β12 Phase Borophene Enhanced PANI Gas Sensor for CO and NH3 Detection

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Abstract
In cases where the carbon monoxide concentration reaches to 50 ppm, and ammonia concentration reaches to 25 ppm in indoor ambient, the symptoms such as lung failure, heart failure, brain damage are present, and urgent medical attention is required. Therefore, the development of a rapid and sensitive sensor in order to detect the level of CO and NH$_3$ gases is the critical issue for health and the environment. In this study, borophene nanosheets with the $\beta_{12}$ phased crystalline structure are produced by ultrasonic sonication. Using borophene nanosheets, Borophene and PANI: Borophene sensors are fabricated to investigate the CO and NH$_3$ gas detection at room temperature. It has been observed that borophene enhances the CO and NH$_3$ gas detection performance of PANI. The results reveal that borophene sensor detected 6 ppm CO gas with 30 s response time and 40 s recovery time, and 50 ppb NH$_3$ gas with 40 s response time and 60 s recovery time at room temperature. On the other hand, PANI: Borophene sensor detected 6 ppm CO gas with 300 s response time and 320 s recovery time and 50 ppb NH$_3$ gas with 100 s response time and 120 s recovery time at room temperature.

1. Introduction
Toxic gases such as carbon monoxide (CO) and Ammonia (NH$_3$) seriously threaten human health. When CO concentration reaches to 50 ppm, and NH$_3$ concentration reaches to 25 ppm in indoor ambient, the symptoms such as lung failure, heart failure, brain damage are present and the urgent medical attention is needed. Therefore, early detection of low-level CO and NH$_3$ gases is a critical issue for human health [1–7].

In recent years, the detection of toxic gases has been the major focus of sensor research. The solid state gas sensor, one of the solid state electronic devices, has attracted attention due to its high sensitivity, high selectivity, low-cost, and small size. Although metal oxide semiconductors gas sensors, which are commonly used in the detection of CO and NH$_3$ gases, benefit from high material sensitivity and quick response time, they generally operate at high temperatures (200–300 °C) [8–15]. Recently, researchers have focused on improving the operation conditions of gas sensors in terms of low-level CO detection at room temperature [16–20].

Among the various conducting polymers, Polyaniline (PANI) has a great attention for the detection of CO and NH$_3$ due to its good chemical stability as well as its good electrical conductivity [20–35]. The sensitivity and selectivity of the PANI-based sensor have been improved by adding nanostructured materials with controllable morphologies. Nanostructures provide high surface area in sensing material, therefore gas molecules are adsorbed from the much more adsorbtion sites on the sensing material, thus providing higher sensitivity [36–43].

In the literature, various PANI: nanomaterial-based sensor studies for the detection of CO and NH$_3$ gases at room temperature were reported. Among them, PANI: Zeolite sensor detected 16-1000 ppm CO gas [43].
Using the sensor based on PANI: CNT, 100–1000 ppm CO gas detection with 36 s response time and 330 s recovery time was reported [44]. PANI: SnO\textsubscript{2} based sensor reached the detection of 25–200 ppm CO gas [45]. Furthermore, PANI: Co\textsubscript{3}O\textsubscript{4} based sensor detected 5075 ppm CO gas with 40 s response time and 90 s recovery time [46] and 200–6000 ppm CO gas detection with 180 s response time and 200 s recovery time with PANI: Au nanoparticles-based sensor was reported [47].

On the other hand, Kumara et al. [48] reported 25 ppm NH\textsubscript{3} gas detection with 213 s response time at room temperature by PANI sensors. For detecting NH\textsubscript{3} gas, PANI/TiO\textsubscript{2} nanocomposite-based sensors have been prepared by several research group [49–54]. The produced sensors generally detected NH\textsubscript{3} gas in the range of 20 ppm – 45 ppb above the room temperature in 1–2 min. Wu et al. [55] investigated the effect of graphene dispersion on NH\textsubscript{3} gas sensing characteristics of polyaniline gas sensor. The sensor detected 1-6400 ppm NH\textsubscript{3} with 50 s response time at room temperature. Yoo et al. [56] prepared O\textsubscript{2} plasma treated MWCNT/PANI based sensor and it detected 20 ppm NH\textsubscript{3} with 100 s response time at room temperature. MWCNT/PANI based sensor produced by He et al. [57] detected 5 ppm NH\textsubscript{3} with 95 s response time at room temperature.

Although there have been inspired theoritical studies about the adsorption of CO molecules to the borophene surface [58–60] in the last two years, there are no experiment reports. Also, there have been only a few reports on the detection of NH\textsubscript{3} gas using borophene based sensors over the last four years [61–66]. As far as there are no experimental reports available based on borophene nanosheet as an ammonia sensor, theoretical reports revealed that borophene nanosheet is a prominent material for detecting NH\textsubscript{3} molecules. In the present work, inspired from the theoretical studies, borophene and PANI: Borophene sensors have been produced to investigate the CO and NH\textsubscript{3} gas detection at room temperature.

### 2. Experimental Details

For use in the fabrication of Borophene and PANI: Borophene sensors, the borophene nanosheets were produced by ultrasonic sonication. 100 mg boron with a particle size of 1.5 µm, purchased from Nanografi, was mixed with 100 mL of Dimethylformamide (DMF) purchased from Merck and then sonicated at 200 W for 3 h in a cabin with controlled Nitrogen (N\textsubscript{2}) flow. Ambient controlled process is extremely critical to suppress oxidization and contamination. In order to obtain well-ordered borophene nanosheets, first exfoliated borophene was obtained after centrifugations for 15 min. at 5000 rpm and 15 min. at 12000 rpm. Then, borophene was carefully collected and dried in a vacuum ambient for 4 h at 50 °C to obtain borophene powder. The structural, chemical, and morphological analysis of borophene were performed by High Resolution Transmission Electron Microscopy (HRTEM), Scanning Electron Microscopy (SEM) and Fourier Transform Infrared (FTIR) Spectroscopy.

As a next step, 1 mg of borophene powder was dispersed in 1 mL DMF. At the same time, 1 mg of borophene powder and 1 mg of PANI powder were mixed very slowly in 2 mL N-Methylpyrrrolidone (NMP)
on the magnetic stirrer for 15 min at room temperature. PANI and NMP were purchased from Sigma-Aldrich. In order to fabricate the sensors, Borophene and PANI: Borophene were spin coated on Interdigital Transducers (IDTs) at 500 rpm. The produced sensors were fixed to the sensor test system, and then the surfaces of the sensors were subjected to a flow of dry to prevent the ambient humidity from affecting the sensor performance. The total flow rate was fixed at 200 sscm to reach a constant baseline. The real-time resistances of conductivity type sensors were measured using the Keithley 2700 Data Acquisition System at room temperature and recorded by a computer with corresponding data acquisition hardware and software. The sensor measurements were carried out in the gas concentration range of 6–30 ppm for CO and 50 ppb-1.5 ppm for NH₃. The CO and NH₃ gas concentrations were controlled by mass flow controllers (MFCs).

3. Results And Discussion

Figure 1 depicts TEM analysis results of the produced borophene. The freestanding borophene nanosheets in DMF are shown in Fig. 1-a. Figure <link> Fig. 1-b and 1-c exhibit FFT diffraction pattern of the individual borophene nanosheet at different magnifications. Borophene nanosheets depict parallel atomic ridges as can be seen from the HRTEM image given in the inset of Fig. 1-c and Fig. 1-d. It was understood that the borophene nanosheets have crystalline structure with a lattice spacing of 0.55 nm. Moreover, the results indicate that the produced borophene is in the β₁₂ phase [67].

Figure 2 shows the SEM and FTIR analysis results of the prepared PANI: Borophene. In the SEM image of PANI: Borophene given in Fig. 2-a, it was observed that it has a randomly growing network shaped in nanometer dimensions. PANI: Borophene and also borophene FTIR results are given in Fig. 2-b. The characteristic peaks of borophene were found at 3479 cm⁻¹ (O-H), 2929 cm⁻¹ (B-B), 2861 cm⁻¹ (B-H), 1653 cm⁻¹ (C = O), 1496 cm⁻¹ (B-H), 1385 cm⁻¹ (B-O), 1255 cm⁻¹ (B-O), and 1091 cm⁻¹ (B – O – B vibrations) [68]. Moreover, FTIR result of the PANI: Borophene were observed at 3273 cm⁻¹ (NH stretching), 2917 cm⁻¹ (B-B), 2849 cm⁻¹ (BH), 1657 cm⁻¹ (C = O), 1585 cm⁻¹ (C-C ring asymmetric stretching), 1490 cm⁻¹ (benzene structure), 1285 cm⁻¹ (C-C bending vibration), 1159 cm⁻¹ (C-H bending), and 808 cm⁻¹ (C-H bending) [69]. According to the FTIR results, it was confirmed that some peaks characteristic of the electrostatic interaction, along with other peaks, suggesting the partial decreasing the intensity of the peak of C = O and O-H groups.

When C and O atoms are adsorbed by borophene nanosheets, a charge transfer mechanism between CO and borophene occurs, C and O atoms gain electrons and therefore borophene nanosheets lose electrons. Therefore, CO gas is a charge acceptor when faced with borophene [58–60]. In this regard, adsorption of CO molecules on borophene has increased the electrical resistance of borophene. Figure 3 depicts CO gas detection results and sensitivity plots of the produced borophene, PANI, and PANI: Borophene based sensors. As shown in Fig. 3-a, the borophene-based sensor has exhibited a linear increase in the resistance change with the increase in CO gas in the 6–30 ppm concentration range. The borophene sensor detected 6 ppm CO gas with 30 s response time, and 40 s recovery time at room temperature.
When the Borophene nanosheets were added to PANI, Borophene nanosheets were decorated around the surface of PANI, providing PANI with higher surface area, and therefore more active sites for the adsorption of the CO gas molecules. PANI: Borophene sensor detected CO gas at room temperature as a result of the adsorption of CO molecules by the surface of the borophene nanosheets, charge transfer mechanism occurred between CO and PANI: Borophene, positive charges transferred to PANI chain. In this regard, adsorption of CO molecules on PANI: Borophene increased the electrical resistance of PANI: Borophene. PANI: Borophene sensor has also showed a linear increase in the resistance change with increase in 6–30 ppm concentration of CO. PANI: Borophene based sensor detected 6 ppm CO gas with 300 s response time, and 320 s recovery time at room temperature. As seen in the graph of response to gas concentration given in Fig. 3-b, PANI: Borophene sensor has higher sensitivity for CO detection than PANI and borophene sensors since borophene nanosheets enhance the CO detection performance of PANI. Moreover, compared to the previously reported CO sensors, both the borophene and PANI: Borophene sensors produced in this study detected low-level of CO gas with short response/recovery times at room temperature [43–47].

When NH$_3$ molecules adsorbed by borophene nanosheets, a charge transfer mechanism between NH$_3$ molecules and borophene occurs, NH$_3$ molecules lose electrons and therefore borophene nanosheets gain electrons. Therefore, NH$_3$ gas behaves as a charge donor when it meets with borophene [60, 61]. Figure 4 shows the results of NH$_3$ gas detection and sensitivity plots of the prepared borophene, PANI, and PANI: Borophene based sensors. As shown in Fig. 4-a, borophene sensor has exhibited a linear decrease in the resistance change with increasing concentration of NH$_3$ in the range of 50 ppb-1.5 ppm. The response of the borophene sensor to the changes in the NH$_3$ concentrations represented by the decrease in the output resistance. The borophene sensor detected 50 ppb NH$_3$ gas with 40 s response time, and 60 s recovery time at room temperature. On the other hand, PANI and PANI: Borophene sensors exhibited a linear increase in response to the increase in NH$_3$ concentration in the range of 50 ppb-1.5 ppm. The responses of the PANI sensor and PANI: Borophene sensor to the changes in the NH$_3$ concentrations are represented by the increase in the output resistance (Fig. 4-b). Likewise, when the borophene nanosheets were added to PANI, a higher surface area and hence more active adsorption sites were provided to PANI for detection of NH$_3$ gas molecules. While NH$_3$ molecules adsorbing on the PANI: Borophene, positive charges transferred to PANI, and N$^+$H bonds are formed. Therefore, electrical conductivity of the borophene nanosheets decreased. PANI: Borophene based sensor detected 50 ppb NH$_3$ gas with 100 s response time, and 120 s recovery time at room temperature. As shown in Fig. 4-c and d, PANI: Borophene sensor has higher sensitivity than PANI and borophene sensors since borophene improves the NH$_3$ detection performance of PANI. In comparison with the previous reported NH$_3$ sensors, the prepared Borophene sensor detected trace-level NH$_3$ gas at room temperature [48–57].

4. Conclusion
Detection of low-level CO and NH$_3$ gases is a critical issue for health and the environment. According to the results, borophene sensor detected 6 ppm CO gas with 30 s response time and 40 s recovery time, and 50 ppb NH$_3$ gas with 40 s response time and 60 s recovery time at room temperature. On the other hand, PANI: Borophene sensor detected 6 ppm CO gas with 300 s response time and 320 s recovery time and 50 ppb NH$_3$ gas with 100 s response time and 120 s recovery time at room temperature. Borophene improved CO and NH$_3$ gas detection performance of PANI as the nanostructures provide high surface area in the sensing material, allowing gas molecules to be adsorbed from much more adsorption sites on the sensing material. In the view of the results, it can be concluded that PANI: Borophene sensor has higher sensitivity than PANI and borophene sensors for both CO and NH$_3$ gas detection and thus it has a great potential for future applications in high-performance CO and NH$_3$ gas sensors.

**Declarations**

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**Compliance with ethical standards**

Conflict of interest: The authors declare no conflict of interest.

**References**

[1] T. Li, Y. Wu, J. Huang, S. Zhang, Gas sensors based on membrane diffusion for environmental monitoring, Sensors and Actuators B: Chemical 243 (2017) 566-578.

[2] D. T. Phan, G. S. Chung, Effects of defects in Ga-doped ZnO nanorods formed by a hydrothermal method on CO sensing properties, Sensors and Actuators B: Chemical 187 (2013) 191-197.

[3] N. D. Khoang, H. S. Hong, D. D. Trung, N. V. Duy, N. D. Hoa, D. D. Thinh, N. V. Hieu, On-chip growth of wafer-scale planar-type ZnO nanorod sensors for effective detection of CO gas, Sensors and Actuators B: Chemical 181 (2013) 529-536.

[4] G. Maduraiveeran, W. Jin, Nanomaterials based electrochemical sensor and biosensor platforms for environmental applications, Trends in Environmental Analytical Chemistry 13 (2017) 10-23.
[5] G. Korotcenkov, B. K. Cho, Metal oxide composites in conductometric gassensors: achievements and challenges, Sensors and Actuators B: Chemical 244 (2017) 182-210.

[6] S. Vallejos, I. Gràcia, E. Figueras, N. Pizurova, J. Hubálek, C. Cané, ZnO-based gas microsensors sensitive to CO at room temperature by photoactivation, Procedia Engineering 168 (2016) 415-418.

[7] S. Basu, P. Bhattacharyya, Recent developments on graphene and grapheneoxide based solid state gas sensors, Sensors and Actuators B: Chemical 173 (2012) 1-21.

[8] A. Guillén-Bonilla, O. Blanco-Alonso, J.T. Guillén-Bonilla, M. Luz Olvera-Amador, V. M. Rodríguez-Betancourt, A. Sánchez-Martínez, J. P. Morán-Lázaro, M. Martínez-García, H. Guillén-Bonilla, Synthesis and characterization of cobalt antimonate nanostructures and their study as potential CO and CO\textsubscript{2} sensor at low temperatures, Journal of Materials Science: Materials in Electronics 29 8 (2018) 15632-15642.

[9] A. Casillas-Zamora, J. T. Guillén-Bonilla, A. Guillén-Bonilla, M. Rodríguez-Betancourt, Y. L. Casallas-Moreno, L. Gildo-Ortiz, M. Luz Olvera-Amador, S. A. Tomás, H. Guillén-Bonilla, Synthesis of MnSb\textsubscript{2}O\textsubscript{6} powders through a simple low-temperature method and their test as a gas sensor, Journal of Materials Science: Materials in Electronics 31 (2020) 7359-7372.

[10] L. Gildo-Ortiz, V. M. Rodríguez-Betancourt, O. Blanco-Alonso, A. Guillén-Bonilla, J. T. Guillén-Bonilla, A. Guillén-Cervantes, J. Santoyo-Salazar, H. Guillén-Bonilla, A simple route for the preparation of nanostructured GdCoO\textsubscript{3} via the solution method, as well as its characterization and its response to certain gases, Results in Physics 12 (2019) 475-483.

[11] J. P. Morán-Lázaro, F. López-Urías, E. Muñoz-Sandoval, O. Blanco-Alonso, M. Sanchez-Tizapa, A. Carreon-Alvarez, H. Guillén-Bonilla, M. D. L. L. Olvera-Amador, A. Guillén-Bonilla, V. M. Rodríguez-Betancourt, Synthesis, characterization, and sensor applications of spinel ZnCo\textsubscript{2}O\textsubscript{4} nanoparticles, Sensors 16 12 (2016) 2162.

[12] D. K. Bandgar, S. T. Navale, S. R. Nalage, R. S. Mane, F. J. Stadler, D. K Aswal, S. K. Gupta, V. B. Patil, Simple and low-temperature polyaniline-based flexible ammonia sensor: a step towards laboratory synthesis to economical device design, J. Mater. Chem. C 3 (2015) 9461-9468.

[13] J. Sun, X. Shu, Y. Tian, Z. Tong, S. Bai, R. Luo, D. Li, C. C. Liu, Facile preparation of polypyrrole-reduced graphene oxide hybrid for enhancing NH\textsubscript{3} sensing at room temperature, Sens. Actuators B: Chem. 241 (2017) 658-664.

[14] S. Sharma, S. Hussain, S. Singh, S. S. Islam, MWCNT-conducting polymer composite-based ammonia gas sensors: A new approach for complete recovery process, Sensors and Actuators B: Chemical 194 (2014) 213-9.

[15] N. Van, H. Nguyen, Q. Dung, P. Dinh, T. Tran, T. Nguyen, D. Chienb, Thin film polypyrrole/SWCNTs nanocomposites based NH\textsubscript{3} sensor operated at room temperature, Sensors and Actuators B:
[16] B. T. E. Thornton, A. Harrison, A. L. Pham, C. E. Castano, C. Tang, Polyaniline-functionalized nanofibers for colorimetric detection of HCl vapor, ACS Omega 3 (2018) 3587-3591.

[17] H. Yoon, Current trends in sensors based on conducting polymer nanomaterials, Nanomaterials 3 (2013) 524-549.

[18] I. Fratoddi, I. Venditti, C. Cametti, M. V. Russo, Chemiresistive polyaniline-based gas sensors: a mini review, Sensors and Actuators B: Chemical 220 (2015) 534-548.

[19] Y. Yang, S. Li, W. Yang, W. Yuan, J. Xu, Y. Jiang, In situ polymerization deposition of porous conducting polymer on reduced graphene oxide for gas sensor, ACS Applied Materials & Interfaces 6, 16 (2014) 13807-13814.

[20] S. J. Park, C. S. Park, H. Yoon, Chemo-electrical gas sensors based on conducting polymer hybrids, Polymers 9, 15 (2017) 155.

[21] G. Ćirić-Marjanović, Recent advances in polyaniline research: polymerization mechanisms, structural aspects, properties and applications, Synthetic Metals 177 (2013) 1-47.

[22] J. Janata, M. Josowicz, Conducting polymers in electronic chemical sensors, Nature Materials 2 (2003) 19-24.

[23] L. Quan, J. Sun, S. Bai, R. Luo, D. Li, A. Chen, C. C. Liu, A flexible sensor based on polyaniline hybrid using ZnO as template and sensing properties to triethylamine at room temperature, Applied Surface Science 399 (2017) 583-591.

[24] G. Wu, N. H. Mack, W. Gao, S. Ma, R. Zhong, J. Han, J. K. Baldwin, P. Zelenay, Nitrogen-doped graphene-rich catalysts derived from heteroatom polymers for oxygen reduction in non-aqueous lithium-O₂ battery cathodes, ACS Nano 6 (202) 9764-9776.

[25] S. Sönmezoglu, R. Tas, S. Akin, M. Can, Polyanilinemicro-rodsbased heterojunction solar cell: structural and photovoltaic properties, Appl. Phys. Lett. 101 (2012) 253301.

[26] E. W. Paul, A. J. Ricco, M. S. Wrighton, Resistance of polyanilne films as a function of electrochemical potential and the fabrication of polyaniline-based microelectronic devices, J. Phys. Chem. 89 (1985) 1441-1447.

[27] Y. Yang, J. Ouyang, L. Ma, R. J. H. Tseng, C. W. Chu, Electrical switching and bistability in organic/polymeric thin films and memory devices, Adv. Funct. Mater. 16 (2006) 1001-1014.

[28] H. Chang, Y. Yuan, N. Shi, Y. Guan, Electrochemical DNA biosensor based on conducting polyaniline nanotube array, Anal. Chem. 79 (2007) 5111-5115.
[29] S. Virji, J. Huang, R. B. Kaner, B. H. Weiller, Polyaniline nanofiber gas sensors: examination of response mechanisms. Nano Lett. 4, 3 (2004) 491-496.

[30] S. Bhadra, D. Khastgir, N. K. Singha, J. H. Lee, Progress in preparation, processing and applications of polyaniline, Prog. Polym. Sci. 34 (2009) 783-810.

[31] G. C. Marjanovicí, Recent advances in polyaniline research: polymerization mechanisms, structural aspects, properties and applications, Synth. Met. 177 (2013) 1-47.

[32] P. Kunzoa, P. Lobotka, M. Micusik, E. Kovacova, Palladium-free hydrogen sensor based on oxygen-plasma-treated polyaniline thin film, Sens. Actuators B: Chem. 171-172 (2012) 838–845.

[33] N. Menegazzo, B. Herberta, S. Banerji, K. S. Booksh, Discourse on the utilization of polyaniline coatings for surface plasmon resonance sensing of ammonia vapor, Talanta 85 (2011) 1369-1375.

[34] N. Menegazzo, D. Boyne, H. Bui, T. P. Beebe Jr., K. S. Booksh, DC magnetron sputtered polyaniline-HCl thin films for chemical sensing applications, Anal. Chem. 84 (2012) 5770-5777.

[35] G. Rizzo, A. Arena, N. Donato, M. Latino, G. Saitta, A. Bonavita, G. Neri, Flexible, all-organic ammonia sensor based on dodecylbenzene sulfonic acid-doped polyaniline films, Thin Solid Films 518 (2010) 7133-7137.

[36] Z. Wu, X. Chen, S. Zhu, Z. Zhou, Y. Yao, W. Quan, B. Liu, Room temperature methane sensor based on graphene nanosheets/polyaniline nanocomposite thin film, IEEE Sensors Journal 13 (2013) 777-782.

[37] Y. Zou, Y. Wang, C. Xiang, C. Tang, H. Chu, S. Qiu, E. Yan, F. Xu, L. Sun, Doping composite of polyaniline and reduced graphene oxide with palladium nanoparticles for room-temperature hydrogen-gas sensing, International Journal of Hydrogen Energy 41, 11 (2016) 5396-5404.

[38] R. S. Andre, F. M. Shimizu, C. M. Miyazaki, A. Riul Jr, D. Manzani, S. J. Ribeiro, O. N. Oliveira Jr, L. H. Mattoso, D. S. Correa, Hybrid layer-by-layer (LbL) films of polyaniline, graphene oxide and zinc oxide to detect ammonia, Sensors and Actuators B: Chemical 238 (2017) 795-801.

[39] D. Zhang, Z. Wu, P. Li, X. Zong, G. Dong, Y. Zhang, Facile fabrication of polyaniline/multi-walled carbon nanotubes/molybdenum disulfide ternary nanocomposite and its high-performance ammonia-sensing at room temperature, Sensors and Actuators B: Chemical 258 (2018) 895-905.

[40] D. Zhang, X. Fan, X. Hao, G. Dong, Facile fabrication of polyaniline nanocapsule modified zinc oxide hexagonal microdiscs for H₂S gas sensing applications, Industrial & Engineering Chemistry Research 58, 5 (2019) 1906-1913.

[41] D. Zhang, Z. Wu, X. Zong, Metal-organic frameworks-derived zinc oxide nanopolyhedra/S, N: graphene quantum dots/polyaniline ternary nanohybrid for highperformance acetone sensing, Sensors and Actuators B: Chemical 288 (2019) 232-242.
[42] D. Zhang, D. Wang, P. Li, X. Zhou, X. Zong, G. Dong, Facile fabrication of highperformance QCM humidity sensor based on layer-by-layer self-assembled polyaniline/graphene oxide nanocomposite film, Sensors and Actuators B: Chemical 255 (2018) 1869-1877.

[43] N. Densakulprasert, L. Wannatong, D. Chotpattananont, P. Hiamtup, A. Sirivat, J. Schwank, Electrical conductivity of polyaniline/zeolite composites and synergetic interaction with CO, Mater. Materials Science & Engineering B: Solid-State Materials for Advanced Technology 117 (2005) 276-282.

[44] Y. Wanna, N. Srisukhumbowornchai, A. Tuantranont, A. Wisitsoraat, N. Thavarungkul, P. Singjai, The effect of carbon nanotube dispersion on CO gas sensing characteristics of polyaniline gas sensor, Journal of Nanoscience and Nanotechnology 6 (2006) 3893-3896.

[45] K. S. Jian, C. J. Chang, J. J. Wu, Y. C. Chang, C. Y. Tsay, J. H. Chen, T. L. Horng, G. J. Lee, L. Karuppasamy, S. Anandan, C. Y. Chen, High response CO sensor based on a polyaniline/SnO$_2$ nanocomposite, Polymers 11 (2019) 184.

[46] T. Sen, N. G. Shimpi, S. Mishra, Room temperature CO sensing by polyaniline/Co$_3$O$_4$ nanocomposite, Journal of Applied Polymer Science 133 (2016) 1-8.

[47] Sh. Nasresfahani, Z. Zargarpour, M. H. Sheikhi, S. F. Nami Ana, Improvement of the carbon monoxide gas sensing properties of polyaniline in the presence of gold nanoparticles at room temperature, Synthetic Metals 265 (2020) 116404.

[48] I. Kumar, I. Rawal, A. Kaur, S. Annapoorni, Flexible room temperature ammonia sensor based on polyaniline, Sens. Actuators B Chem. 240 (2017) 408-416.

[49] Y. Li, H. T. Ban, H. J. Zhao, M. J. Yang, Facile preparation of a composite of TiO$_2$ nanosheets and polyaniline and its gas sensing properties, RSC Adv. 5 (2015) 106945-106952.

[50] H. L. Tai, Y. Jiang, G. Xie, J. Yu, X. Chen, Z. Ying, Influence of polymerization temperature on NH$_3$ response of PANI/TiO$_2$ thin film gas sensor, Sens. Actuators B Chem. 129 (2008) 319-326.

[51] Y. Li, J. Gong, G. He, Y. Deng, Fabrication of polyaniline/titanium dioxide composite nanofibers for gas sensing application, Mater. Chem. Phys. 129 (2011) 477-482.

[52] S. G. Pawar, M. A. Chougule, S. L. Patil, B. T. Raut, P. R. Godse, S. Sen, et al., A Room temperature ammonia gas sensor based on polyaniline-TiO$_2$ nanocomposite, IEEE Sens. J. 11 (2011) 3417-3423.

[53] V. G. Bairi, S. E. Bourdo, N. Sacre, D. Nair, B. C. Berry, A. S. Biris, et al. Ammonia gas sensing behavior of tanninsulfonic acid doped polyaniline-TiO$_2$ composite, Sensors 15 (2015) 26415-26429.

[54] C. Zhu, X. Cheng, X. Dong, Y. M. Xu, Enhanced Sub-ppm NH$_3$ Gas Sensing Performance of PANI/TiO$_2$ Nanocomposites at Room Temperature, Frontiers in Chemistry 6 (2018) 493.
[55] Z. Wu, X. Chen, S. Zhu, Z. Zhou, Y. Yao, W. Quan, L. Bin, Enhanced sensitivity of ammonia sensor using graphene/polyaniline nanocomposite, Sensors and Actuators B: Chemical 178 (2013) 485-93.

[56] K. P. Yoo, K. H. Kwon, N. K. Min, M. J. Lee, C. J. Lee, Effects of O\textsubscript{2} plasma treatment on NH\textsubscript{3} sensing characteristics of multiwall carbon nanotube/polyaniline composite films, Sensors and Actuators B: Chemical 143 (2009) 333-40.

[57] L. He, Y. Jia, F. Meng, M. Li, J. Liu, Gas sensors for ammonia detection based on polyaniline-coated multi-wall carbon nanotubes, Materials Science and Engineering: B 163 (2009) 76-81.

[58] R. Chandiramouli and V. Nagarajan, Borospherene nanostructure as CO and NO sensor- A first-principles study, Vacuum 142 (2017) 13.

[59] V. Aref, A. Horri, M. B. Tavakoli, CO/CO\textsubscript{2} adsorption and sensing on borophene, SN Applied Sciences 2 (2020) 1304.

[60] C.-S. Huang, A. Murat, V. Babar, E. Montes, and U. Schwingenschlögl, Adsorption of the Gas Molecules NH\textsubscript{3}, NO, NO\textsubscript{2}, and CO on Borophene, J. Phys. Chem. C 122 (2018) 14665-14670.

[61] C. S. Huang, et al., Adsorption of the Gas Molecules NH\textsubscript{3}, NO, NO\textsubscript{2}, and CO on Borophene, The Journal of Physical Chemistry C 122, 26 (2018) 14665-14670.

[62] R. Zahra, H. Soleymanabadi, N-H bond cleavage of ammonia on graphene-like B\textsubscript{36} borophene: DFT studies, Journal of Molecular Modeling 22, 4 (2016) 70.

[63] T. T. Luong, P. T. Lam, D. V. An, Toxic Gases on \(\beta_{12}\) Borophene: the Selective Adsorption, VNU Journal of Science: Mathematics-Physics 36 (2020) 2.

[64] B. Feng, J. Zhang, Q. Zhong, W. Li, S. Li, H. Li, P. Cheng, S. Meng, L. Chen, K. Wu, Experimental realization of two-dimensional boron sheets, Nature Chemistry 8 (2016) 563-568.

[65] L. Kong, K. Wu, L. Chen, Recent progress on borophene: Growth and structures, Front. Phys. 13, 3 (2018) 138105.

[66] V. Nagarajan, R. Chandiramouli, Interaction Studies of Ammonia Gas Molecules on Borophene Nanosheet and Nanotubes: A Density Functional Study, Journal of Inorganic and Organometallic Polymers and Materials 28 (2018) 920-931.

[67] D. Ma, R. Wang, J. Zhao, Q. Chen, L. Wu, D. Li, L. Su, X. Jiang, Z. Luo, Y. Ge, J. Li, Y. Zhang, H. Zhang, A self-powered photodetector based on two- dimensional boron nanosheets, Nanoscale 12 (2020) 5313.

[68] D. Ma, J. Zhao, J. Xie, F. Zhang, R. Wang, L. Wu, W. Liang, D. Li, Y. Ge, J. Li, Y. Zhang, H. Zhang, Ultrathin boron nanosheets as an emerging two-dimensional photoluminescence material for bioimaging, Nanoscale Horizons 5, 4 (2020) 705-713.
[69] H. Li, L. Jing, W. Liu, J. Lin, R. Y. Tay, S. H. Tsang, E. H. T Teo, Scalable production of few-layer boron sheets by liquid-phase exfoliation and their superior supercapacitive performance, ACS nano 12, 2 (2018) 1262-1272.