phonon energy  $\hbar\omega_{\text{OP}} = 102$  meV. Indeed, our observed  $v_{\text{sat}}$  is almost completely insensitive to temperature, as shown in Figure 4b.

By comparison, we note that in ref 4 the experimental  $v_{\text{sat}}$  in SiO<sub>2</sub>-supported graphene was best fit with a phonon energy of  $\sim 81$  meV, which corresponds neither to the SiO<sub>2</sub> remote OP ( $\sim 59$  meV) nor to the graphene intrinsic OP ( $\sim 160$  meV). Thus, ref 4 surmised that  $v_{\text{sat}}$  in graphene on SiO<sub>2</sub> is limited by a combination of intrinsic and remote OPs, whereas here it appears that the  $v_{\text{sat}}$  in graphene encapsulated by hBN is primarily limited by the hBN surface OPs. Naturally, more sophisticated simulations (beyond the scope of this work) are needed to confirm these observations, but the simple model present here appears to capture the limiting transport physics.

We do not observe complete velocity saturation nor the negative differential velocity (NDV) predicted in some theoretical models.<sup>10,42</sup> The saturation model of Serov *et al.*<sup>10</sup> predicted the appearance of NDV at high fields but only in the case of strong self-heating and at higher fields than are achievable in this work. As stated earlier, our measurements are limited by the requirement to keep samples stable and measurements repeatable during long high-field stress times. We estimate the maximum device temperature increase achieved in this work in Figure 5, considering the thermal

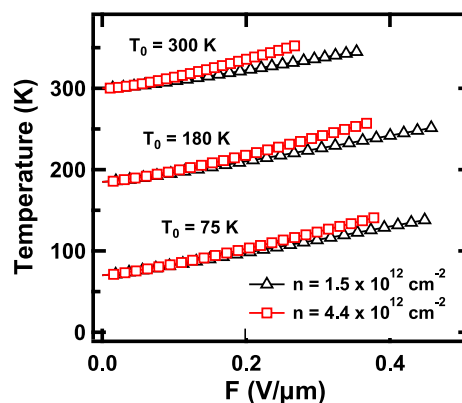


Figure 5. Modeled lattice temperature based on power input at different starting temperatures and carrier densities.  $T_0$  is the substrate temperature, as listed for each estimate.

resistance of the hBN substrate, SiO<sub>2</sub> layer, and Si back gate (details provided in the Supporting Information). The maximum temperature increase is about 70 K in our measurements, insufficient to significantly increase the occupation of the high-energy hBN surface OPs. Thus, the lack of observed high-field NDV in our work is not unexpected; NDV could still occur at higher fields or carrier densities than are probed in this work.

The higher saturation velocity observed in our graphene samples encapsulated by hBN occurs due to a combination of factors. First, the higher-energy surface OPs of hBN compared to that of other substrates leads to a delayed onset of OP emission. Second, the mobility is higher in our samples than has been previously achieved or simulated in high-field studies (*e.g.*, in ref 10) due to lower impurity density. Third, our samples achieve saturation velocity at lower fields (and thus lower power) than was previously possible (*e.g.*,  $\sim 0.2$  V/ $\mu\text{m}$  in Figure 4a versus  $\sim 1$  V/ $\mu\text{m}$  in ref 4), as a consequence of the higher mobility. The lower power leads to less heating in these samples, as shown in Figure 5, with only  $\sim 70$  K temperature

increase *versus*  $\sim 200$  K temperature increase estimated in ref 4 for samples on SiO<sub>2</sub>.

## CONCLUSIONS

We have investigated high-field electric transport behavior in high-mobility graphene encapsulated by hBN. The excellent physical properties of hBN enable us to achieve the highest saturation velocities to date in graphene supported by insulating substrates, a critical property for electronic device applications. We conclude that in graphene encapsulated by hBN, the high-energy hBN surface phonons play an important role in ultimately limiting carrier drift velocity, whereas impurity scattering and lattice heating are less significant. These results suggest that further investigation of high-field behavior in graphene may enable high-electric-field graphene devices with remarkable properties.

## METHODS

Devices were fabricated through mechanical exfoliation of highly ordered pyrolytic graphite and hexagonal boron nitride crystals, followed by van der Waals stacking with poly(propylene carbonate)/poly(methyl methacrylate) stamps<sup>26</sup> onto a 300 nm SiO<sub>2</sub> substrate over a heavily (n++) doped Si global back gate, creating a sandwich of monolayer graphene between two hBN films 32–55 nm thick (see Supporting Information). The heterostructures were annealed<sup>43</sup> at 500 °C in flowing O<sub>2</sub>/Ar (50/5 sccm) for 1 h to remove residues introduced by the transfer process. The devices were then patterned into a Hall bar geometry with a center-to-center voltage probe distance of 4  $\mu\text{m}$  and a width of 2  $\mu\text{m}$  (Figure 1a), using electron beam lithography followed by a dry etch. Low-resistance ohmic edge contacts were made by depositing Cr/Au with electron beam evaporation.<sup>44</sup>

Magnetoresistances were measured with standard lock-in technique in a He vapor variable-temperature insert cryostat with a base temperature of 1.6 K and magnetic fields up to 14 T. High lateral electric field transport measurements were performed in vacuum or <sup>4</sup>He vapor at temperatures between 10 and 300 K using a Keithley 2400 as the voltage source and an Agilent 34401 Digital Multimeter for measuring the voltage drop locally across the device.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsnano.7b03878.

Further device details, discussion of device instabilities,  $\nu_{\text{sat}}$  extraction error estimation, impurity density calculations, mean free path calculation, discussion of  $\nu_{\text{sat}}$  extraction parameter, temperature simulation details, and sequence dependence of  $I$ – $V$  measurements (PDF)

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### Author Contributions

M.Y. began the work and designed the research strategy. M.Y. synthesized encapsulated graphene samples, and W.Y. performed device design, AFM characterization, and electron beam lithography. W.Y. and M.Y. carried out data analysis, while W.Y. produced figures. D.G.G. and E.P. facilitated interpretation of results, with E.P. providing methods for

temperature modeling. All authors discussed the results and revised the paper.

### Notes

The authors declare no competing financial interest.

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#### NOTE ADDED AFTER ASAP PUBLICATION

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