A Review of Nanostructured Resistive-Based Vanadium Oxide Gas Sensors

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Abstract: Vanadium pentoxide (V₂O₅) is a transition metal oxide with features such as high availability, good catalytic activity, unique electrical properties and high conductivity which are appropriate for gas sensing applications. In this review, we discuss different gas sensing aspects of V₂O₅ in pristine, doped, decorated and composite forms. Depending on its synthesis procedure, morphology, sensing temperature and surface conditions, the V₂O₅-based gas sensors show different responses to target gases. Herein, we have discussed the behavior of V₂O₅-based gas sensors to different gases and associated sensing mechanisms. This review paper can be a useful reference for the researchers who works in the field of gas sensors.

Keywords: V₂O₅; gas sensor; morphology; sensing mechanism; toxic gas

1. Introduction

Vanadium (V) is a well-known transition metal which can form different oxides. The principal oxides of vanadium are vanadium monoxide (VO, violet color), vanadium sesquioxide (V₂O₃, green color), vanadium dioxide (VO₂, blue color), and vanadium pentoxide (V₂O₅, yellow color). Presence of oxygen vacancies leads to formation other oxides such as V₃O₇, V₄O₉, and V₆O₁₃ (a mixture of V⁵⁺ and V⁴⁺), and a series of oxides such as V₆O₁₁, V₇O₁₅, and V₈O₁₅ (a mixture of V⁴⁺ and V³⁺). In general, the mixing phases can be categorized into two series of phases namely the Magnéli phase (VₙO₂ₙ₋₁) and the Wadsley phase VₙO₂n+1 [1,2]. Among different phases, V₂O₅ is thermodynamically the most stable oxide and it exist in different polymorphs namely the most stable α-V₂O₅ (orthorhombic), metastable β-V₂O₅ (tetragonal or monoclinic), γ-V₂O₅ (orthorhombic) and δ-V₂O₅ (monoclinic) [3]. Each polymorph is stable at a temperature and pressure range. For example, β-V₂O₅ is stable at high pressure and temperatures [4].

The orthorhombic V₂O₅ has a layered structure and it is comprised of the distorted polyhedra of six oxygen atoms which form octahedral polyhedra with central V atoms [5]. There are three different oxygen positions in the V₂O₅ crystal structure. The VO₆ octahedra are linked, sharing edges through the chain (Oₓ) and corners via the bridging oxygens (Oₖ). Two vanadyl oxygen atoms (OV) form the vertices of the octahedra along the c-axis [6].

V₂O₅ is highly abundant in nature, it has low price and has several oxidation states [7,8]. Accordingly, due to its relatively open layered structure and its unique properties, V₂O₅ has been used in different applications such as water splitting [9], field effect transistors [10,11], supercapacitors [12], IR detectors [13], photodetectors [14], UV sensors [15], optical sensors [16], amprometric gas sensors [17], potentiometric sensors [18] electrochemical sensors [19,20], cataluminescence sensors [21], resistance gas sensors [22,23], gasochromic sensors [24] and humidity sensors [25].
V$_2$O$_5$ with an n-type semiconducting behavior, has a relatively high conductivity (0.5 S·cm$^{-1}$) at room temperature [26]. At high temperatures, stoichiometric V$_2$O$_5$ spontaneously converts to V$_2$O$_{5-x}$ as follows:

$$V_2O_5 \leftrightarrow V_2O_{5-x} + x\frac{1}{2}O_2 \quad x \sim 0.01$$ (1)

Values of “x” vary depending on annealing temperature and oxygen partial pressure during synthesis. As a result, oxygen vacancies form in the oxygen sub-lattice and n-type semiconducting is induced. To be neutral, some V$^{5+}$ ions will be reduced to V$^{4+}$ ions. Electrical conductivity in V$_2$O$_{5-x}$ is due to jumping (hopping) of the electrons from V$^{4+}$ ions to the neighboring V$^{5+}$ ions [26].

Compared with bulk V$_2$O$_5$, nanostructured V$_2$O$_5$ materials have unique electrical and chemical properties and due to their ultrafine sizes, they offer a high surface area which is extremely beneficial for sensing studies [27–30].

Nowadays gas sensors have become widely used in different areas for detection of toxic, hazardous, explosive and greenhouse gases and vapors [31,32]. There are many types of gas sensors. However, resistive-based gas sensors using metal oxides are the most widely used gas sensors due to their unique features such as low price, high sensitivity, high stability, fast dynamics and simple fabrication and operation [33,34]. Figure 1 shows a typical gas sensor substrate, where its front side is equipped with conductive electrodes such as with Pt and its back side is equipped with a heater [35]. Herein, we comprehensively discuss different aspects of the gas sensing properties of V$_2$O$_5$-based nanomaterials. Previously, only one review paper about gas sensing properties of vanadium oxides has been published [36], and herein, we have comprehensively discussed pristine, decorated, doped and composite forms of V$_2$O$_5$ nanostructured materials with different morphologies for the gas sensing studies.

**Figure 1.** (a) Front side of substrate equipped with electrodes, (b) back side of substrate equipped with a heater, (c) sensor holder [35].

### 2. Pristine Nanostructured V$_2$O$_5$ Gas Sensors

Pristine V$_2$O$_5$ gas sensors with different morphologies have been reported in the literature. In this section, we discuss some of most important pristine V$_2$O$_5$ gas sensors. The gas sensing characteristics of V$_2$O$_5$ hierarchical architectures, especially for hollow spheres are rarely reported in the literature. In this regard, V$_2$O$_5$ hollow spheres (500–550 nm in diameter and a shell thickness of 55 nm) were synthesized through a solvothermal route. The hollow spheres were comprised of nanoplates with thicknesses of 50–80 nm and lengths of 70–120 nm. Moreover, for comparison solid nanostructured
spheres were fabricated. The maximum responses ($R_a/R_g$) to trimethylamine (TEA) at 370 °C were 9.7 for $V_2O_5$ hollow spheres and 3.08 for $V_2O_5$ solid spheres, respectively. In fact, the hollow sphere hierarchical architecture with a higher surface area offered more adsorption sites for TEA molecules and a higher response for hollow spheres resulted. The sensing mechanism of the sensor to TEA was related to the reduction of $V^{5+}$ to $V^{4+}$ ions in the presence of TEA. Furthermore, based on XPS studies there was a slight shift to lower binding energy values after exposure of the sensor to TEA gas, confirming formation of $V^{4+}$ ions. In addition, a color change from yellow to dark blue was observed, further confirming the formation of $V^{4+}$ ions. $V_2O_5$ is an acidic oxide, which is highly suitable for the adsorption of basic molecules, such as TEA and consequently a larger response of the $V_2O_5$ hollow spheres sensor to TEA resulted [37].

Generally, resistive based gas sensors work at high temperatures, which need external heaters and increase the power consumption. Therefore, development of room temperature gas sensors not only solves above problems, but also integration with flexible substrates become easier. Furthermore, possible risk of explosion during sensing of explosive gases such as H$_2$ gas significantly decreases. Hollow spheres comprising numerous nanocrystals of $V_2O_5$ as a shell were synthesized by a facile polyol approach for room temperature hydrogen gas sensing. The surface area of hollow spheres was about 356 m$^2$/g and, therefore, it provided a large active surface area for adsorption of target gases. Furthermore, its porous structure led to further enhancement of gas reactions. Furthermore, the sharp corners as well as the edges of the tiny building blocks of hollow spheres were reported as highly active sites for enhancement of the sensing reactions during hydrogen sensing [38].

Another room temperature gas sensor was realized from $V_2O_5$ nanoneedles which were synthesized by a physical vapor deposition method [39]. The sensor exhibited a response ($R_a/R_g$) of 2.37 to 140 ppm acetone at room temperature. The relevant reaction was as follows:

$$(CH_3)_2CO + 4 O_2^- \rightarrow 3CO_2 + 3H_2O + 4e^- \quad (2)$$

The most energetically favorable gas reaction is that a surface oxygen atom attacks the carbonyl carbon to form a C-O bond. Acetone contains the carbonyl group and because of the greater electronegativity of oxygen; a carbonyl group is a polar functional group and, therefore, it has a larger dipole moment ($D = 2.88$), relative to other tested gases, leading to the higher response of the gas sensor to acetone.

Trimethylamine (TMA; (CH$_3$)$_3$N)) is generated from dead fish and, therefore, the concentration of TMA is an indicator of the freshness of fish [40]. Furthermore, exposure to TMA vapor can cause nausea, headaches, and irritation to the eyes [41]. In this regard, spherical $V_2O_5$ hierarchical nanostructures comprised of plenty of nanosheets were produced through a hydrothermal method. The optimal sensor based on spherical $V_2O_5$ hierarchical nanostructures displayed a response of ~2.8 to 100 ppm TMA along with fast response/recovery times (5/28 s) at 240 °C. The spherical $V_2O_5$ nanostructures were comprised of numerous monocrystalline nanosheets, and therefore they have a unique three-dimensional hierarchical structure which provided plenty of active sites for gas molecules. Accordingly, the reaction between chemisorbed oxygen ions and TMA molecules, resulted in a decrease in electrical resistance and contributed to the sensor signal.

$$2(CH_3)_3N+21O^-(ads)\rightarrow N_2+6CO_2+9H_2O+21e^- \quad (3)$$

In addition, in a monocrystalline structure free electrons were able to transfer faster than in a polycrystalline structure, which results in fast response and recovery times of gas sensors and improvement of sensing properties [42].

In another study related to TMA detection, Meng et al. [43] reported the synthesis of $V_2O_5$ flower-like structures assembled by thin nanosheets by the hydrothermal process for TMA sensing researchers. Optimal gas sensors exhibited a response ($R_a/R_g$) of 2.2 to 5 ppm TMA at 200 °C with
long-term stability and good selectivity. The good selectivity was related to the low C=N bond energy and high electron cloud density around N atoms in TMA.

One-dimensional V$_2$O$_5$ nanostructures such as nanorods (NRs) are also very popular for gas sensing purposes [44]. In an effort by Raj et al. [45], V$_2$O$_5$ NRs with diameters in the range of 100–200 nm were synthesized using a solvothermal method. The gas sensor was fabricated in a pelletized form of V$_2$O$_5$ NRs and it showed higher response (R$_a$/R$_g$) to 5 ppm ethanol (1.04) relative to 5 ppm ammonia (1.02). However, not only were the response values low, but also the sensor did not show selectivity to ethanol gas. This can be due to the low surface area of gas sensor, resulting from the dense pellet form of the gas sensor which limited available adsorption sites for the target gas molecules. In another similar study using a pellet form of V$_2$O$_5$ nanostructures, Raj et al. [46] synthesized V$_2$O$_5$ nanostructures with nanoflower morphology via a co-precipitation method. The sensor showed very poor selectivity, and its response to ammonia and ethanol was almost the same.

1-buthylamine is extensively used in many industrial fields. However, it is toxic and harmful for human health and the environment. Moreover, it is not only toxic for human beings, but also is flammable and corrosive [47]. In another study regarding 1-D materials, the role of bottom and top electrodes on the gas response of V$_2$O$_5$ nanofibers (NFs) to 1-buthylamine was investigated [48]. Both bottom electrodes (Type I), or top electrodes (Types II and III) were used. In Type I, interdigitated Au electrodes were applied. Moreover, interdigitated gold electrodes in Type II and III had different gap sizes of 5 nm and 150 nm, respectively. The target gas can be adsorbed as follows (i) intercalation adsorption into the layered structure of the fibers or adsorption on their surface, (ii) adsorption between the inter-fiber contacts, and (iii) adsorption between the fibers and the electrode surface. Only the sensor with bottom electrodes had all three adsorption sites and, accordingly, its response was higher relative to other gas sensors.

In another study related to detection of 1-buthylamine, hierarchical nanosheet-assembled V$_2$O$_5$ microflowers were hydrothermally synthesized. The gas sensor showed a higher response (∼3 times) to 1-buthylamine than the commercial V$_2$O$_5$ particles at 300 °C. The higher response of the flower-like V$_2$O$_5$ particles was related to the higher surface area and the unique structure of synthesized particles. The high selectivity of the V$_2$O$_5$ microflower sensor to 1-buthylamine was related to the selective oxidation of 1-buthylamine on the surface of V$_2$O$_5$. In fact, selective oxidation of primary amines is possible in the presence of vanadic acids. The V$_2$O$_5$ particles showed vanadic acids-like behavior due to interaction between the water molecules on the surface of the sensor, and ultimately this led to better selective oxidation of 1-buthylamine, resulting in a higher response to 1-buthylamine than other tested gases [49].

Yang et al. synthesized flower-like hierarchical V$_2$O$_5$ nanostructures by a hydrothermal method (Figure 2a–d) for 1-buthylamine sensing applications [47]. At 140 °C, the sensor showed a response (R$_a$/R$_g$) of 2.6 to 100 ppm 1-buthylamine with a fast response time of 6 s. On the other hand, the peculiar morphology of the sensing layer with an open structure and high surface area facilitated the adsorption and diffusion of the oxygen and 1-buthylamine. On the other hand, the intercalation of ammonium ions into the layered structures of V$_2$O$_5$ affected the sensing response, where the distances between the layers were changed upon ammonia intercalation, contributing to the resistance change of the gas sensor [47].

The effect of the crystallization temperature on the gas response of V$_2$O$_5$ NFs was investigated by Modaferri et al. [50]. They successfully prepared V$_2$O$_5$ NFs using an electrospinning technique. The samples were crystallized at 300, 400 and 500 °C. The sensor crystallized at 400 °C showed the highest response to ammonia gas at 250 °C. The improved sensing response was related to the more porous structure of this sensor. With increasing sensor porosity, more adsorption sites can be provided for the NH$_3$ molecules. Furthermore, gas molecules can effectively diffuse into the deeper parts of the gas sensor and increases the reactions with already adsorbed oxygen species. Overall, a higher response is expected for more porous structures.
Methane (CH₄) is one of the greenhouse gases which is much more effective at heat trapping in the atmosphere than CO₂. Furthermore, the leakage of methane from pipelines is highly dangerous for human beings. Therefore, the detection of CH₄ is important from different aspects [51]. The morphology dependence of V₂O₅ to methane gas was investigated for V₂O₅ nanostructures. Using a magnetron sputtering technique and under different sputtering powers of 100, 125 and 150 W, V₂O₅ nanostructures were synthesized with three different morphologies, where the morphology of films deposited at 100 W was NR, 125 was nanourchin and 150 W was nanoflower [52]. The resistance of NRs, nano-urchins and nanoflowers were ~15.4, 8.8 and 1.8 MΩ at room temperature (24 °C) as shown in Figure 3a. The nanoflower sensor revealed a higher sensor response among all the gas sensors at 100 °C. The nanoflower sensor displayed a higher sensing response (ΔR/R_a) of 11.2% than NRs and the nano-urchin which had sensing responses of about 8.9 and 9.1% to 500 ppm CH₄ (Figure 3b–d). Enhanced response was related to the morphology of nanoflowers which were comprised of nanosheets as building blocks that eventually provided more active sites for CH₄. Furthermore, they had some voids which led to faster transfer of gases and gas sensing reactions. However, both NRs and nano-urchins had dense structures, limiting their adsorption sites as well as effective diffusion of gases to the depth parts of sensors. The good selectivity to CH₄ relative to H₂ gas was due to the difference in bond dissociation energies of C–H (413 kJ/mol) and H–H (432 kJ/mol). Owing to weaker bond dissociation energy of C–H than H–H, the reaction between C–H and V₂O₅ was easier and hence the sensor response was higher to CH₄ gas relative to H₂ gas.
Helium (He) is a non-flammable gas and the second lightest element on earth, hence it is used in aero structures. Since it is an inert gas, its detection is extremely difficult with common gas sensors [55]. However, He has a relatively low atomic mass and small size, which greatly facilitates its diffusion.
along the sensing layer. In an interesting study, a He gas sensor was introduced by Chauhan et al. [55]. They synthesized V$_2$O$_5$·1.6H$_2$O nanowires (NWs) and V$_2$O$_5$·1.6H$_2$O nanostars with BET surface areas of 3.58 m$^2$/g and 8.38 m$^2$/g, respectively. In fact, nanostar shapes consisted of sharp edges and therefore offered a higher surface area and a higher response, while NWs were stacked together, limiting the gas diffusion and exhibiting a lower response. Hydrated V$_2$O$_5$ contained both vanadium ions (V$^{4+}$ and V$^{5+}$) which act as hopping sites for Polaron. The interaction of helium molecules with the V$_2$O$_5$·1.6H$_2$O nanostructures decreased the average hopping distance, resulting in an increase in the conductivity of the sensing layer. The hopping distance decreased due to an increase in hopping sites in the presence of He gas. This was due to the fact that the He gas molecule itself acted as a hopping site for charge transfer (Figure 5).

Figure 5. Sensing mechanism of hydrated V$_2$O$_5$ gas sensor to He gas [55].

Spray pyrolysis is a simple and inexpensive deposition technique which is able to deposit a large surface area with good uniformity. The effect of substrate temperature on the final sensing performance of V$_2$O$_5$ films to NO$_2$ gas deposited by the spray pyrolysis technique was investigated [2]. The prepared solutions were sprayed onto the glass substrate at different substrate temperatures of 350, 400, 450 and 500 °C (Figure 6). Gas sensing studies showed that the V$_2$O$_5$ thin film sensor deposited at 400 °C had the highest response to NO$_2$ gas at 200 °C.

Figure 6. Deposition of V$_2$O$_5$ thin films at different substrate temperatures [2].
At high substrate temperatures, the formation of reduced $V_2O_{5-x}$ species led to formation of oxygen vacancies. These oxygen vacancies enhanced adsorption of NO$_2$ gas molecules on the sensing layer. However, for the samples deposited at higher temperature, even though it was expected that more oxygen vacancies be produced, particle sizes also were larger. Therefore, the sample deposited at 400 °C, showed the optimal values of oxygen vacancies along with high surface area, which finally resulted in the best sensing response to NO$_2$ gas.

In another similar study, the $V_2O_5$ NRs were spray deposited onto the glass substrates at 400 °C using VCl$_3$ solutions with different concentrations of 10 to 40 mM. The $V_2O_5$ NRs deposited with 30 mM solution exhibited the highest gas response of 24.2% to 100 ppm NO$_2$ gas at 200 °C with response and recovery times of 13 s and 140 s, respectively. The improved sensing response of the optimized gas sensor was attributed to high crystallinity of sensing layer and the formation of a porous structure in which diffusion of gas molecules was facilitated into the depth parts of gas sensor [56].

In another study related to spray pyrolysis deposition technique, nanostructured $V_2O_5$ thin films were spray deposited on the glass substrates. Initial solutions had different concentrations of 0.025 to 0.1 M [57]. It was found that the sensor fabricated from the solution with initial concentration of 0.1 M had the highest sensing performance. In this sensor, a high surface area due to high surface roughness was obtained which significantly increased the response to xylene gas. Initially in air, oxygen molecules were adsorbed on the surface of the gas sensor as follows:

$$O_2(g)\rightarrow O_2(ads) \quad (4)$$

$$O_2(ads)+e^-\rightarrow O_2^- (ads) \quad (5)$$

$$O_2^- (ads)+e^-\rightarrow 2O^- (ads) \quad (6)$$

$$O^- (ads)+e^-\rightarrow O^2^- (ads) \quad (7)$$

Then, the following reaction occurred between the xylene and adsorbed oxygen species:

$$C_8H_{10}+21O^- \rightarrow 16CO_2+10H_2O+21e^- \quad (8)$$

Accordingly, the conductivity of the sensor significantly increased, and led to the appearance of a sensing signal. To demonstrate the formation of CO$_2$ as a byproduct of sensing reactions, a lime water test was conducted. Initially, a solution of saturated Ca(OH)$_2$ with a clear color was prepared. Upon introduction of xylene into the gas chamber, due to the conversion of saturated Ca(OH)$_2$ into CaCO$_3$, its color was changed to milky, confirming the release of CO$_2$ as a byproduct of sensing reaction [53].

Jin et al. [58], prepared random alignment $V_2O_5$ NW and $V_2O_5$ NW microyarn gas sensors for ethanol sensing studies. The response of the microyarn gas sensors reached the maximum value of 9.09 for 1000 ppm ethanol at 330 °C, which was ~3.5 times higher than that of the random alignment NWs (Figure 7). For the random oriented NWs, electrons in their pathways encountered a network of NWs. Accordingly, they should overcome two potential barriers namely (i) electrode–$V_2O_5$ barriers, and (ii) $V_2O_5$–$V_2O_5$ homojunctions barriers. For the microyarn gas sensor, the agglomeration of NWs was prevented effectively, resulting in the exposing of a larger surface area to target gas. In addition, the orderly assembled yarns provided a direct path for flow of electrons, leading to a high response to ethanol gas.
Plasma focus (PF) is a pulse plasma device which generates high temperatures and high density of a plasma column very fast. PF has a high deposition rate, energetic deposition process as well as the ability of working in the presence of reactive gases. In an attempt, V$_2$O$_5$ thin films were prepared by the PF technique using different shots [59]. It was found that the surface morphology of deposited samples had a key role in the gas response of deposited films. A V$_2$O$_5$ thin film prepared with ten shots exhibited the highest H$_2$ gas response among all the gas sensors at 275 °C. The higher response of the optimized gas sensor can be related to the presence of more oxygen vacancies as well as higher surface area as a result of rougher morphology.

Effect of V$_2$O$_5$ film thickness also has been investigated. The nanocrystalline V$_2$O$_5$ thin films with different thicknesses of 423, 559, 694 and 730 nm were deposited onto the glass substrates using a spray pyrolysis technique. The V$_2$O$_5$ film with a thickness 559 nm revealed the highest response (41% to 100 ppm NO$_2$ at 200 °C) due to the higher surface area [60]. This study shows the need for the optimization of film thickness to achieve the best sensing performance.

Table 1 presents the gas sensing characteristics of pristine V$_2$O$_5$ gas sensors, where different morphologies of V$_2$O$_5$ prepared using various methods have been successful for sensing of different gases.

![Figure 7. Response curve of sensors to 1000 ppm ethanol at 330 °C: (a) randomly oriented V$_2$O$_5$ NWs and (b) orderly assembled V$_2$O$_5$ NW microyarns [58].](image)
Table 1. Cont.

| V2O5 Morphology | Synthesis Method       | Target Gas          | Conc. (ppm) | Response (R_a/R_g) or (R_g/R_a) | T (°C) | Response time/Recovery Time (s) | Ref.  |
|-----------------|------------------------|---------------------|-------------|-------------------------------|--------|-------------------------------|-------|
| Flower-like     | Hydrothermal           | 1-butylamine        | 100         | 2.6                           | 140    | 9/49                          | [47]  |
| Nanofibers      | Electrospinning        | Hydrothermal        | 9.5         | 500 *                         | RT     | /−                           | [48]  |
| Flower-like     | Hydrothermal           | 1-butylamine        | 100         | 3.6                           | 300    | 25/14                        | [49]  |
| Sheet-like      | Hydrothermal           | 1-butylamine        | 2.8         | 300                           | 17/14  | /−                           |       |
| Nanofibers      | Sol–gel NH3            |                     | 2.1         |                               |        | 50/350                       |       |
| Flower-like     | DC sputtering CH4      |                     | 11 *        |                               | 100    | 236/247                      | [50]  |
| Hydrothermal    | C8H10                  |                     | 3           | 300                           | 44/74  |                               | [54]  |
| Nano stars      | Hydrothermal           | He                  | 300         | 53 *                          | RT     | 9/10                         | [55]  |
| Nanorods        | Chemical spray         | NO2                 | 100         | 24.2                          | 200    | 13/14                        | [56]  |
|                  | pyrolysis              |                     |             |                               |        |                               |       |
| Nanofibers      | Chemical spray         | C8H10               | 27          | RT                            | 80/50  |                               | [57]  |
|                  | pyrolysis              |                     |             |                               |        |                               |       |
| Nanowires       | Melt quenching         | C2H5OH              | 1000        | 9.09                          | 330    | /−                           | [58]  |
|                  | Chemical spray         | NO2                 | 100         | 50 *                          | 275    | /−                           | [59]  |
| Thin film       | Plasma focus method    | H2                  |             |                               |        |                               |       |
|                  | Chemical spray         | NO2                 |             |                               |        |                               |       |

* Response = \( \frac{\Delta R}{R_a} \times 100; \) RT: Room temperature; PVD: Physical vapor deposition; CVD: Chemical vapor deposition.

3. Decorated/Doped V2O5 Gas Sensors

Based on the above section about pristine V2O5 gas sensors, pristine V2O5 nanostructures suffer from low sensitivity and selectivity, which hinder their applications for sensing applications [61]. Accordingly, different strategies, such as p-n heterojunction formation [62], n-n heterojunction formation [63,64] and noble metal decoration [65] have been proposed to enhance their sensing properties. In the following section, we will discuss different aspects of such gas sensors based on V2O5 nanostructures.

V2O5 decoration is a good strategy to enhance the sensing properties of gas sensors. V2O5-decorated α-Fe2O3 composite NRs were prepared by an electrospinning technique and they had a high surface area of 30.5 m2/g. The composite exhibited a response (R_a/R_g) of 9 to 100 ppm diethylamine along with good selectivity to diethylamine gas and a fast response time of 2 s at 350 °C [66]. Improved sensing performance was related to the formation of V2O5-Fe2O3 heterojunctions and catalytic effect of V2O5 to diethylamine.

In another study, Ko et al. [67], decorated V2O5 nanoislands on the surface of SnO2 NWs using different cycles of atomic layer deposition (ALD) and the effect of ALD cycles was investigated. It was found that the sensor with 50 ALD cycles showed the highest response to NO2 gas. In particular its response to 200 ppb NO2 was ~3.7 at 250 °C. Figure 8a,b displays the energy band diagrams of the sensing layer, before and after equilibrium. V2O5 nanoislands on the SnO2 NWs improved the sensing response by generation of depletion layers at the V2O5/SnO2 interface and modulation of the SnO2 conduction channel. However, the excess amount of V2O5 nanoislands deposited by a higher number of ALD cycles, resulted in the decrease in sensor response. The density functional theory (DFT) calculations shown in Figure 8c, regarding NO2 adsorption energies of both the SnO2 (1 0 1) and V2O5 (0 0 1) planes were −1.5 eV and 1.0 eV, respectively. Thus, it was concluded that the SnO2 surface was more favorable for adsorption of NO2 relative to V2O5. Therefore, the excess amount of V2O5 on the surface of SnO2 (Figure 8d), resulted in a significant decrease in the gas response due to limited exposure of SnO2 to NO2 gas.
which are useful for gas sensing applications [74]. In a relevant study, an RGO surface was decorated with Mn$_3$O$_4$ and V$_2$O$_5$ NOs via a hydrothermal method for detection of H$_2$ gas at 30 °C. The sensor showed a high response ($\Delta R/R_0 \times 100$) of 174% to 50 ppm H$_2$ gas at room temperature. The sheet-like structure of RGO provided a large surface area for gas sensing reactions. In addition, because of the formation of p-n (RGO-V$_2$O$_5$) and p-p (RGO-Mn$_3$O$_4$) heterojunctions, significant modulation of resistance in the presence of H$_2$ occurred, resulting in the generation of a sensing signal [75]. In another study, a V$_2$O$_5$ thin film was prepared by a reactive sputtering technique and then, RGO was decorated over the V$_2$O$_5$ thin film by a drop casting method for NO$_2$ sensing studies. The sensor showed a response of 50.7% to 100 ppm NO$_2$ gas at 150 °C. However, its recovery time was long (778 s). Formation and modulation of the p-n heterojunction at the interface of RGO and V$_2$O$_5$ was the main reason for the bulks.

Porous silicon (PS) is a good candidate for sensing studies due to its offering of a high surface area and a porous structure. In addition it can be simply prepared by a chemical etching process [68]. Therefore, composites between V$_2$O$_5$ and PS can be promising for gas sensing studies. In a relevant study, thin V films were decorated on the PS by sputtering at different times of 30 and 60 min and then, the samples were annealed at 600 °C [69]. The PS/V$_2$O$_5$ NRs structure provided a better response than pristine PS at 25 °C, and the sensor sputtered for 60 min exhibited the highest response of 7.4 to 2 ppm NO$_2$ gas. Both the PS and V$_2$O$_5$ NRs had plenty of dangling bonds, oxygen vacancies and defects, leading to high adsorption of oxygen molecules even at room temperature. In the interfaces between PS and V$_2$O$_5$, p-n heterojunctions formed and, upon exposure to NO$_2$ gas, the significant modulation of electrical resistance in the heterojunctions led to the appearance of a sensing signal.

Graphene and its derivations such as graphene oxide and reduced graphene oxide have high surface areas and unique electrical properties which can be beneficial for gas sensing studies [70,71]. The initial resistance of the GO is high, limiting its practical applications in pristine form [72,73]. However, after the reduction GO to RGO, there are some defects, vacancies and functional groups which are useful for gas sensing applications [74]. In a relevant study, an RGO surface was decorated with Mn$_3$O$_4$ and V$_2$O$_5$ NOs via a hydrothermal method for detection of H$_2$ gas at 30 °C. The sensor showed a high response ($\Delta R/R_0 \times 100$) of 174% to 50 ppm H$_2$ gas at room temperature. The sheet-like structure of RGO provided a large surface area for gas sensing reactions. In addition, because of the formation of p-n (RGO-V$_2$O$_5$) and p-p (RGO-Mn$_3$O$_4$) heterojunctions, significant modulation of resistance in the presence of H$_2$ occurred, resulting in the generation of a sensing signal [75]. In another study, a V$_2$O$_5$ thin film was prepared by a reactive sputtering technique and then, RGO was decorated over the V$_2$O$_5$ thin film by a drop casting method for NO$_2$ sensing studies. The sensor showed a response of 50.7% to 100 ppm NO$_2$ gas at 150 °C. However, its recovery time was long (778 s). Formation and modulation of the p-n heterojunction at the interface of RGO and V$_2$O$_5$ was the main reason for the

**Figure 8.** (a,b) Energy band diagrams of SnO$_2$-V$_2$O$_5$ before and after contact in air. (c) NO$_2$ adsorption on SnO$_2$ (101) V$_2$O$_5$ (001) surfaces. (d) Effect of number of ALD cycles and amount of V$_2$O$_5$ on the surface of SnO$_2$ [67].
detection of NO₂ gas. Moreover, the presence of active sites such as oxygen functional groups on the RGO surface improved the sensing response [76].

Not only can V₂O₅-decoration be a useful technique to enhance the gas sensing properties, but decoration of other metal oxides or noble metals on the surface of gas sensor can also be a good technique to improve the gas sensing properties of V₂O₅-based gas sensors. A P-type CuO with excellent catalytic activity is extensively used for sensing studies [77]. The work function of CuO is 5.3 eV, which is different to that of V₂O₅ (4.7 eV). Therefore, when heterojunctions form between the CuO and V₂O₅, enhanced gas response can be expected. In this context, hollow nanostructures using CuO decorated V₂O₅ nano-strings of pearls were fabricated through an electrosprinning method. The V₂O₅/CuO sensors demonstrated a response (Rₐ/Rₕ) of 8.8 to 500 ppm acetone at 440 °C, which was more than three times higher than that of bare V₂O₅ NFs. The improved performance was related to the generation of CuO/V₂O₅ p-n heterojunctions, which provided plenty of resistance modulation sources and upon exposure to acetone gas higher response was resulted [78].

In another relevant study, CuO NPs-decorated V₂O₅ NWs were fabricated by a two-step process, by combination of hydrothermal and wet-deposition methods [79]. The H₂S response of the sensor was 31.86 to 23 ppm of H₂S at 220 °C. The high response was related to the p-n junction formed at the interface between CuO and V₂O₅ along with conversion of CuO to metallic-like CuS. In air, the potential barriers were formed in the interfaces between two materials. Upon injection of H₂S, the CuO was converted to CuS with metallic-like conductivity. Accordingly, the height of the junction was significantly decreased, resulting in great modulation of electrical resistance and a high response to H₂S resulted.

SnO₂ NPs-decorated V₂O₅ NWs were realized by a two-step mild hydrothermal route for sensing applications [80]. The sensor showed a response of ~16 to 1000 ppm ethanol which was three times higher than that of pristine V₂O₅ NWs. The higher response of the gas sensor was explained on the basis of formation of heterojunctions between the SnO₂ and V₂O₅, formation of V₂O₅- V₂O₅ homojunctions due to networked nature of synthesized V₂O₅ NWs, high intrinsic sensing properties of SnO₂ NPs and efficient electron transport along the conduction band of V₂O₅ NWs.

Fe₂O₃-decorated V₂O₅ nanotubes were fabricated using a two-step rheological phase reaction and hydrothermal synthesis for sensing studies. The sensor exhibited a response (Rₐ/Rₕ) of 2.2 to 1000 ppm ethanol which was slightly higher than the response to toluene gas with the same concentration with a response of 1.5 at 270 °C [81]. However, the authors did not report selectivity of gas sensors over different gases.

Ozone (O₃) is a strong oxidizing gas that can affect the human body severely. TiO₂ NPs were decorated on V₂O₅ NWs via a hydrothermal method for ozone sensing studies. The pristine TiO₂ sensor was not sensitive to O₃ gas. The sensor showed a response of 2.6 (ΔR/Rₕ) to 1.25 ppm O₃ gas at 300 °C, while almost no response was recorded for the pristine TiO₂ sensor. When the sensor was exposed to O₃ gas, following reactions took place [82]:

\[
\begin{align*}
O_3(g) + e^- & \rightarrow O_3^{(ads)} \quad (9) \\
O_3^{(ads)} + O_2^{(ads)} + 2e^- & \rightarrow O_2(g) + 2O_2^{(ads)} \quad (10)
\end{align*}
\]

As a result, electrons were extracted from the surface of the gas sensor and changed the height of potential barriers formed between TiO₂ and V₂O₅. This led to a generation of a sensing signal to O₃ gas.

Noble metal decoration is also a good strategy to enhance sensing properties [83]. V₂O₅ nanoflowers were synthesized via a hydrothermal route and then they were decorated with Au NPs at different loading levels of 0.5, 1.5, 2.5, 3.5, and 5 mol%. The optimal gas sensor with a 3.5 mol% Au NPs showed a response (Rₐ/Rₕ) of ~7.3 to 100 ppm 1-buthylamine at 240 °C, while the response of the pristine gas sensor to the same concentration of 1-buthylamine gas was only 3 at 300 °C. Since there
was negligible difference in the surface area among all samples, the enhanced gas sensing response for the sensor with 3.5 mol% Au NPs was related to the chemical and electronic effects of Au [84].

In another study using the decoration of noble metals on the surface of V$_2$O$_5$, Sanger et al. [85], deposited a Pd/V$_2$O$_5$ thin film by DC magnetron reactive sputtering for H$_2$ gas sensing studies. The deposition of V and Pd were performed at 300 °C for 60 min and 10 s, respectively. A very fast response within 6 s, recovery time of 21 s and a response of 5 was recorded for 100 ppm of H$_2$.

A gasochromic mechanism was proposed for H$_2$ gas sensing, where, based on XPS studies, the formation of vanadium bronze (H$_x$V$_2$O$_5$) was confirmed by an increase in the intensity of the V$^{4+}$ peaks. Furthermore, Pd dissociated hydrogen molecules into atomic hydrogen and subsequently, they were spilled over onto the V$_2$O$_5$ surface, to react with adsorbed oxygen species. Thus, V$_2$O$_5$ was converted to vanadium bronze, with a simultaneous color change from light yellow to light blue.

Generally, only one type of material is used for decoration. However, co-decoration can have more effect on the gas response of gas sensors. For example, it was found that co-decoration of V$_2$O$_5$ and Pd on the surface of SnO$_2$ NPs can significantly enhance both the response of gas sensor to H$_2$ gas and at the same time, it can decrease the recovery time of the gas sensor [86]. It was reported that during the recovery time, re-oxidization of V$_2$O$_5$ led to increase in the recovery time. However, the presence of Pd, significantly decreased the recovery time due to the fact that Pd not only was effective in hydroxyl desorption and oxygen re-adsorption on the SnO$_2$ surface but also it significantly accelerated the re-oxidization of V$_2$O$_5$. Accordingly, co-loading of V$_2$O$_5$ and Pd resulted in a complementarity effect, which improves the sensor response and recovery time at the same time.

Benzene (C$_6$H$_6$) is extensively used as an organic solvent. However, it is a toxic substance, leading to leukemia and lymphomas diseases [87]. V$_2$O$_5$ as dopant has been rarely used for gas sensing studies. A series of pristine and V$_2$O$_5$-doped SnO$_2$ NFs (V$_2$O$_5$/SnO$_2$ = 0.5, 1, 2.5 and 5 mol%) were synthesized via electrospinning for benzene sensing studies [88]. It was reported that the sensor with V$_2$O$_5$/SnO$_2$ = 1 exhibited the highest response to benzene (6.32 at 325 °C to 25 ppm). V$_2$O$_5$ catalyzed benzene into maleic anhydride and activated the benzene ring, resulting in better interaction with adsorbed oxygen species. However, a decrease in gas response for higher doping levels was related to the evaluation of a more compact structure, leading to lower adsorption sites and a lower sensing response.

Table 2 shows the gas sensing properties of decorated or doped V$_2$O$_5$-based gas sensors, where different synthesis methods along with different morphologies and various materials have been reported to realize gas sensors for the sensing of toxic gases.

### Table 2. Gas sensing properties of decorated or doped V$_2$O$_5$-based gas sensors.

| Sensor | Synthesis Method | Target Gas | Conc. (ppm) | Response (R$_e$/R$_a$) or (R$_g$/R$_a$) | Working Temp. (°C) | Response Time/Recovery Time(s) | Ref. |
|--------|-----------------|------------|-------------|--------------------------------------|-------------------|-----------------------------|------|
| Pd decorated porous Sn/V$_2$O$_5$ nanopillars | DC sputtering | NO$_2$ | 2 | 4.5 | RT | 7 | [62] |
| Ru-decorated layer structure V$_2$O$_5$ | Hydrothermal | NH$_3$ | 130 | 4 | RT | -2/-12 | [65] |
| V$_2$O$_5$-decorated α-Fe$_2$O$_3$ nanorods | Electrospinning | C$_2$H$_2$N | 300 | 9 | 350 | 2/40 | [66] |
| V$_2$O$_5$-decorated Sn$_2$O$_3$ NWs | VLS/ALD | NO$_2$ | 200 ppm | 3.6 | 250 | γ | [67] |
| Porous Sn/V$_2$O$_5$ NR composite | Galvanostatic electrochemical etching | NO$_2$ | 2 | 7.4 | RT | γ | [69] |
| rGO/MnO$_x$/V$_2$O$_5$ nanocomposite | Hydrothermal | H$_2$ | 50 | 175 | RT | 82/92 | [73] |
| Pd-decorated CuO NWs | UV irradiation | H$_2$S | 100 | 1.962 | 100 | γ | [76] |
| V$_2$O$_5$/CuO nano-string of pearls | Electrospinning | C$_2$H$_2$O | 500 | 9 | 440 | ~40/~100 | [78] |
| CuO-decorated V$_2$O$_5$ NWs | Hydrothermal and wet-deposition | H$_2$S | 23 | 31.86 | 220 | 130/218 | [79] |
4. Nanocomposites/Nanohybrids of V$_2$O$_5$ Gas Sensors

Core-shell (C-S) nanocomposites are among the most promising structures for gas sensing studies, as in these structures the interfaces between two different materials are maximized, resulting in significant modulation of electrical resistance upon exposure to target gases [89–91]. Fu et al. [40], synthesized V$_2$O$_5$–TiO$_2$ core-shell (C-S) NPs for NH$_3$ studies. For pristine V$_2$O$_5$ NPs, the surface area was only ~16 m$^2$g$^{-1}$ with a pore size of 12.9 nm, while the BET surface area of V$_2$O$_5$@TiO$_2$ C-S NPs was greatly increased to ~151 m$^2$g$^{-1}$, and the average pore size was ~6.4 nm. Thus, the significant increase in surface area was an advantage for C-S NPs, which directly affected the gas sensing studies. The C-S sensor showed a response (R$_a$/R$_g$) of 8.6 to 100 ppm ammonia at 365 °C. Upon intimate contact between the V$_2$O$_5$ and TiO$_2$, electrons moved from TiO$_2$ to V$_2$O$_5$, resulting in the creation of an electron depletion layer on both sides of the TiO$_2$ shell layer. Upon injection of NH$_3$ gas into the gas chamber, the electrons released back caused the narrowing of the electron depletion layers which finally modulated the electrical resistances of the gas sensor. Moreover, based on DFT calculations, the NH$_3$ molecule showed the lowest adsorption energy (~1.04 eV) on the anatase TiO$_2$ (101) surface, which explained the higher selectivity of the gas sensor to NH$_3$ among other tested gases. The optimal sensing temperature of the gas sensor was registered at 365 °C. The reactions on the surface of TiO$_2$ can be shown as follows:

\[
\text{O}_2 + 4e^- \rightarrow 2\text{O}^{2-} \quad (11)
\]

\[
2\text{NH}_3 + 3\text{O}^{2-} \rightarrow \text{N}_2 + 3\text{H}_2\text{O} + 6e^- \quad (12)
\]

\[
2\text{NH}_3 + 4\text{O}^{2-} \rightarrow \text{N}_2\text{O} + 3\text{H}_2\text{O} + 8e^- \quad (13)
\]

\[
2\text{NH}_3 + 5\text{O}^{2-} \rightarrow 2\text{NO} + 3\text{H}_2\text{O} + 10e^- \quad (14)
\]

Thus, more electrons can be released when N$_2$O (x = 1, 2), demonstrating the high response toward NH$_3$ at elevated temperatures (>300 °C).

In another study related to C-S nanocomposites, V$_2$O$_5$/In$_2$O$_3$ C-S NRs were prepared using a solid solution synthesis method, followed by a hydrothermal method. In$_2$O$_3$ as shell, led to the increase in surface active sites for gas adsorption. The sensor showed a response (R$_a$/R$_g$) of 14 to 200 ppm n-propylamine at 190 °C. Higher selectivity of the sensor to n-propylamine was explained on the basis of selective oxidation of n-propylamine.

Additionally, presence of the two types of materials with different reduction-oxidation and acid-base properties affected the selectivity of the gas sensor to n-propylamine [92].

Combination of MoO$_3$, which has layered structure with V$_2$O$_5$ with high catalytic activity can be a good strategy for enhanced gas sensing performance of the MoO$_3$-V$_2$O$_5$ composite.

| Sensor | Synthesis Method | Target Gas | Conc. (ppm) | Response (R$_a$/R$_g$) or (R$_a$/R$_g$) | Working Temp. (°C) | Response Time/Recovery Time(s) | Ref. |
|--------|------------------|------------|-------------|-------------------------------------|---------------------|---------------------------------|------|
| SnO$_2$ NP-decorated V$_2$O$_5$ NWs | Hydrothermal | C$_2$H$_5$OH | 1000 | 1.3 | RT | 20 | [89] |
| Fe$_2$O$_3$ activated V$_2$O$_5$ nanotubes | Hydrolysis | C$_2$H$_5$OH | 1000 | 2.2 | 270 | ~180–180 | [81] |
| TiO$_2$-decorated V$_2$O$_5$ NWs | Hydrothermal | O$_2$ | 1.25 | 2.6 | 300 | ~180–180 | [82] |
| RGO-decorated V$_2$O$_5$ thin film | Reactive sputtering and drop casting | NO$_2$ | 100 | 50.7 | 150 | ~180–180 | [74] |
| Au NP-decorated V$_2$O$_5$ | Two-step in-situ reduction of Au and thermal oxidation as V$_2$O$_5$ | Amines | 100 | 7.5 | 240 | 90/35 | [81] |
| Pd-decorated V$_2$O$_5$ thin film | DC magnetron reactive sputtering | H$_2$ | 100 | 5.7 | 100 | ~6/14.8 | [85] |
| V$_2$O$_5$-doped SnO$_2$ NFs | Electrospinning | C$_2$H$_5$OH | 25 | 6.32 | 325 | 3/47 | [88] |

* Response = $\frac{Ra}{Rg}$ × 100; RT: Room temperature; VLS: Vapor-liquid-solid; NR: Nanorod; NP: Nanoparticle; NF: Nanofiber.
The (MoO$_3$)$_{1-x}$(V$_2$O$_5$)$_x$ thin films with $x = 0.2, 0.4, 0.6$ and $0.8$ were prepared using a chemical spray pyrolysis method. For (MoO$_3$)$_{0.4}$(V$_2$O$_5$)$_{0.6}$ thin film, a gas response of $80\%$ at $200 \degree C$ to $100$ ppm NO$_2$ gas was recorded [93]. The sensing layer with a sheet-like morphology and the presence of voids in its layered structure, provides a lot of adsorption sites for NO$_2$ gas molecules. In addition, NO$_2$ gas was able to diffuse into the depth parts of gas sensor, resulting in more interaction between the gas molecules and already adsorbed oxygen molecules. In another study which was conducted by the same group, Pd was decorated on the optimal gas sensor, (MoO$_3$)$_{0.4}$(V$_2$O$_5$)$_{0.6}$ and a higher gas response resulted due to the catalytic effect of Pd and formation of different heterojunctions [94].

Use of conducting polymers (CPs) can greatly decrease the sensing temperature of the resultant composite material. In this regard, Diniz et al. [95] used a poly(o-methoxyaniline) (POMA)–V$_2$O$_5$ hybrid composite film for NH$_3$ detection. POMA has an OCH$_3$ group which can improve the processability of POMA [96]. The function of V$_2$O$_5$ was to enhance the structural stability during the doping and dedoping of POMA when exposing it to NH$_3$ gas. The sensing mechanism is explained as follows. A p-n heterojunction was formed between the POMA–V$_2$O$_5$ hybrid and, by interaction with NH$_3$ gas, the wide of depletion layers and height of potential barriers decreased, resulting in resistance change of the hybrid composite film [95].

Even low concentrations of NH$_3$ can negatively affect skin and human respiratory organs. This led to the setting of the indoor exposure limit of NH$_3$ to 25 ppm [97]. Au-loaded flower-like V$_2$O$_5$/CuWO$_4$ nanocomposites were synthesized for NH$_3$ studies. The sensor showed a response ($R_a/R_h$) of 2.7 to 5 ppm NH$_3$ at $150 \degree C$, which was higher than the response to other gases. In addition to promising effects of heterojunctions formed between different sensing materials, the Au NPs facilitated the electron flow among the sensing materials and the NH$_3$ and thus a short response time of 35 s was recorded. In addition, Au NPs catalytically increase the dissociative adsorption of O$_2$ molecules as O$^-$ species and, in a so-called spillover process, atomic oxygen species moved to the surface of V$_2$O$_5$/CuWO$_4$, leading to wider depletion layer and acceleration of the gas reactions on the surface of the sensing layer [98].

Zhang et al. [99] developed a series of SnO$_2$/V$_2$O$_5$ composites for sensing of benzene, toluene, ethyl benzene, and xylene (BTEX) gases. At $270 \degree C$, the sensor with 10 wt% V$_2$O$_5$ showed the highest response to BTEX gases. It was reported that V$_2$O$_5$ catalyzed oxidation of benzene into a maleic anhydride, implying that V$_2$O$_5$ was able to activate the benzene ring, then benzene reacted with the absorbed oxygen species easily on the surface of SnO$_2$. The sensor response was decreased for the sensor with 20 wt% V$_2$O$_5$, which could be due to the fact that the intrinsic response of SnO$_2$ is higher than that of V$_2$O$_5$. In fact, when there is too much V$_2$O$_5$, the adsorption sites on the surfaces of SnO$_2$ decrease, leading to a decrease in sensor response [99].

The effect of the nature of polymer (PVP and PVAc) used for the electrospinning process on the sensing response of of V$_2$O$_5$-based gas sensors was investigated. At $260 \degree C$, the V$_2$O$_5$/PVP sensor, showed a response ($\Delta R/R_a \times 100$) of $-7$ to 0.8 ppm NH$_3$ gas which was slightly higher than that of the V$_2$O$_5$/PVA sensor. It was reported that the V$_2$O$_5$/PVP network was constituted of fibers with a smaller diameter which resulted in larger resistance modulation of the gas sensor. In fact, a larger part of the diameter of fibers with smaller diameters was depleted from electrons and this resulted in more intense resistance modulation upon exposure to target gas [100].

Layered V$_2$O$_5$/ZnV$_2$O$_5$ nanocomposites were synthesized via a chemical route for ethanol sensing applications [101]. The sensor revealed a response of $4.3$ to $100$ ppm ethanol at $240 \degree C$. The enhanced sensing properties were related to high mobility of electrons in the layered structure of the gas sensor along with the formation and subsequent modulation of potential barriers between V$_2$O$_5$ and ZnV$_2$O$_5$ in the presence of ethanol gas. Furthermore, TiO$_2$/V$_2$O$_5$ branched NFs were fabricated by an electrospinning process. The sensor showed a high response ($R_a/R_h$) of 24.6 to $100$ ppm ethanol at $350 \degree C$ which was attributed to the high surface area of the branched sensor (33.6 m$^2$/g) and the synergistic effects between TiO$_2$ and V$_2$O$_5$ upon intimate contact [102].
In another study, the effect of ZnO addition on the room temperature toluene sensing properties of ZnO/V$_2$O$_5$ nanocomposite thin films was systematically studied. ZnO/V$_2$O$_5$ nanocomposites were deposited using spray pyrolysis for the detection of toluene at 27 °C [103]. The response to toluene was improved by the addition of V$_2$O$_5$ to the ZnO thin film and the sensor with a composition of 70 wt% ZnO showed a response of 2.3 to 400 ppm toluene which was the highest response among the gas sensors. In fact, in a part formation of heterojunctions, the presence of V$_2$O$_5$ led to further adsorption of oxygen, and ZnO with intrinsic high sensing properties and high electron mobility also contributed to the sensing signal. Table 3 exhibits the sensing properties of various V$_2$O$_5$-based composite gas sensors, where different materials along with various morphologies have been used for sensing of different gases.

### Table 3. Gas sensing properties of V$_2$O$_5$-based composite gas sensors.

| Sensing Material | Synthesis Method | Target Gas | Conc. (Ppm) | Response ($R_a/R_g$) | $T$ (°C) | Response Time/Recovery Time(S) | Ref. |
|------------------|-----------------|------------|-------------|----------------------|----------|--------------------------------|------|
| V$_2$O$_5$/In$_2$O$_3$ core–shells | Hydrothermal | n-propylamine | 200 | 4 | 190 | 48/121 | [92] |
| MoO$_3$-V$_2$O$_5$ thin films | Chemical spray pyrolysis | NO$_2$ | 120 | 80* | 200 | 119/1182 | [93] |
| (MoO$_3$)$_{x}$-[V$_2$O$_5$]$_{1-x}$ sheet composite | Chemical spray pyrolysis | NH$_3$ | 100 | 115 | 39/453 | [94] |
| Au-V$_2$O$_5$/CuWO$_4$ composite | Hydrothermal | C$_2$H$_6$ | 5 | 2.7 | 150 | 35/53 | [95] |
| SnO$_2$/V$_2$O$_5$ composite | Sol-gel | C$_2$H$_4$ | 200 | 10.5 | 275 | 72 | [96] |
| V$_2$O$_5$/polyvinyl acetate NF composite | Electrospinning | NH$_3$ | 0.8 | 6* | 260 | 72 | [97] |
| V$_2$O$_5$/Zn$_2$O$_3$ nanobelt composite | Chemical route | C$_2$H$_5$OH | 2000 | 16.5 | 240 | 72 | [98] |
| TiO$_2$/V$_2$O$_5$ NF composite | Electrospinning | C$_2$H$_6$ | 100 | 24.6 | 350 | 67 | [99] |
| ZnO/V$_2$O$_5$ thin films | Spray pyrolysis | C$_2$H$_4$ | 400 | 2.3 | 27 | 23/28 | [100] |

* Response = $R_a/R_g$ × 100.

5. Conclusions and Outlook

In this review paper, we discuss different aspects of V$_2$O$_5$-based gas sensors. In general, pristine V$_2$O$_5$ gas sensors can show response to a variety of gases. In pristine form, V$_2$O$_5$ gas sensors with different morphologies can be synthesized by using physical methods such as reactive sputtering or by using chemical methods such as hydrothermal and sol–gel methods. Depending on the surface chemistry, morphology and sensing temperatures, the pristine V$_2$O$_5$ gas sensors show different response values to a specific gas. However, in general, the response and selectivity of pristine V$_2$O$_5$ gas sensors is poor. To enhance sensing performance of pristine gas sensors, noble metal decoration can be a good strategy. Noble metals such as Au, Pd and Pt can significantly enhance not only the response of ZnO, but also the selectivity to a specific gas. However, less attention has been paid to systematically optimize the amount of noble metals on the surface of V$_2$O$_5$ and most of researchers only investigated the effect of a specific amount of noble metals on the sensing performance. In addition, composites can also be a good strategy to further enhance the sensing properties such as response, selectivity and response and recovery times.

Formation of heterojunctions with n- or p-type materials is another strategy to increase the overall sensing performance. This strategy may be more cost-effective than noble metal decoration. Furthermore, composite making can be performed in one-step avoiding complex procedures associated with noble metal decoration. The height of heterojunction barriers changes upon exposure of gas sensors to target gases, leading to enhanced gas response.

Unfortunately, some aspects of V$_2$O$_5$-based gas sensors have not investigated yet. For example, the effects of ion-implantation and UV illumination have not reported yet. Furthermore, there is no report about operation of V$_2$O$_5$-based gas sensors in self-heating mode. Moreover, less attention has been paid to nanohybrids between V$_2$O$_5$ and CPs, which can significantly decrease the sensing temperature. In spite of great efforts and advances related to the V$_2$O$_5$-based gas sensors, the selectivity issue is still a serious problem and more works are necessary to solve it. Therefore, it is expected that
future studies related to V₂O₅-based gas sensors will be directed to explore these expected V₂O₅-based gas sensors.

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