**Recent advanced metal oxide nanomaterials to developed hydrogen gas sensors and their nanostructures, morphology effect on sensitivity**

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***Contents:***

Introduction ....................................................................................... 1

***1. Recants advanced nanomaterials to develope Hydrogen gas sensors***.......................................................…………………………..2

***1. (a) Single Metal oxide nanomaterial as H2 gas sensor................................................................................................... 3***

***1. (b) With catalytic materials..............................................................5***

***1. (c) Metal oxide nanocomposite-based H2 gas sensor .....................7***

***1. (d)With Organic nanomaterials.........................................................9***

***2. Advantages and disadvantages of above sensors…………….........12***

1. ***Materials and their structures and morphology effects on H2 gas sensitivity..........................................................................................13***
2. ***Challenges ……………………………….......................................15***
3. ***Future guideline.………………………………………………….16***
4. ***Conclusions.... ................................................................................17***
5. ***References ......................................................................................17***

***Abstract***

Reliable and low-cost hydrogen gas sensors have been developed at a large scale recently. Many metal and metal oxide semiconducting nanomaterials (MOSNs) SnO2, ZnO, TiO2, WO3, MnO2, n-type materials, and CuO, NiO, Cr2O3, Mn3O4, etc., p-type materials, and their composites, metal-doped, are used to develop highly sensitive sensors that show highly stable and selective nature even at low H2 gas concentration. Different treatment and synthesis processes are used to make different structures and morphology to design H2 gas sensors. Sensors with p-n junction structure, heterostructure, and isotype heterojunction structure display high device performance. Additionally, sensor morphology such as thin films, hollow spheres, nanopatterns, nanowires, nanobelt, and nanoparticles also show high performance in detecting low H2 gas concentration (sub-ppb level). Some researchers add noble elements (Pd, Pt, Au, and Ag) to improve the quality of the surface and fast detection time of sensors. These noble metal elements act as catalysts in the reaction between H2 gas and the sensor surface. Some researchers also add organic materials to improve sensors' response. This chapter briefly reviews recent studies based on MOSNs H2 gas sensors with different structures and morphology. The chapter highlights the sensing performance of MOSNs-based H2 gas sensors. The chapter also includes the challenges and future prospectus of MOSN's H2 gas sensors.

***Keywords:*** Advanced nanomaterials, Morphology, H2 gas sensors, Gas sensing response.

***Introduction***

Advanced and environmentally friendly nanotechnologies' use prohibits nanomaterials' production, categorization, and utilization in energy generation, application, storage, and renovation [1]. Nanomaterials-based technology involves various processes and advancements such as hydrogen production, detection, batteries, supercapacitors, photovoltaic cells, fuel cells, and energy renovation and storage [1]. Hydrogen is a promising future energy source due to its wide-ranging potential and absence of fossil fuel emissions. The transportation industry currently contributes to global CO2 emissions, and the demand for clean energy and initiatives to combat greenhouse gas emissions are expected to rise by 20 % until 2030 [2].

Hydrogen offers numerous advantages as a clean energy carrier and can significantly benefit the energy sector by promoting sustainable policies. It can potentially be an excellent option for sustainable and clean fuel in the future [3]. However, it is essential to note that hydrogen has a high burning heat (142 kJ/g H2), an ignition energy of 0.017 mJ, and a flammability range of 4-75% [4].

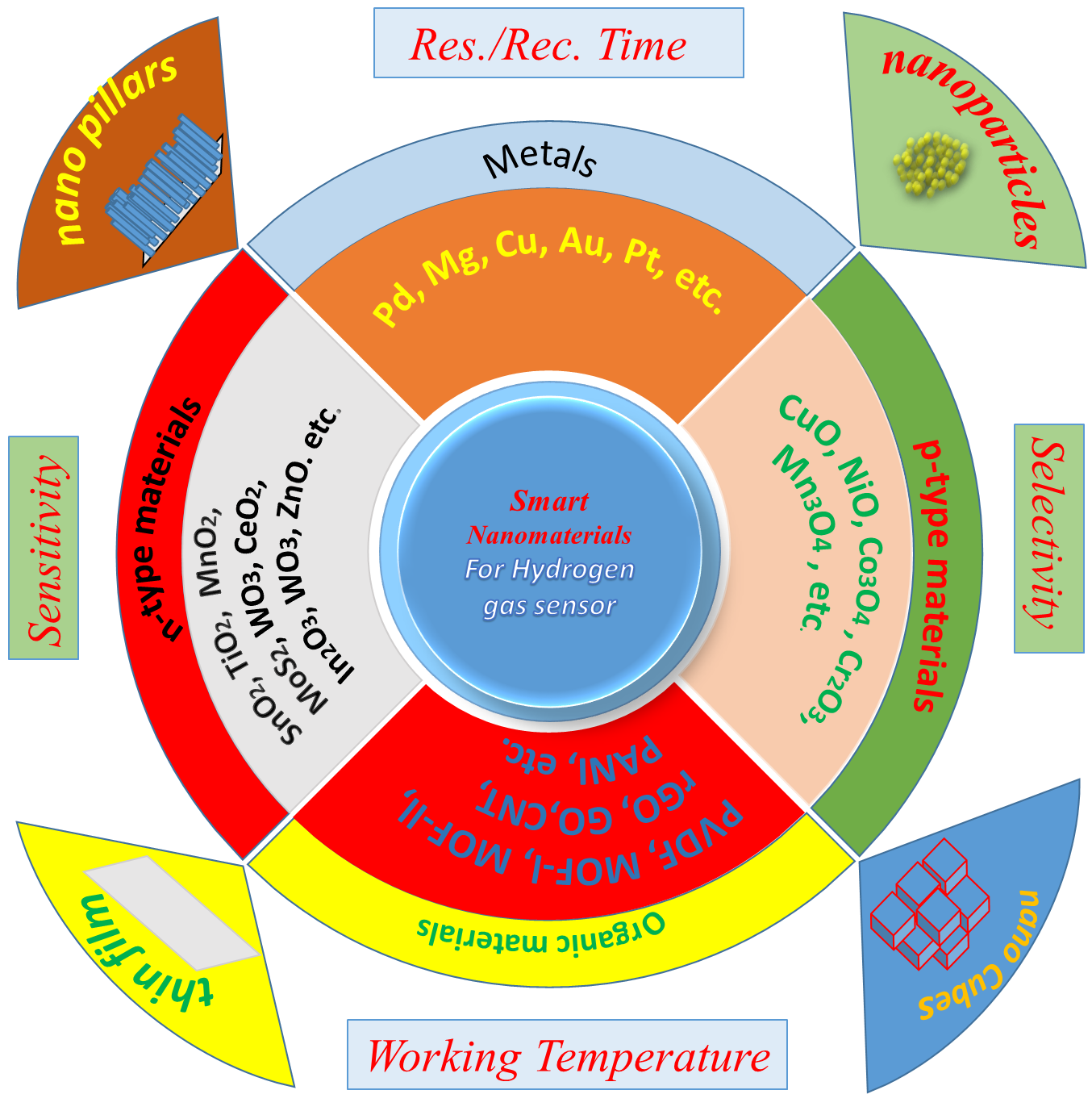
There is an urgent need to quickly and reversibly detect hydrogen gas using a gas sensor. The sensor's working performance significantly depends on the material properties and its sensitive area [3]. Both n-type and p-type semiconductors and metals are commonly used to develop H2 gas sensors, and their effectiveness is influenced by the design of their nanostructures and morphology [5].

In recent years, Yoshitake Masuda [5] presented data on using nanomaterials to develop gas sensors. He showed that n-type materials were more commonly used than p-type materials due to their simpler operation, low cost, and thermal stability [5]. However, this chapter will discuss the general idea of the various types of advanced sensor nanomaterials and their effects on performance based on morphology and structure.

***1. Recants advanced nanomaterials to develop Hydrogen gas sensors***

Hydrogen is both odorless and colorless, and with a small atomic radius, it cannot be directly sensed [6]. Therefore, high-sensitivity detection of H2 gas sensors [7-8] is necessary. A hydrogen sensor's performance criteria include detecting concentrations in the range of 1-100% for fuel cells and 0.01-10% for safety. It should also exhibit selectivity to other reducing gases, high accuracy, low operating temperature, fast response and recovery times, high sensibility, repeatability, long-term stability, low cost, and environmental factors tolerance (pollution and humidity) [8, 10].

There are various types of H2 detection sensors available, including resistive [11-13], conductometric [14-16], catalytic [17-19], optical [20-22], and surface acoustic wave sensors [23-25]. Although these sensors operate on different principles, they all use a sensitive nanomaterial to detect the presence of the gas being analyzed. As a result, developing sensitive materials is crucial for the sensor’s performance and is a key area of research interest. This chapter will delve into certain aspects of the sensitive nanomaterials used in these sensors, as shown in Figure 1. These materials possess different types of morphology, controlled doping concentrations, or complex compositions and can be obtained in various phases.



**Fig.1** Show different type of advanced nanomaterials for production of reliable Hydrogen gas detection sensors.

1. ***(a) Single Metal oxide nanomaterial as H2 gas sensor***

Great progress has been made by researchers in the development of gas sensors that are reliable, stable, and adaptable for real-world applications. Notably, Omer Coban and his team have successfully created p-type NiO, which can detect low levels of H2 gas at low operating temperatures [27]. M. Moschogiannaki and colleagues have also developed a bimetallic cobalt-vanadium-oxide (CoV2O6) gas sensor that operates at room temperature and has impressive sensitivity (65.2%) and quick response and recovery times (94 s/74 s), introduced to 1000 ppm H2 gas [28]. It was determined that the morphology of the sensing material performed a vital role in achieving these positive outcomes.

Previous research has shown that the Cr2O3 sensor structure grown in its natural state effectively detects H2 gas at 200 °C and 300 °C [29]. In a separate study, L. D’Arsi´e et al. created a chemo-resistive gas sensor utilizing vertical SnOx nanopillars on an ITO substrate, which was capable of detecting H2 gas at room temperature with an amount less than five ppm and at 230 °C with a concentration of 10 ppt [30]. In yet another study, α-MoO3 nanoribbons were grown using the hydrothermal method with (001) orientation plane and were found to have superior selectivity at a low concentration of 500 ppb H2. A higher hydrothermal temperature resulted in a wider specific surface area and a larger amount of Mo5+ species, which was conducive to the absorption of oxide species on the nanoribbon sensor [31].

Matteo Tonezzer et. al. grew a zinc oxide two-dimensional series of hexagonal, very thin peculiar shape sheets nanostructures, whose dimensions are a few microns wide, with a thickness in the order of 25 nm. The metallic zinc is fabricated as conductometric H2 gas sensors on a silica substrate. The sensing mechanism based on depletion layer thickness is clarified, explaining the one- and two-dimensional nanostructures widely affect their sensing behavior. The comparison with one-dimensional ZnO nanowires-based structures shows that two-dimensional nanostructures are ideal for gas sensing due to their tiny thickness, which is comparable to the depletion-layer thickness, and their large cross-section, which increases the base current, thus lowering the limit of detection. The response to H2 is good even to sub-ppm concentrations, with response times shorter than 18 s in the whole range of H2 concentrations investigated (500 ppb-10 ppm) at 175 °C [32].

**Table 1.** Semiconductor nanomaterial used to develop H2 gas sensor

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sensitive Materials | Temperature  (°C) | Hydrogen Concentration | Response | Reference |
| NiO Thin film | 300 | 2% | 16% | [27] |
| CoV2O5 films | RT | 1000 ppm | 65.2 | [28] |
| α-MoO3  nanoribbons | RT | 1000 ppm | 90% | [31] |
| ZnO Nanosheets | 175 | 10 ppm | 1.089 | [32] |

Sensor response calculated by S = , S (%) =

Here and resistance in air and target gas of gas sensor.

1. ***(b)With catalytic nanomaterials***

The detection of H2 gas is essential, and materials that facilitate the fast adsorption and desorption process, known as the spillover effect, play a crucial role in this process [33]. In a study by Vipin Kumar et al., Pd/SnO2 sensors were developed and found to have increased sensitivity at an operating temperature of 250 °C with wideness, up to 246.1 nm. The Pd catalytic thin layer is an important component of the sensor materials and exhibited excellent selectivity to H2 gas, even in humid environments. The sensor displayed great sensitivity with a response and recovery time of 58 seconds and 35 seconds, respectively, for 5 ppm of hydrogen gas. Moreover, the sensor was found to be stable even after long time 60 days in humidity [33].

Gautam et. al. observed that Pd could be used as H2 sensing material to detect low concentrations at room temperature. Still, Pd is costly and unsuitable for higher H2 concentration as a single material. To remove this difficulty, fabricating a magnesium-thin film with very thin Pd capping layer can be a cost-effective H2 sensing material [34]. Guy Rahamim et.al. described a colloidal approach to fabricating indium-tin oxide combined with palladium-nickel or platinum nanoparticles sensing layer to H2 gas [3]. The alkyl chains are not permeable to water molecules; dihydrogen can easily diffuse through the catalytic layer [3].

Wu et. al. fabricated core-shell Pt @ NiO-based H2 gas sensor at alumina substrate. The structure and morphology of core-shell Pt @ NiO affect the sensing properties of Pt/NiO, and core-shell Pt @ NiO were investigated. Pt @ NiO (4.25) was observed to have a higher response than Pt/NiO (1.25) and NiO (1.02) to H2 5000 ppm concentration with fast recovery time of 8 s at room temperature and core-shell Pt @ NiO show a better selective hydrogen sensor [35].

Coban et. al. showed that n-type WO3 and p-type NiO were effectively made up, and gas sensor properties were experimental. The n-type WO3 shows increased absorbance and decreases for p-NiO. They observed that Pd thin film has an unbelievable effect on the responses of both sensors, improving the sensitivity, reduced working temperatures, and detection limits of H2 gas. The response and recovery times are faster for Pd/NiO than for Pd/WO3 [36]. Optical absorption changes due to introduced hydrogen gas were analyzed in both the catalytic layer and without it. With the palladium catalytic layer, the NiO sensor showed better response and recovery times of 70 s and 206 s for 2% of H2 gas at 300 °C working temperature and a 150% increase in the responses; the Pd/WO3 sensor achieved the fast response time was 340 s. [36]. R. L. Fomekong et. al. perform hydrogen gas sensing at high working temperatures with pure and 0.5, 1, 2% Ni-doped TiO2 sensors. They concluded that a low amount of Ni (0.5%) sensor shows better response and stability [37].

**Table 2.** MOSNs with catalytic nanomaterials based developed H2 gas sensor

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sensitive Materials | Temperature  (°C) | Hydrogen concentration | Response | Reference |
| Pd/SnO2 thin films | 250 | 500 ppm | 99% | [33] |
| Pd/Mg thin films | RT | 2 bar | 37% | [34] |
| ITO-PdNi  Thin films | RT. | 1% | 114% (ΔI/I0) | [3] |
| Pt@NiO coreeshell | RT. | 5000 | 4.25 | [35] |
| Pd/WO3,  Pd/NiO thin films | 250, 300 | 2% | 340%, 42% | [36] |
| 0.5% Ni doped SnO2 (Nps) | 72% | 10000 ppm | 600 | [37] |

1. ***(c) Metal oxide nanocomposite-based H2 gas sensors***

Two or more than two materials are taken together and deposited and doped into other materials known as complex materials sensors. Xiaoning Meng et. al. show the 1.0 at % Pd/SnS2/SnO2 nano composites sensing material is outstanding for H2 detection. The integration of SnS2 in SnO2 affords excessive influence to stimulate the sensing competence. As an advanced semiconductor sensing material, SnS2 can expressively improve the adsorption and diffusion of H2 molecules as of its 2D nanostructure. The high specific surface area and associated sulfur atoms at the edge of 2D SnS2 deliver extra energy for the reaction to gas molecules.

The 1.0% Pd/SnS2/SnO2 sensor displays a significantly advanced response to H2 gas, with an ultrafast response/recovery 1/9s rate of 1.0% Pd/SnS2/SnO2 sensor to H2 [38]. Xinxiao Zhang et al. demonstrated that Pd-doped-ZnO-SnO2 composites were effectively fabricated, homogeneously deposited on the surface of rGO, and exhibited outstanding H2 gas sensing properties. The results showed that, compared with the pure Pd-doped ZnO-SnO2 sensor, the Pd-doped rGO/ZnO-SnO2 sensor with 3 wt% rGO showed a higher response of 9.4 to H2 100 ppm at a temperature 380 °C, as well as a faster 4 s and 8 s response and recovery time.

In a recent investigation, researchers discovered that a sensor exhibited superior repeatability and renovation [39]. The sensor comprised three layers of SnO2/Pt/WO3 nanofilms, which possessed varying thicknesses of WO3 (50, 80, 140, and 260 nm). The top layer of WO3 acted as a gas filter, heightening the sensor's selectivity. For all the thicknesses tested, the optimal thickness of 140 nm showed gas responses to H2 gases that were only slightly less than those of Pt/SnO2 sensor film [40]. In another study, flexible ZnO-decorated MgO nanocubes and a core-shell type of ZnO/MgO nanocomposite were employed as chemo-resistive sensors to identify hydrogen gas sensing.

Growing in the molar concentration of the Zn precursor from 2 to 3 mole to attain nanoparticles on the core of MgO nanocubes increases and creates a shell. This leads to the formation of two different composite shapes: ZnO-decorated MgO nanocubes (1 and 2 mole) and a core-shell type of ZnO/MgO nanocomposite (3 mole). The composition with 1 mole of ZnO/MgO presented an excellent response (sensitivity of 1.1459), mainly due to the heterojunction development and the spillover effect. The ZnO-decorated MgO nanocubes were found to be suitable for a flexible hydrogen sensor [41].

A recent study revealed that a MoS2-Pt nanoparticle thin film functions as an exceptionally sensitive hydrogen gas sensor. In response to H2 gas, the sensor quickly registers within 4 seconds and recovers within 19 seconds when exposed to a 100 ppm gas concentration. Furthermore, the MoS2-Pt composite film demonstrates a superior sensor response to 10-100 ppm of H2 gas, surpassing the capabilities of present metal sulfide-based sensors. With an impressive lifespan of up to 70 days and reliable selectivity, this sensor represents a significant breakthrough in gas-sensing technology. [42]

CeO2-SnO2 composite oxide heterostructures were utilized to develop ultra-sensitive and highly selective hydrogen gas sensors. The heterostructure exhibited a large surface area and high carrier density of oxides. The gas-sensing properties of CeO2-SnO2 heterostructures demonstrated rapid response; recovery times were 17/24 seconds to H2 40 ppm gas at 300°C, with exceptional sensitivity. The enhanced H2 gas sensing response of 1323 at 60 ppm H2 gas can be attributed to pore diameter, increased surface area, surface defects, and the emergence of CeO2-SnO2 heterojunction at the boundaries between CeO2 and SnO2, resulting in additional active sites. The selectivity of the CeO2-SnO2 sensor for H2 gas was assessed, confirming its capability to detect small amounts of H2 gas [43].

**Table 3**. Metal Oxide nanocomposite nanomaterials-based H2 gas sensors

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sensitive Materials | Temperature (°C) | H2 gas concentration | Response | Ref. |
| 1.0 at% Pd/SnS2/SnO2 nano composites | 300 | 500 ppm | 95 | [38] |
| Pd-doped rGO/ZnO-SnO2 nano composites | 380 | 100 ppm | 9.4 | [39] |
| SnO2/Pt/WO3 nanofilms | 250 | 1000 ppm | 45 | [40] |
| ZnO NPs/MgO cubes | 200 | 3000 ppm | 1.05 | [41] |
| MoS2-Pt  nanoparticles | 150 | 100 ppm | 10 | [42] |
| CeO2-SnO2  heterostructure | 300 | 60 ppm | 1323 | [43] |

***1 (d). With Organic nanomaterials***

Organic semiconductors have gained attention for their various applications, such as organic sensors, photovoltaic cells [44], light-emitting diodes (OLEDs) [45], organic field-effect transistors (OFETs) [46], and supercapacitors. They can potentially improve a new generation of electronic devices with low power consumption, cost, greater reliability, and weightlessness. In recent years, organic semiconductors have become widely attractive as potential nanomaterials for developing gas sensors. Carbon nanotubes (CNTs) and graphene are being used to manufacture gas sensors due to their large active sensing surface area [47-51].

This section delves into the different types of organic materials utilized in H2 gas sensors and how using inorganic/organic materials and renewable resources can enhance their sensing capabilities. Organic materials are an ideal choice for the sensing layer in sensor applications due to their sensitivity and efficacy in detecting gas molecules. Organic semiconductors possess distinctive mechanical and electronic properties that make them well-suited for developing cost-effective devices. Moreover, they demonstrate excellent electrocatalytic activity in terms of redox behavior, such as CNTs, making them an excellent fit for gas detection. Incorporating other materials into pure graphene can also enhance its sensitivity. For example, chemically doping graphene can increase carrier diffusion and the adsorption of gas molecules on the surface [52]. On the other hand, polyaniline (PANI) has been used to create electrochemical gas sensors [53-56], with the gas sensor structure comprising two carbon IDEs and PANI as the sensing layer [57].

Various metal oxide semiconductors such as SnO2, WO3, TiO2, and ZnO are made up of various organic semiconductors such as single-walled or multi-walled carbon nanotubes (SWCNTs and MWCNTs, respectively) and graphene.

Utilizing SMOs and carbon nanomaterials, including CNT, graphene, and activated carbon, can yield exceptional sensor performance characterized by reduced operating temperatures and quicker response and recovery times. This can be attributed to the remarkable conductivity at normal room temperatures, heightened specific surface area, exceptional lattice crystallinity, significant carrier mobility, outstanding chemical stability, diverse surface chemistry, and carbon-based materials' adaptable and porous graphitic network.

It is difficult to evenly distribute carbon nanotubes (CNTs) in composites as they tend to disperse poorly in most solvents. However, Son et al. have successfully developed a wearable hydrogen gas monitoring device that operates at room temperature. This device uses palladium oxide nanoparticles and a biscrolling method to create spinnable carbon nanotube bucky papers. The sensor exhibits remarkable sensitivity to 4% hydrogen concentration, with an ultra-high sensitivity of 1198% and a fast response time of only 2 seconds. The spinnable CNTs prevent agglomeration and enable the introduction of H2 gas, resulting in outstanding H2 sensing. Additionally, graphene improves the selectivity of bare SMOs. Rasch et al. have demonstrated that highly porous (94%) graphene oxide (GO) coated on ZnO microwires can operate at ultra-low power (60-200 nW) and exhibit higher discrimination to H2 detecting at room temperature. The sensor demonstrates a fast response/recovery time of 114 s / 30 s with a lower recognition limit of 4 ppm [59].

Pippara et. al manufactured of a unique nanocomposite film based on tin oxide (SnO2) nanosheets with palladium (Pd) and polyaniline (PANI) doped composite was executed gas sensing from 50 - 400 ppm H2 at room temperature. The highest sensitivity among all the films was 540% for the SnO2/Pd film at 0.4% of the H2 gas towards Pd-doped PANI-SnO2 film with a response/recovery time of 39/53. These results indicated the encouraging upcoming ultra-high sensitivity of SnO2, PANI, and Pd-associated complex films [60]. MOF (metal–organic framework) is one of the new porous material groups whose structures consist of inorganic and organic units connected via strong bonds [61].

MOF-74 families display ultrahigh porosities, high thermal, organic steadiness, and large surface areas [61]. Duy-Khoi Nguyen et. al. showed that for achieving the higher sensitivity of H2 gas, two Co-MOF-74 were considered. To display ultra-high H2 gas sensitivity Co-MOF-74 composites with owing to the high density of Co ions (+2 and + 3 states) located in metal bands in the p-type phase, compared with those of Mg-MOF-74 and Ni-MOF-74. The Co-MOF-74 sensor had more adsorption sites with greater porosity and Co ion attentiveness; accordingly, extra board gas particles were adsorbed [61]. Deepak Punetha et. al. fabricated reduced graphene oxide (rGO), polyvinylidene fluoride (PVDF), and tin oxide (SnO2) tertiary nano composite thick films gas sensor. The nanocomposite of 0.90 (PVDF)-0.10 [x (SnO2)-(1-x) rGO] with different weight percentages (x=0, 0.15, 0.30, 0.45, 0.6, 0.75, 0.90 and 1). The nano composite0.90 (PVDF)-0.10[0.75(SnO2)-0.25 rGO] thick film has been performed superior response. Hence, this structure is measured as an enhanced tertiary nanocomposite for hydrogen gas selectivity. The sensor response time was 34 sec, the recovery time was 142 sec, and the response was 49.2 to 100 ppm H2 gas [62].

**Table 4.** Organic materials with inorganic nanomaterials used as developed H2 gas sensor

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sensitive Materials | Temperature  (°C) | H2 concentration | Response | Ref. |
| PdO/CNT | RT | 4% | 1198% | [58] |
| GO + ZnO | RT | 1000 ppm | 3.4 | [59] |
| Pd-SnO2/PANI | RT | 50 ppm | 19.2 | [60] |
| Co-MOF-I  Co-MOF-II | 200 | 50 ppm | 53.8%  101.4% | [61] |
| rGO/SnO2/PVDF | RT | 100 ppm | 49.2% | [62] |

1. **Advantages and disadvantages of the above sensors**

After thoroughly discussing the materials used in H2 gas sensors, we have made several observations regarding the performance, cost, and environmental impact of the different types of gas sensor measurements. To make it easier to compare, we have compiled a list of the advantages and disadvantages of each type in Table 5.

**Table 5.** Comparison of H2 gas sensors characteristics.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Characteristics | Single element | Two elements | More than two elements | With organic materials |
| Cost | low | low | high | average |
| Lifetime | low | better | high | better |
| Selectivity | average | better | average | better |
| Sensitivity | average | higher | higher | better |
| Response/recovery time | average | fast | fast | fast |
| Environmental degradation toleration | low | better | better | better |

1. **Materials and their structures and morphology effects on H2 gas sensitivity**

Numerous determinations have been made to develop various morphologies of synthesized materials such as, nanosheets, nanoneedles, nanoflowers, nanofibers, nanorods, nanowires, and more. Amit Sanger et. al. successfully created a high response and discriminating H2 sensor by growing Pd-decorated MnO2 nanowalls on an anodized substrate. To create the sensor, the MnO2 nanowall structure was used on an aluminum foil that was first degreased in acetone through ultra-sonication for 15 minutes and then rinsed with deionized water. The anodizing step was performed using 0.3 M oxalic acid at a constant DC voltage of 80 V for an hour at 0°C. The nanowalls were fabricated on the anodization substrate [63].

According to a study by Nguyen Kien et. al., Pd-decorated SnO2 nanowire sensors are suitable for device packaging and practical use in detecting H2 gas. A microheater can be easily integrated with its active sensing element on a chip at low working temperatures. The sensor operates efficiently, consuming only around 50 mW of power, and can function within a temperature range of 100 to 150 °C. At 150 °C, the reaction of H2 molecules and PdOx reduces the potential barrier at the PdOx/SnO2 nanowire interface. This sensor displays a high potential for developing low-cost, high-performance gas-sensing devices [64].

Shu Zhu et al. created an H2 gas sensor by designing a semiconductor film with n-WO3 and a noble metal capping layer of p-PdO nanoparticles. The noble metal oxide nanoparticles were homogeneously dispersed throughout the film [65].

Kumar et. al. developed a Pd/SiC nano-cauliflower sensor on a porous silicon (PS) substrate. The sensor exhibits rectifying diode behavior in dry synthetic air in both the absence and presence of 100 ppm H2 gas at 380 °C and shows a high response rate [66].

In a study conducted by Bing Wang et al., a gas sensor made of SnO2 ultrathin nanosheets on SiC nanofibers was found to have higher sensitivity than a pure SnO2 nanosheet sensor. This was due to the heterojunction effect of SnO2 and SiC. The hierarchical composite comprised two mixed tetragonal rutile SnO2 and cubic SiC phases. In contrast, the pure SnO2 nanosheets were observed to aggregate together, forming sphere-like clusters, which reduced the effective reactive area and gas response. The gas sensor detected hydrogen gas with an ultrafast response and recovery time of 1 second and 15 seconds, respectively [67].

According to research conducted by Ang Li et. al., they utilized a hydrothermal method to create network-structured titanium dioxide (TiO2) nanorods, which were then coated with tin dioxide (SnO2) nanoparticles using a simple solution-coating method. This resulted in the formation of SnO2@TiO2 nanorods (STNRs). The quantity of SnO2 added significantly influenced the microstructure and morphology of the TiO2 backbone. The tests revealed that the 1.0 STNRs sample displayed the highest response of 15.4 to 500 ppm H2 at 100 °C, with an 11-second response and 132-second recovery time. Additionally, the SnO2@TiO2 heterostructured nanorods exhibited exceptional selectivity and repeatability to H2 gas [68].

**Table 6.** Different structures and morphology of sensors effect on H2 gas sensing response.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sensitive Materials | Structure | Temperature (°C) | H2 Concentration | Response | Ref. |
| Pd decorated MnO2 | Nanowalls | 300 | 100 ppm | 11.4 | [63] |
| Pd decorated SnO2 | Nanowire | 150 | 100 ppm | 7.1 (Vgas/Vair) (47mW, 2.1V) | [64] |
| p-PdO/n-WO3 | Nanoparticles/thin film | 160 | 200 ppm | 50.6 | [65] |
| Pd decorated SiC | Nano cauliflowers | 380 | 100 ppm | 14.48 | [66] |
| SnO2@SiC | Nanosheets/nano fiber | 350 | 500 ppb | *-* | [67] |
| SnO2/TiO2 | Nanorods | 100 | 500 ppm | 15.4 | [68] |

It is important to note that the sensing materials discussed above exhibit different sensing performances depending on various factors, such as the nature of the sensor materials, their structure, defects in the sensing layer, and the doping level with other materials.

***Challenges***

The performance of H2 gas sensor materials is a major challenge regarding real gas monitoring. The sensor materials must exhibit sensitivity, long operating life, quick response time, stable selectivity, low power consumption, and affordability. Achieving affordability, in particular, involves reducing maintenance, lowering installation costs, improving sensor operating time, wounding the costs of examining arrangement consequences, and handling statistics. These factors outweigh the rate of developing the device this one. To achieve reliable sensor performance, the special effects of the humidity, pollutants, and temperature must be independently assessed. Coating or doping the sensing thin films are capable methods of reducing the condition of gas sensing characteristics on humidity while maintaining gas recognition. The challenge is integrating and utilizing low-cost materials with desirable characteristics such as mechanical strength, electrical properties, thermal stability, high robustness during bending and folding, and reproductivity. Machine learning algorithms in materials research can help find optimal parameters, shorten experiment duration, and reduce costs [69-71]. Artificial intelligence has recently attracted attention in chemical engineering research to facilitate materials manufacturing processes [72-73].

***Future guidelines***

In the sensor production industry, 3D-printing technologies will be used to minimize fabrication time, achieve the preferred structural design, and reduce the remaining rate [74] in the near future. However, gas sensor recognition systems are cheaper compared to other parts of the recognition structure. Consequently, reducing the costs of more expensive parts like data analysis, installation, conservation, and sensor manufacturing and testing is important. The IoT (Internet of Things) is extensively used in detecting toxic and H2 gas in industries and production. The cryptographic processing algorithms should be used to decrease system overwork and the magnitude of statistics composed by the sensors, to communicate only the essential statistics to the databank via wireless statement [75]. Further investigation into the stability and reliability of these types of sensor structures could provide opportunities for future applications.

***Conclusion***

This chapter delves into different gas sensor materials and compares their characteristics. Various works were examined to highlight the impact of nanomaterial properties and structures on sensor performance. It was observed that no single sensor type can be deemed perfect. However, the drawbacks of single SMO-based gas sensor materials have been reduced through continuous research and development efforts to create optimal heterostructures by combining SMOs with various materials. This has led to a promising increase in response and a decrease in response time, recovery time, and operating temperature. The development of different structures presents opportunities to achieve an affordable and reliable detection and classification sensor system, partially based on advanced nanomaterials.

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