Large-Scale Graphene on Hexagonal-BN Hall Elements: Prediction of Sensor Performance without Magnetic Field

Min-Kyu Joo,†‡#, Joonggyu Kim,‡#, Ji-Hoon Park,‡ Van Luan Nguyen,† Ki Kang Kim,§ Young Hee Lee,*,†‡, and Dongseok Suh*‡

†Center for Integrated Nanostructure Physics (CINAP), Institute for Basic Science (IBS), Suwon 16419, Republic of Korea
‡Department of Energy Science, Sungkyunkwan University, Suwon 16419, Republic of Korea
§Department of Energy and Materials Engineering, Dongguk University, Seoul 04620, Republic of Korea

Supporting Information

ABSTRACT: A graphene Hall element (GHE) is an optimal system for a magnetic sensor because of its perfect two-dimensional (2-D) structure, high carrier mobility, and widely tunable carrier concentration. Even though several proof-of-concept devices have been proposed, manufacturing them by mechanical exfoliation of 2-D material or electron-beam lithography is of limited feasibility. Here, we demonstrate a high quality GHE array having a graphene on hexagonal-BN (h-BN) heterostructure, fabricated by photolithography and large-area 2-D materials grown by chemical vapor deposition techniques. A superior performance of GHE was achieved with the help of a bottom h-BN layer, and showed a maximum current-normalized sensitivity of 1986 V/AT, a minimum magnetic resolution of 0.5 mG/Hz0.5 at f = 300 Hz, and an effective dynamic range larger than 74 dB. Furthermore, on the basis of a thorough understanding of the shift of charge neutrality point depending on various parameters, an analytical model that predicts the magnetic sensor operation of a GHE from its transconductance data without magnetic field is proposed, simplifying the evaluation of each GHE design. These results demonstrate the feasibility of this highly performing graphene device using large-scale manufacturing-friendly fabrication methods.

KEYWORDS: graphene, hexagonal boron nitride, magnetic field sensor, large-area graphene device, graphene Hall element, chemical vapor deposition

With the increasing use of smart devices, there is an urgent need to extend their capabilities by incorporating chip-based sensors with diverse functions, for example, gyroscope, proximity, and pressure sensors. The Hall-effect magnetic sensor (Hall sensor) is one of them, potentially applicable in the fields of biomedical, electromagnetic, and mechatronic engineering.1−4 Material properties required for a Hall sensor include (i) a thin active channel, (ii) high carrier mobility, and (iii) a narrow band gap, based on its operating principle.5−7 While commercial Hall sensors based on silicon-related materials are widely manufactured and used, there have also been many efforts to improve their performance. Active channels consisting of III−V compounds and having two-dimensional (2-D) electron-gas configurations have achieved a thin channel depth and high mobility.8−10 However, exploration to find better Hall sensor materials continues to be driven not only for performance but also by economic reasons.

Recently, monolayer graphene has been considered as a channel material appropriate for Hall sensor application because of its extremely high mobility, ambipolar operation, and one-atom layer thickness, as well as its low carrier density.6,10−14 These unique and beneficial characteristics enable the graphene Hall element (GHE) to be a high performance magnetic sensor having larger Hall-effect current sensitivity (SI) compared with silicon-based magnetic sensors.6,7,10,11,13 In one investigation, the Bmin value was reduced to around 0.5 mG/Hz at f = 3 kHz frequency domain for a GHE, which was encapsulated between exfoliated hexagonal-BN (h-BN) and fabricated by electron-beam lithography (EBL).13 However, these mechanical exfoliation and EBL techniques are only useful for proof-of-concept experiments, and are not feasible for quality-controlled mass manufacturing. Instead, large-area materials synthesized by chemical vapor deposition (CVD) in

Received: July 8, 2016
Accepted: August 31, 2016
Published: August 31, 2016
combination with conventional photolithography fabrication are preferred for the practical fabrication of large-scale GHE arrays.

Here, we demonstrate a CVD-based, photolithographically patterned, highly sensitive GHE array having graphene on a h-BN structure. Although the large-area materials and fabrication methods were applied, the relative standard deviation of the field-effect mobility ($\mu_{FE}$) was less than $\sim 10\%$ (see Figure S1 in the Supporting Information, SI). Not only the superior device performance, but also the deep understanding and analysis for the operation principle of this GHE magnetic sensor were studied, which will help the promotion of 2-D materials toward more practical applications in the field of electronic devices. The entire characterization sequences for the GHE device are summarized in Figure 1.

**RESULTS AND DISCUSSION**

Manufacturing-Friendly Design of GHE in Terms of Material and Fabrication. In the device design stage, we focused on two things. First, the GHE devices are composed of large-area graphene and h-BN layers, both of which are prepared by CVD methods instead of mechanical exfoliation. Second, they are fabricated using standard photolithography techniques instead of electron-beam lithography. Figure 2 shows the overall fabrication procedures of the GHE arrays. Initially, a 20 nm-thick h-BN film was synthesized directly on a 4-in. SiO$_2$/Si wafer by plasma-enhanced CVD (PECVD). Then, the full-coverage monolayer graphene grown by CVD on copper foil was transferred onto the h-BN/SiO$_2$/Si substrate. After that, symmetric crossbar-shaped GHE channel areas were defined using a standard photolithography process, followed by oxygen-plasma reactive-ion etching. Finally, metal electrodes consisting of a Cr/Au (3/70 nm) bimetal layer were formed through the combined processes of photolithography, thermal evaporation of metals and lift-off. The relevant optical images at each fabrication step are included in Figure 2.

Structural Analysis of GHE Using Raman Spectroscopy. Due to its atomically smooth surface and absence of charged impurities, an h-BN layer has been considered as a suitable dielectric substrate for graphene transistors. To make a highly performing GHE magnetic sensor, we used a CVD-grown large-area h-BN layer as a substrate for our graphene device although this CVD thin-film may contain some degree of structural defects. The sample quality of CVD-grown graphene/h-BN heterostructure was evaluated using Raman spectroscopy. Two prominent Raman peaks corresponding to the “G” mode and “2D” mode of monolayer graphene are observed at 1586 cm$^{-1}$ and 2675 cm$^{-1}$, respectively in Figure 3a. Since they are almost equal to the intrinsic values of the $G$ ($\sim 1582$ cm$^{-1}$) and $2D$ ($\sim 2677$ cm$^{-1}$) peak positions, the bottom h-BN thin-film in our sample also plays a role of optimal substrate for graphene. One small peak located at 2454 cm$^{-1}$...
cm$^{-1}$ corresponds to the G* band associated with a double resonance Raman process.$^{19,22}$ Additional analysis of the disorder-related "D" peak is shown in Figure 3b. The Raman spectrum (violet circles) below 1500 cm$^{-1}$ is decomposed into individual Lorentzian lines (long-dashed lines) due to the known peak positions of the D mode of monolayer graphene and the E$_{2g}$ phonon mode of h-BN, even though they are located nearby. The D peak (red long-dashed line) is observed at 1344 cm$^{-1}$ and might be created during the graphene transfer process onto h-BN thin film. The E$_{2g}$ phonon mode of polycrystalline h-BN (orange long-dashed line) appears at 1377 cm$^{-1}$, agreeing with the range of reported values.$^{23−26}$ The remaining peak at 1457 cm$^{-1}$ can be attributed to the third-order transverse optical mode of a silicon substrate (olive long-dashed line).$^{27,28}$ From a pre- and postannealing comparison, no evidence is observed for a blue-shift of graphene’s G and 2D peaks. All such results indicate that a h-BN thin film below monolayer graphene plays an important role in preventing unwanted hole-doping by the silicon oxide substrate (see Figure S2 in the SI).$^{29}$

**Electrical and Magnetic Sensor Properties of GHE.**

Figure 4a presents the dependence of the GHE drain current on the back-gate voltage ($I_D − V_{BG}$) at several drain voltages ($V_D = 10$ mV, 100 mV, 1 V, and 10 V). These $I_D − V_{BG}$ transfer curves exhibit the V-shaped ambipolar behavior typically observed in graphene field-effect transistors. The negligible hysteresis during a $V_{BG}$ sweep indicates that h-BN enables to provide an inert and clean surface to the graphene, as discussed
in the previous Raman analysis section.\textsuperscript{29} The mean value of the field-effect mobility ($\mu_{\text{FE}}$) ranges from 1700 cm$^2$/V s to 3500 cm$^2$/V s, depending on the GHE array. It is worth noting that the voltage at charge neutrality point ($V_{\text{CNP}}$) corresponding to the minimum channel conductance moves substantially as $V_D$ increases. This $V_{\text{CNP}}$ shift related to $V_D$ can be understood in terms of hole-doping effects in the region near the drain electrode.\textsuperscript{30,31}

For the clear description about this hole-doping effect, a simplified energy diagram for the large $V_D$ bias condition is shown in Figure 4b. When the back-gate voltage induces an overall $n$-doping in the graphene channel, the large $V_D$ bias pushes the Fermi level down to make a local $p$-doping region near the drain electrode. Such a carrier-type conversion along the channel originates from graphene’s intrinsic Dirac-cone band structure.\textsuperscript{32,33} The movement of the channel originates from graphene near the drain electrode. Such a carrier-type conversion along the channel will limit the ranges of device-control parameters, which will be discussed in the last section of this article.

The representative linear responses of Hall voltage ($V_H$) as a function of magnetic field (B) between $-5$ kG and 5 kG at the fixed $V_{BG} = 2.5$ V with various $I_D$ conditions are plotted in Figure 4c. The absolute Hall sensitivity $S_A (= \partial V_H/\partial B)$ can be obtained from the linear $V_H$ slope at specific $I_D$ and $V_{BG}$ bias conditions, where the current-normalized Hall sensitivity ($S_I = S_A/I_D$) is equivalent to the conventional Hall effect current sensitivity. Therefore, under the assumption that the magnitude of the hole mobility is similar to that of the electron,\textsuperscript{3,5,12,14}

$$S_I = \frac{S_A}{I_D} \approx -\frac{\alpha \alpha}{e} \left( \frac{n(V_{BG}, V_{CNP})}{n(V_{BG}, V_{CNP})^3 + n_0^2} \right)$$

$$n(V_{BG}, V_{CNP}) \approx \frac{C_{OX}}{e} (V_{BG} - V_{CNP})$$

(1)

where $r_{H}$, $\alpha$, $C_{OX}$, $e$, $n_0$ and $n(V_{BG}, V_{CNP})$ denote the Hall factor, the geometrical correction factor, the oxide capacitance, the elementary unit charge, the residual carrier concentration, and the carrier concentration as a function of $V_{BG}$ and $V_{CNP}$ respectively. By taking the first derivative of eq 1, it can be easily calculated that the maximum magnitude of $S_I$ is $r_{H} \alpha / (2n_e e)$ when $n(V_{BG}, V_{CNP})$ equals $n_0$\textsuperscript{12} which is independent of $I_D$ by definition. However, it should be noted that the position and magnitude of maximum $S_I$ changes as a function of $I_D$ in the experimental data, indicating a need for revision of the above model.

Figure 4d shows the $V_{BG}$-dependence of the Hall effect sensitivity $S_I$ for selected $I_D$ values, while Figure 4e displays the variation of $S_I$ as a two-dimensional contour plot, as a function of $I_D$ (from 10 $\mu$A to 1 mA with 10 $\mu$A steps) and $V_{BG}$ (from $-30$ to 30 V with 0.1 V steps). A slightly asymmetric shape of $S_I$ related to the type of majority charge carriers is observed, and can be ascribed to the difference between field-effect mobility of electrons and holes, as well as to the scattering mechanisms involved in the carrier transport through graphene. In Figure 4e, we can clearly notice that the maximum value of $S_I$ is strongly dependent on the $I_D$ and $V_{BG}$ bias conditions. As the driving current $I_D$ of the Hall sensor increases, the maximum value of $S_I$ decreases gradually and $V_{CNP}$ is positively shifted.

\textbf{Prediction of Magnetic Sensor Performance from Electrical Properties of GHE.} Because the conventional two-band model given in eq 1 does not describe the experimentally observed shift of the maximum $S_I$ as a function of $I_D$, we developed an analytical model that incorporates the transconductance ($g_m = \partial I_D/\partial V_{BG}$) of the GHE. In fact, $S_I$ is equivalent to the Hall coefficient, i.e., $S_I$ is inversely proportional to the carrier concentration $n(V_{BG}, V_{CNP})$ in principle, which can be alternatively described using the voltage difference ($V_{BG} - V_{CNP}$) and the capacitance $C_{OX}$ as expressed in eq 1. Additionally, the empirically determined $g_m$ can be considered to correct for possible errors originating from the $V_{CNP}$ estimation with respect to $V_D$. Then $S_I$ can be expressed in the form of eq 2,

$$S_I = -\frac{r_{H}\alpha}{e} \left[ \frac{\partial V_H}{\partial B} \right] \frac{1}{I_D} \approx -\frac{r_{H}\alpha}{e} \left[ \frac{C_{OX} V_{BG} - V_{CNP}}{V_{BG} - V_{CNP}} \right] \frac{1}{I_D}$$

$$= -\left( \frac{r_{H}\alpha}{e} \right) \left( \frac{V_{BG}}{I_D C_{OX}} \right) \exp \left( -\frac{g_m V_D}{I_D C_{OX}} \right)$$

(2)

It is very interesting that the final form of eq 2 indicates that the Hall sensitivity $S_I$ can be expressed using parameters such as $g_m$, $I_D$, and $V_{BG}$, which can be experimentally obtained without magnetic field. In other words, it implies that the magnetic sensor performance of GHE can be predicted from the normal (i.e., no B field) transconductance data, with no actual experiment under magnetic field.

To check the validity of the above arguments, we plotted simulation curves in Figure 4f by combining the experimental transconductance data in Figure 4a and the analytical model in eq 2. When these simulated $S_I$ curves ($r_{H}\alpha$ used as a fitting parameter has been set to the numerical value 3) are compared to the $S_I$ curves in Figure 4d measured under magnetic fields, the shape and the trend of $S_I$ with respect to $I_D$ in both graphs are quite similar. Therefore, it confirms that the behavior of $S_I$ as a function of $V_{BG}$ and the value of $V_{BG}$ corresponding to the maximum of $S_I$ can be fitted well using this approach. Furthermore, the electrical input parameters $I_D$ (or $V_D$) and $V_{BG}$ giving the maximum $S_I$ can be predicted well, without a full parameter mapping of the response under magnetic field conditions. This can greatly reduce the effort to find optimal bias conditions for GHE performance.

As a result of the direct relation between $S_I$ and the transconductance data via eq 2, several features of $S_I$ observed in Figure 4d can be intuitively understood in relation to the $I_D$ and $V_{BG}$ curves in Figure 4a. For example, no significant variation of $S_I$ up to $I_D \approx 200 \mu$A is attributed to the small variation of $V_{CNP}$ seen in Figure 4a. The degradation of the maximum $S_I$ magnitude at large $V_D$ (or $I_D$) in Figure 4d can be also explained in terms of the $V_{CNP}$ shift as discussed in Figure 4b, where local hole-doping near the drain electrode and inhomogeneous thermal heating in the highly resistive region of the GHE degrades the sensor performance.\textsuperscript{10,30} (See Figure S3 in the SI for the additional 2-D contour plot data of $S_I$ obtained from different GHE devices using eq 2). From this contour plot, the optimal input bias conditions as well as the performance limitations of a GHE magnetic sensor can be actually predicted without magnetic field. Theoretically predicted $V_{BG}$ locations for the $S_I$ maxima as a function of $I_D$...
showed good agreement with the experimentally obtained data under magnetic field as shown in Figure 5. And small deviations can be attributed to contact-resistance effects, neglected scattering mechanisms, and different geometrical correction factors between electron and hole carriers.

The Minimum Magnetic Resolution of GHE. For the estimation of a minimum magnetic resolution \( B_{\text{min}} = \frac{S_V^{0.5}}{S_M} \) where \( S_V \) is the voltage power spectral density, the low-frequency (LF) noise measurement (with a frequency range 5 Hz–1 kHz) was carried out to obtain \( S_V \) as a function of \( I_D \) and \( V_{BG} \) in Figure 6. Initially, we confirmed that the LF noise characteristics are independent of the \( I_D \) direction due to the symmetrical cross bar shape of the GHE device. The representative \( S_V \) curves are presented in Figure 6a for the hole- and electron-dominant regimes, which are controlled by the \( V_{BG} \). Both curves show a general \( 1/f \) trend at low frequencies and eventually saturate to thermal Nyquist noise level at higher frequencies as a result of random thermal motion of carriers in graphene together with uniformly distributed traps around the interface.34–36

Since this thermal noise can be regarded as the minimum LF noise floor, the equivalent resistance value can be extracted from the definition of voltage power spectrum density \( S_V = 4k_BT R \), where \( k_B \), \( T \), and \( R \) are the Boltzmann constant, the absolute temperature, and the equivalent resistance value, respectively.36 The calculated thermal noise was approximately \( 1–2 \times 10^{-16} V^2/Hz \), which is equivalent to the resistance range of 6–12 kΩ. Because such a result matches well with the resistance values obtained in Figure 4a, it confirms the consistency of our noise experiment results. Furthermore, the small magnitude of LF noise can be ascribed to the effect of graphene/h-BN heterostructure. When we consider the \( V_D \) normalized \( S_V \) curves \( (= S_V/V_D^2) \) with respect to different \( I_D \) (see Figure S4 in the SI), it turns out that the LF noise levels are roughly same in both carrier types, and the dependence of

![Figure 5. Comparison between analytical model and experiment. Direct comparison between theoretically predicted \( V_{BG} \) values that correspond to the maximum value of \( S_I \) and values obtained from the magnetic experiments, as a function of \( I_D \).](image)

![Figure 6. Limit of magnetic resolution. (a) The voltage power spectrum of hole- and electron-dominant regimes (left and right panels, respectively) with respect to different \( I_D \). (b) Experimentally obtained \( S_A \) contour plot. (c) The absolute value of \( B_{\text{min}} \) of hole- and electron-dominant regimes (panels as above) with respect to different \( I_D \). (d) Experimentally obtained \( B_{\text{min}} \) contour plot (the red dashed area) at \( f = 300 \) Hz. For the comparison, the 2-D contour plot (back ground panel) is overlapped behind \( B_{\text{min}} \) graph.](image)
the LF noise amplitude on $V_{BG}$ shows a typical trend with a minimum at $V_{CNP}$ as reported previously.\textsuperscript{37,38} In addition to LF noise properties, the trend of $S_A$ (rather than $S_I$) with respect to $I_D$ and $V_{BG}$ should be examined to determine the bias condition of this GHE device for the larger $S_A$ and the better $B_{\text{min}}$ values. The blue and the red portions in Figures 6b corresponds to the maximum $S_A$ operation range of the GHE device with hole- and electron-majority carriers, respectively. Except for the region near $V_{CNP}$ where $S_A$ is close to zero, the entire operating region in terms of carrier concentration, in other words, $V_{BG}$ becomes broader as $I_D$ increases. In an alternative approach, the optimal bias ranges can also be deduced by the analytical method proposed above using eq 2, where the contour plot of $S_A$ with the relationship $S_A = -r_H q g_m / C_{OX}$ and $g_m \approx I_D / (V_{BG} - V_{CNP})$ from the carrier drift model gives roughly the similar tendency (see Figure S5 in the SI for details and limitation of this analytical method).\textsuperscript{35,36,39,40}

After $S_A$ and $S_V$ values are determined, the frequency dependence of the absolute $B_{\text{min}} (= S_V^{0.5}/S_A)$ can be obtained as a function of $I_D$ for both electron- and hole-dominant regimes in Figure 6c and plotted again in the form of two-dimensional graph at $f = 300$ Hz in Figure 6d. Even though the smallest $S_V$ is achieved at $V_{BG} \approx V_{CNP}$, the abrupt reduction of $S_A$ (see the background $S_A$ contour plot in Figure 6d), makes $B_{\text{min}}$ increased rapidly near $V_D$ when $I_D \leq 200 \mu A$. However, when the driving current $I_D$ exceeds 200 $\mu A$, the $B_{\text{min}}$ value ranges from 0.5–30 mG/Hz$^{0.5}$ irrespective of $V_{BG}$ (see the red dashed area and values in Figure 6d), which is comparable to the best reported value using the EBL technique.\textsuperscript{13} Various performance parameters of Hall elements in literature are listed in Table 1.\textsuperscript{7,10,13,41,42} This confirms the superiority of our GHE device in terms of performance compared with Si and III/V semiconductor-based Hall elements and in the aspects of materials and fabrication methods compared with other reported GHEs.

Dynamic Range of GHE. As a magnetic field sensor, a dynamic range, defined as the range of minimum detectable effective magnetic field in the presence of a strong static $B$ field, is one of the important parameters characterizing the sensor performance, especially in the application of a biomedical signal

<table>
<thead>
<tr>
<th>graphene type</th>
<th>$S_I$ (V/AT)</th>
<th>$\mu$ (cm$^2$/V s)</th>
<th>lithography</th>
<th>$B_{\text{min}}$ (mG/Hz$^{0.5}$) at 300 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref 42 CVD</td>
<td>1200</td>
<td>2500</td>
<td>photolithography</td>
<td>NA</td>
</tr>
<tr>
<td>ref 41 epitaxial</td>
<td>1021</td>
<td>3000</td>
<td>EBL</td>
<td>~66 (calculated)</td>
</tr>
<tr>
<td>ref 7 CVD</td>
<td>800</td>
<td>5100</td>
<td>EBL</td>
<td>~20</td>
</tr>
<tr>
<td>ref 10 CVD</td>
<td>2093</td>
<td>6900</td>
<td>EBL</td>
<td>~7</td>
</tr>
<tr>
<td>ref 13 exfoliated</td>
<td>4100</td>
<td>NA</td>
<td>EBL</td>
<td>~0.5</td>
</tr>
<tr>
<td>this work for holes</td>
<td>1447</td>
<td>1600–1700</td>
<td>NA</td>
<td>0.5–30</td>
</tr>
<tr>
<td>this work for electrons</td>
<td>1535</td>
<td>1900–2100</td>
<td>photolithography</td>
<td>1–90</td>
</tr>
<tr>
<td>best GHE</td>
<td>1986</td>
<td>3500–3700</td>
<td></td>
<td>NA</td>
</tr>
</tbody>
</table>

Figure 7. Dynamic range measurement of GHE. (a) Schematic illustration for the effective dynamic range measurement setup. (b) Characteristic curve for the small AC magnetic field ($B_{AC}$) detection under a large DC magnetic field ($B_{DC}$) by the measurement of AC Hall voltage ($V_{H,AC}$) signal. (c) $B_{AC}$ dependence of $V_{H,AC}$ at different $V_{BG}$ with the condition of $I_D = 1$ mA, $f = 10$ kHz, and $B_{DC} = 0.5$ T.
Figure 8. Thermal heating effects on GHE. Imaged temperature contour of GHE for \( I_D = 1 \) mA (left panel), 3 mA, 5 mA, and 7 mA (right panel) at \( V_{BG} = 200 \) V, respectively.

**CONCLUSION**

We have made a centimeter-scale magnetic-field sensor chip having GHE arrays to utilize graphene’s advantageous features as a Hall sensor, such as its complete two-dimensional properties, high carrier mobility, and largely controllable carrier density. For the development to practical manufacturing level, CVD-synthesized two-dimensional materials (graphene and h-BN) and photolithography-based fabrication processes were employed instead of mechanical exfoliation and electron-beam lithography. Even in such situations, the best results we obtained (i.e., 1986 V/AT for the current-normalized sensitivity, 0.5 mG/Hz\(^{0.5}\) for the minimum magnetic resolution at \( f = 300 \) Hz, and a minimum dynamic range of \( \sim 74 \) dB at \( B = 0.5 \) T and \( f = 10 \) kHz) are mostly equivalent to or superior than the values in the literature. A suggested analytical model predicting magnetic sensor performance of GHE without the actual measurement under magnetic fields will help us to determine the sensor parameters for an optimized operational condition. The combination of CVD-grown two-dimensional materials with photolithography will definitely promote the advance of this prototype GHE to the practical manufacturing level.

**EXPERIMENTAL METHODS**

**Device Fabrication.** A 20 nm thick polycrystalline h-BN film was synthesized directly on 4-in. SiO\(_2\)/Si wafer by plasma-enhanced CVD.\(^{44}\) The full-coverage high-quality CVD-grown monolayer graphene on copper foil (3 × 9 cm\(^2\)) was transferred onto the h-BN/SiO\(_2\)/Si substrate by the well-developed bubbler transfer technique.\(^{15}\) Symmetric cross-shaped GHEs having different active channel areas (L × W) were defined ranging from 60 × 12 μm\(^2\) to 240 × 120 μm\(^2\) through standard photolithography and oxygen-plasma reactive ion etching (APS-RF/AT, ALL FOR SYSTEM). Electrodes consisting of Cr/Au metal layers (3/70 nm) were also patterned using conventional photolithography processes, followed by thermal evaporation of bilayer metals and established lift-off sequences. The post-spectral annealing process was carried out at each step for 2 h under a flow of Ar/H\(_2\) = 500/100 sccm at T = 350 °C for the adhesion of h-BN and the complete removal of residual polymers on the surface of graphene. The geometrical factors of channel length, width, and the thickness of monolayer graphene on h-BN heterostructure were confirmed by optical microscopy (Axio imager 2, CARL ZEISS) and atomic force microscopy (SPA 400, SEIKO).

**Optical, Electrical, and Thermal Characterizations.** Raman spectroscopy (XperRam 200, Nano Base) was performed to characterize the quality of monolayer graphene on the h-BN double-layer structure. Electrical transport experiments, including the Hall effect measurements, were carried out at room temperature under high vacuum using a cryostat (PPMS, Quantum Design Inc.) and...
commercial semiconductor characterization systems (4200-SCS, Keithley Instruments and B1500A, Keysight Technologies). Low-frequency noise characteristics were measured using a customized LF noise measurement system in a metal shielding box, consisting of a battery container, a low noise voltage amplifier (SR5113, Signal Recovery), and a data acquisition system (DAQ-4431, National Instruments). Dynamic range measurement data was obtained by commercial semiconductor analyzer (B1500A, Agilent) and lock-in amplifier (SR830, Stanford research) in PPMS. The spatial temperature image of a GHE during its operation was obtained from an infrared thermal-imaging microscope system (InfraScope III, Quantum Focus Instruments). The static DC bias was supplied by a conventional semiconductor analyzer (Agilent 4156C, Agilent Technologies) at ambient conditions inside a metal shielding box.

**ASSOCIATED CONTENT**

**Supporting Information**

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsnano.6b04547.

1. Relative standard deviation of the field-effect mobility of GHE samples; 2. Post annealing effect on Raman spectroscopy of a GHE; 3. Calculated Hall effect current sensitivity ($S_I$) of GHE based on analytical model; 4. Voltage power spectrum ($S_V$) normalized by drain voltage; 5. Numerically calculated $S_I$; 6. Limitation of $R_{min}$ of GHE based on low frequency noise model; 7. Dynamic range measurement of GHE; 8. Feasibility of GHE as a magnetic sensor application using the Arduino (PDF)

**AUTHOR INFORMATION**

**Corresponding Authors**

*E-mail: leeyoung@skku.edu.
*E-mail: energy.suh@skku.edu.

**Author Contributions**

*These authors (M.K.J. and J.K.) contributed equally to this work.

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was supported by the Institute for Basic Science (IBS-R011-D1) (Y.H.L.) and by the National Research Foundation of Korea (NRF-2013R1A1A1076063) (D.S.), funded by the Ministry of Science, ICT & Future Planning, Republic of Korea.

**REFERENCES**

(8) Kuems, V. P.; Black, W. T.; Manat, Y. I.; Guzun, D.; Salamo, G. J.; God, N.; Mishima, T. D.; Doen, D. A.; Murphy, S. Q.; Santos, M. B. Highly Sensitive Micro-Hall Devices Based on Al$_{0.52}$In$_{0.48}$Sb/InSb Heterostructures. *J. Appl. Phys.* 2005, 98, 014506.


