Анотація

Хеморезистивний сенсор сірководню на основі легованого графену

Представлений високочутливий та селективний сенсор сірководню на основі графену. Сенсор був зроблений простим шляхом, що включає у себе декорацію графену срібними наночастинками методом хімічного осадження для того щоб значно підвищити продуктивність H2S газового датчика. Легування металічним сріблом графену, вирощеного з газової фази було досягнуто зануренням в водний легуючий розчин AgNO3 та Fe(NO3)3 при перемішуванні, що призвело до адсорбції графеном наночастинок срібла та заряджених домішок. Це металеве легування сріблом призвело до адаптації електронних властивостей графену і він показав різку зміну питомого опору при наявності H2S газу у порівнянні з нелегованими зразками.

Властивості детектування H2S газу легованим графеном систематично досліджувались, щоб виявити структурні, морфологічні та композиційні властивості зразків, використовуючи аналітичні інструменти, такі як дифракційна рентгенівська спектроскопія, просвічувальна електронна мікроскопія, скануюча електронна мікроскопія та рентгенівська фотоелектронна спектроскопія.

Легований графен здатен детектувати газ сірководню вибірково та повторно, з межею виявлення ~ 100 частинок на мільярд, протягом 6 хв. Механізм, за допомогою якого датчик відчуває наявність газу заснований на зміні щільності носіїв заряду в той час як з поверхні сенсору додаються або віднімаються носії заряду під час впливу сірководню.

Ключові слова: Графен, хеморезистивний датчик, графеновий датчик сірководню, легування графену, легування наночастинками срібла

Abstract

"Highly sensitive chemiresistive H_2S gas sensor based on graphene decorated with Ag nanoparticles and charged impurities"

Chemiresistive sensors based on the materials which change its electrical properties because of the changing of the nearby chemical environment. This class of chemical sensors rely on direct chemical interaction between analyte and the sensing material. The chemical interaction between the sensing material and the analyte can be by covalent bonding, hydrogen bonding, or molecular recognition. Several different types of materials have chemiresistive properties: conductive polymers, metal oxide semiconductors, and nanomaterials like graphene, nanotubes and nanoparticles.

A typical chemiresistor consists of a sensing material that bridges the gap between two electrodes or coats a set of interdigitated electrodes. Thus, the resistance between the electrodes can be easily measured. The sensing material has an inherent resistance that can be modulated by the presence or absence of the analyte. During exposure, analytes interact with the sensing material. These interactions cause changes in the material's resistance. In chemiresistors, the resistance changes are proportional to the amount of analyte present. This allows to measure the amount of analyte present.

Herein, we report a highly sensitive and selective H_2S gas sensor based on graphene decorated with Ag nanoparticles (AgNPs) and charged impurities fabricated using a simple wet chemical method. Doping of chemical vapor deposition–grown graphene was achieved by 4 min immersion in an aqueous solution of $AgNO_3/Fe(NO_3)_3$ followed by decoration with adsorbed AgNPs and charged impurities. The above AgNPs were formed by reduction of Ag^+ ions, since the Ag^+/Ag^0 reduction potential is higher than that of Fe^{3+}/Fe^0.

The above treatment changed the electronic properties of graphene, achieving a dramatic resistivity change in the presence of H_2S gas by generating surface sites for its

adsorption and dissociation and thus allowing real time H_2S level monitoring at ambient temperature with an immediate response.

Doped graphene was demonstrated to selectively and repeatedly sense H_2S gas within 6 min, with the limit of detection being below 100 ppb. The corresponding mechanism is thought to feature a charge carrier density change or graphene to adsorbate charge transfer, with the sensor surface trapping or releasing electrons upon exposure to H_2S gas.

References

[1] Beauchamp, R. O.; Bus, J. S.; Popp, J. A.; Boreiko, C. J.; Andjelkovich, D. A. CRC Crit. Rev. Toxicol. 1984, 13, 25–97. (b) Glass, D. C. Ann. Occup. Hyg. 1990, 34, 323–327.

[2] X. Li, C.W. Magnuson, A. Venugopal, R.M. Tromp, J.B. Hannon, E.M. Vogel, L. Colombo, R.S. Ruoff, J. Am. Chem. Soc. 133 (2011) 2816–2819.

[3] J.W. Wofford, S. Nie, K.F. McCarty, N.C. Bartelt, O.D. Dubon, Nano Lett. 10 (2010) 4890–4896.

[4] M. Batzill, The surface science of graphene: Metal interfaces, CVD synthesis, nanoribbons, chemical modifications, and defects, Surface Science Reports 67, 2012, 83–115.

[5] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva and A. A. Firsov, Science, 2004, 306, 666.

[6] A. K. Geim and K. S. Novoselov, Nat. Mater., 2007, 6, 183.

[7] I. Gierz, C. Riedl, U. Starke, C. R. Ast and K. Kern, Nano Lett.,

[8] J. Kong, N. R. Franklin, C. W. Zhou, M. G. Chapline, S. Peng, K. J. Cho and H. J. Dai, Science, 2000, 287, 622.

[9] H. Chang, J. D. Lee, S. M. Lee and Y. H. Lee, Appl. Phys. Lett., 2001, 79, 3863.

[10] K. Bradley, J. C. P. Gabriel, M. Briman, A. Star and G. Gruner, Phys. Rev. Lett., 2003, 91, 218301.

[11] J. Zhang, A. Boyd, A. Tselev, M. Paranjape and P. Barbara, Appl. Phys. Lett., 2006, 88, 123112.

[12] F. Schedin, A. K. Geim, S. V. Morozov, E. W. Hill, P. Blake, M. I. Katsnelson and K. S. Novoselov, Nat. Mater., 2007, 6, 652.

[13] Y. B. Zhang, J. P. Small, M. E. S. Amori and P. Kim, Phys. Rev. Lett., 2005, 94, 176803.

[14] A. Das, S. Pisana, B. Chakraborty, S. Piscanec, S. K. Saha, U. V. Waghmare, K. S. Novoselov, H. R. Krishnamurthy, A. K. Geim, A. C. Ferrari and A. K. Sood, Nat. Nanotechnol., 2008, 3, 210.

[15] E. H. Hwang, S. Adam and S. Das Sarma, Phys. Rev. B: Condens. Matter Mater. Phys., 2007, 76, 195421.

[16] J. Ristein, Science, 2006, 313, 1057.

[17] T. O. Wehling, K. S. Novoselov, S. V. Morozov, E. E. Vdovin, M. I. Katsnelson, A. K. Geim and A. I. Lichtenstein, Nano Lett.,

[18] X. C. Dong, D. L. Fu, W. J. Fang, Y. M. Shi, P. Chen and L. J. Li, Small, 2009, 5, 1422.

[19] W. Chen, S. Chen, D. C. Qi, X. Y. Gao and A. T. S. Wee, J. Am. Chem. Soc., 2007, 129, 10418.

[20] H. Pinto, R. Jones, J. P. Goss and P. R. Briddon, J. Phys.: Condens. Matter, 2009, 21, 402001.

[21] C. Coletti, C. Riedl, D. S. Lee, B. Krauss, L. Patthey, K. von Klitzing, J. H. Smet and U. Starke, Phys. Rev. B: Condens. Matter Mater. Phys., 2010, 81, 235401.

[22] Y. H. Lu, W. Chen, Y. P. Feng and P. M. He, J. Phys. Chem. B, 2009, 113, 2.

[23] H. T. Liu, S. M. Ryu, Z. Y. Chen, M. L. Steigerwald, C. Nuckolls and L. E. Brus, J. Am. Chem. Soc., 2009, 131, 17099.

[24] L. Liu, S. M. Ryu, M. R. Tomasik, E. Stolyarova, N. Jung, M. S. Hybertsen, M. L. Steigerwald, L. E. Brus and G. W. Flynn, Nano Lett., 2008, 8, 1965.

[25] D. B. Farmer, R. Golizadeh-Mojarad, V. Perebeinos, Y. M. Lin, G. S. Tulevski, J. C. Tsang and P. Avouris, Nano Lett., 2009, 9, 388.

[26] B. Lee, Y. Chen, F. Duerr, D. Mastrogiovanni, E. Garfunkel, E. Y. Andrei and V. Podzorov, Nano Lett., 2010, 10, 2427.

[27] J. H. Chen, C. Jang, S. Adam, M. S. Fuhrer, E. D. Williams and M. Ishigami, Nat. Phys., 2008, 4, 377.

[28] A. Benayad, H. J. Shin, H. K. Park, S. M. Yoon, K. K. Kim, M. H. Jin, H. K. Jeong, J. C. Lee, J. Y. Choi and Y. H. Lee, Chem. Phys. Lett., 2009, 475, 91.

[29] G. Giovannetti, P. A. Khomyakov, G. Brocks, V. M. Karpan, J. van den Brink and P. J. Kelly, Phys. Rev. Lett., 2008, 101, 026803.

[30] H. E. Romero, P. Joshi, A. K. Gupta, H. R. Gutierrez, M. W. Cole, S. A. Tadigadapa and P. C. Eklund, Nanotechnology, 2009, 20,

[31] 245501.

[32] A. Bostwick, T. Ohta, T. Seyller, K. Horn and E. Rotenberg, Nat. Phys., 2007, 3, 36.

[33] J. Choi, H. Lee, K. J. Kim, B. Kim and S. Kim, J. Phys. Chem. Lett., 2010, 1, 505.

[34] T. O. Wehling, A. I. Lichtenstein and M. I. Katsnelson, Appl. Phys. Lett., 2008, 93, 202110.

[35] S. Y. Zhou, G. H. Gweon, A. V. Fedorov, P. N. First, W. A. De Heer, D. H. Lee, F. Guinea, A. H. C. Neto and A. Lanzara, Nat. Mater., 2007, 6, 770.

[36] J. H. Chen, C. Jang, S. D. Xiao, M. Ishigami and M. S. Fuhrer, Nat. Nanotechnol., 2008, 3, 206.

[37] H. E. Romero, N. Shen, P. Joshi, H. R. Gutierrez, S. A. Tadigadapa, J. O. Sofo and P. C. Eklund, ACS Nano, 2008, 2, 2037.

[38] T. Ohta, A. Bostwick, T. Seyller, K. Horn and E. Rotenberg, Science, 2006, 313, 951.

[39] A. H. C. Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov and A. K. Geim, Rev. Mod. Phys., 2009, 81, 109.

[40] H. Liu, Y. Liu, D. Zhu, Chemical doping of graphene, Journ. Of Materials Chem., 21(10), 2011, 3253-3496.

[41] A. C. Ferrari, J. C. Meyer, V. Scardaci, C. Casiraghi, M. Lazzeri, F. Mauri, S. Piscanec, D. Jiang, K. S. Novoselov, S. Roth and A. K. Geim, Phys. Rev. Lett., 2006, 97, 187401.

[42] A. C. Ferrari, Solid State Commun., 2007, 143, 47

[43] S. Pisana, M. Lazzeri, C. Casiraghi, K. S. Novoselov, A. K. Geim, A. C. Ferrari and F. Mauri, Nat. Mater., 2007, 6, 198.

[44] C. N. R. Rao, A. K. Sood, K. S. Subrahmanyam and A. Govindaraj, Angew. Chem., Int. Ed., 2009, 48, 7752.

[45] B. Das, R. Voggu, C. S. Rout and C. N. R. Rao, Chem. Commun., 2008, 5155.

[46] Q. Su, S. P. Pang, V. Alijani, C. Li, X. L. Feng and K. Mullen, Adv. Mater., 2009, 21, 3191.

[47] J. Bong, O. Sul, A. Yoon, S. Choi, B. Cho, Facile graphene n-doping by wet chemical treatment for electronic applications, Nanoscale, 2014, 6, 8503-8508

[48] X. C. Dong, Y. M. Shi, Y. Zhao, D. M. Chen, J. Ye, Y. G. Yao, F. Gao, Z. H. Ni, T. Yu, Z. X. Shen, Y. X. Huang, P. Chen and L. J. Li, Phys. Rev. Lett., 2009, 102, 135501.

[49] L. S. Panchokarla, K. S. Subrahmanyam, S. K. Saha, A. Govindaraj, H. R. Krishnamurthy, U. V. Waghmare and C. N. R. Rao, Adv. Mater., 2009, 21, 4726.

[50] M. Alaiea, M. Jahangiri, A.M. Rashidib, A. HaghighiAsl, N. Izadi, Selective hydrogen sulfide (H_2S) sensors based on molybdenum trioxide (MoO_3) nanoparticle decorated reduced graphene oxide, Mater. Sci. Semicond. Process. 38 (2015) 93–100.

[51] S. Mubeen, T. Zhang, N. Chartuprayoon, Y. Rheem, A. Mulchandani, N.V. Myung, M.A. Deshusses, Sensitive detection of H_2S using gold nanoparticle decorated single-walled carbon nanotubes, Anal. Chem. 82 (2010) 250–257.

[52] S. Sen, V. Bhandarkar, K.P. Muthe, M. Roy, S.K. Deshpande, R.C. Aiyer, S.K. Gupta, J.V. Yakhmia, V.C. Sahni, Highly sensitive hydrogen sulphide sensors operable at room temperature, Sens. Actuators B 115 (2006) 270–275.

[53] J. Kim, K. Yong, Mechanism study of ZnO nanorod-bundle sensors for H_2S gas sensing, J. Phys. Chem. C 115 (2011) 7218–7224.

[54] A. Fattah, S. Khatami, Selective H_2S gas sensing with a graphene/*n*-Si Schottky Diode, IEEE Sens. J. 14 (2014) 4104–4108.

[55] Y.-H. Zhang, Y.-B. Chen, K.-G. Zhou, C.-H. Liu, J. Zeng, H.-L. Zhang, Y. Peng, Improving gas sensing properties of graphene by introducing dopants and defects: a first-principles study, Nanotechnology 20 (2009) 185504.

[56] S.S. Varghese, S. Lonkar, K.K. Singh, S. Swaminathan, A. Abdala, Recent advances in graphene based gas sensors, Sens. Actuators B 218 (2015) 160–183.

[57] A.H. Reshak, S. Auluck, Adsorbing H_2S onto a single graphene sheet: A possible gas sensor, J. Appl. Phys. 116 (2014) 103702.

[58] R.J. Toh, H.L. Poh, Z. Sofer, M. Pumera, Transition metal (Mn, Fe, Co, Ni)-doped graphene hybrids for electrocatalysis, Chem. Asian J. 8 (2013) 1295–1300.

[59] H. Zhang, X. Luo, H. Song, X. Lin, X. Lu, Y. Tang, DFT study of adsorption and dissociation behavior of H_2S on Fe-doped graphene, Appl. Surf. Sci. 317 (2014) 511–516

[60] Y.-H. Zhang, L.-F. Han, Y.-H. Xiao, D.-Z. Jia, Z.-H. Guo, F. Li, Understanding dopant and defect effect on H_2S sensing performances of graphene: A first-principles study, Comput. Mater. Sci. 69 (2013) 222–228.

[61] V. Chakrapani, J.C. Angus, A.B. Anderson, S.D. Wolter, B.R. Stoner, G.U. Sumanasekera, Charge transfer equilibria between diamond and an aqueous oxygen electrochemical redox couple, Science 318 (2007) 1424–1430.

[62] J. Ristein, Surface transfer doping of semiconductors, Science 313 (2006) 1057–1058

[63] F. Maier, M. Riedel, B. Mantel, J. Ristein, L. Ley, Origin of surface conductivity in diamond, Phys. Rev. Lett. 85 (2000) 3472–3475.

[64] H. Liu, Y. Liu, D. Zhu, Chemical doping of graphene, J. Mater. Chem. 21 (2011) 3335–3345.

[65] 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.

[66] Y. Song, W. Fang, A. L. Hsu, J. Kong, Iron(III) chloride doping of CVD graphene, Nanotechnology 25 (2014) 395701.

[67] Z. Jiang, J. Li, H. Aslan, Q. Li, Y. Li, M. Chen, Y. Huang, J.P. Froning, M. Otyepka, R. Zboril, F. Besenbacherb, M. Dong, A high efficiency H_2S gas sensor material: paper like Fe_2O_3/graphene nanosheets and structural alignment dependency of device efficiency, J. Mater. Chem. A 2 (2014) 6714–6717.

[68] K.S. Yoo, S.D. Han, H.G. Moon, S.-J. Yoon, C.-Y. Kang, Highly Sensitive H_2S Sensor Based on the Metal-Catalyzed SnO_2 Nanocolumns Fabricated by Glancing Angle Deposition, Sensors 15 (2015) 15468–15477.

[69] J.-W. Yoon, Y.J. Hong, Y.C. Kang, J.-H. Lee, High performance chemiresistive H_2S sensors using Ag-loaded SnO_2 yolk–shell nanostructures, RSC Adv. 4 (2014) 16067–16074.

[70] Y. Wang, Y. Wang, J. Cao, F. Kong, H. Xia, J. Zhang, B. Zhu, S. Wang, S. Wu, Low-temperature H_2S sensors based on Ag-doped Fe_2O_3 nanoparticles, Sens. Actuators B 131 (2008) 183–189.

[71] K. Novoselov, A. Geim, S. Morozov, D. Jiang, Y. Zhang, S. Dubonos, I. Grigorieva, A. Firsov, Electric field effect in atomically thin carbon films, Science 306 (2004) 666–669.

[72] M.S. Dresselhaus, P. T. Araujo, Perspectives on the 2010 Nobel Prize in physics for graphene, ACS Nano 4 (2010) 6297–6302.

[73] E.M. Córdoba, J.A. Muñoz, M.L. Blázquez, F. González, A. Ballester, Leaching of chalcopyrite with ferric ion. Part III: Effect of redox potential on the silver-catalyzed process, Hydrometallurgy 93 (2008) 97–105.

[74] R. Beams, L.G. Cancado, L. Novotny, Raman characterization of defects and dopants in graphene, J. Phys.: Condens. Matter 27 (2015) 083002.

[75] 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.

[76] B. Cho, J. Yoon, M.G. Hahm, D.H. Kim, A.R. Kim, Y.H. Kahng, S.W. Park, Y.J. Lee, S.G. Park, J.D. Kwon, C.S. Kim, M. Song, Y. Jeong, K.S. Nam, H.C. Ko, Graphene-based gas sensor: metal decoration effect and application to a flexible device, Mater. Chem. C 27 (2014) 5280–5285.

[77] H. Liu, Y. Liu, D. Zhua, Chemical doping of graphene, J. Mater. Chem. 21(2011) 3335–3345.

[78] T. Oh, CVD graphene synthesis on copper foils and doping effect by nitric acid, Trans. Electr. Electron. Mater. 5 (2013), 246–249.

[79] H. Nohira, Journal of Non-Crystalline Solids 303 (2002) 83–87

[80] A.V. Shchukarev and DV Korolkov, CEJC 2(2) 2004 347-36

[81] G.M. Rignanese et al., Phys. Rev. Lett. 79, 5174 (1997).

[82] H. Liu, Y. Liu, D. Zhua, Chemical doping of graphene, J. Mater. Chem. 21 (2011) 3335–3345.

[83] Y. Wang, Y. Wang, J. Cao, F. Kong, H. Xia, J. Zhang, B. Zhu, S. Wang, S. Wu, Low-temperature H_2S sensors based on Ag-doped α-Fe_2O_3 nanoparticles, Sens. Actuators B 131 (2008) 183–189.

[84] C.Y. Sung, S.A. Hashimi, A. McCormick, M. Tsapatsis, M. Cococcioni, Density functional theory study on the adsorption of H_2S and other Claus process tail gas components on copper- and silver-exchanged Y zeolites, J. Phys. Chem. C 116 (2012) 3561–3575.

[85] F.C. Fabiani, G. Fratesi, G.P. Brivio, Adsorption of H_2S, HS, S, and H on a stepped Fe(310) surface, Eur. Phys. J. B 78 (2010) 455–460.

[86] C. Jin, T. Yamazaki, K. Ito, T. Kikuta, N. Nakatani, H_2S sensing property of porous SnO_2 sputtered films coated with various doping films, Vacuum 80 (2006) 723–725.

[87] M.V. Vaishampayan, R.G. Deshmukh, P. Walke, I.S. Mulla, Fe-doped SnO_2 nanomaterial: A low temperature hydrogen sulfide gas sensor, Mater. Chem. Phys. 109 (2008) 230–234

[88] G.H. Jain, L.A. Patil, M.S. Wagh, D.R. Patil, S.A. Patil, D.P. Amalnerkar, Surface modified $BaTiO_3$ thick film resistors as H_2S gas sensors, Sens. Actuators B 117 (2006) 159–165.

[89] C. Wang, X. Chu, M. Wu, Detection of H_2S down to ppb levels at room temperature using sensors based on ZnO nanorods, Sens. Actuators B 113 (2006) 320–323

[90] L. Mai, L. Xu, Q. Gao, C. Han, B. Hu, Y. Pi, Single β-$AgVO_3$ Nanowire H_2S Sensor, Nano Lett. 10 (2010) 2604–2608.

[91] X. Li, Y. Wang, Y. Lei, Z. Gu, Highly sensitive H_2S sensor based on template-synthesized CuO nanowires, RSC Adv. 2 (2012) 2302–2307.

[92] J. Chen, C. Jang, S. Adam, M. Fuhrer, E. Williams, M. Ishigami, Charged-impurity scattering in graphene, Nature Physics 4, (2008) 377 – 381.