



Highly sensitive NO₂ gas sensor based on ozone treated graphene

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ABSTRACT

In the present study, we report a simple and reproducible method to improve the sensing performance of a graphene gas sensor using ozone treatment and demonstrate it with nitrogen dioxide (NO₂) gas. The ozone-treated graphene (OTG) sensor demonstrated remarkable enhancement of the sensing performances such as percentage response, detection limit and response time. The percentage response of the OTG sensor was twofold higher than that of a pristine graphene sensor when it was exposed to 200 ppm concentration of NO₂ at room temperature. It is noteworthy that significant improvement was achieved in the response time by a factor of 8. Extremely low parts-per-billion (ppb) concentrations were clearly detectable, while the pristine graphene sensor could not detect NO₂ molecules below 10 ppm concentration. The detection limit of the OTG sensor was estimated to be 1.3 ppb based on the signal to noise ratio, which is the cutting-edge resolution. The present ozone treatment may provide an effective way to improve the performance of the graphene-based sensor, given its simple process, practical usability and cost effectiveness.

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1. Introduction

Graphene is a fascinating material for sensing due to its large specific surface area for molecular adsorption and outstanding electrical properties such as low noise level and high carrier mobility [1–9]. Gas sensing application of graphene utilizes a charge transfer from adsorbed molecules to graphene or a local electrostatic gating effect resulting in conductance change of graphene, which is quite similar to other solid-state gas sensors [10,11]. However, graphene has definite advantages over other sensing materials because it is a perfectly two-dimensional atomic material, and therefore, has maximum surface area with respect to its volume.

The gas reactivity of low dimensional carbon materials, such as carbon nanotube and graphene, strongly depends on defect density induced by functionalizing the surface with oxygen groups [12,13], which plays an important role in the electrical response for a gas molecule [13,14]. Therefore, controlled introduction of oxygen functional groups is important to enhance the performance of graphene-based sensors by increasing adsorbate binding energy and charge transfer at the reactive sites. A method for optimization

of the oxidation degree as well as homogeneous distribution of oxygen groups on graphene surface remains to be fully established.

Various efforts have been devoted to improve the performance of a graphene gas sensor by tailoring oxidation degree of graphene based on reduction methods [4–7,15], decoration of inorganic nanoparticles [8,16,17] and functionalization with organic polymers [18]. However, it is hard to obtain optimized degree of graphene oxidation for a gas sensor by reduction methods. Moreover, it generally includes complex steps and time-consuming processes. The cooperation with organic/inorganic substances may provide additional sensing capabilities on a graphene gas sensor. However, the process frequently requires cumbersome surface modification and coating processes, which generally lead to a costly way.

In the present study, we report a simple and reproducible method to improve the sensing performance of a graphene gas sensor using ozone treatment and demonstrate it with nitrogen dioxide (NO₂) gas. The ozone treatment is a very practical and effective way to enhance sensing characteristics of graphene by introducing a proper amount of functional oxygen groups on graphene. Furthermore, it enables us to provide uniform distribution of the oxygen groups not only on edges, but also on whole surface of graphene [14].

The ozone-treated graphene (OTG) sensor demonstrated remarkable enhancement of the sensing performances such as percentage response, detection limit and response time. The

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percentage response of the OTG sensor was twofold higher than that of a pristine graphene sensor when it was exposed to 200 ppm concentration of NO₂ at the room temperature. It is noteworthy that significant improvement was achieved in the response time by a factor of 8. Extremely low parts-per-billion (ppb) concentrations were clearly detectable, while the pristine graphene sensor could not detect NO₂ molecules below 10 ppm concentration. The detection limit of the OTG sensor was estimated to be 1.3 ppb based on the signal to noise ratio, which is the cutting-edge resolution.

2. Experimental setup and fabrication

Graphene films were grown on 25 μm-thick copper (Cu) foils (Alfa Aesar, item No. 13382) using CVD method [19]. The Cu foil was annealed at 1000 °C at low pressure with a H₂ flow of 6 sccm for 30 min, and then graphene growth was carried out at 1000 °C by introducing CH₄:H₂ (105:6 sccm) gases for 20 min. After the growth process, the furnace was cooled to room temperature while the CH₄:H₂ flow was maintained.

For a gas sensing tests, gold (Au) lead wires were attached to the electrode of graphene sensor using silver (Ag) paste, and the fabricated sensor was placed in a quartz tube located inside a furnace with a gas inlet and outlet. The sensor was exposed to dry air flow (500 sccm) for 10 min to record an initial sensor resistance, and then the NO₂ gas balanced with dry air were injected for 15 min to measure the sensing signal. To recover the sensor, dry air was supplied into the tube for 30 min. The resistance changes were measured using a multimeter (2000 multimeter, Keithley, USA).

The fabrication of the OTG gas sensor is schematically described in Fig. 1(A). Single layer graphene was grown on a copper foil using chemical vapor deposition (CVD) method. After the synthesis, one side of the copper foil specimen was spin-coated with poly-methyl methacrylate (PMMA) to mechanically support the graphene layer during the transfer procedure to a substrate. The graphene layer on the other side was removed by oxygen plasma treatment, and then the specimen was cut into a piece with the dimension of 15 mm × 5 mm. The specimen was floated on the surface of iron chloride aqueous solution to separate the graphene/PMMA layer from the specimen by etching the copper foil, and then the floating graphene/PMMA layer was subsequently transferred onto a silicon oxide substrate. The PMMA layer was removed by immersing the substrate in chloroform. The thermally evaporated 100 nm-thick gold (Au) electrode with the dimension of 10 mm × 2.5 mm was deposited on both sides of the graphene film by using shadow mask as shown in Fig. 1(A). The 5 nm-thick chrome (Cr) layer was deposited in advance to improve the adhesion and electrical contact between the graphene and the Au electrode.

After fabricating the graphene sensor, Raman spectroscopy analysis was performed to characterize the graphene film as shown in Fig. 1(B). It clearly indicates that the prepared graphene has single layer with a 2D/G peak ratio of 3.3, having symmetric 2D band centered at 2680 cm⁻¹ with a full width at half maximum of 35 cm⁻¹ [19,20]. The D band Raman intensity representing the disorder degree of graphene is negligible as shown in the figure. The graphene specimen was then treated with ozone which was generated by ultraviolet (UV) lamp irradiation (254 nm with an intensity of 20 mW/cm²) in ambient environment. It is well-known that highly reactive ozone molecules can readily oxidize carbon materials [14,21]. The D band began to appear after the ozone treatment for 60 s, and continuously increased with increasing ozone treatment time (see Fig. S1(A)). To quantify oxidation degree of the OTG, the G/D band ratio and the sheet resistance changes were measured with respect to the ozone treatment time as shown in Fig. 1(C). It was observed that as the treatment time increased the G/D ratio decreased, while the sheet resistance increased (see also Table S1). Using the X-ray photoelectron spectroscopy (XPS) measurement of

the carbon 1 s core level (shown in Fig. S1(B)), it was confirmed that the oxygen functional groups including ethers or epoxides and carbonyls with binding energies of 286.5 and 287.8 eV, respectively, were effectively introduced by the ozone treatment.

3. Performance evaluation of the OTG sensor

We investigated the sensing performance of the OTG sensor for NO₂ gas in terms of percentage response, response time and recovery characteristics. Percentage response is defined by the percentile resistance change when the sensor is exposed to a gas as follows:

$$\text{Percentage response} = \frac{R_0 - R_g}{R_0} \times 100\% \quad (1)$$

where R_0 and R_g are the resistances of the sensor before and after the exposure to a gas, respectively. Response time is defined as the time required for the sensor to reach e^{-1} (~36.8%) of the maximum resistance change after the sensor is exposed to gas molecules [22]. The recovery characteristic, which is closely related to binding affinity of gas molecules, is evaluated as follows:

$$\text{Recovery} = \frac{R_a - R_g}{R_0 - R_g} \times 100\% \quad (2)$$

where R_a is the resistance of the sensor exposed to air for a given recovery time.

Fig. 2(A) shows the relative resistance changes of the graphene sensors exposed to 200 ppm concentration of NO₂ gas at room temperature. The sensors were prepared by treating the graphene with ozone from 0 to 90 s, resulting in the different amount of oxygen groups on graphene. It was reported that, upon NO₂ molecular adsorption, an electron charge transfer occurs from graphene to a NO₂ molecule due to its electron-withdrawing power [23]. Thus, the accumulation of hole carrier lowered the graphene resistance as shown in Fig. 2(A). After the gas was injected for 15 min, the graphene sensor with the ozone treatment time of 70 s resulted in the maximum percentile resistance change of 19.7%, which is more than twofold higher than that of the pristine graphene sensor (Fig. 2(B)). It is also noteworthy that the response time was significantly improved by a factor of 8, compared to the pristine graphene sensor as shown in the inset of Fig. 2(A). The oxygen groups might be responsible for the improvements by providing favorable sites on the graphene surface with a higher adsorption affinity of NO₂ molecules. However, when the ozone treatment time exceeded 70 s, the percentage response decreased due to a rapid increase in initial resistance (R_0), caused by an excessive oxidation of the graphene. The recovery characteristics of the sensors were also evaluated based on Eq. (2), and plotted with respect to the ozone treatment time in Fig. 2(B). The recovery of the sensor continuously decreased as the ozone treatment time increased. The results indicate that the desorption of NO₂ gas molecule from the graphene surface is obstructed due to the higher binding energy provided by the oxygen groups, while the increased molecular affinity improves the percentage response by enhancing the charge transfer effect. Since the optimized density of the oxygen functional groups on graphene surface was able to improve gas sensing performance, following investigations were carried out using the graphene sensor with the ozone treatment time of 70 s.

The detection limit of the OTG sensor was investigated by decreasing the NO₂ concentration from 200 ppm to 0.2 ppm at room temperature. The relative resistance changes of the pristine graphene and the OTG sensors were compared with each other in Fig. 3. The pristine graphene sensor was not able to detect the NO₂ concentration below 10 ppm while extremely low concentration of ppb levels were clearly detectable using the OTG sensor with low noise level. Though our experimental system allows the lowest limit of the NO₂ concentration of 200 ppb, the theoretical

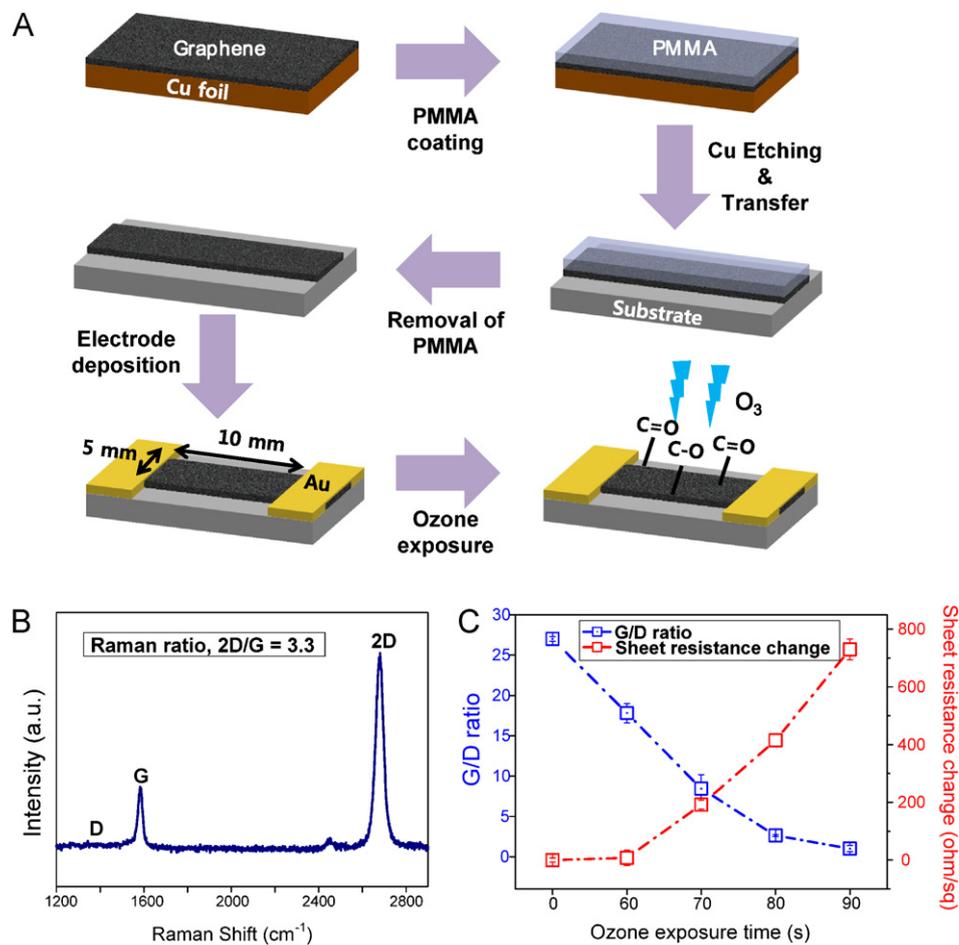


Fig. 1. (A) Schematic draw of the fabrication process for the ozone-treated graphene gas sensor. (B) Raman spectrum of the transferred graphene on a silicon oxide substrate (C) The G/D ratio and the sheet resistance changes with respect to ozone treatment time.

detection limit of the OTG sensor based on the signal to noise ratio is estimated at 1.3 ppb [7].

The inset of Fig. 3 shows the percentage response of the pristine and the OTG sensors with respect to the NO₂ concentration. The correlation between the percentage response and the gas concentration can be understood with the Langmuir adsorption isotherm theory [24]. When a gas molecule occupies a single site on a surface and is not dissociated, the relationship between the surface fraction occupied by adsorbates (θ) and the pressure (P) or concentration of gas molecules is expressed as:

$$\theta = \frac{K \cdot P}{1 + K \cdot P} \quad (3)$$

where the equilibrium constant (K) is defined by k_a/k_d , and k_a and k_d denote the adsorption/desorption rate constants, respectively. It is noteworthy that the percentage response of the OTG sensor was improved compared to that of the pristine graphene sensor as shown in the figure, which indicates the increase of the equilibrium constant (K). The constant K can be increased by either decreasing the temperature of sensing environment or increasing the binding strength of molecular adsorption. Since all the sensors were tested at the same temperature (i.e., room temperature), it confirms that the oxygen groups on the graphene introduced by the ozone treatment provide higher adsorption strength to the NO₂ molecules, as reported in literature [13,25].

The reproducible resistance change of the OTG sensor is shown in Fig. 4. When the sensor was exposed to the 200 ppm NO₂ flow, the percentage response decreased to a saturated value of

~17% after repeating the sensing cycle. However, the recovery increased and reached to a saturated value of 87% as shown in the inset. The NO₂ molecules are adsorbed either on a low energy binding site of graphene (i.e., sp²-bonded carbon with a binding energy of 5–40 kJ/mol) or on a high energy binding site (i.e., the oxygen groups having a wide range of adsorption energy of 40–800 kJ/mol, depending on their chemical bond and binding orientation) [4,26,27]. As the adsorption/desorption cycles were repeated, the response on pure graphene was recoverable. However, the high energy binding sites became occupied tightly by the NO₂ molecules, resulted in non-recoverable response. The strongly adsorbed molecules successively contribute to the reduction of the initial resistance as shown in Fig. 4, and limit the percentage response by reducing accessible binding sites. However, the saturated percentage response (~17%) is still higher than that of the pristine graphene sensor (~9.1%), and thereby suggesting that the charge transfer of the strongly adsorbed NO₂ molecules significantly improves the percentage response and response time [28,29].

The sensor responses with respect to temperature were also investigated (Fig. 5). It was observed that as the temperature increased, the percentage response of the OTG sensor decreased, while the recovery increased. Both the percentage response and recovery dependencies on the temperature can be explained by the equilibrium constant in Eq. (3). High temperature will accelerate the desorption of NO₂ gas molecules from the graphene surface. It results in the increase of the desorption rate constant (or improving the recovery characteristic), leading to the decrease

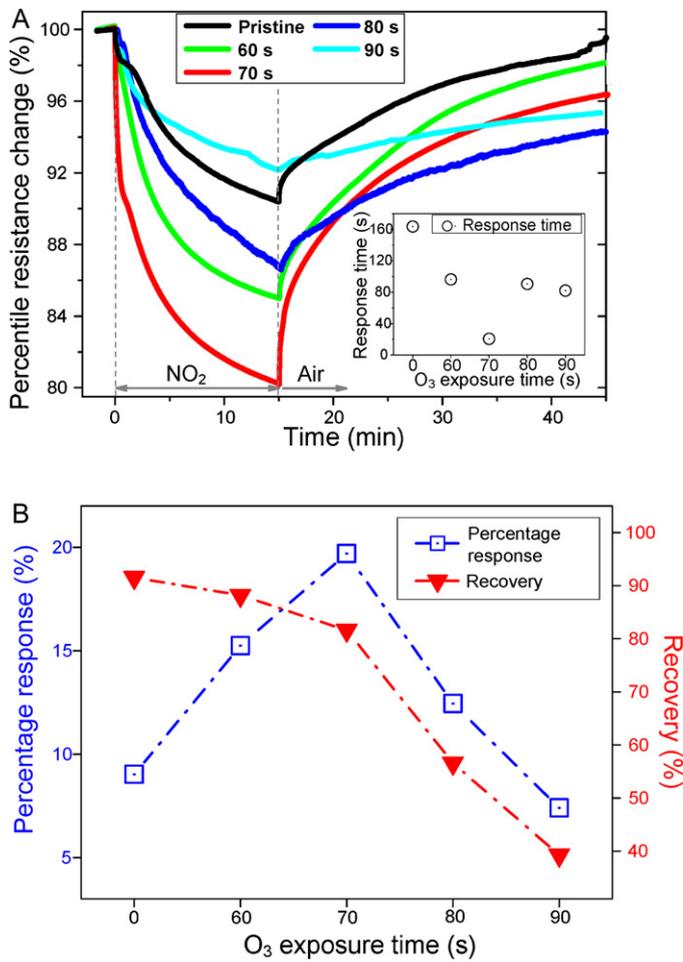


Fig. 2. Sensing performance of the graphene sensor with respect to the ozone treatment time. (A) The percentile resistance changes of the sensors when exposed to 200 ppm NO₂ at room temperature. The NO₂ gas balanced with dry air were injected for 15 min to measure the sensing signal. To recover the sensor, dry air was supplied into the tube for 30 min. The inset shows the response time with respect to ozone exposure time. (B) The percentage response and recovery variations with respect to the ozone treatment time.

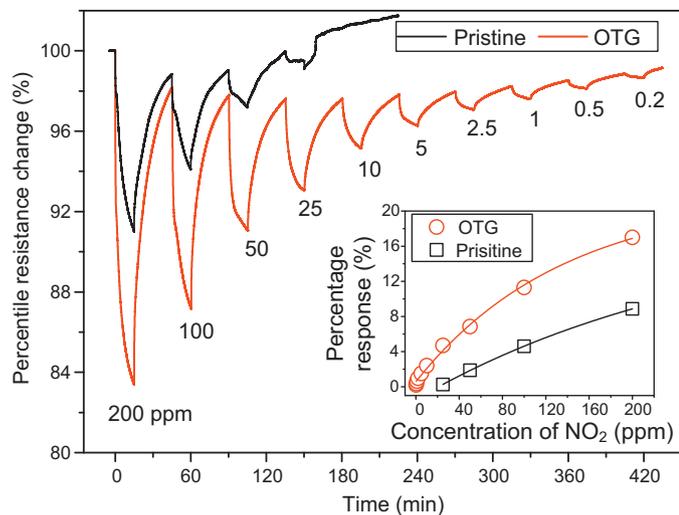


Fig. 3. The percentile resistance changes of the OTG (red) and pristine graphene (black) sensors. The NO₂ concentration was modulated from 200 ppm to 200 ppb. The inset shows the correlation between percentage response and concentrations, which is in agreement with the Langmuir adsorption model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

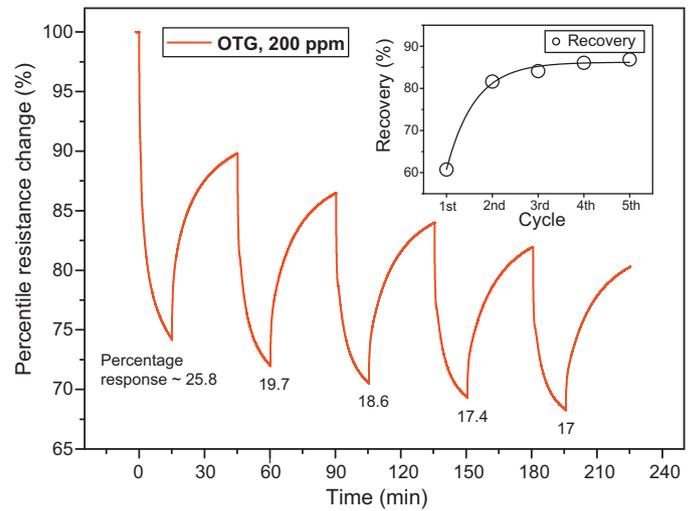


Fig. 4. The reproducible resistance change of the OTG sensor with cyclic exposures to 200 ppm NO₂ gas at room temperature. The percentage response decreased to a saturated value of ~17% after repeating the sensing cycle. The recovery change of the sensor is shown in the inset during the sensing cycles.

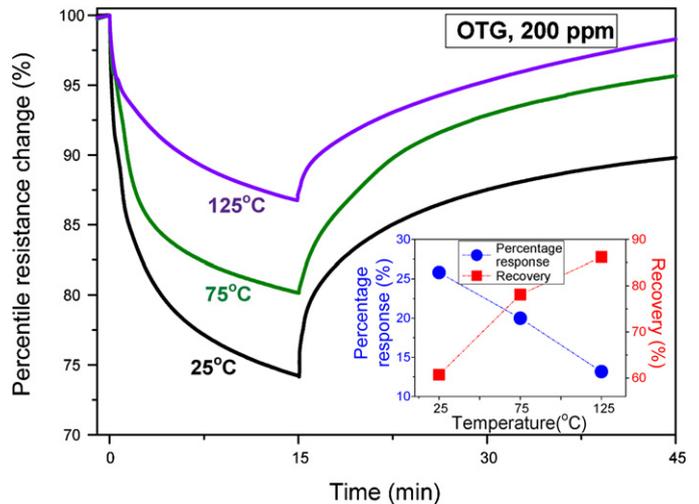


Fig. 5. The percentile resistance changes of the OTG sensor under a 200 ppm NO₂ flow at different operating temperatures ranging from 25 to 125 °C. The percentage response of the OTG sensor decreases as the operating temperature increases, while the recovery increases, as shown in the inset.

of the equilibrium constant. Therefore, the percentage response of the sensor decreases due to the reduction of the surface fraction occupied by the NO₂ molecules.

4. Conclusions

In summary, we successfully fabricated the highly sensitive graphene gas sensor using the ozone treatment. Optimized density of the oxygen functional groups can be readily introduced on the graphene surface by controlling the ozone treatment time. The sensor performances, such as percentage response, response time and recovery were quantitatively evaluated and discussed. The OTG sensor exhibited high percentage response to NO₂ gas with concentrations as low as ppb level, and eightfold faster response time than that of the pristine graphene sensor. The theoretical detection limit based on the signal to noise ratio was about 1.3 ppb. The improvement of the sensor performances is attributed to the oxygen groups on graphene introduced by ozone treatment, providing favorable gas adsorption sites with high binding energy. The

correlation between percentage response and gas concentration was in good agreement with the Langmuir adsorption isotherm model. The present ozone treatment may provide an effective way to improve the performance of the graphene based sensor, given its simple process, practical usability and cost effectiveness.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.snb.2012.02.036.

References

- [1] K.S. Novoselov, A.K. Geim, S.V. Morozov, D. Jiang, Y. Zhang, S.V. Dubonos, I.V. Grigorieva, A.A. Firsov, Electric field effect in atomically thin carbon films, *Science* 306 (2004) 666–669.
- [2] A.K. Geim, K.S. Novoselov, The rise of graphene, *Nat. Mater.* 6 (2007) 183–191.
- [3] F. Schedin, A.K. Geim, S.V. Morozov, E.W. Hill, P. Blake, M.I. Katsnelson, K.S. Novoselov, Detection of individual gas molecules adsorbed on graphene, *Nat. Mater.* 6 (2007) 652–655.
- [4] J.T. Robinson, F.K. Perkins, E.S. Snow, Z. Wei, P.E. Sheehan, Reduced graphene oxide molecular sensors, *Nano Lett.* 8 (2008) 3137–3140.
- [5] J.D. Fowler, M.J. Allen, V.C. Tung, Y. Yang, R.B. Kaner, B.H. Weiller, Practical chemical sensors from chemically derived graphene, *ACS Nano* 3 (2009) 301–306.
- [6] G. Lu, L.E. Ocola, J. Chen, Gas detection using low-temperature reduced graphene oxide sheets, *Appl. Phys. Lett.* 94 (2009) 083111–083113.
- [7] V. Dua, S.P. Surwade, S. Ammu, S.R. Agnihotra, S. Jain, K.E. Roberts, S. Park, R.S. Ruoff, S.K. Manohar, All-organic vapor sensor using inkjet-printed reduced graphene oxide, *Angew. Chem.* 122 (2010) 2200–2203.
- [8] W. Li, X. Geng, Y. Guo, J. Rong, Y. Gong, L. Wu, X. Zhang, P. Li, J. Xu, G. Cheng, M. Sun, L. Liu, Reduced graphene oxide electrically contacted graphene sensor for highly sensitive nitric oxide detection, *ACS Nano* 5 (2011) 6955–6961.
- [9] R. Pearce, T. Iakimov, M. Andersson, L. Hultman, A.L. Spetz, R. Yakimova, Epitaxially grown graphene based gas sensors for ultra sensitive NO₂ detection, *Sens. Actuators B: Chem.* 155 (2011) 451–455.
- [10] J. Kong, N.R. Franklin, C. Zhou, M.G. Chapline, S. Peng, K. Cho, H. Dai, Nanotube molecular wires as chemical sensors, *Science* 287 (2000) 622–625.
- [11] S. Capone, A. Forleo, L. Francioso, R. Rella, P. Siciliano, J. Spadavecchia, D.S. Presicce, A.M. Taurino, Solid state gas sensors: state of the art and future activities, *ChemInform* 35 (2004) no–no.
- [12] Y. Xuan, Y.Q. Wu, T. Shen, M. Qi, M.A. Capano, J.A. Cooper, P.D. Ye, Atomic-layer-deposited nanostructures for graphene-based nanoelectronics, *Appl. Phys. Lett.* 92 (2008) 013101–013103.
- [13] J.A. Robinson, E.S. Snow, Ș.C. Bădescu, T.L. Reinecke, F.K. Perkins, Role of defects in single-walled carbon nanotube chemical sensors, *Nano Lett.* 6 (2006) 1747–1751.
- [14] G. Lee, B. Lee, J. Kim, K. Cho, Ozone adsorption on graphene: ab initio study and experimental validation, *J. Phys. Chem. C* 113 (2009) 14225–14229.
- [15] T.H. Han, Y.-K. Huang, A.T.L. Tan, V.P. Dravid, J. Huang, Steam etched porous graphene oxide network for chemical sensing, *J. Am. Chem. Soc.* 133 (2011) 15264–15267.
- [16] J.L. Johnson, Experimental study of graphitic nanoribbon films for ammonia sensing, *J. Appl. Phys.* 109 (2011) 124301.
- [17] Z. Zhang, R. Zou, G. Song, L. Yu, Z. Chen, J. Hu, Highly aligned SnO₂ nanorods on graphene sheets for gas sensors, *J. Mater. Chem.* (2011).
- [18] L. Al-Mashat, K. Shin, K. Kalantar-zadeh, J.D. Plessis, S.H. Han, R.W. Kojima, R.B. Kaner, D. Li, X. Gou, S.J. Ippolito, W. Wlodarski, Graphene/polyaniline nanocomposite for hydrogen sensing, *J. Phys. Chem. C* 114 (2010) 16168–16173.
- [19] X. Li, W. Cai, J. An, S. Kim, J. Nah, D. Yang, R. Piner, A. Velamakanni, I. Jung, E. Tutuc, S.K. Banerjee, L. Colombo, R.S. Ruoff, Large-area synthesis of high-quality and uniform graphene films on copper foils, *Science* 324 (2009) 1312–1314.
- [20] K.S. Kim, Y. Zhao, H. Jiang, S.Y. Lee, J.M. Kim, K.S. Kim, J.-H. Ahn, P. Kim, J.-Y. Choi, B.H. Hong, Large-scale pattern growth of graphene films for stretchable transparent electrodes, *Nature* 457 (2009) 706–710.
- [21] J.M. Simmons, B.M. Nichols, S.E. Baker, M.S. Marcus, O.M. Castellini, C.S. Lee, R.J. Hamers, M.A. Eriksson, Effect of ozone oxidation on single-walled carbon nanotubes, *J. Phys. Chem. B* 110 (2006) 7113–7118.
- [22] Y. Sun, H.H. Wang, High-performance, flexible hydrogen sensors that use carbon nanotubes decorated with palladium nanoparticles, *Adv. Mater.* 19 (2007) 2818–2823.
- [23] O. Leenaerts, B. Partoens, F.M. Peeters, Adsorption of H₂O NH₃, CO, NO₂, and NO on graphene: a first-principles study, *Phys. Rev. B* 77 (2008) 125416.
- [24] K.J. Laidler *Chemical Kinetics*, New York, 1965.
- [25] Z. Yong-Hui, et al., Improving gas sensing properties of graphene by introducing dopants and defects: a first-principles study, *Nanotechnology* 20 (2009) 185504.
- [26] W.-L. Yim, X.G. Gong, Z.-F. Liu, Chemisorption of NO₂ on carbon nanotubes, *J. Phys. Chem. B* 107 (2003) 9363–9369.
- [27] S.S. Han, H.M. Lee, Adsorption properties of hydrogen on (10,0) single-walled carbon nanotube through density functional theory, *Carbon* 42 (2004) 2169–2177.
- [28] S. Peng, K. Cho, Ab initio study of doped carbon nanotube sensors, *Nano Lett.* 3 (2003) 513–517.
- [29] P. Qi, O. Vermesh, M. Grecu, A. Javey, Q. Wang, H. Dai, S. Peng, K.J. Cho, Toward large arrays of multiplex functionalized carbon nanotube sensors for highly sensitive and selective molecular detection, *Nano Lett.* 3 (2003) 347–351.

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