Electron Excess Doping and Effective Schottky Barrier Reduction on the MoS$_2$/h-BN Heterostructure

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Supporting Information

ABSTRACT: Layered hexagonal boron nitride (h-BN) thin film is a dielectric that surpasses carrier mobility by reducing charge scattering with silicon oxide in diverse electronics formed with graphene and transition metal dichalcogenides. However, the h-BN effect on electron doping concentration and Schottky barrier is little known. Here, we report that use of h-BN thin film as a substrate for monolayer MoS$_2$ can induce $\sim$6.5 $\times$ 10$^{11}$ cm$^{-2}$ electron doping at room temperature which was determined using theoretical flat band model and interface trap density. The saturated excess electron concentration of MoS$_2$ on h-BN was found to be $\sim$5 $\times$ 10$^{13}$ cm$^{-2}$ at high temperature and was significantly reduced at low temperature. Further, the inserted h-BN enables us to reduce the Coulombic charge scattering in MoS$_2$/h-BN and lower the effective Schottky barrier height by a factor of 3, which gives rise to four times enhanced the field-effect carrier mobility and an emergence of metal–insulator transition at a much lower charge density of $\sim$1.0 $\times$ 10$^{12}$ cm$^{-2}$ ($T = 25$ K). The reduced effective Schottky barrier height in MoS$_2$/h-BN is attributed to the decreased effective work function of MoS$_2$ arisen from h-BN induced n-doping and the reduced effective metal work function due to dipole moments originated from fixed charges in SiO$_2$.

KEYWORDS: MoS$_2$, h-BN, substrate doping, interface trap density, Coulomb scattering, Schottky barrier height, dipole alignment

Atomically thin layered materials have all of their atoms on the material surface, making them susceptible to dielectric environment effects. One important feature of this configuration is the enhanced Coulomb scattering effects on a carrier transport due to diminished screening effects, which can be further modulated with adjacent dielectric substrates.1–6 This situation often leads to perturbed intrinsic properties of these layered materials. For example, when two-dimensional (2D) materials such as graphene and transition metal dichalcogenides (TMDs) are transferred onto oxide substrates to fabricate the field-effect transistors (FETs), three main issues are related to the oxide: (i) excess doping in the channel, (ii) carrier scattering from located traps at the oxide, and (iii) surface roughness that provokes straining in the atomically thin TMD layer.7–9

In addition, the substrate-induced effects as mentioned above are hardly distinguishable in the conventional device structure prepared on SiO$_2$ dielectrics. A simple but efficient approach to preserve the intrinsic properties of channel materials is the use of a hexagonal boron nitride (h-BN) thin film as a substrate, which has been successfully demonstrated for use with graphene transistors.7,10 Its inert and flat surface that does not create the strain on the host materials provides an ideal platform for substrates as well as tunnel barriers or flexible insulators, which are critical components in composite 2D optoelectronic devices.8,11,12 Besides, the much cleaner (i.e., less charged impurities) flat surface significantly enhances their field–effect mobility.5,7,8,11,13,14

There have been a number of published reports investigating the carrier transport of molybdenum disulfide (MoS$_2$) on h-BN substrate implicitly evidencing the beneficial impact of h-BN substrate.14,15 For example, the Shubnikov-de Haas oscillation was observed in MoS$_2$ thin film encapsulated by h-BN substrates at temperatures as low as 0.3 K.14 A metal–insulator transition (MIT) mechanism in MoS$_2$/h-BN heterostructure interpreted by a percolation theory was also reported based on capacitance measurements.15 In addition to substrate-induced charge scattering effects, Schottky barrier (SB) and channel access resistance can be inevitably formed at the contact, which often govern the transport properties. However, the effects of h-BN as a substrate to such the effective Schottky barrier height and/or contact resistance reduction are not reported yet. Therefore, improving just the channel quality in semiconductor devices is not sufficient, since their performance is considerably obscured by the contact property. Low contact resistance, highly

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crystalline channels, and better interface quality with gate oxides are required to improve device performance.

Here, we demonstrate that the use of h-BN substrate can comply with all these requirements over the conventional MoS2/SiO2 in terms of (i) excess n-doping effects in MoS2 channel, (ii) suppressed interfacial trap density, (iii) less channel activation energy ($E_a$), (iv) alleviated the Coulombic charge scattering effect, and (v) reduced effective Schottky barrier height ($\Phi_{SB}$) as well as contact resistance ($R_{CT}$) at a metal–MoS2 junction. The h-BN substrate effectively n-dopes MoS2 compared with SiO2 and lowers $\Phi_{SB}$ as well as $R_{CT}$, enabling to the four times enhanced field-effect carrier mobility and the early emergence of MIT.

Figure 1. (a) Optical images (top) and 3D architecture (bottom) of MoS2 devices on SiO2 and h-BN. (b) AFM image of MoS2 on SiO2. The inset describes the thickness profile of monolayer MoS2 on SiO2 along the white line in the AFM image. (c) Raman spectroscopy of MoS2 on SiO2 (red) and h-BN (blue).

Figure 2. (a) Back gate bias dependence of $I_D$ as a function of $T$. The temperature dependence of (b) $D_T$ and (c) $V_{FB}$ with respect to $V_{BG}$. (d) The analytical calculation of $N_D$ as a function of $T$ with respect to MoS2 on h-BN and SiO2 substrates. (e) The numerical simulation of $T$ dependence of 2D surface carrier concentration with respect to $N_D$. 

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Figure 1a illustrates the device architecture under test with corresponding optical images. The h-BN thin film (15 nm) was first exfoliated onto a 300 nm SiO2/Si substrate. Monolayer MoS2 flakes synthesized by chemical vapor deposition (CVD) were transferred on the prepared h-BN/SiO2/Si substrate. The detailed CVD growth procedures are described in the Experimental Section. After identifying two MoS2 flakes, one properly located on h-BN and the other directly on top of SiO2 without h-BN, standard electron-beam lithography and a Cr/Au metallization process with a predetermined design layout were conducted to fabricate contact electrodes. The height profile across MoS2 on SiO2 from atomic force microscope (AFM) confirms a single layer MoS2 (thick ≈ 0.8 nm) (Figure 1b). The dimensions of both samples defined by electrodes are ≈ 12 μm in length (L) and ≈ 10.4 μm in width (W). Detailed AFM images of MoS2/SiO2 and MoS2/h-BN and the thickness profile of h-BN thick film are presented in Supporting Information (SI) Figure S1.

Raman and photoluminescence (PL) measurements were performed on MoS2 flakes deposited on SiO2 and h-BN. Figure 1c shows Raman spectra of these samples; no obvious deviations were observed between the two at the E2g peak position, while the A1g peak was blue-shifted by 2.4 cm−1, resulting in a frequency difference (Δf) between E2g and A1g of about 17.2 cm−1 on SiO2 and 19.6 cm−1 for h-BN. These upshifted Raman peaks indicate that the inserted h-BN layers can effectively alleviate hole doping effects that are caused by charged impurities located in SiO2.13,16,17 In addition, the PL emission spectra (SI Figures S2a and S2b) show that MoS2 on h-BN exhibits a blue-shift in peak energy positions and an increased trion peak intensity relative to the neutral exciton peak, compared to MoS2 on SiO2. It also clearly demonstrates the role of relative n-doping by h-BN as explained by Raman analysis.13,16,18,19 Detailed discussion on the n-doping effect arising from h-BN will be made in the next section.

We here discuss the fundamental temperature-dependent transport properties for two devices and extract the excess doping concentration from them. Figure 2a presents I-VBG transfer curves for MoS2 deposited on h-BN and SiO2 measured at several temperatures as low as 25 K. Currents are normalized by the channel width. We note that MoS2/h-BN exhibits higher on-currents than MoS2/SiO2. The subthreshold swing (SS) was significantly improved to 2.17 V/dec by using the h-BN substrate, from 9.75 V/dec on the SiO2 substrate at room temperature. The flat band voltage (VFB) was downshifted in the case of MoS2/h-BN compared to MoS2/SiO2 substrate, which indicates electron doping in the channel. Furthermore, a signature of MIT was observed near VBG ≈ 40 V in MoS2/h-BN, which was not visible in MoS2/SiO2. Figure 2b displays the temperature dependence of the interfacial trap density (DIT) extracted from SS as described in below eq 1. The temperature dependence of the interfacial trap density (DIT) for the entire temperature range corroborates much cleaner interface provided by the h-BN substrate. Another important parameter VFB is related with the doping level in these systems (Figure 2c). The smaller VFB for MoS2/h-BN indicates more n-doped, which results from the smaller interface trap density. In addition, to demonstrate MoS2 sample variability issue, we fabricated another two devices (MoS2/h-BN and MoS2/SiO2) within one MoS2 flake at the same time and obtained the consistent results with Figure 2a. The further discussions are described in SI Figure S3. We next derive the temperature-dependent doping concentration for two devices by applying the flat band voltage model.

The excess electron doping concentration can be determined using the following equations. In general, SS is defined by gate oxide capacitance and trap density as shown in eq 1,10

$$SS = \ln(10) \frac{k_BT}{q} \left[ \frac{1}{1 + \frac{qD_{IT} + C_D + C_S}{C_{OX}}} \right]$$

$$\approx \ln(10) \frac{k_BT}{q} \left[ \frac{1}{1 + \frac{qD_{IT}}{C_{OX}}} \right]$$

where $q$, $C_{OX}$, $C_D$, and $C_S$ denote electron unit charge, oxide capacitance per unit area (≈ 11.5 nF/cm2 for SiO2 and ≈ 11.0 nF/cm2 for h-BN), the Boltzmann constant, depletion capacitance, and semiconductor capacitance, respectively ($C_D$ and $C_S$ are negligible in monolayer structure).15,21 The flat band voltage $V_{FB}$ (the bias condition where the surface potential of a semiconductor is zero) can be expressed as follows,

$$V_{FB} = \phi_S - (x_{MoS2} + E_C - E_F) + q \left( \frac{N_{IT} - N_{IN/EX}}{C_{OX}} \right)$$

$$= \phi_S - (x_{MoS2} + E_C - E_F) - q \left( \frac{N_{DOE} - N_{IN/EX}}{C_{OX}} \right)$$

$$\approx \phi_S + \frac{E_{fSi}(0) - \frac{4.73 \times 10^{-4} T^3}{T + 636}}{q} + \frac{k_BT}{q} \ln \left( \frac{N_{A_S}}{n_{Si}} \right)$$

where $\phi_S$ is the work function of the gate metal, $x_{MoS2}$ and $\phi_S$ are electron affinities of MoS2 (4.1 eV)22 and silicon (4.15 eV),20 respectively, and $E_C$, $E_F$, and $E_{fSi}(0)$ (≈ 1.17 eV),20 $N_{IT}$, $N_{IN/EX}$, $N_{A_S}$ (≈ 10^19 cm^−3), and $n_{Si}$ (≈ 1.5 × 10^19 cm^−3) are the conduction band edge, Fermi level, band gap energy of silicon, interface trap concentration, intrinsic and/or extrinsic doping density, boron doping concentration for p-type silicon substrate, and intrinsic silicon doping concentration, respectively. Therefore, the last term of the first line in eq 2 describes the band bending caused by the internal gate field induced by the net charge density (−($N_{IT}$ − $N_{IN/EX}$)), which is interpreted as an excess electron doping concentration, $N_{DEE}$ as expressed in eq 2. Using $V_{FB}$ linearly extrapolated from $I_D - V_{BG}$ (Figure 2c) and $D_{IT}$ (Figure 2b), we can extract information on excess electron doping concentration $N_{DEE}$ as illustrated in Figure 2d. Positive $N_{DEE}$ indicates excess free (untrapped) electron concentration, while negative $N_{DEE}$ indicates that the positive interface trapped charges exceed the carriers in number. As a result, most carriers are trapped, so that the charge transport by thermal excitations or hopping becomes much less. In the case of SiO2 substrate, all of the carriers are already trapped within the observed temperature range. However, excess free carrier density in MoS2/h-BN is sustained down to T~165 K, which means that $N_{DEE}$ is greater than the trap concentration $N_{IT}$ ($D_{IT}$ in different units) making the device operate in a depletion mode. Therefore, the h-BN substrate causes a relative n-doping effect compared to SiO2, which is consistent with previous optical analysis.

Taking into account the dependence of $V_{FB}$ on T with regards to material properties of monolayer MoS2 such as bandgap energy ($E_g(T) = E_g(0) - A T^3/(B + T)$, where $E_g(0) = 1.874$ eV, $A = 5.9 \times 10^{-4}$ eV/K, and $B = 430$ K),3 effective in-plane mass...
m*,24,25 2D density of states g2D = g0 * m*/πℏ2, where g0 and ℏ are valley degeneracy around K point and reduced Plank constant,1,3,19−21,25−28 and D1(T), values of N_D_eff range −8.5 × 1011 cm−2 (T = 25 K) ~ 6.5 × 1011 cm−2 (T = 294 K) for MoS2/h-BN device and −16.9 × 1011 cm−2 (T = 25 K) ~ −8.3 × 1011 cm−2 (T = 294 K) for MoS2/SiO2, as displayed in Figure 2d. The difference between N_D_eff values in MoS2 on h-BN and SiO2 indicates the carrier number difference between the two devices at T = 294 K (≈ 1.5 × 1012 cm−2). This value is almost identical to the 1.7 × 1012 cm−2 using a simple approximation (Cox ΔV_FB/q, ΔV_FB ≈ 14.4 V at T = 294 K, where ΔV_FB is the difference in V_FB between the two devices), rationalizing the validity of our approach. To provide an accurate 2D carrier density, the Hall measurement was carried out for both devices and again confirmed the similar range of carrier density difference as plotted in Figure S4f. In detail, discussions are located in SI Figure S4. Finally, the simulated temperature dependence of 2D surface carrier concentration as a function of doping concentration (N_D) of MoS2 on h-BN is calculated from eq 2 and plotted in Figure 2e. The curve for N_D ≈ 5.0 × 1013 cm−2 properly describes the h-BN data in Figure 2e (blue dotted arrow). Therefore, we conclude that N_D ≈ 5.0 × 1013 cm−2 is the total doping concentration of MoS2 on h-BN, much higher than the intrinsic doping density of ≈ 1010 cm−2, and the room temperature n2D ≈ 6.5 × 1011 cm−2 yields ~10 nm depletion width of SB, and this value increases as the temperature decreases.

Figures 3a and 3b displays the temperature-dependent conductance G(T) curves in the insulating regime for several values of V_BG for MoS2 on SiO2 and h-BN substrates. (c) Temperature dependence of R_CT at V_BG = 50 V obtained using 4-probe measurements.

Figure 3. Temperature and gate-bias dependence of G(T) curves of MoS2 on (a) SiO2 and (b) h-BN substrates. The inset in (b) represents the sheet conductivity σ = G L12/W, where L12 = 5.3 μm, which is the distance between voltage probes from the insulating to the metallic regime in the 4-probe measurement, as illustrated in Figure 1a. The crossover of sheet conductance occurs ~0.5 (e2/h) at T = 294 K. (c) E_g curves as a function of V_BG for SiO2 and h-BN substrates.

Figure 4. (a) Temperature dependence of measured μ_FE(T) (symbols) obtained by four-probe measurement at V_BG = 50 V. The respective solid, long-dashed, and dashed-dot lines indicate calculated total mobility, Coulomb-limited mobility (μ_C), and optical-phonon-limited mobility (μ_P). V_BG dependence of (b) μ_C and μ_P as well as (c) their exponents α and β, respectively. (d) ΦSB behavior as a function of V_BG for SiO2 and h-BN substrates. (e) Temperature dependence of μ_P as a function of V_BG = 50 V obtained using 4-probe measurements.
The measured conductivity ($\sigma$) where the gate bias shows MIT is $\approx 0.5 \, (e^2/h)$ at $T = 294$ K. This value is smaller than those of monolayer MoS$_2$ on any oxide substrates or h-BN substrate.  

These data are further analyzed at high $T$ regime (100 K $\leq T \leq$ 260 K) using a thermally activated charge transport mechanism expressed as $G(T) = G_0 \exp(-E_s/k_B T)$, where $E_s$ is the activation energy specifying the energy difference between the Fermi level and the mobility edge, and $G_0$ is the fitting parameter. $E_s$ is extracted from the linear fit of this equation to the data set for each value of $V_{BG}$ (Figures 3a and b). At temperatures below 80 K, the large deviation from the fitting lines is attributed to the existing Coulomb impurities, which strongly localize the carriers at low temperature. Figure 3c shows the $V_{BG}$ dependence of $E_s$ for two devices. It is at least a factor of 3 smaller for h-BN device than for SiO$_2$. Since $G(T)$ was measured using a four-probe method, the obtained $E_s$ indicates the activation barrier within the channel, not the contact-related $\Phi_{SB}$. At a zero gate bias, $E_s$ is 10 meV for h-BN compared with 43 meV for SiO$_2$ and approaches zero near $V_{BG} \sim 20$ V, which can be identified as a MIT point. On the other hand, $E_s$ for SiO$_2$ device decreases with $V_{BG}$ but still finite within our experimentally observed $V_{BG}$ range. This earlier emergence of MIT in h-BN device is ascribed to not only the higher $n$-doping density but also less Coulomb scattering in the channel. The carrier density corresponding to MIT is low, $n_{2D} \approx 1.0 \times 10^{15}$ cm$^{-2}$ ($T = 25$ K) and $\approx 2.6 \times 10^{15}$ cm$^{-2}$ ($T = 294$ K), compared to $\approx 10^{13}$ cm$^{-2}$ previously, indicating the good quality of our h-BN device. Although the exact carrier density should be obtained via Hall measurement for direct comparison, such a trend of earlier emergence of MIT in h-BN device is still valid.

For better insight into the charge scattering mechanism, the $T$ dependence of field-effect mobility ($\mu_{FE} = C_{ox}^{-1}(\partial G/\partial V_{BG}) \cdot (\partial L_{12}/\partial W)$) is analyzed using a simplified Matthiessen’s rule for Coulomb impurity scattering and phonon scattering ($\mu_{FE}(T) = 1/\mu_C(T)^\alpha + 1/\mu_{Ph}(T)^\beta$) where $\mu_C$, $\mu_{Ph}$, $\alpha$, and $\beta$ denote the Coulomb-limited mobility, optical-phonon-limited mobility, and their exponents, respectively. We assume that the surface roughness effect is reflected in $\mu_C$ and other scattering sources produce negligible effects as electron–electron scattering and strain-induced scattering. In addition, long-range scatterers are also excluded in this analysis owing to their negligible contributions to $\mu_C$ as reported publications. This is true since the reported $\mu_C$ range for long-range scatterer is above $\sim 1000$ cm$^{-2}$V$^{-1}$s$^{-1}$ which is much higher than our measured Coulomb mobility. As seen in Figure 4a, a distinct $T$ dependence of $\mu_{FE}$ for both devices is well-described by Matthiessen’s rule, yielding the fitting parameters for the selected $V_{BG}$ range as displayed in Figures 4b and 4c. In the MoS$_2$ on h-BN device, Coulombic contributions dominate $\mu_{FE}$ at $\sim 20$ K, and the phonon contributes even at $\sim 200$ K. Meanwhile, in the SiO$_2$ device, the Coulombic effects govern $\mu_{FE}$ over the observed temperature range. The crossover from phonon scattering to Coulomb scattering is present near $T \sim 170$ K in the h-BN device, indicating the change of dominant scattering source from phonon to Coulomb scatter as $T$ decreases. This critical temperature could be linked to the temperature at which $N_{ph}^{ff}$ changes sign as shown in Figure 2d, although the origin of this behavior is not clear. We obtained an exponent $\alpha \approx 0$ in the h-BN device, an indication of minimal Coulombic scattering influence. However, $\alpha$ of SiO$_2$ is larger than zero and inversely proportional to $V_{BG}$ implying strong Coulombic scattering. The
exponent $\beta$ is almost constant ($-1.5$) for both devices, similar to a theoretical value of $-1.69$.3,29

Now we turn to evaluate the contact quality. Since the large contact resistance in metal–semiconductor junctions arises mainly from the Schottky barrier, we estimated $\Phi_{SB}$ from the thermionic emission current using eq 3,14,22

$$I_D = A^* T^{3/2} \exp\left(-\frac{q\Phi_{SB}}{k_BT}\right) \times \exp\left(\frac{q(V_D - I_D R_{CT})}{nk_BT}\right) - 1 \right)$$

(3)

where $A^*$, $R_{CT}$, and $n$ are the effective Richardson constant, channel resistance, and ideality factor, respectively. From the linear relation of $\ln(T^{3/2}/I_D)$ versus $q/k_BT$, $\Phi_{SB}$ can be easily determined with a properly chosen range of $n$ ($=1-2$) as a boundary condition. Here $I_D$ is measured using a two-probe method to include $R_{CT}$, and $R_{CH}$ was obtained using a four-probe method. As illustrated in Figure 4d, $\Phi_{SB}$ of MoS$_2$ on h-BN is approximately three times smaller than that of MoS$_2$ on SiO$_2$, which corroborates the lower $R_{CT}$ in MoS$_2$/h-BN device shown in Figure 4e. Thus, the four-probe method helps to observe the MIT.

The reduced $\Phi_{SB}$ and $R_{CT}$ are good indications for stronger band bending effect at the metal–semiconductor interface because of the relatively higher n-doping effect at MoS$_2$/h-BN compared to the case of MoS$_2$/SiO$_2$. More specifically, the inserted h-BN substrate makes the Fermi level of MoS$_2$ upshift and reduces the depletion width, which will increase tunneling at the junction. It has been recently reported that the oxygen molecules can lead to extensive dipole alignment effects, the reduced effective work function, and cause the band bending in MoS$_2$ as discussed in silicon transistors.36 As we described earlier, SiO$_2$ contains numerous positively charged trap sites near the surface. These charges induce the image charges in the metal, composing dipoles which modulate the metal work function, and cause the band bending in MoS$_2$ as illustrated in Figure 5. Without h-BN, SiO$_2$ directly contacts with MoS$_2$ and draws the electrons to be neutralized. For this reason, dipole effects can be stronger in MoS$_2$ on h-BN, resulting in lower $\Phi_{SB}$. Although this is a rough sketch, we believe that our suggestion provides a perceptual view on our new finding, Schottky barrier lowering in MoS$_2$/h-BN heterostructure on SiO$_2$.

In summary, we have demonstrated the h-BN effect on electron doping concentration and Schottky barrier lowering based on the temperature-dependent carrier transport of MoS$_2$/h-BN heterostructure. As an optimal substrate, the use of h-BN reveals several advantages over SiO$_2$ substrate: (i) excess n-doping concentration of $\sim 5 \times 10^{13}$ cm$^{-2}$ at high temperature, (ii) suppressed interface trap density by a factor of $S$, (iii) 3-fold less $E_F$, and alleviated Coulomb scattering for the charge transport in the channel, and (iv) three times reduced $\Phi_{SB}$ in metal–MoS$_2$ junction due to a higher energy band bending and dipole alignment effect compared to SiO$_2$. Consequently, the field-effect mobility of MoS$_2$/h-BN at $T = 25$ K was enhanced four times and allowed the operation of MoS$_2$ transistor in the depletion mode, which results in early emergence of MIT. These results will shed light to further enhance the performance of 2D electronic systems.

**Experimental Section. CVD MoS$_2$ Growth Process.** Three types of solutions are first prepared; Solution A—OptiPrep density gradient medium (Sigma-Aldrich, D1556, 60% of (w/v) solution of iodixanol in water), Solution B—Sodium chloride (SC) hydrate (Sigma-Aldrich, C6445) in deionized (DI) water, and Solution C—Solution-phase ammonium heptamolybdate (AHM) precursor (dissolving ammonium molybdate tetrhydrate (Sigma-Aldrich, 431346) into DI water). After mixing all solutions with the ratio of A:B:C = 0.55:3:1, the solution was dropped on SiO$_2$/Si wafer, and the spin-casting process was then carried out. A two-zone CVD system was then employed to respectively control sulfur (zone 1:200 mg of sulfur) and substrate (zone 2) at atmospheric pressure. The further specific growth conditions has been reported elsewhere.37,38

**Device Fabrication.** Mechanically exfoliated multilayered h-BN flakes (purchased from 2D Semiconductors) were first transferred onto 300 nm SiO$_2$/Si substrates. Single layer MoS$_2$ flakes grown using CVD were then placed on SiO$_2$/Si substrates with and without h-BN. After finding clean and properly located MoS$_2$ monolayer flakes and with and without h-BN using optical microscopy (Axio imager 2, Carl Zeiss), Cr/Au metal electrodes (of 2/60 nm thick) were selectively patterned using conventional electron-beam lithography. The geometrical factors of channel length, width, and the thickness of MoS$_2$ flakes on SiO$_2$ and h-BN nanosheets were confirmed by AFM (SPA 400, SEIKO).

**Optical and Electrical Characterizations.** To obtain the optical properties of MoS$_2$ on h-BN and SiO$_2$, Raman (XperRam 200, Nano Base) and photoluminescence (NTEGRA-SPECTRA, NT-MDT) techniques were employed. For electrical transport characterizations, a commercial semiconductor characterization system (4200-SCS, Keithley) and dual-channel system (2636A, Keithley) were used. The operating temperature was controlled using a cryogenic probe system (335, LakeShore).

**ASSOCIATED CONTENT**

§ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.nanolett.6b02788.

Supplementary figures and discussion containing atomic force microscope images, photoluminescence emission spectra, device variability, and Hall effect measurement data for MoS$_2$/SiO$_2$ and MoS$_2$/h-BN, respectively (PDF).

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**Notes**

The authors declare no competing financial interest.
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