Supplementary Information

Direct Ink Writing of Nickel oxide-based Thin Films for Room Temperature Gas Detection

Neha Thakur, Sudha Arumugam, Neethu Thomas, Aarju Mathew Koshy, Parasuraman Swaminathan, and Hari Murthy

S1. Existing NiO-based NO_2 and CO_2 Gas Sensors

Table S1 gives a glimpse of a few NiO-based NO_2 and CO_2 sensors respectively reported in the literature. It is observed from the table that the sensors reported are using complex fabrication methods, high operating temperatures, higher concentrations, long response time, and recovery time.

Table S1. Existing NiO-based NO_2 and CO_2 Gas Sensors

Gas	Method	Material	Temp. (°C)	Conc. (ppm)	Response time, recovery time (s)	Ref
NO_2	Vapor-liquid-solid (VLS)	NiO Nanowire	200	0.2-1	100 s, 500 s	[1]
	Spin-coating	SnO_2-NiO	RT	0.5	184 s, 432 s	[2]
	Hydrothermal	NiO thin film	200	20	100 s, 1000 s	[3]
	Facile solution process	NiO-rGO matrix	100	3-100	15 s, 20 s	[4]
	Chemical spray pyrolysis	NiO	200-250	20	Sensitivity (57.3/%)	[5]
	Spray coating	Mesoporous NiO Nanosheet	RT	50	10 min,10 min	[6]
	Growth	NiO-CNT	RT	1000	30 min, 20 min	[7]
	Electron beam lithography	Graphene	RT	100	150 s, 400 s	[8]
	CVD	Graphene (UV assisted)	RT	100	10 min, 10 min	[9]
	CVD	Graphene	RT	200-0.1	3000 s, 3000 s	[10]
	Spin coating	Ozone Treated Graphene	RT	200	26 s, 20 s	[11]
	Screen printing	WO_3-rGO	RT	0.5-20	9 min, 18 min	[12]
	Drop casting	NiO-Graphene	80	7-60	576 s, 121 s	[13]
	Hydrothermal	NiO-CNC	RT	50	132 s, 164 s	[14]
	Hydrothermal	N_2 doped NiO	200-250	1-8	100 s, 200 s	[15]
	Ultrasonic method	Ni/NiO/Graphene	150	10	20 s, 10 s	[16]

	Gravure printing	rGO-AgNP	RT	50	12 s, 20 s	[17]
	Sol gel	NiO thin films	150	20	2.6 (sensitivity)	[18]
	Sol gel	Ce doped NiO	150	40	29	[19]
	MPECVD	GNWs/NiO-WO_3/GNWs	RT	5-7	300 s, 300 s	[20]
	Deposition	YSZ-NiO	800-900	400	20 s, 180 s	[21]
	DIW	**NiO-Graphene**	**RT**	**5 SCCM**	**10 s, 9 s**	**This Work**
	DIW	**NiO-AgNWs**	**RT**	**5 SCCM**	**13 s, 14 s**	**This Work**
CO_2	Dip coating	NiO/rGO	RT	0-500	16 s, 22 s	[22]
	Hydrothermal	NiO/CNT	RT	4000	10 s, 47 s	[23]
	Spray pyrolysis	Nonporous Graphene Oxide	RT	10 SCCM	25 s, 150 s	[24]
	Facile reduction method	SnO_2-rGO	RT	5-500	41 s, 47s	[25]
	Capacitive layered structure	NiO-$BaTiO_3$	400-800	200-20000	70 s, 90 s	[26]
	Film-forming method	Pt-NiO	RT	5-500	240 s, 600 s	[27]
	SILAR	SnO_2-NiO	RT	5-500	13 s, 34 s	[28]
	Sputtering	TiO_2-AgNP	RT	50 SCCM	10 s, 110 s	[29]
	Plasma etching	GO	45-65	400-40000	3 s, 5 s	[30]
	DIW	**NiO-Graphene**	**RT**	**30 SCCM**	**16 s, 12 s**	**This Work**
	DIW	**NiO-AgNWs**	**RT**	**30 SCCM**	**11 s, 11 s**	**This Work**

S2. IV testing results for three different batch-fabricated sensors

Fig S1 corresponds to the IV testing results of three different batch-fabricated sensors. It is observed that almost the same IV plot is obtained for all batches indicating the batch consistency.

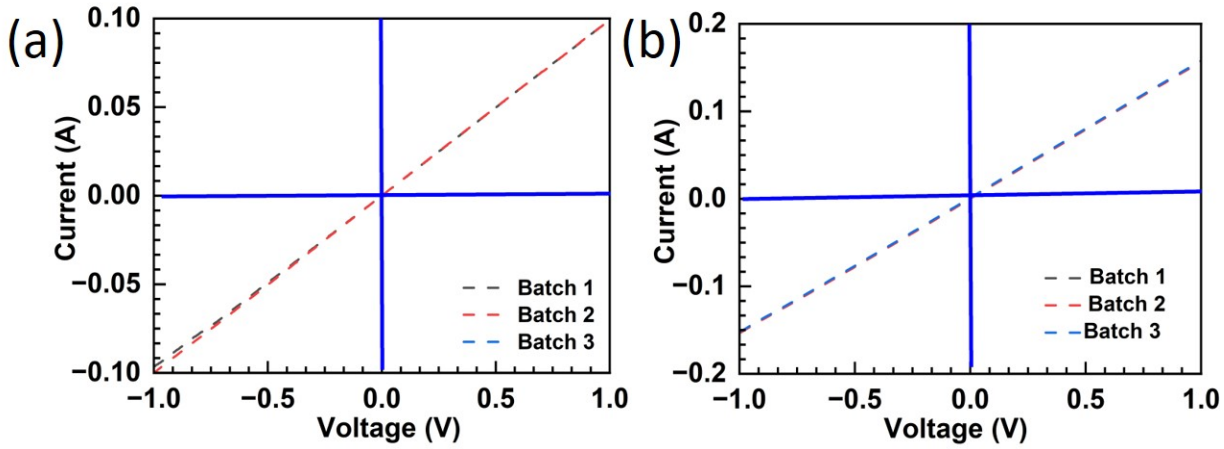

Fig. S1: IV testing results for three different batch fabricated sensors (a) Nickel oxide-graphene (b) Nickel oxide- silver nanowires

References

[1] Kaur, N., Zappa, D., Comini, E.: Shelf-life study of NiO nanowire sensors for NO_2 detection. Electronic Materials Letters 15, 743–749 (2019)

[2] Kumar, R., Mamta, Kumari, R., Singh, V.N.: SnO_2-based NO_2 gas sensor without standing sensing performance at room temperature. Micromachines 14(4), 728(2023)

[3] Gomaa, M., Sayed, M., Patil, V., Boshta, M., Patil, P.: Gas sensing performance of sprayed NiO thin films toward NO_2 gas. Journal of Alloys and Compounds885, 160908 (2021)

[4] Ngo, Y.-L.T., Hur, S.H.: Low-temperature NO_2 gas sensor fabricated with NiO and reduced graphene oxide hybrid structure. Materials Research Bulletin 84,168–176 (2016)

[5] Tan, G., Tang, D., Wang, X., He, L., Mu, T., Li, G.: Preparation of NiO Thin Films and Their Application for NO_2 Gas Detection. International Journal of Electrochemical Science 17(5), 220551 (2022)

[6] Hoa, L.T., Tien, H.N., Hur, S.H.: Fabrication of novel 2D NiO nanosheet branched on 1D-ZnO nanorod arrays for gas sensor application. Journal of Nanomaterials2014, 177–177 (2014)

[7] Jeong, H.Y., Lee, D.-S., Choi, H.K., Lee, D.H., Kim, J.-E., Lee, J.Y., Lee, W. J., Kim, S.O., Choi, S.-Y.: Flexible room-temperature NO_2 gas sensors based on carbon nanotubes/reduced graphene hybrid films. Applied physics letters 96 (21) (2010)

[8] Ko, G., Kim, H.-Y., Ahn, J., Park, Y.-M., Lee, K.-Y., Kim, J.: Graphene-based nitrogen dioxide gas sensors. Current Applied Physics 10(4), 1002–1004 (2010)

[9] Yan, X., Wu, Y., Li, R., Shi, C., Moro, R., Ma, Y., Ma, L.: High-performance UV-assisted NO_2 sensor based on chemical vapor deposition graphene at room temperature. ACS omega 4(10), 14179–14187 (2019)

[10] Yavari, F., Castillo, E., Gullapalli, H., Ajayan, P.M., Koratkar, N.: High sensitivity detection of NO_2 and NH_3 in air using chemical vapor deposition grown graphene. Applied Physics Letters 100(20) (2012)

[11] Chung, M.G., Lee, H.M., Kim, T., Choi, J.H., Seo, D., Yoo, J.-B., Hong, S. H., Kang, T.J., Kim, Y.H., et al.: Highly sensitive NO_2 gas sensor based on ozone treated graphene. Sensors and Actuators B: Chemical 166, 172–176 (2012)

[12] Su, P.-G., Peng, S.-L.: Fabrication and NO_2 gas-sensing properties of reduced graphene oxide/WO3 nanocomposite films. Talanta 132, 398–405 (2015)

[13] Zhang, J., Zeng, D., Zhao, S., Wu, J., Xu, K., Zhu, Q., Zhang, G., Xie, C.: Room temperature NO_2 sensing: what advantage does the rGO–NiO nano composite have over pristine NiO? Physical Chemistry Chemical Physics 17(22), 14903–14911 (2015)

[14] Sun, D., Luo, Y., Debliquy, M., Zhang, C.: Graphene-enhanced metal oxide gas sensors at room temperature: A review. Beilstein journal of nanotechnology 9(1),2832–2844 (2018)

[15] Luan, V.H., Tien, H.N., Hur, S.H., Han, J.H., Lee, W.: Three-dimensional porous nitrogen-doped NiO nanostructures as highly sensitive NO_2 sensors. Nanomaterials 7(10), 313 (2017)

[16] Musayeva, N., Hashimov, A., Khalilova, H., Izzatov, B., Guluzade, S., Alizada,M.: Enhancement effect of Ni and NiO on gas sensing characteristics of carbon nanotube based structures. Fullerenes, Nanotubes and Carbon Nanostructures,1–8 (2023)

[17] Huang, L., Wang, Z., Zhang, J., Pu, J., Lin, Y., Xu, S., Shen, L., Chen, Q., Shi,W.: Fully printed, rapid-response sensors based on chemically modified graphene for detecting NO_2 at room temperature. ACS applied materials & interfaces 6(10),7426–7433 (2014)

[18] Zhao, S., Shen, Y., Zhou, P., Zhang, J., Zhang, W., Chen, X., Wei, D., Fang, P., Shen, Y.: Highly selective NO_2 sensor based on p-type nanocrystalline NiO thin films prepared by sol–gel dip coating. Ceramics International 44(1), 753–759(2018)

[19] Gawali, S.R., Patil, V.L., Deonikar, V.G., Patil, S.S., Patil, D.R., Patil, P.S., Pant, J.: Ce doped NiO nanoparticles as selective NO_2 gas sensor. Journal of Physics and Chemistry of Solids 114, 28–35 (2018)

[20] Kwon, S., Lee, S., Kim, J., Park, C., Jung, H., Kim, H., Kim, C., Kang, H.: Effect of GNWs/NiO-WO_3/GNWs heterostructure for NO_2 Gas Sensing at Room Temperature. Sensors 22(2), 626 (2022)

[21] Miura, N., Wang, J., Nakatou, M., Elumalai, P., Zhuiykov, S., Hasei, M.: High-temperature operating characteristics of mixed-potential-type NO_2 sensor based on stabilized-zirconia tube and NiO sensing electrode. Sensors and Actuators B: Chemical 114(2), 903–909 (2006)

[22] Shanavas, S., Ahamad, T., Alshehri, S.M., Acevedo, R., Anbarasan, P.M.: A facile microwave route for fabrication of NiO/rGO hybrid sensor with efficient CO_2 and acetone gas sensing performance using clad modified fiber optic method. Optik226, 165970 (2021)

[23] George, R., Kumar, L., Alagappan, M.: Synthesis of nanotubular NiO-CNT composite and its application in temperature independent CO_2 gas sensors fabricated using interdigitated silver electrode. Dig. J. Nanomater. Biostruct 14, 213–224 (2019)

[24] Shaban, M., Ali, S., Rabia, M.: Design and application of nanoporous graphene oxide film for CO_2, H_2, and C_2H_2 gases sensing. Journal of Materials Research and Technology 8(5), 4510–4520 (2019)

[25] Lee, Z.Y., Hawari, H.F.b., Djaswadi, G. W.b., Kamarudin, K.: A highly sensitive room temperature CO_2 gas sensor based on SnO_2-rGO hybrid composite. Materials 14(3), 522 (2021)

[26] Ishihara, T., Kometani, K., Mizuhara, Y., Takita, Y.: A new type of CO_2 gas sensor based on capacitance changes. Sensors and Actuators B: Chemical 5(1-4), 97–102 (1991)

[27] Yue, Z., Niu, W., Zhang, W., Liu, G., Parak, W.J.: Detection of CO_2 in solution with a Pt–NiO solid-state sensor. Journal of colloid and interface science 348(1), 227–231 (2010)

[28] Rzaij, J.M., Habubi, N.F.: Enhancing the CO_2 sensor response of nickel oxide-doped tin dioxide thin films synthesized by SILAR method. Journal of Materials Science: Materials in Electronics 33(15), 11851–11863 (2022)

[29] Raza, M.A., Habib, A., Kanwal, Z., Hussain, S.S., Iqbal, M.J., Saleem, M., Riaz, S., Naseem, S.: Optical CO_2 gas sensing based on TiO2 thin films of diverse thickness decorated with silver nanoparticles. Advances in Materials Science and Engineering 2018, 1–12 (2018)

[30] Akhter, F., Alahi, M.E.E., Siddiquei, H.R., Gooneratne, C.P., Mukhopadhyay, S.C.: Graphene oxide (GO) coated impedimetric gas sensor for selective detection of carbon dioxide (CO_2) with temperature and humidity compensation. IEEE Sensors Journal 21(4), 4241–4249 (2020)