Fabrication and NO$_2$ gas sensing performance of TeO$_2$-core/CuO-shell heterostructure nanorod sensors

Sunghoon Park1, Soohyun Kim1, Gun-Joo Sun1, Wan In Lee2, Kyoung Kook Kim3 and Chongmu Lee1*

Abstract

TeO$_2$-nanostructured sensors are seldom reported compared to other metal oxide semiconductor materials such as ZnO, In$_2$O$_3$, TiO$_2$, Ga$_2$O$_3$, etc. TeO$_2$/CuO core-shell nanorods were fabricated by thermal evaporation of Te powder followed by sputter deposition of CuO. Scanning electron microscopy and X-ray diffraction showed that each nanorod consisted of a single crystal TeO$_2$ core and a polycrystalline CuO shell with a thickness of approximately 7 nm. The TeO$_2$/CuO core-shell one-dimensional (1D) nanostructures exhibited a bamboo leaf-like morphology. The core-shell nanorods were 100 to 300 nm in diameter and up to 30 μm in length. The multiple networked TeO$_2$/CuO core-shell nanorod sensor showed responses of 142% to 425% to 0.5- to 10-ppm NO$_2$ at 150°C. These responses were stronger than or comparable to those of many other metal oxide nanostructures, suggesting that TeO$_2$ is also a promising sensor material. The responses of the core-shell nanorods were 1.2 to 2.1 times higher than those of pristine TeO$_2$ nanorods over the same NO$_2$ concentration range. The underlying mechanism for the enhanced NO$_2$ sensing properties of the core-shell nanorod sensor can be explained by the potential barrier-controlled carrier transport mechanism.

Keywords: TeO$_2$ nanorods; CuO shells; Gas sensors; Response; NO$_2$

PACS: 61.46. + w; 07.07.Df; 73.22.-f

Background

In recent years, one-dimensional (1D) nanostructure-based sensors attracted considerable attention owing to their high surface-to-volume ratios [1-5]. Considerable effort has been made to develop 1D nanostructured gas sensors with good sensing performances, but further improvements in the sensitivity of 1D nanostructured sensors are needed. The fabrication of heterostructures [6-8] is a promising technique to improve the sensitivity of the 1D nanostructured sensors. The improved sensing performance of the heterostructured 1D sensors has been attributed to a range of factors including increased potential barriers at the interface of the heterostructure [9,10], modulated depletion layer [11,12], band bending due to equilibration of the Fermi energy levels [13], synergistic surface reactions [14], etc.

Paratellurite (α-TeO$_2$) is a metal oxide semiconductor with a distorted rutile structure [15]. TeO$_2$ has applications in optical storage, laser devices and gas sensors, dosimeters, modulators, and deflectors owing to its unique properties such as high refractive index and high optical nonlinearity [16]. TeO$_2$-nanostructured sensors have attracted less attention compared to other metal oxide semiconductor materials such as ZnO, In$_2$O$_3$, TiO$_2$, Ga$_2$O$_3$, etc. In 2007, Liu et al. [17] synthesized TeO$_2$ nanowires that were sensitive to NO$_2$, NH$_3$, and H$_2$S gases. According to their results, TeO$_2$ 1D nanostructures are promising for producing low power consumption gas sensors. The incorporation of a surface
decoration or heterostructure formation technique can improve their sensing performance further. In this regard, a recent study reported the sensing properties of Pt-doped TeO$_2$ nanorods [16]. On the other hand, this paper reports the synthesis of TeO$_2$-core/CuO-shell nanorods and the sensing properties of multiple networked TeO$_2$-core/CuO-shell nanorod gas sensors toward NO$_2$ gas. The underlying mechanism for the enhanced sensing performance of the core-shell nanorod sensors is also discussed.

**Methods**

TeO$_2$/CuO core-shell nanorods were synthesized using a two-step process: thermal evaporation of Te powder followed by sputter deposition of CuO. TeO$_2$ nanorods were synthesized on a p-type Si (100) substrate in a quartz tube furnace by thermal evaporation of Te powder at 400°C in air without a metal catalyst or the supply of other gas. The thermal evaporation process was conducted at room temperature for 1 h and the furnace was cooled to room temperature. Subsequently, the TeO$_2$ nanorods were coated with a thin CuO layer by sputtering a CuO target by radio frequency (RF) magnetron sputtering from a CuO target. The base and working pressure was $5.0 \times 10^{-6}$ Torr and $2.0 \times 10^{-2}$ Torr, respectively, and the N$_2$ gas flow rate was 20 cm$^3$/min throughout the evaporation process. The RF sputtering power and sputtering time were 100 W and 20 min, respectively.

The structure and morphology of the nanorod samples were characterized by scanning electron microscopy (SEM, Hitachi S-4200, Billerica, MA, USA), transmission electron microscopy (TEM, Philips CM-200, Eindhoven, the Netherlands), and selected area electron diffraction. X-ray diffraction (XRD, Philips X’pert MRD, Eindhoven, the Netherlands) patterns were performed using Cu K$_\alpha$ radiation (0.15406 nm). Energy-dispersive X-ray spectroscopy (EDS) was carried out to examine the elemental composition of the core-shell nanorod samples. The resistance of multiple networked pristine TeO$_2$ nanorod and TeO$_2$/CuO core-shell nanorod sensors were measured using a Keithley source meter-2612 at a source voltage of 10 V at 150°C and 50% RH. The 50% relative humidity might be somewhat high for sensing tests. A flow-through technique was used to test the gas sensing properties. NO$_2$ gas diluted with synthetic air at different ratios was injected into the testing tube at a constant flow rate of 200 cm$^3$/min. The detailed procedures for sensor fabrication and the sensing test are reported elsewhere [18].

**Results and discussion**

Figure 1a shows a SEM image of the TeO$_2$/CuO core-shell nanorods prepared by thermal evaporation followed by sputtering. Each 1D nanostructure exhibited a rod-like morphology with a sharp tip, i.e. a bamboo leaf-like morphology. The core-shell nanorods were 100 to 300 nm in diameter and up to 30 μm in length. XRD was performed to determine the crystal structures of the core-shell nanorods. The XRD patterns of the TeO$_2$/CuO core-shell nanorods showed that the TeO$_2$ cores were crystalline, whereas the CuO shells were polycrystalline (Figure 1b). Most of the XRD peaks of the TeO$_2$/CuO core-shell nanorods were assigned to be the reflections of primitive tetragonal-structured rutile-
type TeO$_2$. In addition, three small reflection peaks were assigned to the 111, 200, and 022 reflections of monoclinic-structured CuO with lattice constants of $a = 0.4689$ nm, $b = 0.342$ nm, $c = 0.513$ nm, and $\beta = 99.57^\circ$ (JCPDS No. 89–5899).

The low-magnification TEM image of a typical core-shell nanorod showed that the nanorod had a uniform diameter along its length direction (Figure 2a). TEM revealed a shell width of approximately 7 nm. A close examination of the high-resolution TEM (HRTEM) image (Figure 2b) shows a fringe pattern in the core region (the lower darker region), suggesting it to be a single crystal. The clear spots in the corresponding selected area electron diffraction (SAED) pattern were assigned to the primitive tetragonal structured TeO$_2$ with lattice constants of $a = 0.4810$ nm and $c = 0.7613$ (JCPDS No. 78–1713) (Figure 2c). On the other hand, the halo-like concentric ring pattern might be due to the polycrystalline CuO shell. The line-scanning EDS concentration profile along the diameter of a typical core-shell nanorod (Figure 2d) revealed a higher Te concentration in the center region and a higher Cu concentration in both edge regions of the nanorod, confirming the TeO$_2$-core/CuO-shell structure.

Figure 3a,b shows the dynamic electrical responses of pristine TeO$_2$ nanorods and TeO$_2$/CuO core-shell nanorods, respectively, to NO$_2$ at 150°C under 50% RH. The sensors were exposed to successive pulses of 0.5- to 10-ppm NO$_2$ gas. The relative response of the p-type TeO$_2$/CuO nanorod sensors is defined as $R_a/R_g$ for NO$_2$, where $R_a$ and $R_g$ are the electrical resistances in the sensors in air and target gas, respectively. In all cases, the resistance returned to its original value after the NO$_2$ gas flow was switched off, confirming the reversibility of the gas absorption and desorption processes. The pristine TeO$_2$ nanorods showed responses of approximately 123% to 203% to NO$_2$ at 0.5 to 10 ppm (Table 1). In contrast, the TeO$_2$/CuO core-shell nanorods showed 1.2- to 2.1-fold stronger responses to NO$_2$ than pristine TeO$_2$ nanorod sensors at the same concentrations.

Figure 3c compares the response to NO$_2$ gas between pristine TeO$_2$ nanorods and TeO$_2$/CuO core-shell nanorods in the NO$_2$ concentration range below 10 ppm. The response of an oxide semiconductor sensor can be expressed as $R = A [C]^n + B$, where $A$ and $B$, $n$, and $[C]$ are constants, exponent, and target gas concentration, respectively [19]. Data fitting gave $R = 7.52 [C] + 132.5$ and $R = 27.48 [C] + 153.9$ for the pristine TeO$_2$ nanorod sensor.
and TeO₂-core/CuO-shell nanorod sensors, respectively. The core-shell nanorod sensor showed stronger response and higher increasing rate in response to NO₂ gas at lower concentrations than the pristine nanorod sensor.

Table 2 lists the responses of the multiple networked pristine TeO₂ nanorod sensor to NO₂ gas along with those of other reported nanomaterial sensors. Overall, the sensing properties of the TeO₂/CuO core-shell nanorod sensor fabricated in this study were comparable to those of other competing nanomaterials (Table 2), but the sensing test conditions such as operating temperature, gas concentration, etc. were different [20-31]. It should be noted that the NO₂ concentration and the test temperature used in this study were mostly lower than those elsewhere. The responses of pristine TeO₂ nanorods and TeO₂-CuO nanorods to NO₂ measured in this study were stronger than those of other metal oxides such as ZnO fibers, ZnO fibre mats, mesoporous WO₃ thin film, and CdO nanowire measured at temperatures lower than 150°C. The response of WO₃-doped SnO₂ thin film was stronger to 500 ppm of NO₂ than those of pristine TeO₂ nanorods and TeO₂-CuO nanorods to 10 ppm of NO₂, but it should be noted that the former response was obtained to a far higher concentration of NO₂. TiO₂ nanofibers, SnO₂ hollow spheres, and Ru-doped SnO₂ nanowire showed stronger responses to NO₂ than those of pristine TeO₂ nanorods and TeO₂-CuO nanorods, but their operation temperatures of the former were higher than 150°C. Pristine TeO₂ nanorods and TeO₂-CuO nanorods showed stronger responses than other metal oxide nanostructures except the above-mentioned nanomaterials.

Figure 4a shows the responses of the pristine TeO₂ nanorod and TeO₂/CuO core-shell nanorod sensors to NO₂ gas as a function of the operating temperature. The optimum operation temperature of TeO₂/CuO core-shell nanorod sensor was 150°C, whereas that of the pristine TeO₂ nanorod sensor was 175°C. This result reveals that encapsulation of TeO₂ nanorods with a CuO thin film resulted in a 25°C decrease in operation temperature. Figure 4b exhibits the selectivity of the pristine and Bi₂O₃ nanoparticle-decorated In₂O₃ nanorod sensors to NO₂ gas over other gases. The sensors
showed the highest response to ethanol among different gases at the same concentration of 200 ppm at 150°C. The underlying mechanism of the enhanced TeO₂/CuO core-shell nanorods can be explained using a barrier-controlled carrier transport mechanism [9,10]. Potential barriers form at three places in the multiple networked TeO₂/CuO core-shell nanorod sensor: at the core-shell interface, the shell grain boundary [40], and the nanorod-nanorod contact. First, the potential barrier at core-shell interface is due to the high density of interface states in the TeO₂-CuO interfacial region. The carriers near the interface are trapped by interface states, so that a depletion layer forms over the TeO₂ core region near the interface to the CuO shell region near the interface. In addition to depletion layer formation, a potential barrier is created at the core-shell interface due to the carrier trapping as shown in Figure 5a [41]. The potential barrier is drawn in the negative energy direction, i.e. the downward direction in Figure 5a because the carriers trapped in the interface are mostly holes residing in p-type TeO₂ core and the p-type CuO shell in the vicinity of the core-shell interface. The other two potential barriers that should be overcome by carriers on their pathways before they reach the electrode of the sensor are at the CuO-CuO homojunction, where two nanorods contact each other (Figure 5b) and at the grain boundary in the polycrystalline CuO shell layers (Figure 5a). The contributions of these two potential barriers might be smaller than that of the potential barrier at the TeO₂-CuO interface because of much smaller numbers of grain boundaries and nanorod-nanorod contacts compared to that of the core-shell interfaces. Each nanorod has a core-shell interface, whereas a CuO shell contains a small number of grain boundaries because it is as thin as approximately 7 nm and the possibility of two nanorods contacting each other in a multiple networked nanorod sensor is generally quite low. Carrier transport is facilitated or restrained because of these energy barriers by adsorption and desorption of gas molecules, resulting in a larger change in resistance, i.e., an enhanced response

| Nanomaterial                      | Temperature (°C) | NO₂ concentration (ppm) | Response (%) | Reference |
|-----------------------------------|------------------|--------------------------|-------------|-----------|
| TeO₂ nanorods                     | 150              | 0.5                      | 123         | Present work |
| TeO₂ nanorods                     | 150              | 10                       | 203         | Present work |
| TeO₂-CuO nanorods                 | 150              | 0.5                      | 142         | Present work |
| TeO₂-CuO nanorods                 | 150              | 10                       | 425         | Present work |
| ZnO nanorods                      | 300              | 0.1                      | 35          | [20]      |
| ZnO nanowire                      | 250              | 20                       | >95         | [21]      |
| ZnO nanobelts                     | 350              | 8.5                      | 81          | [22]      |
| ZnO fibers                        | 100              | 0.4                      | 50          | [23]      |
| WO₃-core/ZnO-shell nanorods       | 300              | 5                        | 281         | [24]      |
| TiO₂ nanofibers                   | 300              | 0.25                     | 7,430       | [25]      |
| In-doped SnO₂ nanoparticles       | 250              | 500                      | 100         | [26]      |
| SnO₂ nanoribbon                   | RT               | 3                        | 116         | [27]      |
| SnO₂ hollow spheres               | 160              | 5                        | 1,150       | [28]      |
| Ru-doped SnO₂ nanowire            | 150              | 200                      | >3,000      | [29]      |
| WO₃-doped SnO₂ thin film          | 100              | 500                      | 2,210       | [30]      |
| In₂O₃ nanowires                   | 400              | 50                       | 360         | [31]      |
| In₂O₃ nanobelts                   | 250              | 50                       | 200         | [32]      |
| WO₃ nanorods                      | 300              | 1                        | 200         | [33]      |
| Au-doped WO₃ powders              | 150              | 10                       | 350         | [34]      |
| Mesoporous WO₃ thin film          | 100              | 3                        | >200        | [35]      |
| MoO₃ lamellars                    | 180 to 300       | 10                       | 118         | [36]      |
| CdO nanowire (porous)             | 100              | 150                      | >150        | [37]      |
| SnO₂-core/ZnO-shell nanofibers    | 300              | 70 to 2,000              | 20 to 320   | [38]      |
| ZnGa₂O₄-core/ZnO-shell nanowires  | 250              | 1                        | 260         | [39]      |
of the core-shell nanorod sensor to NO2 gas. In other words, the heights of the potential barriers are modulated at the three places, resulting in enhanced response of the sensor to the gas.

Conclusions
TeO2/CuO core-shell nanorods were synthesized using a two-step process: the synthesis of TeO2 nanorods by thermal evaporation of Te powder and sputter deposition of CuO. The cores and shells of the nanorods were single crystal TeO2 and polycrystalline CuO, respectively. The responses of the TeO2 nanorods to NO2 were improved approximately 2.1- to 2.1-fold at NO2 concentrations of 0.5 to 10 by coating them with CuO. The responses of the core-shell nanorods to NO2 gas were also comparable or superior to those of the other metal oxide semiconductor nanostructured sensors reported previously. The enhanced response of the TeO2/CuO core-shell nanorods to NO2 gas may be due to modulation of the heights of the potential barriers formed at three different places in the multiple networked 1D nanostructure sensor: the TeO2 core-CuO shell interface, the CuO-CuO homojunction at the contact of two core-shell nanorods, and the grain boundaries in the polycrystalline CuO shell layers.

Competing interests
The authors declare that they have no competing interests.
Authors' contributions
All the authors contributed equally to the paper. All authors read and approved the final manuscript.

Acknowledgements
This study was supported by the 2010 Core Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology.

Author details
1Department of Materials Science and Engineering, Inha University, 253 Yonhong-dong, Nam-gu, Incheon 402-751, Republic of Korea. 2Department of Chemistry, Inha University, 253 Yonhong-dong, Nam-gu, Incheon 402-751, Republic of Korea. 3Department of Nanooptical Engineering, Korea Polytechnic University, 2121 Jeongwangdong, Shiheung-city, Gyeonggi-do 429-793, Republic of Korea.

Received: 26 August 2014 Accepted: 14 November 2014

References
1. Tippins HH: Optical absorption and photoconductivity in the band edge of β-Ga2O3. Phys Rev A 1965, 140:316–319.
2. Yamazoe N: New approaches for improving semiconductor gas sensors. Sens Actuators B 1991, 5:7–19.
3. Gundiah G, Govindaraj A, Rao CNR: Nanowires, nanobelts and related nanostuctures of Ga2O3. Chem Phys Lett 2002, 351:189–194.
4. Zhang HZ, Kong YC, Wang YZ, Du X, Bai ZG, Wang JJ, Yu DP, Ding Y, Hang QL, Feng SQ: Ga2O3 nanowires prepared by physical evaporation. Sol State Comm 1999, 92:677–682.
5. Kim BC, Sun KT, Park KS, Im KJ, Noth T, Sun MY, Kim S, Nahm S, Choi YN, Park SS: β-Ga2O3 nanowires synthesized from milled GaN powders. Appl Phys Lett 2002, 80:679–681.
6. Yan C, Le BH, Kang DJ: Ultrafast single crystalline TeO2 nanowires based hydrogen gas sensors. J Mater Chem A 2014, 2:5394–5398.
7. Sanchez-Castillo MA, Couto C, Kim WB, Dumesic JA: Gold-nanotube membranes for the oxidation of CO at gas-water interfaces. Angew Chem Int Ed 2003, 42:1140–1142.
8. Jagerzki G, Gujrati R, Hoefler L, Pretsch E: Hybridization-modulated ion fluxes through peptide-nucleic-acid-functionized Gold nanotubes. A new approach to quantitative label-free DNA analysis. Nano Lett 2007, 7(6):1609–1612.
9. Wang W, Li Z, Zheng W, Huang H, Wang C, Sun J: Cr2O3 sensitized ZnO electron spin probe nanofibers based ethanol detectors. Sens Actuators B 2010, 143:574–578.
10. Sun P, Sun Y, Ma J, You L, Lu G, Fu W, Li M, Yang H: Synthesis of novel SnO2/ZnSnO4 core-shell microspheres and their gas sensing properties. Sens Actuators B 2011, 156:606–611.
11. Wang L, Kang Y, Wang Y, Zhu B, Zhang S, Huang W: CuO nanoparticle decorated ZnO nanorod sensor for low-temperature H2S detection. Mater Sci Eng C 2012, 32:2079–2085.
12. Liu Y, Zhu G, Chen J, Xu H, Shen X, Yuan A: Co3O4/ZnO nanocomposites for gas-sensing applications. Appl Surf Sci 2013, 263:379–384.
13. Kusor A, Radecka M, Rekas M, Lubecka M, Zakrzewska K, Reszka A: Sensitization of gas sensing properties in TiO2/SnO2 nanocomposites. Procedia Eng 2012, 47:1073–1076.
14. De Lacy Costello BP, Ewen RJ, Ratcliffe NM, Sivanand P: Thick film organic vapour sensors based on binary mixtures of metal oxides. Sens Actuators B 2003, 89:25–166.
15. Kim ID, Rothschild A, Lee BH, Kim DY, Jo SM, Fuller HL: Ultrasensitive chemiresistors based on electron spin TIO2 nanofibers. Nano Lett 2006, 6:2009–2013.
16. Jin C, Park S, Kim H, Lee C: Enhanced gas sensing properties of Pt-loaded TeO2 nanorods. Bull Kor Chem Soc 2012, 33:1851–1855.
17. Li YJ, Li KM, Wang CY, Kuo CJ, Chen LL: Low-temperature electrodeposited Co-doped ZnO nanorods with enhanced ethanol and CO sensing properties. Sens Actuators B 2012, 161:734–739.
18. Jin C, Park S, Kim H, Lee C: Ultrafast multifunctional networked Ga2O3-core/ ZnO-shell nanorods gas sensors. Sens Actuators B 2012, 161:223–228.
19. Williams DE: Solid State Gas Sensors. Bristol: Hilger; 1987.
20. Oh E, Choi HY, Jung SH, Cho S, Kim JC, Lee KH, Kang SW, Kim J, Yun JY, Jeong SH: High-performance NO2 gas sensor based on ZnO nanorod grown by ultrasonic irradiation. Sens Actuators B 2009, 141:239–243.
21. Ahn MW, Park KS, Hoe JH, Park JG, Kim DW, Choi KJ, Lee JH, Hong SH: Gas sensing properties of defect-controlled ZnO-nanowire gas sensor. Appl Phys Lett 2008, 93:263103.
22. Sadik AZ, Chocopan S, Wlodarski W, Ioppolito SJ, Kalantar-zadeh K: Characterization of ZnO nanobelt-based gas sensor for H2, NO2, and hydrocarbon sensing. IEEE Sens J 2007, 7:919–924.
23. Baratco C, Sberveglieri G, Orischuk A, Caruso B, Stasio SD: Low temperature selective NO2 sensors by nanostructured fibres of ZnO. Sens Actuators B 2004, 100:261–266.
24. Ahn S, Park S, Ko H, Lee C: Enhanced NO2 gas sensing properties of WO3 nanorods encapsulated with ZnO. Appl Phys A 2012, 108:53–58.
25. Lindau O, Rothschild A, Zussman E: Processing-microstructure-properties correlation of ultratransitive gas sensors produced by electrophinning. Chem Mater 2009, 21:19–11.
26. Kaur J, Kumar R, Bhatnagar MC: Effect of indium-doped SnO2 nanowires on NO2 gas sensing properties. Sens Actuators B 2007, 126:478–484.
27. Law M, Kind H, Messer B, Kim F, Yang P: Photochemical sensing of NO2 with SnO2 nanoribbon nanosensors at room temperature. Angew Chem Int Ed 2002, 41:2405–2408.
28. Zhang J, Wang S, Wang Y, Wang Y, Zhu B, Xia H, Guo X, Zhang S, Huang W, Wu S: NO2 sensing performance of SnO2 hollow-sphere sensor. Sens Actuators B 2009, 135:610–617.
29. Ramgr NS, Mulli AS, Vajayamohan RK: A room temperature nitric oxide sensor actualized from Ru-doped SnO2 nanowires. Sens Actuators B 2005, 107:708–715.
30. Kaur J, Roy SC, Bhatnagar MC: Highly sensitive SnO2 thin film NO2 gas sensor operating at low temperature. Sens Actuators B 2007, 123:1090–1095.
31. Vomiero A, Bianchi S, Comini E, Faglia G, Ferroni M, Sberveglieri G: Controlled growth and sensing properties of In2O3 nanowires. Cryst Growth Des 2007, 7:2500–2504.
32. Xu P, Cheng Z, Pan Q, Xu J, Xiang Q, Yu W, Chu Y: High aspect ratio In2O3 nanowires: synthesis, mechanism and NO2 gas-sensing properties. Sens Actuators B 2008, 130:802–808.
33. Liu Z, Miyachi M, Yamaizaki T, Shon Y: Faster response and NO2 gas sensing of tungsten oxide nanorod assembled microspheres. Sens Actuators B 2009, 140:514–519.
34. Xia H, Wang Y, Kong F, Wang S, Zhu B, Guo X, Zhang J, Wu S: Au-doped WO3-based sensor for NO2 detection at low operating temperature. Sens Actuators B 2008, 134:133–139.
35. Tech LG, Hon YM, Sheif J, Lai WH, Hon MH: Sensitivity properties of a novel NO2 gas sensor based on mesoporous WO3 thin film. Sens Actuators B 2003, 96:219–225.
36. Rahmani MB, Keshmehr S, Yu J, Sadek A, Al-Moafi A, Latham K, Li Y, Wlodarski W, Kalantar-Zadeh K: Gas sensing properties of thermally evaporated lamellar MoO3. Sens Actuators B 2010, 145:13–19.
37. Guo Z, Li M, Liu J: Highly porous CdO nanowires: preparation based on hydroxy-and carbonate-containing cadmium compound precursor nanowires, gas sensing and optical properties. Nanotechnology 2008, 19:45611.
38. Choi SW, Park JY, Kim SS: Synthesis of SnO2-ZnO core-shell nanofibers via a novel two-step process and their gas sensing properties. Nanotechnology 2009, 20:465603–465608.
39. Chen IC, Lin SS, Lin TJ, Hsu CL, Hsieh TJ, Sheih TY: The assessment for sensitivity of a NO2 gas sensor with ZnGa2O4/ZnO core-shell nanowires- a novel approach. Sensors 2010, 10:3057–3072.
40. Xu C, Tanaw J, Miura N, Yamazoe N: Grain size effect on gas sensitivity of porous SnO2-based elements. Sens Actuators B 1991, 3:147–155.
41. Park S, Ko H, Kim S, Lee C: Role of the interfaces in multiple networked one-dimensional core-shell nanostuctured gas sensors. ACS Appl Mater Interfaces 2014, 6:9595–9600.