RECENT ADVANCED METAL OXIDE NANOMATERIALS TO DEVELOPED HYDROGEN GAS SENSORS AND THEIR NANOSTRUCTURES, MORPHOLOGY EFFECT ON SENSITIVITY

Abstract

Reliable and low-cost hydrogen gas sensors have been developed at a large scale recently. Many metal and metal oxide semiconducting nanomaterials (MOSNs) SnO_2, ZnO, TiO_2, WO_3, MnO_2, n-type materials, and CuO, NiO, Cr_2O_3, Mn_3O_4, etc., p-type materials, and their composites, metal-doped, are used to develop susceptible sensors that show highly stable and selective nature even at low H_2 gas concentrations. Different treatment and synthesis processes are used to make other structures and morphologies to design H_2 gas sensors. Sensors with p-n junction structures, heterostructures, and isotype heterojunction structures display high device performance. Additionally, sensor morphologies such as thin films, hollow spheres, nanopatterns, nanowires, nanobelts, and nanoparticles also show high performance in detecting low H_2 gas concentrations (sub-ppm 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 H_2 gas and the sensor surface. Some researchers also add organic materials to improve sensors' responses. This chapter briefly reviews recent studies based on MOSNs H_2 gas sensors with different structures and morphologies. The chapter highlights the sensing performance of MOSNs-based H_2 gas sensors. The chapter also includes the challenges and prospects of MOSN's H_2 gas sensors.

Keywords: Advanced nanomaterials, morphology, H_2 gas sensors, gas sensing response.

Authors

Vipin Kumar
Department of Physics
CCS University Campus Meerut
Uttar Pradesh, India.
vpachar1991@gmail.com

Ravikant Adalati
Institute Instrumentation Centre
Indian Institute of Technology Roorkee,
Uttrakhand, India.

Pramod Kumar Singh
Department of Physics
Hindustan College of Science & Technology
Farah, Mathura, Uttar Pradesh, India.

Manish Baboo Agarwala
Department of Applied Sciences
Anand Engineering College
Agra, India.

I. 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 CO_2 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 H_2), 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 H_2 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.

II. 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 H_2 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 H_2 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.

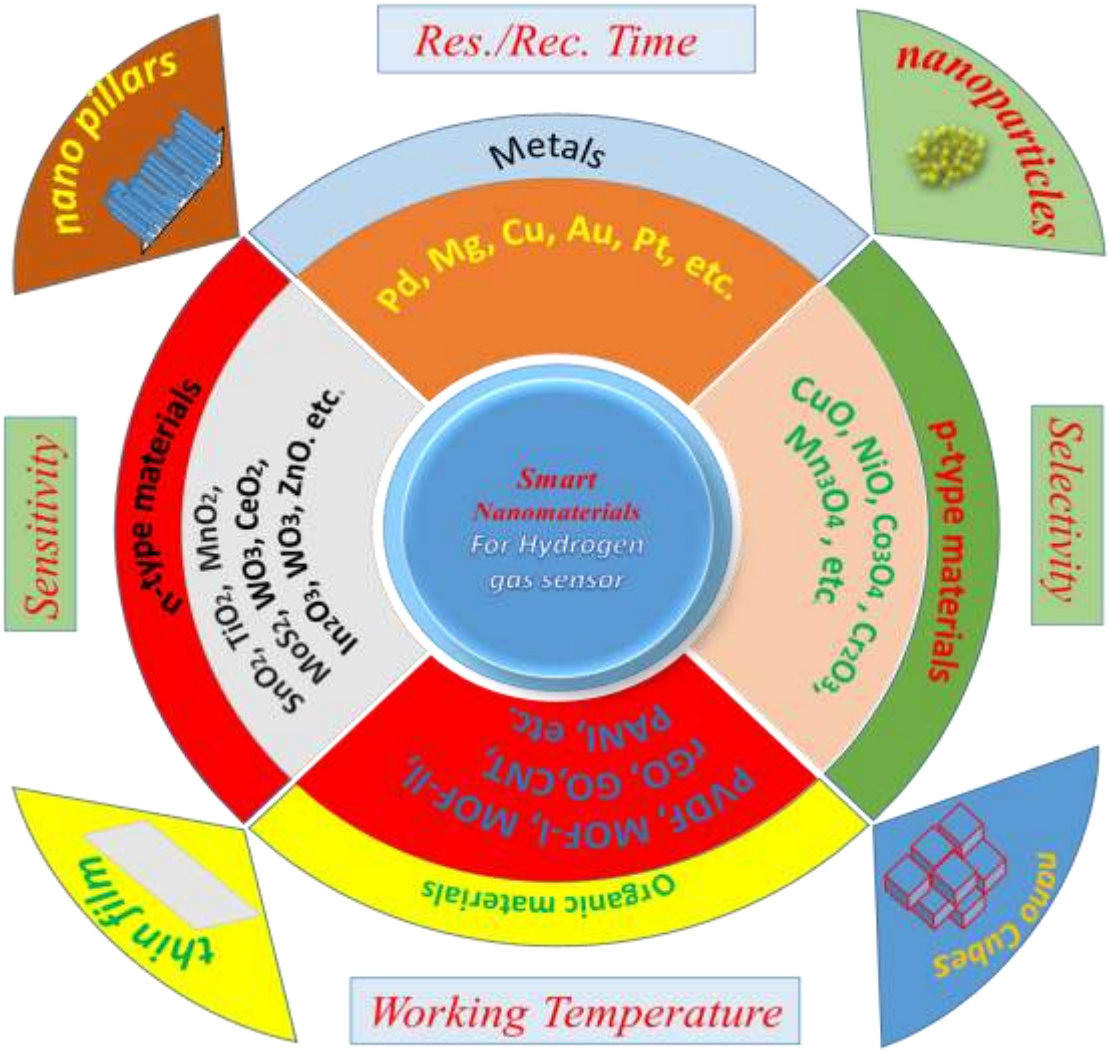

Figure 1: Shows different advanced nanomaterials for fabricating reliable hydrogen gas detection sensors.

1. **Single Metal Oxide Nanomaterial as H_2 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 H_2 gas at low operating temperatures [27]. M. Moschogiannaki and colleagues have also developed a bimetallic cobalt-vanadium-oxide (CoV_2O_6) 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 H_2 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 Cr_2O_3 sensor structure grown in its natural state effectively detects H_2 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 H_2 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-MoO_3 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 H_2. A higher hydrothermal temperature resulted in a wider specific surface area and a larger amount of Mo^{5+} 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 H_2 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. Two-dimensional nanostructures are more suitable for gas sensing than one-dimensional ZnO nanowire-based structures due to their small thickness, comparable to the depletion-layer thickness, and larger cross-section, which increases the base current and lowers the detection limit. Even at sub-ppm concentrations of H_2, the response is good, and the response times are less than 18 seconds in the entire range of H_2 concentrations tested (500 ppb–10 ppm) at 175 °C [32].

Table 1: Semiconductor Nanomaterial used to Develop H_2 Gas Sensor

Sensitive Materials	Temperature (°C)	Hydrogen Concentration	Response	Reference
NiO Thin film	300	2%	16%	[27]
CoV_2O_5 films	RT	1000 ppm	65.2	[28]
α-MoO_3 nanoribbons	RT	1000 ppm	90%	[31]
ZnO Nanosheets	175	10 ppm	1.089	[32]

Sensor response calculated by S = $\frac{R_a}{R_g}$, S (%) = $\frac{R_a - R_g}{R_a} \times 100$

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

2. **With Catalytic Nanomaterials:** The detection of H_2 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 Kumar *et al.*, Pd/SnO_2 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 H_2 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 H_2 sensing material to detect low concentrations at room temperature. Still, Pd is costly and unsuitable for higher H_2 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 H_2 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 H_2 gas [3]. The alkyl chains are not permeable to water molecules; dihydrogen can quickly diffuse through the catalytic layer [3].

Wu *et al.* developed an H_2 gas sensor using a core-shell Pt @ NiO structure on an alumina substrate. The researchers compared the sensing performance of Pt @ NiO (4.25), Pt/NiO (1.25), and NiO (1.02) at an H_2 concentration of 5000 ppm at room temperature. Pt @ NiO (4.25) had a better response and faster recovery time of 8 seconds compared to Pt/NiO (1.25) and NiO (1.02). Core-shell Pt @ NiO was found to be a more selective hydrogen sensor [35].

Coban *et al.* showed that n-type WO_3 and p-type NiO were effectively made up, and gas sensor properties were experimental. The n-type WO_3 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 H_2 gas. The response and recovery times are faster for Pd/NiO than for Pd/WO_3 [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 H_2 gas at 300 °C working temperature and a 150% increase in the responses; the Pd/WO_3 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 TiO_2 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 H_2 gas sensor

Sensitive Materials	Temperature (°C)	Hydrogen concentration	Response	Reference
Pd/SnO_2 thin films	250	500 ppm	99%	[33]
Pd/Mg thin films	RT	2 bar	37%	[34]
ITO-PdNi Thin films	RT.	1%	114% ($\Delta I/I_0$)	[3]
Pt@NiO coreeshell	RT.	5000	4.25	[35]
Pd/WO_3, Pd/NiO thin films	250, 300	2%	340%, 42%	[36]
0.5% Ni doped SnO_2 (Nps)	72%	10000 ppm	600	[37]

3. **Metal Oxide Nanocomposite-based H_2 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/SnS_2/SnO_2 nano composites sensing material is outstanding for H_2 detection. The integration of SnS_2 in SnO_2 affords excessive influence to stimulate the sensing competence.

The two dimensional SnS_2 is an advanced semiconductor sensing material that improves H_2 molecules adsorption and diffusion due to its high surface area and sulfur atoms. It's efficient for gas sensing.

The 1.0% $Pd/SnS_2/SnO_2$ sensor displays a significantly advanced response to H_2 gas, with an ultrafast response/recovery 1/9s rate of 1.0% $Pd/SnS_2/SnO_2$ sensor to H_2 [38]. Xinxiao Zhang *et al.* demonstrated that Pd-doped-ZnO-SnO_2 composites were effectively fabricated, homogeneously deposited on the surface of rGO, and exhibited outstanding H_2 gas sensing properties. The results showed that, compared with the pure Pd-doped ZnO-SnO_2 sensor, the Pd-doped rGO/ZnO-SnO_2 sensor with 3 wt% rGO showed a higher response of 9.4 to H_2 100 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 consisted of three layers of nanofilms made of SnO_2, Pt, and WO_3. The thickness of the WO_3 layer varied between 50, 80, 140, and 260 nm. The top layer of WO_3 acted as a gas filter, which increased the sensor's selectivity. After testing all thicknesses, it was found that the optimal thickness of 140 nm produced gas responses to H_2 gases that were only slightly less than those of the Pt/SnO_2 sensor film [40]. A different study used flexible ZnO-decorated MgO nanocubes and a core-shell ZnO/MgO nanocomposite as chemo-resistive sensors to detect hydrogen gas.

Increasing the concentration of the Zn precursor from 2 to 3 moles during the growth process results in the formation of nanoparticles on the surface of MgO nanocubes, which develop into a shell structure. This process creates two different composite shapes: ZnO-decorated MgO nanocubes at 1 and 2-mole concentration and a ZnO/MgO core-shell type nanocomposite at 3-mole concentration. 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 suitable for a flexible hydrogen sensor [41].

A recent study revealed that a MoS_2-Pt nanoparticle thin film functions as a susceptible hydrogen gas sensor. In response to H_2 gas, the sensor quickly registers within 4 seconds and recovers within 19 seconds when exposed to a 100 ppm gas concentration. Furthermore, the MoS_2-Pt composite film demonstrates a superior sensor response to 10-100 ppm of H_2 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]

CeO_2-SnO_2 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 CeO_2-SnO_2 heterostructures showed high sensitivity, rapid response, and recovery times of 17/24 seconds to 40 ppm H_2 gas at 300 °C. The enhanced H_2 gas sensing response of 1323 at 60 ppm H_2 gas can be attributed to pore diameter, increased surface area, surface defects, and the emergence of SnO_2-CeO_2 heterojunction at the boundaries between SnO_2 and CeO_2, resulting in additional active sites. The selectivity of the SnO_2-CeO_2 sensor for H_2 gas was assessed, confirming its capability to detect small amounts of H_2 gas [43].

Table 3: Metal Oxide Nanocomposite Nanomaterials-based H_2 Gas Sensors

Sensitive Materials	Temperature (°C)	H_2 gas concentration	Response	Ref.
1.0 at% Pd/SnS_2/SnO_2 nanocomposite	300	500 ppm	95	[38]
Pd-doped rGO/ZnO-SnO_2 nanocomposite	380	100 ppm	9.4	[39]
SnO_2/Pt/WO_3 nanofilms	250	1000 ppm	45	[40]
ZnO NPs/MgO cubes	200	3000 ppm	1.05	[41]
MoS_2-Pt nanoparticles	150	100 ppm	10	[42]
CeO_2-SnO_2 heterostructure	300	60 ppm	1323	[43]

4. **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, excellent 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 H_2 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 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 SnO_2, WO_3, TiO_2, and ZnO can be combined with organic semiconductors like single-walled (SWCNTs) or multi-walled carbon nanotubes (MWCNTs) 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 average 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 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 H_2 gas, resulting in outstanding H_2 sensing. It has been demonstrated that the selectivity of bare SMOs can be improved by using graphene. In a study by Rasch *et al.*, it was found that highly porous (94%) graphene oxide (GO) coating on ZnO microwires can function at ultra-low power (60-200 nW) and has a higher H_2 detection capability at room temperature. The sensor shows a quick response/recovery time of 114 s / 30 s and can detect concentrations as low as 4 ppm [59].

Pippara *et al*. manufactured of a unique nanocomposite film based on tin oxide (SnO_2) nanosheets with palladium (Pd) and polyaniline (PANI) doped composite was executed gas sensing from 50 - 400 ppm H_2 at room temperature. The highest sensitivity among all the films was 540% for the SnO_2/Pd film at 0.4% of the H_2 gas towards Pd-doped PANI-SnO_2 film with a response/recovery time of 39/53. These results indicated the encouraging upcoming ultra-high sensitivity of SnO_2, 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 H_2 gas, two Co-MOF-74 were considered. To demonstrate ultra-high sensitivity to H_2 gas, Co-MOF-74 composites were used due to the high density of Co ions in metal bands in the p-type phase, compared to 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 (SnO_2) tertiary nano composite thick films gas sensor.

The nanocomposite of 0.90 (PVDF)-0.10 [x (SnO_2)-(1-x) rGO] with varying weight percentages (x=0, 0.15, 0.30, 0.45, 0.6, 0.75, 0.90 and 1). The nanocomposite 0.90 (PVDF)-0.10[0.75(SnO_2)-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 H_2 gas [62].

A nanocomposite material was developed by combining Polyvinylidene fluoride (PVDF), Tin dioxide (SnO_2), and reduced Graphene oxide (rGO) with varying weight percentages (x=0, 0.15, 0.30, 0.45, 0.6, 0.75, 0.90, and 1). The nanocomposite 0.90

(PVDF)-0.10[0.75(SnO_2)-0.25 rGO] was found to be the most effective in detecting hydrogen gas. The sensor was able to detect the presence of hydrogen gas in 34 seconds, recovered in 142 seconds, and had a response rate of 49.2 to 100 ppm H_2 gas. This structure is considered an enhanced tertiary nanocomposite for hydrogen gas selectivity [62].

Table 4: Organic materials with inorganic nanomaterials used as developed H_2 gas sensor

Sensitive Materials	Temperature (°C)	H_2 concentration	Response	Ref.
PdO/CNT	RT	4%	1198%	[58]
GO + ZnO	RT	1000 ppm	3.4	[59]
Pd-SnO_2/PANI	RT	50 ppm	19.2	[60]
Co-MOF-I Co-MOF-II	200	50 ppm	53.8% 101.4%	[61]
rGO/SnO_2/PVDF	RT	100 ppm	49.2%	[62]

III. ADVANTAGES AND DISADVANTAGES OF THE ABOVE SENSORS

Based on our detailed analysis and discussion of the materials utilized in H_2 gas sensors, we have identified various insights relating to the efficiency, cost-effectiveness, and ecological impact of diverse gas sensor measurements. In order to facilitate a clear comparison, we have consolidated a list of merits and demerits of each type in Table 5.

Table 5: Comparison of H_2 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

IV. MATERIALS AND THEIR STRUCTURES AND MORPHOLOGY EFFECTS ON H_2 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 H_2 sensor by growing Pd-decorated MnO_2 nanowalls on an anodized substrate. A sensor was created using a unique method. First, an aluminum foil was thoroughly cleaned

using acetone and deionized water. Then, a process known as anodizing was performed using a constant DC voltage of 80 V and 0.3 M oxalic acid at a temperature of 0 °C for an hour [63]. This process resulted in the formation of a MnO_2 nanowall structure on the anodization substrate, which was used to fabricate the nanowalls and complete the sensor. This method ensures a high level of accuracy and precision in the sensor's functioning.

According to a study by Nguyen Kien *et al.*, Pd-decorated SnO_2 nanowire sensors are suitable for device packaging and practical use in detecting H_2 gas. A micro heater 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. The reduction of the potential barrier at the interface of PdOx and SnO_2 nanowires occurs at 150 °C, by the reaction of H_2 molecules and PdOx. This sensor displays a high potential for developing low-cost, high-performance gas-sensing devices [64].

Shu Zhu *et al.* created an H_2 gas sensor by designing a semiconductor film with n-WO_3 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 H_2 gas at 380 °C and a high response rate [66].

In a study conducted by Bing Wang *et al.*, a gas sensor made of SnO_2 ultrathin nanosheets on SiC nanofibers was found to have higher sensitivity than a pure SnO_2 nanosheet sensor. This was due to the heterojunction effect of SnO_2 and SiC. The hierarchical composite comprised two mixed tetragonal rutile SnO_2 and cubic SiC phases. In contrast, the pure SnO_2 nanosheets were observed to aggregate together, forming sphere-like clusters, which reduced the effective reactive area and gas response. The gas sensor demonstrated remarkable performance in detecting hydrogen gas. It had a response time of 1 second, which implies that it could detect the gas almost instantly. Additionally, it had a recovery time of 15 seconds [67], which means it could return to its normal state after detecting the gas. Overall, the gas sensor proved to be highly accurate and efficient in detecting hydrogen gas.

According to research conducted by Ang Li *et al.*, they utilized a hydrothermal method to create network-structured titanium dioxide (TiO_2) nanorods, which were then coated with tin dioxide (SnO_2) nanoparticles using a simple solution-coating method. The addition of SnO_2 had a significant impact on the formation of the TiO_2 backbone, resulting in the creation of SnO_2@TiO_2 nanorods (STNRs) with varied microstructures and morphologies. Based on the tests conducted, it was found that the 1.0 STNRs sample recorded the highest response of 15.4 when exposed to 500 ppm H_2 at a temperature of 100 °C, with a response time of 11 seconds and recovery time of 132 seconds. Moreover, the SnO_2@TiO_2 heterostructured nanorods showed exceptional selectivity and repeatability to H_2 gas [68].

Table 6: Different Structures and Morphology of Sensors Effect on H_2 Gas Sensing Response.

Sensitive Materials	Structure	Temperature (°C)	H_2 Concentration	Response	Ref.
Pd decorated MnO_2	Nanowalls	300	100 ppm	11.4	[63]
Pd decorated SnO_2	Nanowire	150	100 ppm	7.1 (V_{gas}/V_{air}) (47mW, 2.1V)	[64]
p-PdO/n-WO_3	Nanoparticles /thin film	160	200 ppm	50.6	[65]
Pd decorated SiC	Nano cauliflowers	380	100 ppm	14.48	[66]
SnO_2@SiC	Nanosheets /nano fiber	350	500 ppb	-	[67]
SnO_2/TiO_2	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.

V. CHALLENGES

The performance of H_2 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 expenses 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 is capable of reducing the condition of gas sensing characteristics on humidity while maintaining gas recognition. The integration and utilization of low-cost materials that possess desirable characteristics such as mechanical strength, electrical properties, thermal stability, high robustness during bending and folding, and reproductively remains a challenge. However, research has shown that machine learning algorithms can aid in the search for optimal parameters, shorten experiment duration, and ultimately reduce costs [69-71]. In addition to this, artificial intelligence has recently generated interest in chemical engineering research as a means of facilitating materials manufacturing processes [72-73].

VI. 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 H_2 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.

VII. 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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