**Nanosensors as a Principal Tool for Remediation of Hazardous Air Pollutants**

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**ABSTRACT**

Air pollution has become a serious problem over the past few decades. High levels of air pollutant and their chemical residues in the atmosphere has a severe impact on human health and the ecosystems. Hazardous gases in the atmosphere include an oxide of carbon, nitrogen, and sulphur, and toxic volatile gases such as ammonia, amides, amines, etc. It is imperative to effectively and in real-time monitor the composition and quantity of hazardous gases in the atmosphere. Nanotechnology presents an excellent opportunity to measure, monitor, manage, and reduce pollutants in the environment. Nanosensors are essential in the field of nanotechnology for several purposes such as spotting physical and chemical changes, keeping track of biomolecules and biochemical changes in cells, and assessing harmful and polluting substances found in the workplace and the environment. With advancements in nanotechnology, nanosensors can detect minute amounts of air pollutants in the environment. This may foster healthy living and working conditions and guard against negative health impacts. This chapter would help readers understand how nanotechnology may be used to develop extremely effective nanosensors for air pollution detection. The advancements made recently in the field of environmental pollutant detection, notably for the sensing of air contaminants, are thoroughly explored.

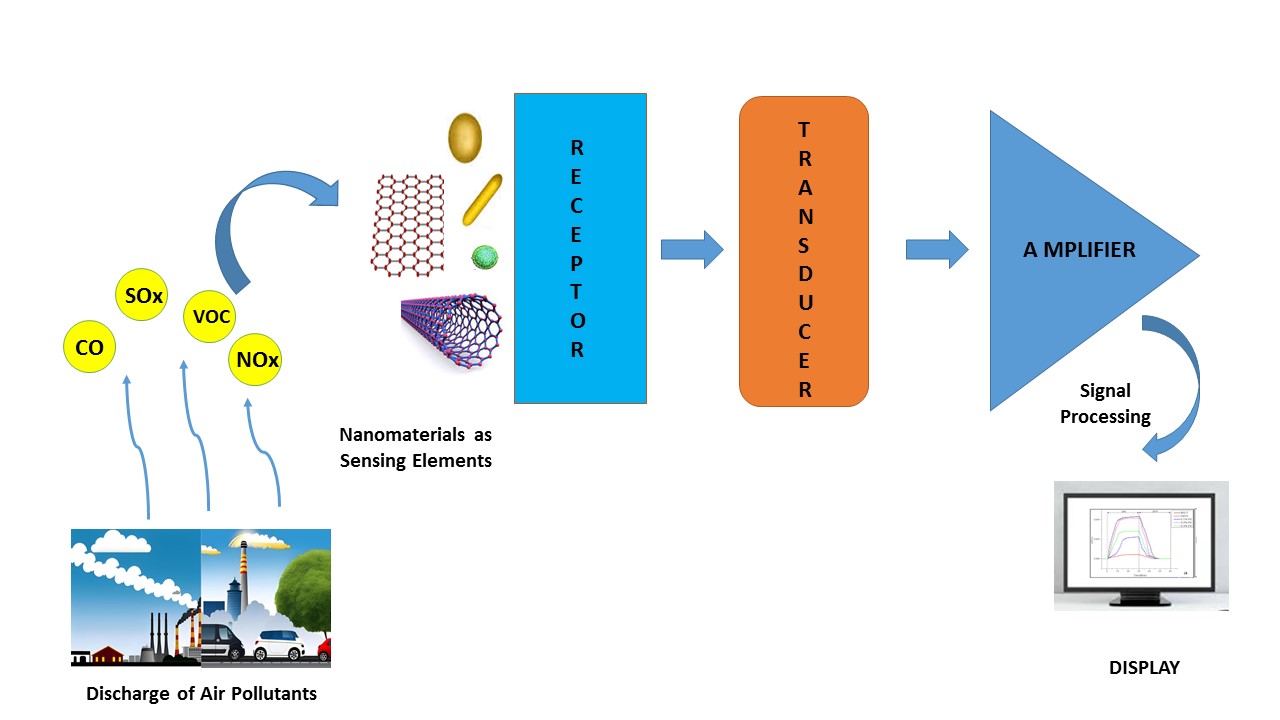
**Keywords-** nanotechnology; nanosensors; nanomaterials; Air pollution, hazardous

**I. INTRODUCTION**

Climate change, global warming, air and water pollution, deforestation, overpopulation, and waste disposal are some of the major environmental concerns that need to be addressed urgently. Air pollution has become a global threat to health and the environment. Air pollution is estimated to cause millions of deaths every year. 6.7 million deaths every year are attributed to outdoor and indoor air pollution. 99% of the world’s population lives in the areas where air pollution limit exceeds the world health organization (WHO) guideline limit (<https://www.who.int/data/gho/data/themes/air-pollution>). WHO estimated 4.2 million premature deaths worldwide per year in 2019 due to ambient pollution in cities and rural areas (<https://www.who.int/news-room/fact-sheets>). The contamination of the indoor and outdoor environment by chemical, physical, or biological entities that changes the characteristics of the atmosphere is referred to as air pollution. Urbanization, Industrial facilities, transport, extensive use of fertilizers, forest fire, household combustion devices, and improper waste management are some of the common sources of air pollution [1]. Air pollutants have adverse effects with significant damage to the environment and health. Smoke from cigarettes, volatile organic compounds (VOCs), dusts from ventilation or solid gases of combustion such as carbon monoxide (CO), nitrogen oxide (NO), and sulphur dioxide (SO2), and airborne microorganism pollution are all examples of indoor air pollutants. However, burning fossil fuels, industrial and vehicular emissions, and human activity all contribute to outdoor air pollution. Hazardous gases in the atmosphere include toxic volatile gases such as ammonia, amides, sulphur, and nitrogen compounds. The composition and amount of hazardous air pollutants must thus be accurately and in real-time monitored [2].

For the past several years, researchers' attention has been focused on accurate screening and monitoring of contamination sources including heavy metal ions, poisonous gas species, and volatile organic compounds (VOCs), due to their severe toxic and harmful impacts on the environment and human health [3,4] Traditional approaches to assessing contaminants, such chromatographic methods, require a lot of time, it demand for expensive equipment and reagents, and require sample preparation. Traditional methods that rely on a network of a few permanent stations loaded with sophisticated analytical tools have significant disadvantages. The equipment is large, bulky, difficult to use, energy-intensive, and expensive to operate and maintain. With the use of modern technology like nanotechnology, it may be possible to develop novel nanomaterials with unique characteristics that can be utilized to reduce pollution over the long term [5]. Greater catalytic performance, high electrical conductivity, better hardness and strength, large active surface area, increased electrochemical signals, long-term preservation of nanomaterial activity, and expansion of research tools are some of the common nanomaterial features.

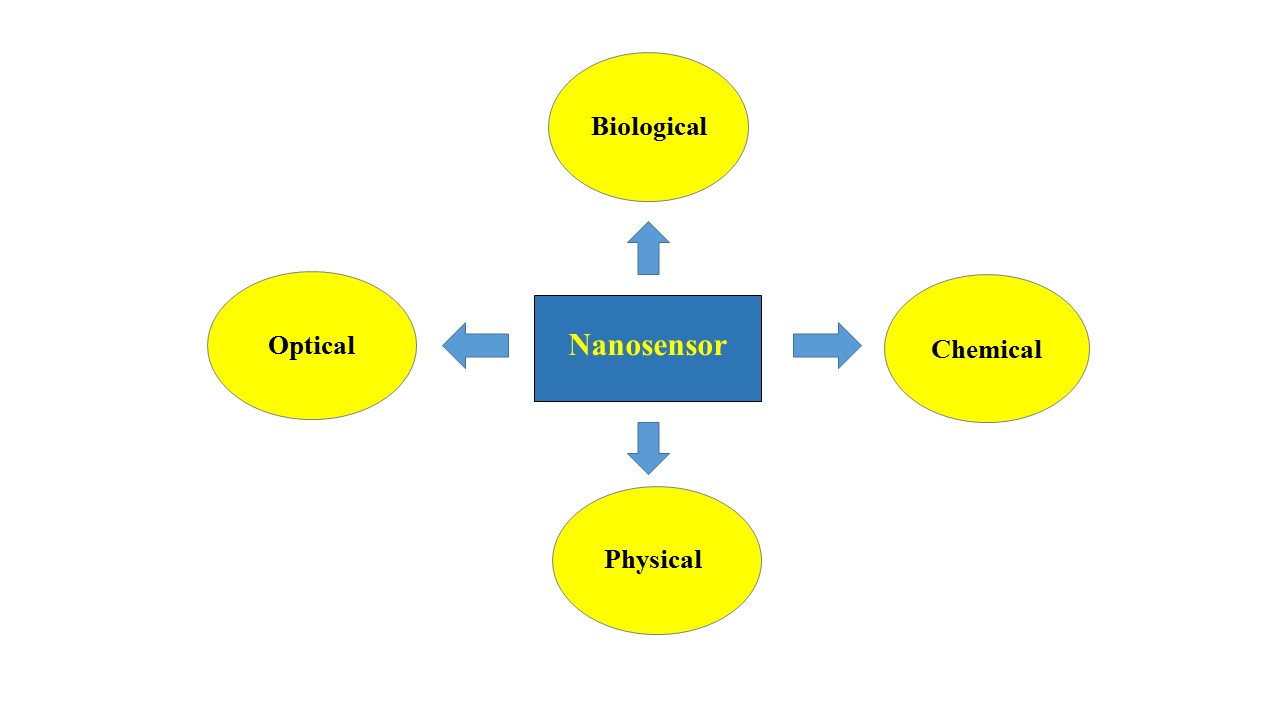
Nanosensors are nanoscale sensing devices that collect information at the nanoscale, monitor and transform physical quantities into signals that are detectable and analyzable. Nanosensors are very sensitive, portable, low-cost, and simple-to- use sensing devices for detecting chemical and biological contaminants. A nano sensor consists of three basic components namely a receptor probe, a transducer element, and an amplifier as shown in figure 1. A receptor interacts with the air pollutants and generates a response that is converted to an electrical signal by a transducer, later it is amplified by an amplifier and converted to a quantifiable output by the signal processing unit. For the objective of identifying chemical and biological pollutants, nanosensors are very sensitive, portable, inexpensive, and easy-to-use sensing devices. Nanomaterials are used as the sensing element in nanosensors [6-10]. Nanomaterials have high surface area-to-volume ratios and their sensitivity can be enhanced by surface functionalization. They are more efficient and more robust due to their greater surface area. In comparison to traditional electrochemical approaches, direct contact between the electrode nanoscale design and the analyte results in significant signal amplification and better signal/noise ratios. Quantum dots, hybrid nanomaterials, carbonaceous nanomaterials, and metal and metal oxide nanoparticles are employed as receptors [11]. Excellent conductivity, stability, affordability, and simplicity of surface functionalization are all characteristics of carbon-based nanomaterials [12]. Graphene and nano/mesoporous carbon, carbon nanotubes (CNTs) are used in a variety of electroanalytical applications. Their nanostructures effectively expose surface groups for the binding of analyte-transduction materials, leading to high environmental pollutant detection capability. Metal nanoparticles offer unique physical and chemical characteristics that have made them popular in many different applications. Numerous metals, including Au, Pt, Pd, Ag, Cu, and Co, have been used for sensing. By adopting specialized signal amplifications, metal nanoparticle-based sensors have great promise for enhancing sensitivity and selectivity. Interest in nanosensor research has been ignited by metal nanoparticles, bio-functionalized nanoparticles, and nanocomposites.

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**Figure 1: The schematic representation of components of the nanosensor.**

**II. TYPES OF NANOSENSOR**

Physical, chemical, optical, and biological nanosensors are the four main categories of nanosensors (figure 2). Some of the most common types of nanosensors include optical, mechanical, vibrational, and electromagnetic. Physical nanosensors are used to track and transform physical characteristics like temperature, force, pressure, and other factors into detectable signals. Chemical nanosensors are used for a variety of purposes, including the examination of environmental sample residue and the monitoring of environmental contaminant levels [13]. Electrochemical sensing of pollutants involves several methods such as Conductometry, Potentiometry, Voltammetry, Colometry, and Impedance spectroscopy [14]. Biological Nanosensors contain antibodies, enzymes, proteins, DNA, etc. as biological recognition systems for selective and real-time measurements [15]. Molecular nanosensors translate biological communication systems into coded signals. Electromagnetic nanosensors detect variations in electromagnetic waves while accounting for quantum events. To power mechanically acquired energy from nanosensor vibration and surrounding biochemical material, mechanical nanosensors may be used to feed the molecular nanosensors. Fluorescent nanosensors work by measuring the emission of a fluorophore as it transitions from an excited state to its ground state [16]. Fluorescence signals are changes via interaction between the pollutant and the nanoparticle or when a sensor's conformation changes. Optical nanosensors may immobilize nanomaterial known as surface Plasmon resonance (SPR) and employ electromagnetic irradiation to detect samples [17].



**Figure 2: Types of nanosensors.**

**III. LATEST ADVANCEMENT IN NANOSENSORS FOR AIR POLLUTION REMEDIATION**

Appropriate control systems with quick pollutant source detection and quantification capabilities are crucial to avoid or reduce the harm caused by air pollution. Sensing air pollutants such as carbon mono oxide, oxides of nitrogen and sulphur, ozone and other volatile compounds is crucial for reducing industrial and transportation emissions, and improving home security and environmental management. The nanostructured materials-based nanosensors recently developed for air pollution remediation are briefly discussed here.

Tin oxide nanowire sensors act as sensitive, fast, stable, and reproducible gas sensors that can be easily integrated into a multi-component array. Palladium-doped tin oxide nanosensor with palladium, at the concentration of 0.1%, 0.2%, and 0.3% by weight was prepared by chemical precipitation method. Among these 0.2% Pd-doped SnO2 showed maximum sensitivity to the exhaust CO gas pollutant [18]. Responses of the Au/SnO2 sensor to 40-1000 ppm CO were about 2-15 times higher than that of the pure SnO2 sensor. In another study the sensitivity of CuO-doped SnO2 NPs (about 20 nm) was found to be 4.3 to 1000 ppm NO in dry air at 200 ºC with response time was about 3 min. [19]. Au/Nd2O3–Ca3Nd2O6 composite-based carbon monoxide sensor demonstrated a linear relationship between the chemiluminescence intensity and the concentration of carbon monoxide in the range of 0.6–125 mg/m3. The detection limit (3σ) of CO was 0.2 mg/m3 [20]. Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate)/poly(*p*-anisidine) nanocomposite sensor was synthesized by the cost-effective “in situ chemical oxidation polymerization” technique and investigated for carbon monoxide (CO) detection property. The nanosensor showed a linear response to different concentrations (50–300 ppm) of CO gas (*R*2 = 0.9885). The response time and recovery time of the CO gas sensor (100 ppm) were found to be about 58 and 61 s, respectively [21].

Quantum dots (QD) have a wide range of shapes, sizes, and chemical compositions, they can be activated by a single energy source. The QDs frequently used in sensors include ZnS, Graphene quantum, CdSe, CdSe/ZnS, CdTe, CdTe/CdS, etc. In a nanosensor graphene sheet and a QD with a recognition element are joined, and when a pollutant is present, the sensor undergoes a change that separates the graphene from the QD and turns the sensor on [22-24]. NO2 gas sensors consisting of reduced graphene–oxide–carbon dots (rGO-CDs) hybrid materials were synthesized via the green one-pot method. It was found that the introduction of carbon dots (CDs) significantly improved the gas-sensing performance of rGO. The Composite structures could detect extremely low NO2 concentrations at room temperature [25]. In a study, ZnO and carbon dots composites-based nanosensors demonstrated high NO gas sensitivity response compared to traditional methods [26]. Gold nanoclusters have unique physicochemical properties such as light stability, excellent biocompatibility, light-induced fluorescence, and outstanding sensing performance. Therefore, they are excellent materials for gas sensors. Nanocluster of Gallium Nitride (GaN) submicron wires with titanium dioxide (TiO2) displayed high selectivity to NO2 detection. Several metal oxide nanoclusters had reported good long-term performance stability at room temperature and humidity, and they are also stable and reliable in various climatic conditions [27, 28]. Oxides of nitrogen, particularly NO2 are a toxic gas that can cause negative effects on the human respiratory system and the growth of plants. A study reported that Ag decoration of the phosphorene surface can improve the adsorption performance of NO2 molecules, enhance the sensitivity and selectivity of NO2 molecules and make the silver-trimmed phosphorene composite system, an ideal material for NO2 gas sensors [29]. A group of researchers investigated gold and polyaniline nanocomposite-based sensors for their CO gas sensing ability and found that these nanosensors had a high response and low noise, a very short response time, a wide dynamic range, and good stability [30].

# Carbon nanotubes based nanocomposites are good gas sensing materials due to their excellent electrical conductivity, high surface area and unique hollow structure. Another advantage of CNTs as sensors is the possibility to achieve high sensing sensitivity at ambient temperature. CNT sensors are adapted to detect several gases like ammonia (NH3), nitrogen dioxide (NO2), hydrogen (H2), methane (CH4), carbon monoxide (CO), hydrogen sulphide (H2S), and sulphur dioxide (SO2) [13]. A study reported that polyethylenimine functionalized single-walled carbon nanotubes (SWCNTs) had 50% higher gas sensitivity towards greenhouse gases compared to single-wall carbon nanotubes [31]. Fluorinated carbon nanotubes have a good sensing response to nitrogen dioxide and ammonia. Polyaniline-modified multi-walled carbon nanotubes show good sensing characteristics of transparent gas and are excellent sensors of CO and NH3 gas at room temperature [32].

# Graphene-based Nanosensors possess unique physical, chemical, and mechanical properties for gas sensing and ultra-low detection limits for air pollutants. Graphene has excellent mechanical, and thermal characteristics. Additionally, they have been widely employed for the detection of gaseous and heavy metal contaminants [33]. Graphene-based NH3 gas sensors have reported excellent sensing response and gas sensing capability. Functionalized graphene oxide had strong selectivity to ammonia gas, which shows good sensing characteristics of ammonia gas. Graphene oxide nanosheets revealed a good sensitive factor and exhibit a good response to toxic gases, including NO2, SO2, CO, and NH3 [34]. Two-dimensional mesoporous ZnSnO3 nanomaterials exhibited good gas sensitivity and sensing ability to formaldehyde gas [35]. Zhou and co-workers fabricated NiO-ZnO Nano disks as Sulfur dioxide (SO2) gas sensors through the hydrothermal method. They observed that sensor gas response, response time, and recovery time of the fabricated NiO-ZnO Nano disks based gas sensor were 16.25, 52 s, and 41 s, respectively, towards 20 ppm SO2 gas at an optimized temperature of 240 °C [36]. Recently, a composite of tin diselenide (SnSe2) functionalized by graphite-phase carbon nitride (g-C3N4) demonstrated an excellent response, strong reversibility, and good selectivity for ppm-level SO2 gas detection [37]. A sensitive SO2 gas sensor based on nanocellulose-prepared tin dioxide has been reported to have high sensitivity and selectivity with a response toward SO2 at 1 ppm was 4.68 s [38].

# Volatile organic compounds (VOCs) are a diverse group of chemical compounds that are rapidly absorbed into the lungs, tracts, and surfaces like the epidermis, where they may have both short and long-term negative health effects due to their varying lipophilicity and volatility, as well as their smaller molecular size and lack of charge. Metallic nanoparticles and metal oxide nanoparticles-based VOC nanosensors offer various advantages over classical sensors such as detection down to very low concentrations (ppm–ppb), higher reproducibility with faster reflexes, and mechanical stability [39]. Sn3N4 NPs, Ni-doped SnO2 NPs, C-doped TiO2 NPs, Pr-doped In2O3 NPs, and Au/Cl co-modified LaFeO3 NPs were engaged in the detection of alcoholic vapors [40]. Semiconducting nanoparticles (NPs) TiO2 NPs, α-Fe2O3 NPs, and Pt-decorated Al-doped ZnO were consumed in selective device-based quantification of acetone with part per billion/parts per million (ppb/ppm) detection limits (LODs) [41]. Co3O4/ZnO hybrid NPs, Ho-doped SnO2 NPs, and CuCrO2 NPs-based sensors have successfully been deployed to detect volatile triethylamine (TEA) and n-butylamine with good response time [42]. V2O5-decorated α-Fe2O3 nanorods (NRds), Au NPs decorated WO3 NRds, Ag NPs decorated α-MoO3 NRds, Cr doped α-MoO3 NRds, acidic α-MoO3 NRds, and NiCo2O4 microspheres were also engaged in the quantitation of volatile organic amines [43]. Au-loaded ZnO NPs and cobalt porphyrin (CoPP)-functionalized TiO2 NPs were described for the quantitation of xylene and BTX (Benzene, Toluene, and Xylene) vapors at 377 °C and 240 °C, respectively. Cobalt porphyrin (CoPP)-functionalized TiO2 NPs showed a high response (Ra/Rg ≥ 5 for 10 ppm at 240 °C; response/recovery time = 40 s/80 s) with a LOD of 0.005 ppm [44]. DNA-based nanosensors have also been reported that use ssDNA, dsDNA, complementary mismatched DNA, aptamers, and G-quadruplex DNA as a recognition element for the detection of environmental pollutants [45].

**IV. CONCLUSION**

Air pollution is a rising issue in the world. Air pollution affects different aspects of health and the environment. Hence, it has become vital to monitor and control the increasing pollutants coming out of the various sources into the environment. Today we need mechanisms, technologies, mitigation strategies, and policies to achieve sustainable development goals regarding air pollution and global threats to health and the environment. Nanotechnology is an emerging technology that provides opportunities to monitor, measure, manage, and reduce air pollutants in the atmosphere. Nanosensors are bioanalytical tools that operate at the nanoscale and are used for the detection and monitoring of environmental pollutants. The development and application of physical, chemical, and biological instruments, systems, and processes build up the market for nanosensors. This chapter intends to provide information on the connection between air pollution control and nanotechnology, as well as establish a relationship between air pollution concerns and the recent development in the field of nanosensors.

**REFERENCES**

1. E. F. Mohamed and G. Awad, “Photodegradation of gaseous toluene and disinfection of airborne microorganisms from polluted air using immobilized TiO2 nanoparticle photocatalyst–based filter,” Environmental Science and Pollution Research, vol. 27, no. 19, pp. 24507–24517, Apr. 2020, doi: 10.1007/s11356-020-08779-0. [Online]. Available: <http://dx.doi.org/10.1007/s11356-020-08779-0>
2. S. Kaivonen and E. C.-H. Ngai, “Real-time air pollution monitoring with sensors on city bus,” Digital Communications and Networks, vol. 6, no. 1, pp. 23–30, Feb. 2020, doi: 10.1016/j.dcan.2019.03.003. [Online]. Available: http://dx.doi.org/10.1016/j.dcan.2019.03.003
3. H. Y. Mohammed et al., “Review—Electrochemical Hydrazine Sensors Based on Graphene Supported Metal/Metal Oxide Nanomaterials,” Journal of The Electrochemical Society, vol. 168, no. 10, p. 106509, Oct. 2021, doi: 10.1149/1945-7111/ac2ddc. [Online]. Available: http://dx.doi.org/10.1149/1945-7111/ac2ddc
4. M. Lu et al., “Graphene Aerogel–Metal–Organic Framework-Based Electrochemical Method for Simultaneous Detection of Multiple Heavy-Metal Ions,” Analytical Chemistry, vol. 91, no. 1, pp. 888–895, Oct. 2018, doi: 10.1021/acs.analchem.8b03764. [Online]. Available: http://dx.doi.org/10.1021/acs.analchem.8b03764
5. E. F. Mohamed, “Nanotechnology: Future of Environmental Air Pollution Control,” Environmental Management and Sustainable Development, vol. 6, no. 2, p. 429, Oct. 2017, doi: 10.5296/emsd. v6i2.12047. [Online]. Available: http://dx.doi.org/10.5296/emsd.v6i2.12047
6. A. Roy et al., “Polyaniline-multiwalled carbon nanotube (PANI-MWCNT): Room temperature resistive carbon monoxide (CO) sensor,” Synthetic Metals, vol. 245, pp. 182–189, Nov. 2018, doi: 10.1016/j.synthmet.2018.08.024. [Online]. Available: http://dx.doi.org/10.1016/j.synthmet.2018.08.024
7. R. Abdel-Karim, Y. Reda, and A. Abdel-Fattah, “Review—Nanostructured Materials-Based Nanosensors,” Journal of The Electrochemical Society, vol. 167, no. 3, p. 037554, Jan. 2020, doi: 10.1149/1945-7111/ab67aa. [Online]. Available: http://dx.doi.org/10.1149/1945-7111/ab67aa
8. M. Chern, J. C. Kays, S. Bhuckory, and A. M. Dennis, “Sensing with photoluminescent semiconductor quantum dots,” Methods and Applications in Fluorescence, vol. 7, no. 1, p. 012005, Jan. 2019, doi: 10.1088/2050-6120/aaf6f8. [Online]. Available: http://dx.doi.org/10.1088/2050-6120/aaf6f8
9. N. Nasiri and C. Clarke, “Nanostructured Gas Sensors for Medical and Health Applications: Low to High Dimensional Materials,” Biosensors, vol. 9, no. 1, p. 43, Mar. 2019, doi: 10.3390/bios9010043. [Online]. Available: http://dx.doi.org/10.3390/bios9010043
10. I. Sayago, M. Aleixandre, and J. P. Santos, “Development of Tin Oxide-Based Nanosensors for Electronic Nose Environmental Applications,” Biosensors, vol. 9, no. 1, p. 21, Feb. 2019, doi: 10.3390/bios9010021. [Online]. Available: http://dx.doi.org/10.3390/bios9010021
11. X. Liu, T. Ma, N. Pinna, and J. Zhang, “Two-Dimensional Nanostructured Materials for Gas Sensing,” Advanced Functional Materials, vol. 27, no. 37, p. 1702168, Aug. 2017, doi: 10.1002/adfm.201702168. [Online]. Available: http://dx.doi.org/10.1002/adfm.201702168
12. V. Schroeder, S. Savagatrup, M. He, S. Lin, and T. M. Swager, “Carbon Nanotube Chemical Sensors,” Chemical Reviews, vol. 119, no. 1, pp. 599–663, Sep. 2018, doi: 10.1021/acs.chemrev.8b00340. [Online]. Available: http://dx.doi.org/10.1021/acs.chemrev.8b00340
13. M. Meyyappan, “Carbon Nanotube-Based Chemical Sensors,” Small, vol. 12, no. 16, pp. 2118–2129, Mar. 2016, doi: 10.1002/smll.201502555. [Online]. Available: <http://dx.doi.org/10.1002/smll.201502555>
14. M. Lu et al., “Graphene Aerogel–Metal–Organic Framework-Based Electrochemical Method for Simultaneous Detection of Multiple Heavy-Metal Ions,” Analytical Chemistry, vol. 91, no. 1, pp. 888–895, Oct. 2018, doi: 10.1021/acs.analchem.8b03764. [Online]. Available: <http://dx.doi.org/10.1021/acs.analchem.8b03764>
15. K. Saha, S. S. Agasti, C. Kim, X. Li, and V. M. Rotello, “Gold Nanoparticles in Chemical and Biological Sensing,” Chemical Reviews, vol. 112, no. 5, pp. 2739–2779, Feb. 2012, doi: 10.1021/cr2001178. [Online]. Available: <http://dx.doi.org/10.1021/cr2001178>
16. S. W. Bae, W. Tan, and J.-I. Hong, “Fluorescent dye-doped silica nanoparticles: new tools for bioapplications,” Chemical Communications, vol. 48, no. 17, p. 2270, 2012, doi: 10.1039/c2cc16306c. [Online]. Available: <http://dx.doi.org/10.1039/c2cc16306c>
17. P. Damborský, J. Švitel, and J. Katrlík, “Optical biosensors,” Essays in Biochemistry, vol. 60, no. 1, pp. 91–100, Jun. 2016, doi: 10.1042/ebc20150010. [Online]. Available: <http://dx.doi.org/10.1042/ebc20150010>
18. J. Sam Jebakumar and A. V. Juliet, “Palladium-Doped Tin Oxide Nanosensor for the Detection of the Air Pollutant Carbon Monoxide Gas,” Sensors, vol. 20, no. 20, p. 5889, Oct. 2020, doi: 10.3390/s20205889. [Online]. Available: <http://dx.doi.org/10.3390/s20205889>
19. G. Zhang and M. Liu, “Effect of particle size and dopant on properties of SnO2-based gas sensors,” Sensors and Actuators B: Chemical, vol. 69, no. 1–2, pp. 144–152, Sep. 2000, doi: 10.1016/s0925-4005(00)00528-1. [Online]. Available: http://dx.doi.org/10.1016/s0925-4005(00)00528-1
20. W. Zhang, F. Yang, J. Xu, C. Gu, and K. Zhou, “Sensitive Carbon Monoxide Gas Sensor Based on Chemiluminescence on Nano-Au/Nd2O3–Ca3Nd2O6: Working Condition Optimization by Response Surface Methodology,” ACS Omega, vol. 5, no. 32, pp. 20034–20041, Aug. 2020, doi: 10.1021/acsomega.0c01481. [Online]. Available: <http://dx.doi.org/10.1021/acsomega.0c01481>
21. M. O. Farea, H. A. Alhadlaq, Z. M. Alaizeri, A. A. A. Ahmed, M. O. Sallam, and M. Ahamed, “High Performance of Carbon Monoxide Gas Sensor Based on a Novel PEDOT: PSS/PPA Nanocomposite,” ACS Omega, vol. 7, no. 26, pp. 22492–22499, Jun. 2022, doi: 10.1021/acsomega.2c01664. [Online]. Available: http://dx.doi.org/10.1021/acsomega.2c01664
22. Y. Liu, L. Wang, H. Wang, M. Xiong, T. Yang, and G. S. Zakharova, “Highly sensitive and selective ammonia gas sensors based on PbS quantum dots/TiO2 nanotube arrays at room temperature,” Sensors and Actuators B: Chemical, vol. 236, pp. 529–536, Nov. 2016, doi: 10.1016/j.snb.2016.06.037. [Online]. Available: http://dx.doi.org/10.1016/j.snb.2016.06.037
23. A. Lesiak, K. Drzozga, J. Cabaj, M. Bański, K. Malecha, and A. Podhorodecki, “Optical Sensors Based on II-VI Quantum Dots,” Nanomaterials, vol. 9, no. 2, p. 192, Feb. 2019, doi: 10.3390/nano9020192. [Online]. Available: http://dx.doi.org/10.3390/nano9020192
24. D. Raeyani, S. Shojaei, S. A. Kandjani, and W. Wlodarski, “Synthesizing Graphene Quantum Dots for Gas Sensing Applications,” Procedia Engineering, vol. 168, pp. 1312–1316, 2016, doi: 10.1016/j.proeng.2016.11.356. [Online]. Available: http://dx.doi.org/10.1016/j.proeng.2016.11.356
25. J. Hu et al., “Enhanced NO2 sensing performance of reduced graphene oxide by in situ anchoring carbon dots,” Journal of Materials Chemistry C, vol. 5, no. 27, pp. 6862–6871, 2017, doi: 10.1039/c7tc01208j. [Online]. Available: http://dx.doi.org/10.1039/c7tc01208j
26. Z. Yu, L. Zhang, X. Wang, D. He, H. Suo, and C. Zhao, “Fabrication of ZnO/Carbon Quantum Dots Composite Sensor for Detecting NO Gas,” Sensors, vol. 20, no. 17, p. 4961, Sep. 2020, doi: 10.3390/s20174961. [Online]. Available: http://dx.doi.org/10.3390/s20174961
27. S. Z. Butler et al., “Progress, Challenges, and Opportunities in Two-Dimensional Materials Beyond Graphene,” ACS Nano, vol. 7, no. 4, pp. 2898–2926, Mar. 2013, doi: 10.1021/nn400280c. [Online]. Available: http://dx.doi.org/10.1021/nn400280c
28. C. Wang et al., “Design of Superior Ethanol Gas Sensor Based on Al-Doped NiO Nanorod-Flowers,” ACS Sensors, vol. 1, no. 2, pp. 131–136, Dec. 2015, doi: 10.1021/acssensors.5b00123. [Online]. Available: http://dx.doi.org/10.1021/acssensors.5b00123
29. K. Xu, X. Huang, and Y. Pan, “Recent development of high‐speed atomic force microscopy in molecular biology,” Micro & Nano Letters, vol. 15, no. 6, pp. 354–358, May 2020, doi: 10.1049/mnl.2019.0313. [Online]. Available: http://dx.doi.org/10.1049/mnl.2019.0313
30. N. Gogurla, A. K. Sinha, S. Santra, S. Manna, and S. K. Ray, “Multifunctional Au-ZnO Plasmonic Nanostructures for Enhanced UV Photodetector and Room Temperature NO Sensing Devices,” Scientific Reports, vol. 4, no. 1, Sep. 2014, doi: 10.1038/srep06483. [Online]. Available: http://dx.doi.org/10.1038/srep06483
31. S. Kumar, V. Pavelyev, P. Mishra, and N. Tripathi, “Thin film chemiresistive gas sensor on single-walled carbon nanotubes-functionalized with polyethylenimine (PEI) for NO2 gas sensing,” Bulletin of Materials Science, vol. 43, no. 1, Feb. 2020, doi: 10.1007/s12034-020-2043-6. [Online]. Available: http://dx.doi.org/10.1007/s12034-020-2043-6
32. F. C. Loghin, A. Falco, J. F. Salmeron, P. Lugli, A. Abdellah, and A. Rivadeneyra, “Fully Transparent Gas Sensor Based on Carbon Nanotubes,” Sensors, vol. 19, no. 20, p. 4591, Oct. 2019, doi: 10.3390/s19204591. [Online]. Available: <http://dx.doi.org/10.3390/s19204591>
33. R. Kumar et al., “Room temperature ammonia gas sensor using ester functionalization of graphene oxide,” Materials Research Express, vol. 6, no. 9, p. 095618, Jul. 2019, doi: 10.1088/2053-1591/ab323c. [Online]. Available: <http://dx.doi.org/10.1088/2053-1591/ab323c>
34. D. Cortés-Arriagada, N. Villegas-Escobar, and D. E. Ortega, “Fe-doped graphene nanosheet as an adsorption platform of harmful gas molecules (CO, CO2, SO2 and H2S), and the co-adsorption in O2 environments,” Applied Surface Science, vol. 427, pp. 227–236, Jan. 2018, doi: 10.1016/j.apsusc.2017.08.216. [Online]. Available: <http://dx.doi.org/10.1016/j.apsusc.2017.08.216>
35. B. Wang, J. Yu, X. Li, J. Yin, and M. Chen, “Synthesis and high formaldehyde sensing properties of quasi two-dimensional mesoporous ZnSnO3 nanomaterials,” RSC Advances, vol. 9, no. 26, pp. 14809–14816, 2019, doi: 10.1039/c9ra01593k. [Online]. Available: <http://dx.doi.org/10.1039/c9ra01593k>
36. Q. Zhou, W. Zeng, W. Chen, L. Xu, R. Kumar, and A. Umar, “High sensitive and low-concentration sulfur dioxide (SO2) gas sensor application of heterostructure NiO-ZnO nanodisks,” Sensors and Actuators B: Chemical, vol. 298, p. 126870, Nov. 2019, doi: 10.1016/j.snb.2019.126870. [Online]. Available: <http://dx.doi.org/10.1016/j.snb.2019.126870>
37. H. Zhang, Q. Pan, Y. Zhang, Y. Zhang, and D. Zhang, “High-Performance Sulfur Dioxide Gas Sensor Based on Graphite-Phase Carbon-Nitride-Functionalized Tin Diselenide Nanorods Composite,” Chemosensors, vol. 10, no. 10, p. 401, Oct. 2022, doi: 10.3390/chemosensors10100401. [Online]. Available: <http://dx.doi.org/10.3390/chemosensors10100401>
38. X. He et al., “A sensitive SO2 gas sensor based on nanocellulose prepared tin dioxide under UV excitation,” Journal of Materials Science, vol. 58, no. 7, pp. 3249–3259, Feb. 2023, doi: 10.1007/s10853-023-08225-9. [Online]. Available: <http://dx.doi.org/10.1007/s10853-023-08225-9>
39. C. Zhao et al., “Highly sensitive acetone-sensing properties of Pt-decorated CuFe2O4 nanotubes prepared by electrospinning,” Ceramics International, vol. 44, no. 3, pp. 2856–2863, Feb. 2018, doi: 10.1016/j.ceramint.2017.11.032. [Online]. Available: <http://dx.doi.org/10.1016/j.ceramint.2017.11.032>
40. F. Qu, Y. Yuan, and M. Yang, “Programmed Synthesis of Sn3N4 Nanoparticles via a Soft Chemistry Approach with Urea: Application for Ethanol Vapor Sensing,” Chemistry of Materials, vol. 29, no. 3, pp. 969–974, Jan. 2017, doi: 10.1021/acs.chemmater.6b03435. [Online]. Available: <http://dx.doi.org/10.1021/acs.chemmater.6b03435>
41. S. Liang, J. Li, F. Wang, J. Qin, X. Lai, and X. Jiang, “Highly sensitive acetone gas sensor based on ultrafine α-Fe2O3 nanoparticles,” Sensors and Actuators B: Chemical, vol. 238, pp. 923–927, Jan. 2017, doi: 10.1016/j.snb.2016.06.144. [Online]. Available: <http://dx.doi.org/10.1016/j.snb.2016.06.144>
42. Y. Yang et al., “Hydrothermal Synthesis of Co3O4/ZnO Hybrid Nanoparticles for Triethylamine Detection,” Nanomaterials, vol. 9, no. 11, p. 1599, Nov. 2019, doi: 10.3390/nano9111599. [Online]. Available: <http://dx.doi.org/10.3390/nano9111599>
43. C. Yang et al., “Hierarchical NiCo2O4 microspheres assembled by nanorods with p-type response for detection of triethylamine,” Chinese Chemical Letters, vol. 31, no. 8, pp. 2077–2082, Aug. 2020, doi: 10.1016/j.cclet.2020.01.011. [Online]. Available: <http://dx.doi.org/10.1016/j.cclet.2020.01.011>
44. Y. Kang, K. Kim, B. Cho, Y. Kwak, and J. Kim, “Highly Sensitive Detection of Benzene, Toluene, and Xylene Based on CoPP-Functionalized TiO2 Nanoparticles with Low Power Consumption,” ACS Sensors, vol. 5, no. 3, pp. 754–763, Feb. 2020, doi: 10.1021/acssensors.9b02310. [Online]. Available: <http://dx.doi.org/10.1021/acssensors.9b02310>
45. V. Kumar and P. Guleria, “Application of DNA-Nanosensor for Environmental Monitoring: Recent Advances and Perspectives,” Current Pollution Reports, Dec. 2020, doi: 10.1007/s40726-020-00165-1. [Online]. Available: http://dx.doi.org/10.1007/s40726-020-00165-1